Research on User Satisfaction of Charging Infrastructure

Jun Ma*, Qinrui Yang*
School of Automotive Studies, Tongji University, Shanghai, China

*Corresponding author e-mail: majun.tongji@foxmail.com, qinrui.yang@outlook.com

Abstract. With the development of electric vehicles, the charging infrastructure and services has become more and more promising. This paper focuses on the user satisfaction study of charging service. Based on the characteristics of electric vehicle charging infrastructure, the user satisfaction of charging service consists of four first-level indicators: using cost, hardware facilities in charging stations, charging station availability, service experience. Then the seconds-level indicators are defined under the first-level indicators respectively. Based on the identified electric vehicle charging infrastructure user cost model, the cost model is established, and the validity of the model is verified by specific cases, which provides a research framework and quantitative data analysis methods for the user satisfaction and user research of electric vehicle charging infrastructure.

1. Introduction
With the increasing number of new energy vehicles in China, the charging demand of new energy vehicles has increased accordingly. By the end of 2018, China had more than 760,000 charging piles, the highest number in the world, including about 300,000 public charging piles and about 460,000 private charging piles.

However, there are still some problems in the current charging infrastructure restricting the development. There is still a large gap in charging facilities. For example, the construction cost of charging piles is high, and the layout of charging piles is irrational. From the user's point of view, the satisfaction of charging service status is low. There is less systematic research on the customer satisfaction of charging service due to lack of quantitative analysis. [1].

Based on the analysis above, we start using hierarchical analysis to break down user satisfaction of charging infrastructure. Then dive into the using cost part to build up quantitative model. Finally use the specific case to validate the model. By doing the research hope to improve the charging infrastructure user satisfaction [2].

2. Indicators of user satisfaction of charging infrastructure
User satisfaction is a measure with a large subjective dimension. To establish quantitative mathematical model, we need to transfer the indicators of importance and satisfaction of subjective into objective mathematical indicators, so we plan to use hierarchical analysis for materialization ranking and program comparison scoring.
2.1. Overview of hierarchical analysis

The analytic hierarchy process (AHP) is the basic method of making decisions on some vague and complex problems, which are mainly applicable to decision-making problems which are difficult to make quantitative analysis. We have hierarchical problems, mainly by the nature of the problem and the overall objectives of the problem to break down into different levels, forming a hierarchical structure model. From top to bottom, the target layer, the criteria layer, the factor layer, and according to the importance of the lower layer to the upper layer, determine the weight of the evaluation factor.

The advantage of hierarchical analysis method is that it can quantitatively analyse subjective feelings, and the disadvantage is that there is a certain degree of subjectivity in the aspect of weight judgment (judgment matrix and comparison matrix construction).

How hierarchical analysis works in detail is figure 1:

![Figure 1. AHP principle](image)

2.2. Identification of evaluation model indicators

According to the literature analysis, on-campus expert interviews, industry expert interviews, user online research, we can determine the evaluation model of the first-level indicators and secondary indicators.

Level 1 metrics include: cost of use, hardware facilities for a single charging station, access to charging stations, and service experience.

Secondary metrics under cost include time cost and charging cost. The secondary indicators under the hardware facilities of a single charging station include the number of charging piles, fast charging pile ratio, charging pile failure ratio, charging pile aging degree, power supply capacity of the grid.

Secondary indicators under the availability of charging stations include charging station layout density, fuel private car parking rate, charging station opening hours. The secondary indicators under the service experience include service attitude, after-sales resolution capability and the accuracy of app response.

The process that new energy vehicle users use the charging service can be divided into several stages: searching and driving to the charging pile location, waiting for or instantly starting using the charging piles according to the occupation status of the charging pile, waiting for the charging process, leaving the charging pile when finished. Time and cost are the two key factors that affect the users when using charging service during the entire process.
3. Charging infrastructure cost model

Based on hierarchical analysis, the first- and second-level indicators affecting user satisfaction are obtained. Next step is quantitative analysis of model with taking use of cost indicators. According to the hierarchical analysis method further subdivision, the time factor should include the road travel time, which has huge impact on the user experience. The money cost of charging process can be divided into charging pile use cost and parking cost [3]. The indicators at cost level are as follows.

![Figure 2. Charging service user satisfaction factors](image)

According to the analysis on the cost factor of the user satisfaction of charging infrastructure, we can obtain 5 indicators that affect the user satisfaction cost. In order to carry out quantitative analysis, the five indicators are converted into cost values for unified analysis and establish the cost model of charging infrastructure usage. The cost model can quantitatively reflect the user's time and expenses in the charging infrastructure, the lower the cost is, the more satisfied the users are. On the contrary, the higher the cost is, the less satisfied the users are.

When the new energy vehicle i uses the charging pile j to complete the charging, the cost $W_{ij}$ of the new energy vehicle user is mainly composed of time consumption and expenses, which includes the

![Figure 3. Cost analysis](image)
road travel time cost $W_{ij}^1$, the wait time cost $W_{ij}^2$, the charging time cost $W_{ij}^3$, The cost consists of charging fee $W_{ij}^4$ and parking fee $W_{ij}^5$. That is, $W_{ij}$ meets the formula:

$$W_{ij} = a_1W_{ij}^1 + a_2W_{ij}^2 + a_3W_{ij}^3 + a_4W_{ij}^4 + a_5W_{ij}^5$$

(1)

A_1 to a_5 of these costs are weighted in total cost, determined by expert interviews, survey and operators. $W^1$ to $W^5$ uses the minimax method for normalization, linearizing the raw data to a range of 0 to 1. The function of data normalization is mainly to remove the volume outline [5], making it possible to compare different characteristics, such as time and cost. The minimax function expression looks like this:

$$\sigma(x) = \frac{x-x_{\text{min}}}{x_{\text{max}}-x_{\text{min}}}$$

(2)

3.1. Charging infrastructure cost model

The road section of the new energy vehicle consists of two parts, from the location where the charging request was initiated to the location of the charging.

This paper assumes that the distance between the two parts is fixed, so the total travel time cost can be obtained by appropriately adjusting the weight value $a_1$ on the basis of the cost of the road travel time of the first stage. Assuming that the new energy vehicle is traveling at a constant speed, the cost of travel time on the road, $W^1$, is calculated as:

$$W_{ij}^1 = \sigma\left(\text{road}_{\text{time}}_{ij}\right)$$

(4)

3.2. The cost of waiting time

Waiting time cost refers to time consumption that when the new energy vehicle to be charged arrives at location of the shared charging pile, the shared charging pile is in a state of occupation, then the vehicle needs to wait for the last new energy vehicle which is charging. The time cost paid for it $W^2$. The wait_time$_{ij}$ is calculated as follows:

$$\text{wait}_{\text{time}}_{ij} = \max\left(T_j - \left(t_i + \frac{d_{ij}}{v_i}\right), 0\right)$$

(5)

That means to compare the moment when the new energy vehicle reaches the charging pile site $t_i+d_{ij}/v_i$ with the available moment of the charging pile $T_j$. If the former is bigger than the latter, the user waiting time is 0. If the former is less than the latter, when the user arrives, the charging pile is occupied, so the stay time is the difference between two moments. The waiting time cost $W_{ij}^2$ is calculated as follows:

$$W_{ij}^2 = \sigma(\text{wait}_{\text{time}}_{ij})$$

(6)
3.3. Cost of charging time

The charging time is determined by factors such as charging voltage, charging current, total battery capacity of new energy vehicles, SOC when the vehicle reaches charging, and SOC expected to be reached. During charging, the SOC value of the new energy vehicle at the t-moment is related to the charging power \( P \) and the power conversion efficiency \( \eta \):

\[
SOC_t = SOC_{t-1} + \frac{\eta_j t_{i} P dt}{c}
\]  

(7)

In the actual charging process, there are the following common charging strategies: one is constant current charging which refers to the entire process of charging the power battery or in stages to maintain the charging current unchanged.

In the late charging, when the power battery at the high SOC, if the current remains the same, it will cause the active substance on the battery’s polar plate to fall off, reducing the number of cycles and service life of the battery. As a result, the ladder current is often used, that is, with the increase of SOC, the charging current gradually decreases; The disadvantage of constant voltage charging is that the initial current is too high, which is easy to damage the battery, and the third is constant current constant voltage charging. When it refers to the charging process, the constant current is first used to charge the power battery. When the battery voltage reaches a certain threshold, it turns into a constant voltage charging mode, until the charging current reaches a certain threshold. Then the charging process ends.

This approach combines the advantages of the first two approaches which is one of the more mainstream charging methods available today. \[7\].

This paper assumes that the battery charge and discharge process is the same energy uniform, which is, to maintain constant power in the process of charging and discharging, the battery charge state and charge and discharge time is similar to linear relationship. Therefore, the charging time is calculated in a way \[8-10\]:

\[
Charge\_time_{ij} = \frac{soc_{t\rightarrow c_i}(soc_{c_i\rightarrow c_j})^{\frac{1}{0.8-P_j}}}{soc_{t\rightarrow c_i}}
\]  

(8)

0.8 is the power conversion efficiency. The charging time cost is calculated as follows:

\[
W_{ij}^3 = \sigma(\text{charge\_time}_{ij})
\]  

(9)

3.4. Charging fee

The charging fee is determined by the amount of electricity charging and the price of electricity. Depending on the charging price, the charging price remains the same during charging, and the charging process is equally charged, so the charging fee is calculated as follows:

\[
\text{charge\_fee}_{ij} = \text{charge\_time}_{ij} \times P_j \times p^c_j
\]  

(10)

Charging spending is calculated as follows:

\[
W_{ij}^4 = \sigma(\text{charge\_fee}_{ij})
\]  

(11)

3.5. Parking fee

Parking fees are determined by the charging time and parking price per hour. Parking charges remain the same during charging, as described below:

\[
\text{park\_fee}_{ij} = \text{park\_time}_{ij} \times p^f_j
\]  

(12)
Charge spending is calculated as follows:

\[ W_{ij}^5 = \sigma(\text{park_fee}_{ij}) \]  

(13)

4. Stimulation
The study assumes that all new energy vehicles to be calculated in the case have the same parameters. For example, a popular plug-in hybrid vehicle in Shanghai, whose main parameters are shown in Table 1.

Table 1. NEV parameter

| Parameter                        | Value       |
|----------------------------------|-------------|
| Battery energy                   | 12 kWh      |
| Mileage                          | 60 km       |
| Electricity consumption per 100km| 20 kWh/100 km|
| Fully charging time              | 2-3 h       |

4.1. Charging pile assumption
In addition to the basic parameters, it is necessary to determine the charging power of each charging pile, charging price, parking charge standard and the business time at which the charging pile is available.

In this case, the charging pile is all AC charging pile with a charging power of 7kW, and the charging power is unchanged when charging, i.e. the charging time is proportional to the expected battery energy, and the charging time calculation method is shown in equation (8). The price of charging pile takes shanghai average price of 1.8 yuan / kWh, parking charges are unified at 5 yuan per hour. Less than one hour is recorded as 1 hour.

In calculating the comprehensive cost \( W_{ij} \), the charging fee \( W_{ij}^4 \) and \( W_{ij}^5 \) are added together first and then normalize processing, as the comprehensive cost \( W_{ij}^3 \).

4.2. Cost weight
The cost weight value is one of the main factors that determine result of the cost. According to the travel habits of users of new energy vehicles, the weight factors \( a_1 \) to \( a_4 \) in the cost \( W_{ij} \) for charging piles are shown in Table 2.

In the morning and evening travel peak hours, we increase the proportion of road travel time cost and reduce the impact of cost costs to reduce the user to the charging pile travel distance.

Because users have different charging preferences, two sets of weight ingress into the model and compare the results.

Table 2. Weight parameters

| Time                | \( a_1 \) | \( a_2 \) | \( a_3 \) | \( a_4 \) |
|---------------------|----------|----------|----------|----------|
| 7am to 9am          | 0.4      | 0.4      | 0.1      | 0.1      |
| 5pm to 7pm          | 0.4      | 0.4      | 0.1      | 0.1      |
| other               | 0.1      | 0.1      | 0.2      | 0.6      |

Figures 4 and 5 show the result of the cost of charging pile selection with different weight values and the average travel distance of the new energy vehicle. The weight of high charge fees adopted the weight value of the other time periods in Table 2. The weight of the high travel distance adopted the weight value of the morning and evening peak hours.
When increasing the driving distance weight and reducing the charge weight, the user wants to go to the charging location as soon as possible. At this time the nearest charging pile from the user is the lowest cost, which can achieve the user's charging purposes. In figure 5, the experimental results show that the average driving distance of the user under the weight of the high travel distance is less than the high charging charge, which also show the validity of the model.
5. Conclusion
Through the study verification, the cost of user charging service is affected by time and cost, and the weight in the model can reflect the degree of the user's cost factor in charging thereby reflecting the extent of impact on user satisfaction from the using cost index. The user satisfaction of charging service can provide a reference on framework, and the cost model can provide quantitative analysis ideas for the research data, which can also provide reference for the improvement plan of charging service user satisfaction.

Acknowledgments
This work was financially supported by the national project - Research on Charging Infrastructure Optimization Based on Scale Application of Electric Vehicle (2018YFE0105100).

References
[1] Meckling J, Nahm J. The politics of technology bans: Industrial policy competition and green goals for the auto industry [J]. Energy Policy, 2019, 126: 470 - 479.
[2] BROOKS A, LU E, REICHER D, et al. Demand dispatch [J]. IEEE Power and Energy Magazine, 2010, 8 (3): 20 - 29.
[3] Choi B R, Lee W P, Won D J. Optimal Charging Strategy Based on Model Predictive Control in Electric Vehicle Parking Lots Considering Voltage Stability [J]. Energies, 2018, 11 (7): 1812.
[4] KEJUN Q, CHENGKE Z, ALLAN M, et al. Modeling of Load Demand due to EV Battery Charging in Distribution Systems [J]. IEEE Transactions on Power Systems, 2011, 26 (2): 802 – 810.
[5] Bessa R J, Matos M A. Optimization Models for EV Aggregator Participation in a Manual Reserve Market [J]. IEEE Transactions on Power Systems, 2013, 28 (3): 3085 - 3095.
[6] SUN X H, YAMAMOTO T, MORIKAWA T. Fast-charging Station Choice Behavior among Battery Electric Vehicle Users [J]. Transportation Research Part D: Transport & Environment, 2016, 46: 26 – 39.
[7] ZHONG F, LI H, ZHONG S, et al. An SOC Estimation Approach Based on Adaptive Sliding Mode Observer and Fractional Order Equivalent Circuit Model for Lithium-ion Batteries [J]. Communications in Nonlinear Science & Numerical Simulation, 2015, 24 (1): 127 - 144.
[8] Zheng J, Wang X, Men K, et al. Aggregation Model-Based Optimization for Electric Vehicle Charging Strategy [J]. IEEE Transactions on Smart Grid, 2013, 4 (2): 1058 - 1066.
[9] Goldberg A V, Radzik T. A heuristic improvement of the Bellman-Ford algorithm [J]. Applied Mathematics Letters, 1993, 6 (3): 3 - 6.
[10] Surve G G, Shah M A. Parallel implementation of Bellman-ford algorithm using CUDA architecture [C]. Electronics, Communication and Aerospace Technology (ICECA), 2017 International conference of. IEEE, 2017, 2: 16 - 22.