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Research on the Time Distribution Characteristics of Charging Demand in Expressway Service Areas of Sichuan Province, China

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Abstract: In order to optimize the charging infrastructure configuration and operation management of expressway service area, based on the charging data of 167 charging stations in expressway service area in Sichuan Province for 134 days, this paper systematically explores the time distribution characteristics of charging demand by using statistical analysis, K-S test, cluster analysis and other methods. It is found that the overall charging peak is from 12:30 to 16:30, the non-holiday peak is from 12:30 to 14:30, and the holiday peak lasts longer from 12:30 to 16:30. The charging demand law of ordinary working day is consistent with that of weekend, which can be combined into non-holiday data; The charging demand intensity on holidays is 2-3 times of that on non-holidays, and there is a significant difference between them in peak hours and the whole day. The weekly dimension characteristics of charging capacity can be divided into two types: non-holiday flat type and holiday fluctuation type. The research results can provide a scientific basis for the planning, construction and dynamic scheduling of charging facilities.

Keywords: Expressway Service Area; Electric Vehicle; Charging Demand; Temporal Distribution Characteristics; Cluster Analysis

1. Introduction

With the continuous increase of electric vehicle, the charging demand of expressway service area, as the key energy supplement node for long-distance travel, is increasing [1], and the service capacity and operational efficiency of its charging infrastructure directly affect the user's travel experience. At a series of press conferences on "China's high-quality economic development results", it was pointed out that although remarkable progress had been made in the construction of charging facilities in expressway service areas in China, by the end of November 2024, the installation rate of charging piles in expressway service areas in China was as high as 97%, the shortage of charging facilities remained prominent during peak periods such as holidays. Taking the National Day holiday in 2024 as an example, the traffic volume of expressways in China reached 68.41 million, of which 15.9% were new energy vehicles, and the demand for charging increased sharply, which brought tremendous pressure to the service capacity and operational efficiency of electric infrastructure. It is of great significance to accurately identify the time distribution characteristics of highway charging demand for optimizing the layout of charging facilities and improving the level of operation and management.

Most of the existing studies focus on the analysis of the charging demand characteristics of urban charging piles, and there are relatively few studies on expressway service areas. Although the "Technical Guidelines for charging infrastructure along Expressways" [2] issued by the MOT in 2022 put forward the recommended value of peak service time, it lacks the empirical support of specific regions. Li Zhi, Li Dongyu, Yan Gangui and other scholars [3-5], mainly from the perspective of the layout of charging facilities, optimize the distribution and capacity configuration of charging facilities by building a model to meet the charging layout of electric vehicles, but in practical application, the model still needs to be further optimized due to regional differences, dynamic changes in traffic flow and other factors. Wang Dawei, Sun Ziwang, Liang Meiling and other scholars [6-8] mainly study and analyze the advantages and disadvantages of different operation modes from the perspective of operation management, and put forward strategies to improve operation efficiency. However, as the operation of charging facilities in expressway service areas is constrained by the difficulties of power capacity increase, high cost of power introduction and high operational pressure, the existing strategies are facing challenges in the actual promotion.

Currently, there is still a lack of in-depth research on the distribution characteristics of charging demand from a temporal perspective, especially for specific regions such as the expressway service areas in Sichuan Province, China. As a transportation hub in western China, Sichuan Province has a dense expressway network and a strong demand for electric vehicles, so the charging demand characteristics of its service area are typical. Therefore, based on the measured data of charging stations in expressway service areas in Sichuan Province, this paper deeply analyzes the time distribution of charging demand, which provides data support for the planning and operation optimization of charging facilities.

2. Research Data

2.1 Data Sources

In this study, 167 charging stations in expressway service areas in Sichuan Province were selected as the research objects, and 134 days of charging operation data were collected, including the charging time, charging duration, charging capacity and other core indicators of charging orders at each station. After the data were preprocessed to eliminate outliers, the effective sample coverage rate reached 98. 7%.

2.2 Definition of Indicators

The daily change of charging demand is reflected by the average charging capacity of different stations in different periods. This indicator refers to the average charging capacity of all stations in a certain charging period during the data calculation period. Specifically:

$$E_{mean} = \frac{\sum_{i,j} E_{i,j}}{N * D}$$

1) $E_{i,j}$ refers to the charging capacity of the ith station in the jth time period;
2) N is the total number of sites, I = 1, 2, 3, ⋯, N
3) D is the total number of days, J = 1, 2, 3, ⋯, D

2.3 Analysis Method

In this study, the statistical description method was used to analyze the mean, standard deviation, quantile and other characteristics of the load. The K-S test was used to verify the difference of data distribution in different periods. The cluster analysis was used to identify the change pattern in the week. All the analysis was completed through the Python data analysis library.

3. Results and Analysis

3.1 Identification of Charging Peak

3.1.1 Overall Charging Peak

Taking the average charging capacity of the average station in each period as an index, the fluctuation trend of charging in 24 hours is analyzed. The results show that the charging demand of charging stations in Sichuan expressway service area remains at a high level from noon to evening. Combined with the recommended value of peak service time of 2-4 hours in the "Technical Guidelines for charging infrastructure along Expressways", the overall charging peak time is determined to be 12: 30-16: 30 (Figure 1).

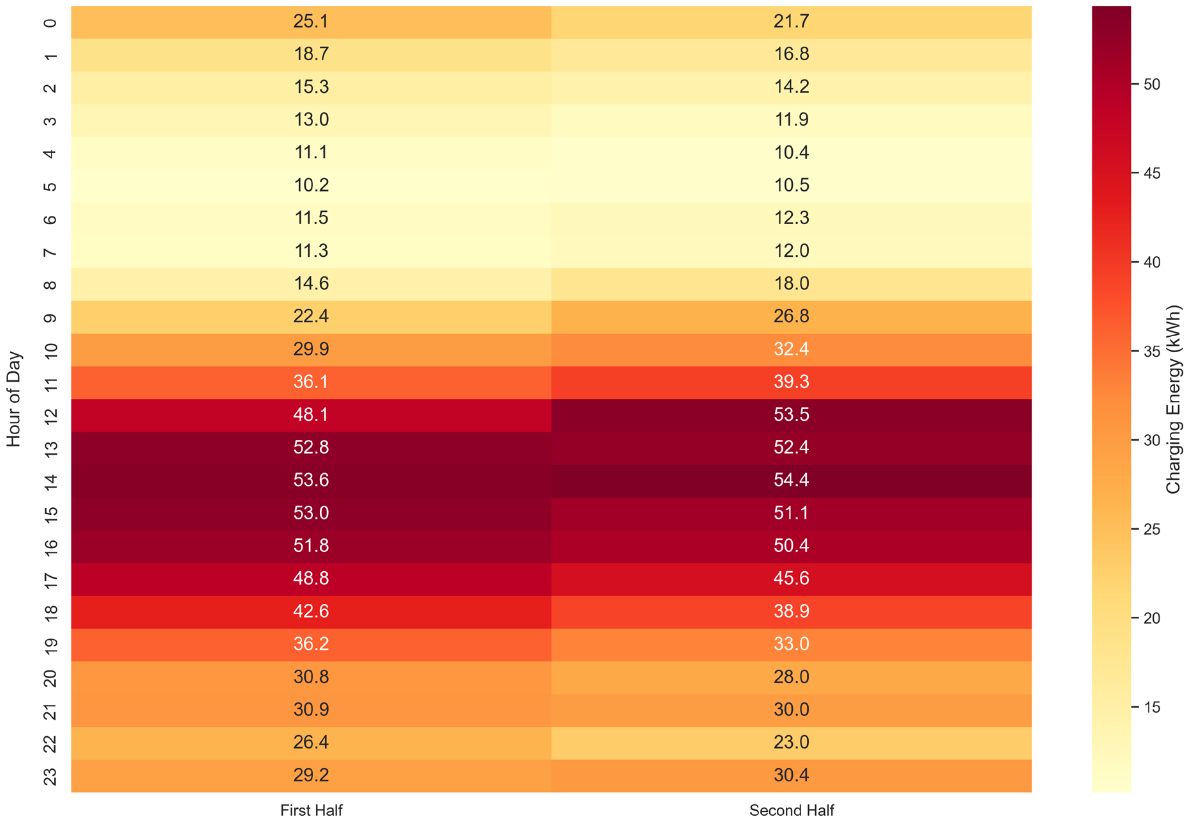

Figure 1: Daily Charing Energy Distribution Heatmap.

3.1.2 Difference Between Peak Charging on Holidays and Non-Holidays

The 134-day data were classified and analyzed according to holidays and non-holidays, and it was found that the peak characteristics of the two were significantly different (Figure 2). The charging peak on holidays is concentrated from 12:30 to 16:30, lasting for 4 hours, while the peak on non-holidays is shortened to 12:30 to 14:30, only 2 hours. The difference is closely related to the characteristics of large holiday travel flow and high user time dominance.

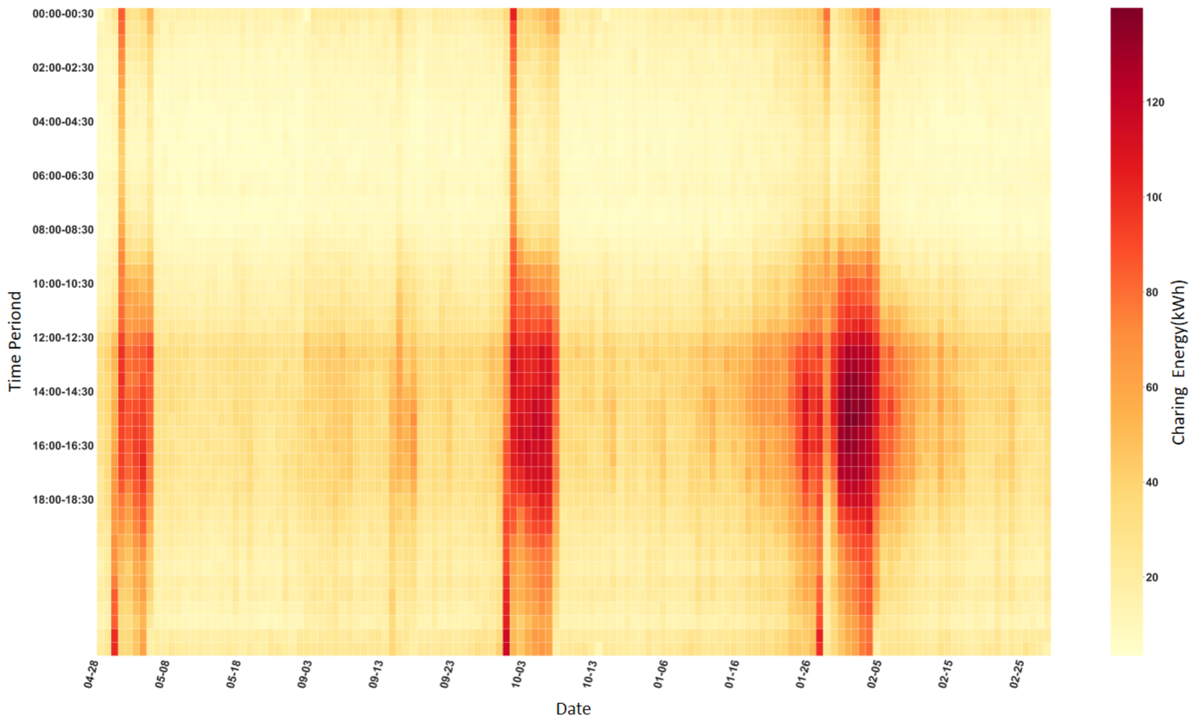

Figure 2: Average Charging Energy by Time Period Heatmap.

3.2 Change Characteristics of Charging Load

3.2.1 Consistency of Demand Law Between Ordinary Working Day and Weekend

The results show that the average station charging time is 28.00 minutes and 29.97 minutes on weekdays and weekends respectively, and the average station charging capacity is 23.64 degrees and 25.27 degrees on weekdays and weekends respectively. The results of K-S test showed that there was no significant difference ($p > 0.05$) in the distribution of charging quantity (statistic=0.19, p=0.37). By combining the hourly trend chart (Figure 3) and the distribution comparison chart (Figure 4), the data of ordinary working days and weekends can be merged into non-holiday data for subsequent analysis.

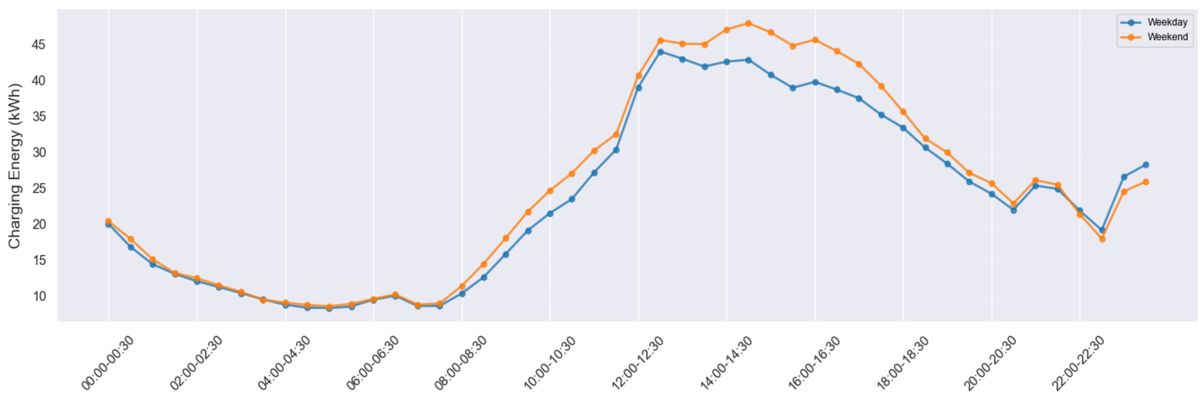

Figure 3: Charging Energy Trend.

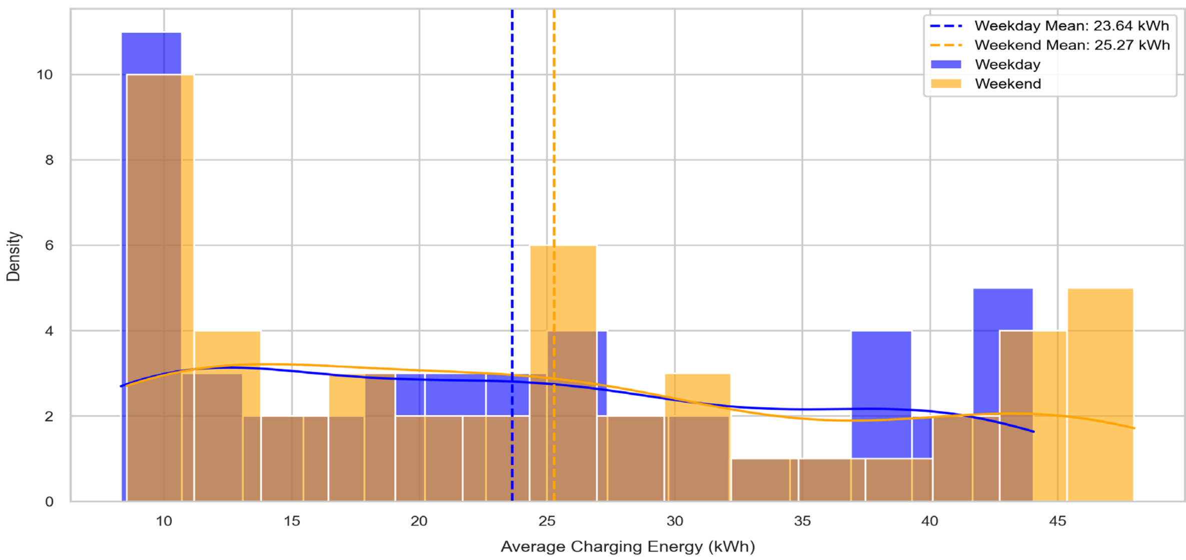

Figure 4: Charging Energy Distribution.

3.2.2 Comparison of Charging Demand on Holidays and Non-Holidays

According to the comparative analysis of the statistical data of holidays and non-holidays, there is a significant difference in the demand of the two periods, which is manifested in the following aspects: (1) In terms of demand intensity, the average charging capacity of holidays is 2.3 times that of non-holidays, and the demand for high capacity increases significantly. (2) In terms of time distribution, the non-holiday electricity demand is concentrated at noon, which is related to short-distance travel combined with dining, while the holiday demand peak lasts longer and is more widely distributed, reflecting the demand for energy supplement after long-distance travel. (3) In terms of volatility, the standard deviation of holiday electricity is larger, indicating that the difference of user charging behavior is more significant. Generally speaking, the demand for charging electricity on holidays is significantly higher than that on non-holidays, and the time distribution is wider and the volatility is stronger, which is in sharp contrast to the short-term centralized energy supplement characteristics of non-holidays.

Table 1: Comparison of Charging Demand on Holidays and Non-holidays

Average charging capacity per unit time of charging station	Holidays	Non-holidays
mean	55.72	24.12
std	27.40	12.42
min	18.10	8.38
25%	31.22	11.97
50%	52.32	23.51
75%	81.31	34.67
max	98.35	44.52

3.3 Weekly variation characteristics of charging demand

Taking the week as a unit, the weekly dimension analysis of the daily change of charging quantity shows that the daily charging quantity fluctuates significantly from Monday to Sunday, and the gap between the maximum and minimum values is very large, which indicates that there is diversity in the trend of change within a week. Through cluster analysis (Figure 5), it is found that the red and green point groups in the three-dimensional cluster diagram are obviously separated. Combined with the elbow rule verification, the optimal number of clusters is determined to be 2 (Figure 6), indicating that there are two types of weekly variation patterns with significant differences. The trend shape of cluster 2 (green point group) is highly similar, showing the characteristics of "stable on Monday and Tuesday, reaching the trough on Wednesday or Thursday, gradually climbing from Thursday, and reaching the peak on weekends". The overall trend is flat, and the difference between weekend and weekday electricity is small, reflecting the characteristics of non-holiday week change. Cluster 1 (red cluster) is characterized by scattered clusters, complex trend fluctuations and no fixed rules, which are marked and verified as weeks with holidays, reflecting the significant impact of holidays on the change of charging load in a week. The weekly variation trend of the two types of significant differences is shown in Figure 7.

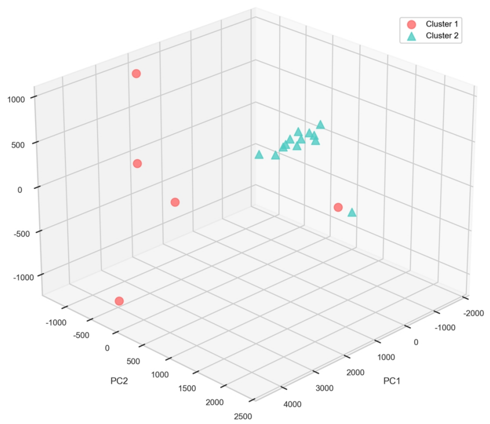

Figure 5: 3D Cluster Distribution.

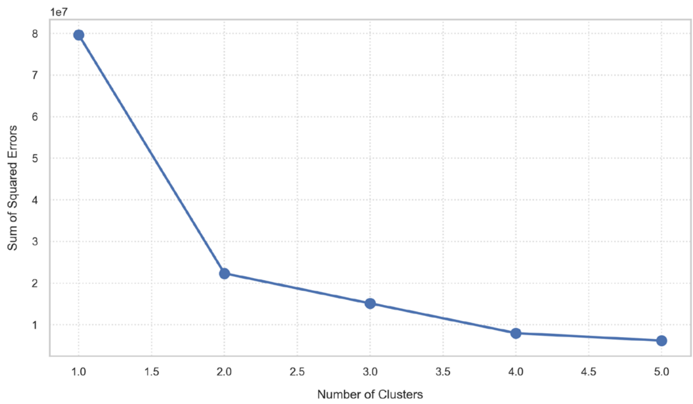

Figure 6: Elbow Method.

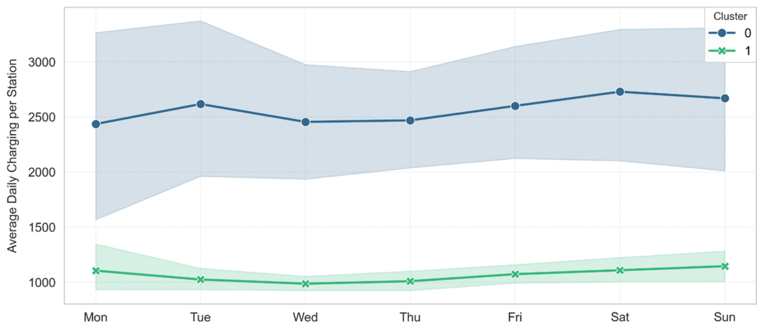

Figure 7: Charging Pattern Cluster Analysis.

4. Conclusion

The study shows that there are obvious differences in the charging demand of expressways in Sichuan Province during holidays and non-holidays, which are mainly reflected in the following aspects: (1) There are obvious differences during peak hours. The holiday peak lasts for 4 hours, and the non-holiday peak is shortened to 2 hours. (2) The difference of demand intensity is large. The intensity of charging demand on holidays is 2.3 times higher than that on non-holidays, and there are significant differences in time distribution and volatility. (3) There is a big difference in the change within a week. There are two types of intra-week change patterns: non-holiday flat and holiday fluctuation. In the future, we can expand the research area and integrate multi-dimensional data, build a refined load forecasting model to optimize dynamic scheduling, optimize the layout and capacity allocation of charging facilities combined with space-time load differences, and further study the user charging decision-making mechanism to enhance service experience.

Acknowledgment

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