Research on Distribution Planning of Electric Vehicle Charging Station Based on Discrete Location Model

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Abstract. For both environmental and economic factors, an increasing of countries begins to focus on electric vehicles (EV). As the EV industry continues to evolve, how to establish enough vehicle charging stations in the right locations is a critical issue. This paper proposes discrete location models to solve the above problems. In order to minimize the cost of building charging stations and to minimize the user's toll costs, a multi-factor discrete location model is built. Using this model, the distribution of charging stations is simulated in Colorado State and Ireland when implementing an all-electric vehicle system. And influence coefficient is added to simulate the impact of new technologies on EV. Through sensitivity analysis, car-share and ride-share services have a negative impact on the number of EV, and increase the time that EV reaches saturation.

1. Introduction
One of the main contributors of atmospheric pollution is the emission of vehicle-polluted gases. Electric vehicles can be a good solution to this problem and it will play an important role in people's life and energy conservation in the future. According to the New York Daily News [1], the total number of electric vehicles in the United States is expected to reach 1.8 million by 2020. In the process of achieving full electric-vehicle system, one of the most important factors that limit the development of electric vehicles is the relationship between the number of charging stations and its location. This paper can make more informed decisions to determine the distribution of charging stations.

At present, most of the research field of electric vehicle charging station planning focuses on the quantity and cost. Zhou Hong Feng (2011) used Game Theory for Electric Vehicle Charging Station to evaluate the layout scheme, and gave the game optimization model and algorithm. Song Zhicheng (2014) used the global optimization capability of the differential evolution algorithm to determine the location and construction level of the maximum revenue for charging stations, and he certified the verification of effectiveness and feasibility through simulation examples. Cheng Hongbo (2016) used the gravity model function to define the charging convenience function, gravitational relations between the number of charging times and convenience were obtained. He established a planning model for future development of electric vehicle charging stations. Using differential evolution algorithm to solve the established model, and did some simulation analysis for a specific example. Lu Fang (2015) researched the site selection, detailed the charging station construction according to the charging demand. He combined the queuing theory model of the electric vehicle charging station, and studied the problem of the location selection of the charging station under different demand modes. Geng Jianchao (2017)
established a daily travel model for people to simulate the changing needs of electric vehicle users. He also established a road traffic network model. He provided a theoretical method for planning the layout optimization of the charging and switching stations from a macro perspective. These above studies made a great progress, but these studies did not consider the impact of multiple factors on the site selection model. This paper used a multi-factor discrete location model to study the location of electric vehicle charging stations, and through some exact examples (America, Ireland) to verify this model, we use Colorado to analyses the charging stations distribution and use Ireland to verify electric vehicles’ relationship between the number of charging stations and its location.

2. Discrete Location Model

Charging stations location selection is important. We must consider the user's convenience and charging stations construction economy. Therefore, the location and number of charging stations relate to the initial construction cost of the charging stations and the charging cost of the user. Based on minimizing these two types of costs, a discrete location model is built.

2.1. Assumptions

- The demand point is not a strict point, but a small area with charging needs.
- We do not consider the user’s preference when choosing a charging station, only consider the proximity principle.
- The power load at each charging station is always sufficient.
- We assume that there is no major change in the population of the selected country. And the population is basically saturated. People do not have large-scale immigration activities.
- We assume that the number of vehicles per capita is unchanged.
- We assume that a destination charging station has 4 charging points and a supercharger station has 8 charging points. Our assumption is well founded. We found the number of charging stations and charging points in Tesla official website and find the average value.

2.2. Model Establishment

Taking into account the different types of charging stations of different construction costs, different regions of different needs, we build this model. With this location model, we can determine where, what type of charging stations to build. Figure 1 is a discrete location model diagram.

![Figure 1. Discrete Location Model Diagram](image)
The model set up is presented. Equation (1) is the objective function of the model. It shows the minimum total cost, including the initial construction cost of the charging stations and the charging cost of the users.

$$\text{min} C = \Sigma I D_n X_{jn} + \lambda \Sigma I Y_{ij} d_{ij}$$  \hspace{1cm} (1)$$

In Equation (1),
$I$ is set of demand point. \( i \in I \) Refers to the demand point.
$J$ is candidate point set of charging stations. \( j \in J \) Refers to the candidate point.
$D_{ij}$ is the distance between demand point \( i \) and candidate point \( d \).
$D_i$ is demand for \( i \) point. The number of vehicles with charging needs. The following are the constraints of the model.
$C_n$ is an \( n \)-type charging station initial construction costs. \( n=1, 2 \).

**s.t.**

$$\Sigma J Y_{ij} = 1$$ \hspace{1cm} (2)$$
$$Y_{ij} \leq X_{jn}$$ \hspace{1cm} (3)$$
$$\Sigma I D_i Y_{ij} \leq \Sigma n S_n X_{jn}$$ \hspace{1cm} (4)$$
$$\Sigma n X_{jn} \leq 1$$ \hspace{1cm} (5)$$
$$\Sigma I X_{jn} = P$$ \hspace{1cm} (6)$$

- Equation (2) shows that the same demand point users in a fixed period of time until a certain type of charging stations to accept service.
- Equation (3) shows that charging services can only be provided when a charging station is set up at the candidate point.
- Equation (4) shows that the service capability of the charging stations must be satisfied.
- Equation (5) shows that only one type of charging station can be established for one candidate point.
- Equation (6) shows that the number of charges to be built is \( P \).

The definition of decision variables is presented.

$$X_{jn} \in \{0,1\}$$ \hspace{1cm} (7)$$
$$Y_{ij} \in \{0,1\}$$ \hspace{1cm} (8)$$

- Equation (7) is the decision variable. Value takes 1 when in the candidate point \( j \) and establish the charging stations is \( n \) type, otherwise is 0.
- Equation (8) is the decision variable. Value takes 1 when in the candidate point \( j \) and receiving services, otherwise is 0.

**Step1:** Further consideration of \( N \)

After reviewing a large amount of relevant literature, we decided to calculate the number of charging stations based on the user’s charging power requirements [2]. Assuming that the number of chargers per charging station is \( n \) and the number of electric vehicles in the area is \( N \), the daily power demand of an electric vehicle is \( Q \). Suppose the number of vehicles that have charging needs each day accounts for of the total electric vehicles and the average charging power per unit is \( q \). Then the number of charging stations in the area is shown in Equation (9).
Step 2: Further assumptions about

The demand for charging in different regions is directly proportional to the population density [3]. Taking into account the different demand for charging stations in urban, suburban, and rural areas, the 0-1 variable is used to indicate whether the demand is within the region. Because urban, suburban, and rural areas have different requirements for charging stations, the demand for demand point \( i \) can be expressed as Equations (10) and (11).

\[
D_i = \sum_{T=1}^{3} D_T Z_s
\]  
\[
Z_s = \begin{cases} 
1, & S = T \\
0, & S \neq T
\end{cases}
\]

In Equations (10) and (11),
- \( D_{1i} \) represents the demand of Demand Points \( i \) in urban.
- \( D_{2i} \) represents the demand of Demand Points \( i \) in suburban.
- \( D_{3i} \) represents the demand of Demand Points \( i \) in rural areas.

Step 3: Further research on service capabilities

Because charging station service capacity is related to its capacity, we study service capability \( S_n \) based on queuing theory. We can think of the charging station’s service system as a multi-service queuing system with a capacity of \( c \). Figure 2 is the charging stations queuing system model.

**Figure 2.** The queuing model of charging station

The M / M / c // queuing theory model is used to study the charging stations service process. We assume that the EV arrives at the charging stations subject to a Poisson distribution with parameter and the EV service time satisfies the negative exponential distribution with parameter Electric vehicle charging system has \( c \) chargers, and the charger’s work is independent of each other. We assume that \( n \) represents the number of customers that arrive. According to the knowledge of queuing theory, we can get the relevant system indicators of charging stations service facilities.

The service intensity of the charging facility is shown in Equation (12).

\[
\rho_1 = \frac{j}{\mu}
\]
Utilization of charging facility is shown in Equation (13).

\[ \rho_0 = \frac{\lambda}{\mu} \]  

(13)

The average queue length in the charging station is shown in Equation (14).

\[ L_q = \frac{\rho_0^{i+1}}{(c-i)(c-p_0)^2} \]  

(14)

The average waiting time in the charging stations is shown in Equation (15).

\[ W_q = \frac{t_q}{\lambda} = \frac{\rho_0^{i}p_0}{\mu c n i (1-p_0)^2} \]  

(15)

Service capacity and the number of charging stations charger has a relationship. In certain cases, the more capacity, the stronger the service ability. Taking into account the construction cost constraints, capacity \( c \) is a certain limit. According to the above formula can get service capacity.

2.3. Solutions and Results

If all vehicles in the United States switch to electric vehicles, we can get the number of charging stations based on the model above, and their distribution between urban, suburban, and rural areas.

3. Numbers of Charging Stations Needed

We assume every gas vehicle replaced by an electric one in the US at present. The current number of gas vehicles in the US is about 0.269 billion [4]. The demand for charging power within a day does not obey the uniform distribution, but obeys the normal distribution with an expected value of 3.2 kw/h. [5] Suppose the proportion of vehicles with charging needs is 10%. We can know that the charging power of a unit destination charger is four kw/h and there is an average of four chargers per destination charging station. In addition, the charging power of a unit super charger is 30kw/h, and each super-charging station has an average of eight chargers.

Therefore, the calculation result according to Equation (9) is, if everyone in the US switched to all-electric personal passenger vehicles, requires 5.380 million destination-charging stations or 0.350 million super charging stations.

4. Distribution of Charging Stations

Taking into account the population density, traffic flow, geographical location, we finally choose to Colorado State as the representative. Then we further investigate the distribution of charging stations between urban, suburban, and rural areas.

Step1: Numbers of charging stations in the Colorado State

Through the Equation (9), we get the required number of Colorado State charging stations about 10,0000.

Step2: Determine in the Colorado State

A region with a population density greater than 1000 / sq.km is defined as urban. The area with a population density greater than 50 and less than 1000 / sq.km is suburban. The area with a population density of less than 50 / sq.km is rural areas

3.61 Million
0.97 Million
0.51 Million

Step3: Simulation of the model

Due to the large number of charging stations, it is difficult to study the distribution of charging stations. Through data analysis, the distribution of charging station demand points and population density. Colorado State maximum distance from north to south is about 450.61 km, the maximum
distance from west to east is about 611.55 km, covers an area of 269.83 thousand square kilometers. To simplify the model, this paper simulated a planned area of 66,000 square kilometres based on the distribution of population density and the total area of the state.

![Figure 3. Layout of demand points and candidate points](image)

Table 1. Station Types and Corresponding Construction Costs

| Charging stations type         | Service capabilities (the number of cars per day) | Construction costs  |
|-------------------------------|--------------------------------------------------|---------------------|
| Destination charging stations | 80                                               | $635263.47          |
| supercharger stations         | 260                                              | $968776.80          |

Tabu search algorithm is used to solve the model. Using MATLAB, the simulation model run independently 30 times, the results obtained are shown in Figure 4.

Table 2. Operation Results

| Optimal results                  |                                   |
|----------------------------------|-----------------------------------|
| The number of charging stations  | Urban 3                           |
|                                  | Suburban 2                         |
|                                  | Rural 1                            |
| Total cost                       | 4.82 million dollars               |
Figure 4. Construction locations and distribution of demand points

4.1. Model Verification

There are 1,200 charging points in the Republic of Ireland and Northern Ireland. But we found that sales of electric vehicles in Ireland are far from expected. According to Electric vehicles in Ireland White Paper, \cite{7} we found that the sale of electric vehicles in 2017 were 447, an increase of only 14% from the 392 sales in 2016. Through the analysis of the various data of the electric vehicle market in Ireland, it can be believed that Ireland is a promising country. So Ireland is used as a case to verify the above model.

5. Charging Network Plan of Ireland

If all of their personal passenger vehicles instantly become all-electric vehicles, then the number of electric vehicles is about 2 million. \cite{8}.

According to the above analysis shows that at this time Ireland need 42,000 charging stations to meet the daily charging needs.

According to the relationship between population density and demand points, we simulate the distribution of charging stations in Ireland considering the different requirements of different charging station types in different regions.

Cork (a city in Ireland) is taken as an example; its number of vehicles is 239,743. According to the equation (9), we get its demand locations is 479.486. In order to simplify the model, we take 2000 is taken as a unit and the distribution of electric vehicle charging stations in Ireland is simulated and shown in Figure 5.
6. Sensitivity Analysis

Transport options are becoming more diversified and there are many factors that have a positive or negative impact on the number of cars purchased, such as car-share, and ride-share services, self-driving cars, rapid battery-swap stations for electric vehicles.

Different coefficients of influence are used to measure the impact of technology on the growth rate of electric vehicles.

We make car-share impact on the number of cars coefficient.
Ride-share services on the number of cars impact coefficient is.
Rapid battery-swap stations on the number of cars impact coefficient is.
The impact coefficient of self-driving on the number of cars is.

\[ x_m' = x_m \cdot \lambda_n (n = 1, 2, 3, 4) \]  

(16)

Therefore, a sensitivity analysis of the logistics model is conducted based on these coefficients.

Figure 5. Layout of demand points and candidate points of Ireland
As can be seen, Car-share and ride-share services improves the utilization of car seats and negatively affect the number of cars from the long run.

Rapid battery-swap stations increase the convenience of electric vehicle travel, which is conducive to the growth of the number of cars.

Self-driving helps to reduce traffic jams, which increases the car's saturation and has a positive effect on the number of cars.

7. Result Analysis

This paper provides in-depth analysis of the factors that influence the location of charging stations. We take the United States as an example, we do a research about the problem of considering the number of Charging Stations established and charging location. The multi-factor charging location model is established by Greedy algorithm. Applying this factor to the Northern Ireland country and finding that the location of the charging station is related to the city’s prosperity.

- In urban, destination charging stations provide short-distance travel services, which are more advantageous than super charging stations. As a result, the city has more destination charging stations, mainly in densely populated areas;
- In suburban, the demand point is significantly reduced, the proportion of super-charging stations also increased significantly;
- In rural areas, the supercharging stations can provide long distance and occupy the charging stations market) the innovation of this paper analysis the issue of establishing a site for charging stations. Through considering a variety of factors. At the same time, apply the Ireland to the model and check this model correctly.

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