Research on Site Selection and Capacity Determination of Electric Vehicle Charging Stations in Urban Commercial Areas

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Abstract: With the growing electric vehicle market, optimal siting and capacity setting for charging stations in commercial districts has gained increasing importance. These areas present complex charging scenarios due to their diverse functions. This paper analyzes user charging behavior and considers both station construction/operational costs and user expenses to develop a multi-objective optimization model for charging station planning. A case study of a commercial district demonstrates the practicality and effectiveness of the proposed model.

Keywords: Downtown;EV charging Stations；Location optimization

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Introduction

As the number of electric vehicles grows, so does the demand for charging infrastructure. This paper develops a multi-objective siting model for charging stations, based on an analysis of user charging behavior and considering both construction operational costs and user expenses.

Foreign scholars have made remarkable progress.Tungom et al.used a time-series linear regression integration method to accurately predict future charging demand at the point of demand[1].Moon and Park et al. estimated the charging demand based on the owner's preference for EVs, the number of hours of charging per day, and the type of charging piles[2].Yagcitekin et al. in the constructed charging station siting and sizing model, the queuing theory and the hierarchical analysis process are merged, which is used to optimise the number of charging stations and to select the optimal location[3].

However, in practice, based on the charging behaviour characteristics of user groups, the demand users of charging station services should be classified.Therefore, this paper focuses on the problem of electric vehicle charging station siting and capacity determination in urban commercial areas. Through the analysis of the charging behaviour of users in commercial areas, the charging demand users are classified, modeling of site selection and capacity of electric vehicle charging stations in commercial areas.

1 Electric Vehicle Charging Station Siting and Capacity Modelling in Commercial Areas

1.1 Charging Demand Measurement

If we consider that there are s road segments linked to the intersection identified as j, the traffic density at node j during the time slot t can be determined using the equation presented in Equation 1.

$$p_t^j = \sum_{e=1}^{s} p_t^e(j, j_e^{'}) \quad (1)$$

In formula 1, pjt represents the traffic flow density at node j at time t;The j’e represents the eth road section connected to the node, e=1,2,3,... ,s;The pet(j,j’e) represents the traffic flow density of the eth road section connected to node j and node j’e at time t.

Assuming that there are a total of Num intersection nodes in the planning area, the total charging demand Q in T time period is calculated as shown in formula2:

$$Q=\sum_{j=1}^{N_{um}}(Q_{sc}+Q_{fc})=\sum_{j=1}^{N_{um}}\int_0^T p_t^j\cdot\alpha\cdot\beta\cdot\left[\theta_{ran}\cdot C_{EV,ran}+\theta_{reg}\cdot C_{EV,reg}\right]dt \quad (2)$$

In equation 2, "Qsc" denotes the cumulative power requirement for charging by spontaneous users within the same zone. "Qfc " stands for the combined power requirement for charging by users with established patterns in the zone. "α" is indicative of the fraction of the population within the planning zone that owns electric vehicles. "β" indicates the portion of electric vehicle owners within the planning zone who have a demand for charging. "θran" reflects the ratio of spontaneous users in the zone, while "θreg" pertains to the ratio of users with set routines. "CEV,ran" is the mean power demand for charging among spontaneous users, and "CEV,reg" is the average power demand for charging among users with fixed habits.

1.2 Calculation of queuing time and minimum travelling distance

1.2.1 Calculation of average queuing time

The queuing waiting time required by the user in the target charging station is calculated in this paper using the M/M/S queuing theory model and expressed using the average waiting time in the station. The arrival rates of fixed charging demand users and random charging demand users are calculated as shown in formula 3:

$$\lambda_{i,sc}=\frac{Q_{i,sc}\cdot k_1}{C_{EV,ran}\cdot T_v}$$
$$\lambda_{i,fc}=\frac{Q_{i,fc}\cdot k_1}{C_{EV,reg}\cdot T_v} \quad (3)$$

In formula 3, λi,sc represent the arrival rate of random users in charging station i; λi,fc represent the arrival rate of fixed users in charging station i;k1 represents the ratio of the number of vehicles that can be serviced during the effective working service period of the charging pile to the number of vehicles that can be serviced throughout the day; and Tv represents the length of the working hours of the charging pile during the non-vacancy period.

1.2.2 Calculation of minimum travelling distance

The shortest travelling distance for the user to reach the target charging station from the current location is calculated with the help of Floyd's shortest path algorithm. The shortest travelling distance is calculated in the steps shown below:

Step 1: Based on the actual road network structure, number the road nodes sequentially;

Step 2: Set the total number of road nodes Num to generate the initial distance matrix D(0)Num×Num. matrix element d(0)kj indicates the distance from road node numbered k to road node numbered. If road node k cannot reach road node j, it is expressed as d(0)kj infinity, as shown in formula 4:

$$d_{kj}^{(0)}=\begin{cases}w_{kj}, & \text{Node k can be directly connected to the node j}\\ \infty, & \text{Node k can't be directly connected to the node j}\end{cases} \quad (4)$$

The parameter wkj represents the actual road distance between two road nodes when the road node numbered k to the road node numbered j can be directly connected;

Step 3: If there exists an intermediate node s such that the road distance travelled by road node k through node s and then to road node j is dkj, update the distance matrix D(m)Num×Num as shown in formula 5:

$$d_{kj}^{(m)}=\min\left(d_{ks}^{(m-1)}+d_{sj}^{(m-1)}\right), s=1,2,\Lambda,N_{um}\text{且}\ s\neq k,j \quad (5)$$

Step 4: According to the above steps continuously update to get the shortest distance matrix D(m+1)Num×Num, if D(m+1)Num×Num≠D(m)Num×Num, return to step 3; otherwise, stop the iteration, and output the shortest path by matrix D(m)Num×Num

1.3 Multi-objective model

1.3.1 The objective function

The goal is formalized within the objective function presented in equation 6.

$$\min F=\psi_1\cdot C_{EVCS}+\psi_2\cdot C_{user} \quad (6)$$

In formula 6,F represents the total social cost of charging station construction; CEVCS represents the charging station construction O&M cost function; Cuser represents the user cost function; Ψ1 represents the coefficient weighing the importance of the charging station construction O&M cost; and Ψ2 represents the coefficient weighing the importance of the cost of the service user.

(1)Charging station construction O&M cost minimization

The charging station construction O&M cost includes the fixed investment cost of the charging station, the cost of purchasing charging piles of different specifications, and the O&M cost with the following three formulas:

$$minC_{EVCS} = \sum_{i}^{N_{ch}} \left[\frac{r_0(1+r_0)^m}{(1+r_0)^m-1} \cdot C(M_{cp,i}) + U(M_{cp,i})\right], i \in E_{num} \quad (7)$$

$$C(M_{cp,i}) = W + q_{sc} \cdot M_{sc,i} + e_{sc} \cdot \ln M_{sc,i} + q_{fc} \cdot M_{fc,i} + e_{fc} \cdot \ln M_{fc,i} \quad (8)$$

$$U(M_{cp,i}) = 0.1 \cdot C(M_{cp,i}) \quad (9)$$

In equation 7, the variable Nch signifies the total count of charging stations intended for establishment within the designated planning zone. Enum denotes the collection of potential charging station locations. The symbol r0 stands for the base discounting percentage. The letter m indicates the duration over which depreciation occurs. C(Mcp,i) is the function that calculates the building expenses for the ith charging station. U(Mcp,i) is the function for the operational and maintenance expenses of the ith station, assumed to be equivalent to 10% of the prior period's construction costs for the stations. W is the constant capital expenditure for constructing the stations. Msc,i is the tally of superchargers present in the ith station. Mfc,i refers to the number of rapid chargers in the ith station. The variable qsc denotes the per-unit cost of superchargers, while qfc represents the per-unit cost of fast chargers. Esc is the expenditure associated with installing superchargers, and efc is the expense for installing fast chargers.

（2）Minimize user costs

The user costs in the planning area include the cost of user waiting time in queues and the cost of power loss, as shown in formula 10:

$$C_{user} = C_{wait} + C_{drive} \quad (10)$$

In formula 10, Cwait represents the annual queuing time cost function of the user; Cdrive represents the annual power loss cost function of the user.

The user queuing waiting time cost function as shown in formula 11:

$$C_{wait} = 365 \cdot \sum_{i=1}^{N_{um}} \sum_{i}^{N_{ch}} \sum_{t}^{T} \left(T_{wait,ran,i} \cdot U_{mum,ran,jit} \cdot T_{ran} + T_{wait,reg,i} \cdot U_{mum,reg,jit} \cdot T_{reg}\right) \cdot X_{ji} \quad (11)$$

In formula 11,T represents the average daily working hours of the charging station; Twait,ran,i represents the average queuing time of random users in charging station i; Unum,ran,jit represents the number of random users going to charging station i at demand node j in time period t; Tran represents the unit time cost of random users;Twait,reg,i represents the average queuing time of station i fixed users; Unum,reg,jit represents the number of fixed users going to charging station i at demand node j in time period t; Treg represents the unit time cost of fixed users; and Xji represents a decision variable indicating whether a user at demand point j chooses charging station i or not, and takes the value 0 or 1.

The power loss cost function of the user arriving at the target charging station is shown in formula 12:

$$C_{drive} = 365 \cdot \sum_{j=1}^{N_{am}} \sum_{i}^{N_{ch}} \sum_{t}^{T} \left(U_{mam,ran,jit} \cdot p_{sc} \cdot \frac{d_{ji}}{Lr} + U_{mam,reg,jit} \cdot p_{fc} \cdot \frac{d_{ji}}{Lr}\right) \cdot X_{ji} \quad (12)$$

In formula 12, psc represents the price of supercharging; pfc represents the price of fast charging; dji represents the shortest travelling distance required for a charging user at demand point j to reach charging station i, calculated using Floyd's shortest path algorithm; and Lr represents the power consumption of an EV per unit of driving mile.

1.3.2 Constraints

(1)The constraints satisfied by the charging demand are as in formula 13:

$$\sum_{j=1}^{N_{um}} \sum_{i}^{N_{ch}} Y_{ji} = 1, Y_{ji} \in \{0,1\} \quad (13)$$

Formula 13 indicates that the charging demand of all users in the region can be satisfied. If the charging demand at demand point j can be satisfied by charging station i, then Yji is 1; otherwise it is 0.

(2)Charging station quantity constraints are shown in formula 14:

$$N_{chmin} \leq N_{ch} \leq N_{chmax} \quad (14)$$

In formula 14,Nch represents the number of charging stations to be built in the planning area; Nchmin represents the minimum value of the number of charging stations;Nchmax represents the maximum value of the number of charging stations.

Number of charging piles constraint are shown in formula 15:

$$M_{fcmin} \leq M_{fc,i} \leq M_{fcmax} M_{scmin} \leq M_{sc,i} \leq M_{scmax} \quad (15)$$

Within equation 15, the variable Mfc,i signifies the quantity of rapid charging stations present at location i; conversely, Msc,i denotes the count of high-capacity charging stations at the same site.

(4)Neighbouring charging station spacing constraints are shown in formula 16:

$$D_{min} \leq D_{ij} \leq D_{max} \quad (16)$$

In equation 16, the variable Dij signifies the spacing between charging facility i and its neighboring charging facility j in proximity to the device; Dmin indicates the shortest separation found between consecutive charging facilities; whereas Dmax denotes the longest separation detected between such facilities.

(5)Average queue waiting time constraints are shown in formula 17:

$$T_{wait,ran,i} \leq T_w$$

$$T_{wait,reg,i} \leq T_w \quad (17)$$

In equation 17, the variable Twait,ran,i signifies the mean delay experienced by random individuals at charging station number i during queueing; similarly, Twait,reg,i denotes the average hold-up for regular patrons at the same charging station; Tw is the constant value assigned to the waiting duration.

2 Case study

2.1 Example Description

In order to verify the feasibility and practicability of the model, this chapter uses the relevant data of a commercial district for simulation. There are a total of 42 intersection nodes in this commercial area, which are divided into 31 study areas based on the status of intersection nodes. The specific road network structure is shown in Figure 1.

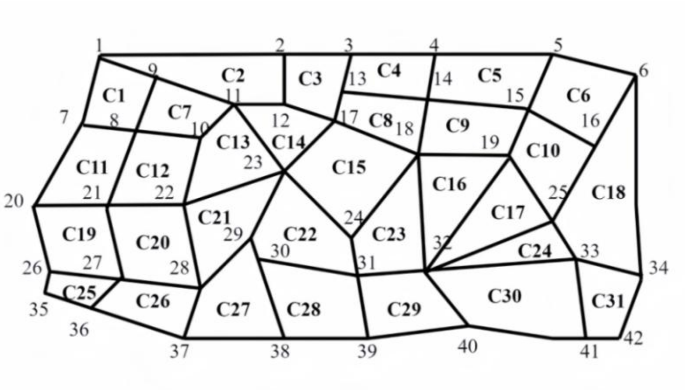

Figure 1:The road network structure

The average daily traffic flow information for the road nodes in the commercial area was obtained by investigating and recording the average daily traffic flow information for a week in the area. The location of the intersection nodes and the location of the alternative charging stations are represented by a planar coordinate system in kilometre; the traffic flow data is in units of vehicles. The some details are shown in Table 1.

Table 1:Road node traffic flow

Knot	Horizontal coordinate	Vertical coordinate	Traffic flow	Knot	Horizontal coordinate	Vertical coordinate	Traffic flow
1	1	4.25	3628	22	2.3	2	4600
2	3.75	4.3	5236	23	3.75	2.5	5738
6	9	4	1286	27	1.4	0.9	2836
7	0.75	3.2	867	28	2.5	0.8	6213

9	1.8	3.9	9765	30	3.4	1.1	8235
13	4.7	3.7	6322	34	9.1	0.9	3367
14	6	3.55	8676	35	0.15	0.7	6896
18	5.8	2.8	9986	39	5.05	0	980
19	7.25	2.75	7230	40	6.6	0.15	1006
21	1.1	2	5036	42	8.8	0	4118

The charging station alternatives are located at suitable sites within the 31 study area, and information on the location of some of the charging station alternatives within the region is shown in Table 2:

Table 2:Alternative point location coordinates

Area code	Horizontal coordinate	Vertical coordinate	Area code	Horizontal coordinate	Vertical coordinate
C1	0.52	1.44	C17	7.1	1.8
C2	1.06	1.56	C18	8.6	1.95
C5	2.76	1.56	C19	0.7	1.5
C6	3.3	1.46	C20	1.85	1.45
C7	0.9	1.36	C23	5.4	1.55
C9	6.65	3.15	C24	7.4	1.3
C10	7.85	2.7	C25	0.7	0.8
C11	0.85	2.6	C26	1.8	0.55
C12	1.9	2.55	C27	2.95	0.55

2.2 Experimental Environment Settings.

This study establishes a multi-objective function for charging station site selection and capacity determination, incorporating weighting coefficients Ψ1 and Ψ2 (where Ψ1 + Ψ2 = 1) to represent construction/operation costs and user costs respectively. The parameter settings are determined as Ψ1 = 0.4 and Ψ2 = 0.6, prioritizing user cost considerations. Detailed parameter configurations are provided in Table 3.

Table 3: Weighting factor setting

Weighting factors	Ψ1	Ψ2	Objective function
User cost	0.4	0.6	$\min F = 0.4 \cdot C_{EVCS} + 0.6 \cdot (C_{wait} + C_{drive})$

2.3 Result

Utilizing the Floyd minimum path algorithm, the minimum travel distances from every demand node within the road network to the prospective charging stations are calculated using the geographical coordinates of the intersection points. Figure 2 depicts the findings concerning the placement and capacity allocation of the charging stations.

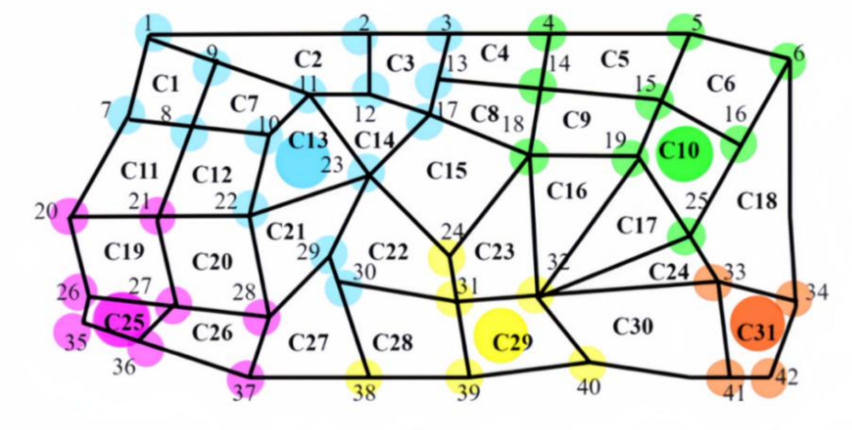

Figure 2:Charging station siting and capacity results

As can be seen from Figure 2, Taking green as an example, the charging station construction area is C10, and the nodes served by this charging station are 4, 5, 6, 14, 15, 16, 18, 19, and 25.

Table 4 presents the results concerning the siting and distribution of electric vehicle charging stations

Table 4:Charging station siting and capacity results

Area code	Number of fast chargers	Number of superchargers	Service Demand Node Number
C10	7	9	4, 5, 6, 14, 15, 16, 18, 19, 25
C13	6	7	1, 2, 3, 7, 9, 10, 11, 12, 13, 17, 22, 23, 29, 30
C25	8	9	20, 21, 26, 27, 28, 35, 36, 37
C29	7	8	24, 31, 32, 38, 39, 40
C31	6	7	33, 34, 41, 42

Based on the analysis of the data shown in Table 4, it can be seen that five charging stations were constructed in the commercial area with a total number of 74 charging piles, and the ratio of the number of super-charging piles to fast-charging piles was 20 to 17, with priority given to the user's cost.

3 Conclusion

The planning of electric vehicle charging infrastructure must balance construction and operational costs with user expenses. This study develops a multi-objective optimization model integrating queuing theory (for calculating waiting times) and Floyd's algorithm (for determining shortest paths), specifically designed to address charging demands from both stationary and mobile users in commercial areas. The model aims to collaboratively reduce both charging station construction and operation costs and user service expenses, with its effectiveness validated through case studies.

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