Allocation of Electric Taxi Charging: Assessing the Layout of Charging Stations Based on Charging Frequency

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Abstract: Recent decades have witnessed the growth of the electric vehicles (EVs) industry due to technological developments. To overcome emerging environmental issues, some metropolises, i.e., Beijing, have employed electric taxi systems, which require tremendous investments in charging stations. However, the supporting charging facilities for EVs are not complete, and in terms of layout, there is also a situation where some charging stations have long charging queues, but some are unvisited. To overcome these difficulties, this paper aims to establish a set of charging stations layout assessment models for the electric taxi based on charging frequency and put forward targeted policy suggestions to make the charging frequency of each station more balanced, to avoid resource waste and undersupply. In this paper, a mathematical model based on integer programming is established in conjunction with the workflow of the electric taxi; in the case study, simulations are performed using the Anylogic platform and the results are statistically analyzed; moreover, we use real-time data to assess the layout of charging stations near and within the Fourth Ring Road in Beijing. The modeling and simulation results show that there is an imbalance in the current charging stations layout in Beijing. More specifically, there is a problem with charging frequency of some stations, which is being too low and some too high. Also, the charging frequency of stations will vary with passenger distribution factors. We classify the studied charging stations into four categories according to their actual usage characteristics and provide specific analysis and optimization suggestions for the different categories. Based on the assessment system in this paper, we also carried out some policy suggestions for further layout optimization. The optimized layout has a more balanced charging frequency, and the variance of charging frequency is reduced largely.

Keywords: assessment; charging frequency; charging stations layout; electric taxi

1 INTRODUCTION

Environmental pollution and energy shortages are two problems faced by the world's automotive industry. With rapid economic developments, the number of vehicles in the world is constantly increasing. Among them, traditional automobiles have an urgent demand for petroleum resources, and their negative impact on the environment has become more and more serious [1-3]. Faced with tremendous pressure from energy and the environment, governments and social planners continue to seek cleaner alternative fuels to reduce traffic emissions [4]. The emergence of electric vehicles (EVs) has brought breakthroughs to solve these two problems mentioned above. Among them, EVs can release the dependence on petroleum resources, also reduce air pollution and noise pollution. To that end, EVs have become a research hotspot in the automotive field, and promoting the transformation of automotive energy and power is also the development focus of the automotive industry [5-8].

To alleviate the environment and energy issues, many cities are actively applying EVs to public urban transportation. The government vigorously promotes the transformation of urban taxis from traditional fuel vehicles to EVs, thereby propagating the thriving of the electric vehicle industry [9].

However, due to its technical characteristics and charging mode, EVs need to be refueled/charged more frequently than the traditional fossil fuel vehicles, which is one of the important reasons to limit its large-scale application [10]. This problem is particularly prominent for the electric taxi group. Therefore, a more balanced layout planning is particularly important. For instance, too dense a charging station layout will lead to a low charging frequency of each station, resulting in the situation of idle resources. Too sparse charging stations layouts will lead to high charging frequency, resulting in a short supply of long lines of charging. The balanced layout of charging stations can not only ensure the minimum operation cost of enterprises but also improve the service level of passengers, promoting the development of the EVs industry [11].

Electric taxi charging stations are scarce resources, especially in urban areas. Therefore, this paper sets the object of research as electric taxis. On the one hand, most of the current electric private cars are charged by private charging piles, and the main users of public charging stations are electric taxi; on the other hand, the government promotes the transformation of the electric taxi, and the layout planning of charging stations is mostly considered from the perspective of social welfare. Based on the charging frequency of stations, this paper establishes a mathematical model of electric taxi charging based on integer programming and puts forward the assessment system of the electric taxi charging stations layout. More specifically, we use the Anylogic simulation platform to simulate the workflow of an electric taxi, and the simulation results are further statistically and analytically analyzed. Moreover, the simulation model is used to investigate the factors influencing the charging frequency of stations. To show the efficiency of our proposed method, we employ a real-time dataset in Beijing. Taking Beijing as an example, the layout of charging stations in and within the Fourth Ring Road of Beijing is assessed. According to our results, the current layout of charging stations in Beijing is unbalanced. For further analysis, we classify charging stations in Beijing into four categories and explain the characteristics of different categories of charging stations and make targeted suggestions for policymakers. With the simulation model, we identified the distribution of demand points as an influential factor in the charging frequency of stations. Based on the above assessment system, we carried out some policy suggestions for further layout optimization, which has a more balanced charging frequency.

In summary, the existing research on the location of EVs charging stations may have the following two potential improvements:(1) First, the charging usage can elucidate

the appropriate charging frequency, while existing research focuses on traffic flow, driving distance, path, etc; (2) Second, most of the current studies aim at optimizing the site selection, but there is a lack of research assessment system for the existing charging stations layout and assessment methods. This paper sets the object of research as electric taxis. The duration of individuals' activities and the actual needs of the electric taxi, especially the feedback of electric taxi demand, are important indicators for selecting the charging stations layout. To fill the literature gap, this paper establishes a framework to assess the layout of electric taxi charging stations based on charging frequency. It also considers other factors such as demand point distribution, EVs distribution, and other influencing factors, and provides implications on the specific operation of different types of charging stations. Under the case study environment, agent technology is used to analyze and assess the layout of electric taxi charging stations.

The rest of the paper is organized as follows: In Section 2, an analytical model is proposed that forms the basis of the research problem. In Section 3, we present the Anylogic simulation models with a real-life case of Beijing city, China. In Section 4, we verify the model through Analysis of Variance (ANOVA). Section 5 discusses the results of the case study. Finally, concluding remarks are presented in the last section.

2 ASSESSMENT MODEL

This section analyzes the workflow of the electric taxi and establishes a mathematical model based on this process. Through the application of agent modelling technology, a case study is provided to analyze the rationality of the existing charging stations layout and construct the assessment system of the charging stations layout. The purpose of this paper is to analyze the charging frequency of the current stations and balance the charging frequency of each station to ensure that the difference in charging frequency lies in a relatively small region.

2.1 Mathematical Model

In the simulation model, the demand simulation model constantly generates demand points and puts the generated demand points into the queue in main. Fig. 1 below shows the workflow of electric taxi:
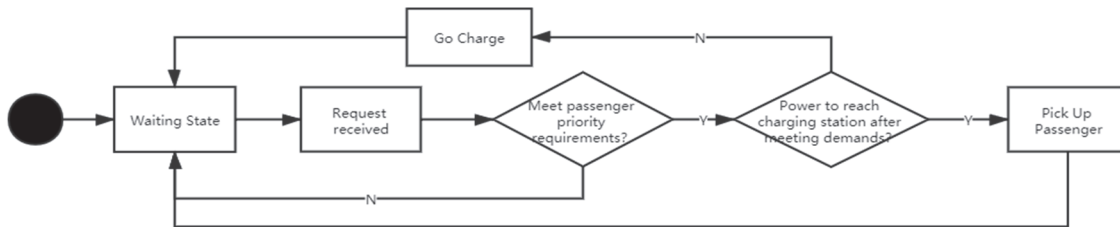

Figure 1 State diagram of electric taxiagent

The workflow of an electric taxi can be summarized as follows. Initially, the electric taxi is in a waiting state. As the passenger demand point arises, the e-Taxi receives a request from the passenger. At this point, the first decision is to determine whether or not it meets the passenger's priority based on its distance from the passenger and the remaining charge. If the demand is not met, the electric taxi returns to the waiting state. If the demand is met, a second decision is made to determine whether the electric vehicle can reach the nearest charging stations after serving the passenger (to ensure that it does not run out of battery and break down). If this is the case, it goes directly to the point of service and returns to the waiting state. If this is not possible, the taxi will first be charged at the nearest charging stations and then return to the waiting state when fully charged.

According to the above electric taxi workflow process, it can be expressed in the following mathematical model. Tab. 1 provides the main parameters employed in the layout assessment problem.

Table 1 Parameter settings

Serial number	Variable name	Variable description
1	S	The consumed electricity per unit distance
2	C	The mileage,the maximum amount of electricity that the taxi can charge
3	i	Electric taxi i
4	j	Current demand point
5	j'	Next demand point
6	c	Charging station c
7	d	Euclidean distance between two points
8	G	A large positive number
9	X_{ijk}	Whether passenger j boards taxi i in sequence k, 0 - 1
10	Y_{ikc}	Whether taxi i charges at station c in sequence k, 0 - 1
11	L_{ik}	The running distance of taxi i in sequence k
12	$Z_{ik}Z_{ik}$	The remaining power of taxi i in sequence k
13	$e_{i,k}$	The first running distance of taxi i in sequence k
14	n_1	The total number of electric taxi
15	n_2	Total number of trips for electric taxi
16	s	Total number of charging station

The total travel distance of electric taxi is as follows:

$$\sum_{i=1}^{n_1}\sum_{k=1}^{n_2} L_{ik} \tag{1}$$

Driving distance includes the distance from the current demand point to the next demand point:

$$d_{jj'} = \sqrt{\left(x_j - x_{j'}\right)^2 + \left(y_j - y_{j'}\right)^2} \tag{2}$$

where $\left(x_j, y_j\right)$ represents the coordinates of the current passenger j, $\left(x_{j'}, y_{j'}\right)$ represents the coordinates of the next passenger j', $d_{jj'}$ represents the distance between passenger j and j'.

The distance from the demand point to the charging point is:

$$d_{jc} = \sqrt{\left(x_j - x_c\right)^2 + \left(y_j - y_c\right)^2} \tag{3}$$

where x_c, y_c represents the coordinates of charging station c, d_{jc} represents the distance between passenger j and charging station c.

$$d_{j'c} = \sqrt{\left(x_{j'} - x_c\right)^2 + \left(y_{j'} - y_c\right)^2} \tag{4}$$

where $d_{j'c}$ represents the distance between passenger j' and charging station c.

Then we show the constraints of the model as follows:
(1) Running distance.
Eq. (5) below describes when the taxi receives a charge from a charging station:

$$L_{i,k} \geq \left(X_{i,j,k} + Y_{i,k,c} - 1\right) 1 d_{j'c} = \left(X_{i,j'k+1} + Y_{i,k+1,c} - 1\right) d_{j'c} \tag{5}$$

Due to the model optimization, we can obtain that $X_{i,j,k} = 1$, $Y_{i,k+1,c} = 1$

Eq. (6) describes when charging atacharging stationdoes not occur:

$$L_{i,k+1} \geq \left(X_{j,j,k} + X_{j,j'k} - 1\right) d_{jj'} \tag{6}$$

(2) Electricity guarantee.
Eq. (7) is the electricity guarantee during taxi running and the taxi charging description:

$$C \sum_C Y_{i,k,c} + Z_{i,k} \geq L_{i,k} \times S \tag{7}$$

Eq. (8) describes the first distance (taxi to chargingstation):

$$G\left(1 - Y_{i,k,c}\right) Z_{i,k+1} \geq S\left(X_{i,j,k} + Y_{i,k,c} - 1\right) d_{jc} \tag{8}$$

Eq. (9) describes the second distance (charging station to passenger):

$$CY_{i,k+1,c} + G\left(1 - Y_{i,k+1,c}\right) \geq S\left(X_{i,j'k+1} + Y_{i,k+1,c} - 1\right) d_{j'c} \tag{9}$$

In the case of $Y_{i, k+1,c} = 0$, ensures that the model has a solution; in the model optimization process, we can obtain $Y_{i,k+1,c} = X_{i,j'k+1} = 1$.
(3) Electricity balance.
Eq. (10) describes when the taxi is charging at the charging station:

$$Z_{i,k} \leq C \sum_c Y_{i,k,c} - S \times e_{i,k} \tag{10}$$

Because electric taxi visits charging stations, so $\sum_c Y_{i,k,c} = 1$.

Eq. (11) describes when the taxi is not charged at the charging station:

$$Z_{i,k+1} \leq Z_{i,k} - S \times L_{i,k} \tag{11}$$

(4) Passenger service.
Eq. (12) assumes that a passenger needs to be served by the taxi and each passenger can only be serviced once:

$$\sum_i \sum_k X_{i,j,k} = 1, \forall j \tag{12}$$

(5) Charging station access.
Eq. (13) ensures that each taxi can only access one charging station at a time:

$$\sum_c Y_{i,k,c} \leq 1, \forall i, k \tag{13}$$

(6) Number of services.
Since electric taxi may or may not carry passengers, there is always the Eq. (14):

$$\sum_j X_{i,j,k} \leq \sum_j X_{i,j,k+1}, \forall i, k \tag{14}$$

2.2 Layout Assessment Model

Combined with the first distance and the second distance, the layout assessment model of charging stations is given in Eq. (15) and Eq. (16).

$$\begin{aligned}\text{Min}\alpha &\left(\sum_{c=1}^s \sum_{i=1}^{n_1} d_{ic} + \sum_j \sum_{c=1}^S d_{cj}\right) X_{i,j,k} - \\ &- (1-\alpha)\left(\sum_{c=1}^s \sum_{i=1}^{n_1} d_{ic}\right) X_{i,j,k} \text{ if } Y_{i,k,C} = 1\end{aligned} \tag{15}$$

$$\text{Min}\alpha\left(\sum_{c=1}^s \sum_{i=1}^{n_1} d_{ic} + \sum_j \sum_{i=1}^{n_1} d_{ij}\right) X_{i,j,k} \text{ if } Y_{i,k,C} = 0 \tag{16}$$

subject to:

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{17}$$

$$d_{cj} = \sqrt{\left(x_c - x_j\right)^2 + \left(y_c - y_j\right)^2} \tag{18}$$

$$d_{ic} = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \qquad (19)$$

Here x_i, y_i, x_j, y_j, x_c, y_c represents the coordinates.

$$\sum Y_{i,k_1} \approx \sum Y_{i,k_2} \approx, ..., \sum Y_{i,k_c} \qquad (20)$$

$$\min(s) \qquad (21)$$

Eq. (17) to Eq. (19) are the distance; Eq. (20) indicates that the assessment process does not stop until the charging frequency of each charging station is similar; Eq. (21) means the minimum number of charging stations is required.

The reasonable construction of charging stations for electric taxis can minimize taxi charging costs and improve the passenger service level. Therefore, in the assessment model, we should consider electric taxi characteristics and passenger demand. Combined with these important factors, we can use the passenger response time, passenger service time, passenger-car distribution, car mileage, etc., to improve the assessment model based on the charging frequency:

(1) obtaining the basic parameter values:

Parameters include $d_{jj'}$, $d_{j'c}$, L_{ik}, Z_{ik}, $e_{i,k}$, X_{ijk}, d_{ij}, d_{ic}, α, C, $n_{1,S}$.

(2) obtaining the situations:

if $(d_{cj} + d_{ij}) \leq C Y_{ikc} = 0$

if $\lambda(d_{ic}) \leq C \leq (d_{cj} + d_{ij})$, $Y_{ikc} = 1$

if $(d_{ic}) > C$ the car cannot move anywhere.

(3) calculating the minimum of the total distance:

We can obtain the corresponding car running distance in different charging situations.

(4) obtaining the results:

The results include the starting point coordinates of the electric taxi, position coordinates of the passenger demand point, charging station ID, remaining mileage of the electric taxi, passenger ID, passenger priority and electric taxi ID.

(5) calculating the charging frequency of different charging stations:

The assessment process does not stop until the charging frequency of each charging station is similar, that is, $Y_{ik1} = Y_{ik2} =, ..., = Y_{ikc.}$

Electric taxi charging stations are scarce resources, especially in urban areas, and a contradiction between supply and demand is inevitable, coupled with uncertainty in passenger demand. Therefore, how to reasonably locate electric taxi charging stations has great significance for improving the service level of electric taxis.

3 MODEL ANALYSIS-A CASE STUDY OF BEIJING CITY

In this study, we took 43 charging stations ("red dot") located in the center of Beijing for the purpose of layout assessment. As the traffic in Beijing is concentrated in the Fourth Ring Road, the distribution of electric taxi is relatively dense in this area, and the construction of charging stations is relatively mature. Therefore, we select

the data of the center of Beijing (near and within the Fourth Ring Road) for research (Fig. 2). The data sources of the study are Baidu maps and evpartner (http://www.evpartner.com/auto/pilemap.html.). Fig. 3 illustrates a partial screen shot of the distribution of electric vehicle stations in Beijing on the website.
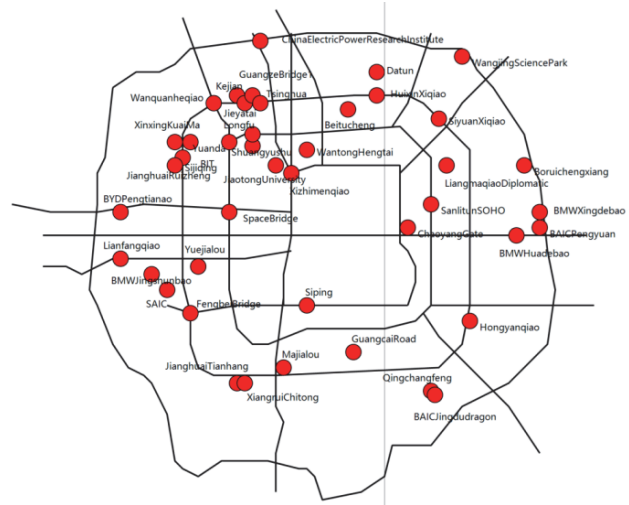

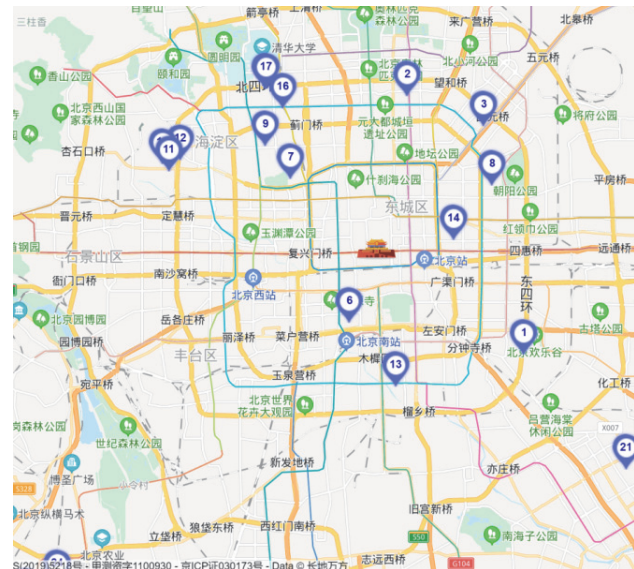**Figure 2** Current layout of charging stations in Beijing city

Figure 3 Distribution of charging stations in Beijing

The simulation process is shown in Fig. 4. The "red dot" represents the location of the charging point, the "yellow dot" represents the randomly generated 50 driving electric taxis, and the "blue dot" represents the randomly generated 500 demand points.

According to reality, Beijing's Fourth Ring Road is 65.3 km long, and the range of the electric taxi can be sufficient for driving within the Fourth Ring Road. Therefore, combining the size of the simulation map with the actual scale, we set the range of the electric taxi to 600 km to ensure that it can drive within the Fourth Ring Road. Besides, the number of electric taxis is set to 50, the number of demand points is set to 500, and the number of iterations is set to 100.

The details of each charging point are shown in Tab. 2 below:

Table 2 Location coordinates of electric charging stations in Beijing

| Number	Name	Coordinate	Detailed Address
1	Datun station	(−10, 182)	
2	HuixinXiqiao station	(−10, 210)	No.1 Huixin West Street, Chaoyang District
3	Beituchengstation	(−47, 228)	
4	Wanquanheqiao station	(−223, 224)	
5	Xizhimenqiao station	(−120, 310)	
6	Space Bridge station	(−200, 360)	
7	Yuejialou station	(−240, 430)	
8	Lianfangqiao station	(−340, 420)	
9	Fengbei Bridge	(−250, 490)	
10	LiangmaqiaoDiplomatic Residence station	(−130, 560)	South of Liangmaqiao Diplomatic Residence B, East side of the East Third Ring Road, Outer Ring Road
11	SiyuanXiqiao station	(70, 240)	No. 11, North Fourth Ring Road East, Chaoyang Distri
12	Sanlitun SOHO station	(60, 350)	Sanlitun SOHO, Sanlitun Street, Chaoyang District, Beijing
13	Hongyanqiao station	(110, 500)	Hongyan bridge beside Sifang bridge, Chaoyang District
14	Jiaotong University station	(−140, 300)	Graduate School of Beijing Jiaotong University
15	Shuangyushu station	(−170, 275)	Shuangyushuhedgehouse Road, Haidian District
16	Kejian building station	(−190, 210)	Kejian building
17	Siping garden in Xicheng	(−100, 480)	1-4, sipingyuan, Xicheng District, Beijing Power Demand Side Management Exhibition Center
18	Ryangmaqiao Diplomatic Residence	(80, 300)	Liangmaqiao Diplomatic Residence on the east side of the outer East Third Ring Road.
19	Chang'an 4S store of Xinxing Kuai Ma Automobile Service Co., Ltd	(−270, 270)	Bungalow, No.15, Changrun Road, Sijiqing Township, Haidian District
20	Sijiqing	(−260, 290)	No.8, Sijiqing Road, Haidian District
21	Yuanda road	(−250, 270)	No.38, West Fourth Ring Road North, Haidian District
22	Guangcai road	(−40, 540)	Fengtai District Beijing Institute of Physical Education
23	Chaoyang Gate	(30, 380)	Sanfeng Hutong, Chaoyang Gate, Chaoyang District
24	JieyataiZhongsheng automobile sales Chang'an 4S store	(−180, 220)	JieyataiZhongsheng automobile sales Chang'an 4S store
25	Guangze Bridge1	(−170, 210)	Beili, Paifang village, Xiaohongmen Township, Chaoyang District
26	China Electric Power Research Institute	(−160, 140)	Xiaoying East Road, Haidian District, Beijing
27	BAIC Jingdu dragon 4S store	(65, 595)	Beili, Paifang village, Xiaohongmen Township, Chaoyang District
28	ChanganqingChangfeng 4S store	(60, 590)	No.91, South Fourth Ring Road East, Xiaohongmen village, Chaoyang District
29	BAIC PENGYUAN 4S store	(200, 380)	No.24 bungalow, No.35 dahuangzhuang, Chaoyang District
30	Brilliance BMW huadebao 4S store	(170, 390)	Balizhuang village, Gaobeidian Township, Chaoyang District (south of Jingtong Expressway)
31	Brilliance BMW Xingdebao 4S store	(200, 360)	No.8, baijialou, Gaobeidian Township, Chaoyang District (800m into Yaojiadian Road, east of huangshandian, Chaoyang District)
32	Beijing BoruiXiangcheng Automobile Sales Service Co., Ltd	(180, 300)	No.5 lijiafeng, Chaoyang District
33	Wangjing Science Park Charging Station	(100, 160)	No. 108, Lize Central Park, Lize Zhong Er Road, Chaoyang District, Beijing
34	JianghuaiTianhangRuichen 4S store	(−190, 580)	No.88, South Fourth Ring Road West, Fengtai District
35	Beijing XiangruiChitong Automobile Sales Co., Ltd	(−180, 580)	Beijing XiangruiChitong Automobile Sales Co., Ltd
36	SAIC JiadaBotong 4S	(−280, 460)	No. 83, Middle West 4th Ring Road, Fengtai District
37	Brilliance BMW jingshunbao 4S store	(−300, 440)	No. 43, Huangzhuang village, Lianshi East Road, Shijingshan District
38	JianghuaiRuizheng 4S store	(−270, 300)	Xipingfang, tongjiafen, Sijiqing, Haidian District
39	BIT charging stationstation	(−200, 270)	No.5, Zhongguancun South Street, Haidian District
40	Beijing Unicom longfu Automobile Sales Co., Ltd	(−170, 260)	No. 108, Zhongguancun East Road, Haidian District
41	Tsinghua garden	(−160, 220)	No.1, Zhongguancun East Road, Haidian District
42	Beijing WantongHengtai Automobile Sales Co., Ltd	(−100, 280)	West side of Xiaoying bridge of Badaling Expressway in Haidian District
43	BYD pengtianao 4S store	(−340, 360)	Bungalow on the east side of Guojin yuan, liaogongzhuang village, Haidian District
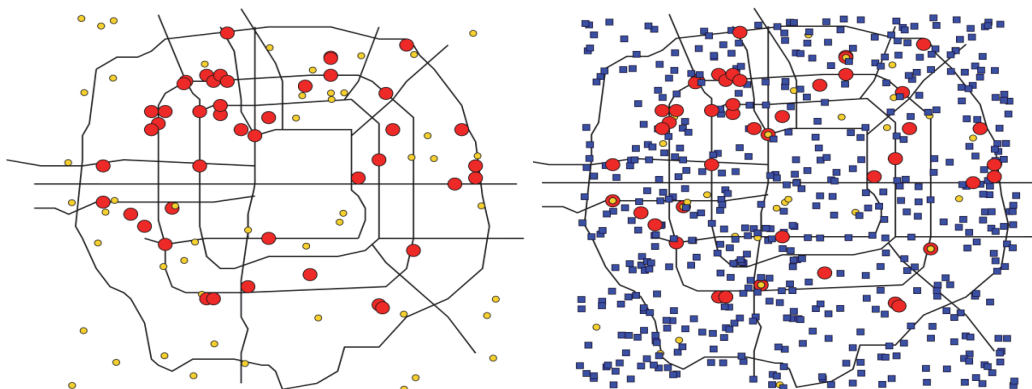
Figure 4 Simulation interface

The data sample obtained from the simulation is shown in the following table:
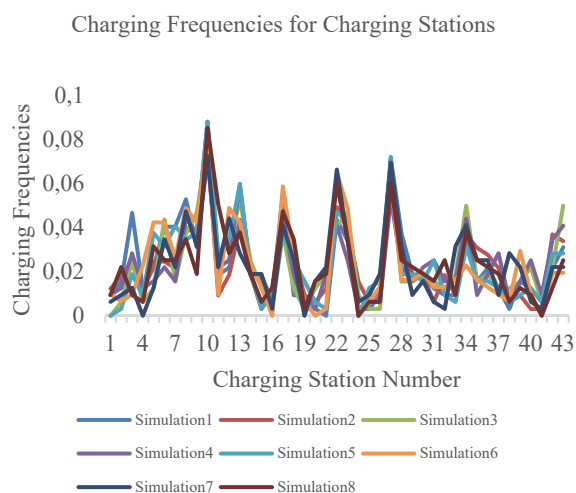
Table 3 Simulation results (part)

$C(x)$	$C(y)$	$P(x)$	$P(y)$	CPI	RM	PID	PP	CID
49	339	37	273	0	257	420	0.891911	20
−114	280	−83	327	0	297	498	0.883322	18
65	595	218	716	27	600	178	0.989365	10
65	595	181	584	27	600	273	0.911536	44
−130	560	−396	651	10	600	133	0.914437	41
−130	560	−247	625	10	600	27	0.920867	40
200	380	115	407	29	600	286	0.890852	9
−176	276	−69	227	0	273	451	0.854508	21
−106	232	82	295	0	345	421	0.862164	12
30	380	−287	206	23	600	472	0.887951	8

The outputs of the simulation include $C(x)$ $C(y)$: the initial position coordinates of the electric taxi, $P(x)$ $P(y)$: the position coordinates of the demand point (passenger), *CPI*: the ID of the visited charging station, *RM*: the remaining mileage of the electric taxi, *PID*: the passenger ID, *PP*: the priority of the passenger, and *CID*: the ID of the electric taxi.

We did a total of eight sets of repeated experiments and counted the charging frequency of each station to plot the corresponding stations charging frequency line graph. As shown in the figure below, the horizontal coordinate is the 43 charging stations and the vertical coordinate is the charging frequency of stations.

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Figure 5 Simulation results (statistics on charging frequency of each station)

To verify the accuracy of the model, we compared our findings with the actual charging station usage data (HuashangSanyou Charging Station). Among them, Liangmaqiao Diplomatic Apartment Charging Station, Sanlitun SOHO Charging Station, and Near Chaoyangmen Charging Station are in good use, while the Wangjing Science Park Charging Station is in poor use. This is consistent with the results in our simulation. The accuracy of the model and the validity of the output are verified.

By observing the trend of the fold line, we can see that the general trend of the eight experiments is more similar. For further analysis, we attempted to probe deeper using statistical methods. We first check the consistency of the results of each simulation experiment, that is, to determine if there is a significant difference between the results of each experiment. Since the data sets are non-normally distributed, we use the non-parametric Kendall test with multiple correlated samples. The Kendall coefficient test for multiple paired samples is also a non-parametric test for multiple paired samples, which can easily enable the analysis of the consistency of the rater's judging criteria. The zero hypotheses are that the judges are not consistent in their judging criteria. As shown in the table below, the value of *Asvmp. Sig.* is 0.964, which is greater than 0.05, so we believe that the 8 groups of experiments are significantly different with low correlation. Therefore, we need to conduct further analysis of the discrepancies.

Table 4 Test statistics

Test Statistics	
N	43
Kendall's Wa	.006
Chi-Square	1.932
d*f*	7
Asymp. Sig.	.964
a. Kendall's Coefficient of Concordance	

The above Kendall test proves that there are large differences and fluctuations in the charging frequency of stations. In order to explore the different characteristics of the charging stations in depth, we calculate the mean and standard deviation of each simulation. In order to unify the measurement dimension of each station's charging frequency, we also calculate the deviation coefficients for each station's charging frequency, as shown in the following table.

In order to better display the different classifications, we perform systematic clustering based on the mean and deviation coefficient of each station's charging frequency.

By observing this clustering spectrogram, we consider it more appropriate to classify the charging stations into four categories, as shown in the following table.

Pinning the above four types of charging stations, we have summarized the following patterns and suggestions for improvements.

(1) For the first type of charging station, it is characterized by a relatively small mean value of the station's charging frequency and a relatively large coefficient of variation. That is, under different demand point distributions and electric taxi distributions, the simulation results can be greatly influenced, but the charging frequency is always low. This indicates that such charging stations are heavily influenced by other factors and there is a partial waste of resources. Therefore, for this

kind of charging station, we need to combine the actual road information, EV distribution, demand point distribution, and other influencing factors, according to the actual situation to make specific adjustments to the parameters, so as to ensure the relative stability of the output results.

Improvement: Adjust the parameters according to the actual situation to reduce the volatility of the results and ensure the charging rate at a more stable level. For the relatively low charging frequency of stations, some station sites should be merged, or reduce size of such station sites.

Table 5 Statistics for each charging station

Number	1	2	3	4	5	6	7	8	9
STDEV	0.004669	0.006611	0.012368	0.006623	0.011439	0.008574	0.009845	0.006883	0.00843
AVERAGE	0.007098	0.011786	0.021954	0.009903	0.024912	0.033135	0.025999	0.04258	0.035471
CV%	0.657828	0.560947	0.563364	0.668739	0.459187	0.258749	0.378669	0.161653	0.237663
Number	10	11	12	13	14	15	16	17	18
STDEV	0.006542	0.013081	0.010631	0.011066	0.002427	0.006454	0.004692	0.008169	0.008396
AVERAGE	0.079997	0.023631	0.031651	0.045686	0.020496	0.01141	0.007064	0.045379	0.022497
CV%	0.08178	0.553562	0.335883	0.242213	0.118424	0.56559	0.664215	0.180011	0.373204
Number	19	20	21	22	23	24	25	26	27
STDEV	0.00502	0.006096	0.008815	0.010714	0.007882	0.005488	0.00313	0.005343	0.006681
AVERAGE	0.006289	0.00786	0.012197	0.051718	0.038646	0.004676	0.006707	0.010655	0.065757
CV%	0.798229	0.775543	0.722714	0.207164	0.203947	1.173785	0.46668	0.501466	0.101603
Number	28	29	30	31	32	33	34	35	36
STDEV	0.007665	0.003691	0.002045	0.007293	0.006673	0.008137	0.008145	0.007089	0.004842
AVERAGE	0.02438	0.016933	0.018523	0.014985	0.013391	0.014612	0.037753	0.019278	0.020441
CV%	0.314395	0.217953	0.110393	0.486684	0.498319	0.556853	0.21574	0.367734	0.236871
Number	37	38	39	40	41	42	43		
STDEV	0.00666	0.00811	0.006733	0.007493	0.003336	0.008097	0.010114		
AVERAGE	0.015728	0.009467	0.016236	0.012608	0.004311	0.024767	0.031436		
CV%	0.423461	0.856726	0.414712	0.594312	0.773861	0.32692	0.321729		

Table 6 System clustering results for charging stations

Types	Number	Characteristics	Description
1	1, 16, 4, 21, 19, 20, 41, 38, 2, 15, 40, 33, 31, 32, 26, 25, 3, 11, 5, 37, 39, 18, 35, 28, 42, 7	Small mean, relatively large coefficients of variation	The charging frequency of this type of charging station is low, and in different simulation experiments, the fluctuation of the charging frequency is relatively large
2	14, 30, 29, 36, 8, 17, 13, 22, 12, 43, 23, 34, 6, 9	Large mean, relatively small coefficient of variation	The charging frequency of this type of charging station is moderate, and the fluctuation of the charging frequency is relatively small
3	24	Small mean, significantly large coefficient of variation	The charging frequency of this type of power station is too low. In different simulation experiments, the charging frequency fluctuates significantly
4	10, 27	Large mean, significantly small coefficient of variation	In different simulation experiments, the charging frequency of this type of site is too high, and the charging frequency fluctuation is significantly small

(2) For the second class of charging stations, they are characterized by relatively large mean values and relatively small coefficients of variation. It indicates that the usage rate of this type of charging station is relatively high and the charging frequency fluctuates less in different simulation experiments. For such charging stations, their layout can be considered more reasonable. But for the individual high mean value of the station, they also need to make corresponding adjustments.

Improvement suggestion: The charging frequency of this kind of station is relatively reasonable. For some of the stations with a relatively big charging frequency, we can combine with the actual situation to expand the capacity or build new charging stations in the vicinity.

(3) For the third type of charging station, its characteristics are small mean value, significant large coefficient of variation. It shows that the frequency of charging to this type of stations varies greatly in different simulation experiments, but is always kept too low. The layout of this class of charging stations is too dense and requires a large adjustment. The adjusted layout can effectively avoid unattended charging stations, high idle rates, and high operating costs.

Improvement: merge some charging stations, or reduce the size of charging stations, so as to balance the excessively low charging frequency.

(4) For the fourth type of charging station, it is characterized by a large mean value and a significantly small coefficient of variation. It shows that in different experiments, regardless of the distribution of EVs and demand points, the charging frequency of this type of charging station is always too high and the charging frequency fluctuates little. The layout of such charging stations is too sparse, and new stations can be built appropriately in the area near the station, thus balancing the excessive charging frequency and the excessive charging pressure.

Suggestion for improvement: Build new charging stations or expand the size of charging stations near such stations.

In the following sections, we will analyze which factors are the key causes of large deviations in the charging frequency, thus providing a theoretical basis for the assessment system and layout optimization of charging stations.

4 ANALYSIS OF FACTORS AFFECTING THE LAYOUT OF CHARGING STATION

Based on the above analysis, it was found that some of the charging stations have a fluctuating in the charging frequency. This indicates that such charging stations are susceptible to influencing factors, which leads to different simulation results. In this section, we will use the Anylogic simulation model to determine the factors that influence the charging frequency of stations. This will enable us to adjust the parameters according to the actual situation and improve the accuracy of the simulation experiments. It also provides theoretical and practical guidance for the assessment and optimization of the charging station layout.

The agent model proposed in this paper will analyze the factors that affect the location selection of the charging point by using distribution factors of electric taxi and the distribution of demand factors. By changing or considering some key factors, we can judge the influence of these key factors on the charging frequency of stations. ANOVA is used to identify the influence of some key factors on the layout of charging stations. There are several levels that affect the charging frequency of stations, and several independent tests are carried out under different levels. It is assumed that the samples at each level are from the normal population with the same variance and mean value, and the samples at different levels are independent of each other. Based on this, the key factors affecting the layout of electric taxi charging stations are obtained in this section. Using the simulation algorithm in the previous section, we can obtain the assessment results of the layout of the electric taxi charging column. Next, we focus on the influence of the distribution of electric taxi, distribution of user demand, and other factors on the layout of charging stations.

4.1 Distribution of Electric Taxi

In the process of model simulation, the distribution of electric taxi follows a uniform distribution. Therefore, we will analyze the influence of the distribution of electric taxis on the layout of charging stations. We will analyze the influence of uniform distribution, triangular distribution, normal distribution, and pert distribution (Fig. 6) on the layout of charging stations. The model randomly generates 500 user demand information and 50 electric taxi information.
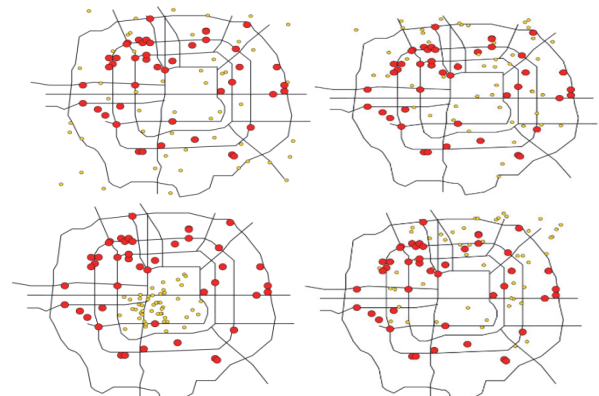

Figure 6 Different distribution of electric taxi

We count the simulation results of EVs under pert distribution, triangular distribution, and normal distribution parameters, respectively, as shown in the following table. Before conducting a one-factor ANOVA, we first verify that the variance of each group is univariate.

Table 8 Test of homogeneity of variances

Frequency			
Levene Statistic	df1	df2	Sig.
.638	2	21	.538

Table 7 Simulation results of electric taxi under different distributions

distribution type	charging frequency simulation results							
Pert	0.015974	0.019481	0.027607	0.025	0.036923	0.050473	0.012539	0.028939
triangular	0.031646	0.01875	0.019108	0.006734	0.030864	0.03537	0.015974	0.01497
Normal	0.015823	0.022436	0.012308	0.016181	0.018462	0.015528	0.022364	0.014706

Table 9 ANOVA with different distributions of EVs

Frequency					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	2	.000	.889	.426
Within Groups	.003	21	.000		
Total	.003	23			

The ANOVA test table shows that *Sig.* > 0.05, which means that the variance of each group is congruent and the next step of the ANOVA test can be performed.

From the above table, it can be seen that the p-value is 0.426 > 0.05. Thus, the type of EV distribution has no effect on the results and there is no significant difference in the results of operation under different EV taxi distributions. Thus, we conclude that the distribution of EVs is not a significant cause of the variation in the charging frequency to EV stations.

4.2 Demand Distribution Factors

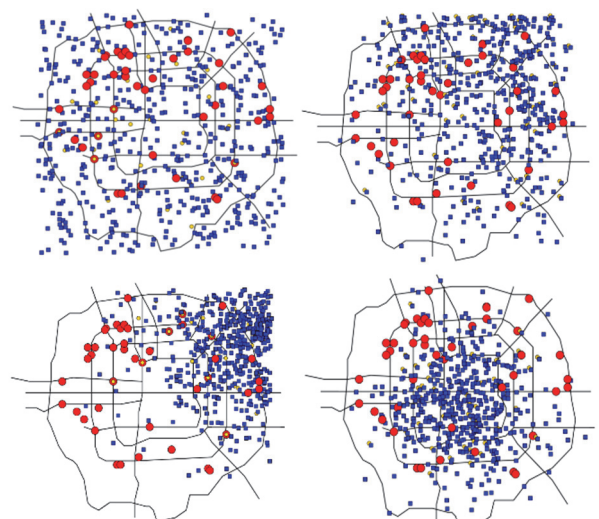In the process of model simulation, the demand distribution obeys uniform distribution.

Figure 7 Different distribution of requirements

Therefore, we will analyze the influence of demand distribution on the layout of charging stations. We will analyze the influence of uniform distribution, triangular distribution, normal distribution and pert distribution (Fig. 7) on the layout of charging stations. Similar to Section 5.1, the model randomly generates 500 user demand information and 50 electric taxi information.

We run the simulation results of demand points under pert distribution, triangular distribution, and normal distribution parameters, respectively, as shown in the following table:

Table 10 Distribution of requirements and charging frequency

distribution type	charging frequency simulation results							
pert distribution	0	0	0	0.00625	0	0	0	0
triangular distribution	0.00926	0.00897	0.01702	0.00418	0.00855	0	0.00873	0
normal distribution	0.01639	0.02235	0.01093	0.03763	0.01093	0.02235	0.03261	0.02864

Table 11 ANOVA with different distributions of demands

Frequency					
	Sum of Squares	*df*	*Mean Square*	*F*	*Sig.*
Between Groups	.002	2	.001	23.102	.000
Within Groups	.001	21	.000		
Total	.003	23			

From the above Tab. 11, we can find that the *p*-value is 0 < 0.05. Thus, the type of passengers' distribution has effects on the results and there is a significant difference in the results of operation under different demand points distributions. It can be concluded that the distribution of demands is a significant cause of the variation in the charging frequency to EV stations.

It can be concluded that the distribution of EVs is not a key factor that affects the charging frequency of station, whereas the distribution of demand points affects the charging frequency of station. The simulation results of the model will show different results according to the different parameter settings of the above factors. The reasonable layout of charging stations plays an important role in the development of electric taxis. The model is helpful to provide a reference for the location of the urban charging station.

In addition to the distribution of electric taxi and the distribution of demand points, the cruising range of electric taxi, road condition information, population density, urban planning, and other factors may also affect the charging frequency of stations. The above factors can also be adjusted using the simulation model in this study and analyzed by the ANOVA method. These influencing factors will cause the experimental results to change, so specific settings and adjustments need to be combined with the actual situation.

5 DISCUSSION

Based on the ideas in the previous section, we perform a simple layout optimization in this section. With the current characteristics of charging station locations in China, we find that most of the current charging station locations are located near universities or near vehicle dealerships. Therefore, we will also consider the location of universities and vehicle sales stores when considering new sites. The object of this study is the electric taxi, which is strongly promoted by the government. During the site selection process, more emphasis was placed on their potential environmental and energy benefits as well as urban planning benefits. Therefore, this paper does not consider the cost factor in the optimization process.
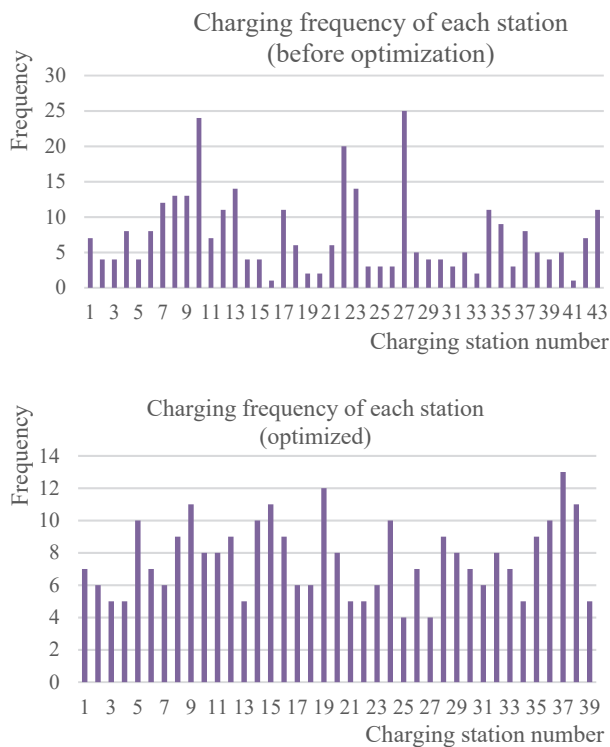
Regarding the optimization scheme, for charging stations that are visited too frequently, we build new alternative sites nearby to smooth the excessive visits. Based on the analysis in the previous section, we choose to locate near Category 4 charging stations (Majialou station and BAIC Jingdu dragon 4S store station) as well as some Category 2 charging stations (Hongyanqiao station, Guangcai road, and GianghuaiTianhangRuichen 4S store station). Newly established charging stations include Capital University of Economics and Business (−180, 540), Beijing Southeast Delica Automobile Trading Co., Ltd. (−230, 620), Beijing Electronic Technology Institute (−260, 560), Beijing University of Technology (90, 460), Beijing HaoyangZhengye Automobile Sales Service Co., Ltd. (40, 500), Beijing Xingrui (Mingde Store) (20, 600), China Public Security University (−110, 680).
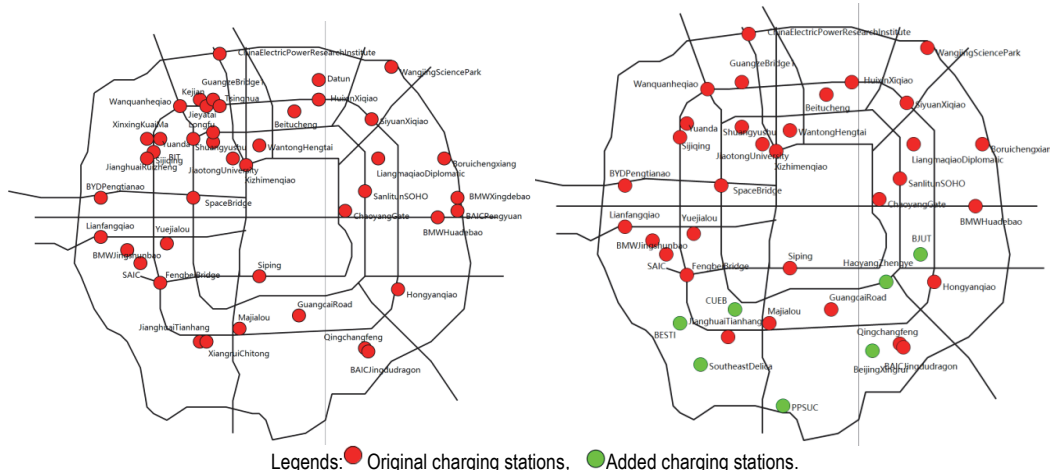
Legends: ● Original charging stations, ● Added charging stations.
Figure 8 The original and optimized layout of charging stations

At the same time, charging stations that are visited too infrequently require appropriate consolidation or reduction of charging station capacity. Based on the analysis in the previous section, we consolidate, dismantle, or reduce the charging capacity of Type III charging stations (Jieyatai charging station) and some Type I charging stations (BIT, Jianghuairuizheng, Xinxingkuaima, BMWXingdebao, BAICPengyuan, Longfu, Datunzhan, Xiangruichitong Charging Station). This reduces the waste of resources due to the density of stations. The pre-optimized and post-optimized layouts are shown in Fig. 8.

In order to control the variables and ensure the consistency of the conditions before and after the simulation, we set the layout of the electric taxi to be uniformly distributed, and the distribution of the demand points to be uniformly distributed as well, and the range of the electric taxi to be set to 600. The charging frequency to each station before and after the optimization is counted separately, as shown in the following figure

Figure 9 The 0riginal and 0ptimized charging frequency distribution map for each charging station

From Fig. 9, we can find that the variance of charging frequency of each station becomes less. By calculation, the charging frequency variance of each station before the optimization is 31.5, and the charging frequency of each station after optimization is 5.3. Using our assessment method, the charging frequency of each station after optimization is more balanced, and the effect has been optimized and improved. The electric taxi charging station assessment system based on the charging frequency is also instructive for the optimization of charging stations.

6 CONCLUSION

This paper establishes an assessment framework for the layout of electric taxi charging stations based on

charging frequency. In this study, a mathematical model is used to describe the process of the electric taxi, and the Anylogic simulation platform is used to simulate the workflow of an electric taxi. At the same time, combining with the layout of charging stations in Beijing, a case study is carried out, and optimization suggestions are put forward according to the analysis results. In this study, we choose the research object like an electric taxi for the following reasons. Firstly, private electric vehicles are mostly charged by personal charging piles, while public charging stations are seldom used. Electric taxis are the main users of public charging stations. Second, the government vigorously promotes the transformation of traditional taxis to electric taxis and provides policy support to the electric taxi industry. This requires the improvement of supporting charging facilities, including layout optimization, location assessment, etc. In light of the existing literature, the current research mainly focuses on the layout and location of the electric vehicle charging station. However, there is a scant investigation into the assessment system model. Therefore, this paper tries to fill this literature gap.

In summary, the main contributions of this paper are as follows.

(1) Theoretically: In light of the current literature, the research on electric vehicle charging stations is mostly focused on the layout and location, and there is less research on the assessment system. This study established an assessment system for the layout of electric taxi charging stations based on charging frequency. The application of the system is more extensive and flexible, and the parameters can be adjusted according to the actual situation to adapt to the case study in different situations. On the other side, a standard for reasonable layout proposed in this paper is that the charging frequency of different charging stations is similar, which is different from previous research. The study also validates the key factor that influences the charging frequency of electric taxi charging stations: the different distribution of demand points. This also provides ideas and research methods for studying other factors that influence the layout. Finally, based on the fact that policymakers are more concerned with social welfare issues, this paper also provides guidance for the optimization and improvement of the layout.

(2) Method: In the method, this research uses a combination of mathematical model and simulation approach. The mathematical model is used to characterize the working process and constraints of the electric taxi. On the other side, the Anylogic platform is used to simulate the working process of the electric taxi for actual operations. The advantage of simulation lies in the flexibility to change parameters and charging station location and other information at any time according to the required conditions. We also combine statistical methods to comprehensively analyze the data to make the assessment system more complete. Moreover, our proposed method can be applied to the assessment of the electric charging station layout in various regions. This assessment system can not only be used to assess the layout of charging stations but also has certain guiding significance for layout optimization.

(3) Practically: Regarding the assessment system of electric taxi charging stations based on charging frequency

established in this paper, on the one hand, it can be used to assess the existing layout. On the other hand, it can also play a guiding role in the optimal layout of charging stations. To test the efficiency of our approach, we choose real electric charging station location data in Beijing, consider endogenous variables such as taxi range, electric taxi distribution, and demand point distribution, provide an assessment conclusion, and optimize the layout. Whereas previous studies have focused on exogenous variables such as battery size, charging capacity, charging power, battery replacement, and construction cost. The analysis of these factors helps to inform the siting of charging stations for an electric taxi. Our work can provide policy recommendations to social planners on the issue of electric taxi charging station layout. The layout of charging stations is assessed by using real datasets, i.e., 1) obtaining basic parameter values, 2) calculating charging frequencies for different charging stations, 3) obtaining specific working paths for the electric taxi, 4) analyzing statistical results and categorizing the results, 5) strategic analysis for the results, and 6) guidance for layout optimization. The analysis model can also be applied to other cases to guide practice.

However, there are some limitations to this paper. Based on the existing foundation, more variables such as road congestion and population density distribution need to be added to the simulation to make the results more accurate and realistic. At the same time, this paper focuses on the research of electric taxis and attaches more importance to their environmental and social benefits, so the influence of cost factors and construction feasibility factors are neglected in the optimization process of site selection. However, in the actual optimization process, exogenous variables such as cost factors and land factors also need to be taken into account. We will address these issues in our future research.

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