Multi-period Planning of Electric Taxi Charging Station Based on Genetic Tabu Hybrid Algorithm

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Abstract. As an auxiliary facility for electric taxi operation, the charging station has important significance for the promotion of electric taxis in terms of location, scale and construction time. Most of the existing research on charging station location focuses on static problems, ignoring the impact of station time on the location model. Therefore, based on the site selection and queuing theory, this paper proposes a multi-period and multi-level electric taxi charging station model, with the goal of the total construction cost, the cost of the station and the minimum waiting cost. Combined with the multi-starting point of genetic algorithm and the strong local search ability of tabu algorithm, the genetic tabu hybrid algorithm for solving this model is designed. The simulation example is used to analyze and verify the validity of the model and algorithm, which can provide important reference for practical multi-period charging station planning.

1. Introduction and literature review

As the global energy crisis continues to deepen and urban air pollution problems become more prominent, energy conservation and emission reduction have become a hot topic for all countries, and new energy vehicles have also ushered in the best opportunity for rapid development. Taxi accounts for a large part of the transportation system. The government and social forces can invest in it to break the problem of electric cars and their charging stations, which called “chickens first or eggs first” dilemma. Therefore, many cities across the country have begun to introduce the electric taxis for pilot projects. As a result of a problem of electric bicycle charging being difficult due to the increasing number of electric taxis, long charging time, unreasonable charging station layout and high construction costs. This paper studies this problem and promotes the development of electric taxis by establishing mathematical models to rationally layout charging stations.

At present, domestic and foreign scholars focus on single-period charging station location research with the goal of minimizing cost in [1]- [6]. Some scholars have also targeted the location of the charging station to maximize the traffic flow of the charging station service in [7]- [10]. Only a few scholars have studied the location of multi-period charging stations. Chung and Kwon [11] considered the two factors of traffic flow and charging station location strategic planning, and proposed a multi-period optimization planning model with the goal of maximizing traffic over the entire period, and solved by CPLEX. Li et al. [12] established a multi-period mixed integer programming model that minimizes the installation cost of the new charging station and the relocation cost of the existing charging station by considering the shortest and deviation paths, and solved by genetic algorithm.
In summary, the current research mainly focuses on the location problem of static electric vehicle charging stations. However, the charging station needs large investment and large scale, which belongs to infrastructure construction. Its construction should pay more attention to multi-period planning, so the multi-period problem needs further study. In addition, the charging behavior of electric taxis has great randomness (Ge et al [13]; Liu et al [14]). When the electric taxi arrives at the charging station, if the charging pile is idle, the charging service can be accepted, otherwise it needs to wait in line for service. The continuous development of the electric taxi market, only considering the unilateral optimization of the charging station investors is less convincing, and studying the overall interests of the charging station investors and users is the future trend. Although Chung and Kwon [11]and Li et al. [12] studied the optimization of multi-period planning, the author did not pay attention to the size of the charging station and the queuing behavior at the charging station and the overall interest of the charging station construction. Therefore, this paper adopts the M/M/c/K model in queuing theory, and establishes a multi-period and multi-level electric taxi charging station location model with the objective function of the whole periods cost including construction cost, the station cost and the waiting cost minimizing. Combined with the multi-starting point of genetic algorithm and the local search ability of tabu algorithm, the genetic tabu hybrid algorithm (GATS) is designed to solve the model, and the validity of the model is verified by comparing with the Forward-myopic method.

The rest of this paper is organized as follows. The multi-period and multi-level electric taxi charging station location model is introduced in Section II. The genetic tabu hybrid algorithm design is set forth in Section III. Computational experiments are presented in Section IV. Finally, conclusions and future research directions are drawn in Section V.

2. Problem description and proposed model

2.1. M/M/c/K queuing theory for charging station system
In the charging station queuing system, the input process refers to the behavior of the electric taxi arriving at the charging station. Since the charging behavior of the electric taxi has great randomness (Ge et al [13]; Liu et al [14]), this paper assumes that the electric taxis of each period arrive at the charging station to obey Poisson distribution; the service time of the charging station is subject to a negative exponential distribution; there are c charging piles in the charging station, and the service of each charging pile is independent of each other; the capacity of the charging station is limited to K. When the electric taxi arrives at the charging station, if there is an idle charging pile, it will directly accept the charging service. If the charging pile is fully occupied, it will enter the queue team to wait for the service, and adopt the first-come-first-served queuing rule when the charging station When the capacity reaches the upper limit K, the electric taxi is rejected from entering the queuing system. The specific queuing model is shown in Fig.1.

![Figure 1. Schematic diagram of electric taxi queuing charging.](image-url)
According to the queuing theory knowledge, relevant indicators of the charging station queuing system can be obtained. The following symbols are used for multi-period charging station limited capacity queuing systems.

1) Identification set
   - \( I \) set of demand points, \( i \in I \).
   - \( J \) set of candidate points for building charging stations, \( j \in J \).
   - \( S \) set of the charging station levels, \( s \in S \).
   - \( T \) set of time periods, \( t \in T \).

2) Model parameters
   - \( \lambda_{jt} \): Arrival rate of the electric taxi at charging station \( j \) at time period \( t \).
   - \( \mu_{js} \): Average service rate at charging station \( j \) with level \( s \).
   - \( c_{js} \): Number of charging piles at the charging station \( j \) with level \( s \).
   - \( t_c \): Average charging time of electric taxi.
   - \( t_d \): Charging station day service time.
   - \( K_{js} \): Limited capacity at the charging station \( j \) with level \( s \).
   - \( w_{it} \): Amount of demand point \( i \) at time period \( t \).
   - \( \rho_{jst} \): Utilization rate of the charging pile at charging station \( j \) with level \( s \) at time period \( t \).
   - \( P_{0jst} \): Probability that all charging piles at charging station \( j \) with level \( s \) at time period \( t \) are idle.
   - \( P_{njst} \): Probability that \( n \) electric taxis receive charging service at the charging station \( j \) with level \( s \) at time period \( t \).

3) Decision variables
   - \( x_{ijt} \): 1 for the demand point \( i \) at the charging station \( j \) to charge at time period \( t \); 0 for the other.

Based on the above symbols, the unit time arrival rate of the electric taxi at charging station \( j \) at time period \( t \):

\[
\dot{\lambda}_{jt} = \sum_{i=1}^{I} \frac{W_{it}}{t_d} x_{ijt}
\]

Charging station service capacity per unit time:

\[
\mu_{js} = \frac{c_{js}}{t_c}
\]

Charging station facility utilization:

\[
\rho_{jst} = \frac{\dot{\lambda}_{jt}}{\mu_{js} c_{js}}
\]

The probability of the charging station being idle:

\[
P_{0jst} = \left( \frac{c_{js}^{\mu} \left( 1 - (a'_{jst}) K_{js} c_{js}^{-1} \right)}{c_{js}! (1 - a'_{jst})} \right)^{-1} + \sum_{z=0}^{K_{js} - 1} \left( \frac{c_{js}^{\mu} (a'_{jst})^z}{c_{js}! z!} \right)^{-1}
\]
The probability that a charging station has $n$ electric taxis to receive charging services:

$$a_{js} = \frac{\lambda_j}{\mu_j}$$

$$P_{nst} = \frac{\left( \frac{\lambda_j}{\mu_j} \right)^{K_{js}}}{K_{js}^{K_{js}} \left( \frac{\mu_j}{\mu_j} \right)^{K_{js}}} P_{nst}$$

Queue length at the charging station:

$$L_{nst} = \frac{a_{nst}^C \left( \rho_{nst} \right)}{c_{nst} \left( 1 - \rho_{nst} \right)^{K_{nst} \cdot c^{+1}}} \left[ 1 - \left( \rho_{nst} \right)^{K_{nst} \cdot c^{+1}} \right]$$

Average waiting time at the charging station:

$$W_{nst} = \frac{L_{nst}}{a_{nst} \left( 1 - P_{nst} \right)}$$

2.2. Model formulation

The mileage of electric taxis is limited, and it is necessary to build a charging station for fast charging to ensure the continuous operation of electric taxis. The construction of the charging station is often completed in periods. The problem is that according to the increasing charging demand, how to establish charging stations in each period can ensure the minimum of the construction cost, the cost of the station and the waiting cost of the whole periods.

2.2.1. Assumptions. (1) The charging demands of electric taxis in different time periods are different and increase with the station time periods;

(2) The number of charging piles installed in each level of charging station is different;

(3) The charging time of the charging pile is the same;

(4) The electric power consumption of the electric taxi is linear with the driving distance;

(5) Disregarding the removal of the charging station;

(6) Each demand point represents a small area, and the demand quantity at the corresponding demand point refers to the total number of electric taxis having charging demand in a small area.

2.2.2. Notations. Parameters:

- $d_{max}$ maximum service radius of the charging station.
- $d_{ij}$ shortest distance from demand point $i$ to charging station $j$.
- $C$ unit time cost of the electric taxi.
- $v$ average daily driving speed of the electric taxi.
- $f_s$ cost of building a charging station with level $s$.
- $f$ cost of constructing a single charging pile.
- $P_t$ maximum number of charging stations established at time period $t$.

Variables:
Objective function (9) minimizes the total cost of the entire periods including the cost of stationing for electric taxis, the cost of waiting, and the cost of station construction and charging piles; Constraint(10) indicates that each charging demand is completed by one charging station; Constraint(11) ensures that each charging station can only build one level; Constraint (12) guarantees that once the charging station is established, dismantling is not considered; Constraint(13) ensures that the charging station meets the maximum service radius constraint; and Constraint (14) requires that the charging taxi go to the built charging station for charging service; Constraint (15) ensures that the queuing system is robust; Constraint (16) indicates the maximum number of charging stations built in each period; (17), (18) are decision variables.

3. Genetic tabu hybrid algorithm design
The problem of charging station location is a typical NP-hard problem in the field of operations research. The nonlinear programming model built in this paper is difficult to solve with an accurate algorithm. Genetic algorithm’s global optimization performance is good and the versatility is strong, but its mountain climbing ability is weak and there will be premature phenomenon and the
convergence effect is not obvious. The tabu search algorithm has strong mountain climbing ability and flexible memory function in the search process. It can jump out of the local optimal solution and avoid the occurrence of premature phenomenon, but the tabu search algorithm has strong dependence on the initial solution. Therefore, the genetic algorithm and the tabu search algorithm are combined to solve the problem.

The specific steps are as follows.

Step 1: Given the initialization parameters, including the maximum number of iterations of the genetic algorithm max-GA, the maximum number of iterations of the tabu search algorithm is max-TS, and the population size is n and m, respectively, where the crossover probability pc, the mutation probability pm;

Step 2: Set the initial algebra t = 0, code, and generate the initial population.

Step 3: Demand point allocation.

1) Assign the demand point to the nearest charging station candidate point;

2) Calculating the demand amount allocated to each candidate point, judging whether the capacity constraint is satisfied, and if so, assigning the demand point to the candidate point, and ending; otherwise, transferring (3) the redistribution of the demand point;

3) Assign unallocated demand points to the nearest candidate points, turn (2) re-test; if not continue, assign to the third nearest candidate point, and so on; until the end of the allocation.

Step 4: Find the fitness value of the initial population.

Set Xi as the ith chromosome of the current population, Z is the objective function value of the ith chromosome, M is a positive large number, and the fitness function is:

Step 5: Genetic manipulation, generating subpopulations and obtaining fitness values.

Select: Use the roulette algorithm to retain part of the chromosomes to the next generation to form new populations;

Cross: Select multiple pairs of chromosomes to cross in a new population with crossover probability.

Mutate: When the probability of a chromosome Xj is pj < pm, TS mutation is performed on the chromosome. Let the initial solution Y = Xj, Ybest = Xj.

Let the initial iteration number g=0, and the taboo table is empty.

1) Select the optimal m chromosomes from the neighborhood of Y as candidate solutions.

2) Select the chromosome with the best fitness value from the candidate solution as Yi, if f(Yi) < f(Ybest) updates Ybest; otherwise, take the optimal value Yi in the neighborhood, and remove the elements in the tabu list, so Y=Yi.

4) Update the tabu form and turn (2).

Step 6: Generate m chromosomes based on the mutation, go to step 3, and continue to evolve.

Step 7: Terminate the evolutionary operation.

The algorithm will be terminated if any of the following conditions are met:

1) The algorithm executes to the maximum number of iterations;

2) All demand points are covered;

3) The best chromosomes do not change within the maximum number of iterations. Finally, when the algorithm terminates, the best chromosome is the satisfactory solution to the problem.

4. Computational experiments

Combined with research practice, this paper gives an example to verify the validity of the model and algorithm. Assume three station establishment periods, and the charging demand points and charging station candidate points of each period are randomly generated from the 50×50 plane, and the number of charging demand points and charging station candidate points increases with the station establishment period. In the first period, there are 20 (1~20) demand points, 7 (A~G) charging station candidate points, the second period has 30 (1~30) demand points, and 10 (A~J) charging station candidate points. There are 40 (1~40) demand points and 13 (A~M) charging station candidate points in the third period. The location of the demand point and the candidate point are shown in Fig. 2.
According to the actual situation of the survey, it is reasonable to assume the amount for each demand point in each period, and the demand increases with the period. Due to the large amount of data on the demand at each demand point in each period, it is not listed here. According to the standard document issued by Beijing Municipality, “Technical Specification for Electric Vehicle Power Supply and Protection: Charging Station”, the service capacity and construction cost of four types of charging stations are shown in Table 1. In combination with the actual, the values of other parameters are shown in Table 2.

![Figure 2. Demand point and candidate point plane position.](image)

**Table 1.** Levels of charging stations and corresponding construction costs.

| Charging station level | Service capabilities | Cost of Construction (Ten thousand yuan) |
|------------------------|----------------------|------------------------------------------|
| 1                      | 70                   | 300                                      |
| 2                      | 110                  | 350                                      |
| 3                      | 250                  | 400                                      |
| 4                      | 350                  | 450                                      |

**Table 2.** Other parameter values.

| Parameter | $d_{\text{max}}$ | $C$ | $v$ | $t_c$ | $t_d$ | $f$ | $K_{j1}$ | $K_{j2}$ | $K_{j3}$ | $K_{j4}$ | $P_1$ | $P_2$ | $P_3$ |
|-----------|------------------|-----|-----|-------|-------|-----|----------|----------|----------|----------|-------|------|------|
| Value     | 20               | 18  | 50  | 0.5   | 24    | 15  | 4        | 8        | 12        | 16        | 6     | 8    | 10   |

According to the above designed algorithm, Matlab R2016a is used for programming, and genetic algorithm and genetic tabu hybrid algorithm are used to optimize respectively. The parameter settings are shown in Table 3 and table 4.

**Table 3.** Parameter settings for GA

| Parameter | Population size | $p_c$ | The maximum number of iterations |
|-----------|-----------------|-------|----------------------------------|
| Value     | 50              | 0.8   | 50                               |

**Table 4.** Parameter settings for GATS

| Parameter | Population size $n$ | Population size $m$ | $p_c$ | $p_m$ | $\text{max-GA}$ | $\text{max-TS}$ | length of the tabu list | The maximum number of iterations |
|-----------|---------------------|---------------------|-------|-------|-----------------|-----------------|-------------------------|-------------------------------|
| Value     | 50                  | 50                  | 0.8   | 0.1   | 50              | 50              | 10                      | 50                            |
4.1. Algorithm convergence analysis

Fig. 3 shows the change curve of the objective function value obtained when running once. It can be seen from the figure that the genetic tabu hybrid algorithm is faster than the genetic algorithm to close to the optimal value, and the obtained result is better.

![Figure 3. Iterative process](image)

In order to verify the stability of the genetic tabu hybrid algorithm, the two algorithms run 20 times respectively, and the obtained optimal value curve is shown in Fig. 4. As can be seen from Fig. 4 the results obtained by the genetic tabu hybrid algorithm are almost the same as the excellent solution, and stability is significantly better than genetic algorithm.

![Figure 4. Optimal value curve.](image)

4.2. Multi-period planning

The multi-period planning scheme obtained in this paper is shown in Table 5. The location of the charging station and the demand point allocation in each period are shown in Figure 5-7. The results show that the multi-period planning solution considers the optimization of the entire periods result, and not limited to the current best, and the higher the level of the initial establishment of the charging station, it can promote the development of electric taxis; It can be seen from the distribution map of the above demand points that although some demand points are close to the charging station, they are
allocated to a relatively remote charging station, because each charging station has a certain capacity limit when the capacity is reached. When reached the upper limit, electric taxis have to go to other charging stations to seek charging services. In addition, electric taxis have a certain time cost, so the loss caused by waiting time will be considered.

Table 5. Multi-period planning scheme.

| Site location | Charging station level |
|---------------|------------------------|
|               | Period 1 | Period 2 | Period 3 |
| A             | 4        | 4        | 4        |
| B             |          |          | 2        |
| D             | 1        | 1        | 1        |
| E             | 3        | 3        | 3        |
| G             | 3        | 3        | 3        |
| K             |          |          | 1        |

Total cost (Ten thousand yuan) 2879.05

Figure 5. Demand point allocation at period 1

Figure 6. Demand point allocation at period 2

Figure 7. Demand point allocation at period 3
4.3. Forward-myopic method solution

In order to illustrate the effectiveness and superiority of the multi-period programming model proposed in this paper, the above example is solved by the Forward-myopic method proposed by Chung and Kwon (2015), that is, the optimal solution in period 1 is solved first. Then, the charging station that has been built in period 1 remains unchanged, retains in period 2 and solves the optimal solution, and so on, until obtaining the optimal solution of the whole problem in period 3. As shown in Table 6, the results show that the Forward-myopic method solves the station construction scheme of each period. The level of the charging station selected in the early stage is lower, and the four are all level 1, and the number of charging stations will gradually increase. The level will also increase accordingly. Compared with the total cost of the multi-period planning scheme, there is a higher cost solved by the Forward-myopic method, increasing by about 21.26%.

| Site location | Charging station level | Period 1 | Period 2 | Period 3 |
|---------------|------------------------|----------|----------|----------|
|               |                        |          |          |          |
| A             |                        | 1        | 1        | 3        |
| B             |                        | 1        | 1        | 1        |
| C             |                        | 1        | 1        | 1        |
| D             |                        | 1        | 1        | 1        |
| F             |                        | 1        | 1        | 1        |
| G             |                        | 1        | 1        | 1        |
| H             |                        | 1        | 1        | 1        |
| I             |                        | 2        | 2        |          |
| M             |                        | 2        |          |          |
| Total cost (Ten thousand yuan) | | 3491.36 | | |

5. Conclusion

In this paper, based on queuing theory, a multi-period and multi-level charging station planning model is established. The genetic algorithm and genetic tabu hybrid algorithm are used to solve the model respectively. The results of the example analysis show that the hybrid algorithm is superior to the genetic in solving the quality and solution speed of the solution. In addition, the optimal charging station construction scheme of the whole periods is compared with the scheme solved by Forward-myopic method, and the validity and superiority of the model are verified. It can provide some reference for the construction practice of charging stations. Because this paper has a strong dependence on the accurate prediction of charging demand in each period, how to accurately predict the charging demand of each period will be the further research direction of this paper.

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