Impact Analysis of Wired Charging and Wireless Charging on Electric Bus Operation: A Simulation-Based Method

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Abstract. In recent years, many cities in the world are committed to promoting the electrification of public transportation. For bus companies, how to select the right charging facilities accurately and quickly has become an urgent problem to be solved. In this paper, we propose a simulation method based on Anylogic to describe the operation of electric buses under wired charging and wireless charging conditions. We provide decision-making suggestions for bus companies by analyzing the impact of wireless charging and wired charging on operation cost and passenger waiting time. According to the simulation results, we found that the waiting time of passengers under wired charging conditions is about 8.63% higher than that under wireless charging in the same operating conditions. The use of wireless charging facilities can effectively reduce the waiting time of passengers.

Keywords: Charging facilities · Electric buses · Passengers waiting time · Simulation

1 Introduction

Electric buses (EBs) have the advantages of zero emission and low noise, which is of great significance to reduce urban motor vehicle exhaust emission and the operation cost of public transport enterprises [1]. A recent study by Bloomberg new energy finance electric predicts that the number of electric buses in operation will double from 386000 in 2017 to 1.2 million, accounting for more than 47% of the total number of urban buses in the world by 2025 [2]. Although EBs have many advantages and develop rapidly, they still have limitations such as short driving range and long charging time [3]. In order to maintain the normal operation of EBs and improve their operational efficiency, the optimization of EBs charging facilities has become an urgent problem for public transport companies.

To solve the charging problem of EBs, there are three charging technologies are used at present: station-based charging [4], battery swapping [5] and wireless lane-based charging [6]. The charging facilities are divided into two categories: wired charging facilities and wireless charging facilities. Wired charging facilities are the most common at present, which have good stability and controllability. However, due to complex

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equipment operation and slow charging speed, wired charging facilities can only be set up in the terminal stations or depots, which limits the charging accessibility of EBs and requires EBs to equip large capacity batteries [7]. The wireless charging facility adopts WPT technology. EBs can be charged without cables and connectors. The wireless charging facility is convenient, and does not have spark and electric shock risk, in addition, the charging speed of it is very fast. They can be set not only at the terminal bus stations, but also at intermediate stations; By setting up multiple wireless charging facilities in bus stations, the battery capacity of EBs can be reduced and the charging efficiency of EBs will be greatly improved [8].

For the selection and optimization of charging facilities, current studies are mainly based on the theoretical analysis model and verified by practical operation [9, 10]. However, due to the shortage of funds, time, materials and so on, it is difficult for researchers to conduct tests directly in the early research stage, which makes it impossible to evaluate the impact of different facilities on bus operation efficiency and passenger satisfaction. Compared with the real experiment, the virtual experiment save a lot of cost and time. In previous studies, Hao et al. developed a dynamic programming model that optimally schedules the bus operating speed at road sections and multiple signal timing plans at intersections to improve bus schedule adherence [11]. Shi et al. used the pre-established Anylogic urban dynamics model to simulate the hourly power demand of private electric vehicles considering population, commerce, housing and transportation infrastructure, and solved the problem of power imbalance [12]. Although many articles used virtual experiments to solve problems, no simulation experiment is used to study the selection of charging facilities.

Anylogic is a simulation modeling software that supports agent-based modeling. The software has specific industry libraries such as process library, pedestrian library and road traffic library, which can meet the needs of EBs simulation experiment. Therefore, based on Anylogic simulation software, this paper constructs the operation status of EBs under wired charging and wireless charging respectively; The program is written with the built-in module of Anylogic to analyze the impact of different charging facilities on passenger waiting time and charging cost, so as to provide suggestion in the selection of charging facilities of EBs.

The structure of the rest of this paper is as follows: the second part expounds the basic operation strategy, the third part analyzes the example, and the fourth part is the conclusion.

2 Problem Description

2.1 Problem Environment Descriptions

It is assumed that only one EBs line is operating on the public transit exclusive lane. The upward direction of the line is represented by u and the downward direction is represented by d; There are $2N$ stations along the line, n is the station number, $n = 1, 2..., N$. The number of initial station and terminal station is 1 and N respectively. It is assumed that the maximum number of EBs which can be put into operation is K, k is the number of EBs, $k = 1, 2, \ldots, K$; the rated battery capacity of EB k is B_k (unit: kWh), the remaining battery capacity of EB k is B_k', and the average energy consumption per hundred kilometers of EB k is C_k (unit: kWh/km).

If EBs use wired charging facilities, a wired charging station will be established at station 1 (i.e. the initial station). Assume that there are M wired charging piles in the starting station, and m is the serial number of wired charging piles, $m = 1, 2, \ldots, M$. It is assumed that the 0–1 variable P_c^m to judge whether the wired charging pile is in use. If the wired charging pile m is used, $P_c^m = 1$; otherwise, $P_c^m = 0$. The charging power of the wired charging pile m is P_w^m (unit: kW).

If EBs use wireless charging facilities, the wireless charging pad will be built at the midway stations. Assuming that the 0–1 variable $F_{n,u}$ is the use state of the wireless charging pad at the upward line, if the wireless charging pad is used at the upward station n, set $F_{n,u} = 1$; otherwise, set $F_{n,u} = 0$. The power of the wireless charging pad at upward station n is $F_w^{n,u}$ (unit: kW). The expression of downward stations is in a same way.

If the driver's rest time T_d is satisfied, EBs operate as far as possible when the available operation time is less than the shift time, the EBs stop operation. Set the total operation shift of each EBs on the same day as X.

2.2 Basic Operation Strategies

Charging Strategy. In the case of laying wired charging facilities, the wired charging pile is only set at the bus departure station. In order to minimize EBs queuing and maintain the health of the battery, EB will charge when the power decreases to a certain level.The minimum state of charge (SOC) for EB to maintain battery health is SOC_y, and the minimum SOC to meet the operation requirements is SOC_l. In order to reduce the charging time, the EB ends the charging behavior when the highest SOC_h is reached each time. It is necessary to judge the charging behavior according to the following strategies every time it returns to the departure station.

When EB arrives at the charging station, enter Step 1.

Step 1: if SOC less than SOC_y, enter Step 2; otherwise, enter Step 6, and set T_{p1} and T_{p2} to 0.
Step 2: if SOC is less than SOC_l and can not be satisfied with the next trip, enter Step 3; otherwise, enter Step 3.
Step 3: if there is no free position for charging pile, otherwise, enter Step 6, and set T_{p1} and T_{p2} to 0.
Step 4: if there is an idle charging pile, EB starts charging and record the charging start time t_{p1} and charging duration T_{p1}, enter Step 5; otherwise, waiting in the charging waiting area and recording the charging waiting time T_{p2}, and then repeat Step 4.
Step 5: EB is charged. If SOC of EB reaches SOC_h, end the charging, record the charging end time t_{p2}, and enter Step 6; otherwise, enter Step 4.
Step 6: if $T_{p1} + T_{p2} \geq T_d$, EB starts the next trip; Otherwise, the EBs will leave when the waiting area rests to T_d (Fig. 1).

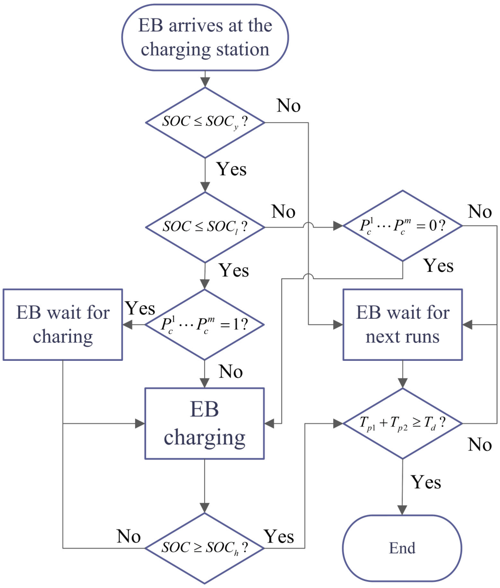

Fig. 1. Wired charging strategy logical flow chart.

In the case of laying wireless charging facilities, the starting station does not need to build charging piles, and the wireless charging pad is set up at the midway station. In order to maintain battery health, EB only uses the time for boarding and alighting when SOC is lower than SOC_y. When EB enters the midway station, the charging strategy will be judged according to the actual situation of passengers getting on and off the bus (Fig. 2):

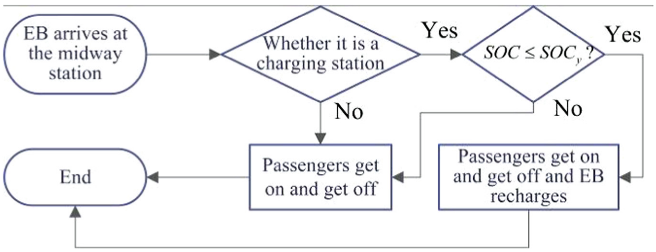

Fig. 2. Wireless charging strategy logical flow chart.

Step 1: when EB arrives at the bus midway station, judge whether the station is equipped with a wireless charging pad. If so, enter Step 2; otherwise, EB will load and unload passengers normally.
Step 2: if SOC of EB is less than SOC_y, enter Step 3; otherwise, EB will load and unload passengers normally.

Step 3: EB stops steadily, passengers start getting on and off, wireless charging facilities start working at the same time, and record the start time t_{f1}; the wireless charging behavior stops while the bus service passengers complete and t_{f2} is recorded.

Passenger Simulation Strategy. The passenger simulation strategy is divided into two parts: one is to determine the passenger arrival probability distribution, and the other is to calculate the passenger boarding and alighting time. When the traffic flow density is small and the overall flow is small, the discrete distribution model is more suitable to describe the pedestrian arrival law [13–15], in which Poisson distribution is commonly used to describe the pedestrian arrival law at the bus station.

$$P(s) = \frac{h^s e^{-h}}{s!} \tag{1}$$

where, h is the average number of arriving passengers per minute and $P(s)$ is the probability that there are exactly s passengers per minute.

Passenger boarding and alighting time T_s can be divided into vehicle opening time T_{s1}, passenger boarding and alighting time T_{pa} and bus closing time T_{s2}:

$$T_s = T_{s1} + T_{pa} + T_{s2} \tag{2}$$

$$T_{pa} = \max\{s_u \cdot T_u, s_d \cdot T_d\} \tag{3}$$

where, s_u and s_d are the number of people getting on and getting off, T_u and T_d are the time for each passenger to get on and get off.

Charging Cost Calculation Strategy. Assuming that the electricity price of the city where the line located is time-of-day tariff, there are q electricity price periods, and the cost per kilowatt hour is M_q in period T_q.

$$C = \begin{cases} M_q \cdot T_k^m, & t_k^{m,s} \in \left[t_q^s, t_q^e\right) \text{ and } t_k^{m,e} \in \left[t_q^s, t_q^e\right) \\ \left(t_q^s - t_k^{m,s}\right) M_q + \sum\limits_{\Gamma=q+1}^{q+\varphi-1} (t_\Gamma^e - t_\Gamma^s) M_\Gamma + \left(t_k^{m,e} - t_{q+\varphi}^s\right) M_{q+\varphi}, & t_k^{m,,s} \in \left[t_q^s, t_q^e\right) \text{ and } t_k^{m,e} \in \left[t_{q+\varphi}^s, t_{q+\varphi}^e\right) \end{cases} \tag{4}$$

Where, C is charging cost, T_k^m is charging duration, $t_k^{m,s}$ and $t_k^{m,e}$ are charging start time and end time, t_q^s and t_q^e are charging start time and end time of q electricity price periods, φ is the total electricity price periods.

3 Example Analysis

3.1 Simulation Parameter Setting

In this paper, a bus line in operation is selected for simulation. The line has five midway stations, with a total mileage of 9.5 km and travel time is about 35 min. The line has eight EBs with the same model and the same battery. The battery capacity is 100 kWh and the average energy consumption per 100 km is 80 kWh. Among them, 4 EBs start

Table 1. Distance between stations and average travel time

Section name	s0–s1	s1–s2	s2–s3	s3–s4	s4–s5	s5–s6
Length of road section (m)	1800	1100	1300	1800	1500	2000
Average travel time (min)	2.8	2.6	4.2	5.0	4.2	4.2

*s0 represents departure station and s6 represents terminal. s1, s2, s3, s4 and s5 respectively represent midway station 1, 2, 3, 4 and 5.

from the departure station and the other 4 EBs start from the terminal station. Midway stations are straight-line midway stations. The distance between stations and average travel time are shown in the Table 1.

In this simulation, the number of wired charging pile m is 3, and the charging power of charging pile P_w is 100 kW; The wireless charging pad is set in the upward and downward of station 2, upward of station 4 and downward of station 5 with large passenger flow. The power of the wireless charging pad is 200 kW; Set the driver's rest time to 300 s; Set the maintenance battery health SOC_y to 50%, the SOC_l to 20%, and the SOC_h to 80%.

For the convenience of the study, it is assumed that no passengers get on and off at the departure station, only passengers get on at the midway station, and all passengers get off at the terminal. Set the door opening time T_{s1} as 1.5 s and the vehicle door closing time T_{s2} as 1.5 s; The boarding time T_u of each passenger is 1.8 s and the alighting time T_d is 1.2 s. The passenger flow at the midway station conforms to the Poisson distribution. The average number of passengers arriving at the midway station per minute is shown in the Table 2.

Table 2. Average passengers arrival rate (pas/min)

Direction	1	2	3	4	5
Upward	1.71	2.31	2.00	2.14	1.57
Downward	1.22	2.45	1.76	1.64	1.88

The city uses time-of-day tariff to adjust the electricity price. The specific electricity price and time period are shown in Table 3.

Table 3. Time-of-day tariff table (CNY/kWh)

Time period	7:00–9:00	9:00–11:30	11:30–14:30	14:30–17:00	17:00–19:00
Electricity price	0.975	1.250	1.500	1.250	1.500

3.2 Establishment of Simulation Environment

The simulation steps are divided into simulation scene construction, simulation module connection and data analysis based on Anylogic's own data statistics function. The simulation scene is mainly set up based on Anylogic's process library, pedestrian library and road traffic library. The specific scene setting is shown in the Fig. 3.:

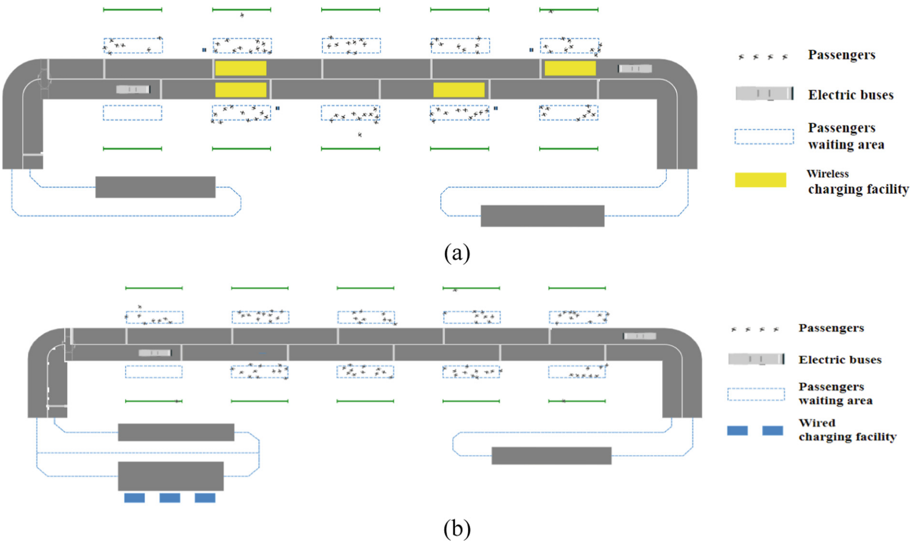

Fig. 3. Laying scenario of wireless charging facilities (a) and wired charging facilities (b)

The simulation module connection is mainly based on Anylogic's process library and pedestrian library. The blue box adopts the process library and the green box adopts the pedestrian library. The specific module connection settings are shown in the Fig. 5.

EBs are produced by the Electric buses source module, moved to the station through the Electric buses move module, and then the Electric buses delay module is used to control the boarding and alighting time of passengers and the Electric buses pick is used to complete the action of obtaining passengers. Passengers are generated by the Passengers source module. Passengers are controlled to move to the station through the Passengers move module, and Passengers wait for boarding by using the Passengers wait module. Finally, the boarding behavior is completed by using the Passengers queue module and Passengers exit module (Fig. 4).

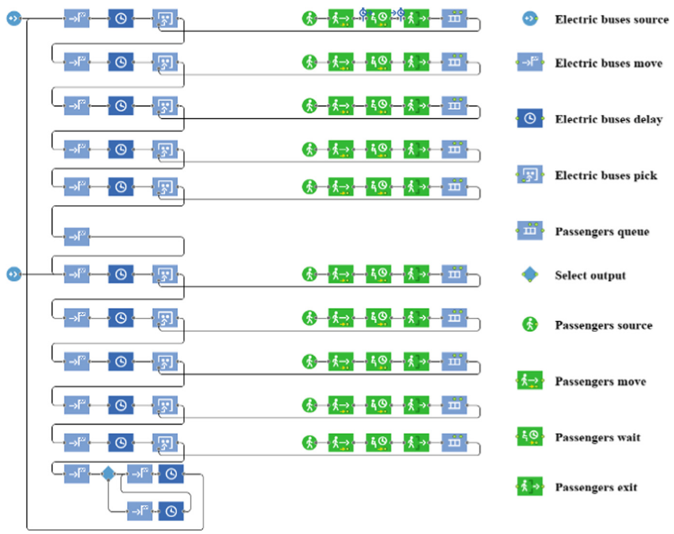

Fig. 4. Connection diagram of simulation module

3.3 Results and Analysis

The model runs from 7:00 a.m. to 19:00 p.m. for a total of 12 h. The waiting time of up and down passengers at each station is analyzed respectively. The results are shown in the Table 4.

Table 4. Waiting time of passengers (s)

Charging facilities	Direction	1	2	3	4	5
Wired charging	Upward	380.4	310.4	390.5	402.3	506.9
	Downward	510.3	530.6	410.3	346.2	339.3
Wireless charging	Upward	367.8	275.1	388.1	368.2	480.6
	Downward	502.4	512.4	379.2	345.2	340.2

It can be seen from the Table 4. that the waiting time of passengers is greater than that of wireless charging under the condition of wired charging. After statistical analysis of all data, the waiting time of passengers under wired charging is about 8.63% higher than that under wireless charging. The use of wireless charging facilities can effectively reduce the waiting time of passengers.

In addition, the total trip of EBs will be different under the influence of different charging methods. Affected by the total trip, the total charging cost of EBs is different. Through data acquisition, the total trip and total charging cost of each vehicle can be obtained, as shown in the Table 5.

Table 5. Total running trips and total charging cost

Vehicle number	Wired charging		Wireless charging	
	Total trip	Total charging cost (CNY)	Total trip	Total charging cost (CNY)
1	13	42.25	14	98.75
2	12	40.75	14	96.88
3	12	76.52	13	90.15
4	12	75.89	13	89.65
5	13	40.25	14	99.25
6	12	43.98	14	99.30
7	12	71.12	13	91.14
8	12	64.28	13	90.45

After statistical analysis, the average total trip of wireless charging is higher 1.25 times than that of wired charging. EB does not need to spend additional time on charging, which effectively makes use of the time for passengers to get on and off, and improves the operation intensity of EBs under wireless charging.

At the same time, the total charging cost of wireless charging is much higher than that of wired charging, and the average charging cost has increased by 37.56. There are two reasons for the increase of charging cost. First, the fleet of wireless charging and wired charging total trip is 108 and 96 respectively. Wireless charging requires more power, resulting in an increase in charging costs. Second, wireless charging is more frequently charged in the peak period of electricity price, while wired charging often occurs in the flat peak period of electricity price, which increases the Total charging cost.

In order to consider the influence caused by the power difference between wireless charging and wired charging, we changed the power of wireless charging facilities to 100 kW and 80 kW. Through simulation, it is found that EB cannot complete daily operation tasks through wireless charging alone. In this case, wired and wireless co-charging is required, so the merits and demerits of wired charging and wireless charging cannot be compared.

4 Conclusions

The construction of EBs charging facilities has always been one of the important directions of EBs research. This paper discusses EBs operation and passenger waiting time under the conditions of wired charging and wireless charging. A bus line is simulated and compared by using Anylogic, which provides a new preliminary investigation method for the construction of bus charging facilities.

This paper only discusses the influence of charging facility selection on EBs from the perspective of simulation, which is still different from the actual operation. However, if you need to further choose charging facilities, it is necessary to conduct more in-depth research in combination with the cost and specific road environment.

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