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Joint Optimal Design of Electric Bus Service and Charging Facilities

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Abstract: With the development of new energy technologies, fuel buses with internal combustion engines are gradually being replaced by electric buses. In order to save on system costs, an optimization model is proposed to jointly design the bus service and charging facilities. Considering the complexity of the original problem, the problem is decomposed into two subproblems, i.e., bus service design and charging facilities design. The bus service design is solved by a genetic algorithm with an embedded enumeration method. The non-linear charging facilities design problem is firstly converted to a linear problem and then solved by existing solving software. Sensitivity analysis of parameters such as passenger flow demand, charging power, and bus stopping time is also conducted to reveal their impact on the optimization of electric bus lines. The results indicate that, compared to the commonly used depot charging strategy, the proposed method reduces the operating cost per unit hour from RMB 16,378.30 to RMB 8677.99, a 47% reduction, and decreases the system cost from RMB 36,386.30 to RMB 29,637.99, an 18.5% reduction. This study addresses the charging and operation problem of electric bus lines. By considering charging vehicles while in operation, a joint optimization model for the operation of electric bus lines and the layout of charging facilities is established. An algorithm based on the combination of a genetic algorithm and enumeration method is designed, combined with a linear programming solver to solve the problem.

Keywords: electric bus; bus service optimization; charging facilities optimization; genetic algorithm; linear programming

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1. Introduction

The transition from buses with internal combustion engines (defined as conventional buses) to electric buses is gaining momentum due to the drawbacks of high emissions and environmental pollution associated with conventional buses. Electric buses offer several advantages over traditional fuel buses, such as noise control, driving stability, high energy conversion efficiency, and reduced environmental impact. This improved efficiency contributes to lower environmental pollution and reduced reliance on fossil fuels, aligning with goals such as "carbon peaking" and "carbon neutrality" [1]. The electrification of public transportation in countries around the world is gradually progressing. By 2019, the electric bus market have expanded to more than 50 countries and regions, including more than 200 cities such as New York, London, Sydney, New Zealand, Cape Town and Los Angeles [2].

However, challenges persist regarding charging difficulty and the high operating costs of electric buses, primarily driven by battery costs. Timely charging is essential for ensuring regular bus operation, underscoring the critical role of charging station locations in the reliability of the entire public transportation system [3]. The planning of charging infrastructure for electric bus transportation systems is important. Appropriate charging station layout can not only save charging time and improve the efficiency of vehicle utilization but also balance the charging supply and demand [4].

To address the challenges and improve the utilization rate of public charging stations, charging facilities are being deployed at bus stops. This strategic placement allows for charging while buses are in operation, leveraging the time passengers spend boarding and alighting. This approach enhances the reliability and efficiency of electric bus operations while reducing operating costs.

2. Literature Review

The determination of the charging station location is important for electric transit system development. Effective charging station deployment can reduce the investment and facilitate the charging process so that the penetration of electric vehicles is improved [5]. Existing studies primarily focus on two main areas: wired charging station layouts and wireless charging facility layouts.

For example, to identify the optimal location of electric bus charging stations, Zhang et al. [6] proposed a model that combines the advantages of a near-neighbor propagation (NNP) clustering algorithm and a map rasterization rule. This model takes into account several influencing factors such as land cost and traffic conditions. To simultaneously optimize the deployment of fast charging stations and the design of battery capacity, Kunith et al. [7] developed a hybrid integer linear programming model with the aim of minimizing the total investment cost of the system, including the cost of building the charging infrastructure and the cost of the batteries. A similar study was also conducted by Wang et al. [8]. In addition, Zhang [9] and Qin et al. [10] investigated charging scheduling and management for electric buses with the aim of reducing the total charging cost.

The placement of wireless charging facilities has received significant research attention with the advancement of wireless power transfer (WPT) technology [11]. These facilities take up a minimal amount of space and can be embedded under the road or fixed at specific bus stops [12]. This allows electric buses to recharge themselves conveniently and quickly by passing or stopping over the charging facility [13]. The optimization of the placement of dynamic charging equipment is often closely related to the capacity of the battery. Young [14] and Jang [15,16] proposed various models, including non-linear, mixed-integer programming (MIP), and correlation models, to allocate wireless chargers and determine electric bus battery capacity for a single route. To determine the location of wireless charging facilities and battery capacity, Jeong et al. [17] developed a mathematical model coupled with battery life considerations. For the siting of charging facilities for conventional buses in wireless charging mode, Liu et al. [18] developed determination and uncertainty models. They used robust optimization methods and an improved genetic algorithm for the solution, with the siting of wireless charging facilities and battery capacity as optimization objectives. Other researchers have incorporated considerations such as battery size and travel costs. However, the above studies are concentrated on a single route. As the transit service is operated in a network, the charging station location optimization models are developed in a bus network [19].

In addition, studies have also been conducted on the integrated planning problem, which includes both the layout and the operation of the charging station. Liu et al. [20] formulated an optimization model for placing electric bus charging stations, charger configuration, charging time, and traffic flow. Their study considered power matching and seasonality factors. He et al. [21] proposed a comprehensive optimization model to deal with the planning of the charging infrastructure, the scheduling of the vehicles, and the management of the charging process for a charging bus system. Their objective was to minimize the total cost, including bus procurement, charging infrastructure, driver, and charging costs. Similar studies were conducted by Rogge et al. [22] and An [23]; they developed a stochastic integer model incorporating time-of-use pricing to jointly optimize charging station location and bus fleet size under stochastic bus charging demand. A Lagrangian relaxation method was used to solve this problem.

These findings provide a comprehensive overview and analysis of the key parameters involved in the optimization process of bus service and charging station layout. However, most of the studies focus on the charging station location determination for a fixed transit system, where bus stop locations and service headway are assumed to be constant. In fact, the transit service has a significant impact on the determination of charging facilities. For example, the bus stop locations are generally selected as the candidates of charging stations, which indicates the transit service and charging facilities should be optimized simultaneously [24].

In light of the above, we propose an optimization model to jointly optimize electric bus service and charging facilities. This optimization problem aims to minimize the generalized system cost. To solve the model, the embedded enumeration genetic algorithm and the linearization techniques are applied. A case study in Chongqing, China is selected to evaluate the proposed method. The results show that vehicle acquisition and operation costs can be reduced, and the reliability of bus services can be enhanced. By optimizing electric bus stops and charging facilities simultaneously, we can achieve more efficient and cost-effective public transportation systems.

The rest of the paper is organized as follows: The next section presents the optimization model, following the notations and assumptions used in this study. Section 4 describes the proposed algorithm procedure and numerical experiments. Section 5 discusses the performance evaluation. Finally, Section 6 summarizes the study and presents the conclusions of this study. Section 7 describes the research limitations and future research directions.

3. Proposed Optimization Model

3.1. Problem Description

Consider that the electric bus is operated in a linear corridor, as shown in Figure 1. Considering the high cost of the battery, to reduce the battery size, the charging stations are located at several bus stops to charge the battery during passengers' boarding and alighting. When the bus arrives at the charging station, the charging bow automatically connects to the connector on the bus for charging.

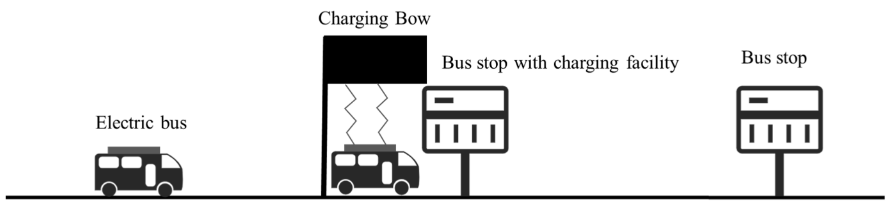

Figure 1. Schematic diagram of the joint layout of bus stops and charging facilities.

This study aims to jointly design the electric bus service and charging facilities. The bus service is characterized by bus stops and service headway, and the charging facilities include the charging station locations at selected bus stops and the battery size. Appropriate battery capacity is designed to minimize the construction and operation costs of electric buses as well as the travel costs for passengers.

3.2. Assumptions

The main assumptions of the model are as follows:

(a) The bus operates on a stop-by-stop basis, with the charging time at each stop corresponding to the duration of the stop;
(b) Passengers select the nearest bus stop to their starting point for boarding and the closest bus stop to their destination for alighting;
(c) Passengers arrive at the bus stops at random intervals;
(d) Each electric bus vehicle has the same battery capacity and passenger capacity;

(e) The high-power charging facilities are equipped at two terminals so that the vehicles depart from the endpoint stops fully charged [12];
(f) The average access/egress between two consecutive bus stops is one-fourth of the stop spacing [25];
(g) The electricity is always sufficient during the charging process.

3.3. Model Setting

3.3.1. Objective Function

This study optimizes several variables, including bus stop location, service headway, charging station location, and battery capacity. The objective is to minimize the overall system cost in unit time, i.e., an hour, which encompasses both the operator's cost, Z_t [RMB] in an hour and passengers' travel cost, Z_u [hour] in an hour. The optimization model's objective function, Z [RMB] can be expressed as follows:

$$Z = Z_t + \alpha_u Z_u \tag{1}$$

Equation (1) represents the objective function, which is a combination of the operator's cost and the passengers' travel cost. The operator's cost consists of the expenses for stop construction and charging station deployment, Z_{t1}, operation cost, Z_{t2}, and fleet size allocation cost, Z_{t3}, expressed as follows:

$$Z_t = Z_{t1} + Z_{t2} + Z_{t3} \tag{2}$$

$$Z_{t1} = c_s N_l + c_{es} N_c \tag{3}$$

$$Z_{t2} = 2c_d \frac{1}{h} L + 2c_t \frac{1}{h}\left(\frac{L}{v_b} + t_d N_l + (t_c - t_d)N_c + t_r\right) \tag{4}$$

$$Z_{t3} = 2\left(c_f + c_{eb} B_{max}\right)\frac{1}{h}\left(\frac{L}{v_b} + t_d N_l + (t_c - t_d)N_c + t_r\right) \tag{5}$$

where c_s, c_{es} are unit bus stop and charging station costs, and N_l, N_c are the total number of bus stops and charging stations. Equation (3) represents the combined cost of stop construction and charging station deployment.

Next, c_d, c_t are the unit distance and time-based operation costs. h is the service headway, and the dispatched vehicles per hour is $\frac{1}{h}$. The term in parentheses in Equation (4) is the cycle time, which is estimated by the time spent at cruising speed, delays at bus stops and charging stations, and the charging time at two ends. Equation (4) represents the operating expenses, comprising two facets: the operational cost dependent on the duration of vehicle operation and the costs incurred per kilometer traveled.

Equation (5) illustrates the fleet configuration cost, encompassing both vehicle acquisition expenses and the associated battery capacity.

Passengers' travel cost consists of walking time, Z_{u1}, waiting time, Z_{u2}, and in-vehicle travel time, Z_{u3}, which can be formulated as follows:

$$Z_u = Z_{u1} + Z_{u2} + Z_{u3} \tag{6}$$

$$Z_{u1} = \sum_{o \in O} \sum_{d \in D} \left(\frac{l_o}{v_w} + \frac{l_d}{v_w}\right) \tag{7}$$

$$Z_{u2} = \sum_{o \in O} \sum_{d \in D} \frac{h}{2} \tag{8}$$

$$Z_{u3} = \sum_{o \in O} \sum_{d \in D} \left(\frac{l_{od}}{v_b} + t_d N_{num}^{od} + (t_c - t_d) N_c^{od}\right) \tag{9}$$

where l_o, l_d are the access/egress distance to/from the nearest bus stops, and v_w is the walking speed. Equation (7) calculates the walking time for passengers to reach the bus stop from their trip origin and from the drop-off stop to the trip terminus. The cost is derived from the ratio of the average travel distance of all passengers within the system's origin-destination pairs and the walking speed of the passengers.

The average waiting time per passenger is half of the headway; thus, Equation (8) represents the cost associated with waiting time for passengers. Since passengers arrive at the bus stops randomly, the probability of their arrival within the time interval $[0,h]$, occupied by the headway, is considered. Equation (9) indicates the cost of passengers' travel time within the vehicle. This includes the vehicle's operating time from the trip's start to end, stopping time at stops, and additional stopping time for charging at charging stations.

3.3.2. Model Constraints

The purpose of the joint optimization problem of electric bus service and charging facilities is to minimize the operating costs and passengers' travel costs. The constraints of the joint optimization model are as follows:

$$N_{\min} \le N_l \le N_{\max} \tag{10}$$

$$h_{\min} \le h \le h_{\max} \tag{11}$$

$$B_s^i \ge B_{\min}, \quad i \in N \tag{12}$$

$$y_i \le x_i, \quad i \in N \tag{13}$$

where $N_{\min}$, $N_{\max}$ are the minimum required and maximum allowed bus stops. Constraint (10) imposes limits on the number of bus stops.

Similarly, Constraint (11) guarantees that the headway remains within the predefined intervals $[h_{\min}, h_{\max}]$.

Constraint (12) dictates the power maintenance of electric buses during operation. Assuming a fully charged state at the starting stop, the vehicle must maintain sufficient power to travel to the next stop with charging infrastructure, ensuring continuous operation and charging at subsequent stops.

Constraint (13) represents the relationship between the number of charging stations and the number of bus stop locations. In the study, bus lines of length L are discretized by length 1, and each interval is represented by a 0–1 decision variable x_i, indicating whether a bus stop is deployed or not. The charging station location y_i is designed based on the location of the identified bus stop, which also uses a 0–1 decision variable to indicate whether or not a charging station is deployed at that bus stop. Since electric bus charging stations need to be deployed at bus stops, a charging station may be deployed only if a bus stop is deployed at location i.

The electric bus's electricity consumption to reach each stop can be expressed as the following equation:

$$B_s^i = B_{\max} - B_u^i + B_c^i, \quad i \in N \tag{14}$$

$$B_u^i = \sum\nolimits_{j=2}^{i} e_b d_{j-1,j} \tag{15}$$

$$B_c^i = \min\left\{\sum\nolimits_{j=1}^{i-1} p t_c y_j, B_u^{i-1}\right\} \tag{16}$$

where B_s^i in Equation (14) is the remaining battery level after arriving at bus stop i, which is determined by the accumulated energy consumption and charging, B_u^i, B_c^i.

The accumulated energy consumption is estimated by the unit distance energy consumption, e_b and the travel distance in Equation (15).

Constraint (16) specifies that the power charged by the vehicle to reach stop i is constrained by the charging capacity of the charging stop preceding station i, as well as by the power consumed at the most recent charging stop prior to reaching stop *i*. This ensures that the actual battery charge does not exceed the battery capacity.

4. Solution

The original problem is non-linear and difficult to solve directly. In order to facilitate the solution process, the problem is decomposed into two subproblems: bus service design and charging facilities design.

4.1. Optimization of Bus Service

The bus stop optimization model is non-linear and falls under the category of NP-hard problems. Therefore, the bus stop location problem is addressed using a genetic algorithm [25], while service headway optimization is achieved through an enumeration method [26].

The proposed algorithm's general scheme is illustrated in Figure 2. The algorithm's steps are outlined as follows:

Step 1: Initialize the current objective function to infinity;
Step 2: Set the current headway to the minimum allowable headway;
Step 3: Calculate the objective function for the current headway of the designated route;
Step 4: Check if the objective function is smaller than the current objective function. If yes, proceed to the next step; otherwise, return to Step 3;
Step 5: Update the current objective function with the calculated objective function;
Step 6: Increase the current headway by 1 min;
Step 7: Check if the headway exceeds the maximum allowable value. If yes, deduct one minute from the current headway to determine the optimal headway and output the result. If not, return to Step 3.

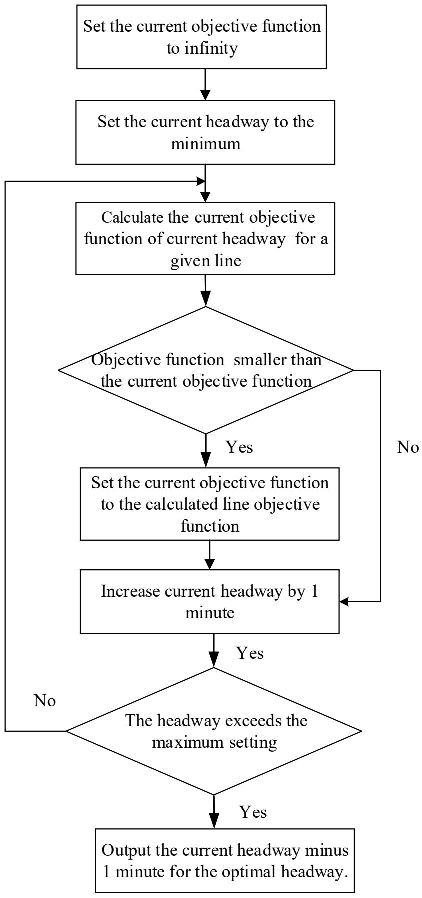

Figure 2. Flowchart of the proposed algorithm.

4.2. Optimized Solution for Battery Capacity and Charging Station

Once the bus stop locations are determined, the remaining problem involves optimizing the onboard battery capacity and charging station locations. This subproblem can be reformulated as a linear programming problem. We found the objective function's expression is linear regarding battery capacity and charging station locations. Constraints regarding charging stations must ensure deployment at bus stop locations and meet power status requirements. Consequently, the original problem can be reformulated into a linear programming problem with decision variables representing battery capacity and charging station locations. This can be expressed as:

$$\min Z_t^e = c_{es}y_i + \alpha_u(t_c - t_d)y_iO_i + \left(2c_t + 2\left(c_f + c_{eb}B_{\max}\right)\right)\frac{1}{h}((t_c - t_d)N_c) \tag{17}$$

$$B_s^i \geq B_{\min} \tag{18}$$

$$y_i \leq x_i, \quad i \in N \tag{19}$$

where c_{eb} is the unit battery cost and $B_{\max}$ is the battery size. The first term on the right-hand side is the total battery cost. O_i is the number of people passing through stop i per unit of time, and the bus stop i will bring additional travel costs $\alpha_u(t_c - t_d)y_iO_i$ for passengers.

Constraint (18) reflects two requirements for the vehicle's power state upon reaching the station: before and after charging. Initially, before charging, the battery power state must meet the minimum power requirement:

$$B_{\max} - \sum_{i=2}^{j} e_b l_{i-1,i} + \sum_{i=2}^{j-1} p t_c y_i \geq B_{\min} \tag{20}$$

Furthermore, given that charging stops are located at bus stops, the battery level should not surpass the battery capacity after charging at these stops:

$$B_{\max} - \sum_{i=2}^{j} e_b l_{i-1,i} + \sum_{i=2}^{j} p t_c y_i \leq B_{\max} \tag{21}$$

The provided model is a linear programming model concerning the decision variables $B_{\max}$ and y_i. It can be efficiently solved using existing commercial software. In our study, we utilized the linear programming tool within Matlab 2024a to address this problem [27].

5. Numerical Examples

To validate the model and algorithm's effectiveness, we employ Chongqing public transportation line 10 as a case study to verify and analyze the optimization method. To assess the advantages of interval charging, we compare the proposed method with the depot charging strategy.

5.1. Parameter Values

Line 10 comprises a total of 12 stops, as listed in Table 1, spanning from Lijiatuo bus terminal to Ciqi street, forming a complete trip. The inter-stop distances range from a minimum of 0.35 km to a maximum of 2.5 km, with an average distance of 1.3 km. The first and last buses depart at 6:00 and 22:15, respectively, with a headway of 5 min [28].

Figure 3 illustrates the number of passengers boarding and alighting at each stop during the peak hour. As the survey only captured passenger demand from south to north, the study assumes a symmetric distribution of passenger demand from north to south to validate the proposed model:

The parameter values are detailed in Table 2. The number of stops is determined based on the actual survey's stop distance range, with a minimum and maximum of 10 and 50 stops, respectively, aligned with the route's length. The headway range is set as {1, 2, . . ., 10} based on passenger flow and historical literature. Coefficients related to operating costs [29–31], vehicle operation [32,33], passenger walking speed [34], energy consumption [35], and charging power [36] are derived from existing studies.

Table 1. Stops and locations of line 10.

Stop Number	Stop Name	Location (km)
1	Lijiatuo bus terminal	0
2	Lijiatuo east	0.35
3	Banan avenue central	0.99
4	Banan avenue	1.7
5	Light railway Qilong	2.9
6	Bagongli	4.6
7	Liugongli	6.8
8	Sigongli	8.2
9	Nanpingnanlu	9.3
10	Huizhanzhongxin	11.4
11	Zhongxin road	13.9
12	Ciqi street	14.7

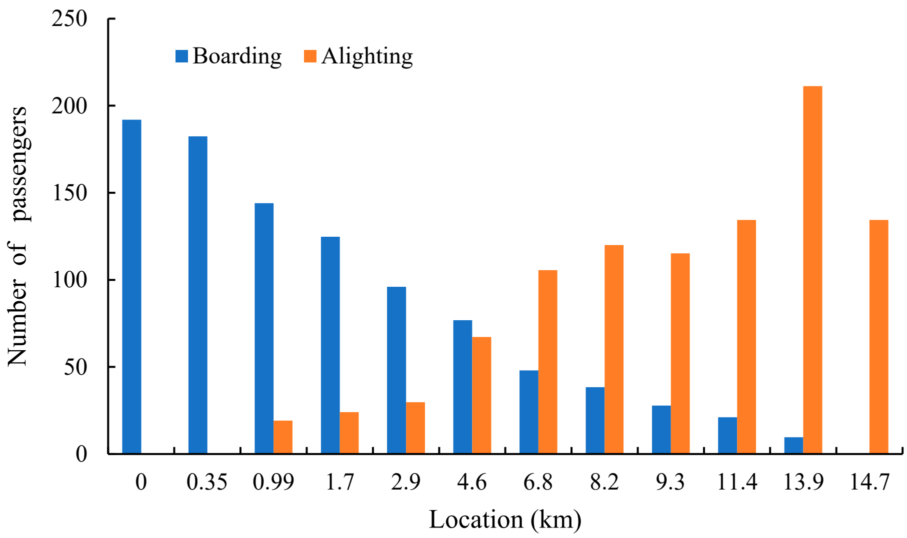

Figure 3. Passenger demand from south to north of peak hour.

Table 2. Model parameter values.

Number	Parameter	Value	Unit
1	α_u	25	RMB/h
2	$N_{\min}$	10	/
3	$N_{\max}$	50	/
4	$h_{\min}$	0.017	h
5	$B_{\min}$	$0.2B_{\max}$	kWh
6	c_s	5.3900	RMB/stop/h
7	c_t	543.62	RMB/h
8	c_f	201.6	RMB/veh/h
9	c_{es}	2.68	RMB/stop/h
10	c_d	4.13	RMB/km
11	t_d	0.008	h
12	t_c	0.025	h
13	v_w	2	km/h
14	c_{eb}	7.12	RMB/kWh/h
15	e_b	1.46	kWh/km
16	p	200	kW
17	$h_{\max}$	0.17	h
18	v_b	20	km/h

In the genetic algorithm utilized in this study, the relevant parameters are defined as follows: the maximum number of iterations is set to 2000, the crossover probability is 90%, the mutation probability is 10%, and the population size is 20 individuals per population.

5.2. Results

The comparison results of the layout between the proposed method and the existing sites using the endpoint charging method are presented in Table 3.

Table 3. Optimized results.

	Number of Stops	Headway (Min)	Battery Capacity (kWh)	Number of Intermediate Charging Stations
Existing services	12	5	26.74	0
Optimized services	19	10	7.98	3
Difference	−7	−5	18.76	−3

The cost results of the proposed method are compared with the cost results of the existing site layout using the endpoint charging method, as shown in Table 4. Analysis of the results indicates that the passenger travel cost per unit hour increased from RMB 20,008 to RMB 20,960, representing a 4.7% rise in passenger travel expenses. Conversely, operating costs decreased from RMB 16,378.30 to RMB 8677.99, marking a 47% reduction in operating expenses. Consequently, the total final system costs decreased from RMB 36,386.30 to RMB 29,637.99, reflecting an 18.5% decrease. This underscores how a 4.7% increase in passenger travel costs can lead to a substantial reduction of 47% in operating expenses, resulting in a significant overall reduction in total system costs.

Table 4. Optimized cost results.

	Passenger Costs (RMB)	Operating Costs (RMB)	Total Costs (RMB)
Existing services	20,008.00	16,378.30	36,386.30
Optimized services	20,960.00	8677.99	29,637.99
Difference	−952.00	7700.31	6748.31

5.3. Summary of Results

(i) After the joint optimization of electric bus stops and charging facilities and equipment, several changes are observed. The number of bus stops increases from the original 12 to 19. The headway increases from 5 min to 10 min, while the battery capacity decreases from 26.74 kWh to 7.98 kWh, leading to a substantial reduction in battery cost. Additionally, the number of intermediate charging stops increases from 0 to 3. These optimizations in bus stops and intervals result in a significant decrease in battery cost.

(ii) Comparing the cost results of using the proposed method with the existing stop layout using the end-point charging method, several observations emerge. The passenger travel cost per unit hour increases from RMB 20,008 to RMB 20,960, representing a 4.7% rise. However, the enterprise operating costs decrease from RMB 16,378.30 to RMB 8677.99, marking a significant reduction in operating expenses. This reduction in operating costs contributes to a decrease in the total system costs from RMB 36,386.30 to RMB 29,637.99, reflecting an 18.5% reduction. The 4.7% increase in passenger travel costs coincides with a 47% decrease in operating costs, ultimately resulting in a substantial reduction in total system costs.

5.4. Analysis of Parameters

5.4.1. Travel Demand

Figure 4 illustrates the trend of average passenger costs after optimization under varying passenger flow conditions. As depicted in the figure, with the increase in the passenger flow multiplier, a larger travel scale gradually emerges. This phenomenon leads to a reduction in the average bus stop distance, subsequently decreasing passenger walking and waiting times, ultimately resulting in reduced average capita cost expenses.

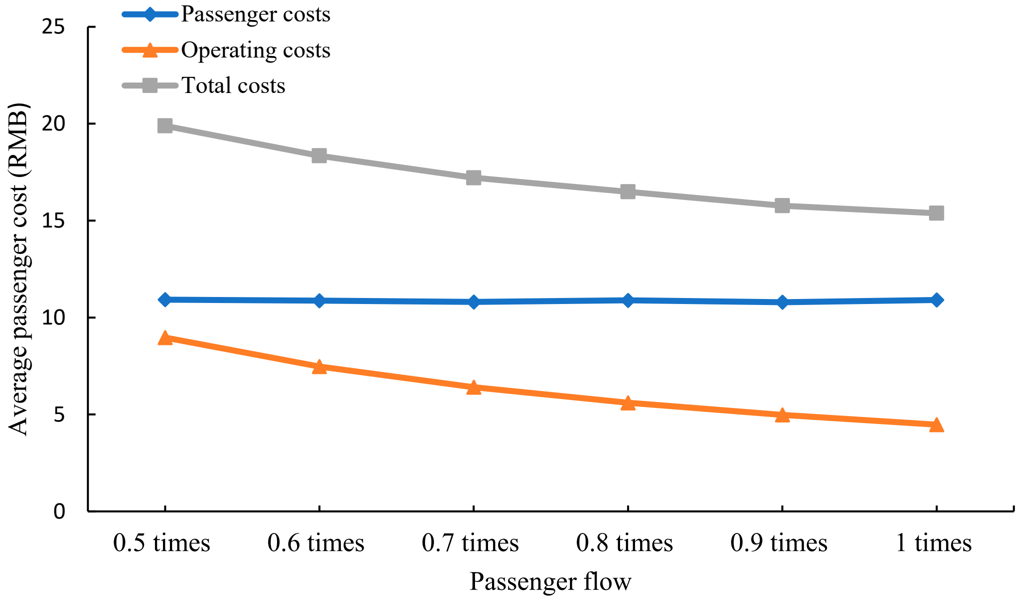

Figure 4. Trends of average passenger costs.

5.4.2. Battery Capacity

Figure 5 depicts the evolution of the battery power state during bus operation for battery capacities of 10 kWh, 15 kWh, 20 kWh, and 25 kWh, respectively. The solid lines in the figure represent the battery state of charge (SOC) during vehicle operation, while the dotted lines indicate the minimum required SOC. The results show that as the battery capacity increases, the required charging stations along the line can be effectively reduced. However, it is noted that the increase in battery capacity needs to reach a certain threshold before the deployment of charging stations can be reduced.

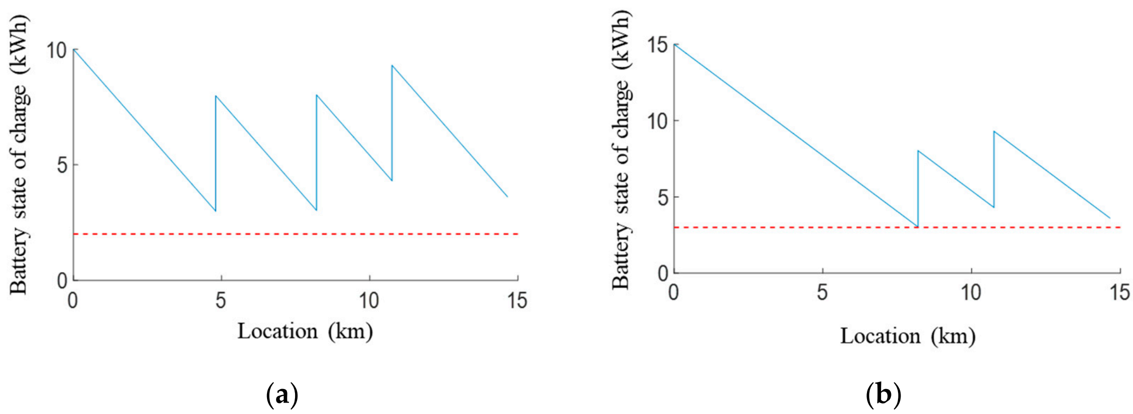

Figure 5. *Cont*.

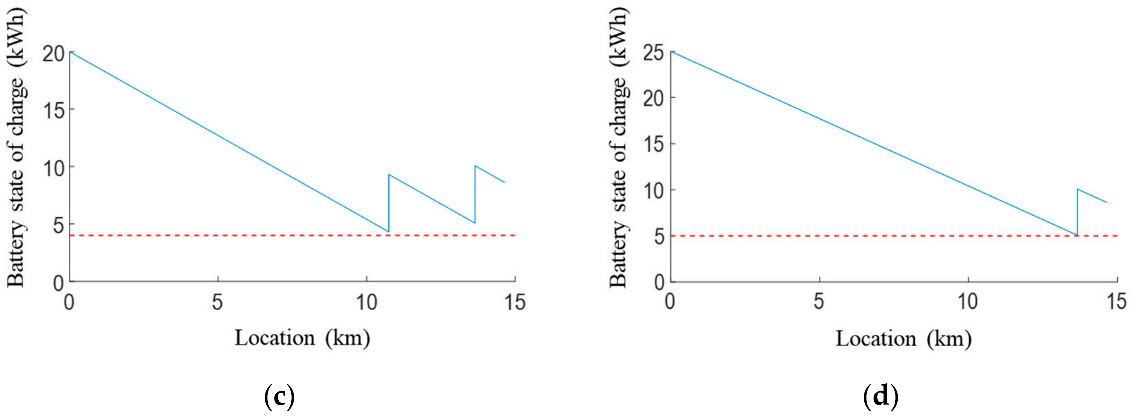

Figure 5. Optimized results of charging position for different battery capacities. (**a**) Battery capacity 10 kWh; (**b**) battery capacity 15 kWh; (**c**) battery capacity 20 kWh; (**d**) battery capacity 25 kWh.

5.4.3. Charging Power of Charging Stations

As depicted in Figure 6, the power state changes when the charging station power is set to 100 kWh, 150 kWh, 200 kWh, and 250 kWh, respectively. The solid lines in the figure represent the battery state of charge (SOC) during vehicle operation, while the dotted lines indicate the minimum required SOC. From the results, it can be observed that under the same initial power condition, when the charging station power is set to 100 kWh, seven charging stations are required. However, as the charging station power increases to 150 kWh, the number of required charging stations decreases to five. Further, when the charging power reaches 200 kWh and 250 kWh, the number of required charging stations decreases to three.

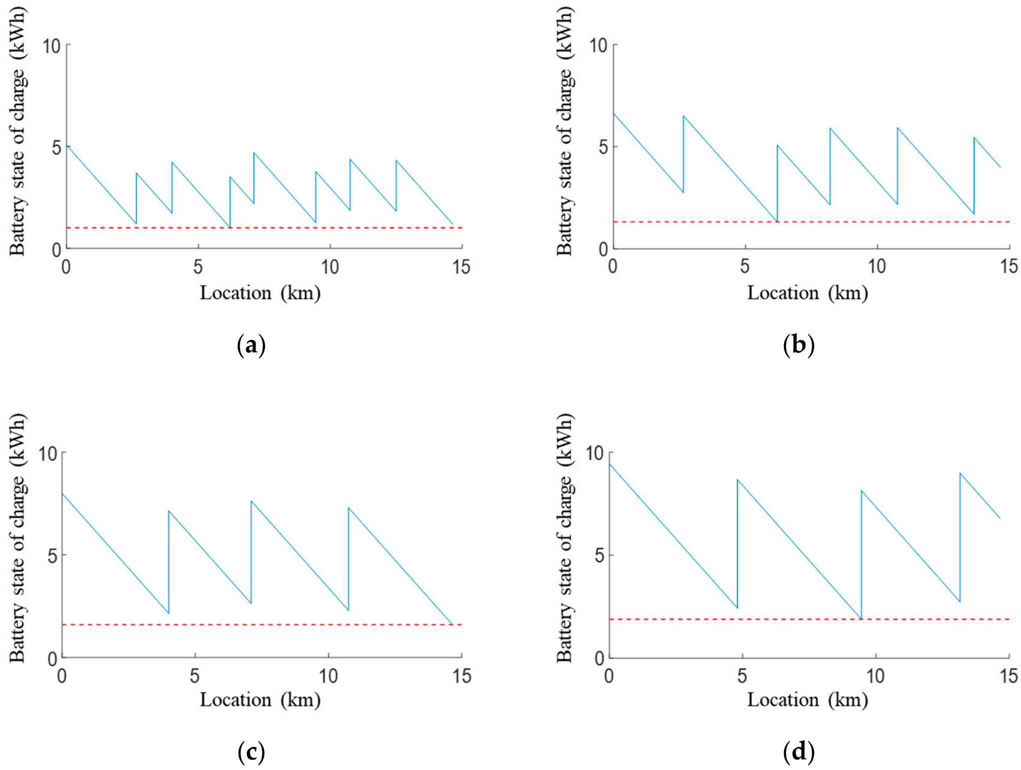

Figure 6. Optimization results of charging positions with different charging powers. (**a**) Charging power 100 kWh; (**b**) charging power 150 kWh; (**c**) charging power 200 kWh; (**d**) charging power 250 kWh.

5.4.4. Stopping Time at Bus Stops

According to the assumption, the charging time of the electric bus is equivalent to the stopping time at the bus stop. The stopping time at the bus stop is directly correlated with the charging capacity and also impacts the deployment of charging stations. In this study, we analyze the electric bus stopping at the bus stop for durations of 1 min, 1.5 min, 2 min, and 2.5 min, respectively. The results are depicted in Figure 7. The solid lines in the figure represent the battery state of charge (SOC) during vehicle operation, while the dotted lines indicate the minimum required SOC. It is observed that the number of required charging stations decreases with the increase in stopping time. However, it is crucial to comprehensively consider the choice of stopping time, as it affects the operating costs of the bus service based on operating time.

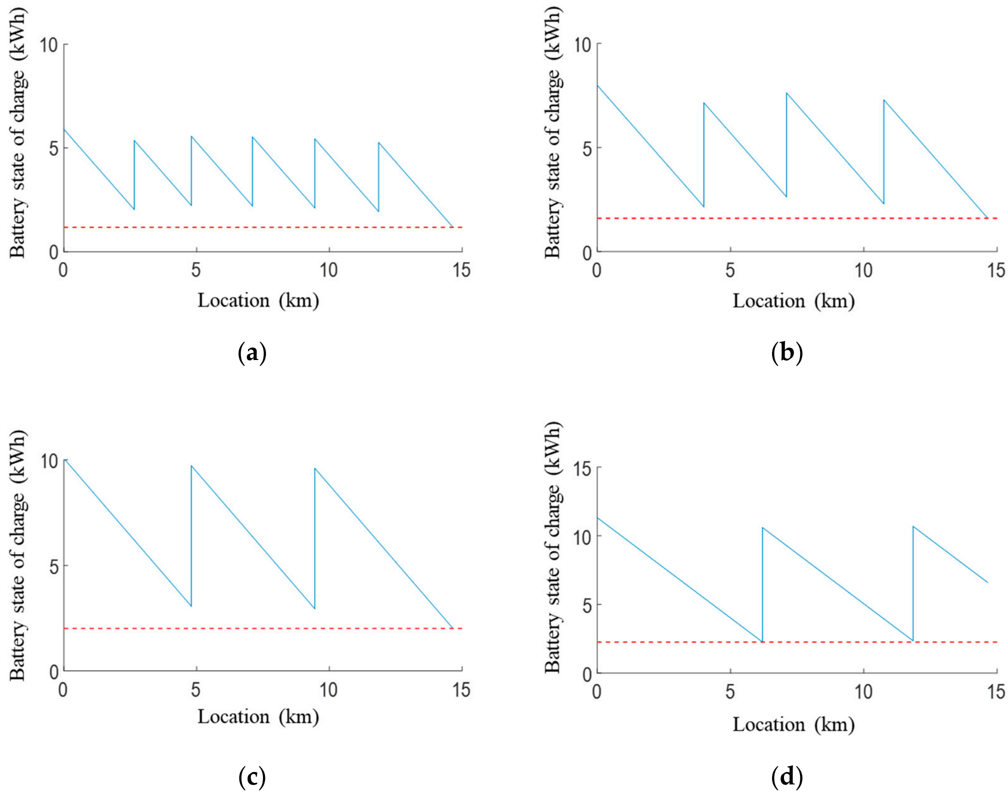

Figure 7. Optimization results of charging locations at bus stops with different stopping times. (**a**) Stopping time 1 min; (**b**) stopping time 1.5 min; (**c**) stopping time 2 min; (**d**) stopping time 2.5 min.

6. Conclusions

In this study, a model is developed to optimize the electric bus service, charging facilities along these lines, and onboard battery capacity. To solve the model, a combination of genetic algorithms with embedded enumeration and linear programming solution algorithms is employed. A bus line example is used to assess the efficiency of the proposed model and algorithm. The key conclusions drawn from this study are as follows:

(i) From the comparison of the results after optimization, it is observed that the passengers' travel costs increased due to the headway increases, resulting in longer waiting times for passengers.

(ii) The reduction in operating costs is primarily attributed to the optimization's increase in headway. Initially, the headway was too dense, resulting in increased bus route operation time due to the higher number of stops. However, by optimizing the headway, the number of vehicles dispatched per unit of time can effectively be reduced. Since operating costs are inversely proportional to the headway, this optimization results in reductions across time-based, distance-based, and fleet configuration operating costs.

(iii) After optimization, the battery capacity experiences a significant reduction. This reduction is attributed to the installation of charging stations along the route, enabling vehicles to be charged during operation to supplement the required power. Consequently, there is no longer a need for large battery capacities to store power for the entire journey. This directly reduces the purchase cost of batteries configured for electric bus vehicles and lowers the total system costs.

7. Limitations and Future Directions

It is worth mentioning that this study still has several limitations. First, the paper only considers a transit route in a corridor; second, we do not consider the impact caused by the uncertainty of demand on the electric system; and third, the operation stage is not considered in this paper. Therefore, in the future, we can extend this study from a line to a network; the dynamic urban environments can be included; and the operation stage can be considered, such as scheduling and timetabling, especially considering the impacts of building loads [37,38]. Finally, the multi-modal method can be considered.

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Abbreviations

The main symbols in this work are defined as follows:

α_u	RMB/h	passenger travel cost factor;
$B_{\max}$	kWh	battery maximum capacity;
$B_{\min}$	kWh	battery minimum power status;
B_s^i	kWh	remaining power when the electric bus reaches bus stop i;
B_u^i	kWh	cumulative power used by the vehicle when it arrives at bus stop i;
B_c^i	kWh	charging power accumulated by the vehicle on arrival at bus stop i;
$B_u^{i,c}$	kWh	cumulative power consumed at the nearest charging site in front of stop i;
C^j	kWh	power charged at bus stop j;
c_s	RMB/stop/h	single-stop construction and maintenance costs;
c_t	RMB/h	operating cost per unit of time;
c_{es}	RMB/station/h	average daily charging station construction, installation, and maintenance costs;
c_d	RMB/km	operating costs per kilometer;
c_{eb}	RMB/kWh/h	unit battery cost considering the loss caused by battery attenuation;
c_f	RMB/veh/h	single-vehicle acquisition costs;
$d_{j-1,j}$	km	distance from bus stop $j-1$ to j between stations;

d	/	indices of destinations;
D	/	set of destinations;
e_b	kWh/km	power consumption per kilometer;
$h_{\min}$	h	minimum headway;
$h_{\max}$	h	maximum headway;
h	h	headway;
i	/	sequence number of discrete corridor;
L	km	length of line;
l_o	km	distance from trip origin to nearest bus stop for passengers;
l_d	km	distance from bus stop to trip end for passengers;
l_{od}	km	distance between bus stops;
$l_{j-1,j}$	km	distance from bus stop $j-1$ to bus stop j;
N	/	set of bus stop labels;
N_l	stop	number of stops;
N_c	stop	number of charging stations;
N_{num}^{od}	stop	number of bus stops from starting point o to d;
N_c^{od}	stop	number of charging stations from starting point o to d;
$N_{\min}$	stop	minimum number of stops on the line;
$N_{\max}$	stop	maximum number of stops on the line;
o	/	indices of origins;
O	/	set of origins;
O_i	pax/h	number of passengers passing through stop i per unit time;
p	kW	charging power;
U^j	kWh	power consumed from stop $j-1$ to stop j;
t_c	h	docking time at charging stations;
t_d	h	docking time at bus stops;
t_r	h	endpoint stopping and slack time;
v_b	km/h	bus operation speed;
v_w	km/h	passenger walking speed;
x_i	/	binary variable to indicate whether the bus stop is located at segment i;
y_i	/	binary variable to indicate whether the charging station is located at segment;
Z	RMB	objective function;
Z_t	RMB	enterprise operating costs;
Z_{t1}	RMB	stop construction costs and charging station deployment costs;
Z_{t2}	RMB	operating cost;
Z_{t3}	RMB	fleet configuration costs;
Z_u	RMB	passenger travel costs;
Z_{u1}	RMB	passenger walking time costs;
Z_{u2}	RMB	passenger waiting time costs;
Z_{u3}	RMB	passenger on board travel time costs;

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