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Optimizing Battery Electric Bus Transit Vehicle Scheduling with Battery Exchanging: Model and Case Study

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Abstract

In China, a significant amount of activity is focused on electric vehicles (EV) in recent years. Propelled by the national government, electric buses powered by installed lithium-ion batteries are operating on some metropolitan streets of China. With the drawbacks of short range and long recharge time, the technical features and operating characteristics of battery electric buses and conventional diesel vehicles are different. These differences lead to great changes of the vehicle scheduling method. It is necessary to learn more about the specific scheduling method of electric buses to update traditional bus operation, management rules and scheduling methods. This paper proposes a study to establish a single depot vehicle scheduling model (SDVS) with specific constraints concerning the operation features of electric buses to solve the electric vehicle scheduling problem. Two independent objective functions of minimizing the capital investment for the electric fleet and the total charging demand in stations are involved in the model. To solve the problem, a modified multi-objective optimization method adopting the basic idea of Non-dominated Sorting Genetic Algorithm (NSGA- II) is established. This analysis is performed by solving the scheduling problem for the electric bus demonstration project to be undertaken in Shanghai. Results are reported and verify the practicability of the method proposed in this paper. These findings were valuable to assist the electric bus operation and EV applications.

Keywords: electric vehicle (EV), battery electric bus, transit vehicle scheduling, Non-dominated Sorting Genetic Algorithm (NSGA- II)

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1. Introduction

1.1. News features of battery electric bus scheduling

Recently, electric buses powered by lithium-ion batteries are starting to operate in metropolitan areas of China. With the difference of the vehicle technical and operating characteristics between battery electric and conventional diesel buses, some new aspects should be taken into account when dealing with the electric bus scheduling problems.

Firstly, mileage constraints for electric bus scheduling are more “rigid”. Under the condition of current battery technology, the scheduled daily driving range for battery electric buses is usually more than the standard range that the current batteries will allow on one charge. Therefore, mid-trip charge is essential. However, most existing approaches for traditional buses consider the vehicle task as one continuous chain of trips that start with a pull-out and end with a pull-in at a bus depot. Less consideration is given to the fact that buses that come back to the depot in the middle of the day generally to get re-fueled and therefore, their afternoon pull-out must be considered as a continuation of the morning task.

Besides, the standby battery amount and the matched scale of charge installations should be concerned. Public charging stations with rapid battery exchanging equipment and faster chargers at higher voltages and currents are the energy solution for electric buses in China. To ensure that fully charged batteries are always available when a bus returns to the battery swap station, a certain amount of extra batteries is maintained at the station. How to determine the standby battery number and the service capability of charging station is a new topic which directly influences the first investment and running costs of electric buses system.

1.2. Scope of this paper

Transit scheduling usually consists of four interrelated components: (1) design of routes; (2) creation of timetables ;(3) scheduling vehicles to trips; and (4) assignment of drivers. The third part is one of the most critical issues faced by transit agencies since. Collectively, it constitutes the largest cost elements in meeting public transportation needs. Hence, this process is taken as the focus of this research. Fortunately, a great deal of researches has been done to solve this problem, which provides meaningful references.

Bus vehicle scheduling problem was defined by Gavish and Shifler (1978) as a branch of the general class of vehicle scheduling problems (VSP). In general, this kind of problem is a problem in which a number of busses starting from one or more depots have to collectively accomplish a number of trips and then return to the depot from which they start. Each trip has a definitive starting point, ending point and its corresponding moment. The multiple depots scheduling (MDVS) is an extension of the single depot scheduling problem (DVSP), with the major difference of housed depots amount. Path length restrictions were taken into account by Bodinet al. (1983), in which constraints were placed on the length of time a vehicle may spend away from the depot or the mileage a vehicle may cover without returning to the depot for service. Bertossi et al. (1987) proved this problem is NP-hard and can be solved only by heuristic procedures. Branco (1989), Freling (1993), Haghani and Banihashemi (2002) extended this research and more effective algorithms were introduced to solve the bus scheduling problem with large scale.

The battery electric bus demonstration project to be undertaken in Shanghai provides a hard-won opportunity to learn more about the specific scheduling method for electric buses. The initial three demonstration lines with one depot owned by a national company are going to operate by the end of 2013. A public charging station with battery exchange service is locating next to the bus depot powering the electric bus lines. The vehicle scheduling problem proposed in this paper deals with the scheduling of a number of electric buses to serve about 119 relatively short trips. The timetables for those trips reflect the varying demand for transportation and are planned in advance. The objective is to schedule buses to trips in such a way that the cost incurred by the fleet size and the charge service are minimized while the operational constraints are satisfied.

The remainder of the paper is organized as follows. The second section shows the electric bus specifications and the characterizations of battery exchange technology. The third section establishes the optimization model for battery bus scheduling. Section four presents the heuristic approach for solving the optimization model. Section five presents a case study and discusses the results. The final section contains the conclusions and recommendations related to this research.

2. Bus specifications and battery exchange technology

2.1 Bus Specifications

The battery electric bus applied in Shanghai features an AC asynchronous motor with an automatic energy management system which has a self-testing module. Two types of dynamical system with LiMn2O4 and iron-phosphate-based Li-ion batteries are installed on electric buses. Both equipped with a 100kW AC motor, no significant difference is observed on most of vehicle dynamic parameters. Details of these two buses are shown in TABLE-1, and the comparison bus is a 12.5-meters diesel bus which is widely used in Shanghai.

TABLE-1 Specifications of battery electric bus and diesel bus

	Type	Battery electric bus		Diesel bus
Vehicle dynamic performance	Model No.	SWB6121EV		SWB6115HP-3
	Size(（L*W*H, mm）	11980*2550*3160		11500×2500×3150
	Acceleration time（s,0-50km/h）	≤25		≤25
	Maximum speed(km/h)	≥70		≥80
	Maximum grade ability (%)	≥20		≥20
	Theory power consumption[-a]	100 kwh/100km		43L/100km
	Ideal driving range in urban conditions(km)	≥80		≥300
	Unload weight(kg)	13900		10600
Power battery	Type	$LiMn_2O_4$	Iron-phosphate	-
	Capacity(Ah)	360	255	-
	Voltage range (V)	312~437	527~595	-
	Peak power(kw)	142	180	-
	Energy density (Wh/kg)	112	115	-
	Weight(kg)	1700	2050	-
Motor	Model No.	JD132	YCVF250L-4	M906LAG CG-250
	Rated/Peak power(kw)	100/150	100/200	-/184
	Rated/Peak torque（Nm）	470/850	-/900	-/895

Note. The power or oil consumption on the vehicle manual is measured in a certain experimental working condition.

As shown in TABLE-1, most vehicle dynamic parameters of electric buses and the diesel buses are on the same level. However, the main differences between the two buses exist in their ideal driving range. The ideal driving range of electric bus in urban conditions is 80km, which occupies only 25% of the comparison diesel bus. This reflects the capacity insufficient of power batteries fixed on the electric buses.

2.2 Battery exchanging technology

Due to their high utilization rate, many electric buses will drive more than the standard range that the current batteries will allow on one charge. As a result, they need to be recharged throughout the day. To ensure that the buses maintain a high operating up-time, these buses must be recharged quickly.

(a)

(b)

FIGURE-1 Battery replacement channels (a) and battery quick exchange robots (b)

The approach being utilized in China to achieve high operating up-time is a rapid battery exchange system (FIGURE 1) whereby the bus pulls into a battery swap station and robotic battery removal systems locate and remove a battery pack on each side of the bus. Next, the system locates and returns the batteries to an open spot in the vertical battery charging banks positioned along walls facing each side of the bus. Following this, the next available fully charged battery pack is located from the charging bank, removed, and placed in each open battery bay on the bus. The entire battery exchange takes approximately 12 minutes from the time the bus enters the station to the time it can return to service. To ensure that fully charged batteries are always available when a bus returns to the battery swap station, a mount of standby batteries are maintained in the station and high-power chargers are installed to simultaneously charge the batteries returned from the field.

3. Model establishment

3.1 Optimization objectives

Three aspects should be conceded when considering the battery electric bus scheduling problem: the minimum number of vehicles to serve all trips (a); the minimum number of standby batteries maintained for the vehicle fleet to ensure the non-stop operation (b); the adequate power supply of the charge station to meet the energy demand of the electric bus system (c). Among them, the former two aspects can be described as the scale of the electric fleet which has a direct influence on the fixed capital investment from the electric bus operator. For electric enterprises, the service capacity of the charging station with its corresponding construction cost is what they most concern. In this paper, the service capacity of charging station is quantified as the total battery amount that the station should charge.

In this paper, all these three aspects were involved in the electric bus scheduling model as two independent objectives to minimize the capital investment for the electric fleet and the total charge demand (battery∗times) that the station should meet in one day operation.

3.2 Modeling assumption

Real world transit scheduling is very complicated. Some assumptions need to be made advanced to model the electric vehicle scheduling problem. In most of vehicle scheduling models for diesel buses, the following conditions are satisfied.

(1) The timetables for trips are planned in advance.

(2) Each trip is run by exactly one vehicle.

(3) Each block of trips starts and ends at the same depot.

(4) Each depot has a given maximum number of vehicles (capacity).

For battery electric buses, another three assumptions are made in this model.

(1) In two conditions the electric vehicles go to the charge station to change its power batteries: (a) the remaining energy cannot afford any of the remaining trips; (b) Charge ahead to reserve for peak hours according to the scheduling scheme.

(2) The whole battery exchange operation will take 15 minutes. The battery will be charged once after replaced from the vehicle and the charging process will not break until it is full charged. Besides, the charging time has a positive linear relationship with the SOC which is only related to the corresponding period of buses/trip mileage. Another 15 minutes are involved as a safety margin. Therefore, the charging time for replaced battery can be calculated by the equation below.

$$\begin{cases} t_{C1} = 3 * (95\% - S_0\%) * 60min \\ t_{C2} = 15min \\ t_C = t_{C1} + t_{C2} \end{cases} \tag{1}$$

(3) Vehicles run strictly on the basis of the timetable. The operation speed of the electric bus is 20km/h including the midway dwell time without the consideration of traffic condition impact.

3.3 Arithmetic Expression

In this paper we derive a multi-objective model to solve the battery electric scheduling problem. This model is a special case of Single Depot Vehicle Scheduling with Route Time Constraints (SDVSRTC) model including the objective function, operational constraints and specific restrictions in consideration of the electric bus operation characteristics. Two independent objective functions are applied in the scheduling model with minimizing the fixed capital investment for the electric bus fleet and the total charge demand for the charge station.

Two different sets of input date are involved in the model. The first set contains parameters covering the conventional bus transit scheduling process. In the second set, battery ID (b), charging time (t_c^b) etc. are involved to calculate the quantity of standby batteries

As input variables, suppose there are (n) trips to be served by vehicles starting from a single depot (o). Each trip (i) has a trip length (li), a starting time (t_s^i), and an ending time (t_e^i). The trips could be served by the same vehicle if the starting time of one trip is greater than the ending time of another trip plus an operation interval for necessary reconditioning for vehicles.

The mathematical formulation of the model is as follows:

$$\min Z_1 = \sum_{k=1}^{m}\sum_{b=1}^{u} A\,x_k + By_b \tag{2}$$

$$\min Z_2 = \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{n} C_{kij}x_{kij} + \sum_{k=1}^{m} x_k \tag{3}$$

Subject to：

$$\sum_{k=1}^{m}\sum_{j=0}^{n} x_{kij} = 1, i \neq j, i \in \{1,2,\ldots \mathrm{n}\} \tag{4}$$

$$\sum_{k=1}^{m}\sum_{j=0}^{n} x_{kij} = 1, j \neq i, j \in \{0,1,2,\ldots \mathrm{n}\} \tag{5}$$

$$t_{ij}x_{kij} \leq t_s^j - t_e^i \tag{6}$$

$$\sum_{k=1}^{m}\sum_{i=1}^{n} x_{k0i} = \sum_{k=1}^{m}\sum_{j=1}^{n} x_{kj0} \tag{7}$$

$$\sum_{i\epsilon n}\sum_{j\epsilon n} x_{kij}\left(l_{0i} + l_i + l_{ij} + l_j\right) \leq R_k \tag{8}$$

$$t_{ij} = \begin{cases} t_{ij}' & \text{if vehicle } k \text{ change its batteries} \\ t_{ke} + t_{ij}' & \text{otherwise} \end{cases} \tag{9}$$

$$t_c^{bi} = 3 * \left(95\% - \mathrm{S}_i^b\%\right) * 60min + 15\,min \tag{10}$$

$$\sum_{k=1}^{m} x_k \leq m \tag{11}$$

All variables are integer.

Where:

A=the price of an electric vehicle with one set of power batteries installed,

B=the price of a standby battery set,

$$C_{kij} = \begin{cases} 1 & \text{if vehicle } k \text{ change its battery between trip } i \text{ and trip } j \\ 0 & otherwise \end{cases}$$

$$x_k = \begin{cases} 1 & \text{at least one trip is run by vehicle } k \\ 0 & \text{otherwise} \end{cases}$$

$$x_{kj} = \begin{cases} 1 & \text{if trip } j \text{ is run by the vehicle } k \\ 0 & \text{otherwise} \end{cases}$$

$$x_{kij} = \begin{cases} 1 & \text{if trip } j \text{ is run before trip } i \text{ by the same vehicle } k \\ 0 & \text{otherwise} \end{cases}$$

$$t = \begin{cases} t_{ij}' & \text{the necessary reconditioning time between trip } i \text{ and trip } j \\ t_{ke} & \text{the time for vehicle to change its battery} \\ t_c^{bi} & \text{the charging time for the battery b after trip } i \end{cases}$$

$$l = \begin{cases} l_{oi} & \text{the distace between depot } o \text{ and the start of trip } i \\ l_i & \text{the length of trip } i \\ l_{ij} & \text{the deadhead distance between trip } i \text{ and trip } j \end{cases}$$

R_k=the driving range of vehicle *k* per change

S_i^b=the remaining energy of battery *b* after trip *i* *m*=the maximum available number of vehicles at depot *o* (capacity of depot *o*)

Formulation (2) and (3) are the objective functions to minimize the capital investment for the electric fleet and the total charge demand for the charge station respectively. Constraints (4)-(7) are operational constraints of bus transit scheduling which ensures the trip connectivity and flow equilibrium of the depot. Constraint (8) ensures the maximum driving range of the electric vehicle per charge is less than an assigned trip chain. Constraints (9) define the operation interval between different trips. Constraint (10) signifies the charging time for batteries replaced from the vehicle. Finally, constraints (11) guarantee the maximum available number of vehicle at depot o.

The formulations presented in (2)-(13) do not include the process to calculate the quantity of standby batteries. However, through these constraints the remaining energy of each replaced batteries together with their exchanging moment are depicted. A corresponding “counter” is added to identify the standby battery amount for objective function (2) calculation. Details of this process are depicted in the following section.

4. Solving algorithm

4.1 Algorithm framework

In this paper, the battery electric bus scheduling problem was formulated as a multi-objective model. To solve multi-objective optimization problems (MOP), Non-dominated Sorting Genetic Algorithm-II (NSGA- II) is one of the most effective approaches. NSGA-II, which is developed by prof. K.Deb is a fast and elitist multi-objective evolutionary algorithm. Recently, this method has become a standard approach to solve the MOP. The basic idea of this algorithm was adopted and. realized on Matlab2008b platform. The framework of the algorithm is show in FIGURE 2.

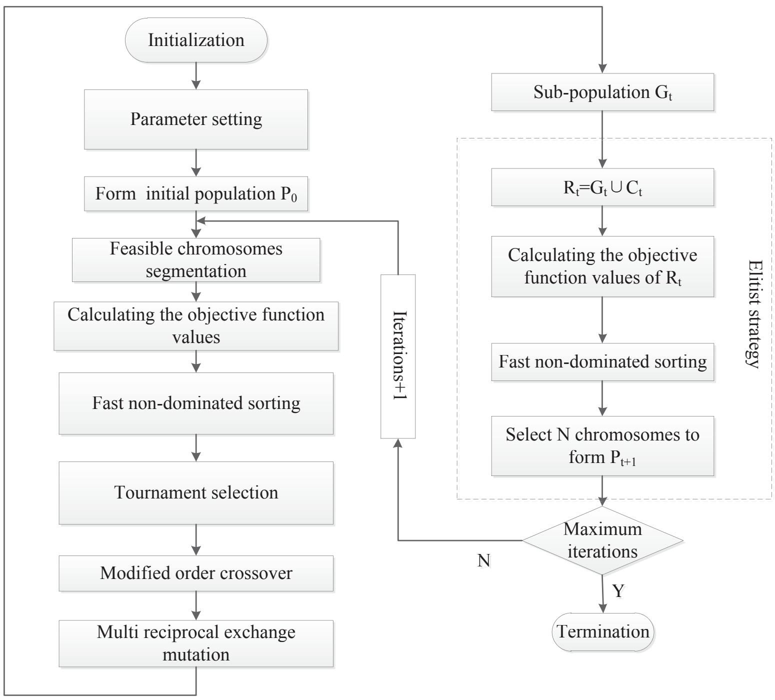

FIGURE 2 Detailed framework and process of the algorithm

4.2 Key operator design

In this section, some key operators are introduced for better understanding. Details of this algorithm are omitted due to the limitation of paper length.

(1) Encoding and initial population

In genetic algorithms, inversion is implemented by changing the encoding to carry along a tag which identifies the position of a bit in the string. In this step, the vehicle scheduling problem is "translated" into a "biological terms" by formatting the chromosome, which is called encoding. Each chromosome in the population is an expression of a possible solution.

The essence of vehicle scheduling problem is a kind of combinatorial optimization problem which aims to find the optimal arrangement and combination of trips satisfied to restrain conditions. Hence, literal permutation encoding comes to be the most effective. In this paper, the chromosome is composed by a literal string with a series of real-numbers differing from each other. Each integral number presents a trip numbers with its corresponding length, starting moment, ending moment etc. Thus, the length of the string is the total amount the trips to be scheduled.

(2) Feasible chromosomes segmentation

The purpose of the chromosomes segmentation is to assign a block of transit trips to electric buses by dividing the literal string generated in the previous step into several trip blocks. Each block presents a trip chain that one corresponding vehicle should complete. Hence, the number of block equals the required amount of electric vehicles. This process is run from the start of the trip string until all the trips are assigned. The pseudo code of this process is shown below.

{Initial chromosomes$S_0 = [s_1, s_2, \cdots, s_i \cdots, s_N]$, $S = S_0$ which presents the undistributed trips. $\mathrm{Num_C} = 0$ which presents the number of trip block already assigned
While ($\mathrm{S} \neq \emptyset$) do
{Generate a trip block $\mathrm{S_1}$ that obeys the constraints;
do

$$Num_C = Num_C + 1 \text{ (Trip block amount update)}$$

Chromosomes deletion：

$$\mathrm{S_2} = \mathrm{S} - \mathrm{S_1}$$

$$\mathrm{S} = \mathrm{S_2} \text{(Chromosomes update)}$$

};

FIGURE 3 Process of the chromosomes segmentation

Two aspects are takenn into account in dividing the trip string: the maximum driving range of vehicles (a) and the connectivity of trips (b). Take trip *i* and trip *j* for example. Firstly, the remaining energy after trip *i* is calculated to judge whether it is sufficient for trip *j*. If it is sufficient, the necessary spacing interval between these trips equals $t_{ij}^{\prime}$, or else plus the battery changing time t_{ke} for trip connectivity judgment. The trips could be served by the same vehicle when the starting time of trip *j* is greater than the ending time of trip *i* plus the necessary spacing interval between two trips depending on whether the vehicle need change its batteries. Besides, once battery exchange occurs, the exchange moment (t_e^i) and the remaining energy (S_i^b) are conserved in the procedure for the standby battery quantity calculation.

(3)Standby battery amount counter

The input date of this standby battery amount counter include the battery exchange moment (t_e^i) and the remaining energy (S_i^b) which are obtained through the steps above. An iterative algorithm is put forward to calculate the standby battery quantity and the framework of this algorithm is shown in FIGURE 4. In this process, each battery has three kinds of states including: battery in vehicle (BV), battery in change (BC) and battery standby (BS). An additional standby battery is added when battery exchange occurs but there is no available battery in the battery bank (BS=0).

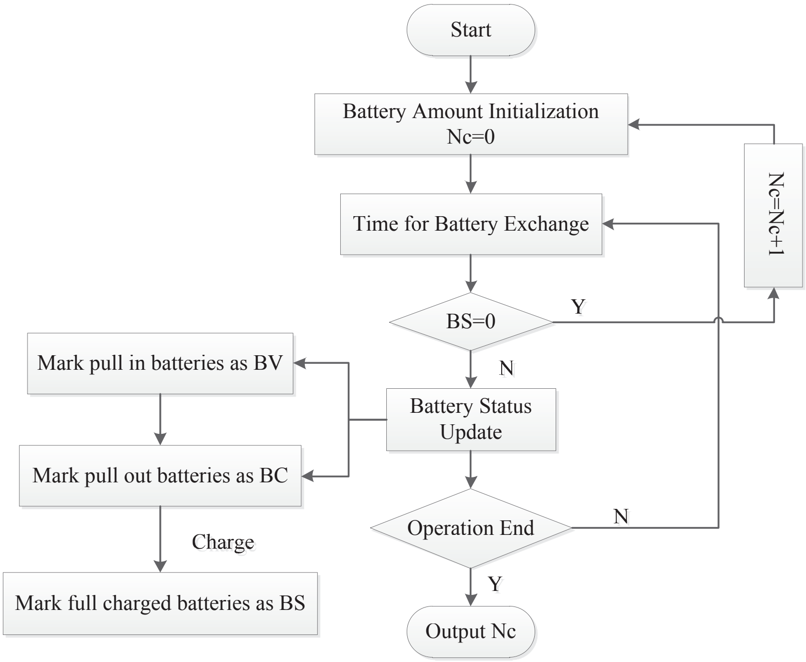

FIGURE 4 Detailed framework and process of the standby battery amount counter

5. Case study

5.1 Bus route information

Details of the three electric bus routes are shown in TABLE-2. These demonstration routes are loop lines with the same starting and ending station at a single bus depot. The charging station is about 50 meters next to the depot. Other parameters are assigned as follows: A=1.2 million RMB, B=0.6 million RMB, t'_{ij} =5 min, t_{ke}=15 min, l_{ij}=0 km, and R_k=64 km considering a 20% safety margin. TABLE-3 shows the timetable of the scheduled trips which are arranged according to the chronological order of trip starting moment.

TABLE-2 Details of electric bus routes

Route No.	Operating Hours	Departure Interval /min		Length /km	A Trip Drive-time /min
		Peak hours	Nonpeak hours		
1	7:00-20:30	15	30	31.5	95
2	6:40-20:20	15	20	20.16	60

3	6:30-20:30	20	15.12	45

Note: The operation speed of the electric bus is 20km/h neglecting the influence of traffic conditions.

TABLE-3 Timetable of electric bus trips

Trip No.	Starting moment	Ending moment	Route No.	Trip No.	Starting moment	Ending moment	Route No.
1	6:30	7:15	3	┆	┆	┆	┆
2	6:40	7:40	2	71	15:00	16:00	2
3	6:50	7:35	3	72	15:00	16:35	1
┆	┆	┆	1	73	15:10	15:55	3
58	13:20	14:20	2	┆	┆	┆	┆
59	13:30	15:05	1	119	20:30	21:15	3

5.2 Result and explanation

Most of multi-objective optimization problems involve simultaneous optimization of several competing objectives. Usually there is no single optimal solution, but rather a set of Pareto optimal points. The solving process is established on Matlab 2008b platform and the results are depicted in FIGURE 5. By means of the approach of NAGA- II, model set converges gradually to 17 points in the resolution space. In FIGURE 5, each red square represents an electric bus scheduling scheme with its corresponding fleeting investment and total charging demand depicted. Typically, both of these two objectives values of Pateto-optimal solutions are reduced compared to that of the set of initial solutions without the optimization process proposed in this paper which proves the validity of the heuristics algorithm.

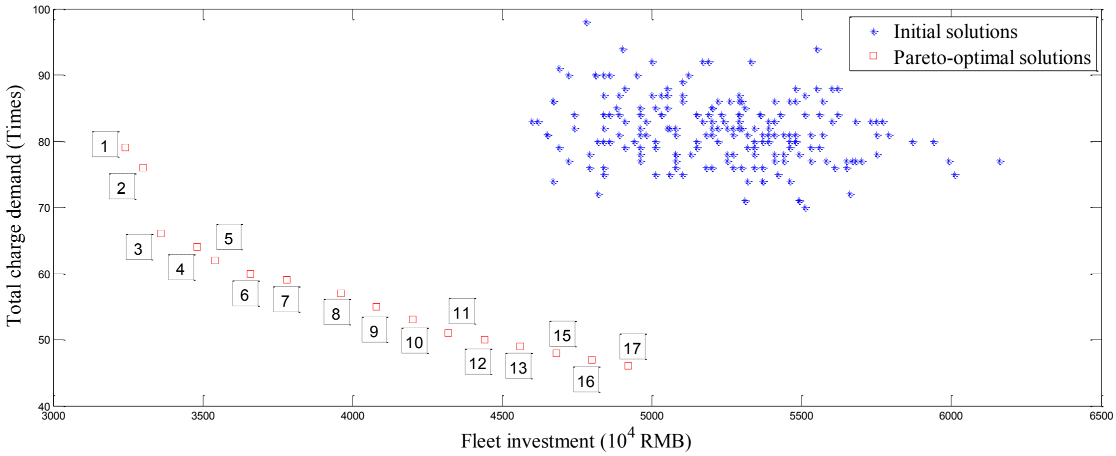

FIGURE 5 Distribution of initial solution and Pareto-optimal solution

In FIGURE5, the parameters analysis results show that a decrease in vehicle fleet investment will result in an increase of the total charge demand which leads to an additional burden on the charging station. When the vehicle fleet investment equals 3.24 million RMB, the total charge demand increases almost 71.4% compared with that of the first solution with a total investment of 4.92 million RMB. Accordingly, the decrease of total charging demand will lead to the increase of vehicle investment budget. In other words, an improvement of fleet investment for battery electric bus operators is at the sacrifice of a load of charging station.

Therefore, there is no absolute optimal solution reducing both of the two objectives simultaneously, each of the schemes depicted as a red square in FIGURE5 is acceptable depending a great deal on the personal preference. For example, Pateto-optimal solution marked "1" with its corresponding scheduling scheme is proposed as best solution when the initial investment of bus fleet is inclined to be most crucial. TABLE-4 depicts the detail scheme of this optimal solution.

TABLE-4 Scheduling scheme of Pareto-optimal solution 1

Vehicle No.	Scheduled trip	Driving range(km)
1	[18-44-BE-87-105-112-BE]	107.1
2	[9-29-47-BE-61-94-BE]	95.76
3	[10-42-55-BE-78-BE]	75.6
4	[20-56-BE-85-116-BE]	98.28
5	[22-50-71-BE-91-BE]	75.6
6	[33-63-79-BE-98-BE]	86.94
7	[3-11-24-BE-43-81-102-BE]	95.76
8	[12-46-62-BE-76-86-107-BE]	123.48
9	[8-49-65-BE-93-115-BE]	108.36
10	[51-75-BE -95-BE]	94.5
11	[14-32-54-BE-73-89-BE]	91.98
12	[4-35-BE-67-84-BE-103-BE]	141.12
13	[19-41-68-BE-83-110-BE]	108.36
14	[17-57-BE-74-88-BE-111-BE]	113.4
15	[40-53-BE-69-82-101-BE]	112.14
16	[28-52-BE-72-106-BE]	98.28
17	[2-21-34-BE-48-BE]	91.98
18	[7-39-66-BE-100-108-114-BE]	110.88
19	[5-15-BE-80-96-BE]	103.32
20	[6-23-BE-45-92-BE]	98.28
21	[1-27-36-60-BE-90-109-BE]	112.14
22	[30-64-BE-104-113-BE]	81.9
23	[31-70-77-BE-97-117]	90.72
24	[13-25-37-BE-58-99-119-BE]	110.88
25	[16-26-38-BE-59-118-BE]	118.44

Note: BE means battery exchange.

6. Conclusions and discussions

The operation of battery electric buses needs a specific scheduling method. In order to better understand this problem, a multi-objective vehicle scheduling model is presented to optimize the electric bus scheduling. This method provides acceptable results in a case study in Shanghai which demonstrates the effectiveness and validity of this method. The method could directly be applied to optimize the battery electric bus operation in other areas.

With the drawbacks of short range and long recharge time, bus routes with short daily trip distance and few passenger loadings are recommended as the electric bus demonstration routes recently. Three types of routes are recommended: suburban line with low service frequency (a), urban streetcar lines (b), and short-range shuttle bus in downtown area (c). Since the electric bus does not emit any pollutants when idling, the bus would also be a good choice in routes that involve a lot of idling or waiting time in downtown.

Besides, details of the algorithm process together with an earnest description and comparison of different scheduling schemes are cut down due to the limitation of paper length. Further discussion is welcomed if need be.

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