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Article *in* Transportation Research Part E Logistics and Transportation Review · December 2023

DOI: 10.1016/j.tre.2023.103335

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Joint optimal vehicle and recharging scheduling for mixed bus fleets under limited chargers

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ABSTRACT

Owing to the high acquisition costs, maintenance expenses, and inadequate charging infrastructure associated with electric buses, achieving a complete replacement of diesel buses with electric counterparts in the short term proves challenging. A substantial number of bus operators currently find themselves in a situation where they must integrate electric buses with their existing diesel fleets. Confronted with the constraints of limited electric bus range and charging infrastructure, the primary concern for bus operators is how to effectively utilize their mixed bus fleets to adhere to pre-established bus timetables while maximizing the deployment of electric buses, known for their zero pollution and cost-effective travel. Consequently, this paper introduces the concept of the joint optimization problem for vehicle and recharging scheduling within mixed bus fleets operating under constrained charging conditions. To tackle this issue, a mixed integer linear model is formulated to optimize the coordination of bus schedules and recharging activities within the context of limited charging infrastructure. By establishing a set of feasible charging activities, the problem of electric buses queuing for charging at constrained charging stations is transformed into a linear optimization model constraint. Numerical simulations are conducted within the real transit network of the Dalian Economic Development Zone in China. The results indicate that the judicious joint optimization of vehicle and charging scheduling significantly enhances the service frequency of electric buses while reducing operational costs for bus lines. Notably, the proportion of total trips performed by electric buses rises to 80.4%.

1. Introduction

The transportation industry represents a significant energy consumer and carbon emitter (Dai and Han, 2023; Utomo et al., 2021). It is noteworthy that the carbon emissions attributed to China's transportation sector constitute approximately 10.4 % of the total carbon emissions, whereas in developed European and American countries, the transportation industry contributes to approximately one-third of the overall carbon emissions (Battaia et al., 2023; Gao et al., 2023; Zeng and He, 2023). Consequently, governmental bodies in various nations have implemented policies, such as purchase subsidies, free parking, and unlimited travel, to encourage the widespread adoption of electric vehicles (Hu et al., 2023; Li and Wang, 2023). Diesel buses, although constituting only a minor portion of urban road traffic, exert a significant environmental impact. For instance, in Shenzhen, China, diesel buses account for merely 0.5 % of the total vehicle population but are responsible for 20 % of the city's carbon dioxide emissions resulting from traffic (Li and Wang, 2023). This phenomenon is largely attributed to the prolonged operational hours of buses, their relatively low traveling speeds, frequent instances of acceleration and deceleration, and extensive mileage (Chen et al., 2023; Qu et al., 2022)(Cui et al., 2023). Consequently, various nations are actively promoting the replacement of diesel buses with electric alternatives.

Realizing the full replacement of diesel buses by electric buses faces huge financial and land pressures (Donmez et al., 2022). The

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https://doi.org/10.1016/j.tre.2023.103335
Received 10 July 2023; Received in revised form 4 October 2023; Accepted 19 October 2023
Available online 30 October 2023

Notations

Indices	Definition
i and j	Index of trips
(i,j)	Index of trip pairs
e	Index of electric buses
d	Index of diesel buses
k	Index of chargers
t	Time slots

Sets

I	Set of all scheduled trips
E	Set of candidate electric buses
D	Set of diesel electric buses
$I_0 = I \cup \{0\}$	Set of all scheduled trips and the trip 0 for all buses to depart from the depot to transit centers to start providing services
$I_{N+1} = I \cup \{N+1\}$	Set of all scheduled trips and the trip $N+1$ for all buses to return from transit centers to the depot after completing all services
$I_{0,N+1}$	$I \cup \{0, N+1\}$
K	Set of all fast chargers
T	Set of all time slots
P	Set of all feasible trip pairs
P^*	Extended set of trip pairs where $i \in I_0$ and $j \in I_{N+1}$
A	Set of feasible charging activities

Parameters

Q	The battery capacity
c_1	The charge consumption rate
C	The diesel capacity
c_2	The diesel consumption rate
d_i	The distance of trip i
a_i	The start time of trip i
b_i	The end time of trip i
d_i^{dc}	The distance from the transit center of trip i to the depot to charge electric buses
d_i^{dd}	The distance from the transit center of trip i to the depot to refuel diesel buses
v	The speed of buses
r_1	The recharging rate of electric buses
r_2	The refueling rate of diesel buses
τ	The time duration of each time slot
u_1	The time interval of each charging activity
u_2	The time interval of each replenishing activity
α_0	The fixed cost of performing a charge
α_1	The unit electricity cost
α_2	The fixed cost of performing a diesel replenishment
α_3	The unit diesel cost
M	The infinite constant
$Q_{\min}$	The minimum charge limit
$C_{\min}$	The minimum diesel limit

Variables

z_e	If the electric bus $e \in E$ is scheduled, $z_e = 1$; otherwise, $z_e = 0$.
z_d	If the diesel bus $d \in D$ is scheduled, then $z_d = 1$; otherwise,$z_d = 0$
$Q_{i,e}$	The remaining charge of electric bus $e \in E$ after completing trip $i \in I$
$Q_{i,d}$	The remaining diesel of diesel bus $d \in D$ after completing trip $i \in I$
$F_{i,e}$	If the electric bus $e \in E$ goes to the depot to replenish charge after completing the service of trip $i \in I$, then $F_{i,e} = 1$; otherwise $F_{i,e} = 0$
$F_{i,d}$	If the diesel bus $d \in D$ goes to the depot to replenish diesel after completing the service of trip $i \in I$, then $F_{i,d} = 1$; otherwise $F_{i,d} = 0$
$Z_{i,t}^{e,k}$	If the electric bus $e \in E$ does choose charger $k \in K$ to start replenishing charge at time slot $t \in T$ after completing the

	service of trip $i \in I$, $Z_{i,t}^{e,k} = 1$; otherwise,$Z_{i,t}^{e,k} = 0$
$x_{i,j,e}$	If the trip pair $(i,j) \in P$ is served sequentially by electric bus $e \in E$, then $x_{i,j,e} = 1$; otherwise $x_{i,j,e} = 0$
$x_{i,j,d}$	If the trip pair $(i,j) \in P$ is served sequentially by diesel bus $d \in D$, then $x_{i,j,d} = 1$; otherwise $x_{i,j,d} = 0$

Fig. 1. Charging an Electric Bus with a Super-Fast Charger (Source: Everyone by Smart Cities Council).

purchase cost of an electric bus is usually two to four times that of a diesel bus. The battery needs to be replaced once in the operation cycle of an electric bus for 6 to 8 years (Cai et al., 2022; McGrath et al., 2022). Usually, the battery cost of an electric bus is close to half of that of an electric bus. The price of a 120 kW DC super-fast charger (see Fig. 1) is 107,200 CNY (Yang et al., 2020; Ji et al., 2022). It is estimated that the investment cost of a large bus charging station including 120 DC fast chargers needs to be 6.191 million CNY. Therefore, huge financial pressures have slowed down the full replacement of diesel buses by electric buses. In addition, the scarcity of land resources in large cities, such as, Beijing in China, Tokyo in Japan, and so on, makes it difficult to deploy large-scale bus charging stations. According to reports, Shenzhen, China has achieved 100 % coverage of electric buses, but most cities are still in a state of mixing diesel buses with electric buses.

Typically, an electric bus will have a third of the range of a diesel bus, and in cold months the ratio may be lower. Even with some super-fast chargers (see Fig. 1), it takes 30 to 50 min for an electric bus to be fully charged, while a diesel bus takes just 3 to 5 min to replenish its diesel (Zhang et al., 2020, 2021, 2022). Therefore, in the case of limited chargers and pre-designed bus timetables, reasonable joint optimization of vehicle scheduling and charging scheduling can promote the use of electric buses with low pollution and low travel cost for a mixed bus fleet (Zhou et al., 2022; Gao et al., 2021). How to determine the chargers being used, and the waiting time for using each charger urgently need to be solved in an urban-scale public transit network under limited chargers. Therefore, this paper studies the joint optimization problem of vehicle scheduling and charging scheduling for mixed bus fleets to promote the trip execution frequency of electric buses in the case of insufficient electric buses and chargers. Secondly, this paper introduces the trip-pair-based set of feasible charging activities to linearly transform the situation of electric buses queuing to charge at limited chargers into an optimization model constraint to solve the urban-scale public transit network.

The remaining sections of this paper are organized as follows: Section 2 summarizes the relevant literature and research gaps; Section 3 further describes the joint optimization problem studied in this paper and summarizes the assumptions made in this paper; Section 4 constructs the mixed integer linear programming model for the joint optimization of vehicle scheduling and charging scheduling; Section 5 conducts numerical simulations using Dalian Economic Development Zone, China as an example; Section 6 concludes the paper.

2. Literature review

Some studies have explored the feasibility of electric buses replacing diesel buses. Xylia et al. (2017) conducted a study on 526 lines in the public transit network in Stockholm, Sweden, and showed that the low operating costs and electricity prices of electric buses can balance the high investment costs of charging infrastructure. Lajunen (2014) and Cai et al. (2022) performed extensive simulations of hybrid buses and electric buses on different bus lines and performed cost-benefit analysis based on energy consumption. Simulation results show that both hybrid buses and electric buses can reduce energy consumption and emissions. Li (2016), Zeng et al. (2022), and Dai et al. (2023) analyzed the key technologies of the existing electric bus operation, and pointed out that current electric buses have great limitations in the operating range and charging time. Shao et al. (2022) studied the balance between total greenhouse gas emissions and operating costs of a mixed fleet of diesel buses and electric buses by incorporating the impact of spatial and temporal passenger flows. The replacement of traditional diesel buses by electric buses is not a one-off process, but a gradual process. Consequently, a great deal of current research is directed at fleets with a mix of electric buses as well as conventional diesel buses (Hu and Li, 2022).

At present, the research on the ratio of electric buses under the mixed bus fleet is mostly analyzed from the perspective of the public transit network. Ercan et al. (2015) and Battaia et al. (2023) used a multi-objective linear programming method to obtain the optimal combination of bus fleets under different driving conditions, and found that the introduction of electric buses has a significant impact on the reduction of life cycle costs, greenhouse gas emissions, and traditional pollutant emissions. Ribau et al. (2015), Borén (2020), and Rupp et al (2020) looked at alternatives to electric buses or hybrid buses to replace traditional diesel buses in the bus transit network, with the aim of reducing carbon emissions and negative financial impacts. Rogge et al. (2018) aimed at reducing costs to obtain the optimal combination of mixed fleets. Santos et al. (2016) studied the bus network data of Porto, Portugal, and obtained the optimal mixed fleet combination. Li et al., (2016a), and Lu et al., (2021a, 2021b) proposed a life-additional benefit cost method based on the additional benefit cost of the remaining life to solve the ratio problem of electric buses in a mixed fleet.

Some scholars have conducted research on the planning of charging facilities for electric buses. The popular plug-in charging conducted by plug-in chargers consists of two charging modes: slow charging and fast charging (Cui et al., 2020, 2022). Slow charging usually takes 6 to 8 h to fully recharge the battery of electric buses (Dai and Han, 2023). When there is a long idle time, electric buses usually choose the slow charging mode to recharge their batteries. Fast charging needs the support of high voltage. High voltage is easy to cause the damage to electric buses. Due to the tight service schedule and large battery capacity, the DC fast charging equipment shown in Fig. 1 is usually deployed at depots for electric buses. Different from the location problems of charging stations for electric vehicles where the deployment of charging infrastructure is affected by the geographical distribution of cities, the number of vehicles, and the type of charging stations (Li et al., 2016b; Yao et al., 2023), charging of electric buses is usually completed at their depots.

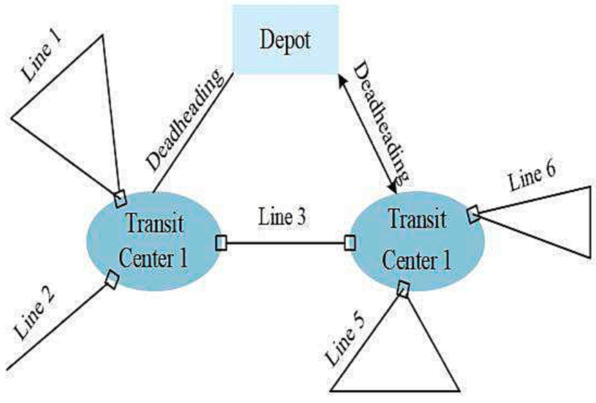
Therefore, research on electric buses focuses more on the deployment of chargers at depots. He et al. (2022) constructed a two-phase optimization framework to achieve the integration optimization of charging scheduling and charging infrastructure planning for electric bus systems where the charging schedules, on-board battery capacity, and charger deployment are optimized at the same time. Hu et al. (2022) proposed an en-route charging method for electric buses, that is, electric buses use the time when passengers get on and off to replenish power to avoid electric buses going to distant depots or charging stations for charging. They developed the joint optimization model of charging schedules and locating fast chargers at bus stops. Since the complete replacement of diesel vehicles by electric buses is difficult to achieve in the short term, Soltanpour et al. (2022) proposed a planning framework to simultaneously address the transport electrification and the three aspects of its interconnection, namely charging scheduling, fleet configuration, and locating charging infrastructure.

Some studies integrated the charging constraints of electric buses to study the scheduling problem of electric buses. Wang et al. (2017), Cai et al. (2022), and Battaia et al. (2023) studied the charging scheduling problem of electric buses with fixed recharging time where the number of plug-in chargers was optimized to minimize the total recharge waiting time of electric buses and the cost of plug-in chargers. Prata (2015) and Prata et al. (2021, 2022) analyzed the complexity of the vehicle-human joint scheduling problem and simplified the scheduling problem into a maximum coverage problem. Pan and Sun (2014), Peña et al. (2017), and Cui et al. (2022) considered a variety of influencing factors when solving the scheduling problem., Shen et al. (2016), Wu et al. (2022), and Tsang and Shehadeh (2023) combined the heuristic algorithm and integer linear programming to solve the vehicle scheduling probability problem with random travel time and the probability distribution of vehicles. Deniz et al. (2019) considered the vehicle scheduling problem of different vehicle types. Ceder (2011), Gkiotsalitis and Berkum (2020), and Liu et al. (2023) analyzed the impact of factors such as the number of empty vehicles and departure time intervals on bus lines. Different from the above simple study of bus charging scheduling and single charging mode, Xie et al. (2023) not only developed the cooperative optimization of driver schedules, charging plans, and bus schedules, but also allowed electric buses to charge through the three charging modes of battery swapping, slow charging and fast charging.

The preceding research primarily centers on two key areas: the scheduling of pure electric bus fleets and the proportion of electric buses within mixed bus fleets. Nonetheless, the current bus fleet exists in a state of heterogeneity, comprising both electric and diesel buses, a situation primarily driven by the elevated procurement costs of electric buses, maintenance expenditures, and inadequate charging infrastructure. Consequently, the present mixed bus fleet faces a scarcity of electric buses and an overabundance of diesel buses. Therefore, it becomes imperative to devise a systematic approach for assigning appropriate bus types to each trip and for optimizing the charging protocols for electric buses. This becomes especially crucial when considering the limited availability of charging stations. Regrettably, there exists a dearth of research addressing the simultaneous optimization of vehicle scheduling and charging protocols for a fleet that encompasses both diesel and electric buses. Finding a solution to the challenge of electric buses queuing for charging at constrained charging stations is of immediate concern. Developing a straightforward model to address this issue is an urgent imperative.

3. Problem description and assumptions

Section 3.1 describes in detail the joint optimization problem of vehicle scheduling and charging scheduling studied for a mixed bus



(a) The Transit Network

Bus Scheduling and Charging Scheduling of Line 1

	Start Time	End Time	Scheduled Bus	Charger Number
Trip 1	8:00	9:00	Electric Bus 1	/
Trip 2	8:30	9:30	Electric Bus 2	/
Trip 3	9:00	10:00	Diesel Bus 1	/
Trip 4	9:30	10:30	Electric Bus 1	Charger 1

(b) The Joint Optimization

Fig. 2. Problem Description.

fleet in this paper. Section 3.2 summarizes the assumptions made in this paper and analyzes the rationale for the introduction of these assumptions.

3.1. Problem Description

Based on the public transit network depicted in Fig. 2 (a), which comprises a single depot, multiple transit centers, and multiple lines, this paper investigates the joint optimization of vehicle and charging scheduling for a mixed bus fleet comprising both electric and diesel buses. All electric and diesel buses make stops at the depot both before and after their scheduling. Furthermore, they are refueled with electricity and diesel at the depot. Each line encompasses multiple schedules, each having predefined start and end times (as illustrated in the schedules of Line 1 in Fig. 2 (b)). We refer to a predefined schedule as a “trip”. The challenge of determining which bus should serve each trip is commonly known as the “vehicle scheduling problem”. Importantly, all buses are only allowed to refuel or recharge during the intervals between two trips and are prohibited from doing so during the service period of any given trip. It is worth noting that a single bus can be assigned to serve different lines as time permits. Despite the proximity of chargers and diesel replenishers within the depot, for safety reasons, they are positioned at a relatively significant distance apart. It is worth mentioning that all chargers are of the super-fast variety, as illustrated in Fig. 1. Each super-fast charger is designed to accommodate a single electric bus at a time. Additionally, it is essential to acknowledge that it takes approximately ten times longer for an electric bus to be fully charged compared to the time it takes for a diesel bus to be refilled with diesel. Consequently, this paper primarily focuses on addressing the challenge of electric buses queuing for charging at limited charger stations, a problem referred to as the “charging scheduling problem for electric buses”. Should the reader wish to explore the scenario involving limited diesel replenishers, they can readily extend the aforementioned issue of queuing electric buses for charging to encompass diesel replenishment constraints as well.

3.2. Assumptions

According to the previous research on bus scheduling and charging scheduling, such as Wang et al. (2017), Battaia et al. (2023), Cai et al. (2022), etc., this paper makes the following similar assumptions to simplify the problem:

(1) The schedule of each bus line is pre-designed and cannot be violated;

The design of the bus timetable is extremely complicated and depends on the passenger flow in each time period, the coordination with the timetable of other public transportation such as the subway, and the nature of its public service. The determination of the bus timetable is beyond the research scope of this paper, and readers can refer to related literature, such as Tang et al. (2021), Gkiotsalitis and Alesiani (2019), etc.

(2) All electric buses (diesel buses, respectively) are homogeneous, have the same battery capacity (diesel capacity, respectively) and can be used to serve trips of all lines;

The model needs to explicitly determine the service trip and charging schedule for each bus. Therefore, this assumption can be relaxed by simply adjusting the optimization model.

(3) The charge consumption rate of electric buses and the diesel consumption rate of diesel buses are fixed regardless of lines, trip time, and passenger capacity;

Determining the charge consumption rate of electric buses and the diesel consumption rate of diesel buses is extremely complex. These consumption rates may depend on temperature, acceleration and deceleration of buses, passenger capacity, and so on. These complex factors may cause the nonlinearity of the optimization model. The reader is referred to studies, e.g., Lu et al., (2021a), Li and Wang (2023), McGrath et al. (2022), etc., to consider the nonlinear charge consumption rate.

(4) The charging rate of electric buses is fixed and not related to the remaining charge;

According to Cui et al. (2022), the charging rate decreases when the remaining charge of electric vehicles is close to 80 % of battery capacity. This variable charging rate can cause nonlinearity of the optimization model. Because the battery capacity of electric buses is large and the charging time is long, the variable charging rate can be converted into a constant to simplify the model construction.

(5) Each fast charger can only provide charging service for one electric bus at a time;

If charging piles are connected to multiple chargers to charge multiple electric buses at the same time, it is only necessary to simply construct each charger as an independent charging pile in the model.

(6) Charging time for electric buses and diesel refill times for diesel buses are fixed;

(7) The limit on the number of diesel replenishers is ignored.

Compared with the charging time of electric buses, the charging time of diesel buses is sufficiently short. The limit on the number of diesel replenishers can also be considered similar to the limit on the number of chargers.

4. Model formulation

Building upon the public transit network's framework, which encompasses a single depot, multiple transit centers, and multiple lines, this paper delves into the concurrent optimization of vehicle and charging scheduling for a mixed bus fleet comprising both electric and diesel buses. All electric and diesel buses adhere to a routine of stopping at the depot both prior to and subsequent to their scheduling. They undergo refueling with electricity and diesel at the depot. Each line within the network incorporates multiple schedules, each delineating predefined start and end times. Importantly, all buses are exclusively permitted to refuel or recharge during the intervals separating two trips and are expressly prohibited from doing so within the service period of any given trip. It's worth noting that, for maximum flexibility, a single bus can be assigned to serve different lines based on prevailing scheduling constraints.

A set E of candidate electric buses and a set D of candidate diesel buses are arranged to serve the scheduled bus routes. Any electric bus $e \in E$ has the same battery capacity Q and the same charge consumption rate c_1 during travel. Likewise, any diesel bus $d \in D$ has the same diesel capacity C and the same diesel consumption rate c_2. Let $z_e \in \{0,1\}$ and $z_d \in \{0,1\}$ be binary variables, indicating whether the electric bus $e \in E$ and the diesel bus $d \in D$ are arranged, respectively. If the electric bus $e \in E$ is arranged, $z_e = 1$; otherwise, $z_e = 0$. Similarly, if the diesel bus $d \in D$ is arranged, then z_d equals 1; otherwise, z_d equals 0. Every arrangement of an electric bus or diesel bus will cause different cost due to the loss of vehicles, tires, etc. The service life of either electric or diesel buses is typically 6 to 8 years, so the vehicle attrition deviations are ignored for electric buses and diesel buses.

For safety considerations, diesel replenishers and chargers are located at the depot. The depot is located in different places from transit centers. All buses return to the depot before serving trips and after serving all scheduled trips. We define a complete trip of a bus as departing from a transit center and returning to that transit center. Let i be a trip and I be the set of scheduled trips. Each trip $i \in I$ has a predetermined distance d_i, start time a_i, and end time b_i, which cannot be violated. Any trip $i \in I$ can be served by one diesel bus $d \in D$ and one electric bus $e \in E$. In order to distinguish buses from leaving the depot to start trip services and returning to the depot after completing all services, we set the trip for all buses to depart from the depot to transit centers to start services as 0, and the trip for all buses to return from transit centers to the depot after completing all services as $N+1$. For simplicity, we set $I_0 = I \cup \{0\}$, $I_{N+1} = I \cup \{N+1\}$, and $I_{0,N+1} = I \cup \{0, N+1\}$.

Since buses may travel to and from different transit centers, we define the distances from transit centers to the depot to charge and refuel electric buses and diesel buses as d_i^{dc} and d_i^{dd} through trip i, respectively. For simplicity, we assume that the speed v of buses from transit centers to the depot is the same. The remaining charge of electric bus $e \in E$ and remaining diesel of diesel bus $d \in D$ after completing trip $i \in I$ are denoted as $Q_{i,e}$ and $Q_{i,d}$, respectively. When completing a trip, electric buses and diesel buses can choose whether to go to the depot to replenish charge and replenish diesel. Let $F_{i,e} \in \{0,1\}$ and $F_{i,d} \in \{0,1\}$ be binary variables, which respectively indicate whether the electric bus $e \in E$ and the diesel bus $d \in D$ go to the depot to replenish charge and diesel after completing trip $i \in I$. If the electric bus $e \in E$ (diesel bus $d \in D$, respectively) goes to the depot to replenish charge (diesel, respectively) after completing the service of trip $i \in I$, then $F_{i,e} = 1$ ($F_{i,d} = 1$, respectively); otherwise $F_{i,e} = 0$ ($F_{i,d} = 0$, respectively).

Bus operators usually use fast chargers to charge electric buses to reduce the number of buses scheduled during operation. Although fast charging can replenish 80 % of the electric vehicle's electricity within 15 min, the recharging rate r_1 of electric buses is lower than the refueling rate r_2 of diesel buses. The diesel replenishment rate is extremely fast compared to the charging rate of electric buses. Therefore, without loss of generality, we ignore the limitation on the number of diesel replenishers. Of course, readers can relax this assumption by imitating the way of dealing with the limitation of the number of chargers below. Due to the high cost of fast chargers and the low charging rate compared to diesel replenishers, fast chargers are limited in the depot and need to be queued for use. Let K denote the set of all fast chargers. $k \in K$ represents a charger. To capture the situation of electric buses queuing to use fast chargers, we discretize time into time slot t based on Wang et al. (2017). The time duration τ of each time slot is determined in advance. Let T be the set of all time slots t during the bus operation. Without loss of generality, we let u_1 and u_2 denote the fixed time intervals of each charging and replenishing activity, respectively. Let $Z_{i,t}^{e,k} \in \{0,1\}$ be a binary variable, which represents whether the electric bus $e \in E$ chooses charger $k \in K$ to start recharging at time slot $t \in T$ after completing the service of trip $i \in I$. If the electric bus $e \in E$ chooses charger $k \in K$ to start replenishing charge at time slot $t \in T$ after completing the service of trip $i \in I$, $Z_{i,t}^{e,k} = 1$; otherwise, $Z_{i,t}^{e,k} = 0$.

Let (i,j) represent a trip pair and P represent the set of all feasible trip pairs. Each trip pair $(i,j) \in P$ where trips $i \in I$ and $j \in I$ belongs to the same bus line and can be served successively by the same bus without empty driving between different transit centers. Let P^* be

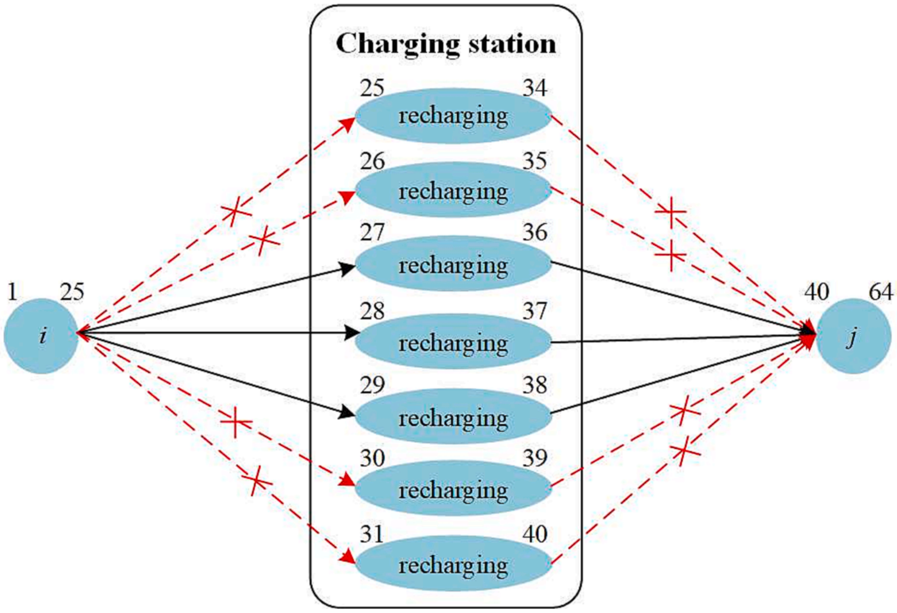


Fig. 3. A Simple Example for Feasible Charging Activities.

an extended set of trip pairs where $i \in I_0$ and $j \in I_{N+1}$. Let $x_{i,j,e} \in \{0,1\}$ and $x_{i,j,d} \in \{0,1\}$ be binary variables respectively indicating whether the trip pair $(i,j) \in P$ is served by electric bus $e \in E$ and diesel bus $d \in D$ in turn. If the trip pair $(i,j) \in P$ is served sequentially by electric bus $e \in E$ (diesel bus $d \in D$, respectively), then $x_{i,j,e} = 1$ ($x_{i,j,d} = 1$, respectively); otherwise $x_{i,j,e} = 0$ ($x_{i,j,d} = 0$, respectively). To avoid affecting the next trip, electric buses and diesel buses could be charged and replenished with diesel during the trip interval $a_j - b_i$ of trip pair $(i,j) \in P$. There are multiple feasible charging activities within the interval of each trip pair. For example, within the trip interval of ten time slots, the charging interval of eight time slots could start at time slots 0, 1, and 2.

We introduce a set A of feasible charging activities to obtain idle chargers. $(i,j,t) \in A$ means that the electric bus that has served trip i starts charging at time slot t before starting to serve trip j. Any t in $(i,j,t) \in A$ satisfies $t \geqslant b_i + d_i^{dc}/v$ and $t + u_1 + d_i^{dc}/v \leqslant a_j$. Through these two restrictions, it is ensured that there is no delay in the service of electric buses for trips. The construction of set A increases the input of the optimization model. However, the set A can on the one hand ensure that electric bus queuing to use limited chargers is integrated into the linearized optimization model and on the other hand reduce decision variables.

Here we explain the advantages of set A through a simple example. For the first aspect, we take a trip interval of 15 time slots and a charging interval of 9 time slots as an example. We assume that trip i whose start time is the first time slot and end time is the 25th time slot and a trip j whose start time is the 40th time slot and end time is the 64th are on the same bus line. The time from the transit center to the chargers in the depot is 2 time slots. We present all charging scenarios in Fig. 3. It can be seen from Fig. 3 that charging from the 27th, 28th and 29th time slots is feasible, and the corresponding elements in the set A are $(i,j,27)$, $(i,j,28)$, and $(i,j,29)$. The available chargers can be filtered and the occupancy time of each charger can be determined through the set A. Therefore, the introduction of set A can consider the situation where electric buses line up to use limited chargers. Next, we discuss the second advantage of introducing set A. The bus lines and timetables are fixed. The optimization model is to assign the appropriate bus for each trip with fixed start time, end time, and distance. The remaining charge and diesel become the main constraint for bus assignment. Although electric buses and diesel buses can only replenish electricity and diesel that are an integral multiple of slot duration τ, the construction of set A avoids introducing new variables to record the time when buses arrive at chargers and the time when charging begins.

The mixed integer linear programming model for the joint optimization of bus scheduling and recharging scheduling for the operator with mixed electric buses and diesel buses is constructed as follows:

$$\min \sum_{i \in I_{0,N+1}} \sum_{e \in E} (\alpha_0 + \alpha_1 r_1 u_1) F_{i,e} + \sum_{i \in I_{0,N+1}} \sum_{d \in D} (\alpha_2 + \alpha_3 r_2 u_2) F_{i,d} \tag{1}$$

$$\sum_{j \in I_{N+1}} \sum_{e \in E} x_{i,j,e} + \sum_{j \in I_{N+1}} \sum_{d \in D} x_{i,j,d} = 1 \forall i \in I \tag{2}$$

$$\sum_{(i,j) \in P} x_{i,j,e} \leqslant z_e M \forall e \in E \tag{3}$$

$$\sum_{(i,j) \in P} x_{i,j,d} \leqslant z_d M \forall d \in D \tag{4}$$

$$\sum_{e\in E} z_e \leqslant |E| \tag{5}$$

$$\sum_{d\in D} z_d \leqslant |D| \tag{6}$$

$$F_{i,e} \leqslant \sum_{j\in I_{N+1}} x_{i,j,e} \forall i \in I e \in E \tag{7}$$

$$F_{i,d} \leqslant \sum_{j\in I_{N+1}} x_{i,j,d} \forall i \in I d \in D \tag{8}$$

$$x_{i,j,e} Q_{\min} \leqslant Q_{j,e} \leqslant Q_{i,e} + (r_1 u_1 - d_i^{dc} c_1) F_{i,e} - c_1 d_j x_{j,e} + Q(1 - x_{i,j,e}) \forall (i,j) \in P^* e \in E \tag{9}$$

$$x_{i,j,d} C_{\min} \leqslant Q_{j,d} \leqslant Q_{i,d} + (r_2 u_2 - d_i^{dd} c_2) F_{i,d} - c_2 d_j x_{j,d} + C(1 - x_{i,j,d}) \forall (i,j) \in P^* d \in D \tag{10}$$

$$Q_{i,e} + (r_1 u_1 - d_i^{dc} c_1) F_{i,e} \leqslant Q \forall i \in I e \in E \tag{11}$$

$$Q_{i,d} + (r_2 u_2 - d_i^{dd} c_2) F_{i,d} \leqslant C \forall i \in I d \in D \tag{12}$$

$$\sum_{k\in K} \sum_{t:(i,j,t)\in A} Z_{i,t}^{e,k} = F_{i,e} \forall i \in I e \in E \tag{13}$$

$$\sum_{e\in E} \sum_{i:(i,j,t')\in A} \sum_{t'=t-u_1+1}^{t} Z_{i,t'}^{e,k} \leqslant 1 \forall k \in K \tag{14}$$

$$F_{i,d}\left(b_i + 2d_i^{dd}/v + u_2\right) \leqslant x_{i,j,d} a_j + T(1 - x_{i,j,d}) \forall (i,j) \in P^* d \in D \tag{15}$$

$$z_e \in \{0,1\} \forall e \in E \tag{16}$$

$$z_d \in \{0,1\} \forall d \in D \tag{17}$$

$$F_{i,e} \in \{0,1\} \forall i \in I_{0,N+1} e \in E \tag{18}$$

$$F_{i,d} \in \{0,1\} \forall i \in I_{0,N+1} d \in D \tag{19}$$

$$Z_{i,t}^{e,k} \in \{0,1\} \forall i \in I_{0,N+1} k \in K e \in E t \in T \tag{20}$$

$$x_{i,j,e} \in \{0,1\} \forall i \in I_0 j \in I_{N+1} e \in E \tag{21}$$

$$x_{i,j,d} \in \{0,1\} \forall i \in I_0 j \in I_{N+1} d \in D \tag{22}$$

The objective function Eq. (1) is to minimize the trip service cost, which includes the electricity cost $\sum_{i\in I_{0,N+1}} \sum_{e\in E} (\alpha_0 + \alpha_1 r_1 u_1) F_{i,e}$ of all electric buses and the diesel cost $\sum_{i\in I_{0,N+1}} \sum_{d\in D} (\alpha_2 + \alpha_3 r_2 u_2) F_{i,d}$ of all diesel buses. α_0 represents the fixed cost of performing a charge. α_1 denotes the unit electricity cost. α_2 represents the fixed cost of performing a diesel replenishment. α_3 stands for the unit diesel cost. Usually, fast chargers have higher implementation cost, so α_0 is higher than α_2. The unit electricity cost α_1 is usually lower than the unit diesel cost α_3. Eq. (2) means that any trip $i \in I$ must be served but not restricted to be served by electric buses $e \in E$ or diesel buses $d \in D$.

Eq. (3) and Eq. (4) are used to determine whether electric bus $e \in E$ and diesel bus $d \in D$ are scheduled for service, respectively. M is a constant whose value can be set to any value greater than the total number $|I|$ of trips. $|\cdot|$ represents the number of elements in the set. Eq. (5) and Eq. (6) ensure that the number of candidate electric buses and the number of candidate diesel buses are limited, respectively. Eq. (7) and Eq. (8) respectively indicate that electric bus $e \in E$ and diesel bus $d \in D$ can choose to charge electricity and supplement diesel after completing trip $i \in I$.

The constraint on the right side of Eq. (9) (Eq. (10), respectively) is used to ensure the relationship between the remaining charge $Q_{i,e}$ and $Q_{j,e}$ (the remaining diesel $Q_{i,d}$ and $Q_{j,d}$, respectively) when the electric bus $e \in E$ (diesel bus $d \in D$, respectively) serves a trip pair $(i,j) \in P^*$. The constraint on the left side of Eq. (9) (Eq. (10), respectively) is used to ensure that there should be remaining charge $Q_{\min}$ (remaining diesel $C_{\min}$, respectively) after the electric bus $e \in E$ (diesel bus $d \in D$, respectively) completes a trip $j \in I_{N+1}$. The remaining charge and diesel limits can avoid the situation that the trip cannot be completed due to excessive charge (diesel, respectively) consumption caused by factors such as weather, temperature, or vehicle load. These uncertain factors above usually have a greater impact on the charge, so the value of $Q_{\min}$ is usually greater than $C_{\min}$.

Eq. (11) (Eq. (12), respectively) ensures that the remaining charge $Q_{i,e}$ (the remaining diesel $Q_{i,d}$, respectively) of electric bus $e \in E$

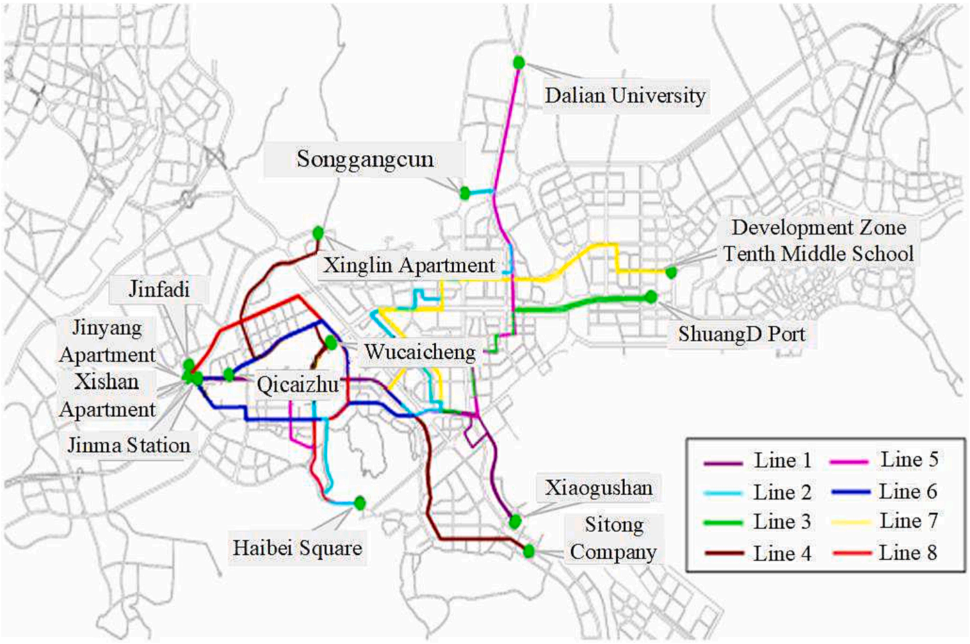


Fig. 4. The Transit Network in Dalian Economic Development Zone, China.

Table 1
Line information.

Lines	Start points	End points	Distance (*km*)	Trip time (*min*)	Total number of trips
Line 1	Xiaogushan	Jinfadi	13.1	43	155
Line 2	Haibei Square	Songgangcun	18.9	64	111
Line 3	Xishan Apartment	ShuangD Port	12.4	42	184
Line 4	Xinglin Apartment	Sitong Company	14.9	47	186
Line 5	Haibei Square	Dalian University	15.6	53	184
Line 6	Qicaizhu	Jinma Station	11.5	35	106
Line 7	Wucaicheng	Development Zone Tenth Middle School	12.9	41	186
Line 8	Haibei Square	Jinyang Apartment	15.7	57	112

(diesel bus $d \in D$, respectively) plus the charged energy at the depot does not exceed the battery capacity Q (the diesel capacity C). Eq. (13) establishes the relationship between $F_{i,e}$ and $Z_{i,t}^{e,k}$ to ensure that if electric bus $e \in E$ arrives at the depot for recharging after trip $i \in I$ is completed, then there must be a feasible time slot t and charger $k \in K$ such that $Z_{i,t}^{e,k} = 1$; otherwise, all $Z_{i,t}^{e,k} = 0$. Eq. (14) ensures that one charger $k \in K$ is allowed to provide charging service for at most one electric bus at the same time. Eq. (15) ensures that diesel bus refueling cannot violate the predetermined start time of the served trip. Eqs. (16) to (22) ensure that the relevant variables are binary variables.

5. Numerical simulations

This section conducts numerical simulations on the bus lines in Dalian Economic Development Zone, China. Section 5.1 describes the bus transit network and parameter settings. Section 5.2 presents the basic test results. Section 5.3 conducts sensitivity analyses.

5.1. Simulation settings

In this section, the mixed integer linear model in Section 4 is tested by taking the 8 bus lines in Dalian Economic Development Zone of China shown in Fig. 4 as an example. The start point, end point, line length and single trip time of each line are shown in Table 1. The battery capacity Q of electric buses is $160kWh$ and the charge consumption rate c_1 is $0.8kWh/km$. Diesel buses have a diesel capacity C of $100L$ and have a consumption rate c_2 of $0.3L/km$. Electric buses are charged at a rate r_1 of $2.4kWh/min$, while diesel buses are replenished with diesel at a rate r_2 of $30L/min$. The time duration τ of each time slot is $1min$. The time interval u_1 of each charging activity is 15 time slots, while the time interval u_2 of each replenishing activity is 3 time slots.

The fixed cost of performing a charge is $1.5CNY$, and the unit electricity cost is $0.7CNY/kWh$. The fixed cost of performing a diesel

Table 2
The results of bus scheduling.

	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8
NT-EB	121	90	153	136	149	85	155	95
NT-DB	34	21	31	50	35	21	31	17
Total cost (CNY)	4252.04	3902.62	4217.24	6073.44	5602.36	2494.02	5592.02	3223.96

Notes: NT-EB denotes the number of trips served by electric buses and NT-DB denotes the number of trips served by diesel buses.

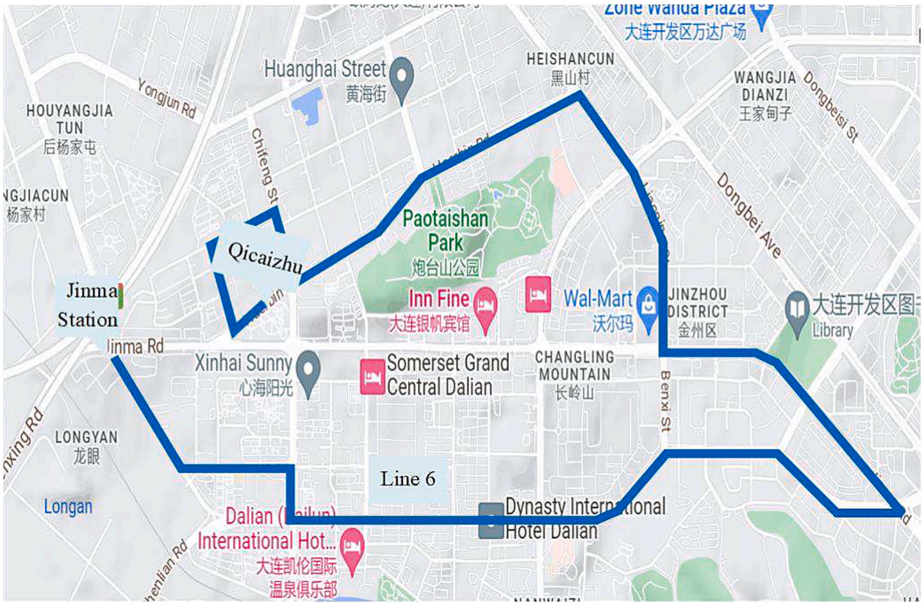


Fig. 5. The Route of Line 6.

Table 3
The scheduled electric bus for each trip on Line 6.

Electric Bus No.	Served trips
1	2 → 15 → 29 → 38 → 47 → 56 → 65 → **74** → 90 → 104
2	6 → 23 → 33 → 42 → 51 → 60 → 69 → **80** → 98→
3	10 → 27 → 36 → 45 → 54 → **63** → 72 → **86** → 102
4	1 → 13 → 28 → 37 → 46 → 55 → 64 → **73** → 88 → 103
5	7 → 25 → 34 → 43 → 61 → 70 → **82** → 100→
6	3 → 17 → 30 → 39 → 48 → 52 → 57 → **66** → 75 → 92 → 105
7	5 → 21 → 32 → 41 → 50 → 59 → 68 → **78** → 96
8	8 → 26 → 35 → 44 → 53 → 62 → 71 → **84** → 101
9	4 → 19 → 31 → 40 → 49 → 58 → **67** → 76 → 94 → 106

replenishment is $1CNY$, and the unit diesel cost is $7.3CNY/L$. According to the introduction of the model construction in Section 4, the infinite number M can take any value greater than the total number of trips, so based on Table 1, M takes the value of 1225. Since the charge consumption rate of electric buses is greatly affected by factors such as temperature and vehicle acceleration, the remaining minimum charge limit $Q_{\min}$ of electric buses is set to 30 % of battery capacity Q, i.e., the remaining minimum charge limit $Q_{\min}$ takes the value of $48kWh$. The minimum diesel limit $C_{\min}$ of diesel buses is set at 10 % of the total diesel capacity C, i.e., the minimum diesel limit $C_{\min}$ takes the value of $10L$.

5.2. Basic results

The results regarding the number of trips conducted by electric buses and diesel buses on each route are presented in Table 2. It is evident from Table 2 that electric buses outperform diesel buses in terms of the number of trips conducted on each route. Specifically, electric buses account for 80.40 % of the total number of trips, which represents a logical and justifiable outcome. This observation can be attributed to the fact that the objective function in Section 4 exclusively considers travel costs, with electricity prices significantly lower than diesel prices. This outcome is particularly advantageous for the existing mixed bus fleet, which faces constraints related to

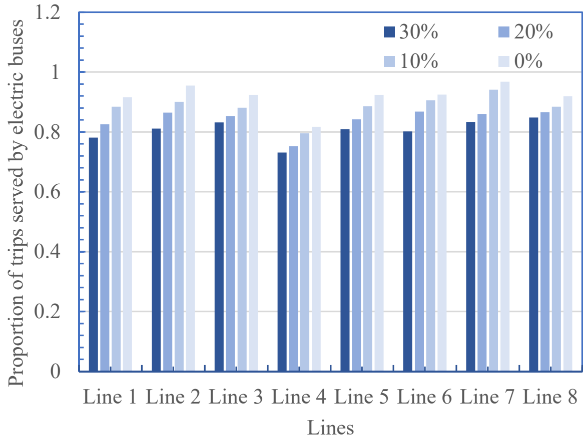


Fig. 6. The Proportion of Trips Served by Electric Buses Under Different Minimum Remaining Charge Limits.

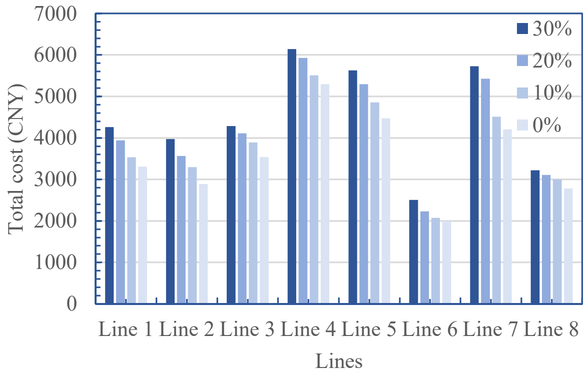


Fig. 7. The Total Cost Under Different Minimum Remaining Charge Limits.

limited electric buses and an abundance of diesel-powered buses. Given the substantial upfront costs associated with electric bus purchases and charger infrastructure construction, it is anticipated that a persistent shortage of electric buses will persist within the mixed bus fleet over the long term. Therefore, the methodology proposed in this paper serves as an effective means of enhancing the efficient utilization of electric buses in mixed fleets with limited electric bus availability.

In order to investigate the factors influencing the scheduling of electric buses and diesel buses and to analyze the resulting scheduling schemes, this section employs Line 6 as a case study to validate the reliability of the simulation results. The route of Line 6 is illustrated in Fig. 5, and the scheduling outcomes are presented in Table 3. Notably, text displayed in bold font signifies the initial trip undertaken by electric buses after returning to the depot for recharging. As exemplified by electric bus 1 in Table 3, it commences its service near the Qicaizhu station's starting point and consecutively serves trips 2, 15, 29, 38, 47, 56, 65, 74, 90, and 104, before concluding its operations by returning to the depot. It is worth noting that many electric buses follow a similar pattern of returning to the depot for recharging after completing multiple trips, subsequently resuming service for the next scheduled trip.

A fully charged electric bus has the capacity to complete seven trips along Line 6. However, in practical operations, certain electric buses only manage to complete five or six trips before necessitating a return to the depot for recharging. Under optimal conditions, each electric bus should strictly adhere to a charging regimen that entails replenishing their charge after every seven trips. Although this approach optimally utilizes battery capacity, it results in all electric buses converging on the charging stations just prior to the evening peak period. This charging pattern not only places increased strain on the charging infrastructure but also poses challenges for bus operator scheduling. Through the implementation of vehicle and charging scheduling optimization, electric bus 2 returns to the depot for charging after completing five trips, whereas electric buses 6 and 9 return for recharging after accomplishing six trips. This approach leads to a more evenly distributed charging schedule for all electric buses. By ensuring that buses are recharged before their batteries are fully depleted, this strategy adequately meets operational demands during peak hours, effectively alleviating pressure on the charging stations and providing greater flexibility in charging options.

5.3. Sensitivity analyses

In this section, sensitivity analyses are conducted to further assess the model's effectiveness in promoting electric buses for trip

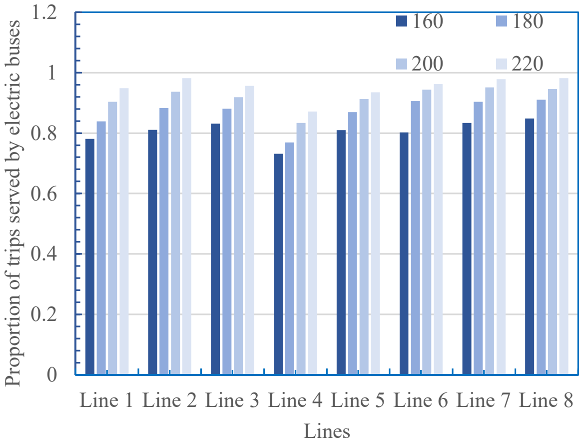


Fig. 8. The Proportion of Trips Served by Electric Buses Under Different Battery Capacity.

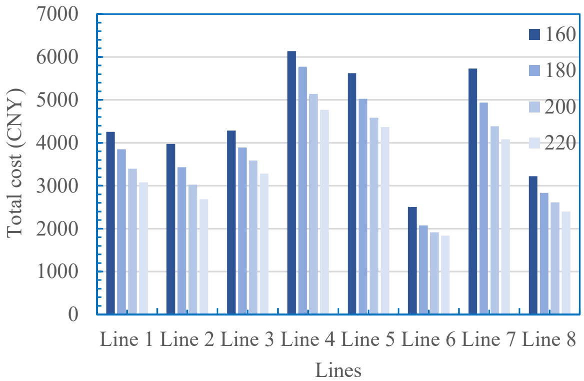


Fig. 9. The Total Cost Under Different Battery Capacity.

service. The establishment of a minimum remaining charge limit for electric buses is necessitated by the significant influence of factors such as temperature, acceleration, and deceleration on the current rate of charge consumption. As battery technology continues to advance, the charge consumption rate is expected to stabilize, allowing for a reduction in the minimum remaining charge limit. Lowering this limit for electric buses can facilitate the completion of more trips on a single charge before necessitating a return to charging stations for recharge. Consequently, this section investigates the impact of various minimum remaining charge limit settings—specifically, 30 %, 20 %, 10 %, and 0 % of battery capacity—through sensitivity analysis.

The proportion of trips served by electric buses under various minimum remaining charge limits is illustrated in Fig. 6, while Fig. 7 displays the corresponding total costs. It is evident from Figs. 6 and 7 that as the minimum remaining charge limit decreases, the proportion of trips handled by electric buses on each route gradually increases, while the total costs gradually decrease. Notably, the most significant increase in the proportion of trips served by electric buses is observed on Line 2, reaching an impressive 14.4 %. In contrast, Line 8 exhibits the smallest increase, with a rise of 7.1 %. Line 2 also experiences the most substantial reduction in total costs, amounting to 27.3 %, whereas Line 8 demonstrates the least reduction, at 13.7 %. Further observations from Figs. 6 and 7 indicate that as the minimum remaining charge limit decreases, both the proportion of trips conducted by electric buses and the extent of cost reduction gradually diminish. This outcome aligns with expectations. It underscores the importance of enhancing the stability of charge consumption rates and reducing the minimum remaining charge limit to promote the usage rate of electric buses for trip services.

The increase in battery capacity can intuitively increase the number of trips served by fully charged electric buses before returning to the charging station for recharging. With the improvement of battery technology, the battery capacity will gradually increase. Therefore, this section selects battery capacities of $160kWh$, $180kWh$, $200kWh$ and $220kWh$ for sensitivity analysis. The proportion of trips served by electric buses with varying battery capacities is depicted in Fig. 8, while Fig. 9 presents the corresponding total costs. Notably, Fig. 8 reveals that Line 2 experiences the most substantial increase in the proportion of trips served by electric buses, with a remarkable 17.1 % rise, and Line 3 also sees a substantial increase of 12.5 %. Examining Fig. 9, we find that the most significant total cost reduction occurs on Line 2, amounting to 32.4 %, while the smallest reduction is observed on Line 4, at 22.3 %.

Upon comparing Figs. 6 to 9, it becomes evident that increasing battery capacity proves to be a more effective means of promoting the utilization of electric buses for trips than reducing the minimum remaining charge limit. However, it's essential to acknowledge that augmenting battery capacity can lead to increased vehicle weight, subsequently elevating the charge consumption rate. Additionally, large battery capacities can pose greater operational risks for electric buses navigating urban roads. Consequently, it is advisable to effectively promote electric buses by judiciously increasing battery capacity while simultaneously reducing the minimum remaining charge limit.

6. Conclusion

Electric buses play a pivotal role in mitigating environmental pollution and reducing travel costs. Consequently, numerous countries are fervently promoting the widespread adoption of electric buses. However, the high procurement costs associated with electric buses, coupled with elevated battery expenses and substantial charging station construction outlays, impede the immediate replacement of diesel buses by their electric counterparts. Many countries will continue to face a shortage of electric buses and an abundance of diesel buses for the foreseeable future. Thus, finding ways to enhance the utilization of electric buses for trip services, despite limited charging infrastructure and electric bus availability, becomes a pivotal strategy for advancing electric bus adoption. In this study, a mixed-integer linear model is developed to concurrently address vehicle scheduling and charging scheduling problems in the context of constrained charging resources. The model effectively resolves the challenge of electric buses queuing for charging under limited charger availability by devising a set of feasible charging activities. Through numerical simulations conducted within the bus transit network of the Dalian Economic Development Zone, we demonstrate the efficacy of the proposed model. The results unequivocally affirm that the model outlined in this paper serves as a potent tool for promoting and popularizing electric buses.

In the future, this paper will be further extended from the following aspects: (1) Variable charging intervals are worth studying to further improve the utilization of limited chargers; (2) The charging rate related to the remaining battery charge should be considered to enable electric buses to choose charging time more effectively; (3) The charge consumption rate related to temperature and passenger capacity should be considered so that the scheduling of electric buses and charging scheduling can take into account the differences in the three different time periods of morning, noon, and evening.

CRediT authorship contribution statement

Shaohua Cui: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Kun Gao:** Conceptualization, Supervision, Validation, Writing – review & editing. **Bin Yu:** Conceptualization, Supervision, Software, Validation. **Zhenliang Ma:** Resources, Validation, Writing – review & editing. **Arsalan Najafi:** Formal analysis, Methodology, Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research is supported by National Natural Science Foundation of China (52225209) , Energimyndigheten and JPI Urban Europe through e-MATS project (P2023-00029).

References

Battaia, O., Dolgui, A., Guschinsky, N., Kovalyov, M. Y., 2023. Designing fast-charge urban electric bus services: An Integer Linear Programming model. Transport. Res. Part E: Logist. Transport. Rev., 171, Art. no. 103065.

Borén, S., 2020. Electric buses' sustainability effects, noise, energy use, and costs. Int. J. Sustain. Transp. 14 (12), 956–971.

Cai, M., Mo, D., Geng, M. S., Tang, W., Chen, X. M., 2022. Integrating ride-sourcing with electric vehicle charging under mixed fleets and differentiated services. Transportation Research Part E: Logistics and Transportation Review, 169, Art. no. 102965.

Ceder, A., 2011. Optimal multi-vehicle type transit timetabling and vehicle scheduling. Procedia Soc. Behav. Sci. 20, 19–30.

Chen, Q., Wang, Q., Zhou, D., Wang, H., 2023. Drivers and evolution of low-carbon development in China's transportation industry: An integrated analytical approach. Energy, 262, Art. no. 125614.

Cui, S. H., Yao, B. Z., Chen, G., Zhu, C., Yu, B., 2020. The multi-mode mobile charging service based on electric vehicle spatiotemporal distribution. Energy, 198, Art. no. 117302.

Cui, S. H., Ma, X. L., Zhang, M. H., Yu, B., Yao, B. Z., 2022. The parallel mobile charging service for free-floating shared electric vehicle clusters. Transportation Research Part E: Logistics and Transportation Review, 160, Art. no. 102652.

Cui, S.H., Xue, Y.J., Gao, K., Lv, M.L., Yu, B., 2023. Adaptive collision-free trajectory tracking control for string stable bidirectional platoons. IEEE Transactions on Intelligent Transportation Systems, Doi,. https://doi.org/10.1109/TITS.2023.3286587.

Donmez, S., Koc, C., Altiparmak, F., 2022. The mixed fleet vehicle routing problem with partial recharging by multiple chargers: Mathematical model and adaptive large neighborhood search. Transportation Research Part E: Logistics and Transportation Review, 167, Art. no. 102917.

Ercan, T., Yang, Z., Tatari, O., Pazour, J.A., 2015. Optimization of transit bus fleet's life cycle assessment impacts with alternative fuel options. Energy 93 (1), 323–334.

Gao, K., Yang, Y., Qu, X., 2021. Diverging effects of subjective prospect values of uncertain time and money. Communication in Transportation Research 1, 100007.

Gao, K., Yang, Y., Gil, J., Qu, X., 2023. Data-driven Interpretation on interactive and nonlinear effects of the correlated built environment on shared mobility. J. Transp. Geogr. 110, 103604.

Gkiotsalitis, K., Alesiani, F., 2019. Robust timetable optimization for bus lines subject to resource and regulatory constraints. Transportation Research Part E: Logistics and Transportation Review 128, 30–51.

Gkiotsalitis, K., Berkum, W. C. V., 2020. An analytic solution for real-time bus holding subject to vehicle capacity limits. Transportation Research Part C: Emerging Technologies, 121, Art. no. 102815.
He, Y., Liu, Z.C., Song, Z.Q., 2022. Integrated charging infrastructure planning and charging scheduling for battery electric bus systems. Transp. Res. Part D: Transp. Environ. 111, Art. no 103437.
Hu, H., Du, B., Liu, W., Perez, P., 2022. A joint optimisation model for charger locating and electric bus charging scheduling considering opportunity fast charging and uncertainties. Transportation Research Part C: Emerging Technologies, 141, Art. no. 103732.
Hu, X., Yang, Z. J., Sun, J., Zhang, Y. L., 2023. Optimal pricing strategy for electric vehicle battery swapping: Pay-per-swap or subscription? Transportation Research Part E: Logistics and Transportation Review, 171, Art. no. 103030.
Hu, B., Li, J.X., 2022. A deployment-efficient energy management strategy for connected hybrid electric vehicle based on offline reinforcement learning. IEEE Trans. Ind. Electron. 69 (9), 9644–9654.
Ji, J., Bie, Y. M., Zeng, Z., Wang, L., 2022. Trip energy consumption estimation for electric buses. Communication in Transportation Research, 2, Art. no. 100069.
Lajunen, A., 2014. Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transportation Research Part C: Emerging Technologies 38, 1–15.
Li, J.Q., 2016. Battery-electric transit bus developments and operations: A review. Int. J. Sustain. Transp. 10 (3), 157–169.
Li, K. P., Wang, L., 2023. Optimal electric vehicle subsidy and pricing decisions with consideration of EV anxiety and EV preference in green and non-green consumers. Transportation Research Part E: Logistics and Transportation Review, 170, Art. no. 103010.
Li, L., Hong, K.L., Xiao, F., Cen, X., 2016b. Mixed bus fleet management strategy for minimizing overall and emissions external costs. Transp. Res. Part D: Transp. Environ. 60, 104–118.
Li, S., Huang, Y., Mason, S.J., 2016a. A multi-period optimization model for the deployment of public electric vehicle charging stations on network. Transportation Research Part c: Emerging Technologies 65, 128–143.
Liu, Y. H., Zuo, X. Q., Ai, G. Q., Zhao, X. C., 2023. A construction-and-repair based method for vehicle scheduling of bus line with branch lines. Computers & Industrial Engineering, 178, Art. no. 109103.
Lu, L., Hong, K.L., Wei, H., Feng, X., 2021a. Mixed bus fleet location-routing-scheduling under range uncertainty. Transp. Res. B Methodol. 146, 155–179.
Lu, T., Yao, E., Zhang, Y., Yang, Y., 2021b. Joint optimal scheduling for a mixed bus fleet under micro driving conditions. IEEE Trans. Intell. Transp. Syst. 22 (4), 2464–2475.
McGrath, T., Blades, L., Early, J., Harris, A., 2022. UK battery electric bus operation: Examining battery degradation, carbon emissions and cost. Transp. Res. Part D: Transp. Environ. 109.
Pan L., Sun Y. W., 2014. Study on vehicle scheduling algorithm in distribution step. 9th IEEE International Conference on Computer Science and Education, 659-662.
Peña, D., Tchernykh, A., Nesmachnow, S., Massobrio, R., Drozdov, A., Y., Garichev, S. N., 2017. Multiobjective vehicle type and size scheduling problem in urban public transport using MOCell. International Conference on Engineering and Telecommunication, 110-113.
Prata, B.A., 2015. A hybrid Genetic Algorithm for the vehicle and crew scheduling in mass transit systems. IEEE Lat. Am. Trans. 13 (9), 3020–3025.
Qu, X., Wang, S., Niemeier, D., 2022. On the urban-rural bus transit system with passenger-freight mixed flow. Communication. Transp. Res. 2.
Ribau, J.P., Sousa, J.M.C., Silva, C.M., 2015. Reducing the carbon footprint of urban bus fleets using multi-objective optimization. Energy 93 (1), 1089–1104.
Rogge, M., Hurk, E.V.D., Larsen, A., Sauer, D.U., 2018. Electric bus fleet size and mix problem with optimization of charging infrastructure. Appl. Energy 211, 282–295.
Rupp, M., Rieke, C., Handschuh, N., Kuperjans, I., 2020. Economic and ecological optimization of electric bus charging considering variable electricity prices and CO2eq intensities. Transp. Res. Part D: Transp. Environ. 81.
Santos, D., Kokkinogenis, Z., de Sousa J. F., Perrotta, D., Rossetti, R. J. F., 2016. Towards the integration of electric buses in conventional bus fleets. 19th IEEE International Conference on Intelligent Transportation Systems, 88-93.
Shao, S., Tan, Z.J., Liu, Z.Y., Shang, W.L., 2022. Balancing the GHG emissions and operational costs for a mixed fleet of electric buses and diesel buses. Appl. Energy 328.
Shen, Y., Xu, J., Li, J., 2016. A probabilistic model for vehicle scheduling based on stochastic trip times. Transp. Res. B Methodol. 85, 19–31.
Soltanpour, A., Ghamami, M., Nicknam, M., Ganji, M., Tian, W., 2022. Charging infrastructure and schedule planning for a public transit network with a mixed fleet of electric and diesel buses. Transportation Research Record: Journal of the Transportation Research Board. 2677 (2), 1053–1071.
Tang, J.J., Yang, Y.F., Hao, W., Wang, Y.H., 2021. A data-driven timetable optimization of urban bus line based on multi-objective genetic algorithm. IEEE Trans. Intell. Transp. Syst. 22 (4), 2417–2429.
Tsang, M.Y., Shehadeh, K.S., 2023. Stochastic optimization models for a home service routing and appointment scheduling problem with random travel and service times. Eur. J. Oper. Res. 307 (1), 48–63.
Utomo, D.S., Gripton, A., Greening, P., 2021. Analysing charging strategies for electric LGV in grocery delivery operation using agent-based modelling: An initial case study in the United Kingdom. Transportation Research Part e: Logistics and Transportation Review 148.
Wang, Y.S., Huang, Y.X., Xu, J.P., Barclay, N., 2017. Optimal recharging scheduling for urban electric buses: A case study in Davis. Transportation Research Part e: Logistics and Transportation Review 100, 115–132.
Wu, W., Lin, Y., Liu, R., Jin, W., 2022. The multi-depot electric vehicle scheduling problem with power grid characteristics. Transp. Res. B Methodol. 155, 322–347.
Xie, D.F., Yu, Y.P., Zhou, G.J., Zhao, X.M., Chen, Y.J., 2023. Collaborative optimization of electric bus line scheduling with multiple charging modes. Transp. Res. Part D: Transp. Environ. 114.
Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., Silveira, S., 2017. Locating charging infrastructure for electric buses in Stockholm. Transportation Research Part c: Emerging Technologies 78, 183–200.
Yang, M., Zhang, L., Dong, W., 2020. Economic benefit analysis of charging models based on differential electric vehicle charging infrastructure subsidy policy in China. Sustain. Cities Soc. 59.
Yao, B., Cui, H., Zhong, Q., Shi, B., Xue, Y., Cui, S., 2023. Dynamic pricing for mobile charging service considering electric vehicles spatiotemporal distribution. KES-STS 2023: Smart Innovation. Systems and Technologies 356, 22–33.
Zeng, Q.H., He, L.Y., 2023. Study on the synergistic effect of air pollution prevention and carbon emission reduction in the context of “dual carbon”: Evidence from China’s transport sector. Energy Policy 173.
Zeng, Z.L., Wang, S.A., Qu, X.B., 2022. On the role of battery degradation in en-route charge scheduling for an electric bus system. Transportation Research Part e: Logistics and Transportation Review 161.
Zhang, L., Zeng, Z., Qu, X., 2020. On the role of battery capacity fading mechanism in the lifecycle cost of electric bus fleet. IEEE Trans. Intell. Transp. Syst. 22 (4), 2371–2380.
Zhang, L., Wang, S., Qu, X., 2021. Optimal electric bus fleet scheduling considering battery degradation and nonlinear charging profile. Transportation Research Part e: Logistics and Transportation Review 154, 102445.
Zhang, L., Zeng, Z., Gao, K., 2022. A bi-level optimization framework for charging station design problem considering heterogeneous charging modes. Journal of Intelligent and Connected Vehicles 5 (1), 8–16.
Zhou, Y., Meng, Q., Ong, G.P., 2022. Electric bus charging scheduling for a single public transport route considering nonlinear charging profile and battery degradation effect. Transp. Res. B Methodol. 159, 49–75.