

Article

Optimal Design for a Shared Swap Charging System Considering the Electric Vehicle Battery Charging Rate

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Abstract: Swap charging (SC) technology offers the possibility of swapping the batteries of electric vehicles (EVs), providing a perfect solution for achieving a long-distance freeway trip. Based on SC technology, a shared SC system (SSCS) concept is proposed to overcome the difficulties in optimal swap battery strategies for a large number of EVs with charging requests and to consider the variance in the battery charging rate simultaneously. To realize the optimal SSCS design, a binary integer programming model is developed to balance the tradeoff between the detour travel cost and the total battery recharge cost in the SSCS. The proposed method is verified with a numerical example of the freeway system in Guangdong Province, China, and can obtain an exact solution using off-the-shelf commercial solvers (e.g., Gurobi).

Keywords: shared swap charging system; electric vehicle; operational design; battery charging rate; binary integer programming

1. Introduction

Electric vehicles (EVs) are a promising technology for reducing the environmental impacts of road transport [1] and have increased rapidly in number over the past ten years [2]. However, there are several barriers to overcome for expanding the adoption of EVs. One problem with large-scale EV adoption is the limited maximum driving range [3,4] and range anxiety [5–8], which may make it difficult to complete some long-distance tours. The other problems are high battery purchase cost [9–11] and long charging time [11–13]. To solve the problems above, an increasing number of researchers have focused on deploying EV charging systems, which will significantly shape current EV coverage [10,14]. These infrastructures can generally be divided into three categories [15]: plug-in EVs (PEVs, i.e., slow chargers and fast chargers) [16], wireless charging EVs (WCEVs, i.e., inductive charging during driving) [17,18], and swap charging EVs (SCEVs) [19,20]. Table 1 shows the comparisons between these infrastructures.

Table 1. EV charging infrastructure comparisons.

EV Type	Charging Mode	Power Refill Rate *	Infrastructure Cost	Operation Cost	Usage Scenarios **	Advantages	Disadvantages
PEV	Slow charging	30–75 miles/h	L	L	Home/workplace	Cheap and safe	Long charging time
	Rapid charging	180 miles/h	H	M	Public charging stations	Charge rapidly; not very expensive	Long charging time; powerful cooling systems required
WCEV	Dynamic charging	–	VH	VH	Designed to use on heavy load traffic corridor/ freeway	Charging while moving; without range anxiety	Extremely high investment cost
	Static charging	20 to 100 miles/h	H	H	Public charging stations	Wireless	Long charging time
SCEV	Centralized battery charging	Swap time can be less than a minute	M	M	Public swap charging stations	Shorten charge time sharply; centralized charging	Battery ownership, purchase cost, standardization, and safety issues in the swap and charge process

* The power refill rate is the travel distance that the EV can travel after an hour of charging. The slow charging at home wall box (7 kW) would take 9 h 25 min from 0–100%. A public charger (22 kW) provides 75 miles of driving range in 1 h of charging. The charging rate of the rapid charger (50 kW or more) can provide up to 90 miles of driving range in 30 min. ** Most often used in these proposed scenarios, other scenarios are omitted due to limited space. Cost abbreviations: L—low; M—medium; H—high; VH—very high. Abbreviations: EV—electric vehicle; PEV—plug-in EV; SCEV—swap charging EV; WCEV—wireless charging EV. Data source: the Renault website of <https://www.renault.co.uk/electric-vehicles/>, the NIO website of <https://www.nio.com/nio-power>, and the WIRED website of <https://www.wired.com/>.

Battery swap stations (BSSs) were originally implemented by the company Better Place, which went out of business in 2013 [15]. Then, five cities in China start testing BSS technology, where they serve personal vehicles, and commercial vehicles [21]. Although BSSs best replicate the experience of existing gas stations, there are still issues that prevent their wide-scale implementation. These include battery ownership, high battery purchase cost, complicated battery standardization issues, and safety issues in the swap and charge process. Since not only do an increasing number of EV consumers expect charging approaches that include short charging times (similar to refueling their current fuel vehicles) [22], but also global economic growth means more people can afford high-cost options, the SCEV mode is becoming increasingly popular [4,19,23–25]. SCEVs are good in that they have both fast and economical charging modes [4,26,27]. As shown in Figure 1, a driver can drive into a battery swap station, and a robot replaces the depleted battery with a fully charged spare [28,29]. This swap time could be very short (e.g., less than one minute based on a report from Tesla) with further automation and refinements on the vehicle [30].



Figure 1. Battery swap automation and refinements on the vehicle (figure source: SUN mobility and Tesla).

Swap charging (SC) can reduce the peak consumption of electricity by centralized charging [30,31] and avoid grid overloading due to mass EV charging [32] because the empty batteries that are swapped out can be charged when electricity is cheap or demand is low. Since SCEVs are considered to be a suitable EV mode, an increasing number of studies on the SC system (SCS) have emerged worldwide [4,19,25,27,33]. The Fluence Z.E. was the first electric car enabled with battery swapping technology and deployed within the Better Place network in Israel and Denmark in 2012 [4,20,27]. Then, with the advanced SC technology, fully automatic battery swapping was even faster than refueling at gas stations. NIO proposed the smallest power swap station in the world which only took up three parking spaces [2,31]. Based on these state-of-the-art battery swapping technologies' tests, some researchers have proposed an advanced concept called shared SCS (SSCS) [31]. The SSCS is an SCS that can provide heterogeneous services and requires online reservations in advance. The SSCS has a lot of differences from the regular SCS mode, and the comparisons are shown in Table 2.

The SCS and the SSCS proposed in this paper are both used for SCEVs, which separate the batteries from the vehicles and allow the SC mode. The SSCS has a few new features, as listed below:

1. **Reserved charging demand:** This feature differs this system from the regular SCS, which can supply service on a come and served basis, as the newly proposed SSCS requires online reservations in advance. All vehicle service strategies (e.g., routing and swapping battery types) can be calculated according to their origins and destinations (ODs), their initial battery power level, etc.
2. **Multi-type battery supplied:** The SCS can only provide fully charged batteries [29], while the SSCS can provide online reservations and allow the BSS to optimally deploy their state of charge (SOC) battery.

3. **Accurate cost calculated:** Different from a regular SCS, where the economic essence is battery leasing, the SSCS conducts energy leasing. In the pricing strategy, the SCS sets a price for each battery, while the SSCS sets a price for the process of recharging the depleted battery to the same power level as the new battery.
4. **Charging rate considered:** In this proposed system, the recharge cost of depleted batteries is calculated by considering the battery charging rate curve. The SSCS can help achieve an optimal charging strategy and improve energy usage efficiency.

Table 2. Comparisons between the SCS mode and SSCS mode *.

EV Type	System Mode	Operation Mode	Battery Type **	Average SC Cost	Charging Rate	Average Charging Cost	Residual Value	Capacity of BSS
SCEV	SCS	Come and served Reserved online in advance	Single	M	–	M	–	–
	SSCS (this paper)		Multiple	L	•	L	•	•

* The symbol • in this table denotes that the factor is considered and symbol – denotes otherwise. ** Battery types: single type—fully charged battery; multiple types—varying state of charge (SOC) batteries. Cost abbreviations: L—low; M—medium. Abbreviations: BSS—battery swap station; SC—swap charging; SCS—swap charging system; SSCS—shared SCS.

1.1. Literature Review

Since public power charging infrastructure plays a critical role in EV systems [7,14,34], an increasing number of researchers have begun to focus on EV routing problems under SC technology and with the battery charging dispatch model [1,4,20,24,25,27,29,30,35], which holds promise to realize long-distance EV travel [4,20]. Here, we summarize some applications and modeling attempts to develop SC in recent years, as shown in Table 3, and the findings can be briefly synthesized as follows.

- The battery charging dispatch model was set up from the grid side to minimize the total cost (e.g., infrastructure deployment cost [4] and sequential decision cost [26]) while satisfying various physical constraints. Later, an increasing number of researchers began focusing on the transportation side due to the massive traffic issue and then dealt with this SCS as a vehicle routing problem (VRP) [27,36,37], location routing problem (LRP) [3,24,38], or battery dispatch management problem [15,26,29,32,39,40]. In this paper, we propose vehicle routing and battery dispatching as two vital indices for optimizing an SSCS.
- Due to technological or application limitations (i.e., an internet-based booking platform; BSS operation information processing center (IPC); centralized vehicle introduction systems) over the past few years, there are only a limited number of recent studies [27] on the BSS online reservation system that focused on various vehicle demands. This study proposes a new operational mode under a new information system (i.e., vehicles require advanced reservations and the IPC gives various service strategies).
- Most previous studies provided only a single battery type (i.e., fully charged battery) [4,36,40], and they only allow depleted batteries to be replaced by a standard SOC battery. However, some researchers have considered providing multi-type batteries, as stated in the references [15,27,29], and the introduction of varying SOC batteries gives more flexibility in optimal applications. Since our SSCS model is based on the battery charging rate, we propose an optimal operation strategy, deploying multi-type batteries simultaneously.

Table 3. Comparison between existing related SC models and our model *.

Authors	Objective Function	Decision Variable	Battery Type	Online Reservation	Various Demands	Battery Charging Rate	Capacity of BSS	Model Approach
Mak et al. (2013) [4]	Building and operating costs	Infrastructure deployment	S	–	–	–	–	MISOCP
Adler and Mirchandani (2014) [27]	Average delay	VRP and battery dispatch	S	•	–	–	•	DP
Yang et al. (2014) [26]	Battery management	Sequential decision	M	–	–	–	–	Simulation
Yang and Sun (2015) [3]	Construction and routing cost	LRP	S	–	–	–	–	MIP
Chen et al. (2017) [37]	Travel distance	VRP	S	–	–	–	–	MIP
Hof et al. (2017) [24]	Construction and routing cost	LRP	S	–	–	–	–	MIP
Amiri et al. (2018) [38]	Total charging cost	LRP	S	–	–	–	•	MINLP
Widrick et al. (2018) [39]	Total reward	Battery dispatch	S	–	–	–	•	DP
Ding et al. (2019) [29]	Total profit	Battery dispatch	M	–	–	•	•	MIP
Jie et al. (2019) [36]	System cost	VRP	S	–	–	–	–	IP
Infante et al. (2019) [40]	Minimum recourse	Battery dispatch	S	–	–	–	•	MILP
Sun et al. (2019) [32]	Battery investment and operating cost	Battery dispatch	S	–	–	–	•	Fluid model
Šepetanc and Pandžić (2020) [15]	Total profit	Battery dispatch and pricing	M	–	–	–	•	MILP
This paper	System operational cost	VRP and battery dispatch	M	•	•	•	•	IP

* The symbol • in this table denotes that the factor is considered, and symbol – denotes otherwise. Battery type abbreviations: M—multiple types (i.e., varying SOC batteries); S—single type (i.e., fully charged battery). Abbreviations: DP—dynamic programming; IP—integer programming; LRP—location routing problem; MINLP—mixed-integer nonlinear programming; MISOCP—mixed-integer second-order cone programming; MIP—mixed-integer programming; VRP—vehicle routing problem.

Although research focusing on BSS strategies has been ongoing, the results are fragmented. Currently, an integrated way of considering the VRP, battery dispatching, and battery charging efficiency (considering the battery charging rate) has not been fully investigated. To bridge these research gaps and realize the vision of the SSCS, this paper proposes an exact approach to describe the EV routing problem and BSS battery dispatching and determine the optimal SSCS design to minimize the overall system operational cost. We formulate this problem into a binary programming model so that it can deal with the various large-scale strategy issues. This model has a binary decision variable and thus quickly solves an exact solution by off-the-shelf commercial solvers (e.g., Gurobi).

1.2. Contributions

This paper focuses on SC technology and proposes a new structured SSCS to overcome the difficulties in optimal swap battery strategies for a large number of EVs with charging requests and simultaneously considers the varying battery charging rate. The contributions of this paper are mainly three-fold.

- First, we propose an innovative binary programming SSCS model to balance the tradeoff between the vehicle travel cost and battery dispatching cost. This model is a linear integer problem that solves exact solutions by off-the-shelf commercial solvers (e.g., Gurobi).
- Second, we propose an optimal operation strategy for deploying multi-type batteries and simultaneously consider the charging process. In this process, a large number of various charging requests with various initial battery power levels are given various charging strategies (i.e., optimal routes to BSS and battery types). These charging strategies can help improve charging efficiency and minimize the overall system operational cost.
- Finally, a numerical example with real-world freeway data from Guangdong Province, China is conducted to demonstrate the applicability of the proposed model and its effectiveness in reducing construction costs. Overall, this paper provides valuable insights into the future integration of BSSs into long-distance freeway services and offers a numerical method for designing an optimal operational plan for this integrated system.

The remainder of this paper is organized as follows. Section 2 introduces the operation characteristics, notation, and concept of the proposed SSCS. Section 3 formulates the SSCS model with alternative systems. Section 4 tests the proposed model with a numerical example in China and conducts corresponding sensitivity analyses. Finally, Section 5 provides conclusions and recommends future research directions.

2. Model Description

This section introduces the operational process of the SSCS and underlying assumptions. For the convenience of readers, we list some notation frequently used in the paper in Table 4.

Consider a set of vehicle stations $\mathcal{I}\{1, \dots, I\}$ in space. For each vehicle station $i \in \mathcal{I}$, there is a BSS. These stations can also be the ODs of vehicles. Consider a set of batteries with varying SOC $\mathcal{Q}\{1, \dots, Q\}$ that a shared BSS can provide. Let $q \in \mathcal{Q}$ denote the battery SOC. For each station, the number of battery types can be different. Consider a set of the vehicle trip characteristic index $\mathcal{U}\{1, \dots, U\}$ which has a series of various travel demands (i.e., origin station i_u^+ , destination station i_u^- , and the initial state of the battery charge q_u^0). Let $x_{u,jq}$ denote whether vehicle i heads to station j and replaces the depleted battery with a well-charged battery in the state of $q \in \mathcal{Q}$.

To fully understand the operation process of an SSCS, Figure 2 shows an example with shared BSS stations $\mathcal{I} = \{1, \dots, 5\}$ and three types of battery SOC $q = \{1, 2, 3\}$. In this figure, on each link between two stations, the segment of a different number represents the travel distance between the stations. The different combinations of colors for the stations represent the battery types they provide.

Table 4. Notation.

Sets	
\mathcal{U}	Set of the vehicle trip characteristic index, $\mathcal{U}\{1, \dots, U\}$
\mathcal{I}	Set of vehicle stations (i.e., origin stations and destinations), $\mathcal{I}\{1, \dots, I\}$
\mathcal{J}	Set of the shared BSS index, $\mathcal{J}\{1, \dots, J\}$
\mathcal{Q}	Set of varying SOC's that shared the BSS provided, $\mathcal{Q}\{1, \dots, Q\}$
Parameters	
u	Index of the vehicle trip characteristics, $u \in \mathcal{U}$
j	Shared BSS index, $j \in \mathcal{J}$
i_u^+	Origin for vehicle trip characteristic index u
i_u^-	Destination for vehicle trip characteristic index u
q_u^0	Initial battery SOC for vehicle trip characteristic index u
q	Battery SOC that shared the BSS provided, $q \in \mathcal{Q}$
q_u	Battery capacity of the shared BSS provided for the vehicle trip characteristic index u . $q_u \in \mathcal{Q}$
$d_{i,j}$	Travel distance between station i to station j
$\Delta d_{i_u^+, j, i_u^-}$	Distance for charging detour, $\Delta d_{i_u^+, j, i_u^-} = d_{i_u^+, j} + d_{j, i_u^-} - d_{i_u^+, i_u^-}$
C_1	Unit detour cost, Yuan/km
C_2	Unit time cost for battery charging process, Yuan/min
C_3	Unit power cost for battery charging process, Yuan/kW
C_4	Unit power salvage value in the battery, Yuan/kW
s	Unit energy consumption per kilometer, kW/km
$f(q)$	Formula of the battery charging time rate with varying SOC
q^L	Lower band of the battery SOC
n_{jq}	Swapping battery supplement at station $j \in \mathcal{J}$, with battery SOC $q \in \mathcal{Q}$
Decision variables	
x_{ujq}	Binary variables, $x_{ujq} = 1$ when vehicle i goes to power station j and the battery is replaced by a new battery with power quantity q ; $x_{ujq} = 0$ otherwise $u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q}$

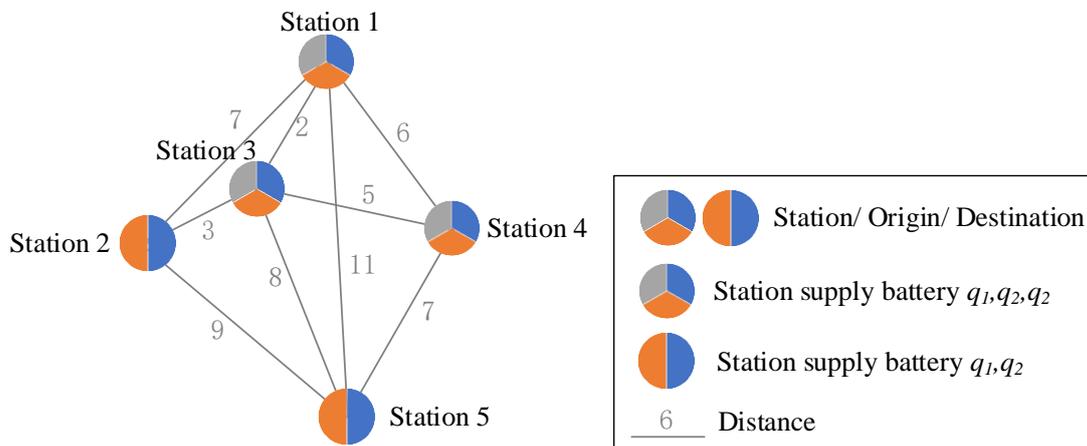


Figure 2. Example network with different battery mode supplies in the SSC station.

In the SSCS, the entire operation process can be divided into three steps, as shown in Figure 3. The vehicle side allows the EV to make online reservations in advance and then follow the instructions from the IPC. The IPC side requires all the vehicles and BSSs to follow centralized guidance, and the BSS side follows the optimal battery replacement and charging strategies. All these system components operate smoothly under the proposed SSCS model.

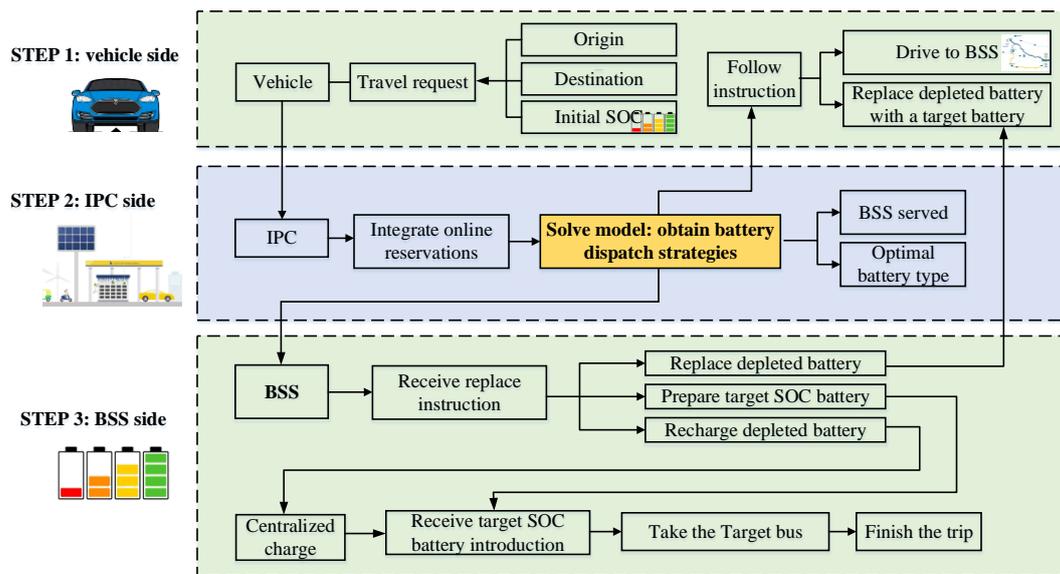


Figure 3. Operation process in the SCS. Abbreviation: IPC—information processing center.

In previous studies [29,41–43], the battery charging rate is a concave function that satisfies formula $f(q) > 0, f'(q) < 0$. The charging time function can be approximately formulated as a piecewise function $f(q) = \begin{cases} k_1q + b_1, 0 < q \leq q_1 \\ k_2q + b_2, q_1 < q \leq q_2 \\ \dots \\ k_mq + b_m, q_{m-1} < q \leq q_m \end{cases}$. In Figure 4, we plot the varying SOC (q), the battery charging rate ($\frac{dt}{dq}$), and the cumulative time functions of the SOC of the batteries.

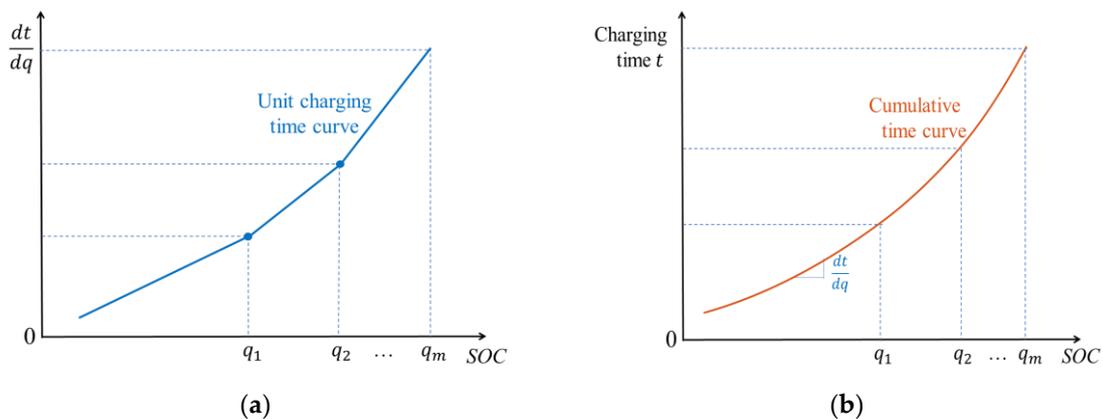


Figure 4. Performances of charging times with current battery power levels: (a) curve of the varying SOC (q) and the battery charging rate ($\frac{dt}{dq}$); (b) cumulative time curve of the SOC of the batteries.

To facilitate the model formulation, we introduce the following assumptions in the investigated problem. These assumptions have been used in other studies on operational design for the SC battery system.

Assumption 1. The battery power consumption of EVs is proportional to the driving distance [37,44]. It is hard to relax this assumption when a battery consumed along a stretch of road is not dependent on the distance; then, the problem becomes an NP-hard problem and appears to be mathematically intractable [14,45,46].

Assumption 2. All vehicles in our system share the same battery capacity size. In the previous study, many researchers have already focused on optimizing the battery size to reach a better system income [47].

Assumption 3. All vehicles in this system reserve swap batteries online and follow the instructions. This assumption will not be strict in the future because of the connected and autonomous vehicle atmosphere and because it has already been applied in previous studies [27].

3. Model Formulation

This section provides a model formulation of the investigated problems. Section 3.1 proposes a model to describe the above-defined SSCS problem. Section 3.2 puts forward the physical constraints that make this model applicable in real-world cases. Finally, Section 3.3 compares this proposed system with the benchmark system.

3.1. Objective Function

The objective function formulated in Equation (1) aims to minimize the SSCS system operational costs, which includes three components: the travel cost of the detour in the swapping battery process (F_1), the total battery cost in the battery recharging process (F_2), and the residual value of electricity power in moving EVs (F_3).

$$\min_{x_{ujq}} F_1 + F_2 - F_3 \quad (1)$$

As shown in Equation (2), F_1 denotes the travel cost of the detour in the swapping battery process, and C_1 denotes the unit detour cost. Let $\Delta d_{i_u^+, j, i_u^-}$ denote the distance of the charging detour, $\Delta d_{i_u^+, j, i_u^-} = d_{i_u^+, j} + d_{j, i_u^-} - d_{i_u^+, i_u^-}$. The total battery cost in the battery recharging process includes charging time costs and charging energy consumption costs. The total battery recharge cost is cumulative and can be calculated by Equation (3). In this formula, let C_2 denote the unit time cost for the battery charging process, and let C_3 denote the unit power cost for the battery charging process. Equation (4) presents the electricity power residual values of the EVs.

$$F_1 C_1 \sum_{u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q}} x_{ujq} \Delta d_{i_u^+, j, i_u^-} \quad (2)$$

$$F_2 \sum_{u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q}} x_{ujq} \int_{q_u^0 - d_{i_u^+, j} s}^q (C_2 f(r) + C_3) dr \quad (3)$$

$$F_3 C_4 \sum_{u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q}} x_{ujq} (q - d_{j, i_u^-} s) \quad (4)$$

3.2. Constraints

The above objective function is subject to a set of constraints, as formulated below.

$$q_u^0 - \sum_{j \in \mathcal{J}, q \in \mathcal{Q}} d_{i_u^+, j} s x_{ujq} \geq q^L \quad u \in \mathcal{U} \quad (5)$$

$$q_u - \sum_{j \in \mathcal{J}, q \in \mathcal{Q}} d_{j, i_u^-} s x_{ujq} \geq q^L \quad u \in \mathcal{U} \quad (6)$$

$$(q_u^0 - d_{i_u^+, j} s) x_{ujq} \leq q_u \quad u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q} \quad (7)$$

$$\sum_{j \in \mathcal{J}, q \in \mathcal{Q}} x_{ujq} \leq 1 \quad u \in \mathcal{U} \quad (8)$$

$$\sum_{u \in \mathcal{U}, q \in \mathcal{Q}} x_{ujq} \leq n_j \quad j \in \mathcal{J} \quad (9)$$

$$x_{ujq} = 0, 1 \quad u \in \mathcal{U}, j \in \mathcal{J}, q \in \mathcal{Q} \quad (10)$$

Constraints (5) and (6) are related to the safety constraints, which mandates that for each vehicle in the SSCS, the lowest power level value should always exceed the lowest level value (q^L) on the right-hand side (RHS). The left-hand side (LHS) in Constraint (5) denotes the battery power level of vehicle u when it obtains access to a BSS, and the LHS in Constraint (6) denotes the battery power level when vehicle u finishes its trip at its destination. Constraint (7) is a limitation that the SOC of a new swap battery is always higher than the SOC of the depleted battery. Constraint (8) is proposed to limit the EV to only swap the battery once in this model, and the side effects of this constraint can be relieved by multiple inputs and by solving this model. In the future, we will try to put forward a more integrated model. Constraint (9) sets some general constraints of the model, which are related to the network battery power balance, similar to reference [38], which describes the maximum permitted capacity of the battery swapped in each BSS.

3.3. Alternative Systems

A single-type battery system (STBS) is used as an alternative system. The only difference between the STBS and SSCS is that each BSS can only supply a fixed SOC of q_F in an STBS, while the SSCS can supply multiple types of SOCs.

4. Numerical Example

To examine the model performance over different network topologies, we present a numerical example with the designed SSCS over the Guangdong Province freeway network and compare it with the alternative STBS simultaneously. As shown in Figure 5a, the input data included 205,876 records of vehicles passing through 14 key toll stations between 17:00 and 18:00 throughout May 2019. We obtained the corresponding vehicle OD demands, as shown in Figure 5b, and assumed that 50% of the passengers use SCEVs. Then, we assumed that the initial battery SOC of these vehicles followed a random distribution.

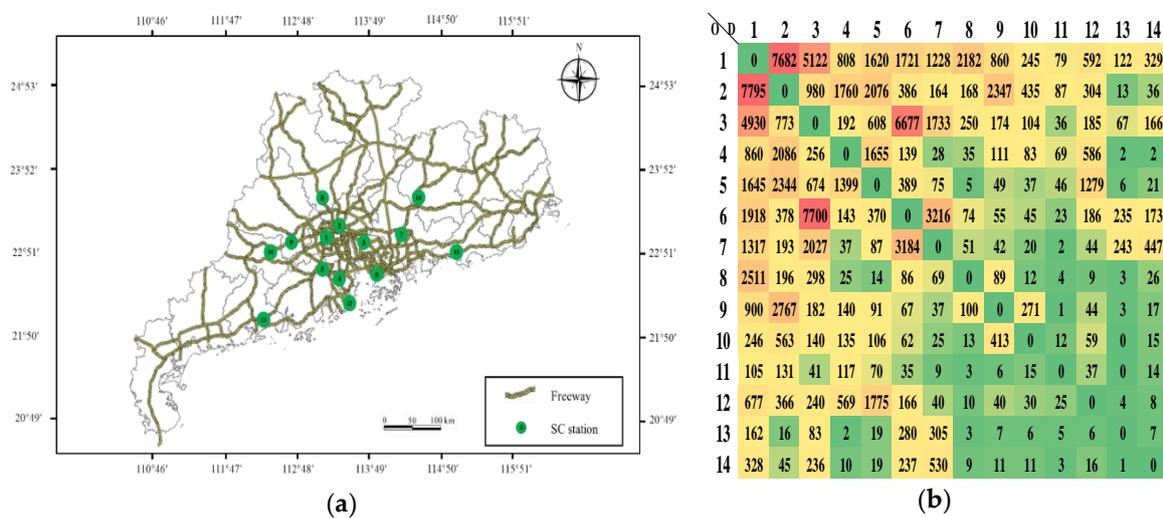


Figure 5. The input data for this numerical example: (a) designed BSSs in Guangdong Province, China; (b) origin and destination (OD) demand distribution.

4.1. Input Parameters

All experiments were performed on a PC with an Intel® Core™ i7-8550U @1.99 GHz CPU and 24 GB RAM. The code was implemented in MATLAB 2019a, calling a commercial solver Gurobi [48–50]. The charging rate we used is normally and approximately fitted to a linear function [41,42], and in this paper, we selected the parameters considering both the vehicle battery characteristics and electric

grid characteristics, which are $f(q) = \begin{cases} 1q + 0.2, & 0 < q < 0.6 \\ 2q - 0.4, & 0.6 < q < 0.8 \\ 4q - 2, & 0.8 < q < 1 \end{cases}$. Other default parameter values were stated in Table 5.

Table 5. Default parameter settings.

Parameter	Description	Value	Data Source
C_1	Unit detour cost	1 Yuan/km	EV travel cost (https://afdc.energy.gov/fuels/)
C_2	Unit time cost	1 Yuan/h	Guangzhou Municipal Human Resources and Social Security Bureau reports in 2019 (http://gzrsj.hrssgz.gov.cn/english/)
C_3	Unit power cost	1 Yuan/kW	Electricity price in China (https://www.ceicdata.com/china/electricity-price)
C_4	Unit power salvage value	0.4 Yuan/kW	Related to the PEV charging price (https://afdc.energy.gov/fuels/electricity_charging)
s	Unit energy consumption/km	0.25%/km	Most EVs are currently capable of approximately 100–250 miles of driving before they need to charge (Data source: UC Davis; https://phev.ucdavis.edu/)
v	Average vehicle travel speed in km/h	100 km/h	The operating speed of EVs on the freeway (http://www.0512s.com/lukuang/G94.html)
p^L	Lower battery power limit	20%	Safety suggestion from EV enterprises (e.g., Beijing Automotive Group Co., etc.)

4.2. Optimal Location Result

By solving the proposed SSCS model, the optimal objective value (system operational cost) is 926.3, with a CPU time of 0.6359 s. Figure 6 shows the battery swaps of different OD pairs. In this figure, on each row and column intersection, the different color circles represent the different battery types (i.e., SOC $q = 60\%$, 80% , and 100%), and the circle size represents the type of dispatch frequency. The results show that the total number of batteries swapped for SOC types of 60% , 80% , and 100% are 139, 940, and 352, respectively.

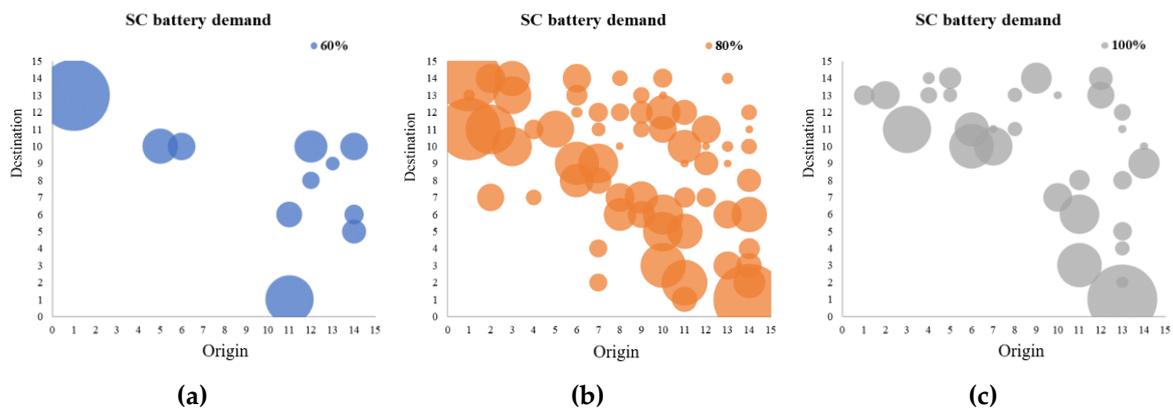


Figure 6. Battery swaps with different OD pairs with battery SOC of (a) $q = 60\%$; (b) $q = 80\%$; and (c) $q = 100\%$.

We compared the SSCS solutions with the benchmark STBS. In this experiment, we compared the system operational cost and the average battery level before and after SC, with the average energy gap filled, the average battery level at the destination, and the average energy consumption over the traveled distance as the criteria to evaluate the performance of the proposed system. Figure 7 shows the comparison between the SSCS and STBS in a multi-type battery deployment. Most of the batteries deployed in the SSCS and STBS were the same except for stations 4, 5, 9, 10, and 12, which indicates that the introduction of multiple types of batteries does not significantly change the total amount of battery management.

More detailed results are shown in Table 6. As we can determine from the comparison result, the total number of batteries the two systems swapped was the same (i.e., 1431). Since they share different battery types (i.e., SSCS has multi-type batteries, and STBS has single-type batteries), their optimal battery levels are different. Compared to the average battery level before SC, the optimal battery level of the STBS (65%) was much higher than that of the SSCS (32.1%), which is not efficient for energy

usage. When compared to the average energy gap the charging process fills, the performance of the SSCS (50.9%) was also better than that of the STBS (35%), which is significantly related to the SC efficiency. Since the average energy consumption for traveled distance was similar (SSCS and STBS are 53% and 54%, respectively), the detour distance did not make a noticeable impact. Overall, the multi-type SC strategies for the SSCS could reduce the system operational cost (54.3%) when compared with the STBS.

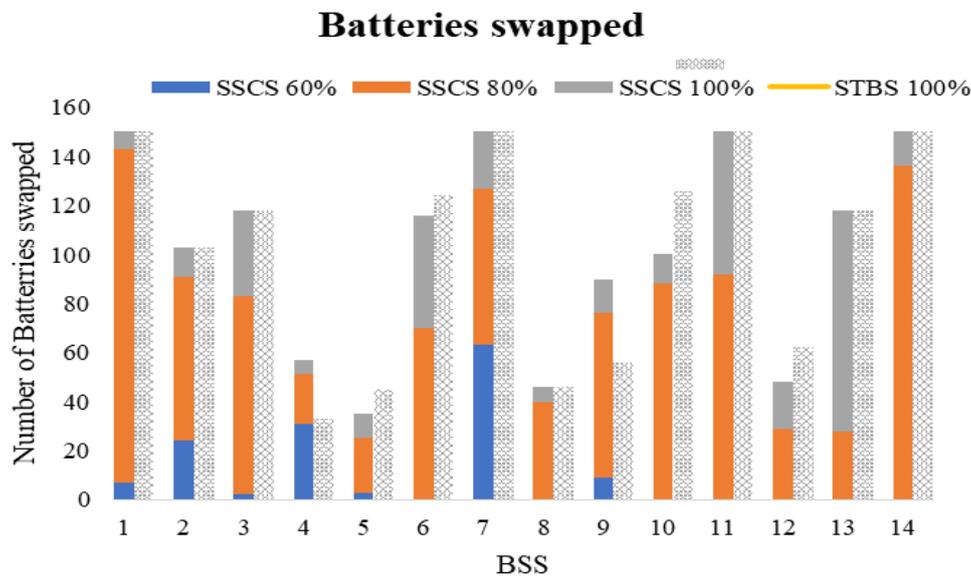


Figure 7. Comparison of the number of swapped batteries.

Table 6. Results comparison with the alternative system.

Evaluation Criteria	SOC	SSCS		STBS	
		Multi-Type	Single Type $q = 100\% *$	Rate **	Rate **
• Total number of batteries swapped	60%	139	–	–	–
	80%	940	–	–	–
	100%	352	1431	–	–
• Average battery level before SC		32.1%	65%	2.025	
• Average battery level after SC		83.0%	100%	1.205	
• Average energy gap filled		50.9%	35%	0.687	
• Average battery level at the destinations (residual energy level)		30.0%	46%	1.533	
• Average energy consumption for traveled distance		53%	54%	1.019	
• System operational cost		926.3	1428.9	1.543	

* $q = 100\%$ indicates that the depleted battery is replaced by a fully charged battery, which is commonly used in the market. ** The rates are calculated by the value of the single-type battery system (STBS) divided by the value of the SSCS.

4.3. Sensitivity Analysis

This section analyzes the sensitivity of critical parameters to the cost components in the SSCS. In each instance, only one parameter is varied, and the other parameters maintain their default values. To evaluate the performances of different parameter combinations, we compared the overall system cost and the multi-type battery combinations. To simplify the sensitivity analysis for vectors C_1 , C_2 , C_3 and C_4 , we varied the values of these parameters and plotted the results in Figure 8. The findings can be briefly summarized as follows.

- We perform a regression analysis of C_1 , C_2 , C_3 , and C_4 with the system operational cost (simplified as F_{SSCS}), as shown in Figure 8a–d and obtain $F_{SSCS} = 541.1C_1 + 304.0C_2 + 276.4C_3 - 436.56C_4 - 78.2$ with $R^2 = 0.995$. This result reveals a high linear correlation with all four critical parameters.
- The optimal result of battery type performance stability with varying values of C_1 , C_2 , and C_3 is shown in Figure 8. The varying value of C_4 can change the optimal strategy significantly, as shown

in Figure 8d,e. The increased value of C_4 would result in an increased number of vehicles holding more residual energy at the destination.

- Figure 8f shows the performance of the average battery charging time with varying C_2 . We learn that C_2 is related to the unit time cost for the battery charging process, and it reaches a plateau period when the value of C_2 is over 1.5.

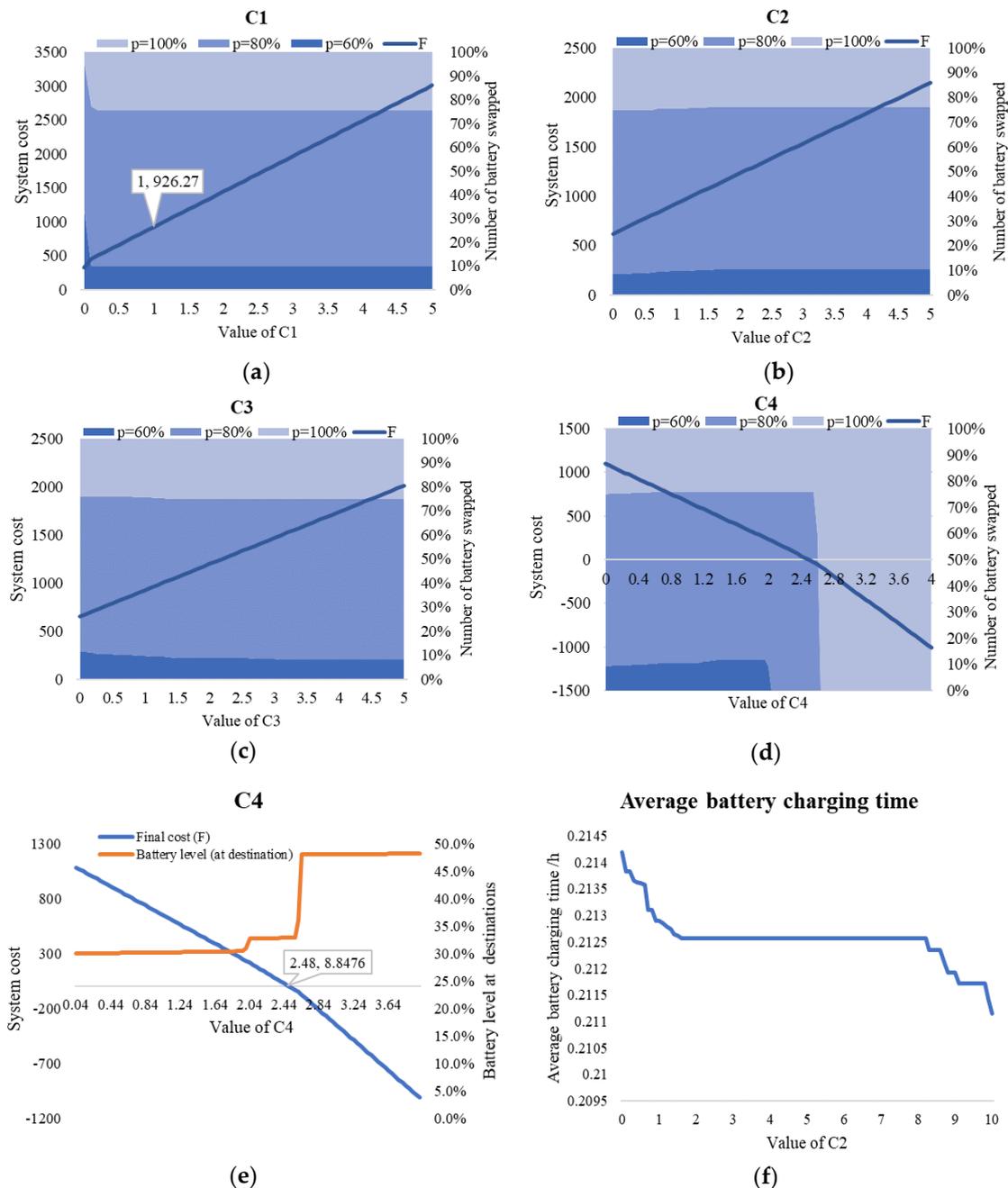


Figure 8. System operational cost performance and number of batteries swapped with varying values of (a) C_1 ; (b) C_2 ; (c) C_3 ; and (d) C_4 . (e) Average battery charging time with varying C_2 . (f) System operational cost performance and battery level at the destination with varying C_4 .

5. Conclusions

SC technology offers the possibility of EVs swapping batteries with other EVs and provides plausible solutions for realizing a long-distance freeway trip. By taking advantage of SC technology,

this paper proposes an exact approach to describe SSCS operations and determine the optimal SSCS design (i.e., optimal swap battery strategies for EVs with charging requests and the consideration of varying battery charging rates simultaneously) to minimize the overall system operational cost. In this proposed SSCS system, we formulated this problem into a binary integer programming model that could be solved by off-the-shelf commercial solvers (e.g., Gurobi). We explored a numerical example to illustrate the applications of this model from the freeway system in Guangdong Province, China, and compare it with alternative systems (the STBS). The SSCS was shown to be more effective than the alternative (e.g., a reduction of 54.3% in system operational cost).

This study can be extended in several directions. Future research can be conducted to explore the dynamic and stochastic demands of SCEVs, more variables such as maintenance and service levels of BSSs, variation of electricity prices, more complicated multi-type SC strategy combinations, associated vehicle coordination, more efficient customized solution methodologies, and the allowance of these vehicles to participate in peak shaving and valley filling to improve unreasonable charging and discharging. Moreover, it would be interesting to examine the impact of combinations of autonomous, modular, and EV technologies into this SSCS.

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