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Article

A Mobile Battery Swapping Service for Electric Vehicles Based on a Battery Swapping Van

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Abstract: This paper presents a novel approach for providing a mobile battery swapping service for electric vehicles (EVs) that is provided by a mobile battery swapping van. This battery swapping van can carry many fully charged batteries and drive up to an EV to swap a battery within a few minutes. First, a reasonable EV battery swapping architecture based on a battery swapping van is established in this paper. The function and role of each participant and the relationships between each participant are determined, especially their changes compared with the battery charging service. Second, the battery swapping service is described, including the service request priority and service request queuing model. To provide the battery swapping service efficiently and effectively, the battery swapping service request scheduling is analyzed well, and a minimum waiting time based on priority and satisfaction scheduling strategy (MWT-PS) is proposed. Finally, the battery swapping service is simulated, and the performance of MWT-PS is evaluated in simulation scenarios. The simulation results show that this novel approach can be used as a reference for a future system that provides reasonable and satisfying battery swapping service for EVs.

Keywords: electric vehicle; battery swapping; battery swapping van; request scheduling; request priority

1. Introduction

In recent years, due to the increasingly significant shortage of non-renewable resources, such as oil and coal, excessive consumption, and the consequent environment pollution, electric vehicles (EVs) have gradually drawn people's attention and become favored as a type of clean energy vehicle [1]. The key issue for the effective operation of EVs is energy replenishment. It is known that there are two main ways to solve this problem: EV charging and battery swapping [2,3]. In general, EV charging requires a long charging process. Thus far, due to policy and money constraints, the charging stations, charging piles and other charging infrastructure are not widely deployed. The abovementioned reasons make it probable that EV users will be forced to stop and wait, which results in waiting anxiety. In addition, EV users trade-off between the remaining battery energy, the location distribution of charging facilities and their travel plans, which easily results in range anxiety [4,5]. Therefore, more researchers and EV operators are turning their attention to battery swapping [6–8]. Battery swapping can provide a new fully charged battery, which does not require depleting the energy of the old battery. Range anxiety is eased, and to some extent infinite mileage is obtained. Because battery swapping only requires a few minutes, waiting anxiety is significantly eased.

However, before the benefit of battery swapping becomes a reality, two problems need to be solved. One is the EV battery technology, which is fundamental for battery swapping. A standardized EV battery with the characteristic of high mileage, high energy density, high recycling ratio, high recovery ratio, environmentally friendly ability and security needs to be developed [9]. Currently, the development of zinc air batteries and zinc nickel batteries can initially meet the abovementioned demand [10]. Therefore, the EV battery technology is not discussed in this paper. The other problem is a reasonable and effective EV battery swapping architecture that can support the effective operation of EV battery swapping.

The current EV battery swapping systems and infrastructure are mainly based on battery swapping stations and battery charging factories. A larger number of batteries are centrally-charged and transported to different battery swapping stations via a logistics system [11]. Most research is this area is focused on the following issues: battery logistics strategy, battery swapping station planning and construction strategy, and battery charging strategy for the battery swapping stations [12,13]. The abovementioned research intends to improve the coverage and service of a battery swapping system. However, these approaches do not realize the objective of "get energy replenishment anytime and anywhere." EV users must drive to a battery swapping station for battery swapping. Due to the obvious constraints of location and number of the existing battery swapping stations, there may still be a queueing and waiting phenomenon [14]. Therefore, a more reasonable and effective EV battery swapping architecture is needed.

To solve this problem, one effective idea is to switch from the existing passive battery swapping mode to the active battery swapping mode. Recently, a new fast EV battery swapping device has been developed. The patents [15,16] indicate that this device can be installed on a van, which transforms the van into a mobile EV battery swapping station. This device has the advantages of accurate positioning and convenient swapping due to its components, such as a positioning pin, positioning hole, positioning track, positioning slot and PLC control system. The operations of removing and installing a battery occur at the same time. Thus, the entire battery swapping process is very fast and lasts only a few minutes (in the experimental environment, it is approximately 3 min). EVs drive into the interior predetermined position of the battery swapping van through the folding slope steel plate to perform an automatic battery swap. Thus, the actual transaction of battery swapping occurs inside the battery swapping van. The mobility of the battery swapping van removes the constraints of location and quantity of EV battery swapping stations. The battery swapping locations are more flexible. When the EV cannot drive due to energy depletion, the battery swapping location is undoubtedly generated based on the EV's location. Otherwise, the battery swapping location can be generated based on the specific battery swapping service scheduling strategy or the driver's actual requirements. Using the battery swapping van, the active battery swapping can be achieved anytime and anywhere. The battery swapping van will provide a fast, convenient, and flexible battery swapping service, and it will ease the pressure of battery logistic system. Based on a battery swapping van, we mainly study the following problem in this paper:

- EV battery swapping architecture based on a battery swapping van

For the effective and efficient operation of an EV battery swapping service based on a battery swapping van, a reasonable EV battery swapping architecture needs to solve the specific process of battery production, charging, transportation, storage, swapping, communication and others and identify the specific functions of each participant of the entire EV battery swapping system and the relationship between them. Moreover, profit mode and some details and practical factors should be discussed. Thus, our first contribution is to establish an EV battery swapping architecture based on a battery swapping van.

- Battery swapping service request scheduling

There are clear battery energy differences between the battery swapping requests of different EV users. Furthermore, the locations of the moving battery swapping van and EVs vary, which leads to the consequent change of battery energy consumption. Therefore, to improve the efficiency and effectiveness of battery swapping service, battery swapping requests need to be distinguished and scheduled based on the advanced management system. Our second contribution is to propose a minimum waiting time based on priority and satisfaction scheduling strategy (MWT-PS) to distinguish and schedule the battery swapping requests. First, we define the battery swapping service request and set its priority according to the State of Charge (SOC). Second, we establish a battery swapping service request queuing model according to the specific battery swapping service mode based on a battery swapping van. Then, we discuss the satisfaction of EV users based on waiting time and request priority and establish the scheduling model. Finally, the MWT-PS is proposed based on the abovementioned analysis.

The rest of this paper is organized as follows: in Section 2, a related work is introduced. In Section 3, the EV battery swapping architecture based on a battery swapping van is established. The battery swapping service request is discussed in Section 4. In Section 5, the battery swapping request scheduling mechanism MWT-PS is proposed. Simulation results are analyzed in Section 6. Section 7 draws the conclusion.

2. Related Work

Currently, the body of work related to EVs is rapidly increasing. For the realization of EVs, many studies have looked at the potential impact, adoption limitation, potential operational pattern and actual usage simulation of EVs in current electricity grids [17–20]. Most research indicates that energy replenishment is a significant factor in making EVs more competitive because of range anxiety among the EV users [4,5].

To help alleviate concerns of range anxiety among the EV users, many effective methods of energy replenishment are analyzed, including location sites of energy replenishment stations, how many stations to construct, energy replenishment strategies, and so on. For both the maximal coverage and minimal costs, the siting of charging stations is analyzed using a case study of Penghu in Taiwan [21]. An ordered EV charging strategy in a charging station to improve charging effectiveness is proposed [22]. The stochastic programming model, which takes into account price variation and the stochastic behavior of vehicle staying patterns, is put forward to achieve the optimal management of EV charging points [23]. A previous study [24] has proposed an integrated EV charging navigation framework that takes into consideration the impact of both the energy and transportation systems to save time of EV users and provide effective charging. A heuristic charging strategy is proposed to improve the real-time charging performance by optimizing the charging rate feasible searching region and saving searching time [25].

In addition to energy replenishment methods that are based on battery charging, the methods that are based on battery swapping have been widely studied. A vehicle flow-interception model is proposed, and the optimal number of battery swapping stations, which included retrofitting of the existing petrol station, is analyzed and specifically evaluates a case study in Alexandria (VA, USA) [26]. Reference [27] presents an integer programming model to determine the location strategy of battery swapping stations and the routing plan of a fleet of EVs that are under a battery driving range limitation. The optimal placement and sizing of the battery swapping stations are studied using the Artificial Bee Colony algorithm [6]. The EV battery swapping station strategy model is proposed that considers frequency and distribution of EV users' arrivals, cooperation of users, and grid load demand curves [28]. References [29,30], respectively, studied a service and operation scheduling model and an economic scheduling model for EV battery swapping stations to succeed in the rolling out of EVs.

All the abovementioned studies assume that EVs conduct most of their energy replenishment at static location energy replenishment stations. However, in practical implementations, mobile energy replenishment options would need to be provided to minimize response times and key indicators, such as latencies and miss ratios, and further help alleviate concerns of range anxiety. Reference [31] proposed a mobile charging platform as an alternative implementation of those static battery recharge options, the implementation could either be in the form of a mobile plug-in charger or a mobile battery-swapping station. The mobile energy replenishment system possesses similar properties to mobile service systems such as ambulance and mobile data collection in WSN. The key factors are usually the location of mobile servers, coverage areas, service queuing models, and so on.

There are many previous studies about such mobile service systems. References [32–34] determined that the location of ambulance bases and coverage areas are usually the key parameters. The reasonable and accurate queuing models of mobile servers are well studied through the analysis of mobile data collection in WSN with mobile data collectors. The most fundamental service queueing discipline of first-come–first-serve (FCFS) is explored in [35,36]. The nearest-job-next (NJN) discipline is explored in [37]. It is clear that battery swapping vans in our EV battery swapping service system can be viewed as a special type of mobile servers. Therefore, we can adopt a similar approach based on a queue theory to analyze the mobile battery swapping process for EVs.

3. EV Battery Swapping Architecture Based on Battery Swapping Van

In this section, a reasonable EV battery swapping architecture is established, which determines three basic issues about how to realize the EV battery swapping service based on a battery swapping van. The first issue is the battery swapping system structure, which should clearly note the main participants of the entire system, identify their functions and roles, and clarify their relationship and communications. The second issue is the economic analysis that consists of profit mode and cost analysis. We mainly analyze the profit source, primary system cost and the cost for EV users. The last issue is the practical factors, which mainly focuses on the realization of battery swapping service based on a battery swapping van such as funds and policies of government agencies, environmental impact of battery swapping van, and so on.

3.1. Battery Swapping System Structure

The application of a battery swapping van brings a clear change to the EV battery swapping. The specific functions of each participant and the roles they played will be consequently changed. To reduce the impact of these changes and provide an effective and efficient EV battery swapping service, the function and role of each participant are determined, especially their changes. The specific process of battery production, charging, transportation, storage and swapping, and communication are described. The relationship between each participant, as shown in Figure 1, is then discussed.

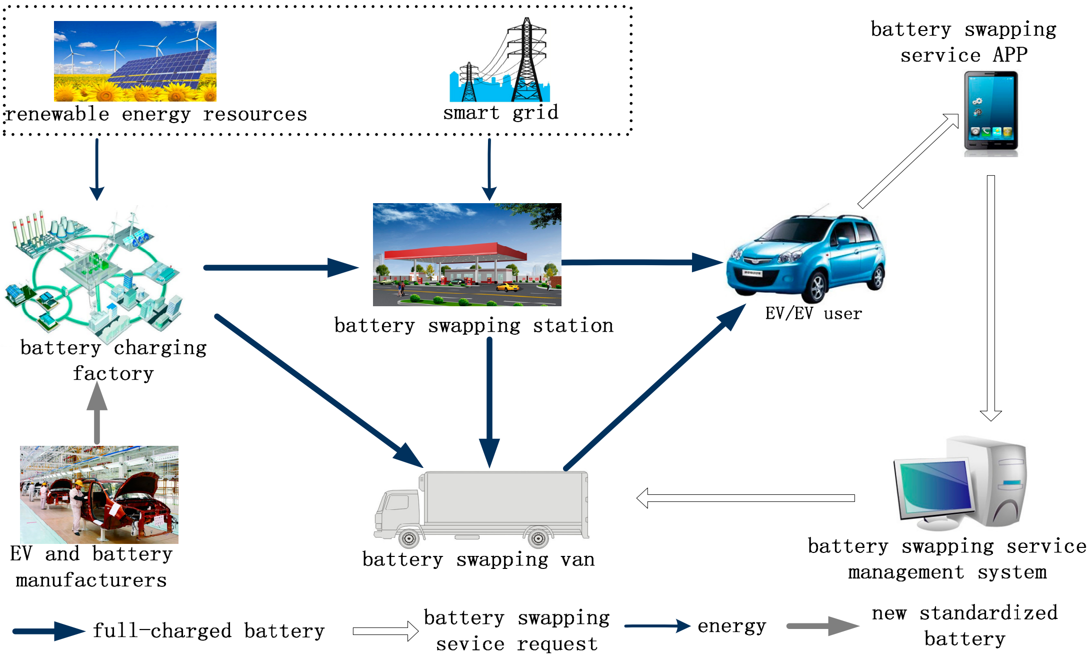


Figure 1. EV battery swapping structure based on battery swapping van.

3.1.1. Battery Swapping Van

The current battery swapping service with a battery swapping station as its core, in essence, is a passive service that needs to wait for users and swap their batteries. If the service does not satisfy the need of EV users, they still suffer from range anxiety. However, the application of a battery swapping van causes a fundamental change. When the number of battery swapping vans gets big enough, a battery can be sent to EV users anytime and anywhere. EV users can choose to stop to wait for a battery swapping van or keep driving until the battery swapping van catches up with them. This will appear as if EV users travel with an energy replenishment device, which will finally eliminate waiting anxiety and range anxiety.

The battery swapping van is equipped with an automatic positioning system and a communication system that can communicate with the battery swapping service management system and EV users via wireless communication technology. With these information communication systems, the scheduling results of battery swapping service requests are received, and the current information about the battery swapping van, such as position, direction and battery storage, are sent to the battery swapping service management system. In addition, the responses for battery swapping requests are sent to the EV users.

The battery swapping van usually replenishes its fully charged battery storage in the battery swapping station. The timing of replenishment is determined by its fully charged battery storage, amount of battery swapping requests and its distance to the battery swapping station. It can also get its fully charged battery storage replenishment in the battery charging factory if the fully charged battery storage of battery swapping station is not sufficient or the battery swapping van is free.

In general, one battery swapping van would have a limited carrying capacity of fully charged batteries. It can only serve a fixed number of EVs before having to return to obtain fully charged replenishments. Therefore, to reduce driving time and improve service efficiency of the battery swapping van, the service area of one battery swapping van should not cover too many roads. The entire district should be divided into some small service areas according to the different population and road densities. One battery swapping van serves one service area that it patrols during its work time. Moreover, to guarantee the satisfaction of EV users, the bordering area should be shared between two adjacent service areas.

3.1.2. EV/EV Users

The existence of a battery swapping van allows EV users to completely get rid of the old "refueling" mode. They do not have to look for a charging station or battery swapping station to get their energy replenishment but simply call a battery swapping service anytime and anywhere. They just need to send their SOC and information about speed, direction and position. Then, they will get fast and accurate battery swapping service with a battery swapping van and have no need to consider how much the SOC is. Even if we set the rule to specify that only the battery whose SOC is less than a certain level can be swapped to prolong the service life of the battery, the commuter demands of EV users still can be guaranteed. The mileage of EV seems to be significantly enhanced.

In this mode, there are two options for the EV users to swap their battery. One option is to swap the battery using the battery swapping van. The other option is to swap the battery at the nearest battery swapping station after judging that the remaining battery energy is sufficient to reach the battery swapping station. The two options are complementary to each other. EV users no longer need to worry about whether the existing battery energy is sufficient or whether there are enough battery swapping stations on their traveling routes, and so on. Finally, the "want to go, then go" will become true.

3.1.3. Battery Swapping Station

Generally, as a commuter tool, an EV is the main mode of daily transportation. An EV is used to commute to work in the morning and go back home at night, with occasional uses for driving to purchase a meal and other destinations during the day. During the peak commute hours, energy consumption is relatively high, and consequently, the battery swapping demand is high. Thus, to only replenish the fully charged battery storage using the battery logistics system may be not enough because of the limited capacity of the fully charged battery storage in the battery swapping station. To guarantee the battery replenishment and alleviate the transportation pressure of the battery logistics system, an effective solution is to deploy a battery charging system at the battery swapping station. This battery charging system is only used to charge the batteries that are swapped out and it is not open to EV users. This not only improves the fully charged battery storage but also plays an important role in balancing peak load in the smart grid.

At this point, the battery swapping station has two approaches for replenishing its battery storage: from a battery charging factory with a battery logistics system and from its own battery charging system. In addition, the battery swapping station has two main functions: to provide a battery swapping service for the EV users directly and to replenish the fully charged batteries for the battery swapping van to provide a battery swapping service for the EV users indirectly.

3.1.4. Battery Swapping Service Mobile APP

EV users receive the battery swapping information, which is published by the battery swapping service management system, and send their real-time battery swapping request via the APP installed on the smart mobile device [38]. Specifically, through the mobile APP, information about the distribution of battery swapping stations, real-time battery swapping price, and real-time distribution of battery swapping vans will be known. Additionally, the EV users can send their real-time position, SOC, driving speed and direction, etc. to launch an accurate battery swapping request for obtaining fast and accurate battery swapping service.

Using the real-time information exchange of the battery swapping service mobile APP, the accurate real-time positions of EV users are automatically located with the mapping software, and EV users do not need to worry about how to describe their location if they are unfamiliar with the area or if the location is not accurately described. The time cost and risk caused by inaccurate users' information are eliminated. Moreover, the EV users can complete the payment, service evaluation and other operations using the mobile APP.

3.1.5. Battery Swapping Service Management System

As the fundamental communication and management platform of battery swapping, the battery swapping service management system offers a variety of battery swapping applications such as battery swapping service reservation, battery swapping service customization, and so on. The battery swapping service management system regularly releases real-time prices. The charge of one battery swapping service is not constant but determined by both real-time price and real-time remaining battery energy of an EV user.

After receiving the battery swapping request of an EV user, the battery swapping service management system schedules the request according to the result of battery swapping request scheduling and assigns the request to the corresponding battery swapping van. Therefore, the battery swapping service management system should keep tracking the real-time position, driving direction and fully charged battery storage of each battery swapping van. Then, the battery swapping service management system sends the acknowledgement of the chosen battery swapping van to the battery swapping service mobile APP in the EV user's smart mobile device. Once this battery swapping task is completed, the battery swapping service management system receives the completion messages from both the battery swapping van and EV user, records and ends the battery swapping service.

3.1.6. Battery Charging Factory

Most EV batteries are centralized-charged in the battery charging factory and then sent to battery swapping stations by the battery logistics system. Occasionally, some battery swapping vans can get fully charged battery replenishment at the battery charging factory. The centralized charging process needs a significant amount of electrical energy, thus, renewable energy resources are an ideal way to share part of energy load to balance the peak energy load in a smart grid. In addition, from the battery charging factory operators' point of view, the deployment of renewable energy resources can save a considerable cost of purchasing energy from the smart grid and increase the operation income because they do not need to purchase energy from the smart grid if the energy provided by renewable energy resources is sufficient.

3.1.7. EV and Battery Manufacturers

For the realization of EV battery swapping based on a battery swapping van, the most important aspects for the EV and battery manufacturers are different from what currently exists. The goal is to develop a set of standard battery production lines and battery installation devices to unify the battery usage of different brand EVs. The reusability and commonality of a unified battery will provide people an enhanced desire to have more than one EV, which results in good sales and finally promotes the battery swapping service. Moreover, this will save battery cost and result in greater investment into the design and transformation of EV patterns and performance, which will reduce the EV cost, makes EV sufficient, and improve profit margins and sales. However, we must admit that this requires a relatively long time to realize and, to some extent, depends on funds and policy support from the government.

The relationship between these seven main participants of the EV battery swapping architecture, which is based on the battery swapping van concept, is shown in Figure 1. The EV and battery manufacturers produce standard-sized batteries and supply them to the battery charging factory and battery swapping stations through the battery logistics system. At the battery charging factory, a battery is charged via the smart grid and renewable energy resources. However, the battery is only charged via the smart grid at the battery swapping station. The battery swapping van generally obtains the fully charged battery storage replenishment from a battery swapping station, and sometimes it can also receive the fully charged battery storage replenishment from a battery charging factory. EV users have two choices for swapping a battery. One option is to drive to the nearest battery swapping station. The other option is to wait for the battery swapping van after the battery swapping request has been sent. The battery swapping van and EV user exchange information with each other via the battery swapping service mobile APP and management system. The EV user sends a battery swapping request via the battery service mobile APP and receives a response message and a real-time price. The battery swapping van follows the scheduling results of the battery swapping service management system to provide the EV user an active battery swapping service.

3.2. Economic Analysis

3.2.1. Profit Mode

The major operators of a battery swapping service must invest in the battery charging factory, renewable energy resources, a battery swapping service management system, a battery swapping station, battery swapping vans, a battery logistics system, and an energy suply. The first three investments are one-time investments. The last four investments depend on the number of battery swapping service EV users, and can be referred to as dynamic investments. However, in these dynamic investments, only the investment in energy clearly increases as the number of battery swapping service EV users increases.

Moreover, some energy loss is unavoidable during the battery charging or discharging process. Due to the battery formula, working temperature, resistance and other factors, energy conversion efficiency cannot be completely 100%. Obviously, energy loss brings additional investment for the major operators of a battery swapping service, and this part of investment also increases as the number of battery swapping service EV users increases.

Their incomes mainly include the battery swapping service income, dividends from EV and battery manufacturers, franchise fees for the battery swapping station and funds supported by the government agencies. The latter is a one-time income, and the rest depend on the number of battery swapping service EV users, which can be referred to as dynamic incomes. In these dynamic incomes, only the battery swapping service income clearly increases as the number of battery swapping service EV users increases.

Therefore, we can approximately calculate the profit of the battery swapping system that is based on a battery swapping van using the formula (profit = service income − investment in energy − investment in energy loss + an approximate fixed profit of other investments and incomes). Then, we can conclude that the profit of battery swapping service is made of selling electrical energy and not by selling cars or batteries.

For the battery swapping service, the service income is calculated as the current battery energy consumption multiplied by a fixed price. This fixed price is set by operators according to their profit expectation, which means that there is no extra cost for EV users once the fixed price is set. Thus, just like oil prices, in most cases, the fixed price only increases as the electricity energy price purchasing from the smart grid rises. The cost is increased by adding a large number of swapping vans, which may not result in additional cost to the EV users. Moreover, the cost of EV users may decrease as the number of battery swapping service EV users increases.

3.2.2. Cost Analysis

In the abovementioned analysis, EV users only pay money for the proposed mobile battery swapping service according to the amount of energy that is necessary and the fixed price that is set by operators. However, in the battery charging mode, EV users not only pay for the energy, but also pay a service fee and a parking fee. Thus, compared with the battery charging mode, our proposed battery swapping service has an obvious cost advantage for the EV user.

The State Grid Corporation of China clearly stipulates that the charging price for EVs must consist of the basic electricity energy price and a service fee. Currently, the charging price is set as 1.2¥/kwh in Beijing. Generally, it will take several hours for an EV to fully charge its battery. For example, it will take about 6 h for a BYD-E6 vehicle (300 km, 57 kwh) to get its battery 80% charged with a charging power of 7.5 kw. If the parking price is 8¥/h and the parking fee of the first hour is free, then the total charging fee is about 94¥. The average charging fee of 1 kwh electricity energy is about 2.09¥. The fixed price of our proposed mobile battery swapping service is close to the basic electricity energy price, it mostly fluctuates between 0.6 and 1.0 in Beijing, so in principle the EV users will pay less for the battery swapping service.

Table 1 shows the major indicators of several typical batteries. The power density and energy density of the four types of batteries are not too different, however the zinc air battery and zinc nickel battery are more suitable as swapping batteries for their higher service life and recycling rate, and lower cost.

Table 1. Major indicators of typical batteries.

Indicators \ Typical Batteries	Nickel Battery	Lithium Battery	Zinc Air Battery	Zinc Nickel Battery
Power density (w/kg)	1300	2000	1000	2700
Energy density (wh/kg)	65–70	110–130	180–220	75–100
Cost (¥/wh)	4.2	9.0	0.6	1.8
Service life (times)	500–600	1500	3000	1600–2000
Recycling rate	5%	3%	90%	90%

For battery charging mode, the operators need to construct as many battery charging stations as possible, and pay the maintenance fees of these battery charging stations. For our proposed mobile battery swapping service, the operators need to acquire many battery swapping vans and a battery logistics system. Next, we calculate the cost of the two modes using the data of the State Grid Corporation of China.

If a battery charging station has 10 battery chargers, then the cost of infrastructure, the cost of energy distribution and the cost of maintenance for one year (employees and devices) are about 2,400,000¥, 2,000,000¥, and 360,000¥, respectively. We can then calculate the cost of a battery charging station as approximately 4,760,000¥. However, the cost of a battery swapping van and the cost of maintenance for one year (employees and devices) are about 100,000¥ and 250,000¥, respectively. The total cost of a battery swapping van is approximately 350,000¥. It may cost 5,000,000¥ to establish a battery logistics system, but it can serve at least dozens of battery swapping stations. Thus, we can conclude that the cost of a battery charging station is at least 10 times more than that of a battery swapping van. Generally, 10 battery swapping vans are enough to meet the battery swapping service requests in the similar coverage area as a battery charging station. Apparently, the operators must pay less for the battery swapping service.

Nowadays, lots of EVs, such as the BJEV-E series (200~260 km, 41.4 kwh), Tesla Model S (372~572 km, 85 kwh), and so on, support battery swapping mode. The Beijing Automotive Group plans to construct 200 battery swapping stations in 2017. The State Grid Corporation of China has turned its focus to the significant battery swapping requirements of bus groups and taxi companies that always have a large number of the same type of EVs. With the investment of these big enterprises, the battery swapping service market may be greatly promoted, and the costs for operators and EV users may consequently get further decreased.

3.3. Practical Factors

3.3.1. Funds and Policies

The most influential factor when realizing the battery swapping systems that are based on mobile battery swapping vans is the funds and policies. In today's EV market, neither the battery charging mode nor the battery swapping mode are dominant. It can be expected that most countries will vigorously promote the wide application of EVs, which means a large amount of investment funds and favorable policies will be needed. Once the battery swapping mode is selected, the infrastructure construction, environment of battery swapping van and operation funds will be significantly promoted. What is more important is the potential and immeasurable role in promoting the battery swapping service market. The EV and battery manufacturers will invest more in battery R&D and EV standardization and manufacture, which is more conducive to the development of battery swapping services. Currently, there is a competition between battery swapping and charging. Only more reasonable designs, more ideal prospects and more EV market share can seize the opportunity to secure more funds and favorable policies. Thus, overcoming the current difficulties of funds and policies and designing a reasonable battery swapping service and operation scheme to be recognized by most EV users and industry participants are what we should do if committed to obtaining more funds and policy support from the government.

3.3.2. Environmental Impact of Battery Swapping Vans

Theoretically, battery swapping vans are able to complete battery swapping requests for EVs at any location. In today's EV application environment, this actually may not be reasonable because of parking or space restrictions, specifically in business districts. To solve this problem, there are two main approaches except for constructing parking spaces by the battery swapping service operators themselves, which is definitely costly and slow. There can be avenues for operators to negotiate addresses for the major parking operators in the areas. This can produce some parking spaces for the battery swapping van. The other avenue is to negotiate with the government agencies to obtain funds and policy support. With the funds and policy support, many parking spaces can be constructed, and some predetermined positions of the road will be opened for parking a battery swapping van. It can be expected that more predetermined positions of the road, even entire roads, will be opened as long as the battery swapping service that is based on a battery swapping van receives rapid development.

Due to the mobility of battery swapping vans and EVs, there are clear differences between different battery swapping service requests. To effectively carry out the battery swapping service, the battery swapping service requests are distinguished, and the battery swapping service is discussed in the next section.

4. Battery Swapping Service

In this paper, an EV battery swapping service that is based on a battery swapping van is discussed. When an EV user wants to use the battery swapping service, a battery swapping service request needs to be sent to the battery swapping service management system. Then, the battery swapping service management system assigns this request to one battery swapping van, which is in a working state in its patrolling area. After the chosen battery swapping van confirms this request, it will drive to the EV user and complete this battery swapping service.

4.1. Service Request Priority

Theoretically, EV users can launch a battery swapping service request anytime and anywhere no matter how much the SOC is. However, this will increase the workload of the entire battery swapping system as well as usage loss of batteries and devices if a battery with a relatively high SOC is swapped. Moreover, there is no doubt that this will seize the opportunity of other EV users with an eager demand for battery swapping. Therefore, it is recommended that EV users should launch the battery swapping service request when the SOC is relatively low. Therefore, a battery swapping request should first contain the information about SOC.

During one service period, the battery swapping van keeps moving, and EVs can stop to wait or keep moving until they meet each other to save time. To provide an accurate battery swapping service as soon as possible, real-time position, driving direction and speed of both the battery swapping van and EV need to be exchanged. Thus, a battery swapping request should also contain this information.

We denote $U_{id}(id = 1, 2, \ldots)$ as the EV user with an ID *id*. The EV user U_{id} launches a battery swapping service request $R_{id}(t, SOC, pos, dir)$ via the battery swapping service mobile APP at time *t*. We, respectively, denote *pos*, *dir* as the real-time position and driving direction at time *t*.

Due to the range anxiety, it is highly unlikely that EV users will launch a battery swapping request when the battery energy is exhausted. When they consider that SOC is as low as possible according to the mileage requirement, convenience, and other factors, they will choose to launch the battery swapping request. However, different EV users launch their battery swapping request with different SOCs. Therefore, to complete as many battery swapping services as possible before the battery energy is exhausted, it is necessary to distinguish different battery swapping requests and prioritize them. For EV users, the fundamental requirement is battery energy; thus, this parameter used to prioritize the battery swapping requests according to SOC. In this paper, the method of setting thresholds and dividing battery energy into several intervals is used. Table 2 shows the battery swapping request priority.

Table 2. Battery swapping request priority.

R_{id}	$SOC \le 5\%$	$5\% < SOC \le 10\%$	$10\% < SOC \le 20\%$	$SOC > 20\%$
priority	1	2	3	4

Currently, the mileage of many EVs such as the BYD-E series (305 km), BJEV-E series (200~260 km), and so on is approximately 200~300 km. The mileage of some EVs such as Tesla Model 3 (345 km), Tesla Model S (372~572 km), and so on is beyond 300 km. Without loss of generality, we choose 300 km as the mileage of EVs for the purpose of calculation in this paper. When the SOC is not greater than 5%, the EV can only drive for approximately ten kilometers or ten minutes at a speed of approximately 50 km/h. Thus, this type of battery swapping request should be responded to in a very short time and has the highest priority. When the SOC is within 5%~10%, the battery energy will not be exhausted immediately but within a relatively short time. This type of battery swapping request is reasonable and should have the second priority. When the SOC is higher than 20%, the EV can drive for at least tens of kilometers more. In most cases, this type of battery swapping request is not urgent and necessary. The priority is obviously the lowest. Generally, it will not be responded to if the battery swapping vans are busy. Moreover, if there is no convincing reason for launching the battery swapping request, the EV user will be given some price penalty or credit penalty.

The priority of battery swapping request will change over time. After waiting for a period of time, the priority of a battery swapping request may increase. The fully charged battery can support driving *s* km, and the speed of EV is *v* km/h. Let SOC_h be the SOC threshold of the higher priority.

Then, after time t_p, the priority of the battery swapping request will increase to the priority that is associated with SOC_h:

$$t_p = (SOC - SOC_h)s / v \tag{1}$$

For example, if the initial priority of battery swapping request is third, 10% < *SOC* ≤ 20%, then after $t_p = (SOC - 10\%)s / v$ time, the priority will be converted into second. Furthermore, after the $t_p = (SOC - 5\%)s / v$ time, the priority will be converted into the first. The conversion time of the battery swapping request priority is shown in Table 3.

Table 3. Conversion time of the battery swapping request priority.

Current Priority \ Next Priority	3	2	1
4	(*SOC*-20%)*s*/*v*	(*SOC*-10%)*s*/*v*	(*SOC*-5%)*s*/*v*
3		(*SOC*-10%)*s*/*v*	(*SOC*-5%)*s*/*v*
2			(*SOC*-5%)*s*/*v*

The content authenticity of the battery swapping request needs to be confirmed. Generally, high priority means that the battery swapping service will be provided to the requesting EV first. Thus, to seek a relatively high priority, some people will on purpose falsely report a lower SOC than the true values. In addition, some people will not cancel a battery swapping request immediately when they changed their battery swapping plans or decided to stop the current travel plans. Thus, we established the EV user's credit model. Let C_{id} be the current credit of the EV user U_{id}. The credit calculation is shown in Equation (2):

$$C_{id} = \begin{cases} C_{id} + \beta\alpha, 0 < \beta \le 1, \text{complete once battery swapping} \\ C_{id} - \alpha, \text{else} \end{cases} \tag{2}$$

where α is the positive constant, β is the positive decimal, C_{id} establishes the upper bound, and β decreases as C_{id} increases, which means that credit is easily destroyed but difficult to be rebuilt.

4.2. Service Request Queuing Model

The general battery swapping process is easily translatable into a service process of the queuing model, where the battery swapping service management system acts as the server, and the event of the EV user requesting a battery swapping service is modeled as the client arrival. Once the EV has completed a battery swap, the event is treated as a client departure.

From the previous analysis in Section 3, to improve the service efficiency and guarantee the EV users' satisfaction, the entire district will be divided into small service areas. Each service area has battery swapping vans that patrol it. One battery swapping van only serves the requests that belongs to its patrolling area. Therefore, each service area should have its own battery swapping service queue.

Moreover, the service area that one battery swapping request belongs to would change over time because of the mobility of EVs. When the EV drives out of one service area, its battery swapping request should be queued in the battery swapping service queue of the adjacent service area. The general battery swapping service queuing model is shown in Figure 2.

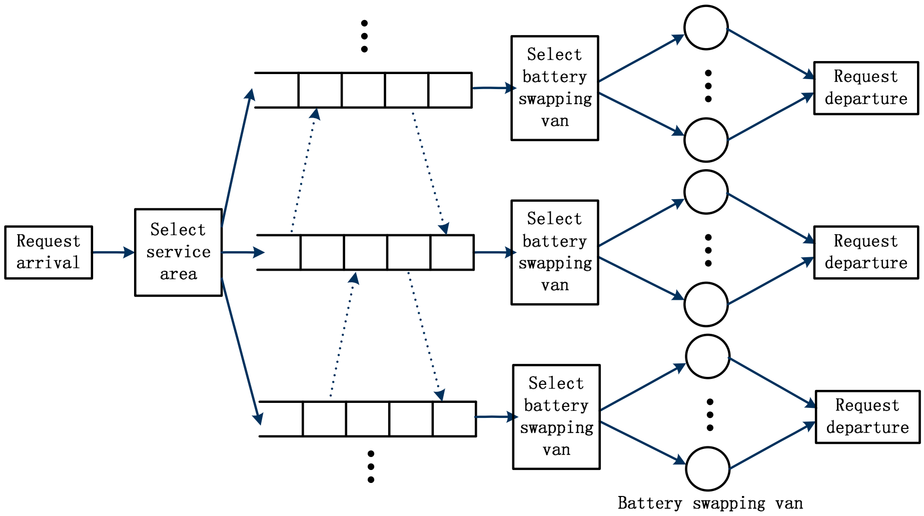


Figure 2. The general battery swapping service request queuing model.

In the battery swapping scenario, the utilization of individual EVs is normally independent from each other, which indicates that their battery swapping requests are launched independently. Therefore, for each single service area, the battery swapping service queuing model is the same. In this paper, we base our analysis on a single service area. The general battery swapping service queuing model for a single service area is shown in Figure 3.

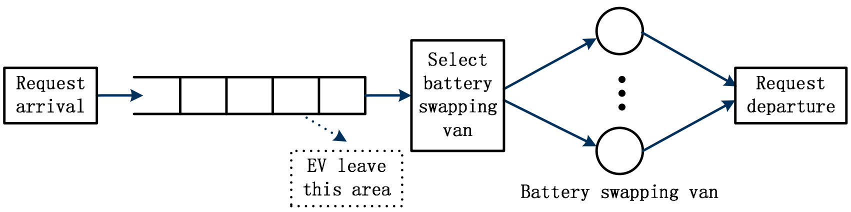


Figure 3. General queuing model for a single service area.

Based on this general battery swapping service queuing model for a single service area, there are several submodules that need to be specified to determine a representative model.

4.2.1. Request Arrival

The request arrival determines the number and frequency of the battery swapping request. For a single service area, the request arrival consists of two parts: the request launched in this area and the request transferred from the adjacent service area. Both of them are independent of each other. Commonly, we can assume a Poisson process to capture the request arrival.

4.2.2. Request Queuing Discipline

The request queuing discipline determines the order by which the requesting EVs will be served. It would refer to the next EV to swap its battery. The disciplines can include HPF (select the request with the highest priority first), FCFS (queuing requests according to the order of their request times), NJN (select the request that is spatially closest to the current position of the battery swapping van first), STDF (select the request that is the same driving direction to the battery swapping van first if the requesting EV is in a parked state), HCF (select the request with the highest credit first), etc.

The SOC is a fundamental factor for battery swapping. The HPF discipline must be considered first. To reduce the driving time and improve the service efficiency, the battery swapping van is regulated only to provide the battery swapping service in its patrolling area. According to this point, the SCF discipline seems to be adopted in our battery swapping service queuing process because it minimizes the driving distance for the battery swapping van to reach the target EV and thus reduces the time. Moreover, to reduce the risk of false reporting or to cancel the request by the EV user, the HCF discipline should also be considered. To make the driving route of the battery swapping van simpler, the STDF discipline needs to be considered. Thus, we should not queue the battery swapping service using an only one discipline but consider them together. In the next section, a further discussion will be given.

4.2.3. Request Departure

The request departure describes the specific battery swapping service process. Two factors determine the request departure process: the service time of an individual battery swapping request and the number of battery swapping vans. When a battery swapping van is selected, the requesting EV is assigned to it. The former consists of two parts: the driving time that the battery swapping van requires to reach the target EV and the time to swap a fully charged battery for the EV, which is assumed to be constant T_s. These two time periods are clearly independent of each other.

The driving time is determined by the distance between the real-time position of battery swapping van and that of the target EV, both driving speeds of the battery swapping van and target EV, and both driving directions. Moreover, the driving time is reduced with a larger number of battery swapping vans. This is because it is more likely for the requesting EV to be assigned a battery swapping van that is spatially closer.

In this section, the analysis provides a basic theoretical reference for the performance metrics. To better understand the battery swapping system that is based on a battery swapping van and to provide more efficient and reasonable battery swapping service, the battery swapping request scheduling mechanism is proposed that is based on further analysis.

5. Battery Swapping Service Request Scheduling

5.1. Request Queuing Model Adjustment

Once a battery swapping service request is assigned to a battery swapping van, it will be completed after a certain time period. This time period is the service time of the current battery swapping request. We can expect the total number of requesting EVs in the service coverage area to be relatively large, and the number of battery swapping vans is relatively low. During the service time, more than one new request would be launched. Moreover, one of the new requests would probably be assigned to the same battery swapping van if the two requesting EVs are spatially closer. Therefore, during peak commute hours, many requests would be assigned to the same battery swapping van in a short time period, and each battery swapping van would have a battery swapping service request queue. Then, the queuing model in Figure 3 will be transformed to a new one, as shown in Figure 4.

This model changes the processing steps of the battery swapping service request. When a request arrives, the first step is the selection of a battery swapping van. The request queuing process that follows some queuing disciplines is set to be the second step. With the consideration of real-time positions and driving directions of the battery swapping vans and of the requesting EV, the corresponding request is assigned to the proper battery swapping van following the principle of a spatially closer assignment.

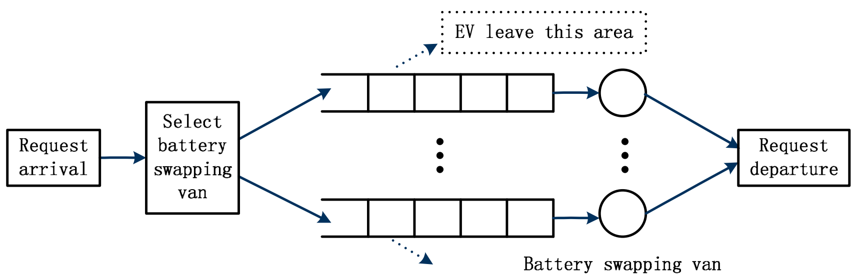


Figure 4. New queuing model for a single service area.

The queue of the entire service area is divided into several sub-queues according to the number of battery swapping vans. The request of the same sub-queue will be served by the same battery swapping van, and the number of requests of each sub-queue is significantly lower than of the entire queue. In the next sub-section, the request scheduling of a single sub-queue is discussed.

5.2. Request Scheduling for Single Battery Swapping Van

5.2.1. Waiting Time Thresholds for EV Users' Satisfaction

EV users will commonly evaluate the battery swapping service in their mind when their requests are completed. The high or low of the evaluation shows their satisfaction, which mainly depends on their waiting times. Theoretically, the shorter time that EV users wait, the stronger satisfaction they have. However, in the realistic battery swapping scenario, EV user's satisfaction does not immediately change with the change of the waiting time. It only obviously changes when the waiting time is beyond some expected threshold. Furthermore, for different EV users, their expected and acceptable waiting time thresholds are not the same.

The EV user's acceptable waiting time threshold is closely related to SOC. Definitely, only without getting a service when SOC falls below the energy threshold can the EV user feel dissatisfied. For a unified analysis, we use an acceptable waiting time threshold of request instead of that of the EV user. Table 4 shows the different waiting time thresholds of request for different satisfaction levels according to the request priority.

Table 4. Waiting time thresholds of request for different satisfaction levels.

Satisfaction / Request Priority	Very Satisfied	Satisfied	Acceptable
1 ($SOC \le 5\%$)	$SOC*s/v$	$2T_0$	$3T_0$
2 ($5\% < SOC \le 10\%$)	$(SOC\text{-}5\%)s/v$	$max(SOC*s/v, 5\%s/v + T_0)$	$3T_0$
3 ($10\% < SOC \le 20\%$)	$(SOC\text{-}10\%)s/v$	$(SOC\text{-}5\%)s/v$	$max(SOC*s/v, 10\%s/v + T_0)$
4 ($SOC > 20\%$)	$(SOC\text{-}20\%)s/v$	$(SOC\text{-}5\%)s/v$	$max(SOC*s/v, 20\%s/v + T_0)$

We establish four satisfaction levels: very satisfied, satisfied, acceptable and dissatisfied. $T_0, (2.5\%s/v < T_0 \le 5\%s/v)$ is a constant, which is set according to the commute hour. The comparison of Table 3 and Table 4 indicates that the change of EV user's satisfaction is synchronized with the change of real-time priority of the corresponding request. Both of them are defined, as SOC falls below some energy thresholds. If the request is completed before its priority changes for the first time, the service is very satisfactory. The more times the request priority changes, the lower the level of EV user satisfaction. The difference between different priority requests is the number of changes that they can endure in the same satisfaction level.

5.2.2. Scheduling Principle

We denoted T_{id}^{w} as the waiting time of EV user U_{id}, which is determined from the time when U_{id} launches the request R_{id} to the time when R_{id} is completed. We denote T_{id}^{s} as the satisfactory waiting time thresholds of R_{id} in column 3 of Table 4. If T_{id}^{w} is not greater than T_{id}^{s}, T_{id}^{w} is considered as a satisfactory waiting time. We should complete the requests within the satisfactory waiting time. From this point of view, R_{id} with a shorter T_{id}^{s} seems to be served earlier.

However, the change of request priority mainly decides the EV user's satisfaction, as shown in Table 4. Sometimes, the shorter T_{id}^{s} does not mean less SOC. It is consistent with the fact that everyone actually wants to be served earlier and has a high expectation in mind. Therefore, T_{id}^{w} should be considered instead of T_{id}^{s}, and we should also consider a request priority.

Actually, the request with priority 1 should be immediately completed, and it is not reasonable to complete the requests with priority 3 and 4 in their very satisfied waiting time thresholds if there are still requests with priority 1 and 2. Thus, the very satisfied waiting time threshold of R_{id} in column 2 of Table 4 is not considered in the request scheduling process.

We should complete as many requests as possible within the satisfactory waiting time. Therefore, based on the abovementioned analysis, three request scheduling principles can be concluded:

(1) Requests should be completed within the satisfactory waiting time as much as possible especially the requests with a priority 1 and 2.
(2) When the satisfaction level is the same, R_{id} with a higher priority should be served earlier.
(3) When both the satisfaction level and priority are the same, R_{id} with a shorter T_{id}^{w} should be served earlier.

5.2.3. Scheduling Model

When the battery swapping van is driving to the requesting EV after it accepts the request, it may receive two types of new requests: (1) the new requesting EV is on the driving route of the battery swapping van; (2) the new requesting EV is not on the driving route of the battery swapping van. The second type of request can be further divided into three types: (1) the new request has a higher priority compared with that of the current target; (2) the new request has the same priority; (3) the new request has a lower priority. Whether to change the service order or not if both orders are acceptable according to the scheduling principles and how to change the service request queuing order if more new requests arrive after we change the service order are what we need to deeply consider and determine.

To solve this problem, we divide the entire request queue of a single battery swapping van into two sub-queues: the head sub-queue Q_h and the tail sub-queue Q_t. The length of Q_h is a constant *N*. When a new request R_{id} arrives, if Q_h is not full, then enqueue R_{id} into Q_h. If Q_h is full, then enqueue R_{id} into Q_t following the scheduling principles. We only schedule the service order in Q_h. After one request is completed, the head request of Q_t will be moved into Q_h and is scheduled if Q_t is not empty. The scheduling model for the single battery swapping van is shown in Figure 5.

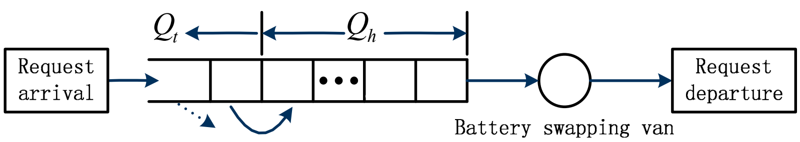


Figure 5. Scheduling model for the single battery swapping van.

In actual operations, the battery swapping service is constrained by the limited carrying capacity of fully charged batteries. Hence, the constant length *N* of Q_h should not be too large. Once the battery swapping van needs to replenish its fully charged battery supply, Q_h needs to be requeued according to the real-time position of the battery swapping van.

5.2.4. Scheduling Strategy

Based on the scheduling model, we propose a scheduling strategy that follows the scheduling principles in this sub-section.

If Q_h is assumed as $< R_1, R_2, ..., R_N >$ at time *t*, the waiting time $T_i^w (i = 1, 2, ..., N)$ of the EV user U_i is calculated as:

$$T_i^w = T_{i-1}^w + T_{i-1,i}^d + T_s \quad (3)$$

where, $T_{i-1,i}^d$ is the time that battery swapping van drives to U_i. $< T_1^w, T_2^w, ..., T_N^w >$ is consequently obtained.

Satisfied scheduling permutation: For *N* requests of Q_h, if in a request permutation $P_j =< R_1, R_2, ..., R_N >$, $(j \in 1, 2, ...N!)$, $T_i^w \le T_i^s$ for each R_i, then P_j is a satisfied scheduling permutation.

For Q_h, there may be more than one satisfied scheduling permutation. We continue to consider request priority. We denote O_i as the value of priority of R_i. For the pair of any two requests $< R_i, R_j >, (i < j)$ in one P_j, if $O_i \le O_j$, then $< R_i, R_j >$ is called a positive-order pair.

Positive-order satisfied scheduling permutation: For Q_h, a satisfied scheduling permutation that has the most positive-order pairs is called a positive-order satisfied scheduling permutation.

There still may be more than one positive-order satisfied scheduling permutation, where the average waiting time $\overline{T^w}$ of *N* requests in a scheduling permutation is considered to serve more requests. $\overline{T^w}$ is calculated as:

$$\overline{T^w} = \sum_{i=1}^{N} T_i^w / N \quad (4)$$

Finally, we determine the positive-order satisfied scheduling permutation with the minimum $\overline{T^w}$ and provide the battery swapping service following the requesting order.

If there is only one satisfied scheduling permutation, then it is our needed scheduling result. If there is no satisfied scheduling permutation, then a permutation with a satisfied scheduling of request with priority 1 and 2 should be chosen and scheduled following the abovementioned process.

Then, we propose a minimum waiting time based on priority and satisfaction scheduling strategy (MWT-PS), as shown in Figure 6.

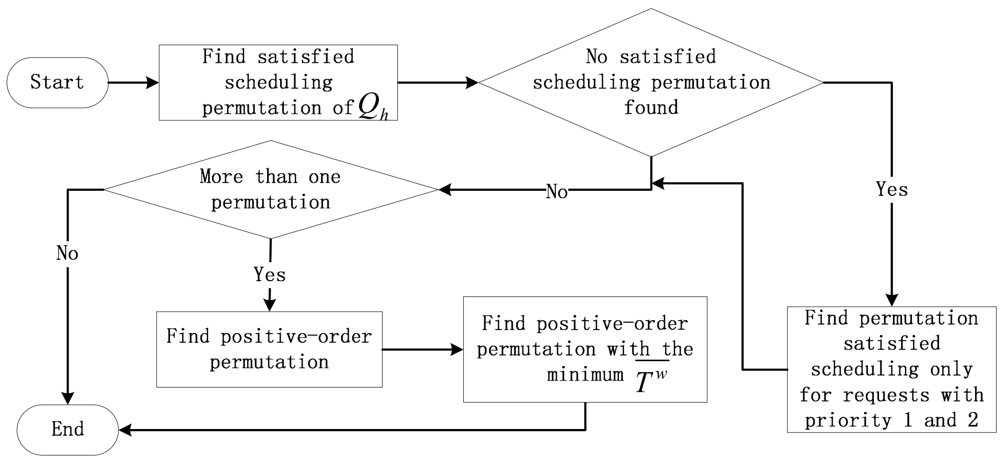


Figure 6. MWT-PS scheduling strategy.

6. Simulation Results

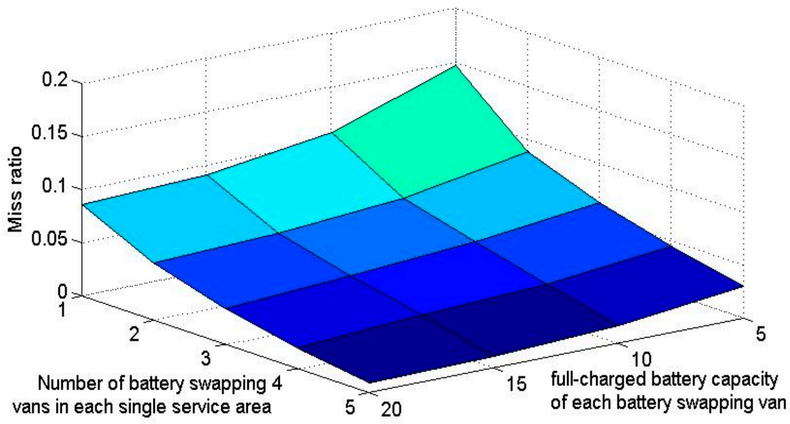
In this section, the battery swapping service is simulated, and the performance of MWT-PS is evaluated. We chose an urban environment that is approximated by the Haidian district in Beijing as the simulation scenario. The entire simulation scenario is divided into four service areas of equal size. We assume that the battery swapping vans are able to complete the battery swapping requests of EVs at any location.

In the design of a mobile battery swapping system, in general, there are some parameters that will significantly affect the performance of the system. We evaluate the system design using two main metrics that represent how well this system is operating. The first metric is the miss ratio r_m, which considers the number of requests that are not completed by the acceptable waiting time of the EV. We denoted M as the total number of requests served during the mobile battery swapping process, and M_0 as the number of requests that fail to be completed. r_m is calculated as:

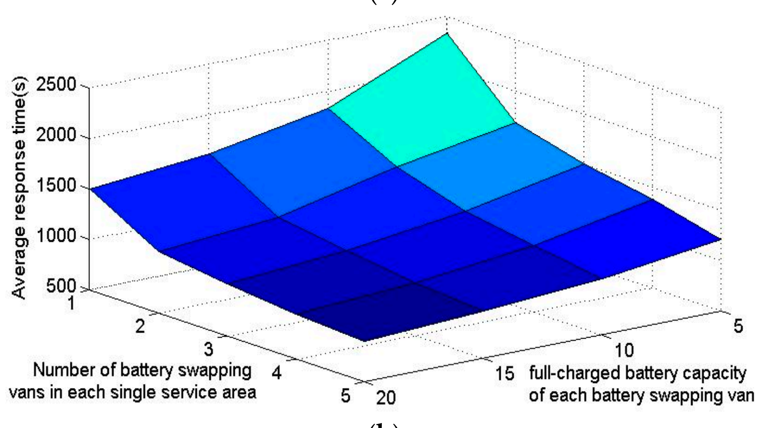
$$r_m = M_0 / M \quad (5)$$

The second metric is the average response time, which is defined as the time taken from when the EV sends out its battery swapping request to the time the request is completed.

In this paper, a fully charged battery is swapped with a fixed swapping time. Due to the limited carrying capacity of the fully charged batteries of each battery swapping van, the battery swapping van without any available fully charged batteries needs to return to battery swapping stations to replenish fully charged batteries. Figure 7 presents their impact on the mobile battery swapping service, examines the number of 1–5 for battery swapping vans in each single service area and the fully charged battery capacities of 5–20 for each battery swapping van.



(**a**)



(**b**)

Figure 7. performance evaluation with respect to the number of battery swapping vans and fully charged battery capacity (**a**) miss ratio; (**b**) average response time.

Larger battery swapping vans and larger fully charged capacity improve the performance in terms of both the miss ratio and average response time, which is intuitive. Although the small fully charged battery capacity seems to lead to large miss ratio and average response time because of a relatively frequent fully charged battery replenishment, the large fully charged battery capacity cannot clearly improve the performance metrics, especially when the number of battery swapping vans is larger than 2 in each single service area. Thus, the number of battery swapping vans and the performance of service queue scheduling are more important as long as the fully charged battery capacity is not too small.

We further evaluate the performance of service queue scheduling and compare between three service scheduling disciplines: FCFS strategy, NJN strategy, and our MWT-PS strategy with five battery swapping vans, each with a fully charged battery capacity of 20 in a single service area. In addition to the miss ratio and average response time, there is still an important metric. It is the satisfaction ratio with priority 1 and 2, which considers the number of requests with priority 1 and 2 that are completed by the satisfied waiting time of the EV. The calculation of satisfaction ratio is similar to the miss ratio. Figure 8 shows the change of three performance metrics with the increasing battery swapping service requests in a commute hour. The results show that the battery swapping service system with our MWT-PS service scheduling strategy can provide a relatively high-quality battery swapping service for the EV users, especially those with more eager requirement for the battery swapping service. The average response time is obtained in the experimental scenario. In the actual battery swapping service scenario, the time may increase to a certain extent due to device standardization, proficiency, traffic, and other force majeure.

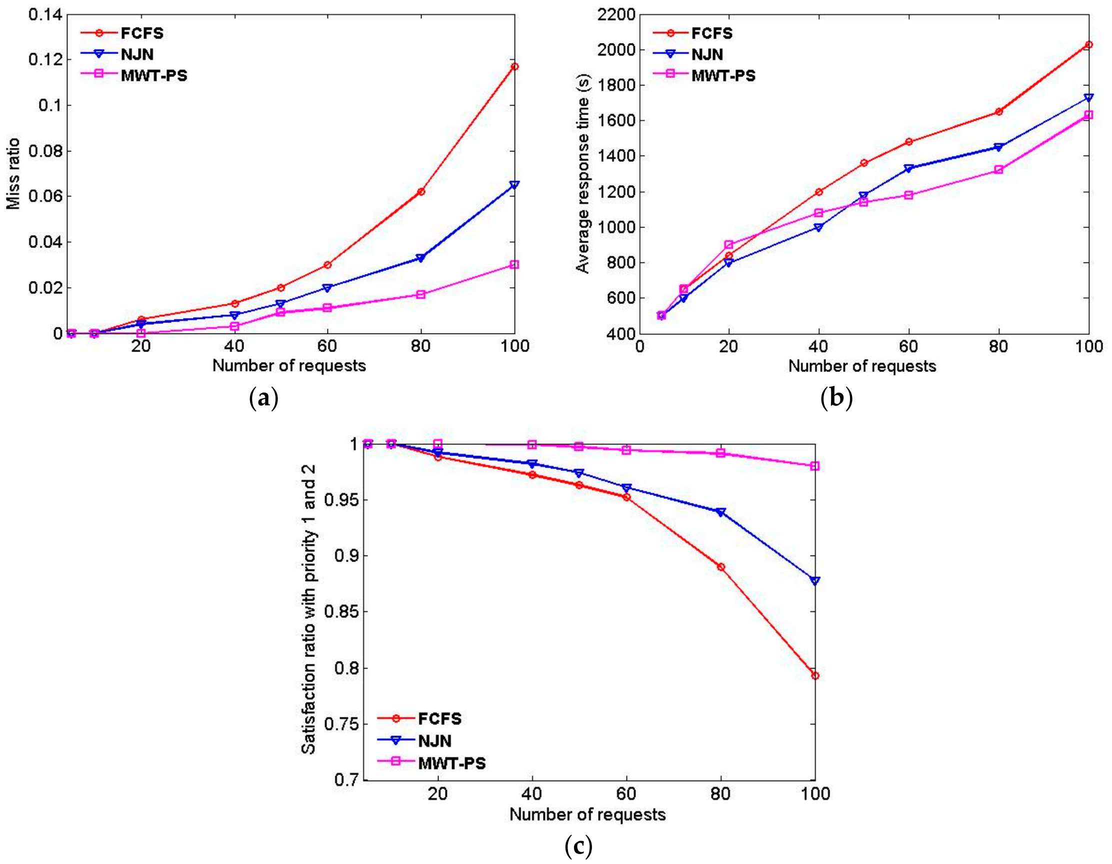


Figure 8. Performance evaluation with respect to the number of requests (**a**) miss ratio; (**b**) average response time; (**c**) satisfaction ratio with priority 1 and 2.

The realization of battery swapping systems that are based on mobile battery swapping vans is still a significant engineering challenge. However, there can be a design possibility for a mobile battery swapping system, and the simulation results show that this novel approach can be used as a reference for a future system.

7. Conclusions

This paper presents a novel approach for providing a battery swapping service for EVs, which is provided by mobile battery swapping vans. A battery swapping van can carry tens of fully charged batteries and drive to an EV to swap a battery within a relatively short fixed period of time. A reasonable EV battery swapping architecture that is based on a battery swapping van is established in this paper. The function and role of each participant and relationships between each participant are determined, especially their changes compared with the battery charging service. The profit mode and some practical factors are discussed. The battery swapping service is described in detail. We set the priorities of the battery swapping service requests according to SOC and their corresponding changes. The general service request queuing models for the entire battery swapping system and single service area are presented. To provide the battery swapping service efficiently and effectively, the battery swapping request scheduling is well analyzed, and the MWT-PS scheduling strategy based on priority and EV users' satisfaction is proposed. Finally, the battery swapping service is simulated, and the performance of MWT-PS is evaluated in the simulation scenarios. The simulation results show that this novel approach can be used as a reference for a future system and provides a reasonable and satisfactory battery swapping service for EVs. As a future work, we will seek to study the exact specifications of implementation of a battery swapping service that is based on battery swapping vans to make the mobile battery swapping system come true earlier.

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Conflicts of Interest: The authors declare no conflict of interest.

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