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Analysis of the Potential of Battery Swapping, Transporting, and Sharing for Electric Taxi Fleets Based on Agent-Based Model

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ABSTRACT

Battery electric taxis are progressively supplanting conventional taxis as a primary mode of transportation, promoting energy conservation and the reduction of carbon dioxide emissions. As an emergent technology, battery-swapping presents several potential advantages but also raises concerns regarding its efficacy, environmental impact, and integration with existing charging infrastructure. This paper introduces and examines four distinct energy replenishment methodologies implemented: Direct Charging, Battery Swapping, Battery Transporting, and Battery Sharing. To assess the performance of these approaches, an agent-based model was developed to simulate driver usage behavior under various mode combinations and four distinct scenario settings. The paper conducts a comparative analysis of traditional taxi charging and direct battery exchange, identifying a selection rate within 5% when ample battery-replacement stations are available. Simulation comparisons of novel charging modes reveal that battery transportation mode is superior with a smaller number of drivers, while the battery sharing mode demonstrates enhanced performance with a larger driver pool. This research provides a valuable instrument for evaluating energy replenishment strategies, facilitating the transition to low-carbon transportation in the context of future smart city development.

Keywords: battery electric taxi, battery swapping, battery sharing, agent-based model, simulation

1. INTRODUCTION

In recent decades, climate change caused by the greenhouse effect is seriously affecting future human survival. Without intervention, in 2030, the total greenhouse gas emissions from vehicles in six countries can reach 2.6 gigatons[1]. As governments around the world gradually attach importance to global climate change, a series of carbon emission plans such as carbon peak and carbon neutrality are gradually implemented[2]. At the same time, electric cars have been widely promoted as a solution to the global problem of greenhouse gas emissions[3], with many governments implementing policies and incentives to encourage the adoption of electric cars.

Although electric taxis are more energy-saving and environmentally friendly, the widespread adoption of electric taxis increases the demand for charging infrastructure. Fast charging stations begin to emerge in urban areas[4], however, they are still not fast enough to meet the high demand for charging from electric taxi fleets. As a result, electric taxi fleets often require more specialized charging infrastructure, such as battery-swapping, in order to meet their needs[5].

In recent years, many newly produced electric vehicles have been equipped with intelligent batteries supported by the Internet of Things (IoT) technology[6]. These intelligent batteries can provide detailed and comprehensive records of a vehicle's real-time GPS position and state of charge (SOC). Driven by real electric vehicle battery information data and electric taxi GPS trajectory data, this study explores the potential benefits and impacts of four energy replenishment modes: Direct charging, battery swapping, battery transporting, and

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battery sharing. In the method section, we first extract real electric vehicles' charging and discharging patterns from their battery information and then simulate the battery usage for electric taxis. To evaluate the potential of the four energy replenishment modes, we set up a bottom-up Agent-Based Model to simulate the traveling and energy replenishment behavior of Electric Taxi Fleets under different energy replenishment modes.

2. RELATED WORKS

Past studies have shown that road transportation is one of the important causes of air pollution[7], where more than 75% of carbon dioxide emissions come from vehicles, especially taxis. Pollution levels are increasing year by year[8]. To deal with the pollution caused by vehicles, the energy used by vehicles is urgent modified. Shi X[9] found that replacing ordinary vehicles with electric vehicles is a feasible way that can effectively prevent global warming and protect the ozone layer. Teixeira A C R[10] found that even if the most unfavorable power generation state, the carbon emissions of ordinary vehicles will be several times more than that of electric vehicles. Therefore, many countries have begun to promote electric vehicles[11, 12].

Researchers have analyzed and improved existing electric vehicles' battery usage and charging convenience. Zhang H[13] et al. calculated the usage status and demand of battery electric vehicles(BEVs) in Japan and believed that the current technology, especially the battery and charging-related infrastructure, has a large gap. At the same time, the simulation experiment of Hu L[14] in New York, USA, shows that current charging piles are insufficient to replace electric taxis for ordinary taxis. But they believe that electric taxis will perform better after charging stations become popular. All in all, the main factor restricting the development of electric vehicles is charging. On the one hand, Due to the small number of charging stations, the additional charging cost for drivers is high. On the other hand, most drivers cannot store spare batteries for replacement due to the high price.

Some of the researchers sought the best electric vehicle by comparing the performance of electric vehicles with multiple energy sources. The existing electric vehicles are roughly plug-in hybrid electric vehicles, ICE Vehicle, Hybrid Electric Vehicle[15], and BEV. After comprehensively comparing carbon emissions, battery life, and many other factors, it can be found that BEVs have apparent advantages over different types of electric vehicles[16], and replacing the battery can alleviate the problem of slow charging to a certain extent. Other researchers believe this problem can be optimized by modifying the location of the charging station.

To mitigate greenhouse gas emissions, promoting electric taxis is crucial. Despite research on optimizing charging routes and station locations, battery replacement has been overlooked due to high costs. However, for taxis under the same company, battery replacement is viable, offering more possibilities for electric taxi development and reducing gasoline taxi reliance. Existing research primarily focuses on battery types, charging station locations, and optimal routes. This paper emphasizes innovation in charging modes.

3. PROBLEM DESCRIPTION

While private BEV owners may not experience many charging issues due to their shorter daily travel distances and the ability to charge their vehicles overnight, taxi drivers face more pressing concerns. The time spent charging or traveling to a charging station represents an economical cost, leading these professionals to optimize their charging strategies and routes to minimize this cost. As the battery-swapping mode becomes available, electric vehicles will have a greater variety of energy replenishment options in addition to the existing charging modes.

This paper introduces and discusses four different energy replenishment modes that have been implemented or are currently under development to address these challenges, as shown in Fig.1. The operating methods for these modes are as follows:

- **Direct charging:** In this mode, the vehicle stays at the charging station for a long time to charge its battery.
- **Battery swapping:** In this mode, the vehicle only needs to stay at the charging station for a short time to complete the disassembling and reinstallation of the battery.
- **Battery transporting:** In this mode, the charging station sends out several battery transporters with batteries to increase its reach. Taxi drivers can complete the battery exchange without coming to the charging station.
- **Battery sharing:** In this mode, taxis can exchange batteries with each other whenever it is convenient and possible. When a taxi with a low battery initiates a request for a battery exchange, the system selects the best idle taxi with sufficient power to perform the exchange.

The specific rules for the four different energy replenishment modes considered in the simulation are explained in Section 4.

4. METHODOLOGY

4.1 Framework

The simulation methodology comprises two parts: input data selection and taxi movement state simulation. Initial data includes taxi ID, time, latitude, longitude, and passenger status. A new dataset is created from drivers with the most data, and the experimental area is divided according to the community discovery algorithm, with core locations representing charging stations. This ensures a realistic charging station distribution while maintaining fixed numbers for comparison.

After establishing the dataset and charging station locations, the simulation begins. Taxis follow two movement patterns based on remaining battery power. With sufficient battery, taxis follow their original trajectory, consuming battery relative to distance traveled. With low battery and no passengers, taxis deviate from their trajectory to charge using a suitable method. The simulation measures extra distance and time consumption related to charging and returning to the original trajectory. Average additional time consumption and charging method selection rates are used to evaluate the effectiveness of the current scheme.

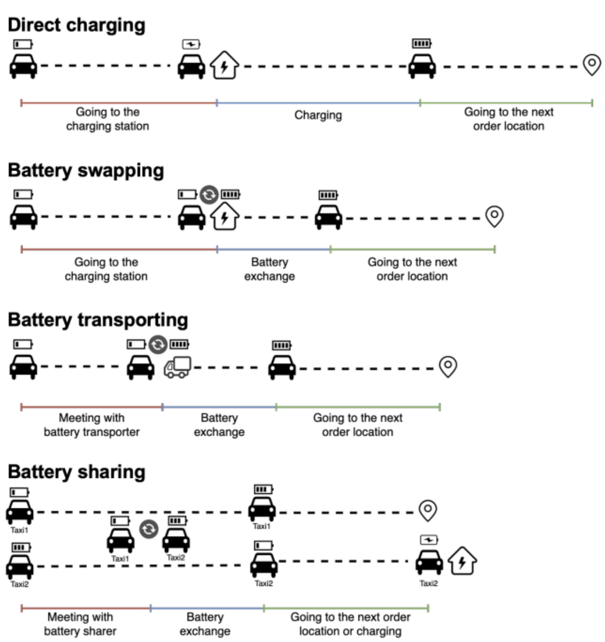

Fig. 1. Four different energy replenishment modes

4.2 Simulation of the four energy replenishment modes

This section highlights differences between four energy replenishment modes:

Direct Charging (Fig.1-A): Idle taxis with less than 20% power select the nearest charging station, minimizing charging time. The taxi charges for an hour, unable to move or carry passengers, and then proceeds to its destination fully charged.

Battery Swapping (Fig.1-B): Similar to direct charging, but taxis quickly exchange depleted batteries for fully charged ones at charging stations, reducing the process to 10 minutes.

Battery Transporting (Fig.1-C): An advanced version of battery swapping, where battery transporters deliver fully charged batteries to taxis on request. This saves time and expands charging station influence, meeting city-wide charging needs with fewer stations.

Battery Sharing (Fig.1-D): Taxis exchange batteries with each other to minimize extra distance during charging. Suitable taxis have higher battery levels and shorter detours to the next destination. After exchanging batteries, one taxi continues with a higher charge, while the other proceeds to a charging station en route to its destination.

4.3 Description of the simulation process

After determining the number and location of charging stations, the battery sharing system began to operate. This system divides taxis into four statuses: parking, driving, charging, and loading passengers. The parking state means the taxi has stayed in the same place for more than 10 minutes. This part of the taxi drivers may be resting. Therefore, these taxis do not consume power and cannot participate in battery sharing. A moving taxi means that it has no passengers yet, and it is moving into the city to find the next passenger. The movement trajectory of this part of the taxi is based on the actual data. The taxis with lower battery power (less than 20% of the remaining power) will find a suitable charging mode and change their trajectory. And taxis with higher power (remaining power of more than 80%) can be selected to participate in battery sharing to help low-battery taxis, thereby reducing the total extra charging time of all taxis. The taxis in the charging state include all taxis that are charging or assisting in charging and they will ignore the new order requests until they finish charging. After entering the charging state, the taxi will prioritize completing the charging task and not participate in passengers' carrying or another new battery sharing. When the taxi has passengers, it needs to prioritize the passengers to the destination. The taxi will not enter the charging state when the power is less than 20% to ensure the passengers' experience, and it will charge after the passenger arrives at the destination.

Then began to simulate the changes in the state of each taxi in each frame(every 30 seconds is considered a frame), including the longitude, latitude, remaining power, and status of the vehicle. Firstly, the position of the non-charging taxi is updated based on the historical trajectory information, and the taxi in the charging state will follow the selected charging route. After determining the position change, the taxi that has changed the position will deduct the remaining power corresponding to the travel distance. A taxi that has not changed its position will determine how long it has stayed at the same point, and if the stop time of this taxi exceeds a certain threshold, its status will be converted to parking. After the battery power is updated, taxis with remaining power greater than 80% and driving status will be considered as possible battery sharers, while taxis with remaining power less than 20% and driving status will be required to be charged.

After the selection of the charging route is completed, the status of the taxi that needs to be charged and the selected battery provider is set to charging, and they will proceed according to the new route before they arrive at the starting place of the following order. When the taxi arrives at the starting place of the next order, it will pick up the passengers, does not participate in battery exchange before sending the passengers to the destination, and will not detour to charge. After all the taxi statuses are updated, the simulation of this frame ends.

5. RESULTS AND DISCUSSION

5.1 Data description

This study uses two BEV trajectory datasets: a small dataset with battery information and a big dataset without battery information. Here we will briefly introduce the two datasets.

Small dataset with battery situation: This dataset consists of data collected from 314 electric vehicles in Shanghai over a period of 92 days from October to December 2020. Each record includes the vehicle ID, the time the data was collected, the longitude and latitude coordinates, and the state of charge of the vehicle's battery. The dataset also includes information about the type of vehicle (sedan, SUV, or MPV) and the power capacity of its energy device.

Big dataset with order infomation: This dataset consists of data about 18,868 BETs in Shenzhen for one day, with each record containing the vehicle ID, time, longitude and latitude coordinates, and operation status (whether the taxi had passengers or not at that time).

5.2 Comparison of direct charging and battery swapping

Direct charging mode is now the most mainstream charging method. But obviously, direct charging mode is very similar to battery swap mode, and when other conditions are the same, the charging time of battery swap mode must be less than direct charging mode. In this chapter, the charging modes only consider these two cases, first selecting a specified number (10-50) of charging station locations and randomly setting a small part (5%-25%) of the charging stations as battery swapping stations that can exchange batteries quickly. Other charging stations can only charge directly to compare the impact of battery replacement methods on traditional charging stations. Due to the randomness in the experiment process, to ensure the reliability of the experimental results, this paper carried out 100 repeated experiments by setting different random seeds. The results of the experiment are shown in Fig.2. The light-colored area of each color shows the highest and lowest percentage of the taxis that have selected the charging station that can replace the battery. The dark solid line is the average during the entire experiment.

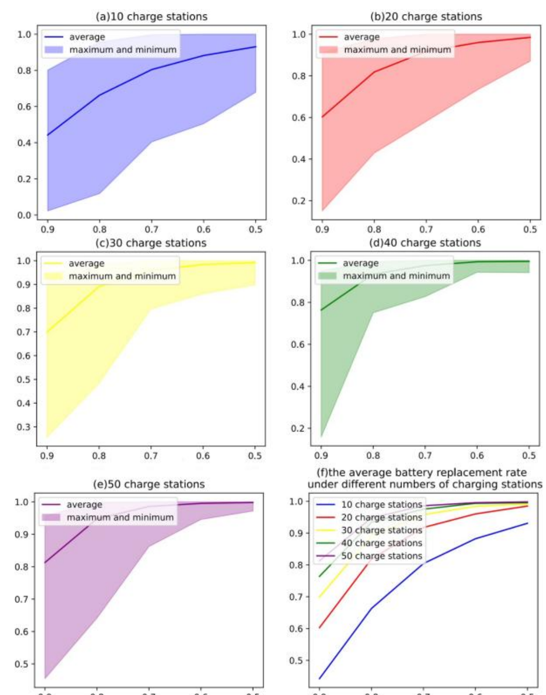

Fig. 2. The comparison results of direct charging mode and

When the number of charging stations and battery swap stations is small, the location of the battery swap station is randomly selected from the charging stations. It is not easy to distribute it in the entire city evenly. So the driver’s selection rate of battery replacement mode fluctuates wildly. However, it can be found in many experiments that when the number of battery swap stations exceeds a certain threshold, most drivers will be more inclined to choose this charging mode without considering the queuing time. This conclusion shows that battery exchange technology can solve the problem of hard-charging of taxis to a large extent in the future, and the direct charging mode can be ignored in the following experiment.

5.3 Comparison of the effects of various charging modes

The remaining three charging modes will not wholly replace each other. Therefore, this section will analyze the following four charging situations based on the battery swap mode: battery swap only, battery swap + transportation, battery swap + sharing, and above. In the battery sharing mode, two taxis participate in the charging together. This experiment compares the sum of the extra distance the taxis need to charge and the time waiting for docking with other vehicles. As shown in Fig.3, after comparing four different energy replenishment modes under the different numbers of charging stations and different numbers of drivers, the selection rate of different charging methods, the average extra time spent on different charging modes, and the total average extra charging time are compared, this paper obtains the conclusions as follows:

1. Battery transportation and sharing reduce extra charging time for taxi drivers, making charging more convenient. Their combined use further reduces charging time.
2. Battery transportation significantly reduces average charging time when transporters are relatively idle. However, its effectiveness decreases with fewer transporters and more drivers needing charging.
3. In battery sharing mode, extra distance from detours affects the selection rate and average extra time. This mode performs better in areas with scarce charging stations and numerous drivers, surpassing battery transportation in such conditions.

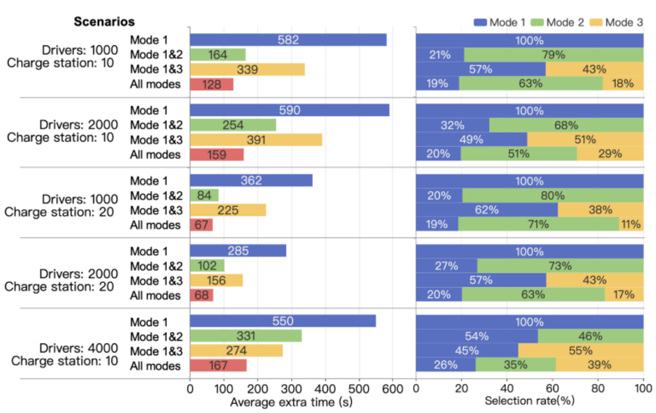

Fig. 3. The performance of three different charging modes in different scenarios

6. CONCLUSIONS

Electric vehicles, including taxis, address greenhouse gas emissions, with governments providing incentives for adoption. Battery swapping technology may meet the growing energy replenishment demand. This paper investigates battery-swapping-based replenishment mode benefits and impacts.

Initially, the paper compares traditional taxi charging with direct battery exchange, revealing a selection rate within 5% when sufficient battery-replacement stations exist. Simulation comparisons of new charging modes show battery transportation mode excels with fewer drivers, while battery sharing mode performs better with more drivers.

Though battery swapping technology faces challenges, it may become significant urban infrastructure as batteries adopt unified standards. Our research offers a valuable tool for evaluating energy replenishment modes, aiding the transition to low-carbon transportation in future smart city design.

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DECLARATION OF INTEREST STATEMENT

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

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