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RESEARCH ARTICLE

Electrifying Urban Transportation: A Comparative Study of Battery Swap Stations and Charging Infrastructure for Taxis in Chicago

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ABSTRACT In recent years, the Electric Vehicles (EVs) industry has experienced rapid growth, driven by advancements in battery technology, environmental awareness, and government incentives. However, traditional charging infrastructure's limited availability and long charging times pose significant challenges, especially for long-distance travel and public service vehicles like taxis, buses, and law enforcement vehicles. This work explores the innovative concept of Battery Swap Stations (BSSs), an emerging technology poised to transform the EV charging landscape. It specifically focuses on electric taxis operating in Chicago's urban environment, highlighting the substantial benefits this technology can offer. BSSs demonstrated to dramatically reduce charging times, improving taxi service efficiency and increasing revenue potential. Instead, conductive charging impacts the working time of taxis across all case studies (as observed in the Level 2 charger scenario) While BSS technology has its drawbacks, such as optimal location challenges and battery management complexities, it has the potential to significantly enhance service quality. Additionally, these stations hold the promise of not only increasing urban transportation system efficiency but also contributing to their sustainability.

INDEX TERMS Electric vehicles, battery swap, charging stations, electric taxis, smart mobility.

LIST OF ABBREVIATION

AC	Alternating Current.
B2G	Battery to Grid.
B2B	Battery to Battery.
BSS	Battery Swap Station.
BEV	Battery Electric Vehicle.
DC	Direct Current.
EV	Electric Vehicle.
G2B	Grid to Battery.
GHG	Greenhouse Gas.
ICE	Internal Combustion Engine.
RES	Renewable Energy Source.
SOC	State of Charge.

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NOMENCLATURE

$Batt_{rec}$	Percentage of battery recharged.
C_{batt}	Battery capacity.
E_{el}	Energy consumption.
F_{aer}	Aerodynamic resistance.
F_{rot}	Rotational resistance.
F_{tot}	Total force.
F_{trac}	Traction force.
Ft_{start}	Starting tractive effort.
P_{aux}	Power absorbed by the auxiliary.
P_{char}	Power of the charger.
P_{el}	Power consumption.
SOC	State of Charge.
$T_{\mathrm{positioning}}$	Positioning time.
T_{swapping}	Swapping time.
T_{tot}	Total swapping time.
T_{waiting}	Waiting time.

TD	Total Distance.
TD_e	Total Distance without passengers.
TD_p	Total Distance with passengers.
a_m	Maximum acceleration for comfort.
c	vehicle consumption for the specific trip.
c_{batt}	Battery consumption.
c_{city}	Average consumption per km in city path.
c_{hg}	Average consumption per km in highway path.
d_{ij}	Distance of the trip from zone i to zone j.
$de(t)$	Deceleration at time t.
km_{trip}	Total distance covered in the trip.
n	Total number of trips.
m_{eq}	Equivalent mass.
t	Available time for charging.
v	Speed.
v_{ij}	Speed of the trip from zone i to zone j.
β_{reg}	Percentage of regenerative braking.
η_b	Braking efficiency.
η_c	Charger efficiency.
η_t	Traction efficiency.

I. INTRODUCTION

Currently, the transportation sector accounts for 12% of the total Greenhouse Gas (GHG) emissions [1], [2]. To promote more environmentally friendly transportation and reduce pollution in urban areas, vehicle electrification stands as an interesting solution among various alternatives [3], [4]. Among different types of Electric Vehicles such as hybrid electric vehicles, fuel cell electric vehicles, and range-extended electric vehicles, Battery Electric Vehicles (BEVs) stand out as the most environmentally friendly choice, primarily due to the complete absence of tailpipe emissions [5]. This is possible through the replacement of the Internal Combustion Engine (ICE) with an electric motor that is powered by a battery pack [6]. The primary limitation of an EV lies in its range, which can vary from 250 km up to 500 km depending on the capacity of the battery. However, it still remains much lower with respect to the ones of traditional ICE vehicles. Other significant issues are related to batteries include their high cost, limited lifespan, and insufficient energy storage capacity [7], [8], [9]. Furthermore, potential buyers are often held back by the availability of charging stations and long charging times [10], [11], [12]. Most of the driver's concerns, especially those related to range and charging, can be alleviated thanks to adequate infrastructure developments. While several technologies exist, traditional charging stations are the most widespread. These stations allow drivers to recharge their vehicle's battery by connecting a cable from the charging point to their car. They offer three different charging levels, with higher levels providing faster charging capabilities due to increased power delivery [13], [14]. Some alternative solutions, like inductive charging and BSSs, have been developed but are not universally available in all markets. The inductive charging technology is currently being investigated for both light and heavy-duty vehicles in static and dynamic conditions, for example in 'Arena del Futuro' project [15], [16]. BSS first appeared in 2012 in Israel by Better Place and later in the United States with Tesla [17], [18]. However, both of these early endeavors faced challenges and ultimately failed due to the limited adoption of electric vehicles at that time. Recently, these stations have reappeared in China, where Nio has taken a prominent role in deploying 1400 BSSs, with ambitious plans to expand this network to 24,000 stations by the year 2025 [19]. It is going to be a huge test environment to see if the technology succeeds. This study aims to evaluate the practical advantages of embracing an innovative charging solution known as BSS, as an alternative to traditional charging stations, which are known to be time-consuming. Right now many governments and policymakers are incentivizing or forcing the adoption of EVs and the reduction of ICE vehicles. From the infrastructure point of view, the charging station takes the vast majority of EU funding [20], [21]. Is it worth noticing that many cities, including Shanghai and Shenzhen, have vigorously promoted the development of electric taxis by introducing electric vehicles into public transportation service systems [22]. Furthermore all taxis in Beijing are planned to be replaced with EVs [23]. To assess the practicality and convenience of this emerging technology, a specific real-world scenario within the city of Chicago has been analyzed. The objective is to conduct a comparative analysis of real data to determine whether BSSs offer tangible benefits compared to traditional public station charging options, Level 2 AC charging, and DC fast charging stations. The use case chosen is a taxi, as it has a higher utilization rate than a private car and therefore a higher battery depletion rate during an average day. The taxi also has a high cost of idle time, since the productive asset cannot be used and a driver could be stuck in a non-value-added activity. Taxis, on the other hand, are concentrated in dense urban areas where EVs perform better in terms of consumption compared to ICE vehicles, and drivers are complaining on media about chargers availability [24].

II. TRADITIONAL CHARGING AND BATTERY SWAP STATIONS

Battery swap station represents an alternative to conventional charging infrastructure, where drivers can swap their discharge battery with a fully charged one in only a few minutes. This approach ensures a level of service comparable to that of traditional fuel stations. Notably, one of the key advantages of BSSs is their speed, which addresses the significant limitation of traditional charging stations [25]. While Level 2 charging stations may take several hours to fully charge a vehicle, even fast-charging stations can still require around 30 minutes or more to achieve a substantial charge. This can be a significant inconvenience for drivers, particularly on long journeys where they need to take extended breaks to recharge [13].

The swapping process starts once the car is correctly positioned outside the station, in the design area. From there, the vehicle automatically drives into the station where is raised thanks to a lift., the battery is first unlocked and then vertically lowered downward. This is made possible by lifting equipment located in a pit beneath the vehicle. The depleted battery is then transported to a nearby recharging center using a separate lift. Simultaneously, a previously charged battery is selected, removed from one of the recharging units, and then transported from the recharging center to the first lifting mechanism. Here, the new battery is correctly aligned and lifted into the vehicle for installation Subsequently, the electric vehicle is lowered back to the ground and is now equipped with a fully charged battery, ready to leave the station [26]. The time required for the entire process may vary and includes three different components:

1) Positioning Time ($T_{\text{positioning}}$): It is the time required for the vehicle to be properly positioned in the station.
2) Swapping Time (T_{swapping}): This is the actual time required to remove the old battery and install the new one.
3) Waiting time (T_{waiting}): Refers to the duration the driver spends in a queue. It may be equal to zero if there are no other vehicles utilizing the station.

Total swapping time can be calculated using 1.

$$T_{\text{tot}} = T_{\text{positioning}} + T_{\text{swapping}} + T_{\text{waiting}} \tag{1}$$

However, these stations offer several other advantages beyond reduced charging times. As electric vehicles gain popularity, they can alleviate service pressure on traditional charging infrastructure by providing an alternative solution. Demand for electrical energy and its impact on the grid are two crucial factors that must be taken into consideration. The primary issue is related to demand uncertainty and variability that depends on numerous factors such as traffic flows, routes, and hours [27], [28]. This problem is directly linked to energy consumption: if the demand is high the station will need to resort to purchasing energy in the volatile real-time market, in addition, it might need to offer discounts for non-fully charged batteries or it might be unable to guarantee the service. On the other end, if the demand is lower, the excess energy can be sold in the real-time market or stored in batteries for later use. Estimation of demand must be done to find the best location, making the initial battery investment, and ensuring sufficient battery capacity to satisfy the daily demand. To efficiently recharge all the batteries and maintain competitive costs, these stations need to interact bidirectionally with the power system [29]. The stations maximize profitability by purchasing energy during low-cost periods of the day for battery charging, utilizing the Grid to Battery mode (G2B). During high-cost periods, these stations can switch to Battery to Grid (B2G) mode, selling excess electricity back to the grid by discharging batteries. Additionally, they can optimize energy consumption by transferring energy between batteries through Battery to Battery (B2B) mode [30]. Considering the high electricity consumption of each station for recharging batteries, renewable energy sources (RES) can be used when constructing these stations, including solar photovoltaic panels and Wind energy [31]. Optimizing the use of RES not only reduces supply costs from the energy market but also lowers emissions of pollutants such as CO2 and NOx. Nevertheless, the integration of intermittent energy sources into the current power infrastructure poses significant challenges. Addressing issues related to frequency fluctuations and power quality becomes imperative to ensure the stability and reliability of the power system [32].

TABLE 1. Units for magnetic properties.

Advantages	Disadvantages
Fast service	Location and availability
Alleviate service pressure on traditional charging infrastructure	Demand uncertainty and variability
Better interaction with the grid	More complex infrastructure
Leasing service and battery management	state and performance of the batteries

Furthermore, BSS introduced a new option for battery ownership, the leasing service. Without this typology of service, each driver must return to the station of the initial battery swap, resulting in time loss for drivers and space inefficiency for the station as they store and recharge batteries awaiting their owners. In this way drivers are freed from maintenance worries, stations avoid managing individual batteries, and the costs of vehicles are reduced [33]. The centralized management of battery recharging by the station further adds to the benefits, enabling strategic load shifting to off-peak hours. By distributing EV charging more evenly throughout the day, battery swap stations play a key role in mitigating the challenges associated with simultaneous power peaks from both EVs and residential loads allowing an efficient resource utilization [34].

Despite the introduction of a leasing mode, battery degradation and ownership can still represent an obstacle. Some EV owners may still experience apprehension related to the state and performance of the batteries in their vehicles. Nevertheless, other concerns are still present especially linked to the availability of these stations, their optimal number and location. [35]. As BSSs represent a relatively new technology, their adoption and proliferation are currently limited to China, with some experimentations in northern Europe [36]. In contrast, traditional charging stations are widespread and experiencing rapid growth, easily accessible in the most developed EV markets [37]. Additionally, different models of cars are provided with different batteries, and this must be considered in both the planning and operation stages to satisfy the demand. Currently, there are no international standards for swapping stations and battery packs, limiting the use of BSS to specific vehicles. To serve all customers, stations must be equipped with a stock of batteries with different capacities and characteristics [27]. The main advantages and disadvantages of BSSs are summarized in Table 1.

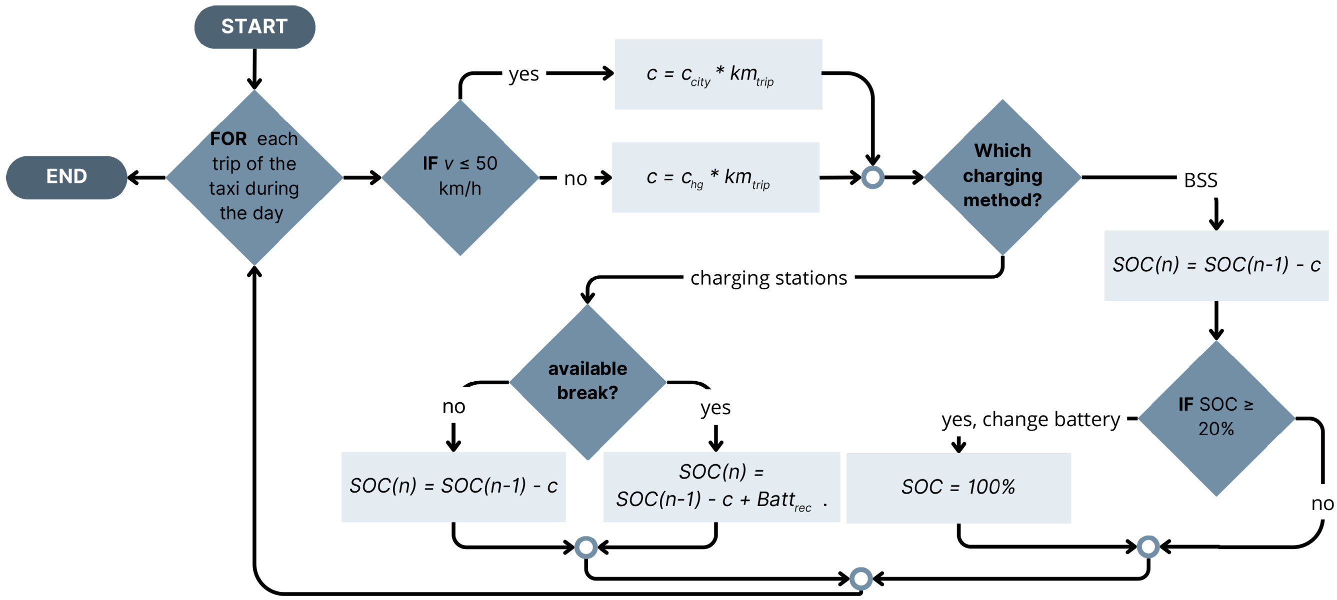

FIGURE 1. **Flowchart of the model.**

III. DESCRIPTION OF THE MODEL

Figure 1 shows the model that provides a comprehensive perspective on how EV batteries' SOC evolves in response to varying charging modes, encompassing Level 2 chargers, DC chargers, and BSSs. The model analyzes each individual trip made by a specific taxi during a working day separately. As a first step, consumption is calculated based on the distance traveled and the average maintained speed. The driver can freely choose to use traditional charging stations BSS. In the first case, these are usable only if the driver has a break, while BSS is used only if the SOC at the end of the trip is below 20%. This model's ability to consider EVs' charging mode and real-world travel scenarios makes it a valuable tool for assessing the interplay between charging infrastructure and usage patterns.

To calculate the energy consumption [%] with greater accuracy, the model categorizes individual trips into distinct scenarios, aligning with the operational context. The criterion for differentiation is the trip's average speed. If the speed exceeds 50 km/h, consumption rates typical of highway driving conditions are applied, while lower speeds are assumed to represent urban driving conditions. Consequently, the vehicle consumption for that specific trip is calculated using 2.

$$c = \begin{cases} c_{ciy} \cdot km_{trip}, \\ c_{hg} \cdot km_{trip}. \end{cases} \tag{2}$$

The vehicle's SOC is evaluated at the end of each trip based on the selected charging mode, and this is crucial for understanding how different charging methods impact the EV's state of charge.

Charging stations can be used only if there is an available break following the trip. In cases where there is insufficient time for recharging or it is unnecessary, SOC of the specific trip n ($SOC(n)$) is updated based on energy consumption using 3.

$$SOC(n) = SOC(n-1) - \; c[\%] \tag{3}$$

Alternatively, when drivers opt to make a stop for recharging, the $SOC(n)$ is recalibrated, taking into account not just the energy expended during the trip but also the energy replenished during that particular time interval ($Batt_{rec}$) as reported in 4.

$$SOC(n) = SOC(n-1) - \; c + Batt_{rec}[\%] \tag{4}$$

Equation 5 has been used to calculate the $Batt_{rec}$. Different factors has been considered including the charger's power (P_{char}), the battery capacity (C_{batt}), and an efficiency (η_c) of 0.8.

$$Batt_{rec} = \frac{t[min] \cdot P_{char}[kW] \cdot \eta_c}{C_{batt}[kWh] \cdot 60[\frac{min}{h}]}[\%] \tag{5}$$

In the case of the drivers choosing to employ a swap station, the swap is performed only when the battery SOC at the end of the trip is below 20%, which has been calculated using 3. The threshold of 20% for initiating a battery swap is a practical decision, as it ensures that the battery is adequately depleted before performing a swap, optimizing the utilization of the swap station. Moreover, when a new battery is installed, the SOC is reset to 100%, signifying a fully charged battery for the subsequent journey.

A. CONSUMPTION CALCULATION

To have a good approximation of the real energy consumption a microsimulation has been done for two sample tracks, one classified as a city path and another as a highway path. The two have been used to estimate the consumption of the trip based on the proportion of the two.

In the mechanical model used, the (P_{el}) is strictly correlated to the traction force (F_{trac}). These passages describe the calculation of (F_{trac}) acting on a vehicle in different scenarios:

- When the vehicle is traveling at a constant speed, F_{trac} is equal to the total force (F_{tot}) at that instant of time, which depends on two different factors, rotational resistance (F_{rot}), and aerodynamic resistance (F_{aer}), and is calculated using 6.

$$F_{\text{trac}}(t) = F_{\text{tot}}(t) = F_{\text{rot}}(t) + F_{\text{aer}}(t) \tag{6}$$

- When the vehicle is in an accelerating phase, F_{trac} equals the starting tractive effort (Ft_{start}). The force is calculated using 7.

$$F_{\text{trac}}(t) = Ft_{\text{start}} = m_{eq} \cdot a_m \tag{7}$$

  where m_{eq} is the equivalent mass measured in [kg] and a_m the maximum acceleration for the comfort of the passengers measured in [m/s^2].
- When the driver is neither accelerating nor braking F_{trac} is equal to zero.
- In the case of braking, the force is negative, and it depends on the deceleration at that moment ($de(t)$) and the aerodynamic resistance as reported in 8.

$$F_{\text{trac}}(t) = de(t)[m/s^2] \cdot m_{eq} + F_{\text{aer}}(t) \tag{8}$$

As a result, it is possible to calculate the P_{el} while varying the F_{trac} as follows:

- When F_{trac} is positive, Equation 9 is applied, assuming a traction efficiency (η_{t}) of 0.75.

$$P_{\text{el}}(t) = \frac{\frac{F_{\text{trac}} \cdot v[m/s]}{\eta_t} + P_{\text{aux}}}{1000} \tag{9}$$

- When F_{trac} is negative, Equation 10 is utilized, taking into account a braking efficiency (η_{b}) of 0.8 and a 70% regenerative braking component (β_{reg}).

$$P_{\text{el}}(t) = \frac{\frac{F_{\text{trac}} \cdot v[m/s] \cdot \eta_b \cdot \beta reg}{100} + P_{\text{aux}}}{1000} \tag{10}$$

The analysis was conducted using the Tesla Model 3, a widely used vehicle in the region due to its high popularity and adoption. A Level 2 station with a capacity of 22 kW and a fast charging station with a capacity of 75 kW have been taken into consideration. To better understand the consumption under different driving conditions two different scenarios has been identified:

- City path: This scenario accounts for energy consumption in urban settings characterized by speeds below 50 km/h. Here taxis may encounter frequent stops, traffic lights, and city-specific driving conditions that affect its consumption.

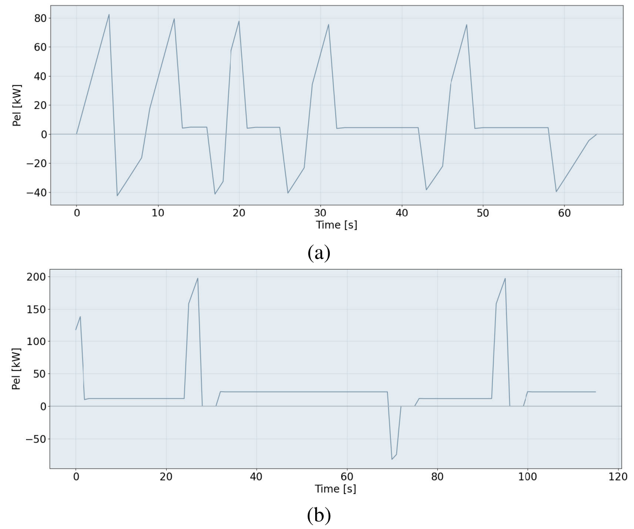

FIGURE 2. Variation of power consumption in (a) city path and (b) highway path.

- Highway path: This scenario is characterized by higher speed, mainly straight stretches and occasional curves where vehicles merely decelerating rather than coming to a complete stop.

Figure 2 shows respectively the variation in power consumption for urban and highway path, which present the higher consumption.

The percentage of battery charge consumed at a given moment in time "t" has been calculated using 11.

$$c_{batt} = \frac{E_{\text{el}}(t)}{C_{batt}} \tag{11}$$

where E_{el} is the energy consumption, which depends directly on the power consumption (P_{el}) and has been calculated for each instant of time. Fig. 3 shows respectively the variation in energy consumption for urban and highway paths, which present the higher consumption.

The variations in driving scenarios significantly impact energy consumption and actual driving range, often deviating from the manufacturer's claimed values. The real autonomy of vehicles tends to be lower than the initially declared. Table 2 reports the key values regarding consumption in the two different scenarios that has been calculated taking into account the maximum speed, acceleration, deceleration and regenerative braking.

TABLE 2. Characteristics of city and highway paths.

	City	Highway
c_{batt} [%/km]	0.268%	0.347%
E_{batt} [kWh/km]	0.201	0.260
Range [km]	370	<300
Max energy cons. [kWh]	0.172	0.784
Max power cons. [Wh]	82.30	197.26

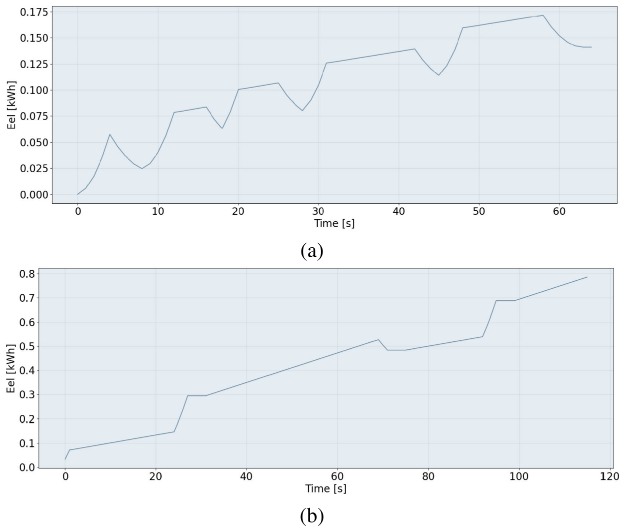

FIGURE 3. Variation of energy consumption in (a) city path and (b) highway path.

IV. ANALYSIS OF THE CASE STUDY

A. ANALYSIS AND DISCUSSION OF RESULT

This paper present an analysis based on Chicago taxi fleet behaviour [38]. Battery swap stations present an appealing solution for electric taxi fleets, addressing the challenges associated with recharging time and ensuring that electric taxis remain operational and profitable [39]. Cabs present several characteristics that make them particularly interesting including [40]:

1) Predictable usage patterns: Taxis typically exhibit predictable usage patterns, which simplify planning and locating charging infrastructure.
2) Ownership structure: Taxis in United States are either owned by individual drivers or managed by companies [41]. In the latter case, they often have a uniform fleet that helps mitigate issues related to battery compatibility, making it more feasible to implement BSS service.
3) High mileage and extended operating hours: These vehicles usually run high mileage per day and have extended operating hours, resulting in a higher demand for charging stops. Using BSS would allow them to operate continuously with minimal charging interruption and extend their daily mileage.

Currently, electric taxis have already been adopted in several cities including London, Shenzhen, and Amsterdam [42]. However, these vehicles typically rely on traditional charging stations as their primary charging infrastructure option, which often have longer charging times compared to refueling for gasoline or diesel vehicles. Long charging times can reduce the operational availability of electric taxis, and directly impact their earnings. The study proposes BSS as a solution to this challenge by minimizing downtime and keeping electric taxis on the road longer, thereby increasing their overall efficiency. BSS employs various techniques and methods for removing batteries from vehicles, depending on factors such as the battery's location and the vehicle type. The primary methods are reported in Table 3, with "bottom swapping" being the most used for cars, due to the position of the battery on the bottom of the vehicle. "Bottom swapping" is a method where the battery is accessed and replaced from the underside of the vehicle and is the one that has been adopted for this analysis.

TABLE 3. Application of different techniques [43].

Swap Technique	Application
Sideways Swapping	Light heavy vehicles
Rear Swapping	Vehicles with batteries placed in the back
Top Swapping	Buses
Bottom Swapping	Private car

B. PRELIMINARY ASSUMPTION

Given that taxis mainly operate during the daytime, the assumption is that they can be completely charged overnight, starting the workday with a 100% SOC [44].

A single taxi on a specific day has been selected to conduct the analysis. The total daily distance (TD) covered by a single taxi was considered as the sum of the total distance covered by trips with passengers (TD_p) and empty ones (TD_e) as reported in 12.

$$TD = TD_{\mathrm{passengers}} + TD_{\mathrm{empty}} \tag{12}$$

The data provided by the city of Chicago includes information solely on taxi journeys with passengers, omitting details about the routes they take to reach a pickup point. Consequently for each empty trip starting from an origin zone i and ending in a zone j, the speed and distance are determined by calculating the averages of all trips made in the same month that share the same starting and ending points using 13.

$$\begin{cases} v_{ij} = \dfrac{\sum_{k=1}^{n} v_{ij,k}}{n}, \\ d_{ij} = \dfrac{\sum_{k=1}^{n} d_{ij,k}}{n}, \end{cases} \tag{13}$$

This research will include three distinct case studies, each distinguished by different travel distances, trip volumes, and operational hours. The analysis was conducted using data from all active taxis in Chicago until April 2023, provided by the Chicago Government [38]. Each case study involves a comparative examination of charging times, specifically evaluating Level 2 chargers, DC chargers, and BSS. It is crucial to remember that the limited availability of fast-charging stations and the potential for them to be occupied can impact the charging schedule. The objective is to determine the charging method that best aligns with the needs of taxi drivers, enabling them to efficiently complete their daily shifts. The adoption of Battery Swap Stations is explored for its potential advantages, including a reduction in the number of charging stops and the ability to conclude the working day with remaining charge.

C. FIRST CASE STUDY

This case study examined a taxi's journey covering a total distance of 480 km of which 400 km were with passengers. The taxi exhibited increased activity during daytime hours, starting from 10:00 in the morning and peaking in the evening. However, the driver has only three available breaks as opportunities to recharge the vehicle at charging stations without having to give up trips.

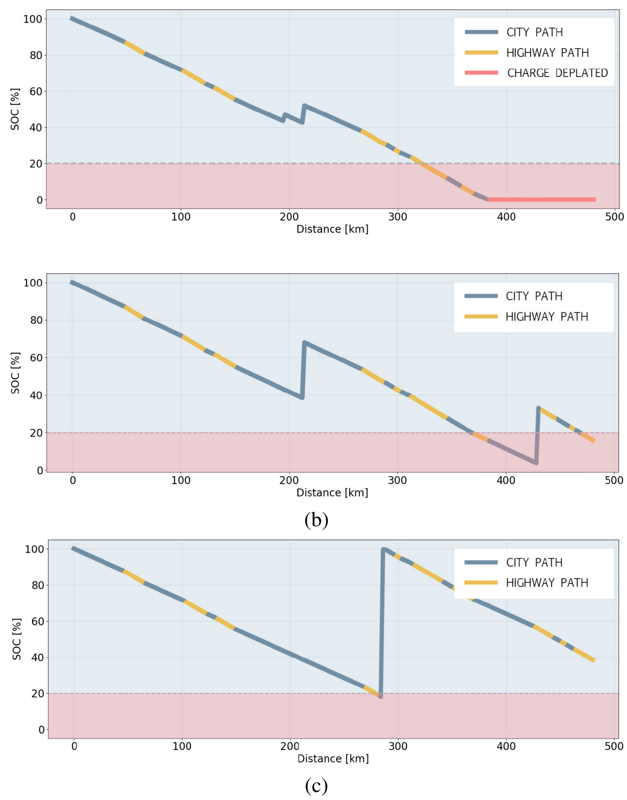

FIGURE 4. **1st case - Variation of SOC using different charging methods: (a) Level 2 Charger, (b) DC Charger, (c) BSS.**

Figure 4 presents a visualization of the state of charge fluctuation when employing various charging methods. Attempting to complete a full working day using Level 2 chargers, as demonstrated in Figure 4a, is not feasible. This would imply an earlier and longer stop to recharge the battery, leading to the cancellation of trips and causing financial losses. On the other hand, using faster charging stations enables the completion of the workday but forces the driver to undertake several trips with a charge level below 20%, as illustrated in Figure 4b. This situation could potentially evoke feelings of range anxiety, and in the event of heavy traffic or unforeseen delays, there is no guarantee of successfully concluding the journey. Nevertheless, when making use of BSS, enables the driver to reduce the number of stops to charge and to conclude its day with some remaining charge. Additionally the SOC remains consistently above the 20% threshold, alleviating concerns related to range and reducing anxiety. This is shown in Figure 5c.

D. SECOND CASE STUDY

In the second case study, the analyzed taxi covers a greater total distance of 521 km, compared to the previous scenario, while maintaining the same distance traveled with passengers. The workday extends from 10:00 in the morning to midnight, with a fairly consistent number of passenger. Multiple breaks are available, with a particular concentration occurring in the late afternoon and evening hours.

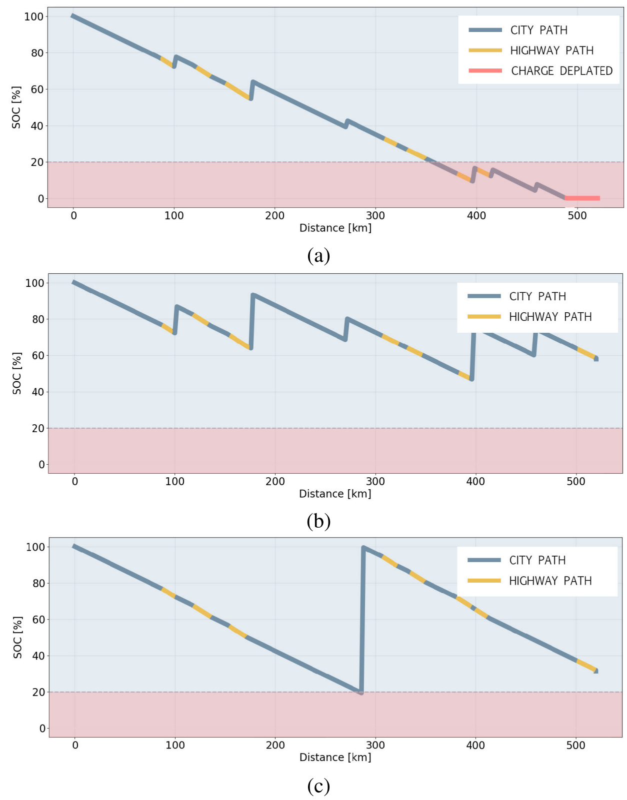

FIGURE 5. **2nd case - Variation of SOC using different charging methods: (a) Level 2 Charger, (b) DC Charger, (c) BSS.**

This distribution makes it possible to successfully conclude the workday when utilizing fast chargers. However, it requires several stops using each available break, as illustrated in Figure 5b. Conversely, if the driver relies on Level 2 charging stations as depicted in Figure 5a, it is impossible to complete the workday. The SOC drops below 20% when there are still 150 km of driving left and is complexly deplete when 40 km are missing. As a result, the final breaks prove ineffective for recharging purposes, and the driver must give up some trips early in the afternoon to recharge the vehicle or conclude the workday earlier. In this case, the use of BSSs represents an alternative to the fast charging stations, enabling the driver to make a single stop for recharging, and concluding its working day with a SOC still above the 20%. This scenario is presented in Figure 5c.

E. THIRD CASE STUDY

The last case study investigated a taxi's journey covering a total distance of 497 km, of which 413 km were dedicated

TABLE 4. Comparison between the main characteristic of the three different scenarios.

Scenario	Break characteristics	Recharging station	BSS	Km run in city	Km on highway
1st Scenario	Few pauses during the day, mainly in the early afternoon or late evening	Level 2: not adequate DC level: range anxiety	Allow to end the trip and has remaining charge capacity	62% [294 km]	38% [186 km]
2nd Scenario	Many pauses during the day, but no one in the afternoon	Level 2: not adequate DC level: adequate	Allow to end the trip and has remaining charge capacity	74% [384 km]	26% [136 km]
3rd Scenario	Short pauses during the early morning and in the afternoon	Level 2: not adequate DC level: not adequate	Allow to end the trip and has remaining charge capacity	65% [312km]	35% [168 km]

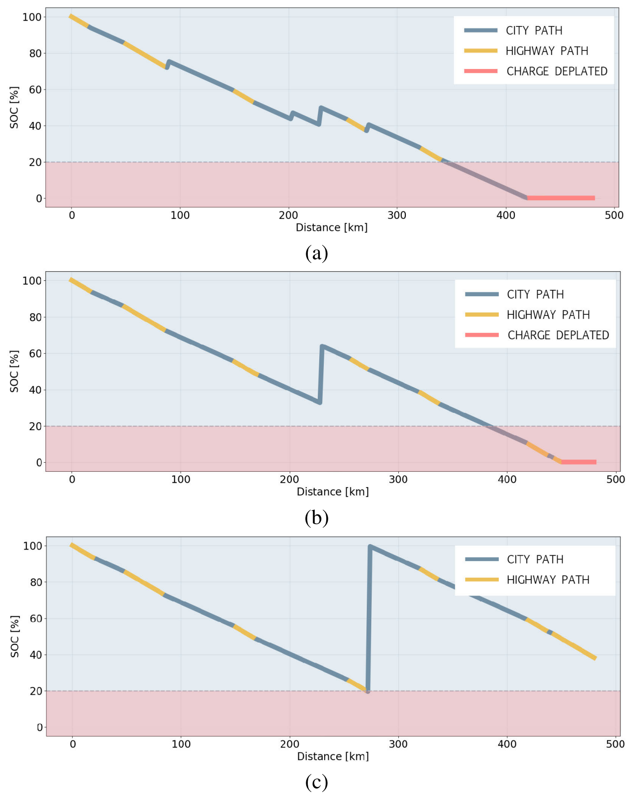

FIGURE 6. 3rd case - Variation of SOC using different charging methods: (a) Level 2 Charger, (b) DC Charger, (c) BSS.

to passenger trips. In contrast to previous scenarios, this taxi departs early in the morning experiencing fewer and briefer breaks, primarily occurring shortly after the morning departure and during the early afternoon.

This significantly affects the feasibility of recharging using conventional charging stations. Neither Level 2 chargers nor fast chargers can ensure the completion of the journey as illustrated in Figure 6a and Figure 6b. The absence of breaks in the late afternoon for recharging the vehicle leads to an early conclusion of the workday unless the driver chooses to give up some trips for recharging. As a result, this entails a financial loss for the driver. In this context, introducing swapping stations is the only solution to provide a charging method that allows the driver to successfully conclude his working day, as depicted in Figure 6c.

F. COMPARISON OF THE CASE STUDY

Table 4 serves as a comprehensive summary, establishing a correlation between the distribution of breaks and the practicality of implementing Battery Swap Stations. In certain situations, exemplified by the third scenario, the adoption of BSS proves to be indispensable due to the inadequacy of traditional charging methods in enabling electric vehicles to match the service quality of traditional ICE vehicles. In the other scenarios these stations proves to be a competitive alternative to traditional charging methods, as they allow to reduce the number of stop needed for recharging, maintaining the SOC of the vehicle above 20% throughout the entire working day. However, it becomes evident that the feasibility of implementing a battery swap service is closely linked with the availability of daily breaks. The distribution of breaks emphasizes the importance of aligning break times with the needs of electric taxi operators, for which an efficient use of recharging time is essential.

V. CONCLUSION

The goal of this study was to assess the feasibility of introducing BSS as an alternative to conventional charging methods, especially considering their extended charging times. It underscores their limitation, which can be especially challenging for taxi drivers with diverse schedules and work patterns. Firstly has been estimated the realistic consumption during service, 0.201 kWh/km for city path and 0.260 kWh/km for kWh. Then the comparison between Level 2 chargers, fast charging stations, and BSSs underscores the importance of choosing the right charging infrastructure to match the specific needs and operational patterns of taxi drivers.

BSSs, with their ability to quickly provide a fully charged battery, appear to be a valuable solution for taxi drivers who rely on their vehicles for extended shifts. Level 2 chargers, while widely available, prove inadequate due to their longer charging times, directly impacting a taxi's operational hours (Three real cases over three had to increase their stop time). DC chargers offer a quicker solution but still necessitate multiple charging sessions throughout the day, which may not always align with the driver's schedule (One real case over three had to increase their stop time) and can lead to range anxiety (One real case over three had to work with SoC under 20%). BSSs, with their ability to quickly provide a fully charged battery, appear to be a valuable solution for taxi drivers who rely on their vehicles for extended shifts. The adaptability of BSS to various taxi operating patterns, as demonstrated in the case studies, validates its effectiveness as a solution for urban transportation networks. Additionally, the ability to minimize downtime, enhance operational flexibility, address range anxiety, maintain consistent service quality, are all factors that contribute to the attractiveness of Battery Swap Stations as a more convenient and time-efficient choice compared to traditional charging methods. Nevertheless, there are still significant challenges associated with their relatively high cost, availability of the necessary infrastructure, and compatibility with various battery types. Additional research efforts can be directed toward addressing issues such as the optimal placement of these stations and enhancing battery management. However, this technology emerges as a promising industry with significant potential for the future, especially considering the growing electric vehicle market and the opportunities for collaboration with car manufacturers.

REFERENCES

[1] R. Hannah, R. Max, and R. Pablo. (2020). *CO_2 and Greenhouse Gas Emissions*. Our World Data. [Online]. Available: https://ourworldindata.org/co2-and-greenhouse-gas-emissions

[2] D. Hoornweg, L. Sugar, and C. L. T. Gómez, "Cities and greenhouse gas emissions: Moving forward," *Environ. Urbanization*, vol. 23, no. 1, pp. 207–227, Apr. 2011, doi: 10.1177/0956247810392270.

[3] V. Monteiro, J. Afonso, J. Ferreira, and J. Afonso, "Vehicle electrification: New challenges and opportunities for smart grids," *Energies*, vol. 12, no. 1, p. 118, Dec. 2018. [Online]. Available: https://www.mdpi.com/1996-1073/12/1/118

[4] K. Hamada, M. Nagao, M. Ajioka, and F. Kawai, "SiC—Emerging power device technology for next-generation electrically powered environmentally friendly vehicles," *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 278–285, Feb. 2015.

[5] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, "A review on electric vehicles: Technologies and challenges," *Smart Cities*, vol. 4, no. 1, pp. 372–404, Mar. 2021.

[6] A. Di Martino, S. M. Miraftabzadeh, and M. Longo, "Strategies for the modelisation of electric vehicle energy consumption: A review," *Energies*, vol. 15, no. 21, p. 8115, Oct. 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/21/8115

[7] S. G. Selvakumar, "Electric and hybrid vehicles—A comprehensive overview," in *Proc. IEEE 2nd Int. Conf. Electr. Power Energy Syst. (ICEPES)*, Dec. 2021, pp. 1–6.

[8] J. Verma and D. Kumar, "Metal-ion batteries for electric vehicles: Current state of the technology, issues and future perspectives," *Nanosc. Adv.*, vol. 3, no. 12, pp. 3384–3394, 2021.

[9] B. Frieske, M. Kloetzke, and F. Mauser, "Trends in vehicle concept and key technology development for hybrid and battery electric vehicles," in *Proc. World Electric Vehicle Symp. Exhib. (EVS)*, Nov. 2013, pp. 1–12.

[10] X. Zhang and G. Wang, "Optimal dispatch of electric vehicle batteries between battery swapping stations and charging stations," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.

[11] F. Schneider, U. W. Thonemann, and D. Klabjan, "Optimization of battery charging and purchasing at electric vehicle battery swap stations," *Transp. Sci.*, vol. 52, no. 5, pp. 1211–1234, Oct. 2018.

[12] X. Yu, F. Wang, and H. Wang, "Optimal battery swapping and charging strategy considering on-site solar generation," in *Proc. IEEE/IAS Ind. Commercial Power Syst. Asia*, Jul. 2023, pp. 1082–1087.

[13] M. Brenna, F. Foiadelli, C. Leone, and M. Longo, "Electric vehicles charging technology review and optimal size estimation," *J. Electr. Eng. Technol.*, vol. 15, no. 6, pp. 2539–2552, Nov. 2020.

[14] Ç. Dericioğlu, E. Yirik, E. Ünal, M. U. Cuma, B. Onur, and M. Tümay, "A review of charging technologies for commercial electric vehicles," *Int. J. Adv. Automot. Technol.*, vol. 2, no. 1, pp. 61–70, 2018.

[15] R. Simeone and A. Montepara, "Recharge traveling: The electric road system," in *Proc. Int. Conf. Transp. Develop.*, Jun. 2023, pp. 310–319.

[16] M. Henke and T.-H. Dietrich, "High power inductive charging system for an electric taxi vehicle," in *Proc. IEEE Transp. Electrific. Conf. Expo. (ITEC)*, Jun. 2017, pp. 27–32.

[17] B. K. Sovacool, L. Noel, and R. J. Orsato, "Stretching, embeddedness, and scripts in a sociotechnical transition: Explaining the failure of electric mobility at better place (2007–2013)," *Technolog. Forecasting Social Change*, vol. 123, pp. 24–34, Oct. 2017.

[18] H. Wu, "A survey of battery swapping stations for electric vehicles: Operation modes and decision scenarios," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 10163–10185, Aug. 2022.

[19] P. Lienert, N. Carey, and N. Shirouzu. *Insight: Inside China's Electric Drive for Swappable Car Batteries*. Accessed: Oct. 11, 2023. [Online]. Available: https://www.reuters.com/business/autos-transportation/inside-chinas-electric-drive-swappable-car-batteries-2022-03-24/

[20] *Transport Infrastructure: Over EUR 352 Million of EU Funding to Boost Greener Mobility*. Accessed: Nov. 2023. [Online]. Available: https://cinea.ec.europa.eu/news-events/news/transport-infrastructure-over-eur-352-million-eu-funding-boost-greener-mobility-2023-09-11_en

[21] *EU Just Transition Fund Community Facilities EV Charging Scheme*. Accessed: Nov. 2023. [Online]. Available: https://www.pobal.ie/programmes/eujtf-ev/

[22] S. Yuying, P. Peng, C. Mingxi, and W. Bing, "Study on load distribution and economic benefit of electric taxi charging station," in *Proc. CSAA/IET Int. Conf. Aircr. Utility Syst. (AUS)*, vol. 2020, Sep. 2020, pp. 1084–1089.

[23] Y. Feng and X. Lu, "Construction planning and operation of battery swapping stations for electric vehicles: A literature review," *Energies*, vol. 14, no. 24, p. 8202, Dec. 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/24/8202

[24] B. J. Mortimer, A. D. Bach, C. Hecht, D. U. Sauer, and R. W. De Doncker, "Public charging infrastructure in Germany—A utilization and profitability analysis," *J. Modern Power Syst. Clean Energy*, vol. 10, no. 6, pp. 1750–1760, Nov. 2022.

[25] M. O. Tarar, N. U. Hassan, I. H. Naqvi, and M. Pecht, "Techno-economic framework for electric vehicle battery swapping stations," *IEEE Trans. Transport. Electrific.*, vol. 9, no. 3, pp. 4458–4473, Sep. 2023.

[26] E. Aarsen, "Electric vehicle service center and method for exchanging and charging vehcile batteries," U.S. Patent 5 963 998, Dec. 7, 1999.

[27] M. R. Sarker, H. Pandžic, and M. A. Ortega-Vazquez, "Optimal operation and services scheduling for an electric vehicle battery swapping station," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 901–910, Mar. 2015.

[28] N. Raj, M. Suri, and K. Sireesha, "Forecasting of EV arrivals at battery swapping station using GA-BPNN," in *Proc. 2nd Global Conf. Advancement Technol. (GCAT)*, Oct. 2021, pp. 1–6.

[29] M. R. Sarker, H. Pandžic, and M. A. Ortega-Vazquez, "Electric vehicle battery swapping station: Bus. case and optimization model," in *Proc. Int. Conf. Connected Vehicles Expo. (ICCVE)*, Dec. 2013, pp. 289–294.

[30] D. Cui, Z. Wang, P. Liu, S. Wang, D. G. Dorrell, X. Li, and W. Zhan, "Operation optimization approaches of electric vehicle battery swapping and charging station: A literature review," *Energy*, vol. 263, Jan. 2023, Art. no. 126095.

[31] S. M. Miraftabzadeh and M. Longo, "High-resolution PV power prediction model based on the deep learning and attention mechanism," *Sustain. Energy, Grids Netw.*, vol. 34, Jun. 2023, Art. no. 101025.

[32] H. Patil and V. N. Kalkhambkar, "Grid integration of electric vehicles for economic benefits: A review," *J. Modern Power Syst. Clean Energy*, vol. 9, no. 1, pp. 13–26, Jan. 2021.

[33] S. S. Ravi and M. Aziz, "Utilization of electric vehicles for vehicle-to-grid services: Progress and perspectives," *Energies*, vol. 15, no. 2, p. 589, Jan. 2022.

[34] H. Patil and V. N. Kalkhambkar, "Charging cost minimisation by centralised controlled charging of electric vehicles," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 2, Feb. 2020, Art. no. e12226.

[35] M. Saha, S. S. Thakur, and A. Bhattacharya, "Optimal EV charging and battery swapping station allocation with traffic-aware energy loss minimization using butterfly optimization algorithm," in *Proc. IEEE 3rd Int. Conf. Sustain. Energy Future Electric Transp. (SEFET)*, Aug. 2023, pp. 1–6.

[36] Accessed: Nov. 2023. [Online]. Available: https://www.nio.com

[37] E. M. Szumska, "Electric vehicle charging infrastructure along highways in the EU," *Energies*, vol. 16, no. 2, p. 895, Jan. 2023, doi: 10.3390/en16020895.

[38] *City of Chicago Taxi Trips. Data Portal*. Accessed: Nov. 2023. [Online]. Available: https://www.chicago.gov/city/en.html

[39] J. Leijon and C. Boström, "Charging electric vehicles today and in the future," *World Electr. Vehicle J.*, vol. 13, no. 8, p. 139, Jul. 2022. [Online]. Available: https://www.mdpi.com/2032-6653/13/8/139

[40] H. R. Sayarshad and V. Mahmoodian, "An intelligent method for dynamic distribution of electric taxi batteries between charging and swapping stations," *Sustain. Cities Soc.*, vol. 65, Feb. 2021, Art. no. 102605.
[41] H. O. Gao and V. Kitirattragarn, "Taxi owners' buying preferences of hybrid-electric vehicles and their implications for emissions in New York City," *Transp. Res. A, Policy Pract.*, vol. 42, no. 8, pp. 1064–1073, Oct. 2008.
[42] J. Bischoff and M. Maciejewski, "Agent-based simulation of electric taxicab fleets," *Transp. Res. Proc.*, vol. 4, pp. 191–198, Jan. 2014.
[43] S. R. Revankar and V. N. Kalkhambkar, "Grid integration of battery swapping station: A review," *J. Energy Storage*, vol. 41, Sep. 2021, Art. no. 102937.
[44] J.-M. Clairand, M. González-Rodríguez, R. Kumar, S. Vyas, and G. Escrivá-Escrivá, "Optimal siting and sizing of electric taxi charging stations considering transportation and power system requirements," *Energy*, vol. 256, Oct. 2022, Art. no. 124572.

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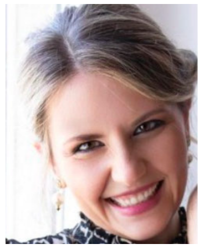

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