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Feasibility Study and Economic Analysis of an Add-On Battery for Electric Vehicles

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ABSTRACT

This research reviewed challenges in electric vehicles (EVs) charging during trips and proposes a novel powertrain architecture that is cost-effective and time-efficient for EVs to instantly increase their range without deviating from their route. The main objective is to study the feasibility and economic analysis of an additional battery for EV applications without disturbing the traction battery under unknown future charging requirement information about EVs, which helps reduce waiting time at charging stations, mitigate the problem of battery swapping, charging 100% through renewables, reduce the negative impact of EVs on the power grid. This study considers an add-on battery of 15kWh capacity offered as battery-as-a-service (BaaS), available at charging stations or delivered at remote locations for users. We conducted an economic analysis, comparing EVs with and without add-on batteries alongside traditional petrol and diesel vehicles. Based on the results obtained, it can be inferred that adopting this framework reduces the travel time by 55 minutes but increases the cost by US$ 0.176 compared to fast charging for a 400 km trip. We can conclude that EVs with main traction and add-on batteries provide a tradeoff between cost and time and are beneficial for both EV user and add-on battery charging and swapping station (ABCSS) operators.

1. INTRODUCTION

According to recent data from the International Energy Agency (IEA), road transportation accounts for three-quarters of CO_2 emissions. Electric vehicles (EVs) offer a promising solution for reducing greenhouse gas emissions and promoting sustainable transportation. In 2020, registrations for EVs surged by 41%, and based on current policies, the global EV stock is expected to soar from 11 million to nearly 145 million by 2030 [1]. Although the EV adoption percentage is increasing, the maximum percentage adoption is from 2-wheelers and 3-wheelers but not 4-wheelers (4-W) due to range anxiety and longer charging times [2]. The range of 4-W EVs has improved with advancements in battery technology, but it still falls short compared to traditional internal combustion engines (ICE) vehicles in terms of waiting time and range. This underscores the pivotal role of diverse and accessible EV recharging infrastructure to cater to the growing population of EVs. Battery swapping enables quick replacement of drained EV batteries but faces challenges with battery health from users and the need for multiple battery types from battery swapping station operators due to lack of standardization [1]. EVs are promoted for their eco-friendliness, but their charging often relies on non-renewable energy sources, thus undermining the goal of shifting to EVs. The Chinese government’s policy supports vehicle-battery separation, enabling companies to offer battery-as-a-service (BaaS) for on-demand battery rentals, boosting EV adoption and complementing plug-in charging [1]. Integrating a large number of EVs into the power grid impacts peak demand and grid stability. Therefore, developing smart battery-swapping infrastructure that coordinates charging with renewable energy availability can optimize clean energy use.

A. *Related Work*

Prasad *et al.* [2] reviewed optimal energy recovery technologies from the perspective of cost, emissions and fuel economy suggesting EV range extender for enhancing EV adoption. Nezamuddin *et al.* [3] proposed vehicle to vehicle recharging with the aim of recharging batteries without getting off-route. In [4], Yang *et al.*, employed fuzzy logic for the energy management of EVs with a fuel cell as a range extender. Boonraksa *et al.* [5] proposed a photovoltaic-based (PV-based) battery swapping station for electric buses intending to reduce waiting time and reduce EV impact on the grid. Bairwa *et al.* [6] proposed a mobile battery swapping station for EVs detailing its operational mechanism and user interaction via an app and solar assisted charging process. In [7], Xu *et al.*, modeled the interaction between transportation and electricity networks to assess the flexibility of EV charging in increasing renewable

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energy utilization. Tavakoli *et al.* [8] analyzed the individual and combined effect of PV and EV integration on grid stability and concluded that each can alone disrupt the grid, but coordinated operation can potentially reduce energy costs and carbon footprint.

B. Challenges

One of the primary hurdles hindering the widespread adoption of EVs is range anxiety and charging time. Though several solutions, such as battery swapping and fast charging have been developed to mitigate this issue, the problem remains unsolved. Battery swapping, introduced to reduce charging wait times, faced challenges due to non-standardized sizing and concerns about swapped battery health, resulting in limited adoption. Although a positive stride, fast charging stations still lack the convenience of ICE vehicles due to longer pit-stop times, faster battery degradation, and negative impact on the grid.

C. Motivation

The charging and battery swapping infrastructure needs substantial investment and expansion to meet the growing demand without negatively impacting the grid and environment [9]. While larger battery capacity extends EV range, it raises costs and power demands due to increased weight, highlighting the need for innovative powertrain architectures that provide a tradeoff between cost and range. This includes the development of standardized batteries to ensure compatibility across different models and brands, reducing the risk of mismatches. Additionally, increasing the number of charging stations and integrating them with renewable energy sources can alleviate grid stress and promote sustainable transportation.

D. Contribution

This study proposes a novel powertrain architecture that alleviates EV users range anxiety and reduces the pit-stop time to zero. A 15kWh additional battery slot is integrated into the powertrain architecture without disturbing the traction battery, offering convenient access to users for battery swapping. A feasibility and economic study are performed to observe the impact of the add-on battery (AOB) on the constraints faced by EV users, such as waiting time and corresponding range. Economic analysis has been conducted comparing EVs with and without AOBs from both EV user and add-on battery charging and swapping station (ABCSS) operator perspectives, considering actual costs.

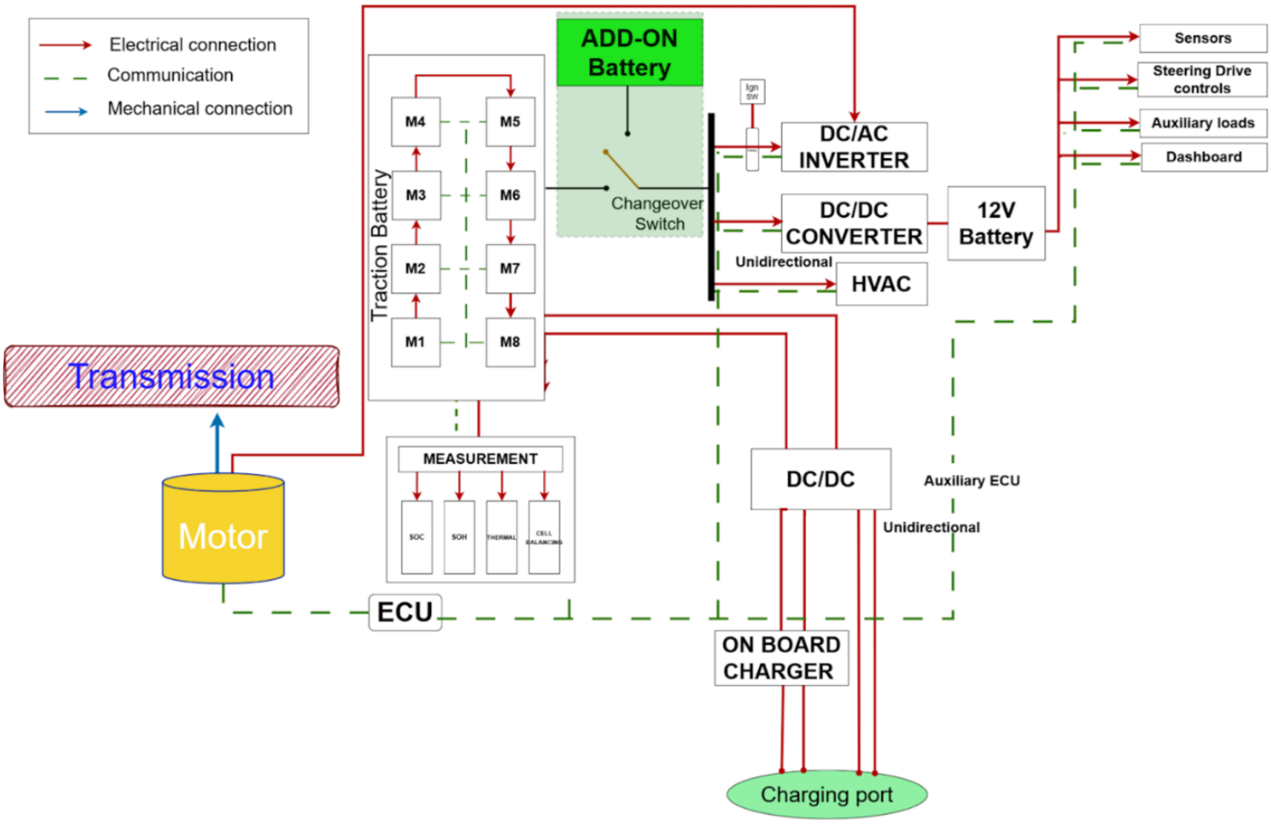

Fig. 1. Proposed powertrain framework with add-on battery.

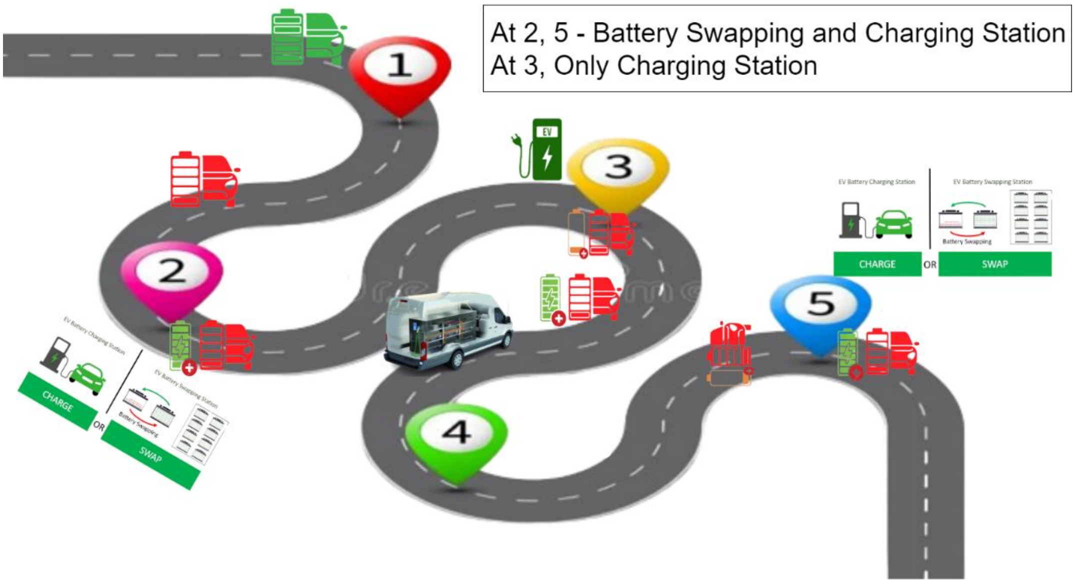

Fig. 2. Illustration of framework adaption with add-on battery as a service.

2. STATE OF THE ART

Figure 1 illustrates a proposed powertrain architecture designed to significantly reduce the waiting time at CS and instantaneous increase in the range of EVs, bringing it on par with the quick refueling process observed in ICE vehicles. The vehicle powertrain architecture has a fixed traction battery and a slot for the AOB. There is a change-over switch connecting the loads to one of the energy sources. By default, the switch will be connected to the traction battery and can be changed manually depending on the energy source the user wishes to use. An AOB with a standard rating of 15 kWh is considered in this study. When the main traction battery SOC is nearing its minimum, the user initiates a search for a charging station. After reaching the ABCSS, the user may opt for charging the main traction battery or AOB without needing to replace the main traction battery, depending on convenience. If opted for charging the main traction battery gets charged, and the changeover switch remains in the same position. In the other scenario, when the user opts for an AOB, it will be placed in the add-on battery slot and the switch needs to be changed to connect loads to the AOB. Due to this framework, the traction battery state of charge (SOC) remains as it is without further depleting below the lower threshold although the trip continued with less waiting time at ABCSS. An EV user driving on a trip can also get a charged AOB from the mobile battery swapping station (MBSS) at a remote location along their route, reducing range anxiety. MSS are located along highways, either at designated depots or at ABCSS. The implementation of the framework along the travel path with different SOC levels of both batteries has been illustrated with the route map in Figure 2. From here, the main traction battery's and add-on battery's SOC are represented as SOC_main and SOC_add, respectively. The journey commences at location 1, with the main battery having a full charge. After covering a certain distance and before approaching location 2, the SOC_main decreases to 30%; hence, the user initiates a search for the nearest charging station (CS). ABCSS is at location 2 where the user requests an AOB. The user continues the journey after taking the add-on battery, and post location 3, the SOC_add drops to 20%, prompting the user to search for the nearest CS to swap the current AOB. With the SOC_add declining to 10% and no nearby CS in sight, the user procures an AOB on the spot from MBSS. This process persists until reaching the destination, as explained in Figure 3. This solution offers users flexibility in recharging, allowing them to choose based on cost effectiveness and waiting time considerations. The proposed framework doesn't replace the existing charging infrastructure but acts as a premium service for customers who value time compared to little cost difference. The proposed architecture provides significant additional range at minimal cost, reducing wait time at charging stations, charged by renewables, and ensuring 100% green mobility.

In the flowchart, 'R' indicates the residual range, 'dist.' indicates remaining travelling distance, 'm_Abat' indicates mass of the AOB, 'aux = 0' indicates the user did not opt for AOB its slot is empty, 'aux = 1' indicates the user opted for AOB and AOB is placed in its slot.

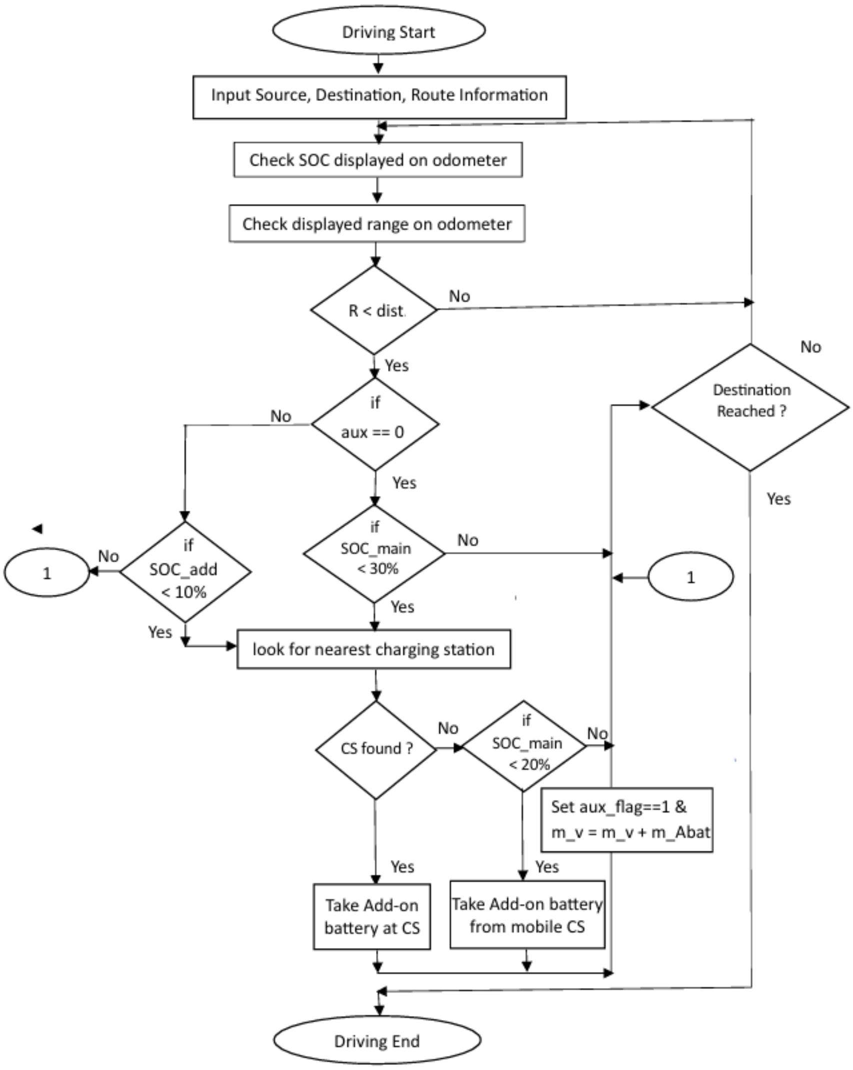

Fig. 3. Working flow of the proposed framework.

3. INPUT DATA

A 60 km drive cycle data has been used for the feasibility study and to analyze the impact on power consumption due to the integration of an additional battery. The capacity of the AOB is considered 15 kWh, and its corresponding weight is 90 kg [10]. The initial SOC_main is considered 35% to simulate the user's search for CS at low SOC levels and observe the switch to the AOB when SOC_main drops below 20%. The EV specific energy consumption is considered 135 Wh/km with climate control in the ON state**.**

A. Assumptions

1. Each ABCSS has an MBSS, which can supply add-on batteries to designated location requested by the EV user.
2. The AOB has sensors whose parameters are sent to the cloud for processing, mitigating the need for individual BMS [11].
3. The ABCSS is present for every 20 - 25 km.
4. The ABCSS primarily relies on solar rooftop to charge the AOBs.
5. The MBSS is also an EV only.

B. Benefits

1. The waiting time at the CS is minimal.
2. The ASCSS operators can charge the batteries with renewables, hence mitigating the impact on the grid and pollution.
3. The reduced operating costs of EVs and minimal recharge time comparable to traditional ICE vehicles contribute to the accelerated adoption of its eco-friendly alternative.
4. The problem associated with the battery swapping is avoided, as the main traction battery was not swapped at any point.
5. It is also beneficial for ASCSS operators as they charge at zero or minimal costs and rent at some marginal cost.
6. Prevents energy loss from storing and discharging excess solar power during peak load hours.

4. RESULTS AND DISCUSSION

This study investigates the performance and usability of an EV in two distinct scenarios: EVs equipped with and without an AOB. In both cases, the user searches for the nearest CS when the SOC_main drops to 30%. In case 1, without an AOB, if the user does not find a CS before

20% SOC_main, the user drives until he finds the CS or reaches the destination, whichever is nearer. Whereas in case 2, with an AOB, if the user finds the CS before 20% SOC_main, he rents an additional battery from the ABCSS. In another situation where SOC_main reaches 20% but still can't find the charging station, the user stops the vehicle immediately and opts for an AOB from the MBSS to avoid the health degradation of the main battery. An important aspect to consider in economic analysis is the energy consumption by the MBSS during the delivery of an AOB to the location specified by the user. The overall rental cost includes all factors such as AOB rental duration and charges for remote location delivery.

Figure 4 shows the variation in SOC and the corresponding range with and without AOB. In the figures, the "..._A0" and "..._A1" indicate the parameters without and with an Add-on battery, respectively. It can be observed that integrating an AOB increases the range in short duration.

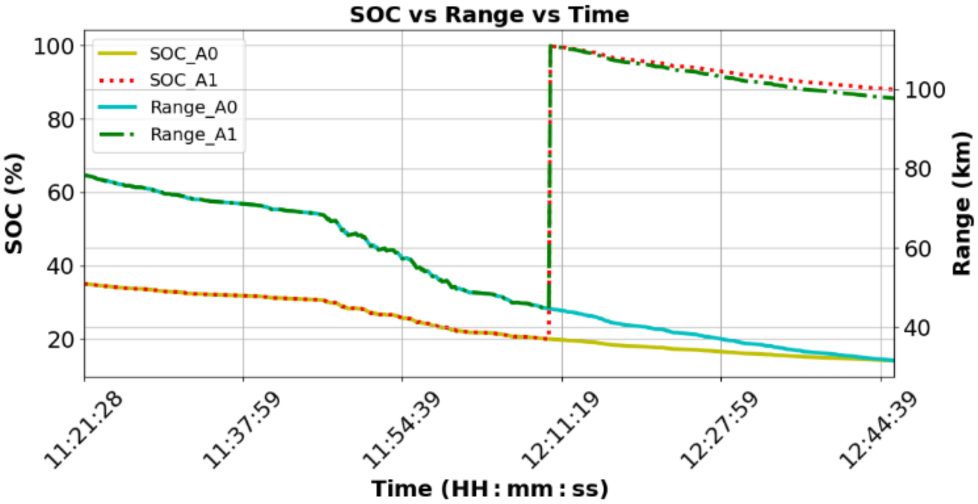

Fig. 1. Variation in SOC with and without add-on battery.

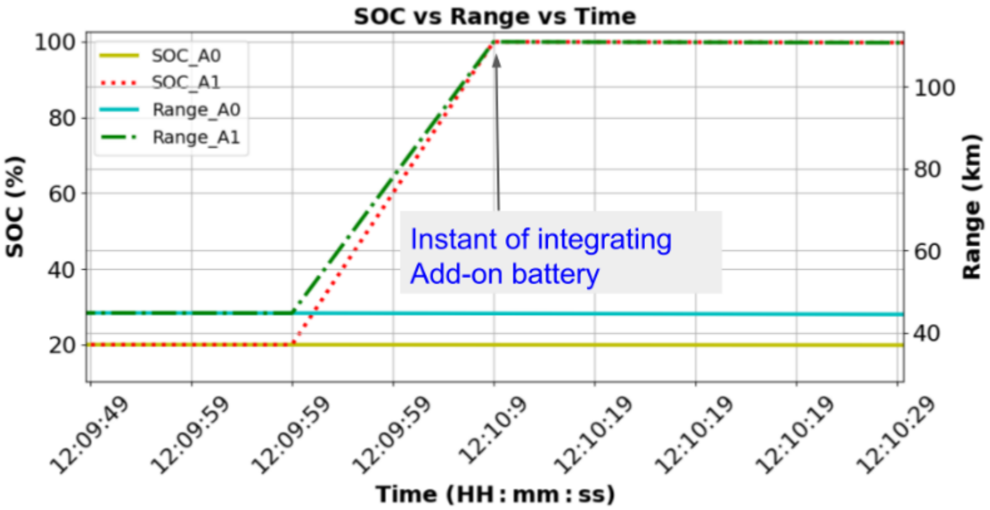

Fig. 5. Instant of integrating add-on battery.

Figure 5 depicts the instant of connecting an AOB at 12:10:9 hrs. Figure 6 shows the power required for propulsion and power generated due to regenerative braking. Both powers have a complimentary nature, and the values indicate only magnitude but not direction. Figure 7 shows the forces a vehicle must overcome to propel forward and the variation of these forces after integrating an additional battery. In Figures 6 and 7 after 12:10:9 hours, more energy is needed for propulsion following the connection of an AOB, attributed to the increased vehicle weight.

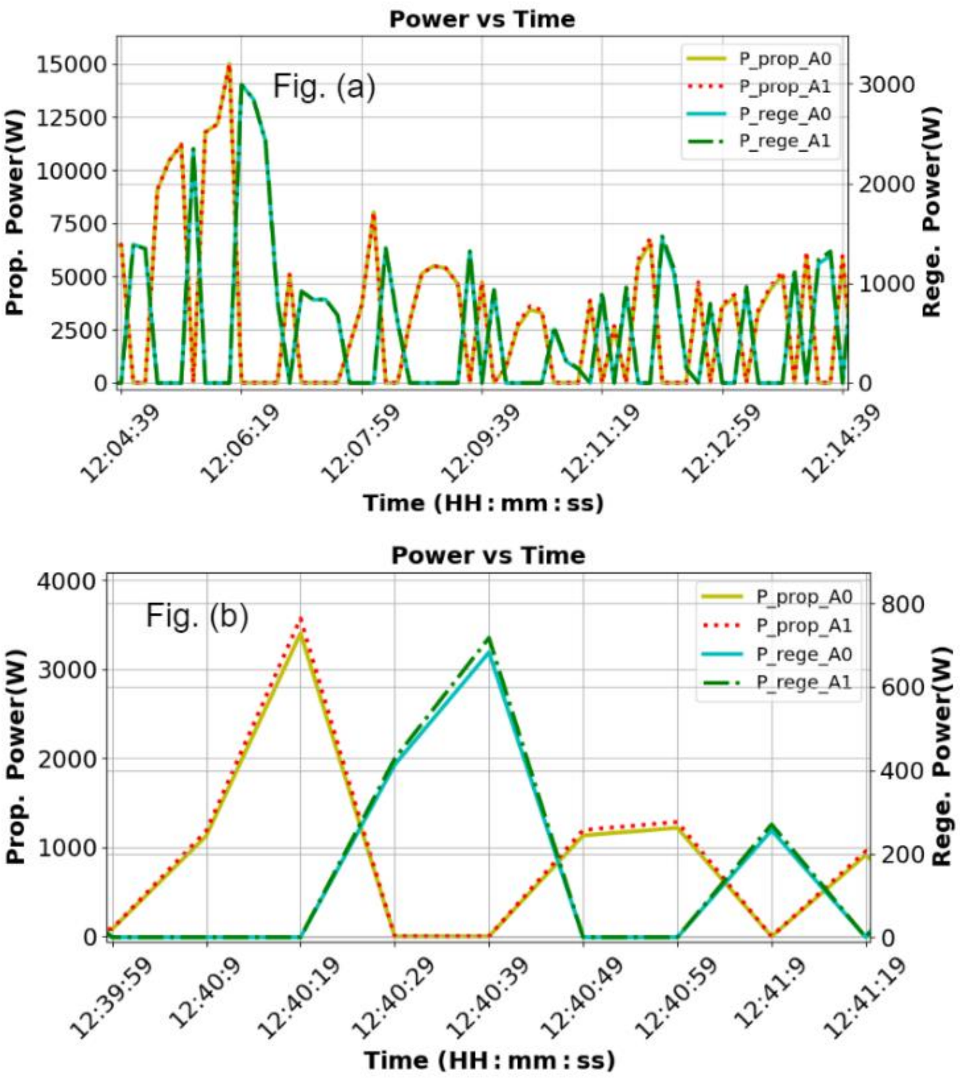

Fig. 6. (a) Variation of propulsion and regeneration power (b) Detailed power variations with and without add-on.

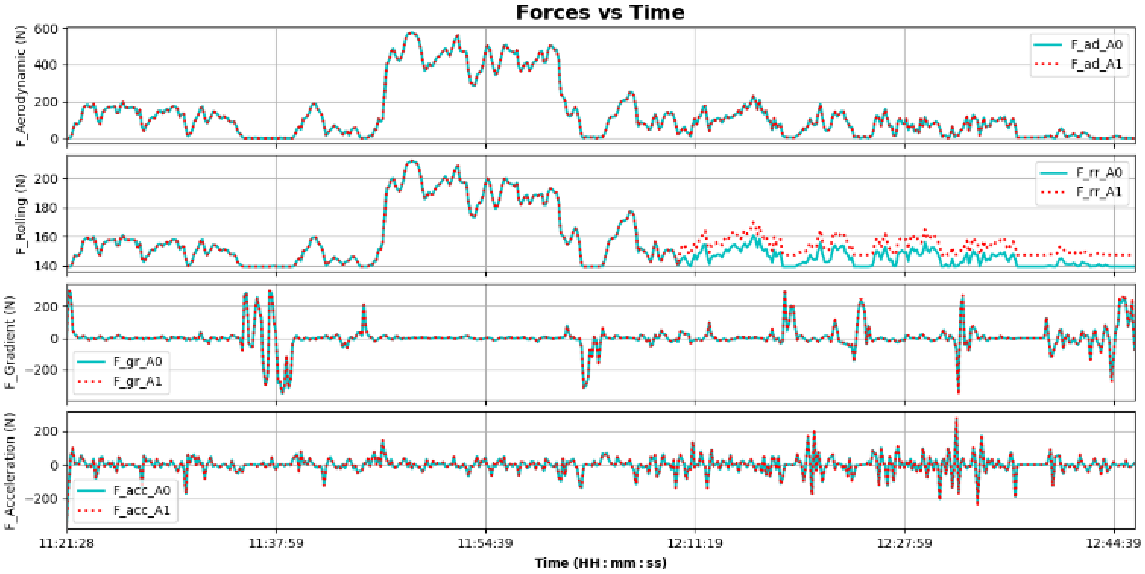

Fig. 7. Forces acting on a vehicle.

The percentage change in various parameters due to increased vehicle weight at instant 12:28:19 hours have been compared and analyzed as shown in Table I. The percentage change in weight due to additional battery was 6.43%. This leads to an increase in rolling resistance, gradient, and acceleration forces by 5.70%, 6.44%, and 5.76% respectively. There is no change in aerodynamic force as it is independent of the vehicle weight. The battery power and energy increase at that instant is 1.33%, and 1.43% respectively. From 12:10:09 hours to the end of the trip at 12:46:18 hours, the energy consumption without the AOB was 1,76,631 Wh, while with the AOB it was 1,79,492 Wh. This represents an increase of 2.86 kWh, resulting in a 1.62% rise in overall energy consumption.

The description of scenarios A to F, as indicated in Table II are provided below:

Scenarios:

A → EV without opting AOB and slow charging at ABCSS
B → EV opting AOB at ABCSS
C → EV opting for an AOB at a remote location
D → EV without opting AOB and fast charging at ABCSS
E → Petrol
F → Diesel

Table I. Vehicle Performance with and without add-on battery.

Timestamp: 12:28:19 hours			
Parameter	Without Add-on	With Add-on	% change
Vehicle weight only (kg)	1400	1490	6.43
Aerodynamic force (N)	45.95	45.95	0
Rolling resist. force (N)	143.37	151.54	5.70
Gradient force (N)	15.06	16.03	6.44
Acceleration force (N)	8.5	8.99	5.76
Traction power (W)	0	0	0
Regeneration power (W)	397.46	414.19	6.43
Battery power (W)	1256.71	1239.98	1.33
Battery energy (Wh)	3.49	3.44	1.43

Table II. Comparison of refueling methods for a 400 km trip.

Scenario	A	B	C	D	E	F	Units
Distance to be travelled	400	400	400	400	400	400	km
Vehicle mileage [12]	8	8	8	8	15	20	km/ kWh (or) km/Lt
Travelled distance	200	200	200	200	200	200	km
Fuel consumed	25	25	25	25	13.33	10	kWh (or) Lt
Initial fuel cost per unit	0.091	0.091	0.091	0.091	1.294	1.176	US$/kWh (or) US$/Lt
Consumed fuel cost	2.265	2.265	2.265	2.265	17.255	11.765	US$
Refuelling required for remaining distance	100	100	100	100	100	100	km
Fuel required by user	12.5	12.5	12.5	12.5	6.67	5.0	kWh (or) Lt
Fuel req. with constraint	15	15	15	15	7.67	6.0	kWh (or) Lt
Refuelling cost per unit	0.118	0.118	0.118	0.294	1.294	1.176	US$/kWh (or) US$/Lt
Required fuel cost	1.765	1.765	1.765	4.412	9.922	7.059	US$
Delivery distance	0	0	5	0	0	0	km
Delivery cost	0	0	0.235	0	0	0	US$/km
Battery rental charges	0	0.706	0.706	0	0	0	US$/hr
Battery rent duration	0	4	4	0	0	0	hr
Wait time at CS	240	5	25	60	5	5	min
Total travel time	640	405	425	460	405	405	min
Total fuel cost	4.029	6.853	8.029	6.676	27.176	18.823	US$

Table III compares various refueling methods for electric, petrol, and diesel vehicles over a trip distance of 400 km. The comparison highlights significant differences in fuel costs, travel times, and refueling logistics across all vehicles. The analysis considers different recharging methods, such as slow charging, opting for an AOB at ABCSS, opting for an AOB at a remote location, fast charging, and traditional refueling of petrol and diesel vehicles. The analysis begins by calculating the fuel consumption for each vehicle type over the first 200 km. The consumption for EVs, petrol, and diesel vehicles are 25 kWh, 13.33 liters, and 10 liters respectively and their corresponding fuel costs are US$2.265, US$17.255, and US$11.765, respectively. The initial fuel cost is 0.091 US$/kWh [13], accounting for the EV user charging the vehicle at home before the trip. Since the distance to be traveled is considered 30% more than the actual distance, the remaining distance to be completed is 100 km. The required fuel to complete the trip is 12.5 kWh for EVs, 6.67 liters for petrol vehicles, and 5 liters for diesel vehicles. Additional fuel is also filled beyond the exact requirements to account for constraints. Therefore, the overall refueling for electric, petrol, and diesel vehicles will be 15 kWh, 7.67 liters, and 6 liters respectively. Refueling costs are calculated based on the method opted: slow charging, AOB at CS, and AOB at the remote location; any of the three methods costs 0.118 US$/kWh; fast charging costs 0.294 US$/kWh; petrol refueling costs 1.294 US$/Lt; and diesel refueling costs 1.176 US$/Lt. The total fuel costs for completing the trip vary significantly between methods. Slow charging results in the lowest total fuel cost of US$ 4.029 but entails the longest travel time of 640 minutes due to a 240-minute wait time at the CS to reach 50% SOC. Opting for an AOB at CS incurs a total fuel cost of US$ 6.853 and reduces total travel time to 405 minutes, including a minimal 5-minute waiting time. Fast charging strikes a balance with a total cost of US$ 6.676 and a travel time of 460 minutes, including a 60-minute waiting period. The existing fast charging method, *i.e*, Scenario D, incurs US$ 6.676 over 300 km in 460 minutes, while the proposed method, *i.e*, Scenario B, costs US$ 6.853 over the same distance in 405 minutes. In contrast, the slow charging method *i.e* Scenario A, takes 640 minutes to cover the same distance at a cost of US$ 4.029. Hence, opting for an EV equipped with an additional battery saves 55 minutes but raises the expenditure by US$ 0.176, compared to stopping solely for fast charging of the traction battery. The proposed method emerges as a more economical and time-effective solution compared to the existing charging methods. Therefore, adopting this framework provides a significant additional range at minimal cost, reducing wait times at CS. These batteries can be scheduled for charging based on historical EV arrival data or pre-scheduled bookings allowing them to be charged during renewable generation hours and off-peak times, thereby reducing grid impact and ensuring 100% green mobility.

The economic analysis of CSO for an initial investment of 20 batteries is as follows:

- Cost of 15 kWh battery [14] = US$ 2,176.47
- Life cycles of each battery [10] = 1500 cycles
- Grid charging cost for CSO [15] = 0.095 US$/kW
- Charging cost to user by CSO = 0.118 US$/kW
- Fixed charges to DICSOM = 0.588 US$/kW/Month
- Investments:
  - Cost of 20 AOB batteries = US$ 43,529.41
  - Fixed charges to DISCOM for 4 years with 100 kW contracted maximum demand (CMD) = 50*100*12*4 = US$ 2,823.53
  - Charging cost for 20 batteries = 15*8*1500*20 = US$ 42,352.94
- Returns:
  - Rental charges for each AOB = US$ 0.706*4 = US$ 2.283
  - Charging cost for 15 kWh AOB - 15*10 = US$ 1.765
  - Revenue for 1 cycle: 240 + 150 = US$ 4.588
  - Revenue for 1500 cycles for 1 AOB = US$ 4.588*1500 = US$ 6,882.35
  - Revenue for 20 AOBs = US$ 6,882.35*20 = US$ 137,647.06
- Profit = Lifetime revenue - charging cost - battery investment – fixed charges to DISCOM
  = 137,647.06 – 42,352.94 -,43,529.41 – 2,823.53
  = US$ 48,941.18

Based on the above calculations, it is evident that the minimum profit to the ABCSS operator after the lifespan of 20 batteries is US$ 48,941.18. Therefore, an EV user equipped with the flexibility of an AOB can cover the same distance in the same time frame, enjoying a cost advantage of US$ 11.971 and US$ 20.323 over a diesel and petrol vehicle user, respectively. The ABCSS operator profit stands to significantly increase by opting for renewable energy sources for charging, which offer charging rates lower than US$ 0.094.

5. CONCLUSION

This paper proposes a powertrain architecture enabling EV users to drive further distances without requiring mid-route stops with the goal of reducing driver range anxiety economically and efficiently. EV users generally start searching for the CS when the SOC main is near 30%, provided the range is less than the distance to be traveled. Two case studies were done with and without considering AOB for EVs. In Case 1, without an AOB, the user continues driving to the nearest CS even when the SOC_main falls below 20%. In Case 2, with an AOB, the user can choose an AOB from an ABCSS if a CS is found before 20% SOC_main or from an MBSS if no CS is found at 20%. In both cases, users continue driving with SOC main at 20% if the destination can be reached before it drops to 10%. Various approaches to reaching the destination with electric and conventional vehicles have been analyzed and compared. For the same trip, an EV with an AOB saves 55 minutes of time, requires an additional 2.86 kWh of energy, and costs US$ 0.176 more than an EV without the AOB. The results indicate that adopting this framework is beneficial in reducing waiting times at charging stations, charging from renewables during off-peak hours, reducing EV impact on the grid, and providing the possibility of mobile charging, thereby enabling EVs to operate as 100% green mobility.

6. FUTURE WORK

For future work, developing an autonomous charge scheduling algorithm for add-on batteries while ensuring maximum utilization of rooftop PV power to meet maximum charging demand.

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