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Citation for the original published paper (version of record):
Zeng, Z., Qu, X. (2023). What's next for battery-electric bus charging systems. Communications in Transportation Research, 3. http://dx.doi.org/10.1016/j.commtr.2023.100094

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Communications in Transportation Research 3 (2023) 100094

Contents lists available at ScienceDirect

Communications in Transportation Research

journal homepage: www.journals.elsevier.com/communications-in-transportation-research

Editorial

What's next for battery-electric bus charging systems

1. Introduction

As one of the priorities for government subsidies and financial incentives, the global stock of electric buses (EBs) has exceeded 670,000 units by the end of 2021 (IEA, 2022). Despite recent achievements in procuring EBs, it still represents less than 4% of the global fleet size. The large-scale implementation of this grid-dependent technology confronts two key challenges: (1) limited range combined with long charging time and (2) insufficient charging infrastructure (Perumal et al., 2021).

These impediments are now being tackled by (1) high energy density and (2) the opportunity for fast charging. We are optimistic about battery technology, but the current experiments are still a long way from becoming commercially viable. Besides, the authors argue that the utilization of the pricey charging station/lane will be unexpectedly low. With two terminal chargers available for energy replenishment, the authors approximated the daily charging requirement for sixteen EBs on the fully electrified bus Line 16 in Gothenburg, Sweden. The result in Fig. 1(a) indicates that the average daily occupancy was 10.3%, with Terminals 1 and 2 seeing 10% and 10.76%, respectively. We expect utilization to grow as the market and investor expectations mature. The amount of enhanced usage through shared charging stations will, however, be considerably constrained due to the particular position and access time of bus terminals.

The motivation for this work is the unsolved problems of existing strategies, such as insufficiency and underutilization of chargers. As shown in Fig. 1(b), we propose three charging technologies that outlook the global trend to grapple with the problems.

2. Vehicle-to-vehicle wireless charging

Vehicle-to-vehicle (V2V) charging allows buses to recharge each other. This technology expands the transport network into two interdependent dimensions, the flow of vehicles and the flow of energy. When a safe distance for energy transmission between EBs is established, energy transfer is feasible in a dynamic wireless V2V charging system. Since the energy source is always entering the network and sustaining the energy transfer, in an ideal system, no EB on the road network would experience mileage anxiety. When one EB is ready to finish the last timetabled trip, it distributes the leftover energy as far as possible around the road network while reserving a little amount of power for getting to the depot. This strategy, in theory, maximizes energy efficiency, provided that transmission losses are insignificant. However, due to the added dimension of energy flow, the complexity of the system operations becomes substantially increased.

Technically, the magnetic resonant coupling wireless power transmission technique is a potential option for V2V charging due to its high-power transfer efficiency and long transmission distance. The transmitter and receiver coils are embedded in the front and back of the EB, respectively. With this approach, power is wirelessly delivered with high efficiency across large air gaps. Efficiencies are estimated to be above 90% when the distance is smaller than 1 m at a standstill (Kurs et al., 2007). However, a long-distance energy transfer with dynamic lateral shifts is a game-changer. Assuming a distance of 5–8 m between two EBs (one-second headway), the predicted power efficiency is next to none (Imura and Hori, 2011). To stimulate the development, the challenge would be: (1) meeting safety regulations (e.g., IEEE safety criteria for broad public exposure, and (2) maintaining effective power transfer under dynamic high-power requirements.

Given this, we believe that V2V wireless transmission will be appealing when power efficiency reaches roughly 45% (Kurs et al., 2007), i.e., slightly below the average value for dynamic charging lanes.

3. Mobile charging vehicle

Mobile charging vehicles (MCVs) are designed to deliver energy across a local grid via bidirectional chargers and then distribute it to EBs via a specialized aggregator. The aggregator oversees the interaction of MCV and EB, as well as the communication with the grid for energy replenishment. We speculate that an MCV may be wired for energy transfer and connected to the target EB, drawing inspiration from the architecture of the modular bus.

According to this technology, the bus charging station changes from being fixed to active, with MCVs following the EB on a timetabled trip and replenishing it with sufficient energy during the journey. As a result, buses will be freed from reliance on fixed charging locations; instead, all charging tasks could be completed en route. Besides, MCVs can also provide charging services at night if the schedule is more intensive than the fleet size of the MCV. Thus, the original EB charge scheduling problem is transformed into an MCV routing problem and an MCV charging problem.

In general, the cost of MCV energy supply is determined by the total battery degradation costs, electricity prices, energy delivery expenses, and the value of time savings. Taking the example of Line 16 in Gothenburg city, we consider a typical EB with a 200 kWh battery capacity serving 10 timetabled trips running back and forth with an average energy usage of 22.12 kWh per trip. With the MCV providing an output of 400 kW and carrying a 700 kWh high-power battery to charge the EB, we conclude that this approach would hardly be profitable unless the energy delivery cost for one EB is less than $0.63 when we exclude the $221.2 from the battery wear. Reduced output power makes this technique more

https://doi.org/10.1016/j.commtr.2023.100094
Received 2 February 2023; Received in revised form 20 February 2023; Accepted 21 February 2023
Available online xxxx

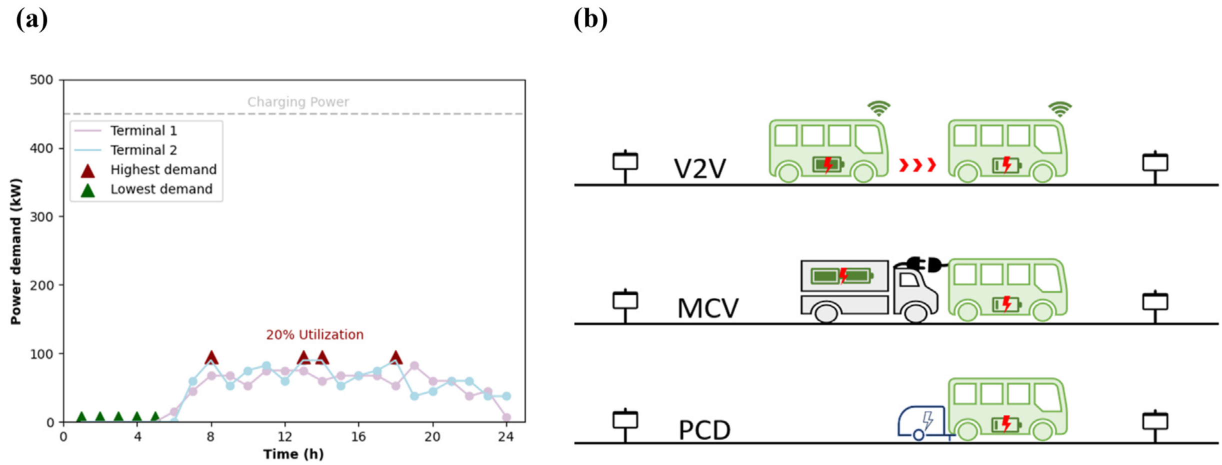

Fig. 1. EB system shortcomings and solutions. (a) Low usage of terminal chargers for bus Line 16 in Gothenburg, Sweden. Note that the energy demands between time points t and $t+1$ are aggregated in time point $t+1$. (b) Three charging strategies for future EB system.

cost-effective and lowers MCV development expenses but results in a considerable rise in the demand ratio between MCVs and EBs. In addition, the results show that the charging efficiency is set to 95%, which is currently only suitable for the lower output such as 2-level chargers (e.g., 6.6 kW). The calculation details are illustrated in the Appendix.

4. Portable charging devices

The portable charging device (PCD) further reduces the dependence on energy replenishment from other vehicles. It can be seen as a backup battery with sufficient energy to power an EB for at least one timetabled trip. Large interchange stations, therefore, are set up as 'battery banks' in this system, where EBs with charging needs arrive and are connected to one or more PCD(s), which are then unloaded to the next en-route 'battery banks' when the PCD battery is depleted.

Weight, energy transfer efficiency, ownership cost, and lifespan of PCD are all key factors to consider. To avoid putting an extra burden on the EB, the PCD may be designed in the shape of a trailer, moving with the EB rather than being attached to the body. PCD differs from MCV in that it cannot be actively suspended on or disengaged from the EB, and it usually has a smaller battery aimed at serving one EB. On the other hand, this technique requires little initial outlay and is adaptable to several uses. PCD is therefore seen as the measure that can be commercialized the fastest for the EB system. There are already commercially viable applications aimed at light-duty electric vehicles that provide an emergency rescue service, and the battery capacity ranges from 3 to 8 kWh with an efficiency of up to 85% (Moghaddam et al., 2021).

It is worth noting, however, that the energy density of PCDs will still not push the technical limits of Li-ion batteries. Although neither the price nor the capacity of the PCD can be broken in a short amount of time, it is possible to add and remove tiny batteries for continuous energy delivery in the early stages. This concept can therefore be employed as a temporary rather than a long-term fix until high-capacity batteries are developed.

5. Concluding remarks

There are substantial connections between EB and charging resources due to low battery capacity, long charging time, and insufficient charging facilities. Previous research has revealed that increasing energy density and providing en-route charging alternatives may help address these flaws. We are concerned about the practicality and efficiency of the suggested measures, and we believe that increasing battery density is now technically challenging. Besides, low utilization of fast charging at fixed places is observed, occupying less than 11% of the time, which indicates a huge waste of scarce resources.

We, therefore, propose three charging systems to address the challenge of how to balance upfront investment with actual utilization. V2V wireless charging system expands the physical road network into two dimensions, vehicle, and energy flow, allowing energy to be continuously transferred to maximize the use of the energy flow. MCVs are based on the modular bus architecture, in which a high-power and high-battery-capacity vehicle serves as a mobile charging station recharging EB batteries en route. Similar to the V2V mode, energy transfer efficiency remains a big concern. The third strategy is the PCD, which is promising to commercialize with portable batteries that can be hung and removed to charge EBs while traveling, although this is a temporary solution until high-density batteries are made available.

However, it is important to note that these solutions must be approached with counter-intuitive managerial implications in mind. For example, simply increasing battery density may not be the most cost-effective choice, and high utilization of chargers may not be necessary for maximizing resources. The design of the charging system must take into account a holistic approach considering policy, technology, operations, and economics.

Therefore, to effectively invest in electric vehicle charging infrastructure, decision-makers must not only consider technical feasibility but also carefully weigh the trade-offs between upfront investment and actual utilization. By taking a comprehensive and strategic approach, the electric vehicle charging system can be optimized to meet the needs of both the public transportation system and its users.

Declaration of competing interest

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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 52221005 and 52220105001).

Appendix

Here we evaluate the cost-efficiency of MCV based on the monetary saving of charging time and electricity expenses. We consider an EB with a battery capacity of 200 kWh traveling back and forth on a specific bus route. Each trip consumes 22.12 kWh. Therefore, at most the 10th trip requires MCV charging en route. Based on the real-world operating data of Line 16 in Gothenburg, Sweden, the input parameters are listed in Table A1.

Table A1
Input parameter for MCV operating.

Parameter	Value	Parameter	Value
Line length	15.8 km	Value of time for EB driver	31.2 $/h
Bus trip consumption	22.12 kWh	MCV unit consumption	1.8 kWh/km
Number of trips	10	Energy price	0.07 $/kWh
Charging power	400 kW	Unit battery cost	1000 $/kWh
MCV battery capacity	700 kWh	Battery cycle life	1000
Charging efficiency	0.95	EB battery capacity	200 kWh

The time required for charging can be calculated as

$$\text{Charging\_time} = \frac{\text{Bus\_trip\_consumption} \times \text{Number\_of\_trips}}{\text{Charging\_power} \times \text{Charging\_efficiency}} = \frac{22.12 \times 10}{400 \times 0.95} = 0.58 \text{ h}$$

The charging time equivalent monetary value (value of saved time) can be calculated as

$$\text{Value\_of\_saved\_time} = \text{Value\_of\_time\_for\_EB\_driver} \times \text{Charging\_time} = 31.2 \times 0.58 = \$18.1$$

The electricity expenses for both EB and MCV can be estimated as

$$\text{Electricity\_expenses} = (\text{Bus\_trip\_consumption} \times \text{Number\_of\_trips} + \text{Line\_length} \times \text{MCV\_unit\_consumption}) \times \text{Energy\_price} = (22.12 \times 10 + 15.8 \times 1.8) \times 0.07 = \$17.47$$

*Note that MCV is assumed to run a full timetabled trip with the EB.

Battery wear cost is described as

$$\frac{\text{Unit\_battery\_cost} \times \text{battery\_capacity}}{\text{Cycle\_life}} \times \text{Number\_of\_cycle} = \frac{1,000 \times 700}{1,000} \times \frac{22.12 \times 10}{700} = \$221.2$$

The boundary condition for energy transferring cost can be further calculated by the difference between the total electricity price and the value of saved time:

$$\text{Value\_of\_saved\_time} - \text{Electricity\_expenses} = 18.1 - 17.47 = \$0.63$$

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