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ADDRESSING CHARGING INFRASTRUCTURE LOCATION PROBLEM CONSIDERING DYNAMIC DEMAND AND SUPPLY

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Abstract

Known for their environmentally friendly, cost-effective, and quiet operation, electric buses come forward as ideal public transportation solutions for urban areas. On the other hand, their limited driving range, depending on their battery capacities, hinders their wider adoption. Implementing the opportunity charging strategy can serve as a solution to address this inherent challenge of electric buses. This strategy allows buses to charge at bus stops using wireless chargers during the dwell time. However, it introduces another challenge, known as the Charging Infrastructure Location Problem (CILP), which involves optimizing the charger locations on transit networks. Several studies have approached CILP, adopting the opportunity charging strategy. Nevertheless, these studies either evaluate energy levels concerning bus routes or assume predetermined charging durations at stops. However, it is a fact that each electric bus operating on the same route is supplied a different amount of energy due to the total number of passengers boarding and alighting throughout the entire operating period. Furthermore, each bus consumes different amounts of energy due to its schedule throughout the operation period. This study develops an optimization model to minimize the charging infrastructure investment cost in an electric bus network under dynamic supply and demand. The model assesses the energy level of each bus individually by calculating the recharging duration at each stop for each bus depending on the number of boarding and alighting passengers and taking into account the impact of time-dependent link travel times on energy consumption. The developed optimization model is tested on a small-scale network. The results demonstrate that when the energy level of each bus is assessed individually, notable differences exist in the energy levels among buses operating on the same route. Additionally, solving the model more realistically using charging durations obtained from passenger boarding/alighting numbers instead of predetermined charging duration leads to significant increases in the charging infrastructure investment cost.

Keywords: charging infrastructure location problem, opportunity charging, electric bus, optimization

1 Introduction

Over the last decade, an extremely increasing population and number of vehicles have substantially caused transportation-based problems. By accounting for a considerable proportion of trips, particularly in urban areas, utilizing transit systems characterized by high passenger capacity appears to be a viable way to address such problems. Despite transit systems being relatively sustainable and environmentally friendly compared to other modes

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of transportation, the prevalent use of conventional internal-combustion buses (e.g., diesel buses) – the backbone of transit systems – contributes to approximately 34% of the overall emissions in the transportation sector, as reported by [1]. Hence, in recent years, one of the contemporary subjects on which researchers have concentrated has been to create sustainable and eco-friendly transit networks. In a global effort to mitigate environmental effects related to transportation, legislative actions such as the Kyoto Protocol and the Zero-Emission Vehicle Mandate have extended the adoption of alternative fuel vehicles [2]. However, using alternative fuels does not entirely eliminate greenhouse gases (GHGs). Consequently, electric buses emerge as the most convenient option among alternative fuel buses for creating sustainable and eco-friendly transit networks [3].

Electric buses, characterized by their silent, environmentally friendly, and energy-efficient operations, represent an optimal technological solution for urban areas. However, the limited driving range of electric buses, typically varying from 200 to 300 kilometers [4] and 40 to 250 kilometers [5], poses a significant challenge. Given these limitations in driving range, maintaining their continuous operational functionality throughout the entire operation period becomes a thoughtful and challenging task. This limitation hinders the widespread adoption of electric buses [2]. To address this limitation and ensure their uninterrupted operation during the entire operation period, recharging them within the operation period becomes imperative.

There are three different charging strategies related to charging electric buses [6, 7]. The first strategy is the depot charging strategy, also known as overnight charging. In this strategy, buses are typically charged with a plug-in cable at the depot. Their driving ranges are naturally limited and proportional to the battery capacity. Therefore, in order to provide the uninterrupted service of electric buses throughout the entire operation period, very large battery capacities are required. This significantly increases the purchase cost of electric buses. Moreover, since mounting a larger battery capacity doesn't completely alleviate the issue of the limited driving range, the buses still need to stop for recharging purposes [8]. This leads to the necessity of an additional bus to continue service while the original bus is recharged in the depot. The second strategy is the dynamic charging strategy, in which the bus transfers energy while in motion. This strategy significantly increases the driving range of buses and eliminates the downtime for recharging purposes. However, incorporating this technology in transportation networks is considerably difficult due to the prohibitive implementation cost [7]. The third strategy is the opportunity charging strategy, which enables buses to recharge their batteries during layovers at terminals or dwell times at intermediate bus stops with high charging power [9], hence eliminating downtime for the charging purposes avoiding the necessity for an extra bus and appearing useful and reasonable approach.

The introduction of electric buses has given rise to the Charging Infrastructure Location Problem (CILP), which involves locating chargers in the transit network in order to charge electric buses while minimizing investment costs. In the literature, there are studies adopting the depot charging strategy, such as [10-12], as well as studies embracing a dynamic charging strategy, such as [2, 13]. Several studies have also addressed the CILP by adopting the opportunity charging strategy, such as [14-17], as in the present study.

The studies mentioned above, adopting the opportunity charging strategy, assess the energy states in terms of lines instead of individual buses since they utilize the frequency-based transit assignment approaches, which result in average values related to lines, ignoring the variation of demand and supply over time. However, in real-world transit networks, every bus serving the same route consumes and is supplied with different amounts of energy throughout the entire operation period because of the dynamic nature of transit networks. Fluctuations in demand over time induce that throughout the operation period, different buses serving the same route are supplied with different amounts of energy since the total number of alighting/boarding passengers at charging stops, so the total dwell time (i.e., maximum recharging time) varies. On the other hand, dynamic supply (e.g., time-dependent link travel times) leads to each bus, operating on the same route, consuming different amounts of energy throughout the operation period due to time-dependent energy-consuming systems, such as HVAC. [18] consider the impact of dynamic demand on the amount of energy transferred but neglect the effect of time-dependent link travel times on the amount of energy consumed. Therefore, there is no study that takes into account these two phenomena that affect energy consumption.

To this end, this study aims to develop a mathematical model for the CILP that assesses the energy state of each bus individually by considering the impact of time-dependent link travel times on the amount of energy consumed during the operation period, as well as the effect of demand fluctuations on amount of the energy transferred. Computational experiments are conducted on data consisting of the number of passengers boarding/alighting at each stop for each run of each bus on a transit network throughout the operation period. The remaining sections of this paper are as follows: Section 2 describes the problem and introduces the mathematical model, while Section 3 presents the results obtained. Lastly, concluding remarks and research suggestions for future studies are given in Section 4.

2 Problem description and mathematical formulation

This study addresses the problem of determining stops to be equipped with a wireless charger by adopting the opportunity charging strategy. The stops are determined with the aim of minimizing the charging infrastructure cost, . Furthermore, the equipped stops should also ensure that all buses have enough energy throughout the entire operation period to maintain an uninterrupted service.

Let us denote the set of buses operating for route by . Each bus is assigned for a set of runs on the respective route, and this set of runs is represented by . When a bus on route arrives th stop along the run , it has the recharging opportunity during the dwell time if the relevant stop is equipped with a charger. The dwell time at th stop for run of bus operating for route is obtained by multiplying the number of boarding () and alighting () passengers at this stop by the average boarding (and alighting time () per passenger, to calculate the total boarding and alighting times. Subsequently, the dwell time or maximum recharging time for the bus at a wireless-charger stop is the greater one of the total boarding time and the total alighting time. Additionally, the assumptions below are adopted to simplify the problem, as in previous studies [12-14, 17]:

- Buses exploit overnight charging and begin daily service with a full battery.
- Buses can recharge only at service stops en route; that is, unable to be recharged during layover times between their consecutive runs.
- Batteries must be kept between as the upper limit and as the lower limit during the entire operation period to maintain battery health.
- All chargers are of the same type, and the electric bus fleet is homogenous.

In accordance with the given objectives, constraints, and assumptions, a mathematical program presented below is developed to individually handle the energy state of each bus.

$$\min Z_1 = \sum_{s \in \mathbf{S}} \Delta_s \times C_s \quad \forall s \in \mathbf{S} \tag{1}$$

$$c_{r,b,k,j} \leq \Delta_s \times max\left\{ \hat{\mu}_{r,b,k,j} \times \hat{t}, \check{\mu}_{r,b,k,j} \times \check{t} \right\} \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^r, \forall k \in \mathbf{K}^{r,b} \tag{2}$$

$$c_{r,b,k,j} \geq 0 \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^r, \forall k \in \mathbf{K}^{r,b} \tag{3}$$

$$E_{r,b,k,j+1} = E_{r,b,k,j} - e_{r,b,k,j,j+1} + \left(\frac{c_{r,b,k,j+1}}{3600}\right) \times CP \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^{r}, \forall k \in \mathbf{K}^{r,b} \tag{4}$$

$$E_{r,b,k,j} \geq e_{r,b,k,j,j+1} + BC \times SOC_{min} \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^{r}, \forall k \in \mathbf{K}^{r,b} \tag{5}$$

$$e_{r,b,k,j,j+1} = l_{r,j,j+1} \times \varphi^{1} + t_{r,b,k,j,j+1} \times \varphi^{2} \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^{r}, \forall k \in \mathbf{K}^{r,b} \tag{6}$$

$$E_{r,b,k,j} \leq BC \times SOC_{max} \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^{r}, \forall k \in \mathbf{K}^{r,b} \tag{7}$$

$$E_{r,b,1,1} = BC \times SOC_{max} \quad \forall r \in \mathbf{R}, \forall b \in \mathbf{B}^{r} \tag{8}$$

Eq. (1) aims to minimize the charging infrastructure cost. Each stop s incurs a specific cost, C_s, for the installation of a charger. Constraint 2 ensures that recharging time, $c_{r,b,k,j}$ is equal to or less than the dwell time if a charger is installed at the stop (that is, $\Delta_s = 1$), while Constraint 3 expresses that recharging time is non-negative. Eq. (4) fulfills the energy balance for successive stops. Constraint 5 ensures the minimum required energy while leaving a stop. Eq. (6) represents the energy consumption model that depends on lengths and travel times of links. Constraint 7 guarantees the maximum allowable amount of energy for buses during the entire operation period. Lastly, Eq. (8) determines the initial amount of energy at the beginning of the operation period for each bus.

3 Results

The developed mathematical model is tested on a network of 16 stops and 25 buses assigned to operate a total of 411 runs on 10 routes. To illustrate the data format, the data consisting of the number of passengers boarding and alighting in various runs of Bus 1 serving Route 2 is presented in Table 1 as an example since providing the data of every run of every bus is impossible. The mathematical program developed for the CILP was executed on an Intel Core i7 computer with a 3.6 GHz CPU and 16 GB RAM utilizing the Mixed-Integer Linear Programming (MILP) toolbox of MATLAB. The average processing time per optimization took approximately 4 hours. The parameter values and the assumed charger installation cost in euros for each stop are given in Table 2 and Table 3, respectively.

Table 1 Num. of passengers boarding/alighting along runs of Bus 1 on Route 2

Run	**Stop #**										
	5	**6**	**9**	**11**	**14**	**15**	**14**	**11**	**9**	**6**	**5**
1	0/0	12/0	5/5	2/2	0/4	9/8	4/3	9/1	24/1	19/11	0/49
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4	20/0	23/5	14/14	6/16	5/8	11/25	15/1	10/4	11/16	6/7	0/25
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
10	48/0	34/15	35/32	11/29	3/13	31/42	40/5	13/20	25/28	7/36	0/27
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
14	17/0	0/3	0/4	0/2	0/2	0/6	2/0	0/0	0/0	0/2	0/0

Table 2 Assumed parameter values

Parameter	Value	Parameter	Value
$\hat{t}$	3.8 sec	SOC_{min}	20%
$\check{t}$	1.6 sec	SOC_{max}	90%
CP	250 kWh	φ^1	1.2 kWh/km
BC	300 kWh	φ^2	0.1 kWh/min

Table 3 Charger installation costs for stops

Stop #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
C_s (10^3€)	173	139	87	97	133	97	90	132
Stop #	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
C_s (10^3€)	173	139	87	97	133	97	90	132

The optimal solution obtained from the model incurs a charging infrastructure cost of 411,000, equipping stops 4, 6, 8, and 14 with a charger. Table 4 presents the comprehensive outputs concerning the total amount of energy transferred and consumed, as well as the amount of energy remaining at the end of the operation period. When examining the remaining energies of buses, significant variations are observed even among buses serving the same route. For instance, there is an approximately considerable difference of 83 kWh between Buses 1 and 3 on Route 7. These findings underscore the importance of individually addressing the energy status of each bus, taking into account dynamic demand and link travel times. Although the buses on Route 1 complete the operation period with the lowest energy amount, they do not fall below , 60 kWh. On the other hand, the buses on Route 6 are the least energy-transferred buses on the network since Route 6 includes only one stop (Stop 8) equipped with a charger. Therefore, the recharging times for the buses on this route are relatively shorter.

Two additional scenarios have been conducted to investigate the impact of dynamic demand on the transferred energy amount and the impact of dynamic link travel times on the consumed energy amount. In Scenario 1, instead of deriving the recharging times of buses at stops from the number of boarding/alighting passengers, we assumed a fixed value of 20 seconds. In Scenario 2, we assumed that the energy consumption between two stops solely depends on the length of the link by eliminating the influence of time-dependent link travel times on energy consumption. The results are presented in Table 5, demonstrating the impact of dynamic demand and link travel times on the problem.

Table 4 Energy state analysis for each bus in the network

Route #	Bus #	Number of runs	Transferred energy [kWh]	Consumed energy [kWh]	Remaining energy [kWh]
1	1	19	165.49	365.91	69.58
	2	19	175.57	366.12	79.45
	3	19	179.08	365.95	83.13
2	1	14	198.94	247.91	221.02
	2	13	195.98	231.67	234.31
3	1	30	88.88	226.64	132.24
4	1	11	100.51	175.68	194.83
	2	11	85.25	174.92	180.33
	3	11	98.91	175.42	193.49
5	1	19	204.19	337.29	136.90
	2	19	187.50	336.94	120.56
	3	19	183.81	337.05	116.77
6	1	9	81.05	204.06	146.99
	2	9	72.46	203.68	138.79
	3	9	96.08	204.43	161.65
7	1	16	218.90	355.52	133.38
	2	15	281.00	334.10	216.89
	3	15	274.48	333.94	210.54
8	1	15	286.78	338.59	218.18
	2	15	241.98	338.26	173.72
	3	15	301.85	338.30	233.54
	4	14	284.46	317.34	237.12
9	1	29	279.47	299.31	250.16
	2	28	276.32	289.55	256.77
10	1	18	187.85	350.09	107.76

Table 5 Comparative results among scenarios

Scenario	Charging infrastructure cost	Charging stops
Baseline	411,000	{4,6,8,14}
1	751,000	{3,5,6,7,8,13,14}
2	219,000	{3,8}

4 Conclusion

In this study, in order to fill the research gap in the literature, a mathematical model that assesses the energy state of each bus individually was developed for the CILP adopting the opportunity charging strategy, also considering the impact of dynamic demand (i.e., varying number of boarding/alighting passenger through the operation period) and dynamic supply (i.e., time-dependent link travel times) on the energy state of buses. The results indicate significant differences among buses serving the same route. This emphasizes the importance of evaluating the energy state of buses individually by taking into account the mentioned variables.

The main limitation of the study is the necessary processing time, such that solving the mathematical model even on a toy network necessitates a duration of 4 hours. For this reason, the computational time required for the application of the model to large-scale networks with numerous runs becomes a subject of curiosity. However, the model can be utilized in small/medium-scale networks by using passenger boarding/alighting data and run' details provided by public transportation companies and by calibrating parameter values for the location where the model will be conducted.

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