CHEMICAL ENGINEERING TRANSACTIONS

VOL. 97, 2022

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-96-9; **ISSN** 2283-9216

DOI: 10.3303/CET2297026

Electric Bus Charging Schedule for Multiple Route via Mathematical Modelling

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The electric bus is a promising solution for tackling carbon emissions, as it can replace the steadily growing numbers of diesel buses in the public transportation sector resulting from high travel demand. An electric bus has lower energy storage compared to a diesel bus and requires a longer refueling time. The charging schedule for an electric bus must be well organized to fulfill bus energy demand and passenger travel demand. This study developed a mathematical model to schedule the charging times of electric buses on multiple routes, based on a 24-hr day with a single charging station and a limited number of chargers. The model helps to minimize overall costs, including the charger cost (based on the number of chargers installed) and operating cost (based on the electric tariff). The results indicate that 2 chargers are sufficient to provide energy for 8 buses on 3 different routes. This model can assist transit planners in determining the optimal number of chargers to install at a bus depot and planning bus charging schedules. However, the electric buses' limited battery storage capacity inhibits savings incurred by the electricity tariff.

1. Introduction

Around 6% of worldwide greenhouse gas emissions are attributable to public transportation (Basma et al., 2020). Diesel buses are a significant source of greenhouse gas emissions in metropolitan areas due to their widespread use in public transportation. Hence, the electrification of public buses seems to be a promising solution to tackle the issue of carbon emissions and air pollution. By electrifying public transportation, local air pollutants such as nitrous oxide (NOx) and particulate matter (PM) released by traditional buses may be reduced (Xylia et al., 2019). Lim et al. (2021) indicated that electric buses could be a future trend in transportation, with several countries such as China, Japan, and the UK already implementing electric buses in their transportation system. Dietmannsberger and Burkhardt (2021) indicated that switching diesel buses to electric buses would incur 30% higher costs, with the main cost attributed to the cost of the battery. Moreover, installing a higher battery capacity would also significantly increase annual maintenance costs although the electric bus has lesser components to be maintained than the diesel bus. On top of that, the electric bus's limited battery capacity limits its travel distance and constraints bus service (Perumal et al., 2022). Thus, this study developed a model that can help schedule an electric bus service with limited battery capacity to minimize the overall cost of implementing electric buses in the transportation system. The main objective of this study is to develop a mathematical model that can help plan an electric bus charging schedule based on its travel demand without compromising energy demand, while minimizing overall cost, including the capital cost of the electric bus chargers and operating cost due to electric tariff, which varies based on time. The electric cost at the bus stop, which is based on the tariff of the commercial area, can be categorized as peak hour or non-peak hour. The model is used to carry out a sensitivity analysis with the main parameter being the number of electric chargers for the electric bus. This model can assist transportation planners to plan bus charging schedules and determine the optimal number of chargers to install at a bus depot.

Paper Received: 4 July 2022; Revised: 24 September 2022; Accepted: 30 September 2022
Please cite this article as: Lim L.K., Ab Muis Z., Hashim H., Ho W.S., Chee W.C., 2022, Electric Bus Charging Schedule for Multiple Route via Mathematical Modelling, Chemical Engineering Transactions, 97, 151-156 DOI:10.3303/CET2297026

2. Literature Review

Manzolli et al. (2022) summarized the recent electric bus trend. One of the current trends includes the schedule-based charging optimization framework and the development of meta-heuristics to solve difficult MILP models involving fleet scheduling. Studies have also discussed charging optimization problems because electric buses have limited energy storage and longer service trips. Dirks et al. (2022) developed a model to determine a cost-optimal, multi-period, long-term strategy for the integration of battery electric buses into metropolitan bus networks. The model helped to reduce the total cost of ownership and determined the potential reductions of nitrogen oxide emissions. Dirks et al. (2022) also suggested integrating medium-power charging facilities with medium-capacity batteries based on battery capacity and charging power. However, the model did not study the number of chargers or adjusted this factor to integrate with the bus route. Also, the model did not consider the number of chargers that could be accessed or the high capital cost of electric bus chargers.

Sung et al. (2022) proposed a simulation model with a heuristic algorithm to schedule an electric bus charging timetable without considerable simplification. The model can help heuristically optimize the mix of heterogeneous buses and chargers based on compatibility. The model was developed to minimize total costs, including bus, charger, and electricity costs. The model solved the problem using a heuristic algorithm but did not schedule the bus charging service using an overall schedule. Previous studies did not include the overall schedule or the number of chargers in their scheduling model. In this study, a model was developed to help schedule a charging timetable for electric buses on multiple routes to minimize overall cost, including the charger cost with varied numbers of chargers and operating costs.

3. Mathematical modelling

A mathematical model was developed to help schedule the charging schedule for an electric bus based on a minimum operating cost without compromising the energy demand of the bus. There are 2 sets in this model: time (T) and bus (B). The model was run based on a daily schedule of 24 h. There are 288 periods divided into 5-minute intervals. For the Bus set, the model includes 8 buses. The model also includes 3 routes. Bus 1, Bus 2, and Bus 3 belong to Route 1; Bus 4, Bus 5, and Bus 6 belong to Route 2; and Bus 7 and Bus 8 belong to Route 3.

Several assumptions were made: (1) The bus battery capacity is the depth of discharge; (2) The distance for each route is a whole cycle that starts from Larkin Sentral and ends at Larkin Sentral; (3) The bus can only be charged at Larkin Sentral; (4) The energy consumption of the bus is constant; and (5) The lifetime of the charger is 10 y, with 3% interest.

Eq(1) shows the objective function, where the overall cost is the sum of the operating cost and the annualized capital cost in which the overall cost is minimized. Eq(2) is used to determine the annual operating cost by summing up the energy used each hour and multiplying it with the energy fee that varies with time. The energy fee varies according to peak hour or non-peak hour. Eq(3) is used to determine the capital cost of the electric bus charger. Eq(4) is used to determine the energy charged into every bus every hour based on the total energy used every hour.

$$min\ OverallCost = OperationCost + CapitalCost \times (\frac{IR((1+IR)^{LT})}{(1+IR)^{LT}-1}) \tag{1}$$

$$OperationCost = \sum_T EnergyUsed_T \times EnergyFee_T \times 365 \tag{2}$$

$$CapitalCost = MaxChargerUsed \times UnitCostCharger \tag{3}$$

$$EnergyUsed_T = \sum_B EnergyToBus_{B,T} \tag{4}$$

Eq(6) to (12) are the equations for the constraint of battery capacity, charging and discharging capacity, charging capacity, and charging rate. Eq(5) is the equation for calculating the energy storage of the electric bus. This equation will decide the charging value based on the energy in the battery and the travel demand for each bus. The equation is developed in loop mode. Eq(6) is used to set the maximum energy storage in the bus and Eq(7) is used to calculate the current state of charge.

$$EnergyInBus_{B,T++1} = EnergyInBus_{B,T} + EnergyToBus_{(B,T)} - TravelDemand_{B,T} \tag{5}$$

$$EnergyInBus_{B,T} \leq MaxBusBatteryCapacity_B \tag{6}$$

$$\frac{EnergyInBus_{B,T}}{MaxBusBatteryCapacity_B} \times 100\ \% = SOC_{B,T} \tag{7}$$

Eq(8), Eq(9), and Eq(10) are the binary constants to limit the bus so it can only charge when it is not traveling. A dummy number is put into these equations. Eq(11) and Eq(12) are the limitations set to limit the number of buses charging at the same time based on the number of chargers available at the bus station. Eq(12) is used to limit the charging rate of the bus

$$EnergyToBus_{B,T} \leq BCC_{B,T} \times 100{,}000{,}000 \tag{8}$$

$$TravelDemand_{B,T} \leq BDN_{B,T} \times 100{,}000{,}000 \tag{9}$$

$$BCC_{B,T} + BDN_{B,T} = 1 \tag{10}$$

$$\sum_{B} BCN_{B,T} = NumChargerUsed_T \tag{11}$$

$$NumChargerUsed_T \leq MaxChargerUsed \tag{12}$$

$$EnergyToBus_{B,T} \leq MaxChargingRate \tag{13}$$

4. Case study

This paper took the bus system in Johor Bahru (PAJ) as a case study. Three routes were selected and included in the model. All the buses are only allowed to charge at Larkin Station and will rest at Larkin Station before starting their service trip. The route detail is listed in Table 1. The bus travelling time is based on the current bus schedule. The bus travels based on the existing bus service schedule. A Scenario Analysis was carried out based on the number of chargers. There are 8 chargers in Scenario A, as there are 8 buses in the service. There are 3 chargers in Scenario B, as the maximum number of buses in each route is 3. Scenario C was developed based on the model decision. The lifetime of the chargers is assumed to be 10 years.

Table 1: Route Information

Route Name	No of Bus	Starting Point	Ending Point	Distance (km)	Trip Duration (min)	Average Energy (kWh/ trip)	Number of Trip per day	Bus Battery Capacity (kWh)
P101	3	Larkin Sentral	JB Sentral	42.6	55	9.6276	33	275
P102	3	Larkin Sentral	Hud Sri Stulang	38.8	35	13.7795	33	275
P211	2	Larkin Sentral	Taman U	46.2	60	9.5711	14	175

5. Results and discussion

The model indicates that it is possible to reduce the number of chargers with a well-designed electric bus charging schedule. The model helps to schedule the charging period for each bus throughout the non-service period and the service period to ensure energy demand is fulfilled. Table 2 shows the overall cost for each scenario. The unit cost for a charger is 76,800 USD. Scenario C has a minimum total cost of 87,727 USD consisting of a 36,637 USD annualized charger cost and a 51090.03 USD operating cost per year, while Scenario A has a maximum total cost of 197,055 USD, consisting of a 146,548 USD annualized charger cost and a 50,507 USD/yr. operating cost. The amount of charging energy at peak hours increased slightly when the number of chargers decreased. A high number of chargers could help reduce the operating cost by avoiding charging during peak hours, but the high purchase cost of chargers makes this option economically unfeasible. Due to the limitation of the bus battery, the energy used for charging during peak hours is nearly the same for all scenarios based on Table 2:

Table 2: Potential savings and energy usage

Scenario	A	B	C
Number of Charger	8	3	2
Annualized Capital Cost for Chargers (USD)	72,026	27,009	18,006
Annual Operation Cost (USD)	50,507	50,657	51,090
Peak (kWh/day)	5,175.9	5,228.8	5,381.5
Off Peak (kWh/day)	2,793.2	2,740.3	2,587.6

Figure 1(a) shows the state of charge (SOC) of Bus 01 of Route 1 in different scenarios. The increasing trend of the line indicates that the bus is charging while a decreasing trend means that the bus is supplying the travel demand. No change in the SOC indicates that the bus is idle, where the bus is neither traveling nor charging. Before the operating period, Bus 01 will be fully charged in every scenario. The model prefers the bus to be fully charged not only to ensure that the bus has enough energy to fulfill travel demand but also to reduce charging during peak hours to avoid high charging costs. During the peak hour period, Bus 01 has more idle time in Scenarios A and B compared to Scenario C. In Scenario C, the charger usage is more limited due to the low number of chargers.

Figure 1(b,c,d) indicates the average SOC for different routes in different scenarios. It is more challenging to arrange the charging schedule for Route 1, as the route has more trips and a lesser gap time in between the trips compared to Route 2 and Route 3. In Scenario A, the highest SOC for Route 3 is around 73%, as the buses do not have to store a high amount of energy for the whole day trip while the buses on Route 1 and Route 2 will be fully charged before departing to avoid charging during peak hours. In Scenario B, only the bus on Route 2 is fully charged before departing. In Scenario C, the buses have a higher SOC before departing, especially the buses on Route 3, as they have to store more energy before service hours so that the chargers can be prioritized for Route 1 and Route 2. Before ending the service hour, the bus will try to use all its residual energy instead of charging earlier, as the peak-hour electric tariff lasts until 10 p.m. In Scenarios A and B, there are no more charging events after 1900, except for Route 1.

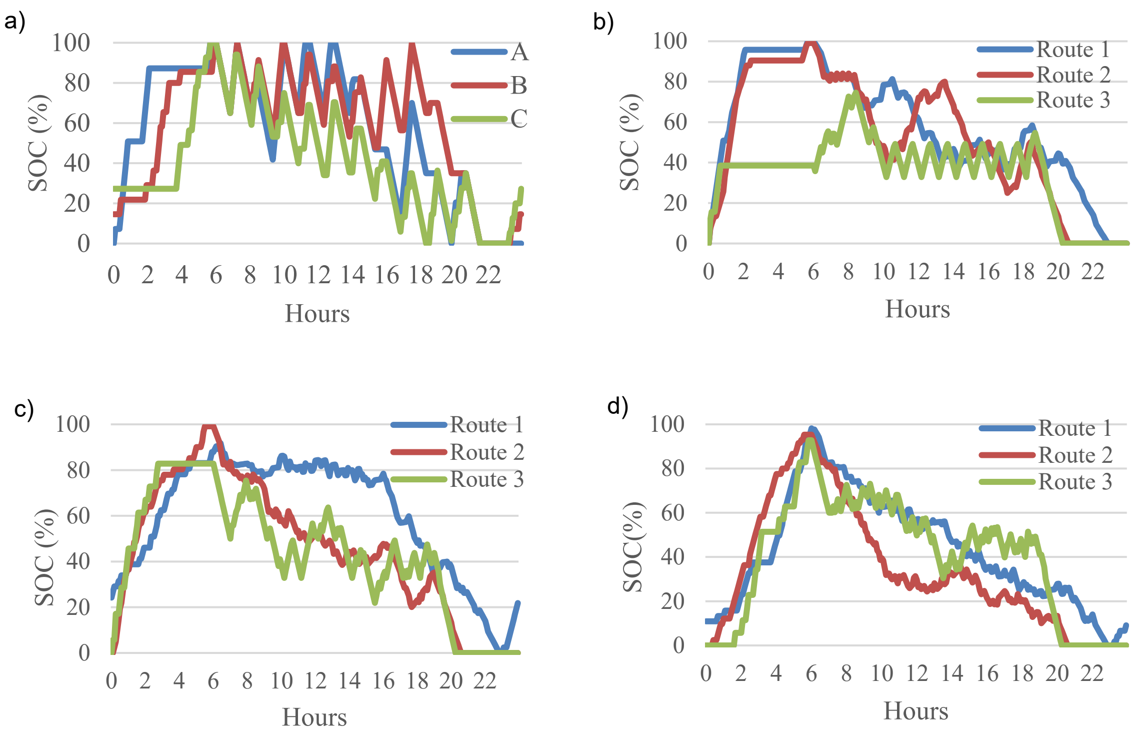

Figure 1:Different SOC for electric buses (a) SOC of Bus 1 in each scenario (b) Average SOC in Scenario A (c) Average SOC in Scenario B (d) Average SOC in Scenario C

Figure 2 shows the total energy transferred to each electric bus each hour. In every scenario, the energy charged into the buses decreases sharply after 1900, as the buses have enough residual energy to finish their trip. For Scenarios A and B, there are certain hours that the electric buses are not being charged. Nevertheless, the maximum energy charged into the buses peak at 870 kWh in Scenario A, but this case is not recommended because it may bring disturbance to the electric grid. The energy grid is more evenly distributed in Scenario C.

a)

b)

c)

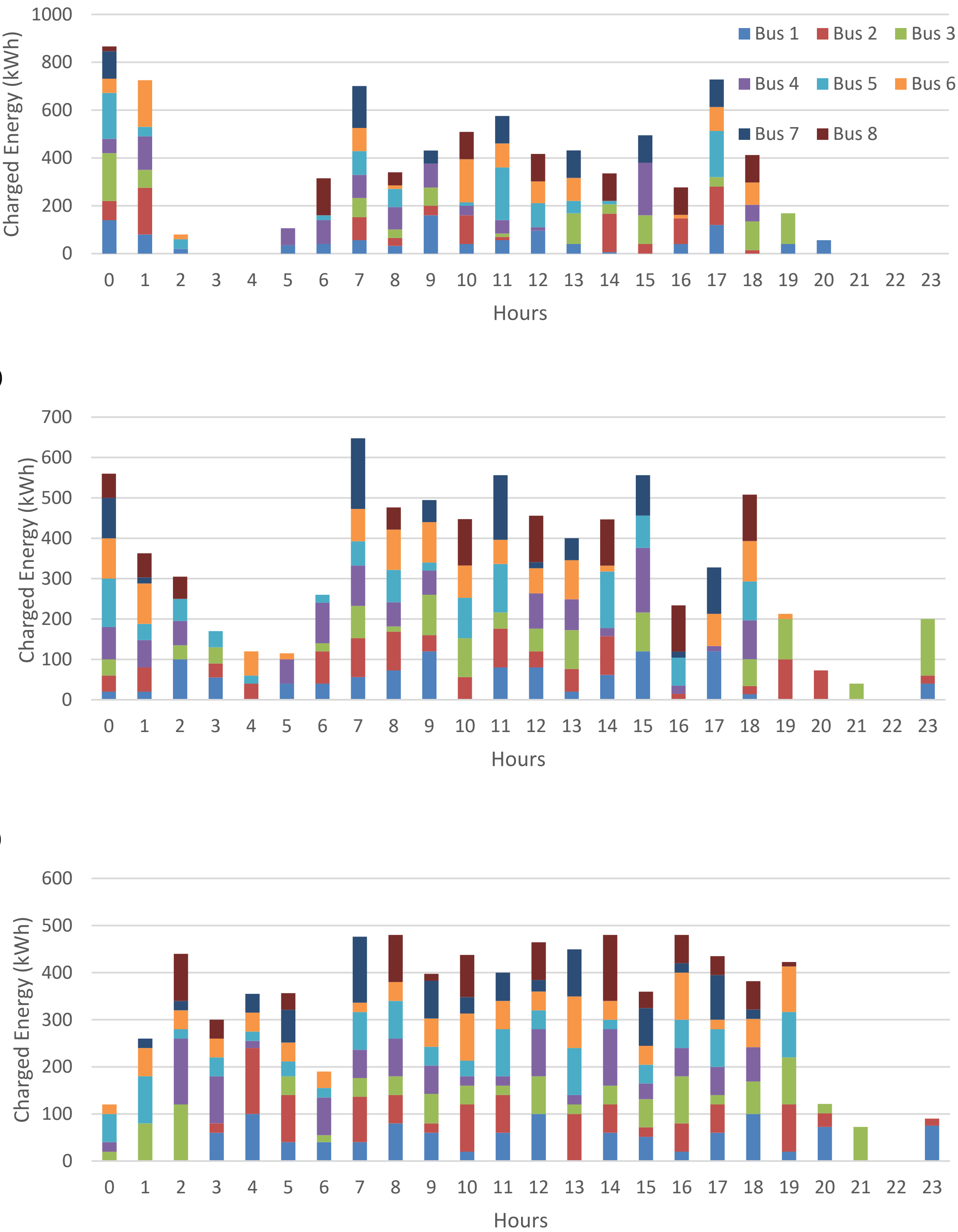

Figure 2: Energy charged into buses by hours in (a) Scenario A, (b) Scenario B and (c) Scenario C

Figure 3 shows the energy provided by the grid to the electric bus. In scenario A, the highest energy provided by the grid exceeded 160 kWh, while in scenario C, it was mainly maintained at around 40 kWh as scenario C only provided 2 chargers. This can help maintain the grid's stability. In Scenario C, there is more charging duration during the peak hour from 8 a.m. to 10 p.m.

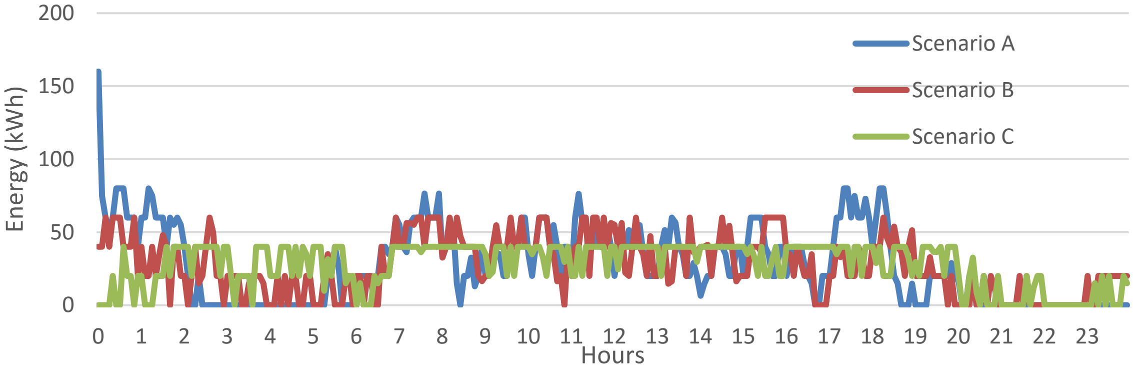

Figure 3: Energy charged into buses by hours in each scenario

6. Conclusion

The model developed in this study proves that the charging schedule for an electric bus on multiple routes can be optimized to reduce the number of chargers required for electric buses from different service routes. The model helps to reduce the number of chargers from 8 to 2, which, in turn, may help save up to USD 109,328. There are low potential savings from the price of the tariff due to the electric bus's limited battery storage. By avoiding charging during peak hours, and having a high number of chargers, operating costs can be reduced; but, due to the high cost of charger purchases, this solution is not economically viable. This model can help transit planners to plan bus charging schedules and identify the optimal number of chargers to be installed at a bus depot. Future work could improve on the current model by including multiple charging locations.

Acknowledgments

The authors would like to acknowledge the Ministry of Higher Education for funding this study through the Zamalah Scholarship and the Fundamental Research Grant Scheme (FRGS) with vote number R.J130000.7851.5F184, Universiti Teknologi Malaysia.

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