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Exploring the viability and effects of opportunity charging in electrified transit networks

Peter Benoliel[1,2], Alan Jenn[2], Gil Tal[2]

[1]*Corresponding Author, pkbenoliel@ucdavis.edu*

[2]*Institute of Transportation Studies, University of California - Davis, 1590 Tilia St, Davis, CA*

Summary

This study explores the circumstances when opportunity charging is economically viable in an electric transit bus network. A mixed-integer linear program was developed to optimize the mix of charging infrastructure in a network. The model was run on 78 transit networks, and the viability of opportunity charging was examined. One investigation found that overall opportunity charger duty cycle of 50% or greater was required at higher costs, though lower duties were viable if costs were lower. By examining several scenarios, key insights about investment decisions over many different types of networks are presented.

Keywords: BEV, charging, infrastructure, public transport, transportation network

1 Introduction

There is a concerted effort in the transit bus industry to transition buses from traditional fossil-fuel vehicles to zero-emission buses (ZEBs), a category that includes both fuel cell electric buses (FCEBs) and battery electric buses (BEBs). Studies have found that transitioning from conventionally fueled vehicles to electrically- or hydrogen-powered vehicles is an effective means of curbing greenhouse gas emissions contribution [1], There have been several high-profile deployments of ZEBs in China and Europe, as well as the United States. According to a survey performed by CALSTART, there are currently 3,533 ZEBs either deployed or on order across the United States [2]. Approximately a third of these vehicles are in the state of California. In December 2018, the California Air Resources Board (CARB) adopted a regulation require that transit fleets begin the shift to zero-emission buses known as Innovative Clean Transit (ICT), which affects the purchase of new buses beginning in 2023 [3]. CARB estimates that the California transit bus fleet will complete the transition to 100% ZEBs by the 2040s.

Although California has the most well-developed ZEB policy, New York also has a program for the replacement of diesel commercial vehicles, including transit buses. Additionally, several states have signed onto the Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding (MSMOU), a statement of cooperation between the signees that include 15 states and the District of Columbia. Although it is not legally binding, the MSMOU represents a statement of fostering “a self-sustaining market for zero emission medium- and heavy-duty vehicles through the existing Multi-State ZEV Task Force, which will serve as a forum for state coordination, collaboration and information sharing on market enabling actions, research, and technology developments.” [4]. The action plan laid out in the MSMOU primarily consists of committing to funding and other incentives to encourage the development of a market for ZEBs in their respective states. On a federal level, new funding for ZEBs has recently been introduced in the Infrastructure Investment and Jobs Act. Signed into law in 2021, this act will provide a total of $18.4 billion into federal programs to promote low- and no-emission vehicles, a pool of funding that can be used for ZEBs (among other uses).

As a result of these policies, several transit agencies in the United States have begun developing plans for full-scale transitions to ZEBs, and a few of these agencies have already completed the transition. These transitions have come with a fair share of challenges, from costs of transitioning to the specific strategy or strategies and infrastructure that should be used in a ZEB fleet, to issues of knowledge and operation of the fleets. This study presents a look into the structural solutions that may be used by fleets across the USA to transition transit bus fleets to BEBs.

1.1 Costs of Transitioning a Fleet

The high costs of ZEB fleet transitions have been examined as parts of demonstration-scale deployments [5], [6], and have been used as inputs in other studies focusing on total cost of ownership [7], [8]. Most transitions have focused on the vehicles, as these represent the highest upfront cost of the transition and are central to the success of the network. However, vehicles cannot operate without their accompanying infrastructure, and the entire system must be considered when planning a transition. Interviews with transit agencies revealed that planning perspective decisions are not necessarily about the parts that cost the most. Although several studies have found that infrastructure costs represent a relatively small part of the overall cost of transitioning to a ZEB fleet [9], [10], the selection of infrastructure and charging strategy (or strategies) is one of the first decisions that gets made after planning a full BEB fleet transition. This infrastructure decision drives the rest of the transition process for transit agencies, and these decisions can carry significant implications on the makeup of the transit agency for years or decades to follow.

The cost of lithium-ion (Li-ion) batteries is a frequently researched topic, especially as the costs of Li-ion batteries has come down in the decades since the technology was first made commercially viable [11]–[13]. These falling costs have been identified as a key factor in the commercialization of transit buses and other heavy-duty vehicles [14], [15]. The cost of batteries has to be weighed against the cost of opportunity charging infrastructure, which can reduce the required battery pack size of the vehicles in the system under certain conditions [16], [17]. However, these conditions are often applicable to the networks being studied; there have been few to no systematic studies examining large numbers of networks to understand what trends may exist between different networks when considering this tradeoff.

1.2 Network Case Studies

There have been many different studies on the costs and methods of transitioning individual networks. The issues surrounding such a transition are numerous and complex. Optimization studies have been performed focusing on everything from vehicle scheduling [18]–[20] to optimizing a fleet transition over time [7], [21], [22] to examining the different types and locations of charging infrastructure [23]–[25]. These studies have reached a variety of conclusions based on the nature of the network that was the focus of their study, however, the authors are unaware of any larger-scale studies of many different real networks with the intention of examining how a transition to ZEBs may differ between them. This study examines the interrelated nature of several aspects of transit agencies affect the transition to BEBs by developing an optimization method that can be generally applied to many different transit networks to study the most important characteristics of BEB transitions.

2 Methods and Data

The model presented in this work is a mixed-integer linear program (MILP) optimization model that is generally applicable to transit agencies with a static general transit feed specification (GTFS) feed. This model focuses on tracking individual buses as they move through the system and understanding the effects of different route characteristics on the overall system.

2.1 Model Assumptions

MILP is a common formulation for solving transit network optimization problems [21]–[24]. This model is based on several assumptions about the vehicles and the system in which they operate:

- It is assumed that all buses are identical apart from the sizes of their battery packs. This includes the cost, energy use on a given route, passenger capacity, and other factors that may come into play during vehicle operation.
- It is assumed that the network operates in a deterministic fashion according to its timetable. The effects of traffic and other delays are ignored, as are issues with the charging schedule and other sources of uncertainty that could have a significant impact on the effectiveness of the transit network as these are not the focus of this study.
- It is assumed that the transit agency being modeled possesses enough depot chargers to recharge all service vehicles to full overnight, and that the marginal cost of continuing to use those chargers during the day is negligible. As a result, it is assumed that daytime depot charging is available at no cost.
- All costs that are present in the network regardless of the sizes of the battery packs and type(s) of charger(s) installed are not factored into the optimized cost of the model. Most notably, this means that costs of vehicles (aside from their batteries) and energy purchase are ignored, as well as costs related to operation, training, construction and installation, and other miscellaneous costs associated with running a transit network.

2.2 Model Data

2.2.1 General Transit Feed Specification

The inputs for this model are primarily taken from each network's GTFS data feed. These data feeds are maintained by transit networks for use in external applications and are traditionally available through from either transit agencies or third parties. Most frequently, developers use these feeds to create applications that keep track of the times and locations of buses within the networks using "dynamic feeds" that allows customers to avoid wait times and better plan their trips on the network. These feeds also contain a "static feed" containing information about the routes and trips within a network, including trip times, stop locations, and location information about both. This model uses these feeds to construct a set of tables that are used to represent the timetable, stops, and candidate charging locations in the model, as well as to find the energy use of the buses on each route.

2.2.2 Energy Data and Energy Use Modeling

For this model, energy requirements are generated on a bus-route-pair basis from a model developed by Ambrose and others[26]. Ambrose's model uses data from the FleetDNA dataset developed by the National Renewable Energy Laboratory (NREL) [27] to develop energy demands for a particular bus-route combination using a transit agency's GTFS data feed. By using information present in the GTFS data and employing regression on the FleetDNA dataset and using characteristic velocity, acceleration, and network size as the most significant indicators of energy use, Ambrose's model can develop an estimation for energy use on any transit route that is present in a transit network's GTFS data feed.

2.3 Modeled Transit Networks

This project makes use of the GTFS feeds of many transit networks in the United States. These feeds were accessed using OpenMobilityData (previously TransitFeeds)[28], an open-source repository and API to access the feeds of different transit agencies around the world. Of the over 800 feeds within the repository, 78 networks were identified as having feeds suitable for use in the optimization model. These networks were each optimized as described above. Table 1 contains a set of summary statistics for the set of modeled networks.

Table 1: Summary statistics for modeled networks

	Units	Average	Standard Deviation	Minimum	Maximum
Number of routes	Routes	12.9	12.3	1	60
Average route time	Minutes	47.6	47.5	13.7	298.7
Average route length	Miles	25.1	37.6	3.6	201.1
Average of route velocity	Mph	24.9	8.9	9.9	53.0
Average energy use	kWh/mile	2.49	0.37	1.94	3.86

States with at least one network included in the study are mapped in Figure 1.

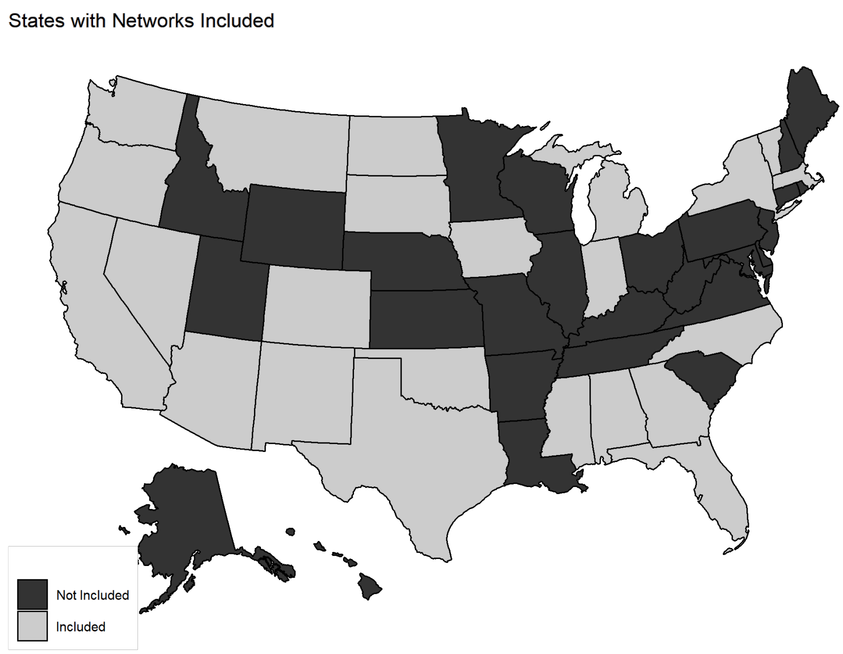

Figure 1: A map indicating the states with networks included in the study. Light states were included; darkened states had no networks suitable for this model.

2.4 Scenarios

To determine the number of vehicles modeled for each network, a minimum number required to satisfy the trips demanded was established, and an amount was added to better match the number of vehicles that are available to transit agencies. For the base case scenario, the number of vehicles was increased by 30% over the minimum. In addition to the base case, two additional scenarios for the number of vehicles were developed: a 'few vehicles' and a 'many vehicles' scenario. For the few vehicles scenario, an increase over the minimum required vehicles of 10% was used; for the many vehicles scenario, this increase was 50%. These vehicles were each assigned to a specific route in the system based on where they were needed. These limits serve to establish a theoretical minimum and maximum number of vehicles a transit agency might use in a transitioned BEB system.

For each of the vehicle scenarios, four levels of opportunity charger cost were developed. Opportunity charging costs are highly volatile and not very well reported in situations where they have been installed, and their cost varies based on the particular technology used in the implementation of opportunity charging (Johnson et al., 2020), so a wide range of prices were used as scenarios. The four levels of opportunity charger cost were \$300,000, \$200,000, \$150,000, and \$50,000. These scenarios will be referred to as the “pessimistic”, “grounded”, “optimistic”, and “pushed” scenarios respectively. Each of these cost levels was run for each vehicle scenario to explore the impacts of both the pricing and various other route characteristics on the outputs of the model.

3 Results and Discussion

3.1 Charger Placement and Use

When deciding whether to build opportunity charging into a transit network, the network operator has two strategic decisions to make: how many chargers to install, and where to install them. In general, central locations are preferred for opportunity charging, and chargers at the periphery of the networks are the first to get dropped from networks as the cost of chargers increases. An example of this relationship in the County Connection transit network (a medium-sized transit network in the state of California) is shown in Figure 2.

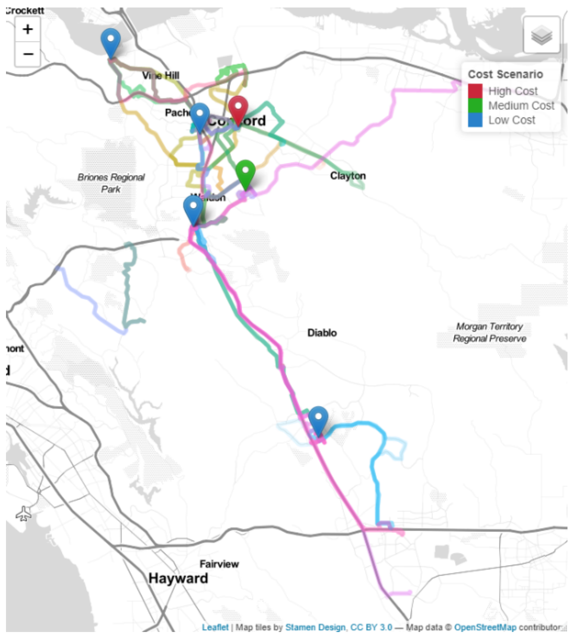

Figure 2: A map of the County Connection network with the locations of installed chargers in different scenarios. Note that each of the scenarios installed locations include the locations at higher costs (for example, the low-cost scenario has chargers at all six locations).

County Connection utilizes one charger in the high-cost scenario, two chargers in the medium-cost scenario, and six chargers in the low-cost scenario. As Figure 2 shows, the chargers exclusive to the low-cost scenario are located on the periphery of the network and are placed at hubs where two to four routes intersect, allowing buses on these routes to utilize the chargers to lower the need for batteries. In the medium- and high-cost scenarios, these peripheral chargers are no longer economically viable, and only the chargers in the central location of the network where the most routes intersect remain as an economical choice. These peripheral chargers tend to have lower duty cycles than their central counterparts, only being used by the buses that must travel longer distances.

The population of modeled networks shows the same trend for networks that purchase chargers in all cost scenarios. Although mapping these networks individually is impossible, the duty cycle of the chargers across scenarios can be used to illustrate this effect. This relationship is shown in Figure 3.

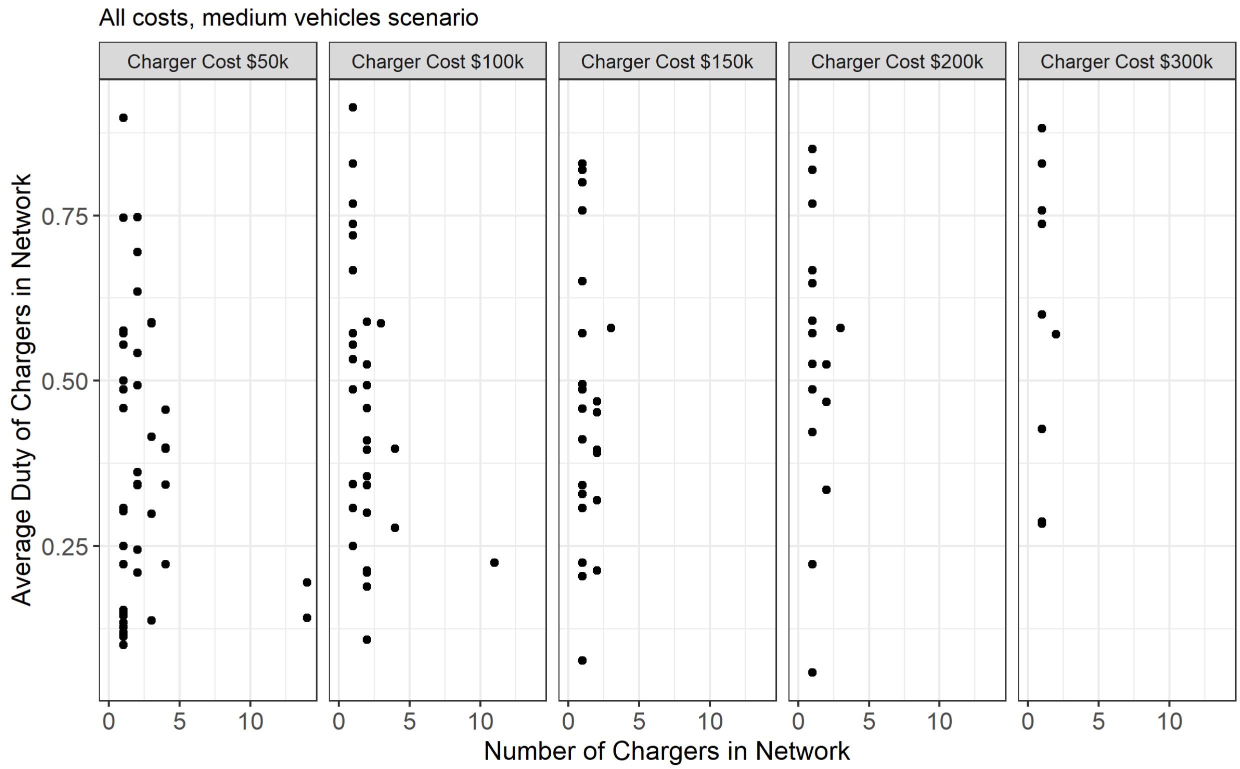

Figure 3: Number of opportunity chargers in a network versus the average duty cycle of all opportunity chargers in the network. Note that each point represents an entire transit network, and networks with no opportunity chargers are omitted.

In the low-cost scenario of Figure 3 (left-hand side), several networks have single chargers with very low duty cycles (8%-15%). These chargers are likely to be peripheral chargers that serve individual routes with a long travel distance. Because the cost of chargers is so low in this scenario, it is cost effective to replace large battery packs with infrastructure in this case. However, as the cost increases, the economic viability of these peripheral chargers decreases, until at the highest cost case, no duty cycles below 25% are economically viable (and most chargers have a duty cycle of at least 50%-75%). This fact is illustrated more directly in Figure 4.

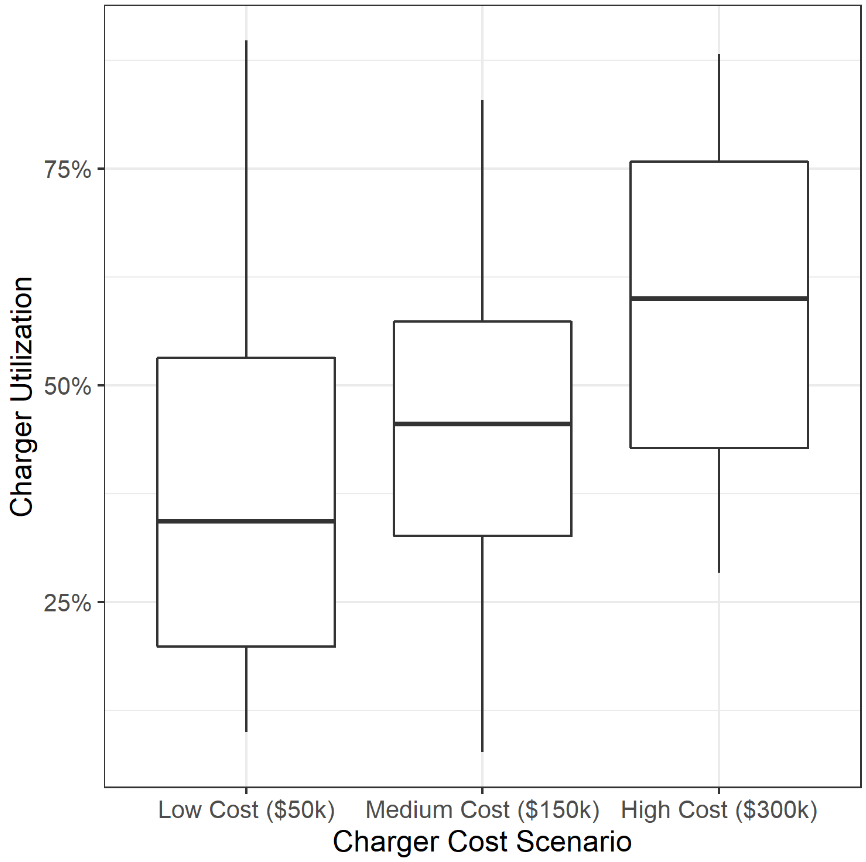

Figure 4: A box plot of the range and average of the average network opportunity charger duty for the low-, medium-, and high-cost scenarios

Although it is difficult to identify single characteristics as the cause of high charger utilization, the biggest predictors in the data appeared to be the overall regularity of the routes, as well as networks with a schedule that didn't have too many buses in the key locations at the same time, allowing buses to 'cycle' through the opportunity chargers. Additionally, other studies have shown that characteristics of individual routes within a network can be used to estimate which of those routes is well suited for BEBs and opportunity charging [7], [21], [22].

3.2 Effects of Opportunity Charger Installation

Overall, when the costs of opportunity chargers were low, more networks opted to install opportunity charging in more parts of the network. However, the opportunity charging infrastructure's presence has other effects throughout the network. Primarily, these effects are centered on the sizes of the battery packs in the vehicles of the network. Figure 5 shows an example of how the presence of more opportunity charging can impact the architecture of a network.

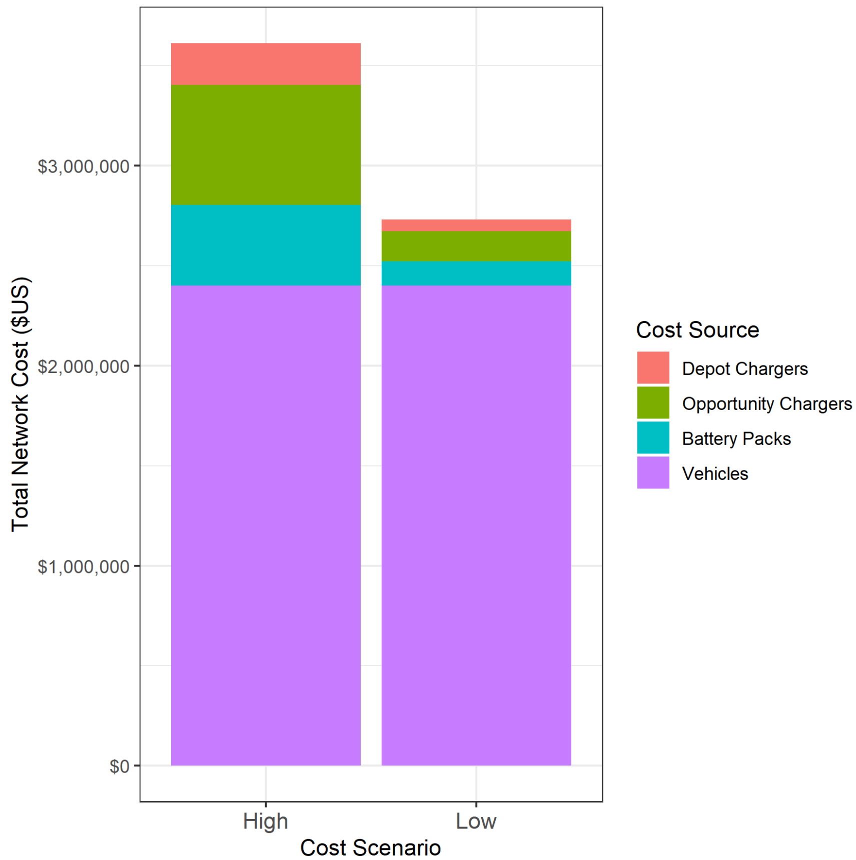

Figure 5: Total cost breakdown for Huntsville Shuttle for high opportunity charger cost scenario and low opportunity charger cost scenario.

Figure 5 shows the breakdown of costs between the two cost scenarios for the Huntsville Shuttle, a small transit network in Huntsville, Alabama. The only cost difference between the two is that of the opportunity chargers. The number of vehicles in the network is fixed, so that cost remains fixed between the two scenarios. However, the total amount of money spent on both depot chargers for overnight use and battery packs (which scales to the total size of the battery packs) also decreases, implying that both fewer depot chargers and smaller battery packs are required. Having fewer depot chargers is both a cost-saving measure and a way to decrease the strain that a BEB network could place on the local electrical grid, as fewer buses need to be plugged in at the same time. By having a smaller battery pack, the weight of the vehicles can be reduced, which can lead to further energy savings.

4 Conclusions

This paper presented a unique study examining the trends of BEB transition at network level by modeling the optimal battery packs and charging strategies of more than 75 networks in the United States. As transit networks begin transitioning from traditional fossil fuels to zero-emission technologies, the question of what infrastructure is needed and where to install it will become more important. Currently, the dominant strategy to recharging buses is to purchase a depot charger for each BEB and recharge all buses overnight. This strategy results in a requirement for larger battery packs among vehicles. The results of this study indicate that opportunity charging has several roles to play in the transition of transit networks to BEBs. First, especially if the chargers can be acquired cheaply, they can serve as a way to replace several large battery packs. If the network is particularly compatible with opportunity charging due to overall regularity of routes that are neither too long nor run too frequently, they can even overtake traditional depot charging as the primary energy delivery method in a network (though this is very rare).

As with any representative model, there are limitations and tradeoffs that must be made. In this model, there are two major limitations that could have affected results, as well as several less impactful assumptions and limitations that were made to improve the feasibility of running the model. This model assumed that, on a given route, all vehicles performed equally in terms of energy use per mile. However, the different sizes of battery pack represent a significant portion of the weight of the vehicles being modeled. This difference in weight is enough to potentially affect the energy use performance of the vehicle [7], [17] and may carry a high enough associated cost to encourage smaller batteries with more opportunity charging. However, this model did not capture those differences. These results are not reflective of the impacts that having a physically larger or smaller battery pack may have on the effectiveness of a vehicle.

This model uses very simple costs for the economic components of the situation. In some cases, this is unavoidable; aspects like construction, permitting, and labor related to the installation of opportunity chargers will have a high variance from situation to situation, and aren't predictable in a model that seeks to represent as many transit agencies as possible. By simplifying most costs to single values (cost per kWh for batteries, energy costs for recharging, etc.), this study narrowed its focus to examine the impact of easily measurable data that can be obtained from a GTFS feed on the fitness of a network for opportunity charging. However, the results indicate that these economic factors may be the dominant factor in evaluating network fitness for opportunity charging. As this model is not designed to measure the impact of those economic factors, no definitive statement can be made.

In addition to the factors described above, there are several other factors that may contribute to issues in the model. The number of buses and the routes they serve are fixed as an input to the model, preventing the model from developing the network to run in an optimal matter. This kind of network design optimization is beyond the scope of this project. Additionally, external factors of energy use, such as climate control or passenger load, are not taken into consideration for this model. Although these factors and others can contribute significantly to vehicle energy use [29]–[31], they are not the primary focus of this study. While these factors may have an impact on the individual designs of the tested networks, they would not impact the trends of the characteristics of focus in this study.

This study has several implications for transit agencies and governing bodies when considering a transition to BEBs. First, it is important to consider opportunity chargers as a potential alternative to larger battery packs planning a BEB network. These chargers may be able to save networks significant amounts of money depending on the relative costs of chargers and batteries and can have positive knock-on effects throughout the rest of the network, especially in terms of vehicle energy use and material requirements. Expected duty cycle can be a good indicator of the relative viability of an opportunity charger, as chargers with higher utilization provide a better return on investment, even in the high-cost scenarios. Governments may consider introducing heavier subsidies for these chargers, as even a small increase in the number of opportunity chargers deployed can have a huge impact on battery pack requirements in certain circumstances. Finally, some networks will struggle to be able to electrify completely if BEBs are the sole technology available without significantly improved range availability. With current vehicle energy use figures, the largest required battery pack modeled was over 1.5 MWh, more than twice as large as the largest commercial BEB battery packs being produced today. Alternative technologies such as fuel cell electric buses, fossil-fuel hybrid buses, or other transit options will be required to meet the needs of these very long route requirements.

This model only examines the economics of transitioning a transit network to 100% BEBs, and there are several other considerations that could be taken. As discussed, opportunity charging can lower the need for battery packs in vehicles. At a certain scale, this could prove a viable method to lower the demand for certain critical materials and lower the overall cost of the BEBs. This would be significant, as capital investment is frequently cited as the main obstacle for adoption by transit agencies. Additionally, only networks up to a certain size were able to be modeled due to computational limitations. However, the model presented in this study is very generalizable, and with more computing power, it is possible for larger and more complex networks to be modeled without changing the approach. This generalizability makes this model a great tool to base a wide-ranging study on many different types of networks to investigate the transition of public transit bus networks to BEBs.

Acknowledgments

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References

[1] K. G. Logan, J. D. Nelson, and A. Hastings, "Electric and hydrogen buses: Shifting from conventionally fuelled cars in the UK," *Transportation Research Part D: Transport and Environment*, vol. 85, p. 102350, Aug. 2020, doi: 10.1016/j.trd.2020.102350.

[2] H. Hamilton, R. Chard, B. Lee, F. Silver, and J. Slosky, "Zeroing in on ZEBs," Dec. 2021.

[3] *Article 4.3. Innovative Clean Transit*. California, USA: California Air Resources Board, 2018.

[4] *Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding*. 2020.

[5] A. Kontou and J. Miles, "Electric Buses: Lessons to be Learnt from the Milton Keynes Demonstration Project," 2015. doi: 10.1016/j.proeng.2015.08.455.

[6] L. Eudy, R. Prohaska, K. Kelly, and M. Post, "Foothill Transit Battery Electric Bus Demonstration Results," 2016.

[7] M. Rogge, E. van der Hurk, A. Larsen, and D. U. Sauer, "Electric bus fleet size and mix problem with optimization of charging infrastructure," *Applied Energy*, vol. 211, no. February 2017, pp. 282–295, 2018, doi: 10.1016/j.apenergy.2017.11.051.

[8] A. Sheth and D. Sarkar, "Life Cycle Cost Analysis for Electric vs. Diesel Bus Transit in an Indian Scenario," *International Journal of Technology*, vol. 10, no. 1, p. 105, Jan. 2019, doi: 10.14716/ijtech.v10i1.1958.

[9] S. Pelletier, O. Jabali, J. E. Mendoza, and G. Laporte, "The electric bus fleet transition problem," *Transportation Research Part C: Emerging Technologies*, vol. 109, pp. 174–193, Dec. 2019, doi: 10.1016/j.trc.2019.10.012.

[10] M. Nicholas, "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas," 2019.

[11] C. McKerracher *et al.*, "Electric Vehicle Outlook 2021," 2021.

[12] B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles," *Nature Climate Change 2014 5:4*, vol. 5, no. 4, pp. 329–332, Mar. 2015, doi: 10.1038/nclimate2564.

[13] M. S. Ziegler, Juhyun Song, and J. E. Trancik, "Determinants of lithium-ion battery technology cost decline," *Energy & Environmental Science*, vol. 14, no. 12, pp. 6074–6098, Dec. 2021, doi: 10.1039/D1EE01313K.

[14] A. Burke and A. K. Sinha, "Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040," 2020. doi: 10.7922/G2H993FJ.

[15] B. Nykvist and O. Olsson, "The feasibility of heavy battery electric trucks," *Joule*, vol. 5, no. 4, pp. 901–913, Apr. 2021, doi: 10.1016/J.JOULE.2021.03.007.

[16] A. Kunith, R. Mendelevitch, and D. Goehlich, "Electrification of a city bus network—An optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus

systems," *International Journal of Sustainable Transportation*, vol. 11, no. 10, pp. 707–720, Nov. 2017, doi: 10.1080/15568318.2017.1310962.

[17] T. Thitacharee and A. Sripakagorn, "Electrification of Public Transport with Fast Charging in Traffic Congested Cities," *SAE Technical Paper Series*, vol. 1, 2016, doi: 10.4271/2016-01-1718.

[18] T. Paul and H. Yamada, "Operation and charging scheduling of electric buses in a city bus route network," *2014 17th IEEE International Conference on Intelligent Transportation Systems, ITSC 2014*, vol. 1, pp. 2780–2786, 2014, doi: 10.1109/ITSC.2014.6958135.

[19] A. Bagherinezhad, A. D. Palomino, B. Li, and M. Parvania, "Spatio-Temporal Electric Bus Charging Optimization with Transit Network Constraints," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5741–5749, Sep. 2020, doi: 10.1109/TIA.2020.2979132.

[20] A. Abdelwahed, P. L. van den Berg, T. Brandt, J. Collins, and W. Ketter, "Evaluating and optimizing opportunity fast-charging schedules in transit battery electric bus networks," *Transportation Science*, vol. 54, no. 6, pp. 1601–1615, Nov. 2020, doi: 10.1287/trsc.2020.0982.

[21] A. Islam and N. Lownes, "When to go electric? A parallel bus fleet replacement study," *Transportation Research Part D: Transport and Environment*, vol. 72, pp. 299–311, Jul. 2019, doi: 10.1016/j.trd.2019.05.007.

[22] M. Xylia, S. Leduc, P. Patrizio, F. Kraxner, and S. Silveira, "Locating charging infrastructure for electric buses in Stockholm," *Transportation Research Part C: Emerging Technologies*, vol. 78, pp. 183–200, May 2017, doi: 10.1016/j.trc.2017.03.005.

[23] T. Uslu and O. Kaya, "Location and capacity decisions for electric bus charging stations considering waiting times," *Transportation Research Part D: Transport and Environment*, vol. 90, p. 102645, Jan. 2021, doi: 10.1016/j.trd.2020.102645.

[24] Y. Lin, K. Zhang, Z.-J. M. Shen, and L. Miao, "Charging Network Planning for Electric Bus Cities: A Case Study of Shenzhen, China," *Sustainability*, vol. 11, no. 17, p. 4713, Aug. 2019, doi: 10.3390/su11174713.

[25] Y. T. Hsu, S. Yan, and P. Huang, "The depot and charging facility location problem for electrifying urban bus services," *Transportation Research Part D: Transport and Environment*, vol. 100, p. 103053, Nov. 2021, doi: 10.1016/J.TRD.2021.103053.

[26] H. Ambrose, N. Pappas, and A. Kendall, "Exploring the Costs of Electrification for California's Transit Agencies," *ITS Reports*, vol. 2017, no. 03, Oct. 2017, doi: 10.7922/G2PZ570Z.

[27] "Fleet DNA Project Data," *National Renewable Energy Laboratory*, 2019. https://www.nrel.gov/transportation/fleettest-fleet-dna.html (accessed Mar. 21, 2020).

[28] "OpenMobilityData - Public transit feeds from around the world." https://transitfeeds.com/ (accessed Dec. 14, 2021).

[29] K. Kivekäs, A. Lajunen, J. Vepsäläinen, and K. Tammi, "City Bus Powertrain Comparison: Driving Cycle Variation and Passenger Load Sensitivity Analysis," *Energies (Basel)*, vol. 11, no. 7, p. 1755, Jul. 2018, doi: 10.3390/en11071755.

[30] L. Liu, A. Kotz, A. Salapaka, E. Miller, and W. F. Northrop, "Impact of Time-Varying Passenger Loading on Conventional and Electrified Transit Bus Energy Consumption," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2673, no. 10, pp. 632–640, Oct. 2019, doi: 10.1177/0361198119852337.

[31] J. Vepsäläinen, K. Otto, A. Lajunen, and K. Tammi, "Computationally efficient model for energy demand prediction of electric city bus in varying operating conditions," *Energy*, vol. 169, pp. 433–443, Feb. 2019, doi: 10.1016/j.energy.2018.12.064.

Authors

Peter Benoliel is a fifth-year Ph.D. student at the University of California – Davis. He is in the Transportation Technology and Policy program within the Institute of Transportation Studies and work in the Plug-in Hybrid and Electric Vehicle center. Peter's studies focus on electrification of public transit buses, with infrastructure and charging strategies as particular interests. Prior to joining UC Davis, Peter obtained an MSE in Automotive Systems Engineering from University of Michigan – Dearborn in 2017, and a BS in Mechanical Engineering from George Washington University in 2013.

Alan Jenn is currently an assistant professional researcher at the Plug-in Hybrid and Electric Vehicle (PH&EV) group of the Institute of Transportation Studies (ITS) at the University of California, Davis as well as an affiliate at Lawrence Berkeley National Laboratory. He graduated from Carnegie Mellon University with a PhD in the department of Engineering and Public Policy (EPP) and has undergraduate degrees in Molecular and Cell Biology, Music, and Energy and Resources from the University of California, Berkeley. Alan's research is focused on plug-in electric vehicles (PEVs): integration with the electric grid, adoption of the technology, use in ride-hailing companies (such as Uber and Lyft), and its impact on transportation finance.

Gil Tal holds a Ph.D. in Transportation Technology and Policy from UC Davis, and an M.A. in geography and environmental policy and planning from the Hebrew University in Jerusalem. Between 2008 and 2010 Dr. Tal was a post-doctoral researcher with the Center for Global Metropolitan Studies and the UC Transportation Center at UC Berkeley. At the PH&EV center Dr. Tal is leading projects on the future need for electric vehicle infrastructure, and the correlation between charging infrastructure, travel behavior and the demand for EV's. He is currently leading research on number of projects including a study on local planning and deployment of electric vehicle infrastructure, a study on GIS tools for infrastructure planning, a multi-state study of new plug-in vehicle buyers, and a study on the secondary market of plug-in vehicles in California.