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Project Title
Integrated Strategic and Operational Planning for a Fast-Charging Battery Electric Bus System

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Research Needs
As an integral part of a multimodal transportation ecosystem, the public bus system provides an economical and sustainable travel mode that plays a key role in reducing traffic congestion and exhaust emissions (Liu and Song, 2017). Conventional bus fleets, however, are mainly powered by diesel engines characterized by low energy efficiency, exhaust emissions, and oil dependence. In recent years, the battery electric bus (BEB) has been increasingly viewed as a promising alternative for bus fleets (Mahmoud et al., 2016). Compared to diesel buses, BEBs have several advantages, including higher energy efficiency, zero tailpipe emissions, improved reliability, a lower maintenance burden, and the capability for using renewable energy sources, such as wind, solar, and water energies (Kühne, 2010, Mahmoud et al., 2016). Moreover, BEBs are easier to deploy and more flexible in their operation than trolley buses.

BEBs are being rapidly embraced by public transit agencies due to their environmental and economic benefits. For example, by the end of 2017, the total BEB sales in China had reached 316,978 (Dixon, 2018). Moreover, the city of Shenzhen in southeastern China owns a total of 16,359 buses and had achieved a 100% BEB fleet at the end of 2017 (Lu et al., 2018). In the United Kingdom, BEB fleets have been deployed in the cities of London, Nottingham, and Liverpool (Ayre, 2018). In Toronto, Canada, the Toronto Transit Commission has started testing BEBs and plans to have an emission-free transit fleet by 2040 (Bow, 2018). In the United States, BEB pilot programs have been conducted or future plans established in many areas, including New York (New York State Pressroom, 2018), Chicago (Chicago Transit Authority, 2014), Park City, UT (Proterra, 2017), Salt Lake City, UT (Utah Transit Authority, 2016), Los Angeles, CA (Kinman, 2017), Washington DC (DDOT, 2018) and King County, WA (King County Executive, 2017).

Although BEBs have many advantages and have been adopted by a number of transit agencies, due to limitations in battery technology, they are disadvantaged by cumbersome and costly on-board batteries. Moreover, it takes very long time to recharge BEBs using either standard or slowcharging methods. The emerging fast-charging technology promises the potential to offset these drawbacks. With fast-charging technology, a BEB with a modest battery capacity can utilize the dwelling times between trips to quickly recharge its battery and maintain continuous operation. Fast-charging technology has been adopted by many BEB demonstration projects, and promising results have been reported (e.g., Eudy et al., 2015; Miles and Potter, 2014; Li, 2016; McNaughton, 2018).

Despite the advantages of fast charging, the high initial cost of fast-charging stations is a major barrier to their implementation (Qin et al., 2016). To reduce capital costs, fast-charging stations should be strategically deployed in a BEB system. Determining the appropriate battery capacity and the scheduling of battery recharging should also be given priority consideration. The combination of well-designed charging stations, battery capacities, and recharging schedules will minimize the total cost of a BEB system while ensuring its normal operation. Another consideration is that rapid charging may lead to very high power costs, also known as demand charges. Demand charges can comprise a substantial proportion of the BEB operating expenses. In the city of Tallahassee, for instance, researchers reported that demand charges account for $75.2\pm8.6\%$ of the total electricity bill for a fleet of five electric buses (Qin et al., 2016). Therefore, demand charges must be carefully considered when planning a fast-charging BEB system.

A few studies have addressed the planning problem for electric buses. With a fixed battery capacity for BEBs, Xylia et al. (2017) proposed an optimization model for the location of BEB fast-charging stations. Kunith et al. (2017) developed a cost-optimization model for determining BEB battery capacities and the deployment of fast-charging stations. Liu et al. (2018) proposed a robust optimization model for the strategic planning of a fast-charging BEB system under energy consumption uncertainty. Qin et al. (2016) utilized a simulation model to identify the optimal recharging strategy for a single-line fast-charging BEB fleet in Tallahassee, Florida. However, these studies either focused on the charger deployment and battery sizing problem with a simplified assumption regarding recharging scheduling, or investigated the recharging scheduling problem for a given battery and charger configuration. There has been scant research simultaneously considering the strategic and operational planning of a BEB system. To the best of our knowledge, only one study has focused on concurrent network planning and recharging scheduling for a BEB system i.e., that by Wang et al. (2017). These authors developed an optimization model to concurrently determine the deployment of fast-charging stations and BEB recharging scheduling. However, they neglected the design of battery capacities, which is a key component in BEB planning. Nor did they consider the demand charges, which can represent a significant proportion of the operation cost of fast-charging BEBs. The objective of our proposed project is to fill these research gaps.

In this project, we simultaneously consider and optimize the battery and charger configurations of a fast-charging BEB system, as well as its recharging scheduling during operation. We also explicitly consider the demand charges of high-power recharging activities of BEBs.

Research Objectives

This project proposes an integrated modeling framework to concurrently develop strategic and operational plans for a fast-charging BEB system. The proposed project will accomplish the following two objectives:

1. Develop an optimization framework that simultaneously determines the deployment of fast-charging stations, the battery capacities of BEBs, and the recharging scheduling of BEBs.
2. Conduct a case study to demonstrate the effectiveness of the proposed model and analyze the impact of different parameter values on the total cost of a fast-charging BEB system.

Research Methods

In the proposed research, we will develop a mathematical programming framework that integrates strategic and operational planning for a fast-charging BEB system. The objective of the optimization is to minimize the total cost of a fast-charging BEB system by simultaneously determining the deployment of fast-charging stations, the size of BEB batteries, and the recharging scheduling of BEBs. The optimal design should ensure the normal operation of a fast-charging BEB system.

The total cost of a fast charging BEB system has two components: implementation and operation. The system implementation cost includes the cost of the on-board battery pack and the cost of the fast-charging stations. The operation cost includes the cost of the cumulative electricity energy usage and demand charges. The integration of the BEB battery design, charging station deployment, and recharging scheduling should ensure that each BEB has enough energy to perform its assigned trips. During normal operation, a BEB should be able to maintain a predetermined minimum state of charge. We will use an energy consumption model to calculate the electricity consumption of the BEBs. To design a robust bus system, we will consider road grade, worst-case passenger load, and auxiliary devices to determine the electricity consumption. We will also explore the most appropriate solution algorithms with reference to the properties of the formulated models.

We will then conduct numerical studies to evaluate the performance of the proposed methodology and sensitivity analyses to identify the impacts of different factors on the total cost of a fast-charging BEB system.

Expected Outcomes

This project is expected to produce an optimization framework for simultaneously determining the deployment of fast-charging stations, the battery capacities of BEBs, and the recharging scheduling of BEBs for a fast-charging BEB system. The research findings will have theoretical significance as well as offer a wide range of applications for implementing more sustainable public transportation systems. The end product will be useful to public transit agencies for the development of cost-effective and sustainable BEB systems.

Relevance to Strategic Goals

The proposed project contributes to two goals of the Mountain–Plains Consortium, i.e., environmental sustainability and economic competitiveness. Compared to conventional diesel buses, BEBs are characterized by improved energy efficiency, zero tailpipe emissions, and the capacity for using renewable energy sources, such as wind, solar, and water energies. The proposed modeling framework can help transit agencies to optimize their planning of a fast-charging BEB system. The research results have potential to facilitate faster adoption of BEBs in urban areas and thereby improve environmental sustainability and the livability of urban communities.

Furthermore, making public transportation more cost-effective and sustainable may contribute to the improvement of its service quality and mode share, which will help to reduce traffic congestion and support regional economic competitiveness.

Educational Benefits

One graduate student will help conduct this research and receive training in transportation data collection and analysis, optimization, and public transportation planning and operation. The research results will provide fresh material and case studies for expanding the transportation curricula at USU.

Technology Transfer

The research results will be disseminated via publication in peer-reviewed professional journals and presentations at state and national meetings and conferences. All data collected from the research project will be stored in a repository from which information will be easily retrievable should anyone wish to use it. The research results will also be incorporated into a wide variety of education, training, outreach, and workforce development activities.

Work Plan

The proposed research will be conducted over an 18-month period according to the following schedule:

Tasks	Duration
Literature Review We will conduct a thorough literature review on the planning of fast-charging BEB systems.	2 months
Formulation of Integrated Planning Problem We will formulate the integrated strategic and operational planning for a fast-charging BEB system as a mathematical programming problem.	5 months
Solving the Integrated Planning Problem We will explore and compare the performance of solution algorithms identified in the literature review.	4 months
Case Study We will conduct several numerical studies to evaluate the proposed methodology and sensitivity analysis to assess the impact of different factors on the total cost of a fast-charging BEB system.	5 months
Report Writing	2 months

Project Cost

Total Project Costs:	$100,000
MPC Funds Requested:	$50,000
Matching Funds:	$50,000
Source of Matching Funds:	LTAP

References

Ayre, J., 2018. New BYD ADL Electric Bus Fleet Deployed In London — Route 153 Now Fully Electric. https://cleantechnica.com/2018/02/13/new-byd-adl-electric-bus-fleet-deployed-london-route-153-now-electric/ (Accessed 05/14/2018)

Bow, J., 2018. THE TTC BATTERY-ELECTRIC BUS DEMOS. https://transit.toronto.on.ca/bus/8528.shtml (Accessed 05/15/2018)

Chicago Transit Authority, 2014. CTA Announces First Electric-Powered Buses Added to its Fleet. https://www.transitchicago.com/cta-announces-first-electric-powered-buses-added-to-its-fleet/ (Accessed 05/14/2018)

DDOT, 2018. Mayor Bowser Celebrates Arrival of New Electric Circulator Buses. https://ddot.dc.gov/release/mayor-bowser-celebrates-arrival-new-electric-circulator-buses (Accessed 05/14/2018)

Dixon, T., 2018. CHINA 100% ELECTRIC BUS SALES DROP TO ~89,546 IN 2017. https://evobsession.com/china-100-electric-bus-sales-drop-to-89546-in-2017/ (Accessed 05/15/2018)

Eudy, L., Prohaska, R., Kelly, K., Post, M., 2016. *Foothill Transit battery electric bus demonstration results* (No. NREL/TP--5400-65274). National Renewable Energy Lab.(NREL), Golden, CO (United States).

King County Executive, 2017. King County Executive announces purchases of battery buses, challenges industry to build next-generation transit. https://www.kingcounty.gov/elected/executive/constantine/news/release/2017/January/10-battery-buses.aspx (Accessed 05/14/2018)

Kinman, M., 2017. DASHing to a Clean Electric Bus Future for Los Angeles. https://environmentcalifornia.org/blogs/blog/cae/dashing-clean-electric-bus-future-los-angeles (Accessed 05/14/2018)

Kunith, A., Mendelevitch, R., Goehlich, D., 2017. 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*, 11(10), 707-720.

Kühne, R. (2010). Electric buses–An energy efficient urban transportation means. *Energy*, 35(12), 4510-4513.

Li, J. Q., 2016. Battery-electric transit bus developments and operations: A review. *International Journal of Sustainable Transportation*, *10*(3), 157-169.

Liu, Z., Song, Z., 2017. Robust planning of dynamic wireless charging infrastructure for battery electric buses. *Transportation Research Part C: Emerging Technologies*, 83, 77-103.

Liu, Z., Song, Z., He, Y., 2018. *Planning of Fast-Charging Stations for a Battery Electric Bus System Under Energy Consumption Uncertainty* (No. 18-03360).

Lu, L., Xue, L., Zhou, W., 2018. How Did Shenzhen, China Build World's Largest Electric Bus Fleet? http://www.wri.org/blog/2018/04/how-did-shenzhen-china-build-world-s-largest-electric-bus-fleet (Accessed 05/15/2018)

Mahmoud, M., Garnett, R., Ferguson, M., Kanaroglou, P., 2016. Electric buses: A review of alternative powertrains. *Renewable and Sustainable Energy Reviews,* 62, 673-684.

McNaughton, A., 2018. Electric vehicle 'fast chargers' installed in Kimball Junction. https://www.parkrecord.com/news/summit-county/electric-vehicle-fast-chargers-installed-in-kimball-junction/ (Accessed 05/15/2018)

Miles, J., Potter, S., 2014. Developing a viable electric bus service: the Milton Keynes demonstration project. *Research in Transportation Economics*, *48,* 357-363.

New York State Pressroom, 2018. Governor Cuomo Announces All-Electric Bus Pilot Program to Reduce Emissions and Modernize Public Transit Fleet. https://www.governor.ny.gov/news/governor-cuomo-announces-all-electric-bus-pilot-program-reduce-emissions-and-modernize-public (Accessed 05/14/2018)

Proterra, 2017. PARK CITY TAPS PROTERRA FOR UTAH'S FIRST ZERO-EMISSION, BATTERY-ELECTRIC MASS TRANSIT FLEET. https://www.proterra.com/press-release/park-city-taps-proterra-for-utahs-first-zero-emission-battery-electric-mass-transit-fleet/ (Accessed 05/14/2018)

Qin, N., Gusrialdi, A., Brooker, R. P., Ali, T., 2016. Numerical analysis of electric bus fast charging strategies for demand charge reduction. *Transportation Research Part A: Policy and Practice*, 94, 386-396.

Utah Transit Authority, 2016. UTA Announces Plans to Add First All-Electric Buses to Fleet. https://www.rideuta.com/news/2016/04/UTA-Announces-Plans-for-All-Electric-Buses (Accessed 05/14/2018)

Wang, Y., Huang, Y., Xu, J., Barclay, N., 2017. Optimal recharging scheduling for urban electric buses: A case study in Davis. *Transportation Research Part E: Logistics and Transportation Review*, *100*, 115-132.

Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., Silveira, S., 2017. Locating charging infrastructure for electric buses in Stockholm. *Transportation Research Part C: Emerging Technologies*, 78, 183-200.