ABSTRACT

Battery electric buses (BEBs) have emerged as a promising solution for urban areas seeking to curb emissions while offering efficient public transportation. However, their widespread adoption faces financial and operational challenges. This thesis presents a multifaceted approach to address these challenges through electrification under budget and optimized system and operational design for electric buses. The research spans three interconnected objectives, all centred around the goal of enhancing the viability and sustainability of BEBs in urban transit.

The first objective, focusing on phased electrification for sustainable bus transit systems within budget constraints, acknowledges the significant promise of BEBs. However, it also underscores the considerable expenses associated with adopting BEBs, particularly due to the requirement for extensive charging infrastructure. Acknowledging the financial constraints faced by most transit agencies, the study proposes a framework for phased electrification under budget. This approach allows transit agencies to strategically transition from diesel/CNG buses to BEBs over time while staying within budget limitations.

At the heart of this framework lies an optimization model designed to identify the most suitable routes for BEB deployment and determine optimal charging infrastructure placement. The model considers critical parameters, including opportunity charging duration and budget allocation and was applied to the large bus network of New Delhi, India. The study's sensitivity analysis highlights the significance of these factors in shaping the daily electric bus mileage (e-mileage), a pivotal metric for electrification success. The results offer urban transit agencies a tangible blueprint for transitioning to a BEB system in a phased manner under budget that will promote long-term sustainability in urban transportation.

BEBs provide significant environmental advantages, yet their restricted driving range and extended charging periods pose operational hurdles for transit organizations. There is a

delicate trade-off between BEB battery capacities and charging infrastructure, spurred by the advent of fast-charging technology. This innovation holds the potential to notably enhance the daily driving range of BEBs while concurrently diminishing charging durations and battery dimensions.

The second objective explores how the size of BEB batteries can be adjusted in relation to the deployment of fast-charging infrastructure. By utilizing fast-charging technology, the study seeks to extend the daily driving range of BEBs and reduce the time required for recharging, thereby potentially decreasing the size of batteries needed. However, the study identifies a potential trade-off associated with this approach. While fast-charging stations offer the benefit of quicker energy top-ups, they may also lead to longer queues at terminals due to increased demand for rapid recharging across the entire network during daily operations.

Consequently, these extended queues may disrupt the schedules of BEBs, hindering their ability to fulfil their assigned duties within the designated timeframe and causing inefficiencies in public transit systems. This underscores the importance of carefully considering the deployment of fast-charging infrastructure in conjunction with BEB battery sizes. While fast-charging technology offers advantages such as extended driving range and reduced charging times, its implementation must be managed to minimize potential drawbacks, such as increased terminal congestion and scheduling disruptions. Strategies for optimizing the placement of charging infrastructure, scheduling procedures, and operational protocols may be necessary to maximize the efficiency and reliability of BEB operations while minimizing service disruptions.

Achieving the desired trade-off necessitates a thorough examination. Thus, an optimization model is crafted to ascertain the most efficient battery sizes and charger setups, factoring in constraints on waiting times by modelling M/M/1 queues at each charger of the charging stations. Implemented on a public bus subnetwork in New Delhi, the findings of this research emphasize the pivotal relationship among battery capacities, charger configurations, and operational effectiveness. Transit authorities can leverage this integrated modelling approach to devise optimal BEB systems that adhere to service level agreements and operational benchmarks.

The third objective delves into the intricate relationship between the planning of BEB system and the scheduling of their charging activities. Recognizing that these aspects are closely intertwined, the study introduces an optimization framework to aid BEB operators in making strategic decisions regarding the configuration of charging stations (location, number of chargers, charging power).

This framework considers a range of factors that impact decision-making, including the initial capital investment required for setting up charging infrastructure, ongoing operational costs associated with maintenance and electricity consumption, fluctuating energy prices, and potential demand charges that may be incurred. By incorporating these variables into the optimization model, the study aims to provide a comprehensive understanding of the trade-offs involved in different charging station configurations.

Furthermore, the study acknowledges the uncertainty surrounding energy consumption, which can vary due to factors such as weather conditions, route changes, and passenger demand. To address this uncertainty, the researchers develop a robust counterpart to the deterministic optimization model. This robust formulation allows for more flexible decision-making under uncertain conditions while still ensuring that the resulting solution remains tractable and practical for real-world implementation.

Overall, the results of the study highlight the importance of considering both BEB planning and charging scheduling decisions in an integrated manner. Modelling strategic and operational decisions together facilitates more holistic decision-making, alignment of goals, optimization of resources, adaptability to change, and ultimately, improved performance. By utilizing the optimization framework developed in this study, BEB operators can make informed decisions that minimize electricity costs and optimize recharging schedules, ultimately enhancing the sustainability and economic viability of their BEB systems.

In conclusion, this thesis provides a comprehensive overview of a research trilogy aimed at advancing the sustainability and practicality of Battery Electric Bus (BEB) systems in urban transportation. This thesis introduces innovative strategies such as initiation of bus electrification by addressing financial constraints, optimized system design considering delay modelling at the charging stations, and integrated BEB system design and charging scheduling modelling to tackle the challenges faced by transit agencies. These research efforts offer actionable insights that can transform urban transit systems into cleaner, more efficient, and economically viable alternatives. As cities worldwide seek to reduce emissions and promote sustainable public transportation, these studies provide valuable guidance to pave the way for a greener and more sustainable urban future.

Keywords: e-mobility, e-mileage, Battery electric bus (BEB), partial bus electrification, charging infrastructure design, battery sizing, queueing theory, waiting time, charging delay, Charging infrastructure planning, Charging scheduling, Integrated optimization framework, Energy consumption uncertainty, Robust optimization