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DEVELOPING A SMART AND SUSTAINABLE PUBLIC TRANSPORTATION SYSTEM: A CASE STUDY IN CAMDEN, NEW JERSEY

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DEVELOPING A SMART AND SUSTAINABLE PUBLIC TRANSPORTATION-SYSTEM: A CASE STUDY IN CAMDEN, NEW JERSEY

by

Zahra Vafakhah

A Thesis

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Dedications

I would like to dedicate this work to my parents, my thesis advisor, Dr. Mohammad Jalayer, my spouse, my siblings, my friends, and the people who have supported me in my academic career.

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I would like to thank my adviser Dr. Mohammad Jalayer, associate professor in the department of civil and environmental engineering, for the opportunity he had offered me to work with him. His keen transportation understandings have assisted me in developing both my career and me as a person. He has been a great advisor and always worked with me to make this research complete on time.

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Finally, I would like to thank Camden Health Initiative for supporting this research.

Abstract

Zahra Vafakhah
DEVELOPING A SMART AND SUSTAINABLE PUBLIC TRANSPORTATION SYSTEM: A CASE STUDY IN CAMDEN, NEW JERSEY
2022–2023
Mohammad Jalayer, Ph.D.
Master of Science in Civil Engineering

The transportation sector is a major contributor to air pollution and Greenhouse Gas (GHG) emissions. As a significant source of emissions, public transportation presents an opportunity for mitigation through electrification. However, transitioning to an electric bus fleet necessitates substantial investments in bus procurement and charging infrastructure. To address the associated costs, this study introduces a mixed-integer linear mathematical model developed to optimize the location of on-route fast charging stations within bus networks. The central objective of this optimization formulation is to minimize the overall cost of establishing the charging infrastructure. The study employs a real-world case study focusing on a Camden, NJ, USA bus network. Key considerations include optimizing charging station locations considering time constraints at bus stops to avoid schedule delays and inconvenience for passengers during the charging process. Furthermore, the study investigates the sensitivity of the optimization model in response to variations in parameters. Notably, battery capacity, charger power, average energy consumption, dwell time, and minimum and maximum state of charge significantly affect the optimal locations and required number of chargers. The insights generated from this study are anticipated to offer valuable guidance to policymakers, practitioners, and researchers involved in planning the transition of bus fleets towards zero-emission vehicles.

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Chapter 1

Introduction

1.1 Background

Air quality has emerged as a paramount concern for governments worldwide, with a substantial proportion of pollution originating from fossil fuels and combustion-powered vehicles. The transportation sector contributes significantly to Greenhouse Gas (GHG) emissions. In 2020 alone, global transportation accounted for 16.2% of total emissions, with passenger travel vehicles responsible for 45% of GHG emissions within the sector (Manzolli & Trovão, 2022). Public transportation, especially in densely populated urban areas, plays a pivotal role in shaping GHG emissions (Baharum et al., 2019). Projections indicate that by the year 2050, approximately 68% of the global population will reside in urban environments (Perumal & Lusby, 2021).

In the United States today, a substantial portion of transit buses remain conventional, contributing to significant pollution levels. The emissions of diesel-powered buses have been closely linked to various health issues, including asthma. Adopting an all-electric bus fleet for public transit presents a promising solution.

Despite the potential benefits, implementing electric buses in the U.S. has been relatively limited. According to estimates from Bloomberg New Energy Finance (BNEF), by 2017, there were approximately 385,000 electric buses globally. However, in the U.S., this number was notably lower, with only around 360 electric buses in operation. Notably, a considerable majority of electric buses were deployed in China.

These forecasts of BNEF projections suggest that by 2025, electric buses will make up just 5.1% of the total U.S. bus fleet, in contrast to China's anticipated 72.4% market penetration for electric buses. As such, there arises a critical need for increased focus and attention on the implementation of all-electric bus fleets in the United States, both to address pollution-related concerns and to align with global trends in sustainable transportation (Liu, 2019).

Moreover, as outlined in the New Jersey Department of Environmental Protection's (NJDEP) Greenhouse Gas (GHG) emission inventory report, transportation in New Jersey accounts for a staggering 34% of total GHG emissions, positioning it as the largest source of such emissions within the state (NJDEP, 2022). In line with New Jersey's Global Warming Response Act (GWRA), which sets ambitious targets, the state is committed to an 80% reduction in GHG emissions by 2050, compared to levels in 2006 (DEP, 2017).

In the pursuit of minimizing the carbon footprint, numerous strategies have been employed over the past decades, including initiatives to enhance the energy efficiency and environmental impact of motor vehicles. A key component of this strategy is the introduction of Zero Emission Buses (ZEBs), also called Electric Buses (E-Buses). Unlike their conventional counterparts powered by combustion engines, ZEBs produce no tailpipe emissions, aligning well to reduce GHG emissions. Their deployment is particularly crucial in underserved communities, where the potential health benefits are still comprehensively evaluated (Rickenbacker et al., 2019; Rajan, 2021).

The global adoption of ZEBs has experienced remarkable growth, surging over 80-fold between 2011 and 2017, largely driven by improved policy incentives. By 2020, the global number of electric buses in operation had reached 600,000. Despite this progress, ZEBs and their associated infrastructure remain relatively novel and necessitate further testing and evaluation.

However, the ongoing transition to electric buses requires even greater acceleration to align with the importance of achieving long-term global climate goals. The paramount objective is maintaining global warming below the critical 2 degrees Celsius threshold. To this end, the deployment of low or zero-emission technologies needs to double over the next two decades (Sclar et al., 2019; Deliali et al., 2021; Rodrigues & Seixas, 2022). This underscores the imperative for greater acceleration and intensified research efforts.

1.2 Importance of Public Transit in New Jersey

Public buses play a pivotal role in serving the residents of New Jersey. In the fiscal year 2019, out of 267.3 million public transit trips, more than half, accounting for 141.2 million trips, were made using public buses (U.S. Census Bureau, 2019). However, despite many dependences on public transit, there is inequity in transit access and use. Individuals with low income who rely on public transit often have limited car ownership, while some car-owning households still utilize public transit as a complement. Additionally, certain cities in New Jersey, including Jersey City, Newark, and Camden, have higher proportions of people of color who face reduced access to private vehicles, particularly within the Black community (National Equity Atlas, 2018; U.S. Census Bureau, 2020).

Examining the workforce, the percentage of New Jersey workers using public transit for commuting varies: 8.1% for white workers, 15.9% for Black workers, 23.0% for Asian workers, and 12.8% for Hispanic/Latinx workers (Rajan, 2021). Census data also illustrates that 36% of public transit users in New Jersey belong to the low-income bracket (earning $35,000 or less annually), while approximately 30% fall within the high-income bracket (earning $75,000 or more annually), underlining the significance of public transit for a wide range of income groups (Rajan, 2021).

1.3. Research Hypothesis

The primary hypothesis of this study is to test whether various parameters, including battery capacity, charger’s power, average energy consumption, minimum and maximum state of charge, dwell time, and charger’s efficiency, significantly affect the optimal number of on-route fast chargers at terminals and intermediate stops.

1.4. Research Objectives

The primary objective of this study is to minimize the costs of transitioning from a conventional bus fleet to an all-electric bus fleet, as in the case study, the City of Camden, NJ. Specifically, this study investigates the minimization of on-route fast-charging infrastructure costs. The high investment associated with on-route fast-charging infrastructure is challenging for many decision-makers. To alleviate the related costs, this study develops a mixed-integer linear mathematical model to optimize the on-route fast charging station numbers and locations for bus networks. Also, the optimum number of chargers is evaluated to ensure no delay for passengers.

1.5. Organization of Dissertation

The first chapter introduces the research problem, highlights the study's significance, offers background information on the study area and issue, and outlines the research objectives and hypotheses. Chapter 2 presents a comprehensive literature review, exploring the impact of electrification on air and noise pollution reduction and its implications for public health. It investigates the associated costs for agencies, different classifications of battery electric buses' charging infrastructure, challenges in transitioning to ZEB fleets, and provides guidance for transit agencies on planning for electrification.

Chapter 3 summarizes an extensive literature review of transit agencies' experiences with ZEB implementation, covering performance measures, fuel efficiency, and electrification costs. It also examines available funding sources, incentives, and efforts for transit electrification, as well as safety regulations and standards related to electric vehicle systems and charging infrastructures.

Chapter 4 develops an optimization model to identify the optimum locations and number of on-route fast chargers at the terminal and intermediate stops as the case study, City of Camden, NJ. This chapter reviews previous studies on charging station optimization, addresses their significance and limitations. It also evaluates the sensitivity of different parameters on the optimization model and the optimum solution.

Lastly, Chapter 5 concludes the research by summarizing findings from earlier chapters, highlighting study limitations, and providing recommendations for future work. These recommendations are aimed at assisting transit agencies, policymakers, practitioners, and researchers in accelerating the transition to transit electrification.

Chapter 2

Zero-Emission Bus Fleet: A Review of Impacts, Costs, Challenges, Future Directions

2.1. Introduction

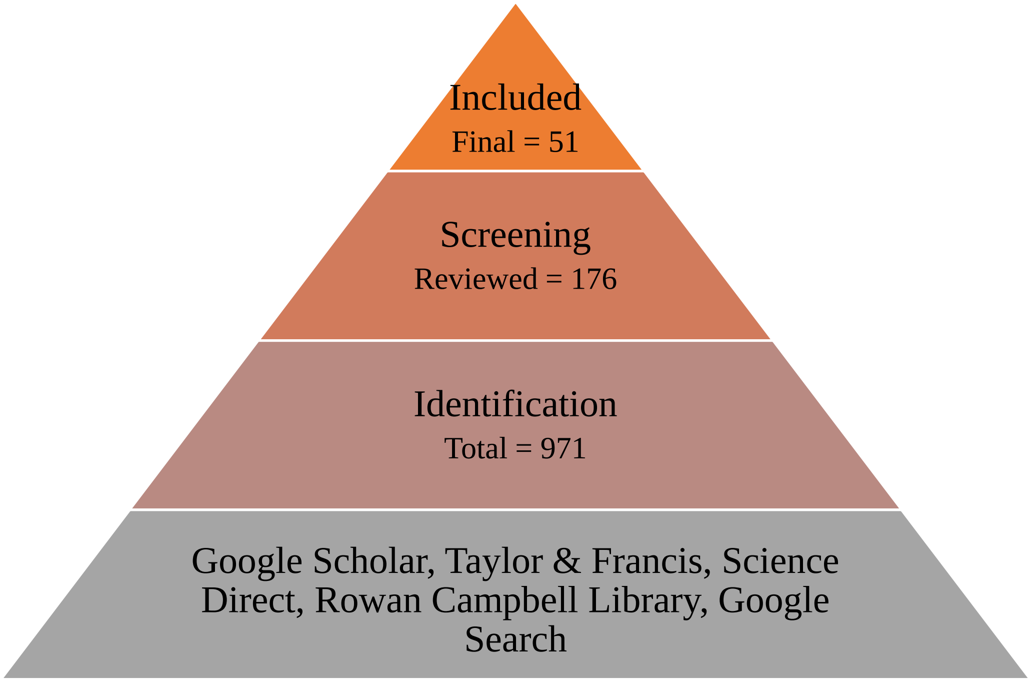
This chapter reviews the profound effects of public transportation electrification through Zero Emission Buses (ZEBs) on various aspects, including public health, air quality, noise pollution, related costs, and potential savings associated with ZEB fleets. This chapter specifically focuses on two primary types of electric buses: Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs). It also delves into the nuances of BEB charging infrastructure categories and charging methods. Furthermore, the chapter investigates the challenges agencies and governments confront in their journey toward electrification. Alongside these insights, the chapter offers a comprehensive guideline to aid agencies in planning and establishing an electric bus fleet. The insights gathered in this chapter serve as invaluable resources for agencies, policymakers, practitioners, and researchers actively engaged in or exploring the transition to ZEBs.

2.2. Research Methodology

To offer a comprehensive understanding of Zero Emission Buses (ZEBs) encompassing their impacts, costs, savings, challenges, charging infrastructures, and guidance for electric fleet establishment, an extensive search across literature reviews, transit agency reports, the ZEB market, and government policies were undertaken. The research encompassed databases like Google Scholar, Taylor & Francis, ScienceDirect, Rowan Campbell Library, and Google Search. A time frame of the past 15 years was chosen for focus, and keyword-based searches were employed. General keywords such as "electric bus," "battery electric bus," and "zero-emission bus (ZEB)" were used, with specific keywords for each study aspect, such as "charging infrastructure" and "challenges related to electric bus implementation." The initial stage yielded 971 relevant studies. Following title screening, abstract review, and full-text evaluation, 176 studies were thoroughly assessed, ultimately culminating in the selecting of 51 documents. The sequential selection process is visually depicted in Figure 1.

Figure 1

Selection Process of The Documents in Stepwise Track



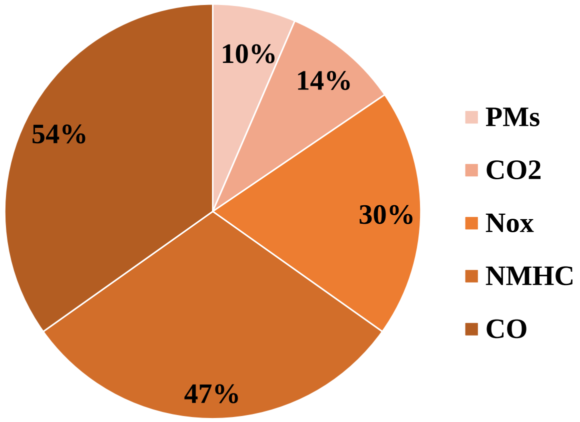
2.3. Impact of ZEBs on Public Health and Air Quality

The impact of on-road transport on air pollution and greenhouse gas (GHG) emissions is significant today. Emissions generated from traffic encompass pollutants like nitrogen oxides (NO_x), particulate matter (PMs), carbon dioxide (CO_2), carbon monoxide

(CO), and non-methane hydrocarbons (NMHC), as depicted in Figure 2 (Requia et al., 2018). These vehicle-generated pollutants have been directly linked to health issues such as asthma, lung cancer, premature mortality, dementia, Alzheimer's disease, and hypertension (Requia et al., 2018). Moreover, beyond their immediate health consequences, air pollutants contribute to climate change, amplifying the likelihood of extreme weather events like floods, storms, droughts, and wildfires (Requia et al., 2018). The economic effects of pollution emissions are also substantial, affecting households, businesses, and governments alike due to increased healthcare expenses, work or school absenteeism, impacts on agriculture, and the broader challenge of climate change (Rajan, 2021; cte, 2021).

Figure 2

Worldwide Pollution Emissions for the On-Road Transport Sector



Older conventional vehicles typically lack advanced emission control technologies, resulting in more substantial pollution impacts (Cooper et al., 2012). Despite the positive environmental and public health contributions of public transit, conventional buses, especially those with considerable age, can generate adverse effects that could be mitigated or eliminated through the adoption of electric bus fleets. Research in 2014 for Barcelona and Madrid revealed that fleet electrification led to an 11% and 17% reduction in NOx emissions, respectively (Soret et al., 2014). Similarly, a California emission analysis demonstrated an impressive 80% reduction in CO2/km by Battery Electric Buses (BEBs) compared to diesel buses over their operational lifespan (Lajunen & Lipman, 2016).

Electrification not only offers environmental benefits but also yields substantial societal cost savings. Societal cost assesses the financial consequences of climate change, encompassing effects like extreme weather events, the spread of disease, and food insecurity. Its scope spans across businesses, families, and governments, all of which experience the economic impacts of these climate-related challenges. Annual savings of approximately $3,000 per bus can be realized through carbon reduction (Rajan, 2021; cte, 2021). By scaling up to an all-electric bus fleet, New Jersey could save an annual average of $8 million solely from greenhouse gas reduction, with total savings projected at $95.9 million over the electric buses' lifespan (Rajan, 2021; Aber, 2016). Furthermore, transitioning to electric buses can reduce pollution-related healthcare costs and decrease work missing due to illness. A study by the Metropolitan Area Transit suggested that electrifying a bus fleet in Washington D.C. could result in $8 million in annual healthcare savings for residents. Similarly, the potential health savings per bus could reach $150,000 for New York City and $55,000 for Chicago (Rajan, 2021; Aber, 2016).

The deployment of ZEBs holds the promise of eliminating tailpipe emissions from public transportation. However, it's important to note that emissions are not solely limited to tailpipe pollutants generated during bus operation. They can be categorized into three main groups: tailpipe emissions (occurring during the actual bus operation), upstream emissions (stemming from power plants during the phases of extraction, processing, and fuel distribution), and well-to-wheel emissions (encompassing both the bus's operational emissions and the emissions from power plants during fuel or energy production) (cte et al., 2020).

To effectively eliminate emissions associated with electricity production, a key strategy is the decarbonization of the power sector through the adoption of renewable energy sources like solar power. This approach enhances the pollution-reduction impact of electrification (Aamodt et al., 2021). For instance, the Worcester Regional Transit Authority (WRTA) report highlights that integrating solar panels into electric bus charging stations could potentially mitigate 49 tons of CO2 emissions through the generation of 70,000 kilowatt-hours of clean electricity (WRTA, 2015).

Notably, certain regions such as California and Hawaii have made significant commitments to transition their electricity generation to 100 percent renewable sources by 2045. Moreover, on a broader scale, the United States has set a federal goal of achieving a zero-emission power sector by 2035, further emphasizing the drive towards cleaner energy (Aamodt et al., 2021; Kampshoff et al., 2022)

By replacing conventional bus fleets with electric counterparts, a sustainable and environmentally friendly option is presented that significantly reduces pollutant emissions and mitigates air pollution levels. Recognizing these electric vehicle benefits has led to global actions such as the C-40 Fossil Fuel Free Streets Declaration, in which 94 cities have committed to exclusively purchasing electric buses starting in 2025.

Notable cities like San Francisco, Seattle, New York, and Chicago are among those embracing this declaration (Liu, 2019).

2.4. Impact of ZEBs on Noise Pollution Reduction

Public transportation significantly contributes to overall traffic noise, with heavy-duty vehicles like diesel buses being particularly noisy and potentially causing high annoyance levels. Noise pollution from traffic poses considerable health and economic concerns for densely populated cities, affecting hearing, cardiovascular health, sleep patterns, and property values (Borén, 2020). In urban environments with lower average speeds, powertrain noise often dominates over tire/road noise as the primary source of noise (Borén, 2020; Laib et al., 2019).

Transit electrification emerges as an effective strategy to mitigate noise generated by traffic. A comparison between diesel and electric buses at a constant low speed of 15 km/h revealed potential noise reductions of up to 12 dBA (decibels A), with acceleration generating a difference of up to 20 dBA (Laib et al., 2019). Electric buses contribute to reducing external noise levels and provide improved interior noise and vibration control, enhancing passenger comfort (Sclar et al., 2019).

However, while electric vehicles bring about positive noise reduction effects that promote public health, the reduced vehicle noise can pose safety risks for pedestrians and riders, potentially increasing the likelihood of accidents (Praticò & Fedele, 2021). This concern is particularly relevant for pedestrians with visual impairments or those who may not be cautious enough, especially at low speeds where electric buses emit minimal practical sound (Gabsalikhova et al., 2021). Research indicates that electric vehicles may be detectable at distances of less than 5 meters at low speeds of 10 km/h, whereas conventional vehicles are detectable up to 50 meters (van Kleef, 2020). The National Highway Traffic Safety Administration (NHTSA) found that pedestrian accidents are 37% more likely with electric vehicles than with conventional cars (Gabsalikhova et al., 2021).

Electric vehicles need to be equipped with artificial vehicle alert systems to address this issue. Moreover, standards and regulations related to electric vehicle noise levels are crucial for comprehensive pedestrian safety. Standards such as ISO 16254 (road vehicle sound measurement), SAE J2889 (road vehicle minimum noise measurement), and the United States Federal Motor Vehicle Safety Standards (US FMVSS) have been considered to address the issue of low electric vehicle noise, with some of these becoming mandatory as of 2020.

2.5. Costs of ZEBs

2.5.1. Procurement, Maintenance, and Operation

Electric buses offer numerous cost advantages over their conventional counterparts, primarily stemming from lower operating expenses, including fuel and maintenance costs. While the initial upfront investment for electric buses is notably high, these costs can be offset over their lifespan through maintenance and fuel savings. Furthermore, through initiatives such as The Low-or-No Emissions Grant program, the federal government offers funding for the procurement of zero or low-emissions transit buses and the construction of associated facilities. This approach effectively eliminates upfront costs. Procurement costs for electric buses vary based on manufacturers, specifications, and agency locations, thus relying on global price trend analyses to estimate E-bus costs (Sclar et al., 2019; Liu, 2019).

Studies indicate that, in 2018, the average lifetime cost of a single electric bus for a transit agency, encompassing upfront purchase, fuel, and maintenance costs, was approximately $1,000,000. In contrast, it reached $1,400,000 for CNG and diesel buses (cte, 2021; Lynch et al., 2018). However, as no transit agency has seen a Battery Electric Bus (BEB) through its entire lifecycle, the precise lifecycle costs remain unconfirmed (Metro Transit & AECOM, 2022).

BEBs demonstrate significantly higher fuel efficiency than diesel buses, with an average of 17.35 miles per diesel gallon, equivalent to diesel buses' 4.2 miles per diesel gallon. Foothill Transit, for example, reported fuel costs of approximately $0.45/mile for BEBs and $0.28/mile for CNG buses over six years of data (Jeffers & Eudy, 2021).

The transition to electric transportation is expected to yield increased savings due to the gradual decline in battery and bus purchasing costs, consistent with ongoing trends (Lajunen & Lipman, 2016; Quarles et al., 2020). Battery costs, comprising about a quarter of an electric bus's expense, have seen annual price reductions. By 2018, lithium-ion battery prices dropped to $176/kWh, an 82% drop from $1,000/kWh in 2010. This reduction is attributed to the rise of light-duty electric vehicles, electronics consumption, and grid battery applications, contributing to lower overall electric bus costs (Liu, 2019; Finance, 2018).

Additionally, some manufacturers are designing lighter electric buses to achieve similar prices to diesel buses. The decreasing battery costs have also facilitated battery leasing options, enabling transit agencies to spread battery payments over the electric bus's lifespan (Rickenbacker et al., 2019).

Comparative data from King County Metro, Long Beach Transit, AC Transit, and OCTA Transit, collected during their bus electrification pilot programs, highlight the trend of reduced maintenance costs per bus for electric buses compared to conventional buses. Although fuel costs per mile are higher for electric buses, their greater fuel efficiency mitigates the overall fuel expense (shown in Table 1).

It's important to note that electric buses' fuel cost (electricity cost) varies based on factors like charging methods, peak demand periods, government policies, and regional electricity rates. In the U.S., electricity costs for BEBs have ranged from $0.11 to $0.88 per mile (Deliali et al., 2021).

2.5.2 Charging Infrastructure

Charging infrastructure costs can significantly vary based on site characteristics, necessitating a thorough route analysis to design the infrastructure, select installation locations, and estimate associated expenses (Rajan, 2021). To illustrate, King County Metro Transit estimated in 2017 that installing a fast charger to accommodate four Battery Electric Buses amounted to $144,000 while serving two electric buses with a slow charger incurred $34,000 (Metro, 2017). Additionally, on-route charging stations might be essential to support electric buses along their routes. While these stations cause higher upfront costs, the presence of high-power chargers leads to increased charging expenses. For instance, a 500 kW on-route overhead fast-charging station could cost $500,000, comprising $350,000 for equipment and $150,000 for installation (Liu et al., 2019).

Table 1

Comparison of Maintenance Cost of Electric Bus and Conventional Bus

Evaluation results	Electric bus	Conventional bus
King County Metro (BEB & Diesel) (Eudy & Jeffers, 2018a)		
Bus Procurement Cost	798,000	497,000
Maintenance cost ($/mile)	0.26	0.46
Maintenance cost ($/bus)	7,229	10,717
Fuel economy (miles/dge[1])	15.9	5.3
Fuel cost ($/mile)	0.57	0.30
Long Beach Transit (BEB & CNG) (Eudy & Jeffers, 2020)		
Bus Procurement Cost	1,002,500	546,000
Maintenance cost ($/mile)	0.44	0.54
Maintenance cost ($/bus)	7,057	21,427
Fuel economy (miles/dge)	20.71	3.49
Fuel cost ($/mile)	0.61	0.43
AC Transit (FCEB & Diesel) (cte, 2021)		
Bus Procurement Cost	1,235,000	475,000
Maintenance cost ($/mile)	0.63	0.43
Maintenance cost ($/bus)	17,211	22,016
Fuel economy (miles/dge)	9.14	4.15
Fuel cost ($/mile)	1.08	0.40
SARTA (FCEB & CNG) (Eudy et al., 2019)		
Bus Procurement Cost	2,400,000	533,000
Maintenance cost ($/mile)	0.33	0.33
Maintenance cost ($/bus)	8,718	18,920
Fuel economy (miles/dge)	5.63	4.70
Fuel cost ($/mile)	1.06	0.45

[1]Diesel Gallon Equivalent

2.5.3 Training

Implementing electric buses within a fleet requires comprehensive training for all staff involved in the electric bus sector, spanning operations, maintenance, facilities, and related aspects. The duration of the training depends on the agency's assessment of staff familiarity with the technology, with a recommended minimum of 80 hours (Linscott & Posner, 2021). The training curriculum encompasses safety protocols, personal protective equipment (PPE), and preventive maintenance. Supplementary courses can investigate topics such as steering, brakes, suspension systems, diagnostic systems, and door operations for maintenance personnel. Familiarity with the fueling process is recommended for all operation and maintenance staff. Training on potential hazards and appropriate response procedures is also crucial for first responders and local emergency personnel (cte, 2021; Linscott & Posner, 2021).

Though training costs are often included within labor costs rather than separately detailed, some reports offer insight into these expenditures. According to an NJ Transit report, estimated annual training costs for laborers in operations and maintenance, not exclusively for a particular bus, amounted to $3,900,000 and $1,500,000, respectively (cte, 2021; Deliali et al., 2021; Rajan, 2021).

2.6 Charging Infrastructure for Battery Electric Buses

Electric vehicle chargers are crucial in replenishing the vehicle's energy storage, the battery. They are tasked with converting alternating current (AC) power from the source to direct current (DC) power suitable for recharging. These chargers can be categorized based on location, either within the vehicle itself, known as an onboard charger (used for AC charging), or positioned outside the vehicle as an off-board charger (employed for DC charging) (Dericioglu et al., 2018; Khan et al., 2018).

In AC charging, an electric vehicle connects to an AC supply network, utilizing a cable connection to channel AC power from the grid to an onboard charger, facilitating the recharging process. Conversely, DC charging involves transmitting power directly from an external source to the off-board charger, which transfers it to the electric vehicle through a cable. DC charging encompasses three distinct power levels: level 1 (0-40 kW), level 2 (40-100 kW), and level 3, also referred to as DC Fast Charging (DCFC), which exceeds 100 kW (Dericioglu et al., 2018; Khan et al., 2018).

The efficiency of DC fast charging is typically evaluated based on the time required to achieve an 80% charging rate, given that the remaining portion to reach full charge demands a significantly longer duration. It's important to note that both onboard and off-board chargers necessitate a converter, as the vehicle's energy storage device, the battery, exclusively stores power in the direct current format (Dericioglu et al., 2018; Khan et al., 2018).

Charging electric vehicles involves three distinct methods for connection: conductive charging, inductive charging, and battery swapping. Conductive charging entails establishing a physical connection between the vehicle's Power Electric Interface (PEI) and the power supply through a cable. This method offers two connection options: plug-in charging and overhead charging (as shown in Figure 3) (Dericioglu et al., 2018; Khan et al., 2018).

In contrast, inductive charging, also known as wireless charging or the contactless method, eliminates the need for a physical connection between the charging infrastructure and the electric vehicle. Instead, charging occurs wirelessly through electromagnetic transmission (as depicted in Figure 4) (Dericioglu et al., 2018; Khan et al., 2018).

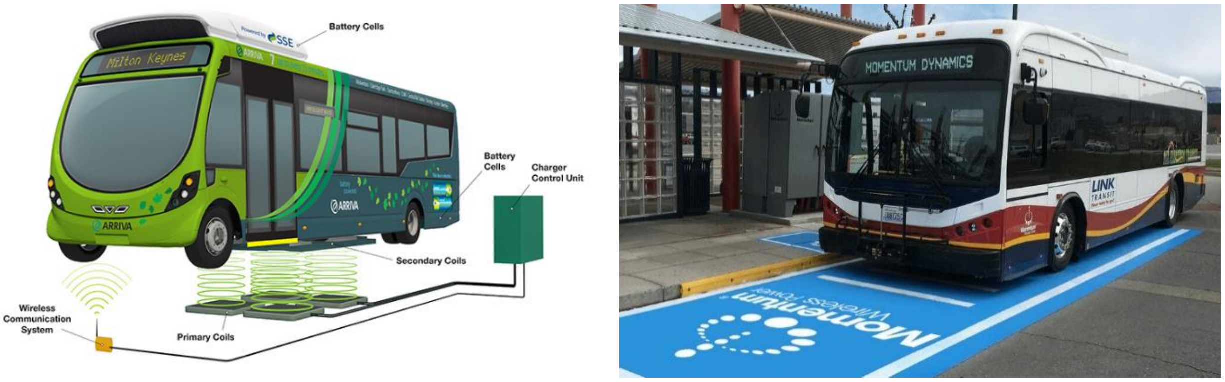
In the battery-swapping approach, the vehicle's recharging process doesn't occur within the vehicle itself. Instead, a fully charged battery is exchanged at a swapping station for a discharged one, effectively replenishing the vehicle's energy reserves (Dericioglu et al., 2018; Khan et al., 2018).

Figure 3

Overhead Charging vs. Plug-in Charging (Sources: Volvo, 2016; Morris, 2018)

Figure 4

Inductive Charging (Sources: Owano, 2014; Hampel, 2021)



In terms of electrical safety, inductive charging surpasses conductive charging due to its lack of physical connection and elimination of shock hazards. However, despite this advantage, conductive charging remains the preferred choice. This is due to its cost-effectiveness and efficiency, as it doesn't incur the high power losses associated with inductive charging (Dericioglu et al., 2018; Khan et al., 2018).

Researchers are actively working to improve inductive charging due to its user-friendly nature and its potential to contribute to advancements in the electric mobility industry. While the battery swapping method is often rejected by manufacturers. This is because sourcing batteries that perfectly fit a vehicle's specifications in terms of dimensions, shape, type, and internal connections can introduce complexities (Dericioglu et al., 2018; Khan et al., 2018).

Charging infrastructure for electric buses can be categorized into two types based on location: in-depot charging and on-route charging (Liu et al., 2019). Each method has advantages and disadvantages, and the choice between them depends on a comprehensive cost evaluation.

In-depot charging involves setting up charging stations within bus depots or garages. Although this approach reduces the flexibility of deploying Battery Electric Buses (BEBs) on various routes, it has a lower charging infrastructure cost. Moreover, the recharge process can be scheduled during off-peak hours, minimizing electricity costs. Utilizing low-power chargers for extended periods in bus depots also helps manage charging expenses. Another advantage is that transit agencies often own depot properties, eliminating the need to acquire additional land for charging stations (Liu et al., 2019; Wendel, 2019).

Conversely, on-route charging requires higher initial investments. The use of high-power chargers results in increased charging costs. (Liu et al., 2019; Wendel, 2019). Installing charging stations in densely populated urban areas with limited space can be challenging. Additionally, charging during non-off-peak hours can lead to higher costs. However, on-route charging offers greater flexibility than in-depot charging, which can be deployed on any route. It also enables longer route travel even with reduced battery pack sizes (Wendel, 2019).

It's important to note that the introduction of electric buses and the installation of associated charging infrastructure have implications for electric utilities and the power grid. The existing infrastructure's capacity must be assessed to determine whether it can accommodate the increased load or if upgrades are necessary to meet the heightened power demand. Additionally, an examination of the electric utility's rate structure is essential. This evaluation should consider factors such as energy charges, time-of-use charges (varying by time of day and season), and demand charges, as these variables can influence the cost considerations for electric bus operations (Aamodt et al., 2021).

2.7. Challenges for Electrification

While electric buses offer numerous benefits to urban environments, their widespread adoption faces governmental, industrial, topographical, and climatic challenges. Also, another issue is the disproportionate concentration of electric bus growth, with China alone operating 99 percent of the global all-electric buses, alongside the prevalence of such systems in developed countries. Therefore, to adopt electric buses worldwide efficiently and equitably, the barriers related to all developed and developing countries would be considered (Sclar et al., 2019). This part discusses the major barriers to employing an electric bus fleet.

2.7.1. Financial Barriers

The initial cost of electric buses, which encompasses procurement expenses and charging infrastructure setup, surpasses that of conventional buses. Although the long-term expenses are expected to be lower for electric buses due to reduced maintenance and fuel costs, this does not alleviate the challenge posed by the higher initial capital cost, which is gradually decreasing (Aamodt et al., 2021; NESCAUM, 2022). As a result, the extensive adoption of electric buses faces challenges.

Transit agencies do have the option to lease electric buses, though such availability is usually limited to small order sizes and pilot programs. Consequently, financing remains a significant challenge to the extensive adoption of electric buses. Furthermore, there exists a gap in the procurement model suitable for agencies, as the prevailing approach primarily focuses on upfront costs and often does not consider total lifetime expenses. This lack of an appropriate model makes it challenging to accurately account for the comprehensive costs associated with electric buses (Liu, 2019; Sclar et al., 2019).

Insufficient government incentives and limited sources of financing also pose barriers to the operation of Zero-Emission Buses (ZEBs). For instance, in the United States, the Federal Transit Administration's Low or No Emissions Grant Program represents the primary subsidy initiative to fund transit bus electrification. However, this initiative faces challenges such as insufficient funding and intense competition among transit agencies seeking electrification funding. As a result, not all projects that apply for funding receive awards; only a subset of projects is successful. The selection process involves evaluating projects based on criteria, including alignment with local plans and financial commitments, technical and legal considerations, and implementation strategies. Furthermore, each funded project typically covers procuring 2-4 buses and related infrastructure, much less than the reasonable bus fleet (Liu, 2019; Sclar et al., 2019).

2.7.2. Novel Technology and Required Planning

Planning the operation of electric buses and establishing the necessary charging infrastructure differs significantly from conventional buses. Adopting novel technology requires transit agencies and their staff to invest time and effort in becoming familiar with its difficulties. This often involves potential adjustments to routes and schedules to accommodate the performance characteristics of electric buses. The selection of appropriate technology, encompassing electric buses, batteries, and charging infrastructure, hinges on compatibility and alignment with the unique features of each route. Moreover, the chosen charging methodology must balance electricity rates and optimal operational costs for the operator's benefit (Aamodt et al., 2021).

Given this technology's pioneering nature, there is a risk of component unavailability or discontinuation and challenges in maintaining adequate maintenance services. Additionally, the relative novelty of electric bus technology translates to a need for more performance data compared to conventional buses. This uncertainty surrounding planning, lifespan, and lifetime costs can create hesitations among potential investors (Aamodt et al., 2021).

Notably, the design of electric bus components and battery systems deviates from that of conventional buses. Moreover, the associated charging infrastructure and methods must be fully standardized and rigorously tested for wide-scale market utilization and reliable revenue service. Studies have reported negative experiences, such as unexpected weight increases, malfunctioning doors, and damaged air suspension valves (Sclar et al., 2019).

Adopting electric buses also raises considerations about electricity demand and grid infrastructure enhancement to meet the expanded capacity requirements. Although not always feasible, the integration of renewable energy generation should be considered by relevant agencies to ensure a consistent energy supply (Blonsky et al., 2019).

2.7.3. Range and Power Limitations of BEBs

The range of electric buses depends on the manufacturer and model, with numerous case studies showcasing improvements in range performance over time. For instance, in 2011, Shenzhen had to replace two battery electric buses for every diesel bus, whereas by 2016, this ratio had significantly improved to around 1.03 battery electric buses per diesel bus. Despite this progress, a number of cities still deal with range limitations that prevent electric buses from covering all routes effectively. In some cases, these limitations result in reduced daily services.

To address this within BEBs, incorporating additional batteries can extend their range. However, this solution introduces the trade-off of increased bus weight, which might surpass road weight limits in certain areas. Implementing on-route charging also alleviates range concerns. However, as previously noted, the associated infrastructure costs, non-peak charging expenses, and installation complexities in densely populated regions present their challenges.

Moreover, the specific range of an electric bus can vary due to fluctuations in battery performance arising from environmental conditions. For instance, colder weather can diminish current production, reducing battery mileage capacity. Cold temperatures also divert battery capacity toward heating systems. Similarly, high temperatures impact the range due to battery capacity allocation for cooling services. Alongside range limitations, operators often complain about power constraints due to overcrowding and uphill terrain, causing slower ascents that lead to schedule delays (Sclar et al., 2019; Aamodt et al., 2021; Wendel, 2019).

To address the issue of range limitations in battery electric buses, the implementation of fuel cell electric buses (FCEBs) emerges as a potential solution. Nevertheless, while FCEBs alleviate the range constraints seen in BEBs, their utilization presents challenges, previously discussed, encompassing higher procurement costs, availability and hydrogen expenses, and lower power generation efficiency (Hua et al., 2014).

2.7.4 Production and Recycling of Lithium-ion Battery for BEBs

To produce EV batteries, extraction of some minerals like lithium, copper, nickel, cobalt, manganese, and other critical minerals are required. Some of these extractions are not conducted in a developing nation with sufficient regulatory protections, leading to negative environmental impacts and public health risks. Furthermore, most of the batteries' production is implemented in Asia, thus the United States must establish its own battery supply chain to minimize the related risks. Also, to reduce the extraction of raw material, some approaches like recycling should be considered to increase the battery life cycle (NESCAUM, 2022).

2.8 How the City Can Establish Zero-Emission Fleet on its Public Transit

The establishment of a new fleet within a city necessitates a comprehensive study and thorough investigation. To initiate this process, the transit agency should present a comprehensive zero-emission plan as a foundational report for fleet renewal toward zero-emission operations. Subsequently, the agency can evaluate the feasibility of introducing a new fleet into the existing public transit system. This section outlines the key steps and information collection aspects to be considered in developing a zero-emission plan.

In this context, this section draws from three comprehensive reports on establishing zero-emission fleets (cte et al., 2020; cte & AECOM, 2020; Metro Transit & AECOM, 2022). Given the long-term nature of fleet transition and the potential for changing conditions, it becomes imperative to rely on simplifying assumptions. These assumptions include defining a specific timeline for the fleet transition, creating transition cycles to facilitate gradual implementation, establishing a projected lifespan for Zero-Emission Buses (ZEBs) within the transit system, and determining mid-life points for maintenance overhauls.

1. **Consideration of Case Studies**, Transit agencies that have successfully implemented Zero-Emission Buses (ZEBs) are valuable sources of insight for study and learning. A deeper understanding can be fostered by examining their experiences, the benefits they've gained, and the challenges they've encountered. Case studies encompassing a diverse range of factors can contribute significantly. These include varying fleet sizes, technology choices for vehicles and infrastructure, climate conditions, and the geographical areas in which ZEBs have been deployed.
2. **Requirements and Data Collection,** It is crucial to gather information about the existing fleet and its historical performance and details about the facilities, infrastructures, operational procedures, and maintenance conditions. Additionally, data regarding bus routes, bus blocks, the annual fixed-route mileage covered by the transit agency's current services, the duration during which buses are in operation, and the annual fuel consumption of the current fixed-route fleet need to be collected.

3. **Service Assessment,** Numerous tools and methodologies are available to assess the current service while considering the specific constraints for implementing electric buses. Route modeling and simulation serve as one effective approach for this assessment. Developing a route model involves gathering essential data such as distance, time, bus speed, acceleration, and roadway grade (the degree of incline or slope). This information performs analyses including battery degradation, accessory load, and varying passenger load. Such analyses estimate real-time bus performance, range, and fuel efficiency. Ultimately, these calculations yield the average energy consumption per mile. This comprehensive understanding of energy consumption, based on variables like routes, bus size, passenger load, and temperature, provides valuable guidance for bus procurements and infrastructure preparation.
4. **Fleet Assessment,** Identify the appropriate type and scale of the Zero-Emission Bus (ZEB) fleet that aligns with the study area's requirements. Additionally, formulate a timeline schedule outlining the projected phases and estimate the total capital costs associated with introducing the new ZEB fleet as a replacement for the current bus fleet.
5. **Fuel Assessment,** Having acquired ZEB performance data through the bus and route modeling and simulation conducted in earlier stages, the next step involves analyzing this data to calculate the daily energy demands. These results will then serve as the foundation for determining the quantities and associated costs of the prospective ZEB fleet. Also, it is well advised to include charging analysis in the assessment process to ensure precise energy consumption estimations. This entails simulating both on-route

and depot charging scenarios, allowing for the accurate estimation of fuel costs and energy consumption.

6. **Facilities Assessment,** This step involves the identification of the necessary infrastructure to accommodate the Zero-Emission Bus (ZEB) fleet. The assessment process determines the requisite charging capacity based on factors such as fleet size, fuel consumption evaluations, and the comprehensive expenses of installing the charging infrastructure. Furthermore, facilitating the deployment of electric buses necessitates establishing or enhancing infrastructure elements. Typically, the optimal approach for determining the charging infrastructure size involves considering the fleet size, the frequency of buses during peak hours, and the capability of entire electric buses to undergo simultaneous charging without the need for vehicle movement.
7. **Maintenance Assessment,** This step involves the computation of the entire lifetime maintenance expenses for both the projected future fleet and the current fleet. Typically, these calculations demonstrate that BEBs result in maintenance savings compared to conventional internal combustion vehicles that was previously discussed.
8. **Emission Assessment,** In this step, a comparative analysis is conducted to underscore the advantages of Zero-Emission Buses (ZEBs) by comparing the emissions generated by both BEBs and conventional buses. The principal advantage of replacing the fleet with ZEBs is reducing GHG emissions. Emissions calculations typically encompass three primary categories: tailpipe emissions (arising during bus operation), upstream emissions (emanating from power plants during extraction, processing, and fuel transition), and well-to-wheel emissions (encompassing both bus operation and power plant emissions during fuel or energy production).

9. **Total Cost of Ownership Assessment,** Considering all the information gathered in the preceding steps, this stage comprehensively considers all associated lifetime costs. This encompasses both total and annual costs for both the Zero-Emission Bus (ZEB) fleet and the current fleet.
10. **Constraints, Risks or Barriers**, Assessing potential constraints, risks, or barriers to implementing Zero-Emission Buses (ZEBs) within the study area. Factors such as the availability of funds for plan execution and the accessibility of suitable buses need to be carefully considered.

2.9 Conclusion

It is well recognized that air pollution and noise pollution from conventional fossil fuel-burning vehicles harm public health. Substituting these conventional vehicles with zero-emission vehicles is widely recognized as a sustainable solution to mitigate the transportation sector's air pollution and GHG emissions. The implementation of Zero-Emission Buses (ZEBs) is projected to yield significant benefits, including notable reductions in air pollution and noise pollution, leading to associated cost savings. Furthermore, the higher upfront cost associated with electric buses, particularly Battery Electric Buses, is anticipated to be offset over their operational lifespan due to lower maintenance and operational expenses than conventional buses. While advancements in bus electrification technology have been made, challenges persist. Manufacturers, practitioners, researchers, and policymakers work collaboratively to address these challenges. Notably, studies demonstrate that the reduced health-related costs attributed to pollution and the potential for healthier future generations underscore the importance of increased investment from federal, state, and local governments.

Chapter 3

Zero-Emission Bus Fleet in U.S.: A Review of State Practices, Funding Sources, Safety Regulations and Standards

3.1 Introduction

This chapter investigates a comprehensive examination of various aspects. It considers the status, practices, and experiences associated with electric buses in the United States. Additionally, the chapter explores safety standards and regulations concerning electric vehicles and their corresponding charging infrastructures, with a specific emphasis on heavy electric vehicles. Furthermore, a thorough discussion includes federal, state, and private funding sources and incentives to promote the widespread adoption of electric buses across the U.S.

Moreover, the chapter pays thorough attention to the initiatives undertaken in New Jersey to reduce air pollution through electrification efforts. The outcomes of this chapter furnish valuable insights into the prevailing and past status of electric buses in the U.S., as well as the combined endeavors of governments, private companies, and agencies dedicated to the cause of electrification.

3.2 Zero Emission Bus Fleet in the U.S.

There are several distinct types of zero-emission buses, including Battery Electric Buses (BEBs), Fuel Cell Electric Buses (FCEBs), and supercapacitor buses, each with its operating principles and advantages.

Battery Electric Buses (BEBs) operate through an onboard battery system powered by electricity from the grid. Importantly, BEBs are emission-free in operation, with no tailpipe emissions, making them a zero-emission mode of transportation. While electricity generation for battery charging may have associated air pollution, the transition to BEBs from conventional buses leads to a reduction in overall air pollution. A case in point is the city of Seneca, South Carolina, where the operation of BEBs resulted in the elimination of 6,611,740 lbs. of tailpipe emissions. Although 909,467 lbs. of emissions were indirectly released during the bus charging process, the net effect was a reduction of 2,702,274 lbs. of emissions, as reported (Deliali et al., 2021; cte, 2021; Horrox & Casale, 2019).

Fuel Cell Electric Buses (FCEBs), on the other hand, utilize fuel cells and batteries to generate electricity for propulsion. These buses derive electric power from stored hydrogen, with only water and heat as byproducts. While FCEBs do not have the same range constraints as BEBs, their use involves considerations regarding hydrogen production and transportation, as well as the high inflammability of hydrogen. Despite these challenges, FCEBs are gaining traction, particularly as technology improves and refueling infrastructure expands (Deliali et al., 2021; cte, 2021; Hue et al., 2014).

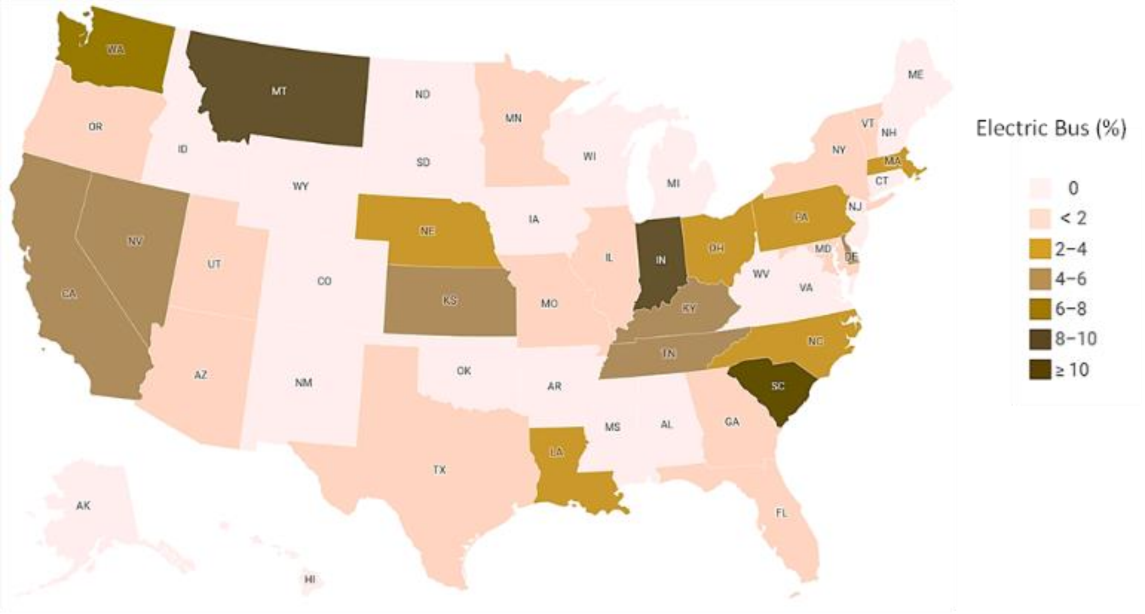
Supercapacitor buses represent another category of ZEBs, employing supercapacitors to store electricity. Known as Electric Double-layer Capacitors (EDLC) or ultracapacitors, these devices offer high power density but lower energy density than other energy sources. According to the study, the average power density for li-ion battery is 1,500-10,000 W/L. In contrast, supercapacitor has a power of around 100,000 W/L . They find application in hybrid configurations, supplementing battery, or fuel cell systems to enhance a ZEB's power output (Şahin et al., 2022; Soltani et al., 2018; Ortenzi et al., 2019).

In the United States, Battery Electric Buses (BEBs) are more prevalent than Fuel Cell Electric Buses (FCEBs), possibly due to higher procurement costs, hydrogen expenses, and lower power generation efficiency associated with FCEBs. The adoption of FCEBs could be encouraged through technology advancements, increased manufacturer options, and expansion of refueling infrastructure. Transit agencies aiming to extend routes while minimizing fleet size particularly consider FCEBs, as one FCEB can replace two BEBs in operational capacity (Hue et al., 2014). The year 2021 saw a 27% growth in BEB and FCEB adoption, with 3364 BEBs and 169 FCEBs deployed, delivered, ordered, or funded, driven by environmental targets set by the Biden Administration (Hamilton et al., 2021; Linn & Look, 2022). Notably, California leads with 1,371 ZEBs, largely due to the Innovative Clean Transit (ICT) regulation mandating zero-emission transit bus sales by 2030. The New York and New Jersey region also showed remarkable growth, with a 138% increase in BEBs from the previous year (Hamilton et al., 2021).

The latest update from the National Transit Database (NTD) in 2020 reveal the distribution of active electric buses across U.S. states. In Figure 5, the percentage of active electric buses to the total fleet for each state of the U.S. is illustrated. According to the map, South Carolina has the highest percentage of electric buses in its fleet (25 out of 247) (Miller, 2022).

Figure 5

The Percentage of Electric Bus to Total Fleet Within the United States



3.3 Successful Practices of Electric Buses in the United States

Since public bus transportation is the essential mode of transportation in the U.S., an effort for its improvement is required. Regarding problems with diesel buses, governments and transit agencies are trying to transfer to electric buses. This section discusses some successful employment experiences of electric buses in several cities, including Seneca, Chicago, King County, New York City, Washington DC, and Greater Los Angeles.

3.3.1 Seneca, SC

In September 2014, Seneca, SC achieved a global milestone by transitioning its entire municipal transit system to all-electric buses, operated by Clemson Area Transit (CAT). A comparison conducted between 2014 and 2018 revealed significant advantages of the electric fleet over its diesel counterpart. Notably, the electric fleet achieved an impressive 16.5 miles per gallon equivalent (MPGe), a striking contrast to the diesel fleet's 3.8 MPG. This transition resulted in a substantial reduction of over 160,000 gallons in diesel consumption and a decrease of more than 2.7 million pounds of carbon dioxide tailpipe emissions over four years (Horrox & Casale, 2019).

The benefits extend beyond fuel efficiency. The electric buses demonstrated a remarkable durability of brake components. While the agency had to change the brakes for diesel buses every 30,000 to 40,000 miles, electric buses surpassed 100,000 miles without requiring brake replacement. Moreover, the electric buses surpassed performance expectations in certain areas. Initial projections indicated that after six years, battery capacity should reach 80 percent, signaling a need for replacement. However, as the sixth year arrived, the buses were still maintaining a charge of 98-100 percent (Horrox & Casale, 2019).

The transition from a diesel fleet to an electric one came with challenges and concerns. Notably, Seneca experiences substantial temperature variations, with average highs of 90°F in summer and lows of 30°F in winter. This posed uncertainty about how the electric buses would perform under such conditions. While the battery exhibited resilience to cold weather, using the heater and defroster during winter caused the battery to be drained. Conversely, the system initiated charging processes in extreme heat to prevent battery overheating, thus extending charging times. The manufacturer has been diligently addressing these issues to optimize performance. Additionally, electric buses encountered difficulty navigating a major hill in other service areas of CAT. Thankfully, the manufacturer successfully resolved this challenge, making it a non-issue (Horrox & Casale, 2019).

Despite the existing problems, CAT emphasizes that its electric fleet radically surpasses its diesel buses. Many of the problems that the diesel buses face (such as cold-water leaks and freezing up) do not apply to electric buses. This is because electric buses have around 70 moving parts, in contrast to diesel buses with 3700 moving parts. As a result, electric buses require no oil changes and offer substantial savings in terms of wear and tear costs (Horrox & Casale, 2019).

3.3.2 Chicago, IL

The deployment of electric buses in Chicago marked one of the initial endeavors to test these buses under extreme cold weather conditions. In 2014, the Chicago Transit Authority (CTA) introduced electric buses into service. The operational performance of these buses surpassed expectations, prompting the CTA to make the ambitious decision to transition its entire fleet to electrification by the year 2040 (cta, 2022).

A significant concern revolved around the performance of lithium-ion batteries in cold weather conditions. To address this issue, CTA and the bus manufacturer collaborated to enhance reliability prior to actual operations. These collaborative efforts encompassed the design of high-quality rechargeable batteries with a lifespan of 12 years. Additionally, measures were taken to ensure battery durability, including the incorporation of heaters fueled by a minimal amount of fossil fuel, thereby preventing battery drainage. An automated battery management system was also established to detect and isolate cells with abnormal behavior, thus safeguarding the integrity of the entire battery cells (cta, 2022).

As a result of deploying these buses, the agency realized significant annual savings, amounting to over $24,000 in fuel costs and $30,000 in maintenance expenses compared to the diesel buses purchased in 2014. Furthermore, the electric buses demonstrated their efficiency by operating successfully and reliably in Chicago's diverse weather conditions, including extreme temperatures (cta, 2018).

3.3.3 Greater Los Angeles, CA

Foothill Transit, a transit service operating in Greater Los Angeles, initiated its fleet electrification plan in 2010 with the introduction of three BEBs as a pilot project. Notably, Foothill Transit holds the distinction of being the first U.S. transit agency to deploy BEBs with on-route fast charging station (Foothill Transit, 2019; Metro Transit & AECOM, 2022). The agency is actively assessing the performance of BEBs in revenue service, with a particular focus on comparing their cost and performance metrics against conventional buses over time (Jeffers & Eudy, 2021; Metro Transit & AECOM, 2022).

Over a span of six years (2010-2016), the agency reported significant benefits resulting from the replacement of conventional buses with electric ones within its fleet. This transition translated into savings of 200,000 gallons of natural gas and a reduction of 2,616 tons of greenhouse gas emissions (Metro Transit & AECOM, 2022).

The agency considered some priorities. Firstly, route and block selection is based on the principle of prioritizing service to disadvantaged communities. Secondly, emphasis is placed on routes connecting to transit hubs, thereby maximizing accessibility for a larger number of riders. Simultaneously, considerations are made for accommodating on-route charging infrastructure. Additionally, the topographical characteristics of routes are considered to ensure optimal energy consumption efficiency (Metro Transit & AECOM, 2022).

As an early adopter, the agency encountered various challenges. Notably, it was observed that the performance of fast-charge Battery Electric Buses had degraded over a five-year period. Additionally, the unavailability of replacement parts for first-generation technology resulted in BEBs being taken out of service. While manufacturers progressively improved and replaced failed components in later-generation models, the agency struggled with the difficulty of sourcing replacement parts for early-generation buses and chargers. This led to extended periods of out-of-service buses awaiting replacement parts. Furthermore, the inherent complexity of BEBs compared to conventional technology translates to longer repair times needed for identifying and diagnosing issues (Metro Transit & AECOM, 2022).

3.3.4 King County, WA

King County Metro Transit (Metro) is responsible for public transit services in King County, WA. In 2016, Metro started deploying a battery-electric bus fleet, which has now become a prominent feature of the region's transportation network. With a clear commitment to sustainability, the agency has set a target of operating a fully zero-emission fleet by 2035. Moreover, starting in 2020, the agency has taken a significant step by committing to exclusively purchase zero-emission buses (Metro, 2022a; Metro, 2022b).

Starting in 2016, the agency initiated testing of three battery-electric buses. Given their successful performance during the initial phase, Metro made the decision to extend testing with an additional eight electric buses. The comprehensive testing phase yielded invaluable insights into various aspects, including range, battery sizing, electricity consumption, charging methodologies, and operational limitations. These findings played a pivotal role in the development of standards encompassing procurement, information technology, training, and more (DOT, 2017; Metro, 2015).

The pilot program placed a significant emphasis on assessing the performance of electric buses under varying road and weather conditions. In general, the buses performed well, with only minor issues encountered. For example, during colder months, the charging time for the batteries was slightly reduced, and the range achievable on a full charge was somewhat lower than anticipated (Horrox & Casale, 2019).

One of the notable and recurring expenses for the agency pertains to monthly demand charges for electricity, which constituted 54 percent of Metro's utility bills (Monthly demand charges refer to charges assessed by utilities based on a customer's peak consumption from the grid within a specified timeframe (Eudy & Jeffers, 2018a)). In cases with a limited number of buses, demand charges are calculated based on the mileage covered, resulting in higher energy costs per mile. As the fleet size grows and buses are recharged more frequently, overall electricity consumption increases. Impressively, peak energy demand does not experience a proportional rise. Consequently, demand charges constitute a smaller proportion of the total electricity costs (Horrox & Casale, 2019).

In King County, higher per-mile costs are observed during the winter due to elevated electricity rates in that season. This is attributed to reduced vehicle mileage during winter, leading to higher demand charges (Eudy & Jeffers, 2018a). However, these charges do not pose a constraint, as the costs associated with fixed assets such as chargers and demand charges are returned through increased utilization rates, resulting in reduced overall energy costs. The expansion of the fleet, varied charging schedules, and increased daily recharging to extend mileage coverage do not proportionally increase demand charges. Over time, demand charges are anticipated to constitute a smaller proportion of the total electricity costs. Metro is confident that the implementation of electrification and the deployment of charging infrastructure will ultimately lead to lowered energy expenses in comparison to diesel buses (Horrox & Casale, 2019).

In economic justification, Metro also considers electric buses' societal benefits and public health. It estimates that for the life cycle of a 40-foot diesel-hybrid bus, the total societal cost (costs from environmental pollutants that are greenhouse gases, air pollutants, and noise) is $121,000, compared to $19,000 for a 40-foot electric bus. Metro is confident about the investment return of electric buses (Metro, 2017).

3.3.5 Washington D.C.

Between 2018 and 2020, the District Department of Transportation (DDOT) undertook the implementation of a pilot program known as the BEB Pilot on the DC Circulator transit system. This initiative involved the deployment of 14 battery electric buses (BEBs). The primary objective of the program was to facilitate a comprehensive comparison between the performance of BEBs and diesel buses. The insights gathered from this comparative analysis would subsequently inform a well-informed, long-term decision concerning the potential transition to an all-electric bus fleet (DDOT, 2021).

The overall aim of the project encompassed several key facets. These included evaluating the cost-effectiveness of electric buses relative to their diesel counterparts, assessing the ability of BEBs to fulfill the specific requirements of the transit system, weighing both positive and negative impacts of the service, and studying the feasibility of potentially replacing diesel buses with BEBs in the future (DDOT, 2021).

DDOT partnered and coordinated with several public and private organizations for the buses, chargers, utility interconnections, and several software providers and consultants. These combined efforts were instrumental in ensuring the successful operation of the pilot program. Central to the program's effectiveness was the collection and meticulous analysis of relevant data. Key data points encompassed aspects such as fuel economy, travel range, charging durations, and travel times. One noteworthy finding emerged from the analysis: the actual travel range of the buses fell short of their nominal range (up to 250 miles). The computed average travel distance settled at approximately 108 miles (DDOT, 2021).

Furthermore, a comprehensive evaluation encompassed environmental impacts, maintenance considerations, and the reliability of BEBs. The most important finding was a significant reduction in battery performance during the winter months. The decline in performance was attributed to the heightened demand for the heating, air conditioning, and ventilation systems, coupled with the need for increased power during the cold winter temperatures. Reports indicated that for each degree decrease in the environmental temperature, there was a corresponding 2.1% increase in BEBs power consumption. As a result, the range experienced a reduction of up to 14% between the fall and winter seasons (DDOT, 2021).

In response to these identified impacts, DDOT initiated the formulation of a series of strategic interventions. For instance, for the winter, a winterization protocol was developed by DDOT to prepare buses for the condition ahead of service. This protocol entailed pre-setting the vehicles' temperatures and strategically substituting buses with lower State of Charges (SOCs) with those with higher SOCs. This substitution strategy was aimed at ensuring uninterrupted service even in challenging weather. Additionally, the recommendations included the construction of enclosures to counteract the challenges posed by summer heat. These enclosures were designed to safeguard both buses and chargers from the potential risks of overheating (DDOT, 2021).

Based on the conclusive findings of the Department of Energy and Environment (DOEE), a potential replacement of Battery Electric Buses (BEBs) with diesel buses (with a sample size of 14 buses) could yield a notable reduction of 431 metric tons of CO2e emissions emitted from tailpipes annually. Due to a positive conclusion of the BEB Pilot, the transition to an all-electric fleet was committed by DDOT (DDOT, 2021).

3.3.6 New York City, NY

The New York City Transit (NYCT), The MTA (Metropolitan Transportation Authority) bus operator, provides public transit service in New York City. NYCT did not share any report of their agency's experience with BEBs. Nevertheless, as presented within this segment, they have offered insights into their strategic initiatives and collaborative efforts to transition to a Zero Emission Bus (ZEB) fleet. The agency aims to convert its all-bus fleet to Battery Electric Bus (BEB) by 2040 to help improve air improvement for New Yorkers (MTA, 2018). In 2018, the MTA initiated a three-year pilot program to assess the feasibility of its 2040 long-term plan and evaluate the electric bus fleet's capacity and durability for four-season operation (Catania et al., 2019).

In pursuit of MTA's 2040 objective to establish an all-electric bus fleet, numerous pivotal stakeholders collaborate alongside the primary decision-maker, MTA. These stakeholders encompass Consolidated Edison (Con Ed), a prominent utility company, New York Power Authority (NYPA), the NYC Mayor's Office of Sustainability, New York State Energy Research and Development Authority (NYSERDA), New York State Governor's Office, and the New York State Public Service Commission (PSC) (Catania et al., 2019).

The New York City Transit (NYCT) has articulated that transitioning to alternative public transit options from personal vehicles would yield an annual reduction of 17 million metric tons of carbon emissions. Notably, adopting an all-electric bus fleet will further enhance carbon footprint mitigation (Mass Transit, 2019).

According to a study conducted by Columbia University, implementing an all-electric bus fleet within the MTA framework can achieve an annual reduction of approximately 575,000 metric tons of CO2. Furthermore, regarding the potential healthcare savings stemming from improvements in air quality, an approximate annual benefit of $100 per New Yorker has been estimated (Aber, 2016).

Of particular significance, the transition to an all-electric fleet will yield specific implications for communities of color. This importance is underscored by a report from the New York City Environmental Justice Alliance, which highlights that 75 percent of bus depots in New York City are situated within these communities (NYC-EJA, 2018). Beyond its impact on air quality enhancement, the technology's quieter operational profile compared to diesel vehicles underscores its advantageous role in densely populated urban areas like New York City (Mass Transit, 2019).

3.4 Performance Measures and Related Costs of BEBs and FCEBs for the U.S. Transit Agencies

As previously mentioned BEBs and FCEBs are two types of ZEBs operating in the U.S. transit fleet. In this section, the performance measures and related costs reported by several transit agencies are presented and compared. Table 2 and Table 3 provide a summary of delineating performance metrics, fuel efficiency, and associated costs that have been compiled to systematically evaluate the performance of electric buses across both revenue service and pilot programs. This approach offers a comprehensive overview of the electric bus deployment, enabling a reasonable assessment of their viability and effectiveness in real-world operational scenarios.

Table 2

Summary of FCEBs Performance for Several Transit Agencies

Evaluation results	**Sunline Transit**	**AC transit**	**OCTA Transit**	**SARTA**	**AC transit**	**OCTA Transit**
Reference	(Eudy & Chandler, 2013)	(Eudy et al., 2016b)	(Eudy & Post, 2018)	(Eudy et al., 2019)	(cte, 2021)	(cte, 2021)
In-service performance						
Data collection period	March 2012–February 2013	Jan 2015-Dec 2015	Jun 2017-May 2018	Feb 2018-Jan 2019	Jan 2020-Feb 2021	Feb 2020-Feb 2021
Number of buses in study	1	13	1	5	10	10
Fleet total mileage	42,988	366,267	20,979	130,798	274,195	295,862
Avg monthly mileage per bus	3,582	2,492	1,748	2,180	2,109	2,465
Number of road calls	NA	NA	NA	35	45	50
Miles between road calls	3,908	4,513	2,338	3,737	7,808	4,625
Availability (%)	85	74	70	68	73	67
Fuel efficiency						
Fuel economy (kWh/mi)	NA	NA	4.28	NA	NA	NA
Fuel economy (miles/kg H_2)	6.54	5.47	6.46	4.99	8.08	8.46
Costs						
Fuel cost ($/mi)	1.22	1.58	2.01	1.06	1.08	0.96
Maintenance ($/bus)	16,721	35,003	9,943	8,718	17,211	16,497
Maintenance cost ($/mi)	0.39	1.15	0.47	0.33	0.63	0.56
Maintenance cost-propulsion system only ($/mi)	0.12	0.65	0.14	0.15	NA	NA
Bus purchase cost (M$)	2.4	2.5	1.4	2.04	1.015	1.015

Table 3

Summary of BEBs Performance for Several Transit Agencies

Evaluation results	**Foothill Transit**	**King County Metro**	**County Connections**	**Long Beach Transit**	**DART**	**Foothill Transit**
Reference	(Eudy & Jeffers, 2017)	(Eudy & Jeffers, 2018a)	(Eudy & Jeffers, 2018b)	(Eudy & Jeffers, 2020)	(Plautz, 2018; Gick et al, 2022)	(Jeffers & Eudy, 2021)
In-service performance						
Data collection period	Aug 2015-Dec 2016	Apr 2016-March 2017	June 2017-May 2018	Jan 2018-Dec 2018	July 2018-Jan 2019	Jan 2017-Dec 2020
Number of buses in study	12	3	4	10	7	2
Fleet mileage	902,281	83,128	51,550	161,275	45,020	153,005
Ave monthly mileage per bus	2,400	2,309	1,074	1,344	1,072	1,594
Number of roads calls[1]	146	NA	11	38	19	NA
Miles between road calls	6,180	2,771	4,686	4,244	2,168	8,053
Availibility[2](%)	90	80.6	76.9	70.9	NA	76.1
Fuel efficiency						
Fuel economy (kWh/mi)	2.16	2.36	2.84	1.82	2.69	2.10
Costs						
Fuel cost($/mi)	0.43	0.50	0.73	0.42	0.43	0.45
Maintenance cost ($/bus)	11,444	7,229	4,991	7,057	11,702	43,137
Maintenance cost ($/mi)	0.19	0.26	0.39	0.44	1.82	0.564
Maintenance cost-propulsion system only ($/mi)	NA	0.05	0.10	0.04	NA	0.225
Bus purchase cost (M$)	0.904	0.798	1.053	1.002	0.97	0.88
Infrastructure cost (M$)	0.998	NA	NA	NA	NA	0.665

[1] Road Calls: In-service bus failure that leads to significant schedule delay or requires on-route replacement (Jeffers & Eudy, 2021).

[2] Availability: The ratio of the number of available days to the number of days planned for the operation of the bus in service in percentage (Jeffers & Eudy, 2021).

Based on the agency's report, the average fuel cost of BEBs is much lower than FCEB, so the average fuel cost for all mentioned agencies for BEBs is 0.49 $/mile, and for FCEBs is 1.32 $/mile. Regarding maintenance cost, both electric buses have almost the same average maintenance cost of 0.6 $/mile. Regarding bus procurement cost, the FCEBs are much more expensive than BEBs, so the average bus procurement cost for FCEBs is about 1,720,000$, and for BEBs is 930,000$.

3.5 Funding Sources for Public Bus Electrification in the U.S.

3.5.1. Federal

Today, in the United States, the federal government supports vehicle electrification in several ways, such as programs and grants. The Federal Transit Administration (FTA) is the principal funding source, preparing appropriations to state and local authorities for zero and low-emission transit buses (Liu, 2019; Canis et al., 2019). In 2021, President Biden, with the signing of the Bipartisan Infrastructure Law, triggered the largest long-term investment in infrastructure for $550 billion over five years (The fiscal year of 2022 to 2026). Many FTA programs were supported under this law, including bus and bus facilities programs (low or no emission program was introduced as one part of this program), bus testing programs, programs related to electrification, and many other transportation programs. According to the law, $108 billion is allocated to federal public transportation programs that will also include zero-emission buses (FHWA, 2023; FTA, 2022a; FTA, 2023a). All primary funding programs related to transit bus electrification were expressed in this part.

3.5.1.1 Low or No-Emission Grant Program. The Low-or-No Emissions Grant program is the most remarkable program presenting funding for transit bus electrification annually by FTA. In 2015, the program was administered by President Obama to provide funding to purchase or lease transit buses with zero or low emissions. The allocated funds can also be utilized for the ownership, lease, or construction of related facilities (Liu, 2019; Canis et al., 2019). In 2021, the funding reached $182 million to increase the pace of electrification and help achieve the Biden-Harris Administration's goal of 50% greenhouse gas emissions reduction by the decade’s end (FTA, 2021). Following the government policies, the grant for the fiscal year of 2023 provided $1.7 billion, which is the largest ever grant for a low or no emission program–meaning that it will enable FTA to support more projects (FTA, 2023b).

3.5.1.2 Investments in Research and Development (R&D). Federal investments in research and development have been conducted to lower battery costs, increase vehicle range, and reduce charging times. Also, other EV infrastructure investments have been made. To reduce the overall cost of vehicle electrification, as one approach, the federal government has invested in transportation electrification R&D. Under the Obama Administration, vehicle electrification became a national priority, prompting actions such as increased investment in battery R&D, the allocation of funds for establishing battery manufacturing facilities within the United States, and the initiation of EV research and development initiatives by the Department of Energy (DOE) (Canis et al., 2019).

Congress provides funding for electric vehicle technologies R&D through annual appropriations to the Office of Energy Efficiency and Renewable Energy (EERE) (Canis et al., 2019). For example, in the fiscal year 2019, funding for vehicle technologies aimed at transportation electrification research included $163.2 million for the battery and electrification technologies subprogram, $10 million for transportation electrification, and $37.8 million for the Clean Cities program, which offers competitive grants to support alternative fuel infrastructure and vehicle deployment activities (Canis et al., 2019).

3.5.1.3 Other Supports and Grants. Vehicle fleet electrification, particularly for transit buses, gained significant legislative support during the 116th Congress. The Green Bus Act of 2019 mandates that any bus leased or purchased using funds from the Federal Transit Administration (FTA) for public transportation must be a zero-emission bus (Canis et al., 2019). While certain federal programs are not exclusively designated for bus electrification, they are closely linked to electric buses. These include the Bus and Bus Facilities Grant Program, the Urbanized Area Formula Grant, Formula Grants for Rural Areas, the Capital Investments Grants program, and the Federal Highway Administration's Congestion Mitigation and Air Quality program (Liu, 2019).

The Congestion Mitigation and Air Quality Improvement (CMAQ) Program by the Federal Highway Administration (FHWA) is another noteworthy initiative. Originating in 1990 as part of the Clean Air Act, the program was reauthorized in 2015 as part of the FAST-ACT. CMAQ grants are allocated to states aiming to meet air quality standards by reducing vehicle-related pollutants such as carbon monoxide, ozone, and particulate matter. States with competitive projects stand a chance to receive the award, with project types ranging from alternative fuel vehicles and their necessary facilities to infrastructure for pedestrians, bicycles, and public transit, as well as improvements to diesel vehicles (Liu, 2019).

In May 2022, the U.S. Department of Energy (DOE) introduced two programs focused on electric vehicle development as part of the national battery supply chain. These programs, titled "Battery Materials Processing and Battery Manufacturing" and "Electric Drive Vehicle Battery Recycling and Second Life Applications," are funded through the bipartisan Infrastructure law, amounting to $3.1 billion (Randall, 2022).

3.5.2 State and Private

Alongside substantial federal support, various states, and private entities, including power companies, have offered incentives encouraging transit agencies to accelerate the transition from conventional buses to zero-emission buses (ZEBs). These incentives encompass grants, reimbursement funding, loans, tax credits, rebates, and discounts for vehicle purchases, as well as support for infrastructure installation, electricity expenses, and exemptions from testing or inspection for electric vehicles.

The commitment of several states to the deployment of medium and heavy-duty zero-emission vehicles (ZEVs), including transit buses, was triggered by the signing of a memorandum of understanding (MOU) involving 17 states and the District of Columbia (USDOE, 2023). Moreover, the Volkswagen Mitigation Trust funds were allocated towards electrifying transit buses across various U.S. states and tribes.

Among private incentives, the National Electric Highway Coalition (NEHC) stands out as a significant initiative involving contributions from 45 states. This collaboration among electric utility companies aims to establish electric vehicle fast-charging infrastructure along key U.S. routes, promoting widespread adoption of electric vehicles. As depicted in Figure 6, most states offer incentives within both private and state domains, except Alaska, Nebraska, and Vermont, which exclusively provide state incentives.

Conversely, Georgia and West Virginia exclusively offer private incentives. This encouraging trend suggests that shortly, the United States may witness the absence of conventional transit buses, underscoring the ongoing efforts to overcome challenges and transition toward cleaner transportation solutions.

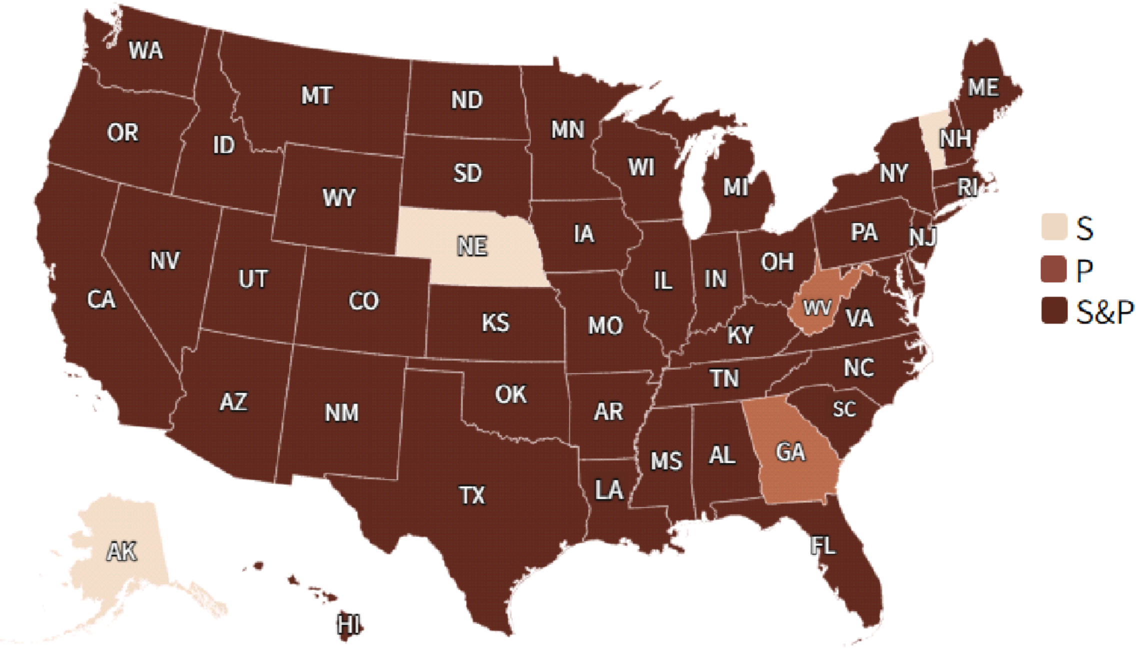
3.5.3 New Jersey State

3.5.3.1 New Jersey' Legislation. In April 2018, a pivotal legislative initiative was introduced to establish a comprehensive refund program for electric vehicles. Rooted in this legislative framework, the Board of Public Utilities (BPU) assumed responsibility for funding and executing the program to adopt light-duty plug-in electric vehicles (LDPEVs) through rebate incentives. Notably, the bill went beyond the scope of LDPEVs, with a provision outlining the BPU's responsibility to explore the potential benefits of electrifying heavy-duty and medium-duty vehicles in a large range, including public and school buses. An essential dimension of the bill was the directive for the program's benefits to extend to urban communities, low-income populations, and others adversely affected by limited mobility options (NJ legislature, 2018a).

In October 2018, significant legislation was made by introducing a bill that fostered the adoption of plug-in electric vehicles (PEVs). This bill emphasized developing robust programs, initiatives, and objectives to promote PEV utilization. Notably, the central objective revolved around expanding charging infrastructure, accompanied by a comprehensive review of policies, regulations, and initiatives to facilitate this expansion. A key highlight of this bill was that by 2025, the New Jersey Transit Corporation should exclusively procure new buses as plug-in electric vehicles. This transition was to be executed with a priority on addressing environmental justice, low-income, and urban communities. Eventually, the bill was approved and signed as law by Governor Phil Murphy in January 2020 (NJ legislature, 2018b; NJ legislature, 2020; State of New Jersey, 2020).

Figure 6

State (S) and Private (P) Incentives Related to Transit Electrification in the United States



In 2018, Assembly Environment and Solid Waste Committee introduced a bill to establish the Volkswagen Settlement Utilization Fund to decrease air pollution generated from vehicles and associated equipment. According to the bill, the Department of Environmental Protection (DEP) is directed to use the funding to establish and implement programs related to the bill’s purpose. On of the goals of the programs is that it should encourage people to use zero emission vehicles and construct related infrastructures through public education and subsidization for public and private infrastructures' construction (NJ legislature, 2018C).

3.5.3.2 Medium and Heavy-Duty Vehicle Electrification Grants. The New Jersey Department of Environmental Protection (NJDEP) offered incentives to pay the additional cost of replacing all-electric vehicles with diesel vehicles. The paid cost covers all additional expenses, including charging infrastructure establishment. This incentive applies to various vehicle types, including transit buses, school buses, shuttle buses, and garbage trucks. Projects in overburdened communities will be a priority. Funding for this initiative stems from the Regional Greenhouse Gas Initiative (RGGI) (USDOE, 2023).

3.5.3.3 Goals of deployment of Plug-in Electric Vehicle (PEV) and Electric Vehicle Supply Equipment (EVSE). To meet the state goal, NJ works to increase the number of PEVs and associated infrastructure. By December 31, 2032, New Jersey Transit Corporation is mandated to direct 100% of new bus acquisitions towards Zero Emission Vehicles. Also, the New Jersey Department of Environmental Protection (NJDEP) enacts a public education program designed to raise awareness about the advantages of PEVs, communicate the state's PEV goals, and provide information on available incentives for both PEVs and EVSE (State of New Jersey, 2020; USDOE, 2023).

3.5.3.4 Medium and Heavy-Duty ZEV Deployment Support. As previously mentioned, New Jersey and 16 other states and the District of Columbia signed a memorandum of understanding (MOU) to support state Zero Emission Vehicle (ZEV) programs collaboratively. As discussed earlier, this coordinated effort is facilitated through the Multi-State ZEV Task Force. (USDOE, 2023).

3.5.3.5 Requirement for Alternative Fuel Bus or Low Emission Bus Deployment. According to New Jersey's ZEV-related regulations, the New Jersey Transit Corporation (NJTC) is mandated to procure buses equipped with pollution controls to reduce particulate emissions. Additionally, these buses must not be powered by conventional diesel fuel. NJTC must adhere to these requirements; however, if NJTC cannot meet them, NJTC must submit a report to the New Jersey Senate and General Assembly detailing the reasons. In such cases, the state legislature may grant exemptions to the organization (DOS, 2022).

3.5.3.6 Energy Master Plan. The Energy Master Plan (EMP) in New Jersey is designed to guide achieving its transportation sector electrification goals by 2050. The EMP entails a range of programs to ensure the realization of this objective. These include supporting the deployment of 330,000 light-duty electric vehicles (EVs) by 2025, establishing a widespread network of electric vehicle supply equipment (EVSE) across the state, offering incentives for EVSE installations, educating both consumers and fleet owners about EVs, transitioning state fleet vehicles to EVs, collaborating with industry to develop incentives for medium and heavy-duty all-electric or fuel-cell vehicles, as well as exploring policies to accelerate the adoption of alternative fuels (State of New Jersey, 2022).

3.6. Safety Regulations and Standards for Low/Zero Emission Vehicles (LZEVS)

Today, some standards and regulations have been developed for the safety of LZEVs and their associated charging infrastructures nationally and internationally, and some are specifically assigned to heavy LZEVs. It's important to differentiate and recognize the similarities between standards and regulations. They both consider technical aspects that bring together governmental, non-governmental organizations, or industry through activities. Conversely, regulations set up legal limitations on values and test procedures in contrast to standards that are voluntary technical considerations for those willing to impact them (Cazzola, 2020).

Ensuring safety through adherence to standards and regulations plays a pivotal role in providing secure vehicles and infrastructure, thus mitigating potential risks to people and the environment, and ultimately reducing the costs associated with the transportation of both people and goods. These regulations are a collaborative effort involving prominent organizations such as the United Nations, the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the Society of Automotive Engineers (SAE) (Cazzola, 2020).

3.6.1. The United Nations Global Technical Regulation 20 (UN GTR 20)

The establishment of UN Global Technical Regulations (GTRs) falls under the framework of the 1998 Agreement of the World Forum for the Harmonization of Vehicle Regulations (WP.29), where participating governments commit to incorporating UN GTRs into their national legislation (Cuenot, 2020). As a result, many national regulations are aligned with these global standards.

The primary objective of UN GTRs is to establish safety standards for heavy and light electric vehicles that are equivalent to those of conventional internal combustion engine vehicles. In 2018, this effort aimed to define the performance criteria for electric vehicles and their battery systems, preventing hazardous incidents during normal operation and after crashes. These regulations encompass various types of electric vehicles, including battery electric, fuel cell, hybrid, and plug-in hybrid vehicles.

Significantly, these regulations include performance requirements and test procedures to address unique safety considerations, such as risks associated with high-voltage circuits, electric shocks, and potential hazards linked to rechargeable electric energy storage systems (REESS), including fire hazards and emissions of harmful gases (Cazzola, 2020).

3.6.2. Applied International Standards in the U.S. for Electric Vehicles

This section provides an overview of key international standards related to electric vehicles from both ISO and SAE. The scope of these standards is concisely summarized in separate tables, namely Table 4 and Table 5. Another noteworthy international standard is UL2580, which outlines critical safety tests for batteries used in four-wheel electric vehicles. It's important to note that these tests primarily focus on ensuring the safety of individuals and do not assess battery performance or reliability (UL Standards, 2022).

Table 4

ISO Standards for Electric Vehicles (Cazzola, 2020; ISO, 2022)

Standards	**Scope**
ISO 6469-1:2019	Specified safety requirements for RESS (Rechargeable Energy Storage System) of electric vehicles for persons' protection. For all four parts of ISO 6469, comprehensive information related to personnel's safety of manufacture, maintenance and repairs is not provided. Also, when it is said electric vehicles in these four parts, it means all-electric vehicles except related requirements for mopeds and motorcycles.
ISO 6469-2:2022	Specified requirements for operational safety, specifically to electric vehicles, for persons' protection inside and outside the vehicle. There is no consideration related to driving automation features.
ISO 6469-3:2021	Specified electrical safety requirements for voltage class B (high voltage according to this standard) electric circuits of electric systems propelled electric vehicles and their auxiliary electric systems. Specifically, it includes electrical safety requirements related to electric shock and thermal incidents for persons' protection.

Standards	**Scope**
ISO 6469-4:2015	Specified safety requirements for electric systems propelled electric vehicles and their auxiliary electric systems for persons' protection inside and outside the vehicle. Specifically, electrical safety requirements for vehicle post-crash conditions are considered. It applies to electric vehicles, including circuits with voltage class B (The last review and confirmation of this standard was conducted in 2021, and therefore it remained as a current version).
ISO 21498-1:2021	Part 1 and 2 of ISO 21498 apply to electric propulsion and auxiliary systems voltage class B of electric vehicles and to components and electric circuits of these systems. Specifically, characteristics of voltage sub-classes associated with DC electric circuits and specifications related to the operation and design systems and components are provided. Electrical safety is not mentioned in this part.
ISO 21498-2:2021	Part 2 of ISO 21498 focuses on characterizing the DC voltage class B terminals of specified components in part 1. Test requirements, test conditions, and testing methods are expressed.
ISO 12405-1: 2011 , 2: 2012	Test procedures are specified in part 1 for high-power applications and in part 2 for high-energy applications to determine the fundamental characteristics of lithium-ion battery packs and systems in terms of performance, being reliable, and prevention of abuse (these are the last version of these standards, and only they have been revised by ISO 12405-4:2018).
ISO 12405-3:2014	Specified test procedures and safety requirements for lithium-ion battery packs and systems with voltage class B used for four-wheel electric vehicles. In this standard, the safety of battery packs and systems during repair, maintenance services, vehicle manufacture, transport, and storage is not evaluated, and only the safety during the performance is tested (This is the last version of the standard, and only it has been revised by ISO 6469-1:2019).
ISO 12405-4:2018	Test procedures apply for either high-energy applications or high-power applications to determine the essential characteristics of lithium-ion battery packs and systems in performance, being reliable and electrically functional.
ISO 21782 (1-3): 2019	Part 1 includes specified test procedures for the performance of electric propulsion components with voltage B and their combinations. Part 2 and part 3 are specifically test procedures related to the motor system and both motor and the inverter, respectively (The electric propulsion components mean inverter, DC/DC converter, motor, and combinations mean motor system).
ISO 21782(4,5,7) : 2021, 6:2019	Part 4-7 includes specified tests for the performance of DC/DC converter, the operating load of the motor system, motor and inverter, and DC/DC converter, respectively, in electric propulsion system with voltage class B in electric vehicles.

Table 5

SAE Standards for Electric Vehicles (Cazzola, 2020; SAE, 2022)

Standards	**Scope**
SAE J1766_201401	Recommended practice for the safety of electric, fuel cell, and hybrid vehicles with specified high voltage systems during and post-crash to protect occupants.
SAE J2929_201302	Safety requirements for battery system for electric and hybrid vehicles employing lithium-based rechargeable cells with definition of pass/fail criteria in testing.
SAE J2344_202010	Safety instruction for vehicles with high voltage systems like electric vehicles, hybrid electric vehicles, and fuel cell vehicles during the performance and in case of charging but does not consider the safety during manufacture, repair, or maintenance.
SAE J2464_202108	Specified test procedures for the safety of RESS for electric and hybrid electric vehicles. This standard does not specify pass/fail criteria.

All the essential international and national regulations and standards were initially developed within a unified framework that applied to heavy and light-duty electric vehicles. However, it's important to recognize that heavy-duty vehicles have distinct specifications compared to their light-duty counterparts, particularly in battery storage size, technology, and the integration of charging and electric vehicle systems. For instance, heavy-duty vehicles necessitate larger and more robust batteries due to their heavier weight and longer travel distances. Additionally, the configuration of these vehicles differs, requiring more intricate integration of components from various sources. Furthermore, heavy-duty vehicles may demand higher power levels during the charging and discharging. Moreover, as seen in the development of technologies like pantographs, the concept of charging while driving becomes more relevant for medium and heavy vehicles. Addressing thermal runaway is also a fundamental concern in regulations and standards, especially for heavy vehicles due to the larger component sizes (Cazzola, 2020).

Thermal runaway represents a failure mode in battery cells, deriving from factors like mechanical damage or charging processes. It can result in the emission of potentially toxic or corrosive gases, fire, and, in extreme cases, even explosions. Furthermore, thermal runaway can be triggered by manufacturing defects and inadequate control management. In addition to the aforementioned hazards posed by thermal runaway, there is a phenomenon called thermal propagation, where the failure of one cell can lead to the failure of neighboring cells. Given the substantial size of battery packs in heavy vehicles, issues related to thermal runaway and its propagation are particularly significant (Cazzola, 2020).

These mentioned distinctions have prompted the exploration and formulation of distinct international regulations and standards for heavy vehicles. Examples of such standards include SAE J2910 and SAE J3125. These standards outline specific test procedures for electrical safety, standardization of battery packs, and battery pack system integrity in fully electric and hybrid electric buses and trucks, respectively (As shown in Table 7) (Cazzola, 2020).

3.6.3 Applied International Standards in the U.S. for Charging Infrastructure

Organizations such as ISO, IEC, and SAE oversee international standards relevant to electric vehicle charging. These standards address various charging approaches, including conductive, inductive, and battery swapping, as outlined in Table 6. As previously mentioned, the unique charging requirements of heavy vehicles necessitate the development of distinct standards and regulations. SAE J3105 is the major international standard for heavy electric vehicle charging, which encompasses requirements for conductive power transfer systems in heavy electric vehicles. An overview of the standards of heavy electric vehicles and their corresponding charging infrastructure can be found in Table 7.

Table 6

Standards and Regulations for Electric Vehicle Charger (Cazzola, 2020; ISO, 2022; SAE, 2022; IEC, 2023)

Standards	**Scope**
Conductive Charging	
IEC 62196	Series of standards for connectors in conductive charging method including plugs, socket-outlets, vehicle inlets and vehicle connectors for electric vehicles.
IEC 61851	Series of standards related to the safety of the charging station and the communication between vehicle and charger including vehicle to grid functionality. The IEC 61851-1 is a radical standard for conductive charging on route electric vehicles with a maximum voltage of 1000 v for AC charging and 1500 V for DC charging. Specifications for safety for the connection of the electric vehicles and charger, including operating conditions and characteristics of the charger and electric safety requirements, are expressed.
ISO 17409	Standards for the required specifications for electric vehicle charging with an external electric power supply.
ISO 15118	Series of standards for electric vehicle and grid communication.
SAE J1772	Specifications for connectors in conductive charging method including plugs, socket-outlets, vehicle inlets and vehicle connectors for electric vehicles (most relevant for North America and Japan).
SAE J2953	Requirements and specification to consider appropriate charger for a specific electric vehicle.
SAE J3068	Standards related to electric vehicle power transfer system using an AC three-phase capable coupler.
Inductive Charging	
IEC 61980	Series of standards and specifications for the equipment needed for electric power transfer in wireless electric vehicle charging method.
ISO 19363	Safety-related requirements for the on-board equipment enabling wireless power transfer to charge electric vehicles.
SAE J1773	Recommended practices to charge electric vehicle with inductive method
SAE J2954	Safety, interoperability, and electromagnetic compatibility’s specifications for light plug-in electric vehicles in wireless electric vehicle charging method.
Battery Swapping	
IEC 62840	Series of standards for electric vehicle battery swap systems.

Table 7

Standards and Regulations for Heavy Electric Vehicle and Charger (Cazzola, 2020; *SAE, 2022*)

Standards	**Scope**
SAE J2910_201404	Recommended practice for the design and test of class 4 through 8 hybrid electric and electric trucks and buses for electrical safety. It addresses the safety concerns of electrical systems in commercial vehicles (with voltages greater than 60 VDC or 30 VAC RMS)
SAE J3125_202211	Integration of battery pack systems in bus electrification.
SAE J3105_202001	This document covers the general physical, electrical, functional, testing, and performance requirements for conductive power transfer. It has also subdocument specifically for Vehicle-Mounted Pantograph Connection.

In addition to international regulations and standards, the United States has implemented various national regulations and standards applicable to electric vehicles. For instance, the Federal Motor Vehicle Safety Standards (FMVSS) encompass a set of regulations focused on ensuring the safety of electric vehicles, overseen by the National Highway Traffic Safety Administration (NHTSA) (National Archives, 2017). The National Electrical Code® (NEC®, formally known as ANSI/NFPA 70), also serves as a safety standard for installing and wiring electrical equipment in industrial, commercial, and residential buildings. This code has relevance to the safety of infrastructure related to electric vehicles. While initially developed for U.S. application, the NEC has gained international recognition and adoption (NEC, 2022).

3.7 Conclusion

This chapter provides a comprehensive overview of the implementation of electric buses in the U.S. It investigates various aspects, including the current electric bus statistics across states, states' practical experiences in operating electric buses, funding sources for electrification encompassing federal state and private incentives, and the application of safety standards and regulations within the U.S. An analysis of agency reports reveals that the overall expenses associated with Fuel Cell Electric Buses (FCEBs) remain comparatively higher than Battery Electric Buses (BEBs), spanning procurement, maintenance, and operational costs. However, ongoing advancements in FCEB technology, coupled with the growth of hydrogen fuel availability and FCEB manufacturing plants, are anticipated to enhance understanding and safety aspects of flammable fuels, thereby fostering a greater inclination towards integrating FCEBs into fleets. Studies indicate that agencies have reported positive experiences after implementing battery electric buses, although accompanied by certain challenges. Among these challenges, power limitations stand out as a significant hurdle. Deploying high-power supercapacitors as a hybrid fuel can enhance the efficiency of electric buses during revenue service. Notably, there are no reported instances of supercapacitor hybrid electric buses in the country. In light of these observations, it is recommended that governmental bodies and relevant agencies expedite the electrification of the entire bus fleet with a focus on all-electric buses. Strategic investment in integrating this bus variant holds promise for advancing sustainable transit solutions.

Chapter 4

Zero-Emission Bus Fleet: An Optimization Model for Electric Bus Charging Station Location

4.1 Introduction

Conventional vehicular systems, encompassing diesel, compressed natural gas, and related technologies, give rise to a multitude of concerns, including both air and noise pollution, adversely affecting public health and global climatic conditions. Recent studies conducted in 2021 underscore the predominant role of the transportation sector, attributing 28.5 percent of GHG emissions within the United States as the principal contributor to air pollution (Tiseo, 2023). Within this sector, passenger-heavy road vehicles constitute an integral component of public transportation, exerting a noteworthy impact on urban air quality.

Furthermore, a notable concern arises with conventional heavy-duty vehicles, which generate substantial noise emissions reaching up to 90 decibels along typical urban roadways (decibel is a noise measurement unit) (Stewart, 2023). This noise level will be annoying, specifically in dense cities (Borén, 2020). These cumulative disruptions underline the immediate necessity of transitioning towards cleaner and quieter transportation alternatives.

The adoption of Electric Buses (E-Buses), that is also called Zero Emission Buses (ZEBs), represents a pivotal approach to mitigating pollution from public passenger transit. This technology produces no tailpipe emissions, resulting in a zero-emission operation (Rajan, 2020). Among the various types of all-electric buses, Battery Electric Buses (BEBs) are the prevailing choice in the United States.

The implementation of Battery Electric Buses (BEBs) faces several challenges, including limitations in travel range compared to conventional buses, increased weight, and reduced passenger capacity (Sclar et al., 2019; Kunith et al., 2017). Employing lighter batteries is advisable to address these issues, as it enhances passenger capacity and reduces vehicle weight. Adopting lighter batteries necessitates applying on-route fast chargers due to the reduction in travel range. The integration of fast chargers enables BEBs to operate along the same routes as conventional buses, effectively mitigating travel range concerns. This allows for recharging during dwell and terminal layover times, even with loading passengers during in-service periods (Kunith et al., 2017; Tzamakos et al., 2023). However, installing fast-charging infrastructure comes with substantial costs. Hence, there is a significant need to optimize the required chargers to minimize overall infrastructure expenses (Uslu & Kaya, 2021).

Several studies have been dedicated to optimizing the location of charging stations. However, a few studies (Tzamakos et al., 2023; Uslu & Kaya, 2021) considered time constraints at bus stops and the importance of applying several chargers at terminals since several bus lines will be converged at terminals, and the number of chargers should be adequate to facilitate the simultaneous recharging of multiple electric buses. For a more comprehensive understanding of this topic, the subsequent section will investigate a detailed literature review.

The objective of this study is to determine the optimal placement of on-route fast charging stations at both intermediate and terminal bus stops. Additionally, the study seeks to optimize the number of chargers required per terminal charging station to enable simultaneous charging of multiple Battery Electric Buses (BEBs). To achieve this, a mixed-integer linear mathematical programming model was developed with the aim of minimizing the cost associated with establishing charging infrastructure. The effectiveness of the proposed mathematical model was evaluated using data from a real-world case study, the City of Camden, NJ, USA. The results and insights obtained from this optimization model hold significant value for practitioners and decision-makers in the transportation sector. These findings will facilitate the development of an efficient all-electric bus network, contributing to improved air quality and the overall well-being of communities.

The subsequent section investigates a comprehensive literature review, examining studies that have employed optimization models to minimize the cost of implementing electric bus fleets. Following this, the methodology section presents the mathematical formulation and programming model utilized in this study. Subsequently, the paper moves on to a discussion of the case study, offering insights into the numerical results and sensitivity analysis conducted to assess the impact of various parameters. Finally, the paper concludes with a summary of the key findings and a comprehensive closing discussion.

4.2 Literature Review

Researchers have responded to the constrained budget for public electric bus fleet implementation by exploring avenues for cost reduction through optimization. In 2016, Wang et al. (2016) introduced optimization models to identify optimal electric bus charging station locations. They tackled two scenarios, one incorporating battery sizes and the other without, formulated as integer linear programming. Simulation and model evaluation focused on satisfying energy requirements and charging station power capabilities to ensure electric buses serve designated routes without time constraints.

Another study addressed the optimization of fast-charging stations while considering waiting costs. A mixed-linear optimization model was developed to minimize electrification costs for BEB fleets with fast-charging infrastructure. This model accounted for battery capacity and charging infrastructure trade-offs, integrating time constraints to prevent delays in layovers and dwell times, ultimately preventing passenger delays. The model's validity was established by application to Berlin's bus network (Kunith et al., 2017).

A further investigation in 2018 aimed at tackling deployment costs for BEBs. Researchers formulated a model to minimize the deployment expenses of replacing diesel or CNG buses with BEBs. The model encompassed electric bus procurement and charging station installation. The study effectively determined the optimal number and placement of on-route and in-depot charging stations and the requisite number of electric buses. The model's applicability was demonstrated using existing bus routes operated by the Utah Transit Authority (UTA) (Wei et al., 2018).

Regarding the lifecycle cost of electric buses, Bi et al. (2018) proposed a multi-objective optimization model to minimize life cycle costs. This model balanced battery capacity and wireless charging station numbers on depots and routes. Optimization also factored in GHG emissions and energy consumption throughout the lifecycle. The model's application on the University of Michigan, Ann Arbor bus routes showcased its effectiveness. The study further explored parameter sensitivity and different scenarios, offering valuable insights.

Iliopoulou et al. (2019) investigated on-route fast charging station optimization and route design with highlighted the trade-off between passenger satisfaction and operator costs in route design. Their findings demonstrated the potential for substantial operator cost reductions with a 25 percent increase in average passenger travel time. The research underscored the interrelated battery capacity, charging power, state of charge, and recharging time.

In 2020, Nahum and Hadas (2020) introduced a multi-objective non-linear optimization model to determine wireless charging station locations. The model focused on cost minimization associated with charging infrastructure and battery costs while maximizing environmental benefits by reducing noise and air pollution. The study's validation employed simulated route and bus network scenarios.

Uslu and Kaya (2021) focused on fast charging stations for intercity bus networks. Their mixed-integer linear mathematical model aimed to minimize charging infrastructure costs and expenses for each charging stop. The study incorporated queueing theory and time constraints to prevent passenger and timetable delays. Sensitivity analysis highlighted the travel range's pivotal role in cost minimization.

Stumpe et al. (2021) presented an optimization model in 2021 to minimize up-front capital costs associated with fast-charging infrastructure, electric buses, and operational expenses. The study explored factors' sensitivity through numerical experiments on real case studies, providing practical guidance for decision-makers.

Liu et al. (2021) developed a mathematical model in 2021 focusing on optimizing charging station locations, configurations, and bus frequency, considering the impact of varying air temperatures on battery performance, and charging rate acceptance by batteries. The model's successful testing in Beijing extended its applicability to other cities with similar local weather data.

More recently, Tzamakos et al. (2023) presented a mixed-integer linear programming model to minimize charging infrastructure costs while identifying suitable on-route fast charging station locations in urban all-electric bus networks. They incorporated queueing theory to curtail electric bus waiting times at terminals, mitigating schedule delays.

In this lecture, we have reviewed numerous studies that focus on optimizing the development of a cost-effective BEB fleet. Many of these studies have focused on identifying the optimal charging infrastructure locations. As previously mentioned, only a limited number of studies, namely Tzamakos et al. (2023) and Uslu & Kaya (2021), have considered the time constraints at bus stops and the necessity of incorporating multiple chargers at terminals. This is particularly important at terminals since they must be able to serve electric buses arriving from multiple lines simultaneously, necessitating adequate charging resources to prevent charging conflicts.

The studies above have utilized queuing theory to ensure sufficient chargers within the limited layover time. However, it's worth noting that these studies relied on a simplified M/M/1 queue model, which is designed for single-server systems with the same service times (average service time is assumed). However, the charging time (service time) is different due to different route lengths. When dealing with multiple chargers and varying service times, the mathematical complexity increases, making applying the queue model more complex.

Therefore, in this study, we do not apply the queue model in the optimization formulation. Instead, we recommend a rigorous investigation into the validity of the results, especially concerning terminals servicing multiple converged lines. To accomplish this, we evaluate the terminal recharging process with the highest bus frequency during the peak hour, representing a worst-case scenario. This assessment ensures that charging and waiting times remain within the terminal's layover time.

4.3 Methodology

4.3.1 Problem Overview

We presented a mathematical model for the optimum on-route fast charging station locations and numbers at bus stops on a fully electric transit network. The network includes bus stops (start, intermediate, terminal) and routes. Battery electric buses (BEBs) are a type of vehicle deployed for the transit network. They recharge with fast charging at terminals and intermediate stops that can be charged along the route without taking BEBs out of service (Liu et al., 2019). Some assumptions are adopted to develop and apply a model:

- Each bus must reach a maximum state of charge on arrival at the terminal, which is considered as being fully charged in this study.
- Each route has specified buses that operate only for that route (Liu et al., 2018).
- Per charging station in a terminal can have several chargers to serve several BEBs simultaneously (Iliopoulou & Kepaptsoglou; 2021).
- There is no charging conflict for BEBs at intermediate stops.
- All BEBs have sufficient energy at the end of the service operation (end of the day) to return to the depot.

- The transit fleet is all BEBs with the same specifications; thus, they have the same battery capacity and travel range (Stumpe et al., 2021).
- The charger with the same specification is established for intermediate and terminal stops.
- Dwell time is the pickup and drop-off time at the intermediate stop with loading passengers.
- Layover time refers to the period during which a bus remains stationed at the terminal stop without loading passengers.
- Terminals are potential origin-destination bus stops for fully charged.
- On-route charging station means the potential charging station at an intermediate or terminal stop.
- The bus fleet is located at a single depot, and every morning, they depart for their designated bus lines to start service operations. (Stumpe et al., 2021).

4.3.2 Mathematical Formulation

This section introduces the formulated mathematical optimization model, encompassing the objective function subjected to multiple constraints. Table 8 presents all notations, comprising sets, parameters, and decision variables utilized within the model.

Objective Function:

$$\text{Min } c \sum_{i \in Sm, r \in R} x_{i,r} + c \sum_{i \in St} y_i \tag{1}$$

Subject to:

$$ECd_{i,r} = ECave * Dd_{i,r} \qquad \forall\, i \in Ss, r \in R \tag{2}$$

$$SOC_{i,r} = SOCin - \left(\frac{ECd_{i,r}}{BC}\right) \qquad \forall\, i \in Ss, r \in R \tag{3}$$

$$E_{i,r} = SOC_{i,r} . BC \qquad \forall\, i \in Ss, r \in R \tag{4}$$

$$EC_{i,i+1,r} = ECave * D_{i,i+1,r} \qquad \forall\, i \in S, r \in R \tag{5}$$

$$t_{i,r} \leq x_{i,r}.\left(dt_{i,r} - tc - tdc\right) \qquad \forall\, i \in Sm, r \in R \tag{6}$$

$$t_{i,r} = \left(\frac{(SOCmax.BC) - E_{i,r}}{p.\ Cef}\ (3600)\right) \qquad \forall\, i \in St, r \in R \tag{7}$$

$$E_{i+1,r} = E_{i,r} + \left(\frac{t_{i,r}.p.c_{ef}}{3600}\right) - EC_{i,i+1,r} \qquad \forall\, i \in S, r \in R \tag{8}$$

$$E_{i,r} \geq EC_{i,i+1,r} + (SOCmin.BC) \qquad \forall\, i \in S, r \in R \tag{9}$$

$$E_{i,r} \leq (SOCmax.BC) \qquad \forall\, i \in S, r \in R \tag{10}$$

$$x_{i,r} \in \{0,1\} \qquad \forall\, i \in Sm,, r \in R \tag{11}$$

$$x_{i,r} = 0 \qquad \forall\, i \in St,, r \in R \tag{12}$$

$$En_{i,r} = \left[(SOCmax.BC) - E_{i,r}\right].f_{i,r} \qquad \forall\, i \in St, r \in R \tag{13}$$

$$y_i \in \{1, \dots, k\} \qquad \forall\, i \in St \tag{14}$$

$$SR_i = y_i.p \qquad \forall\, i \in St \tag{15}$$

$$AR_i = \sum En_{i,r} \qquad \forall\, i \in St \tag{16}$$

$$SR_i - AR_i \geq 0 \qquad \forall\, i \in St \tag{17}$$

Table 8

Notation for Optimization Formulation

Notation	Description
Sets	
R	Set of routes of the bus network
S	Set of all network bus stops
Ss	Set of initial bus stops
Sm	Set of intermediate bus stops
St	Set of terminal bus stops
Indices	
i	Unique identifier for each bus stop
r	Unique identifier for each route
Parameters	
C	Cost of charging station establishment
$ECave$	Average energy consumption per km in kWh
$Dd_{i,r}$	Deadhead trip from depot to the service trip (distance from depot to the start bus stop i for route r in km)
$SOCin$	Initial state of charge at depot
BC	Battery Capacity in kWh
$D_{i,i+1,r}$	Distance from segment i to i+1 on route r in km
$dt_{i,r}$	Dwell time in intermediate bus stop i for route r
tc	Coupling time to connect to the charger
tdc	Decoupling time to disconnect from the charger
$SOCmax$	Maximum allowed state of charge
$SOCmin$	Minimum allowed state of charge
P	Charger power in kW
Cef	Charger's efficiency
$f_{i,r}$	BEBs' frequency arrives at the terminal stop on route r per hour (BEB/hr)
Decision Variables	
$x_{i,r}$	Binary variable, equal to 1 if a charger is in the intermediate stop i, 0 otherwise
y_i	Integer variable, indicates the required number of chargers to be located at terminal stop i
$ECd_{i,r}$	Deadhead trip energy consumption, from depot to the start bus stop i on route r in kWh
$SOC_{i,r}$	State of charge for the start bus stop i on route r
$E_{i,r}$	Energy remaining after leaving stop i on route r
$EC_{i,i+1,r}$	Energy Consumption from stop i to i+1 for route r in kWh.
$t_{i,r}$	Charging time at bus stop i on route r
$En_{i,r}$	Required energy in terminal stop i for route r to reach the maximum state of charge in kWh
SR_i	Service rate at terminal stop i over the unit of time
AR_i	Required energy for BEBs arriving at terminal stop i over the unit of time (kWh)
k	Maximum number of chargers per terminal charging station

The objective function (1) aims to minimize the overall cost of establishing on-route fast charging stations at intermediate and terminal stops. Constraints (2) and (3) determine the energy consumption during deadhead trips, which involve the trip from the depot to the start of the service trip. These constraints are aimed at determining the initial state of charge for the electric buses as they commence their service trips. Constraint (4) specifies the energy level with which the electric buses start on their service trips.

Furthermore, Constraint (5) describes the energy consumed between each successive bus stop based on the average energy consumption. This consumption is influenced by a multitude of factors, including the average vehicle speed, vehicle specifications, topography, traffic congestion, pedestrian crossings, time of operation, weather conditions including temperature and season, passenger loading, and driver behavior (Tzamakos et al., 2023; Hjelkrem et al., 2021; Aamodt et al., 2021). Additionally, auxiliary power usage, encompassing functions like heating, air conditioning, ventilation, lighting, and other support systems, also impacts energy consumption (Hjelkrem et al., 2021).

As previously discussed, this study employs the average energy consumption. Equation (6) introduces a charging time constraint at intermediate stops. When chargers are established at every intermediate stop on each route, the charging time must not exceed the dwell time minus the charger coupling and decoupling time. Additionally, Constraint (7) specifies the required charging time at the terminal to reach full charge.

Constraint (8) defines that the remaining energy at each stop equals the energy at the preceding stop, incremented by the energy received from the charging station at the previous stop (if present), and reduced by the energy consumed during travel between these consecutive stops. Furthermore, Constraint (9) guarantees that an electric bus can successfully complete a trip between two consecutive stops without exceeding the minimum allowable energy threshold. Constraint (10) ensures that the energy level at each stop remains below the maximum allowable energy threshold.

It's important to note that the consideration of both maximum and minimum states is to ensure preserving battery lifespan (Tzamakos et al., 2023; Mohamed et al., 2017). Constraints (11) and (12) specify the binary decision variable, applicable solely to intermediate stops, and set to zero for terminal stops. Constraint (13) states that when electric buses for each route arrive at the terminal, they must receive adequate energy to reach maximum state of charge and then continue their daily operation. In this equation, the hour characterized by the highest bus frequency at the terminal is considered to assess the maximum arrival rate for the bus frequency. This frequency indeed represents the worst-case scenario. If the number of chargers proves sufficient to accommodate this worst-case scenario, it will be adequate for all daily operations.

Constraint (14) defines the set of values for the integer decision variable, representing the necessary number of chargers to be positioned at terminal stop i. The maximum value depends on the government and private companies’ decisions (Uslu & Kaya, 2021). Constraint (15) quantifies the level of service the charging station provides, considering the specific power available at each terminal within a unit of time. Constraint (16) refers to the cumulative energy demand of all Battery Electric Buses (BEBs) from all routes arriving at the terminal over the unit of time. Constraint (17) guarantees that the number of chargers allocated to each terminal is adequate to accommodate all arriving electric buses per hour.

4.4 Application on Case Study and Numerical Results

4.4.1 Data Collection

The proposed model is demonstrated and evaluated on a City of Camden, NJ transit network. The network encompasses 10 routes (bus lines) and 1172 bus stops, all depicted in Figure 7 and Figure 8. The geographical locations of these bus stops were gathered from the NJ Transit timetable and online operational map for weekdays (Eudy & Jeffers, 2018a), and each route is assumed to remain consistent across all days and hours. The mixed-integer mathematical programming model is solved through the utilization of the Pyomo framework in conjunction with the Gurobi solver. All parameters relevant to the mathematical model have been detailed Table 9. Additionally, Table 10 provides bus frequency at the terminal for each route, a data derived from the NJ transit timetable.

Table 9

Applied Parameters to the Optimization Model for the Case Study

Parameters	Value	Parameters	Value
$\boldsymbol{BC}$	198 kWh	tdc	5s
$\boldsymbol{ECave}$	1.5 kwh/km	$dt_{i,r}$	30s
$\boldsymbol{SOCin}$	0.8	p	600 kW
$\boldsymbol{SOCmin}$	0.2	c_{ef}	0.96
$\boldsymbol{SOCmax}$	0.8	c	700,000 $
$\boldsymbol{tc}$	5s	-	-

Figure 7

Camden Routes and Bus Stops (Routes 405, 407, 413, 419, 453)(Source: NJ Transit, 2023b)

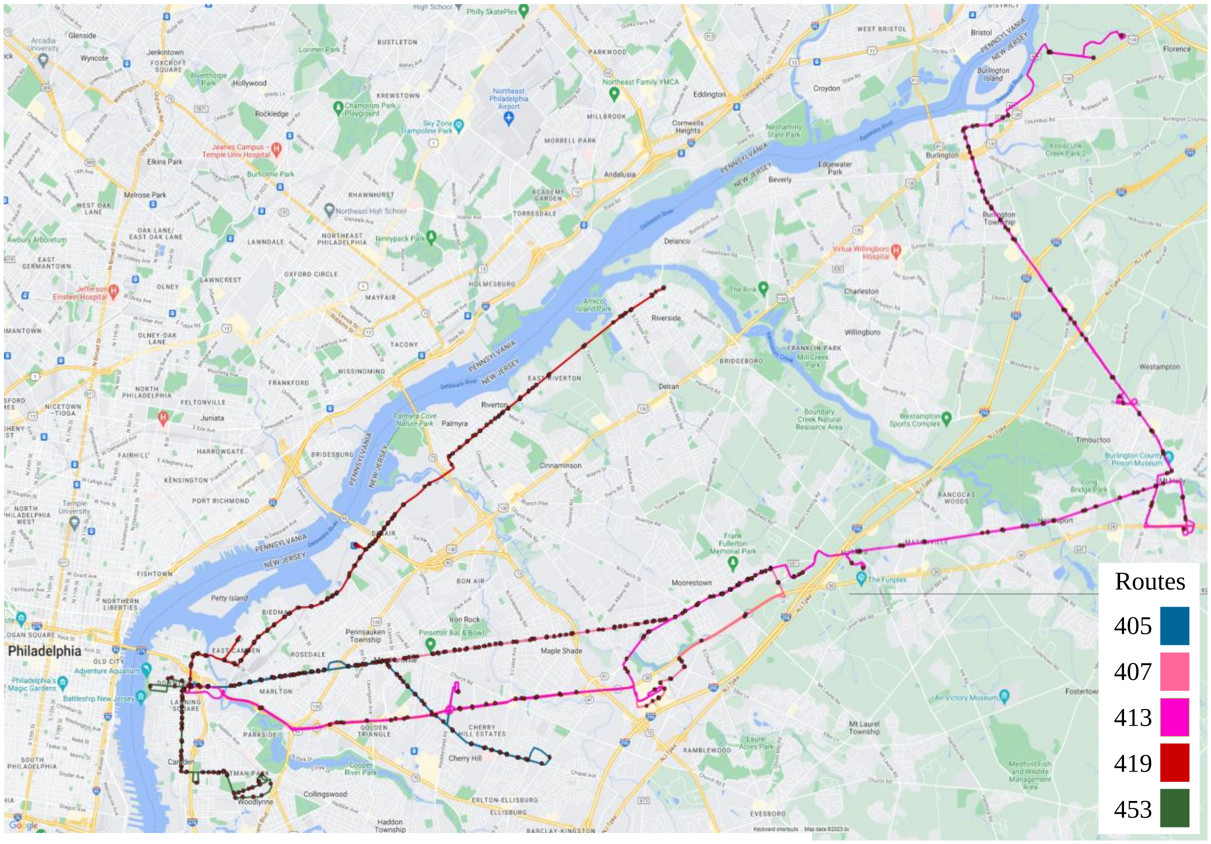


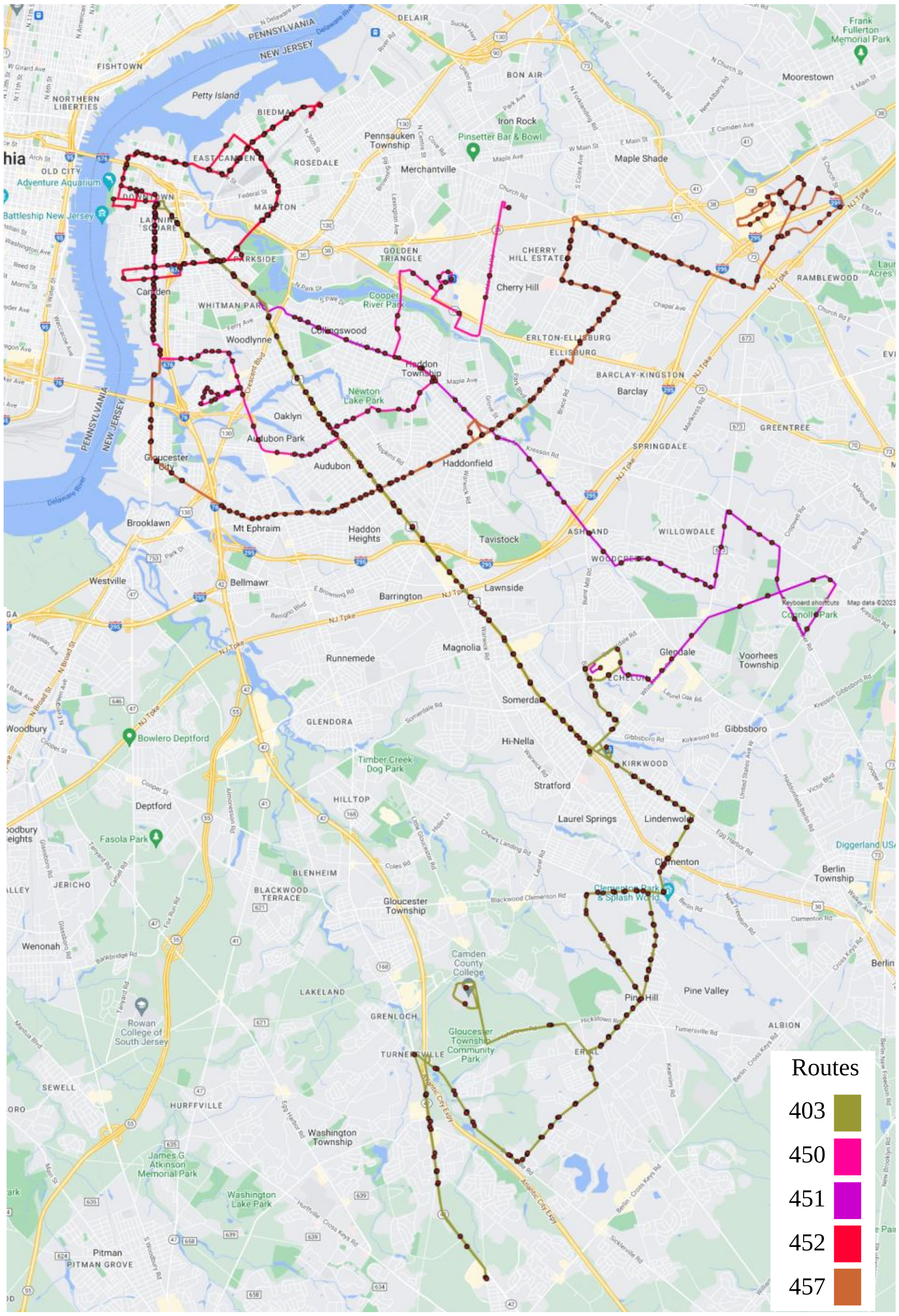
Table 10

Route Length and Bus Frequency Arrives at the Terminals for Camden Bus Routes

Route	#Route,#TerminalStop	Frequency (EBs/hr)	RouteLength (km)
403 Camden-Turnersville	1,1 - 1,4	3 - 3	55.77
405Camden-Merchantville-Cherryhill mall	2,1	3	14.63
407Camden-Merchantville-Moorestown mall	3,1	1	24.98
413 Camden-Florence light rail station	4,1 - 4,5	3 - 2	60.57
419 Camden-Riverside light rail station	5,1	1	21.12
450 Camden-Audubon-Cherryhill mall	6,1	2	25.50
451 Camden-Vorhees town centers	7,1	1	31.06
452 Camden-36th streetlight rail station	8,2	2	19.50
453 Camden-Ferry ave Patco	9,3	2	7.58
457 Camden-Moorestown mall	10,1	1	32.26

Figure 8

Camden Routes and Bus Stops (Routes 403, 450, 451, 452, 457)(Source: NJ Transit, 2023b)



The terminal is established as the point where BEBs start and end the service loop. However, some long bus routes can have a second terminal. Nonetheless, certain extended bus routes might incorporate a secondary terminal. In the context of this case study, considering the battery capacity and the maximum travel range of BEB, bus lines exceeding 50 km in length are assumed as long routes, warranting the assignment of two terminal stops—one at the origin and another at the destination. Long routes, Routes 1 and 4, are assigned two terminals, which means that BEBs achieve a full charge following a one-direction trip. In contrast, BEBs for the remaining routes will arrive at the terminal after completing their loop service trips. Also, it is assumed that the entire BEB fleet is stationed at the same depot, Walter Rand Transportation Center (WRTC), serving as a transportation hub in Camden.

To assess the average energy consumption, calculating the average speed is required. Under the assumption that forthcoming Battery Electric Buses (BEBs) are similar to the existing speed of current diesel buses operating within Camden, the bus speed was computed utilizing data from the online NJ Transit bus map. After evaluating diverse routes and operational schedules, an average bus speed of 25 km/h was determined. This average speed closely aligns with the diesel bus operations in King County Metro, Seattle, which maintains an average speed of 23 km/h.

The report further establishes the average energy consumption for their BEBs at 1.5 kWh/km. Given the assumption of uniformity in all other factors affecting average energy consumption, we maintain an average energy consumption value of 1.5 kWh/km for Camden, like the BEBs operated in King County Metro (Eudy & Jeffers, 2018a)

In terms of the state of charge, the practical range of 20-80% is adopted (Mohamed et al., 2017). As specified in our assumptions, the Battery Electric Buses (BEBs) commence their operations from the depot with a maximum state of charge (SOC). The cost of the charging infrastructure is derived from the reported average costs documented across various transit agencies' experiences (The National Academies, 2018). The chosen electric bus model is the 40-foot New Flyer Excelsior (The National Academies, 2018), and the selected charger is an ultra-fast charger from Heliox company (Fast charger with the power greater than 400 kW called ultra-fast charger (Rasool et al., 2021)) (Heliox, 2023). Furthermore, to ascertain dwell time, on-site data collection was conducted across diverse routes, timings, days, and locations within the City of Camden. An average value of 30 seconds was reached.

4.4.2 Mathematical Model Solution

The ultimate optimal solution yielded the installation of six ultra-fast chargers at strategic network terminals. This encompasses two chargers located at the WRTC terminal stop, which serves as a convergence point for eight routes (routes 1-7, 10). Additionally, a single charger is allocated for the second terminal of routes 1 and 4, as well as the terminal stops of routes 8 and 9. Notably, there is no need for on-route fast charging for intermediate stops.

The optimized minimum value of the objective function is computed at $4.2M. Given the varying route lengths, the charging time for Battery Electric Buses (BEBs) differs at the terminal stops. These charging times for all bus network terminals are detailed in Table 11.

As previously indicated, two chargers are designated for the WRTC terminal stop (terminal stop 1) to accommodate buses from eight converging routes. While these chargers are sufficient to fully charge all arriving buses at the terminal, there is uncertainty regarding their adequacy to achieve full charge within the limited layover time. It is essential that the combined waiting and charging time remains within the layover time. As discussed earlier, while the application of queuing theory could address charging conflicts, its implementation becomes complicated when dealing with multiple servers and varying service times.

Table 11

Charging Time at Terminals for All Bus Network Routes

#Route, #TerminalStop	ChargingTime (min)	#Route, #TerminalStop	ChargingTime(min)
1,1	9	5,1	7
1,4	9	6,1	8
2,1	5	7,1	10
3,1	8	8,2	8
4,1	10	9,3	3
4,5	10	10,1	10

In this study, the adequacy of charger numbers for each terminal is established through an investigation into charging time and waiting time during peak hours, representing a worst-case scenario when terminal bus frequency is at its maximum. Table 12 presents the assessment of charging time at the WRTC terminal. The examination reveals that, considering the summation of charging time and waiting time for each bus route, all values remain under Camden's maximum layover time of 20 minutes (NJ

Transit, 2023a). This substantiates the sufficiency of chargers allocated for the WRTC terminal.

Table 12

Evaluation of Charging Process at Peak Hour (4:30-5:30 Pm) at WRTC

Charger 1	**Charging Time (min)**	**Time**	**Waiting Time (min)**	**Charger 2**	**Charging Time (min)**	**Time**	**Waiting Time (min)**
4:29 (route2)	5	4:29-4:34	-	4:29 (route4)	10	4:29-4:39	-
4:44 (route3)	8	4:44-4:52	-	4:49 (route1)	9	4:49-4:58	-
4:49 (route6)	8	4:52-5:00	3	4:55 (route10)	10	4:58-5:08	3
4:58 (route4)	10	5:00-5:10	2	5:04 (route2)	5	5:08-5:13	4
5:08 (route1)	9	5:10-5:19	2	5:15 (route4)	10	5:15-5:25	-
5:24 (route5)	7	5:24-5:31	-	5:24 (route2)	5	5:25-5:30	1
5:29 (route6)	8	5:31-5:39	2	5:29 (route1)	9	5:30-5:39	2
5:32 (route7)	10	5:39-5:49	8				

4.4.3 Sensitivity Analysis

In this section, a sensitivity analysis is undertaken to explore the impact of parameter values on both the number of chargers and, subsequently, the cost of charging infrastructure. The evaluation encompasses parameters such as battery capacity, charger power, average energy consumption, minimum and maximum state of charge, dwell time, and charger efficiency. The specific parameter values are detailed in Table 13.

Table 13

Values of Parameter in Sensitivity Analysis

BC (kWh)	P (kw)	ECave (kWh)	SOC	Dwell (s)	Cef
70	350	1.8	0.1-0.9	40	0.85
100	400	2.2	0.2-0.8	50	0.9
150	450	2	0.3-0.7	60	1
300	500	2.5	-	-	-

4.4.3.1 Battery Capacity. The optimization outcomes are compared across varying battery capacities—namely 70, 100, 150, and 300 kWh—to explore the model's sensitivity to battery size. Upon analysis, a consistent count of six terminal chargers emerges for all battery capacity values. However, an exception surfaces with the 70 kWh battery capacity, which necessitates five terminal chargers. This difference is seen at terminal 1, WRTC, where the requirement is reduced to one charger, unlike other battery capacities with two chargers. As battery capacity decreases, there's a notable surge in the count of intermediate stop chargers required for the bus network. For a battery capacity of 70 kWh, the BEB necessitates a substantial 128 intermediate stop chargers, with the highest demand recorded on route 1, calling for 27 chargers. In contrast, BEBs equipped with 100, 150, and 300 kWh capacities necessitate 71, 6, and zero intermediate chargers, respectively. This pattern underscores the direct correlation between declining battery capacity and the subsequent rise in charging infrastructure costs.

4.4.3.2 Dwell Time. We examined optimization results for various dwell times (40, 50, 60 seconds) with a BC of 150 kWh. Networks with dwell times of 40 and 50 seconds necessitated five intermediate chargers (two for route 4, one for route 7, and two for route 10) and six terminal chargers. In contrast, a network with a 60-second dwell time required four intermediate chargers (two for route 4, one for route 7, and one for route 10) and the same six terminal chargers. This indicates that increasing the dwell time reduces the need for intermediate chargers, leading to lower charging infrastructure costs.

4.4.3.3 Charger's Power. The optimization results are compared across various charger power levels—350, 400, 450, and 500 kW. Among these, the charger power of 350 kW exhibits the highest requirement for terminal chargers, totaling eight (with four chargers allocated for WRTC, terminal 1). In contrast, charger powers of 400, 450, and 500 kW all result in a consistent total of seven terminal chargers, with three chargers designated for WRTC. In terms of intermediate chargers, none are required across all charger power levels. The optimization findings highlight a trend where, assuming equal charging infrastructure costs for chargers of different power capacities, the necessity for chargers increases as charger power decreases. Consequently, this leads to an augmented charging infrastructure cost. Furthermore, as charging power increases, recharging time diminishes. For instance, at route 1, WRTC, a charger with 350 kW power results in a 15-minute charging time, while a charger with 500 kW power leads to a 10-minute charging time.

4.4.3.4 Minimum and Maximum State of Charge. As previously specified, the thresholds for this case study's minimum and maximum state of charge are assumed to be 20 and 80 percent. The optimization results are compared with two alternative ranges, 0.1-0.9 and 0.3-0.7, to assess the impact of different state of charge thresholds. Upon evaluation, the outcomes indicate that the number of terminal chargers remains consistent at 6 for both the 0.1-0.9 and 0.2-0.8 state of charge thresholds. However, for the 0.3-0.7 state of charge range, the requirement increases to 23 intermediate chargers and 6 terminal chargers. This observation underscores that employing a state of charge range between 0.3 and 0.7 contributes to an increase in charger demand and, consequently, an increase in charging infrastructure costs.

4.4.3.5 Average Energy Consumption. As discussed earlier, various factors exert an influence on average energy consumption. The optimization results for different consumption rates—1.8, 2, 2.2, and 2.5 kWh—are compared to investigate the effect of differing average energy consumption levels. Across these variations, the terminal charger requirement remains uniform at 7, with three chargers assigned to WRTC. Regarding intermediate stop chargers, the outcomes diverge: an average energy consumption of 1.8 kWh necessitates zero intermediate chargers. At 2 kWh, eight intermediate stop chargers are essential for routes 4, 7, and 10, peaking at four chargers on route 10. For BEBs with an average energy consumption of 2.2 kWh, the demand increases to 27 intermediate chargers across routes 1, 4, 7, and 10—with route 4 demanding the most, at ten chargers.

The highest intermediate charger demand emerges at an average energy consumption of 2.5 kWh, including 66 chargers for routes 1, 3, 4, 6, 7, and 10—route 4, leading with 22 chargers. This trend underscores that heightened average energy consumption levels directly impact the charger requisites, consequently driving up charging infrastructure costs.

4.4.3.6 Charger’s Efficiency. To explore the charger's efficiency impact, the optimization results are assessed across three efficiency values: 0.85, 0.9, and 1. The variation in charger efficiency does not exert influence over charger location or number. However, its effect is evident in charging times at terminals. As charger efficiency increases, the necessary recharging time diminishes. For instance, considering route one at WRTC, terminal 1, a charger efficiency of 0.85 yields a 10-minute recharging time, while a charger efficiency of 1 reduces it to 8 minutes.

4.5 Conclusion

This study introduces a mixed-integer linear optimization mathematical model developed to establish efficient on-route fast-charging infrastructure within bus networks. The model's primary objective is minimizing on-route fast charging station costs while strategically determining optimal locations and numbers for chargers at terminal and intermediate stops. The model's efficacy is demonstrated through real-world data collected from the City of Camden, NJ, verifying its applicability. Through a thorough sensitivity analysis, the study highlights the profound impact of varying parameter values, including battery capacity, charger power, average energy consumption, minimum and maximum state of charge, and dwell time, on the costs associated with charging infrastructure. The findings underscore the relationship between these parameters and infrastructure expenses.

Chapter 5

Summary of Results and Future Work

This study provided a comprehensive understanding of public transportation electrification, such as its positive impacts, challenges, related costs, assigned safety regulations and standards, allocated funding sources and incentives, and their specifications and features. Also, it provided an evaluation and feasibility of all-electric bus fleet implementation as a case study in the City of Camden, NJ. To this end, the study developed an optimization model to minimize charging infrastructure costs. The model aims to find the optimum locations and number of on-route fast charging stations at terminals and intermediate bus stops. A detailed summary of studies and results is presented in the following sections.

5.1 Summary of Results

5.1.1 Literature Review

The literature review provided comprehensive understanding of transit electrification that the findings of this review will provide a single-point resource for policymakers, practitioners, and researchers to better plan for a fleet transition to ZEBs underway. The literature review can be summarized as follows:

- Conventional vehicles make a remarkable contribution to air pollution, GHG emissions and noise pollution that threaten public health.
- Transition to electrification will help to eliminate the issues associated with conventional vehicles.

- A California emission analysis demonstrated an impressive 80% reduction in CO2/km by Battery Electric Buses (BEBs) compared to diesel buses over their operational lifespan.
- A comparison between diesel and electric buses at a constant low speed of 15 km/h revealed potential noise reductions of up to 12 dBA (decibels A), with acceleration generating a difference of up to 20 dBA.
- Despite positive effects of electric vehicles, their low vehicle noise can pose safety risks for pedestrians and riders. Therefore, consideration of standards and regulations related to electric vehicle noise levels are crucial.
- Research indicates that electric vehicles may be detectable at distances of less than 5 meters at low speeds of 10 km/h, whereas conventional vehicles are detectable up to 50 meters.
- Upfront costs for electric buses are higher than those for conventional buses, but they can be compensated for during their lifetime through maintenance and fuel savings. According to studies the average lifetime cost of a single electric bus for a transit agency, encompassing upfront purchase, fuel, and maintenance costs, was approximately $1,000,000. In contrast, it reached $1,400,000 for CNG and diesel buses.
- There are barriers to electrification, including financial obstacles and the challenges posed by new technology when compared to conventional vehicles. Additionally, range and power limitations of battery electric buses (BEBs), as well as concerns related to the production and recycling of BEB batteries, further contribute to these barriers.

- Based on mentioned reports from various U.S. transit agencies, challenges related to the implementation of BEBs include uncertainties about bus performance in varying temperatures, insufficient power for hilly terrain, difficulties in finding replacement parts, longer repair times due to new technology diagnosis, and notable battery performance reduction during winter months.
- The Low-or-No Emissions Grant program, administered by the Federal Transit Administration, stands out as a significant initiative that provides annual funding for transit bus electrification that the grant exclusively for the fiscal year of 2023 provided $1.7 billion.
- Standards and regulations have been developed both nationally and internationally to ensure the safety of Low and Zero Emission Vehicles (LZEVs) and their associated charging infrastructures. Given the substantial differences between light and heavy electric vehicles, some of these standards are specifically designated for heavy LZEVs.
- Despite the many positive experiences with BEBs and FCEBs by various agencies, power limitations remain a significant challenge. The deployment of high-power supercapacitors as hybrid fuel can enhance the efficiency of electric buses.
- According to the study, the average power density for li-ion battery is in the range of 1,500 to 10,000 watts per liter (W/L). In contrast, supercapacitors truly stand out with an impressive power density of approximately 100,000 W/L.

5.1.2 Analysis Results

The presented optimization model aimed to identify the optimal locations and number of on-route fast chargers for an all-electric transit fleet, using the City of Camden, NJ transit network as a case study. The summary of its results is as follows:

- The optimal solution for the case study entails the installation of six ultra-fast chargers at network terminals with a cost of $4.2 million.
- The cost of charging infrastructure increases as battery capacity decreases. For instance, in our case study, BEBs equipped with a 198 kWh capacity require zero intermediate chargers and six terminal chargers, while those with a 150 kWh capacity necessitate six intermediate chargers and six terminal chargers. This translates to a significant $4.2 million reduction in charger costs.
- The cost of charging infrastructure increases as average energy consumption increases. For instance, for the case study, BEBs with a 198 kWh battery capacity require only six terminal chargers when the average energy consumption is 1.5 kWh. However, if the consumption rises to 2 kWh, the number of required chargers increases to seven terminal chargers and eight intermediate stop chargers, resulting in a $6.3 million increase in charger costs.
- The cost of charging infrastructure increases as charger power decreases. For example, for the case study, deploying a 600 kW charger requires only six terminal chargers, while a 500 kW charger necessitates seven terminal chargers that shows $700,000 decrease in chargers' cost.
- The increase in dwell time decreases the required number of intermediate chargers, which leads to a decrease in charging infrastructure costs. For example, in our case

study, a BEB with a 150 kWh battery capacity and a 40-second dwell time requires five intermediate chargers and six terminal chargers. However, if the dwell time increases to 60 seconds, the number of intermediate chargers decreases to four, leading to a $700,000 reduction in charger costs.

- Variations in the charger's efficiency do not impact on the location or number of chargers. However, they do influence the charging time at terminals. An increase in the charger's efficiency results in a decrease in the required recharging time. For instance, for the case study, a charger with an efficiency of 0.85 results in a 10-minute recharging time for a specific route, while a charger with an efficiency of 1 reduces it to just 8 minutes.

5.2 Limitation

While this study has indeed made significant contributions, it's important to note its limitations. Presently, NJ Transit operates diesel buses for revenue service in the City of Camden, and as a result, we lack information regarding the average speed of battery electric buses in this context. To bridge this gap, we utilized available online NJ transit bus map data to monitor the daily operations of diesel buses. We proceeded with the assumption that future battery electric buses would maintain the same speed as the current diesel buses operating in Camden. Despite these acknowledged limitations, the study's results remain dependable and continue to offer insightful conclusions.

5.3 Recommendations and Future Work

The findings of this study's analysis can offer valuable insights to researchers, practitioners, and policymakers, aiding them in determining suitable numbers and locations for on-route fast charging infrastructure. Based on the result of the proposed optimization model, the installation of six ultra-fast chargers at terminals with a power of 600 kW and the deployment of a battery electric bus with a capacity of 198 kWh for the transit network of the city of Camden is recommended. This decision indicates the most cost-effective and efficient approach to meeting the city's transportation needs while reducing emissions. In terms of future work, the following recommendations can be a guide to make a more accurate solution:

- Rather than relying solely on current in-service diesel bus data, transit agencies can opt for pilot programs with electric buses to determine their average speed and energy consumption. This approach allows for informed decisions in establishing charging infrastructure.
- As previously noted, numerous factors influence average energy consumption, including the average vehicle speed, vehicle specifications, topography, traffic congestion, pedestrian crossings, time of operation, weather conditions including temperature and season, passenger loading, and driver behavior. For future research, it would be beneficial to comprehensively consider all these influencing factors when investigating average energy consumption.
- In this study, the queue model was not employed in the optimization model to charge electric buses at terminals due to the unacceptability of using the same average service time for charging and mathematical complexity of applying different service times for the queue model. In the future, applying the queue model directly as a constraint within an optimization model could be explored.

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