NOVEL DESIGN OF CHARGING INFRASTRUCTURE FOR ELECTRIFIED BUS TRANSIT NETWORK SYSTEMS

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This thesis is submitted for the degree of Doctor of Philosophy

August 2022

To my Beloved parents Afolabi and Victoria Asaolu

To my wife Mary and my children Enoch, Nathaniel and Joana

“Climate change is a global problem, and transport systems' electrification is considered a critical component of global climate solutions.”

DECLARATION

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ABSTRACT

Developed countries globally are designing and implementing strategies to reduce long-term greenhouse gas emissions and increase resilience to climate change, with electric vehicle (EV) adoption as a priority. In developing countries, the electrification of public transport and fleet vehicles will likely progress ahead of privately owned ones as these can be more readily regulated to encourage adoption. However, it is likely that a mixture of public and private charging infrastructure would be deployed but that 'hub-based solutions supported by renewable energy mini-grids present an attractive option.

This work develops a mathematical modelling toolkit to model the BRT system electrification modelling. The mathematical model that manages the routing of BEBs is extended to a longitudinal dynamic model that describes transit buses' energy consumption rate. To support this, a mathematical optimisation process for determining the critical design variables of allocation of the conductive and inductive chargers is also presented. The proposed mathematical analysis is based on designing and modelling multi-terminal (hub) charging infrastructure to cater to the bus transit network system's charging demand.

This novel charging optimisation tool is developed to demonstrate how multiple charging strategies can be employed for a fleet of BEBs to study essential factors of the transit system: such as the trade-offs between alternative charger designs, charger locations, battery sizes, and cost.

In this scenario, a series of contextualised simulation studies have been undertaken that focus primarily on the current situation in Lagos, Nigeria. The simulation results for the average power consumption of BEBs show that traffic conditions and route congestion increase the BEB energy consumption. Also, the BEB charging study shows that this proposed transit charging strategy saves costs and could be a key for energy management for the BEB transit network. Furthermore, this work estimates the possible GHG emission saving figure based on the case study.

ACKNOWLEDGEMENTS

Over the last three and a half years, developing this PhD thesis has been one of the most demanding yet satisfying experiences. This research would not have been possible without the assistance and encouragement of numerous individuals, to whom I wish to express my heartfelt gratitude:

First, I would like to express my gratitude to Professor Stuart Galloway, my academic supervisor, for his invaluable guidance, unwavering encouragement, and regular objective meetings that help shaped this research work. I will be eternally grateful to him for the opportunity to begin, grow, and complete this PhD under his supervision.

Additionally, I would like to express my profound gratitude to the Nigerian Petroleum Technology Development Fund (PTDF) for sponsoring this research work.

Sincere appreciation is also extended to former and current colleagues in the Distributed Energy Research (DER) and Aircraft Electrical Systems (AES) groups for making this much more enjoyable than it would have been otherwise. I would like to express my gratitude to Dr Rory Telford, Dr Bruce Stephen, Damien Frame, Kyle Smith, Calum Edmunds, Madalisto Chikumbanje, Allison Strachan, and Lewis Hunter for their assistance with this work at various times.

It is difficult to find the appropriate words to articulate my heartfelt appreciation for my wife, children, and parents. None of my accomplishments would have been possible without their love and kindness. Similarly, I am indebted to my uncle, Professor S S Asaolu, and academic mentors, Dr I B Oluwafemi, for their unflinching support from thousands of miles away that has sustained me throughout these years.

Finally, I would like to express my gratitude to all of the friends who helped make these years in Glasgow so enjoyable and unforgettable and who assisted me in balancing the sometimes-difficult academic life. They all contributed, perhaps unknowingly, to the completion of this study in some way. I want to express my heartfelt appreciation to the group of Nigerian students who attended Strathclyde University between 2017 and 2021. Specifically, Jamiu Aladejana welcomed me upon my arrival in Glasgow and provided me with my first accommodation. Additionally, I want to express my gratitude to Ajayi Taiwo and Dr Fyail Jibji-Bukar from the Institute of Energy and Environment for their friendship over the years. They were sharing the challenges of the PhD journey, and the daily lunch made this experience extremely enjoyable.

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LIST OF ABBREVIATIONS AND ACRONYMS

A. Abbreviations

ADVISOR	Advanced Vehicle Simulator
BEB	Battery Electric Bus
DER	Distributed Energy Resources
DSM	Demand Side Management
ESS	Energy storage systems
EB	Electric Bus
EV	Electric Vehicles
GHG	Greenhouse Gases
HVAC	Heat, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
LoS	Level of Service
PBT	Public Bus Transit
SoC	State of Charge
PSO	Particle swarm optimisation
BRT	Bus Rapid Transit
VKT	Vehicle-kilometres Travelled
LAMATA	Lagos Metropolitan Area Transport Authority
HEB	Hybrid Electric Bus
EM	Electric Motor
FCEB	Fuel Cell Electric Bus
BSS	Battery Swapping Station
MG	Micro-grid

B. PARAMETERS

A	BEB cross section area (m^2)
a_t	BEB acceleration at time *t* (m/s^2)
$a_{t,j,d}$	BEB acceleration at time *t*, trip *j*, and distribution *d (*m/s^2*)*
C_t^D, C_r	Drag, rolling resistance coefficient
E_b^{cap}	BEB battery energy capacity
$E_{t,d}^{cons}$	BEB energy consumption rate
E_t	BEB energy status at any instance
E_{lr}^{trip}	Route Energy demand in kWh/km
$F_t^a, F_t^g, F_t^r, F_t^p$	Aerodynamic, grade, rolling resistance and traction forces
$F_{t,j,d}^p$	BEB traction force at time *t,* trip *j*, and distribution *d* (N)
$F_{t,j,d}^b$	BEB brake force at time *t*, trip *j*, and distribution *d* (N)
g	Gravitational force (m/s^2)
l_r	Length of the route
M_t, $M_{t,j,d}$	Mass of BEB at any instance
P_{aux}	BEB auxiliary power demand
$P_{t,d}^{cons}$	Power consumption of the BEB
R_{wheel}	Wheel radius
S	Split ratio
$SOC_{(t)}$	State of charge at the time (t)
SOC_b^{max}, SOC_b^{min}	Max, min state of charge of the BEB
T_{cap}	Transmitter capacity
$T_{t,j,d}^m$, $T_{t,j,d}^w$	Motor and wheel torque
t_d^{end}	End time for distribution *d* (mins).

t_d^s Start time for distribution *d* (mins).

t_d^{wait} Waiting time after each trip within distribution *d* (mins).

t_d^{cycle} Cycle time for distribution *d* (mins).

t_d^{trip} Trip time for distribution *d* (mins).

$v_{t,j,d}$ BEB speed at time *t*, trip *j*, and distribution *d* (m/s).

$w_{t,j,d}^m$, $w_{t,j,d}^w$ Motor and wheel rotational speed

ρ Air density (kg/m^3)

$\emptyset_{t,j,d}$ Road slip angle at time *t*, trip *j*, and distribution *d* (deg.)

$\eta_{con}, \eta_m, \eta_T$ Conversion, motor and transmission efficiency

E_b^{cap} BEB *b* battery energy capacity (kWh).

E_b^{max} Maximum energy threshold in BEB *b* (kWh).

E_b^{min} Minimum energy threshold in BEB *b* (kWh).

$E_{b,j,d}^{arr}$ Energy capacity of the BEB *b* after trip *j* in assignment d (kWh).

$E_{b,j,d}^{dep}$ Energy capacity of the BEB *b* at the start of trip *j* in assignment d (kWh).

$E_{b,j,d}^{ch,l}$ Energy gained by BEB *b* via charging with low-priority charger during trip *j* in assignment d (kWh).

$E_{b,j,d}^{ch,m}$ Energy gained by BEB *b* via charging with medium-priority charger during trip *j* in assignment d (kWh).

$E_{b,j,d}^{ch,h}$ Energy gained by BEB *b* via charging with high-priority charger during trip *j* in assignment d (kWh).

$E_b^{i,i+n}$ Energy required by BEB *b* to travel from terminal i to i+n (kWh).

C_b^{bat} Cost of BEB *b* on-board battery (£/kWh).

C_{ch}^l Cost of charging with low-priority charger (£).

C_{ch}^m Cost of charging with medium-priority charger (£).

C_{ch}^h Cost of charging with high-priority charger (£).

C_f^l Fixed cost charge for using low-priority charger (£).

C_f^m Fixed cost charge for using medium-priority charger (£)

C_f^h Fixed cost charge for using high-priority charger (£).

C Cost of energy per kWh (£).

C_{inst}^l Low-priority charger installation cost (£).

C_{inst}^m Medium-priority charger installation cost (£).

C_{inst}^h High-priority charger installation cost (£).

C_{inst}^{ind} Inductive charger installation cost (£).

C_{WPT} Wireless power transmitter expenditure cost (£).

C_{cable} Inductive cable expenditure cost (£).

Ch^{Select} Charging priority selector.

P_{ch}^{ind} Power capacity of the inductive charger (kW).

$P_{use(b,j,d)}^{ind}$ Power used by BEB b when moving over inductive cable in trip j within assignment d (kW).

$t_{b,j,d}^{arr,i}$ Arrival time of the BEB b at the bus terminal i after trip j in assignment d (minutes).

$t_{b,j,d}^{ch,i}$ BEB b conductive charging duration at the bus terminal i after trip j inassignment d (minutes).

$t_{b,j,d}^{ch,l}$ BEB b low-priority charging time for trip j in assignment d (minutes).

$t_{b,j,d}^{ch,m}$ BEB b medium-priority charging time for trip j in assignment d (minutes).

$t_{b,j,d}^{ch,h}$ BEB b high-priority charging time for trip j in assignment d (minutes).

$t_{ind(b,j,d)}^{ch}$ BEB b induction charging in trip j within assignment d (minutes).

$t_{b,j,d}^{s,i}$ BEB b scheduled departure time conductive at the terminal i for trip j in assignment d (minutes).

$t_{ind(b,j,d)}^{trav}$ BEB b travelling time over induction cable in trip j within assignment d (minutes).

T_{cap} Transmitter capacity (kWh).

η_{ch} Charger efficiency (%).

$P^{\iota}_{(max)}, P^{m}_{(max)}, P^{h}_{(max)}$ Maximum power capacity low, medium and high priority conductive charger respectively (kW).

d^{S}_{i}, d^{e}_{i} Start and end of inductive cable (m).

$d^{trav}_{ind(b,j,d)}$ BEB b travelling distance over induction cable in trip j within assignment d (minutes).

N_b Number of BEB b.

N^{ind}_{ch} Number of inductive chargers.

$N^{\iota}_{ch}, N^{m}_{ch}, N^{h}_{ch}$ Number of low, medium and high priority.

N_{WPT} Number of wireless power transmitters.

$n(T^{l})$ Number of routes distance that requires a low-priority chargers.

$n(T^{m})$ Number of routes distance that requires medium-priority chargers.

$n(T^{h})$ Number of routes distance that requires a high-priority chargers.

$n(M)$ Total of routes combination in the transit network.

$n(D)$ Number of diagonal elements in the matrix .

T Matrix representation of the routes combination in the transit system.

$P^{cons}_{t,j,d}$ Power consumption of the BEB b in time t used for trip j in assignment d (kW).

$P^{\iota}_{(t)}, P^{m}_{(t)}, P^{h}_{(t)}$ Power used by low, medium and high-priority conductive charger over time interval t (kW).

$P^{total}_{(t)}$ Power used by all the chargers in the transit network over a time interval (t) (kW).

$\propto^{l}, \propto^{m}, \propto^{h}$ Probability for low, medium and high priority charged BEBs, respectively.

β Binary variable for inductive charging

B_{cap} BEB battery capacity (kWh)

$C_{BEB}, C_{WPT}\ C_{WPR}, C_{bat}, C_{cable}$ Costs of BEB, WPT, WPR, battery and cable (£)

d^{e}_{i}, d^{e}_{i} Start and endpoint of inductive cable (m)

E_t BEB energy status at any instance (kWh)

N_{BEB}, N_{WPT} Number of BEB, WPT

$P_{gain(t)}$, $P_{use(t)}$ Power gain, use by the BEB (kWh)

T_{cap} Transmitter capacity (kWh)

$c1, c2$ Acceleration coefficients

$nVar$ Number of variables

G Best previous positions of all particles

t Current iteration of the algorithm.

t_{max} Maximum number of iterations

$r1, r2$ Random variables

ub, lb Upper and lower bound

X_i, V_i Position and velocity of the particle

w, w_{min}, w_{max} Inertia weight, min. and max. weight

P_i Best previous positions of i-th particles

$GBEST, PBEST$ Global and personal best particle position

C. INDICES

b Indices for transit network battery electric buses (BEBs)

r Indices for transit network routes

i Indices for the terminal in the transit networks.

j Indices for BEB's trips.

t Indices for time steps.

b Indices for transit network BEBs.

d Indices for BEB's assignments.

D. SETS

$\mathcal{B}$ Set of transit buses (BEBs)

$\mathcal{R}$ Set of transit network routes

S_d Set of transit schedule trips with distributions d

D Set of transit network assignments.

J_d Set of trips within the assignment d.

τ Set of optimisation time steps.

1 INTRODUCTION

Air is an integral part of numerous indispensable cycles on Earth; the air is needed to live by most species, including human beings. The component of air in Earth's atmosphere is about 78% nitrogen and 21% oxygen. Air also has insignificant amounts of other gases, such as neon, hydrogen, and carbon dioxide. Air also contains lots of microscopic particles, and these tiny particles in the air are called aerosols. Aerosol, like dust, is picked up naturally when the wind blows. Air can also carry soot, smoke, and other particles from vehicle emissions, power plants, and industrial production, which are the main contributors to air pollution [1]. Air becomes polluted when it contains harmful concentrations of mixed particles and gases such as soot, smoke, methane, and carbon dioxide. Famous among the air pollutants are particulate matter, black carbon, ground-level ozone (O_3), nitrogen dioxide (NO_2), nitrous oxide (N_2O), sulphur dioxide (SO_2) and carbon monoxide (CO).

The world health organisation indicates that nine out of ten people have to breathe in air with a high level of pollutants [2]. Air pollutants' health consequences include respiratory infections, asthma, chronic obstructive pulmonary disease, and lung cancer, even in combination with stroke and heart diseases [3]. Air pollution is considered to account for the death of about 7 million people annually [4]. In 2017, air pollution contributed to about 9% of global deaths [4]. Air pollution has been considered one of the world's leading risk factors for mortality [5]. The cities have been considered to account for 64% of global energy use and 70% of carbon emissions [6] [7]. The increase in the population living in the cities is likely to increase in these proportions unless the cities lead towards sustainable energy transition and decarbonisation.

Developed countries are making an effort to improve the air quality in their cities, with about 51% reported in 2018 to meet the WHO air quality guideline [8][9]. However, less than 3% of the cities in developing countries could meet the WHO air quality standard (WHO 2018C) [8]. In 2019, the transport sector emissions accounted for 24% of global emissions and road transport emissions are responsible for 75% of the total emissions in the transport sector (IEA, 2020) cited in [10]. In addition, CO2 emissions from the global transportation sector fell by more than 10% in 2020, owing to global lockdown measures imposed by the Covid-19 [10]. The 2019 road transport emission figures compared to 1990 have seen road transport emissions have increased by 68% [11]. Decarbonising road transport has urged the public to seek a sustainable means of transportation. The international energy agency (IEA) has determined that walking, cycling, and public transport as the city modes of transport could reduce significant emissions and save about one trillion dollars by 2050 [7].

With cities' transport decarbonisation in mind, zero-emission Battery-Electric Buses (BEBs) are recently receiving increasing attention globally. Their adoption can be generally attributed to emissions reduction (UITP, 2017) [12]. Also, the battery-electric bus can reduce emissions and costs and transport more people simultaneously than an individual passage vehicle. In [13], the authors estimate that it takes about 100 electric cars to accomplish the same environmental relief as can be gained from a single 18 m battery-electric bus. In addition to the potential emissions reduction when electricity originates from renewable sources, electric buses offer significant additional benefits such as zero-emission, quiet operation, high efficiency, reliability, and better acceleration than traditional buses [14].

Compared to trolley bus technology, they eliminate the need for constant grid connection, and the transit route can be modified without infrastructure change (e.g. pantographs). The cost of ownership is lower compared to diesel buses [14]. In [15], the comparative on-road evaluation of diesel buses with battery-electric buses BEBs is examined. In this work, the BEBs cuts petroleum use by 85–87% compared to a diesel bus and attain a 32–46% decrease in fossil fuel use and 19–35% in CO2 emissions while evaluating from a life-cycle perspective. However, other types of fuels can cut transport emissions (e.g. hydrogen); none of them includes such an attractive set of benefits for addressing the challenges of modern urbanisation as electricity does (the overall grid to wheels efficiency of BEVs is about 50% and 60% for fast and slow charging respectively, while hydrogen has an overall grid to wheels efficiency is about 30% [16],[17])).

Generally, developed countries are planning and implementing schemes for reducing greenhouse gas emissions, and the critical focus is the electrification of the transport system. Examples include the European roadmap to road transport's electrification [18] and the UK transport energy infrastructure roadmap to 2050 [19]. These documents (ref. [18] and [19]) detail the plan on how the UK and EU are planning to electrify the vehicular transport system by the year 2050 [19]. However, the electrification of public transport and transit networks is likely to evolve ahead of the individual owned vehicle because it can be controlled by government policy and deliberate investment in public transport infrastructures [20]. For example, most public transit buses in Shenzhen, China, are electrified using an overnight charging strategy [21]. Notably, the power infrastructure (i.e. energy need and the energy capacity of charging infrastructure) for public transport fleets is different from that for individual passenger vehicles. The electric public transport system's charging infrastructures are more of a hub base (i.e., terminals, depots, and bus stops) that can be powered easily with renewable energy mini-grids [20]. A similar example is Daimler central charging station for electric buses in Mannheim, Germany. The charging station uses both plugin and pantograph chargers [22]. Another example is a high-power electric bus charging station introduced in America by Proterra. This Proterra charging station uses energy from RES (solar) and the grid. The electric bus charging station can simultaneously charge up to 100 buses with the 125 kW capacity chargers. This charging station also has the capacity for vehicle-to-grid (V2G) [23].

In developing countries (most especially in sub-Saharan Africa), investments in urban transport infrastructure have been considered a tool to engage in reducing congestion, time, energy consumption, safety, improvement of environmental outcomes, and enhancing the economic development of the contemporary cities [24], [25], [26], [27]. Studies have shown that changes in the economic fortunes of developing countries' city inhabitants significantly affect transportation systems, particularly automobile dependency. This expulsion of vehicles on urban routes has correspondingly increased road traffic congestion and GHG emission provision [28]. In many developing cities, the public transportation system is characterised by disorganised and largely unregulated demand that outstrips supply. Consequently, many citizens are often left out of productive employment and other urban life benefits [29]. Enhancing these cities' functionality depends on improvements to transport networks and providing reliable, affordable, and safe access to urban opportunities. Firms and workers can collectively generate scale and specialisation with better urban mobility and enhance productivity growth.

A typical example is Lagos (Nigeria), which has a population of about a 21million. The characteristics of the Lagos transport system include the unavoidable daily experience of the worst traffic situation due to road congestion and GHG emissions predominantly from automobiles [30]. Lagos has a diesel-based bus rapid transit (BRT) system that connects people from the suburbs to the central business district [31]. The greening of this public asset, in combination with the favourable greenhouse gas (GHG) solutions, is an attractive option for policymakers to eliminate 'drive-way congestion and support the adoption of EVs [32] [33].

1.1 The need for the electric transit system

Private car ownership has soared significantly over the last few decades globally, and this trend will continue. For example, between 2008 and 2020, the number of licensed drivers in the USA increased by about a 19million [34]. In Great Britain, this figure increased by 4million [35]. In Lagos, Nigeria, it is estimated that more than 5 million cars and 200 thousand commercial vehicles are on the road, with a daily average of 227 vehicles per road kilometre [36]. However, there will always be many people who will not have access to a car and therefore be reliant on some form of public transport if their mobility demands are to be met (in the UK, about 31% of people are without cars) [37]. Also, it is generally accepted that lifestyle changes have increased dependence on mobility to access opportunities for jobs, shopping, education, health, leisure and recreation. It implies that there is an ever-growing demand for transportation. Generally, mobility is a means to an end, not an end in itself. People move about to carry out planned activities at various locations where those activities can take place [38] [39].

Walking, cycling, motorcycle, private cars, and public transport are the conventional passenger transport modes in urban areas. Walking and cycling are for short trips, mainly the former [38] [32]. For example, In Great Britain, the average distance a person walked in 2016 was 198 miles, and the average distance people cycled was 53 miles [40]. Suppose motorcycle activity is considered as providing for a comparatively small fraction of trips. In that case, the significant competition between modes in urban areas lies between private cars and public transport. In the idealistic scenario, it is expected that car owners would be prepared to avoid using their car and shift to public transport. Nonetheless, since most people who have a car will use it, transfer to public transport will only happen if there are sensed advantages over individual vehicles. This shift will probably occur if travel by car has become difficult, costly and unreliable [41]. Therefore, it is vital to examine the existing urban travel situation, particularly during peak travel periods.

As car ownership increases, more journeying is made by car and fewer by public transport. Limited travel by public transportation means inadequate revenue or limited-service frequency, or fare increase by the transport operators [37] [38]. Fare and limited service further discouraged the use of public transport and increased individual passenger vehicle use. Increased private vehicle travel worsens road congestion, making travel by bus also delayed and unreliable, thus encouraging personal car travel [42]. Therefore, the downward spiral of bus public transport usage seems inevitable. However, increasing car travel has created many severe detrimental consequences, of which the three most important that are enumerated in [38] are:

1. Traffic congestion

Traffic congestion is an abnormality common in most cities and is increasingly happening outside the regular commuter peak periods of travel. The effects of traffic congestion include visual pollution, increased noise and lost economic output. Traffic congestion also causes traffic diversion onto unsuitable roads as drivers attempt to find alternative routes to avoid congestion, increasing journey times, making the journey unreliable, and unacceptable driver stress and frustration. Traffic congestion impinges adversely on the level of service that can be provided by public bus transport (but paradoxically can make bus transit (with busway)-based public transport more attractive) [43] [44] [45].

2. Energy consumption and air pollution

Although manufacturers are continually developing more efficient engines, cars use finite petroleum products. Increasing public transport use relative to the car will conserve this essential resource [46]. Increasing car travel increases air pollution [47] [48]. On a global, 88% of CO2 emissions, 48% of NOx and 37% of volatile organic compounds originate from road vehicles [38]. Word-wide transport emission control is considered a critical issue requiring urgent attention to salvage human health and the planet. Figure 1-1 shows the GHG emissions from different modes of transport. Apart from walking and cycling, the GHG favourable means of transportation is the use of public transport.

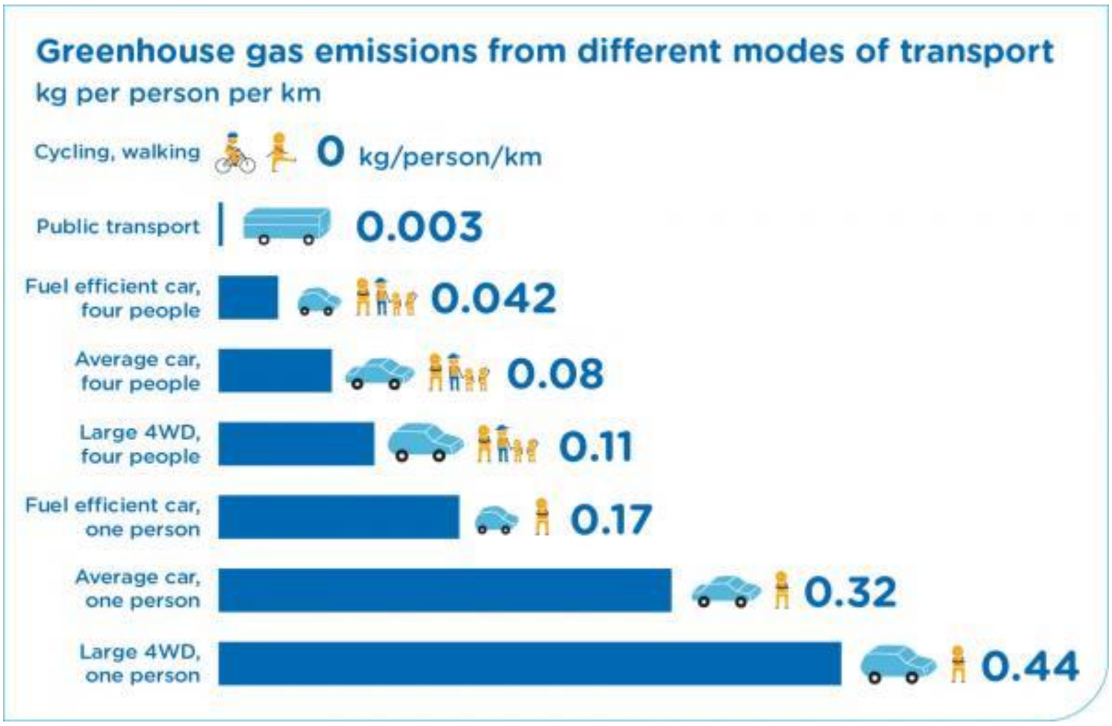

Figure 1-1 GHG emissions from different modes of transport (Adopted from [49])

3. Safety

Vulnerable road users such as motorcyclists, cyclists and pedestrians are prone to a higher risk of accidents with increased travelling vehicles [50], [51]. Hence, the improved use of public transport would have significant safety advantages.

Nonetheless, individual vehicles have many benefits to city residents. However, it has gotten to a level that using personal vehicles results in traffic congestion that extends beyond the regular morning and evening peak periods and results in ever-increasing and unreliable travel times [38],[52]. Therefore, it is likely that if a satisfactory and reliable public transport service were to be introduced for many journeys, a shift from car to public transport could be envisioned [53], [54].

The regular bus services use the same road as other vehicles and consequently are subjected to traffic congestion. In order to mitigate traffic congestion, bus lanes with flow or contra-flow can be introduced to enable buses to avoid traffic [29]. Also, roads may be constructed for the exclusive use of dedicated buses (busways). For example, buses are usually subjected to road traffic except for the BRTs with a dedicated busway [29]. The former is cheap, but it creates a barrier to other movements (including pedestrians) that need to cross because buses are given signalled priority over other traffic junctions, increasing a traffic delay [38]. Bus services on busways avoid delays to services operating on the ordinary road network [55], [56]. They can be readily linked with residential, industrial, and shopping areas with regular bus operations.

In summary, increased public transportation usage is necessary, especially in urban areas, which significantly benefits environmental protection and transportation mobility. Adopting transit systems (rapid bus transit with busways, light rail, and subways) is considered a possible form of public transport capable of solving the urban transport problem. It is most likely that bus transit will move ahead of other transit means in developing countries. Because it is affordable, safe, reduces congestion, minimises transport energy consumption, and reduces GHG emissions [57] (especially with electrified bus transits systems [58]).

Apart from an electrified transit system's emission benefits, the electric powertrain's added advantage is its electric drive motors' greater energy conversion efficiencies than the Internal Combustion Engine (ICE). The energy conversion efficiency for the electric drive motors is about 76% (i.e., from the on-board battery to the wheels), which is about five times higher compared to the typical efficiency of the ICEs of 16% (i.e., from on-board fuel storage to drive the wheels) [59]. Therefore, the electrification of the bus fleet can be used as a tool to make a considerable shift from individual vehicles to public transport that will provide a valuable benefit in eliminating road congestion and reducing GHG emissions [39], [60]–[63].

1.2 Problem definition

Scientific research, international agencies, public attention, and political interest in problems associated with transportation, energy and the environment have motivated the adoption of electric vehicles (EV) and renewable energy generation. Developed countries globally are designing and implementing strategies for reducing long-term GHGs and increasing resilience to climate change impact with EV adoption as a priority. Examples include adopting battery electric vehicles in Denmark, where the goal is to have one million EVs out of 2.5 million cars by 2030 [64]. In Sweden, the EV has a massive 49.4% share in 2020, four times more than the 11% share in 2019 [58] [65]. In Norway, 64.5% of all vehicles sold in 2021 were electric-only vehicles [66].

There is a growing interest in low carbon solutions in developing countries, including investment in renewable energy resources and EV adoption. An example is Nigeria's low carbon development plan to cut GHG emissions by 20% by 2030 [67]. Also, the Rwandan government has committed to reducing emissions by 38% by 2030, which equates to 4.6 million tonnes of CO_2 [68]. Kenya's government has set a target of 5% of newly registered vehicles being electrified by 2025 [69]. Morocco's government intends to save 23% on energy in the transportation industry by 2030 [70]. Egypt is developing a national e-mobility strategy to create the first 100 vehicles in August 2022 and build 3,000 charging stations [69]. Hence, integrating EV charging demand into the power system is a global challenge.

Several studies in the literature focused on mitigating the challenges of adopting personal BEVs. This literature explores the incorporation of the energy storage system with the BEVs parking lot to reduce charging demand pressure on the grid (i.e., enhances peak shaving and valley filling), reduce the capital investment on the construction of BEVs charging infrastructure, and minimise operation expenditure [71],[72]. The studies on the design of BEV charging stations vary in the literature [72]–[78]. The main objectives of the design of charging stations are to (i) determine the vehicles energy demand, (ii) ensure that the allocation of charging infrastructure satisfies the BEVs charging schedule, (iii) minimising the investment in the charging station infrastructures, (iv) satisfying the BEVs SoC and power distribution constraints, and (v) exploring the opportunity of the EVs charging stations to deliver ancillary services.

Besides the majority, research efforts are devoted to promoting personal BEVs. The electrification of transit buses has been considered the most promising approach to fast-track EV adoption and reduce GHG emissions [79]. Transit bus fleets operate on fixed dedicated routes to carry passengers using a predetermined daily operating schedule, making them a possible target for full electrification [80]. Also, the electrified transit bus system can take full advantage of renewable power generation [81]. In this regard, BEB technologies with onboard batteries and chargers are a prominent solution for moving toward zero-emission public bus transit systems [82].

However, in developing countries, EV adoption has been confronted with more complex challenges because the accessibility to electricity is considered insufficient (for example, the average access rate to electricity in Africa is 43% [83]). Therefore, accommodating EVs in the electricity system is a technical, social, and economic problem. The electricity system will likely have to cope with increases in demand from EVs and the electrification of other sectors, such as consumers, agriculture, cooling and industry needs. Moreover, the interest in low carbon transport is beyond just tokenism, as some countries are building EV assembly plants [84]. Nevertheless, the transition from ICE internal combustion engines to EVs is not smooth. There are similar barriers to Europe, such as lack of charging infrastructures, cost and flawed policies [85]. However, to improve the EV's growing uptake in developing countries, it is vital to provide an alternative energy source to support the EV charging infrastructures without dependence on the existing power system such as solar renewable mini-grid.

In developing countries, the electrification of public transport may progress ahead of individual passenger vehicles because it can be driven by regulations that will encourage early adoption. Notably, the power infrastructure for public transport fleets is different for consumers because the charging infrastructures are more nodal [86] (i.e. terminals, deports and bus stops) that can be supported by co-located renewable energy technology mini-grids and other DERs. For example, in Lagos, Nigeria, which has about 21 million inhabitants, there exists the worst traffic congestion and GHG emission predominantly from automobiles [30], even with an existing bus rapid transit BRT [87]. The greening of this public transport that combines a favourable GHG solution and does not impact the incumbent road could be attractive to promote policies that will eliminate high-way congestion and promote EV adoption in developing countries.

There is already a considerable body of research work addressing the issues of EV charging, and a common theme is the need to apply demand-side management to control the timing of these additional power system loads [88]–[91]. Some work has considered how EV charging loads could be dynamically controlled to contribute to frequency response services (often via aggregators) [92]–[94]. While offering an important downstream low voltage solution, this area has not been studied extensively in developing countries. However, some work has looked into applying off-grid systems to electric vehicle charging in developing countries. Specifically, in [95], the authors looked into the possibility of using an electric Tuk-tuk (a three-wheeled vehicle used for public transport in Asia and Africa) battery charging station in the rural areas of the Democratic Republic of Congo (DRC).

Moreover, in [96], the authors considered the demonstration of a low-cost electric vehicle charging station for developing countries using four solar panels of 255 watts each, batteries, a charge controller, and an inverter. In [75] and [76], the authors recognised the importance of low-cost renewable energy source charging infrastructures in developing countries. However, the models are only applicable to small and low-range electric vehicles, and typically they are challenged in their ability to scale by limited grid capacity or shortages in a (centralised) generation.

The work of this thesis will be to assess the infrastructure needs and estimate the energy demand to achieve an eco-friendly city and reduce traffic congestion through the adoption of electrified bus-based passenger transport solutions. A case study for Lagos in Nigeria that focuses on the bus rapid transit BRT located there will be a common point of reference and focus for this work. The transiting of the Lagos BRT system into an electrified system is critical for improving mass passenger transport in the city while advancing low emission transport solutions. However, the Nigerian grids are weak, with the voltage being sensitive to the connection on the new load. The incumbent generating capacity is not sufficient for the domestic and industrial demand [97]. The overall available capacity as of 2019 is 3.7GW; however, peak demand is 8.25GW [98]. According to a recently published report by the National Bureau of Statistics, Nigerians only get 6.8 hours of daily electricity from the national grid [99]. In this scenario, it is vital to address charging infrastructures that will support the integration of electric vehicle electrification with little to no dependence on the existing power system.

Previous work on the analysis of the interactions between the transit operation and energy demand of the BEBs transit system, [29], [70], [78], [101], [102] sheds light on several challenges, such as but not limited to; (i) the impact of charging strategies and charging technologies on the transit demand (ii) the effect of charger capacity upon the operational demand profile and the charging duration of buses; (iii) the impact of the route traffic situation and other BEB requirements to preserve the operational schedule; and (iv) the consideration for renewable generation mix to meet the transit demand; (v) the impact of BEBs transit energy demand on the utility grid (i.e., voltage, transformer's, feeder's capacity, power balance and security of supply). Hence, due to the lack of security of power supply in developing countries and the variation in bus transit operation and utility grid profile, it is essential to carry out a comparative evaluation of various charging strategies and charging technologies, and investigate how to optimise trade-off of transit operation, utility grid demand profile, and BEB configuration (battery size, charger power, and the number of required chargers) in orde to enhance transport electrification, reduce emission and problematic congestion in the developing countries.

The work of this thesis will outline the performance requirements for a practical system and determine a suitable charging infrastructure for transit bus operation in developing countries. The context of this work suggested that large and expensive onboard batteries are not necessary for city-scale applications, and recharging times are conserved to a minimum. This will ensure that battery-electric buses can be used for similar duty cycles as conventional vehicles without compromising the transit operational schedule—the recommendations are intended to be technically realistic and financially viable in the developing countries' circumstances.

1.3 Research objectives

With the increasing population of cities, transport demand, individual vehicle usage, traffic congestion, and pollution, there comes the need to consider the shift from the existing means of transportation in the cities to a more reliable, healthy and sustainable means. This thesis will provide supportive research to facilitate the adoption of electrified bus transit systems and their alignment with the power system in the context of developing countries by offsetting the present research gaps that challenge the realisation of electrified bus transit networks as a means to mitigate GHG emission and traffic congestion in developing countries cities. The main hindrances to adopting onboard battery-based electric vehicles in developing countries include weak grid, limited range, and economic viability. Therefore, the development of novel charging strategy, planning and transit operation models must maintain the state of charge of the BEB on-board battery, charging infrastructure and power availability constraints while optimising their infrastructure economic metrics. In light of the above, this thesis will address the following objectives:

1. To investigate and analyse the impact of traffic congestion on BEB energy consumption and GHG emissions. This analysis can support transit bus operators to precisely evaluate the energy consumption characteristics of BEBs in diverse operating environments and enhance the accurate schedule of the BEB transit fleets.
2. To investigate and model the alternative means and strategy of charging the battery-electric bus for challenging grids (common in developing countries) that do not typically support the overnight charging strategy of large battery-sized buses commonly used in Europe and China.
3. To develop and analyse the techno-economic model of the multi-terminal-based inductive charging system for a bus transit network. This will primarily be concerned with capital costs to optimise the length of inductive cable, power transmitters' location, power transmitter's capacity, onboard battery capacity, and the number of power transmitters.
4. To estimate the daily BEBs charging power demand for the designed transit-based charging model.

The electrification of the public transit system that can meet these set objectives can be based on the array of different charging technologies. These charging technologies can include a combination of conductive and inductive charging technology, minimisation of energy usage, reduced electric buses' onboard battery and minimisation of the overall investment cost.

1.4 Summary of contributions

This thesis makes the following key contributions:

1. This thesis presents a wide-ranging review of the electrification of bus transit systems. This review ascertains the developments in the research area and finds gaps for future research works.

2. The development of a mathematical modelling toolkit is developed for BRT system electrification modelling: The bus transit electrification mathematical formulation presented in this thesis is distinct from what has been presented in previous similar research work. This mathematical model considers the critical decision variables such as location of the charging infrastructure, onboard battery capacity and cost for allocating charging infrastructure to determine the transit system charging demand and satisfy the transit optimisation objective. This type of mathematical model improves the accuracy of the dynamic transit system analysis. Another important mathematical model is for multi-terminal priority charging presented in this work. This mathematical model is the basis for the priority-charging model, described as the aggregate numbers of battery-electric buses that charge at the BEB terminal with the high, medium, and low charging priority. The advantage of this type of model is the aggregation of transit energy demand to avoid peaks and valley issues and reduce the energy use by the transit system.

3. The modelling capability of combined inductive and conductive charging infrastructure: this thesis presents the use of both conductive and inductive charging technology for the bus transit system. The system is designed to minimise onboard battery and reduce bus dwelling time due to the long charging duration. Such a system is developed to manage the system energy demand and ensure that the operational service is reliable by optimising the charging station infrastructure: charger operating capacity and chargers' number. Integrating a conductive and inductive charging system that can reduce on-board BEB battery is considered an advantage on already challenged grids

4. Energy consumption modelling related to GHGs for Lagos: This thesis presents a method for calculating the average energy consumption rate for bus transit fleets while considering route traffic conditions. This model overcomes the disadvantage of

using the manufacturer's nominal BEBs energy consumption value. Furthermore, based on the Lagos BRT case studies, a case study of carbon emissions savings of electrified BRT systems is computed by comparing the consumption of diesel and electric buses in various traffic scenarios with the associated GHG emission figure.

5. The design and economic modelling of inductive charging only infrastructure system that provides some information on the costs for the Lagos BRT: The terminal-based inductive charging infrastructure's design and economic modelling reduce the size of the electric bus's onboard battery while reducing the capital cost of the transit system. The inductive charging infrastructure model determines the size of the batteries, the location of the transmitter, and the length of the inductive cable. This study demonstrates that financial savings are attainable if the inductive chargers are located a nearly equal distance apart.

1.5 Thesis outline

The remainder of this thesis is structured as follows:

Chapter 2 introduces bus transit systems, types of transit buses and their characteristics, transitways, types of chargers and chargers' technologies, and bus schedule system, referred to in the remaining part of this thesis. This review chapter also examines the battery-electric buses' energy consumption, electric transit system and charging strategies, resource modelling for electric vehicle charging systems, and the impact of low carbon transport systems. The review indicates a considerable body of research work addressing the issues of EV charging, and a common theme is the need to apply demand-side management to control the timing of these additional power system loads. This area has been studied extensively but not in developing countries. However, research into providing an alternative energy source such as solar renewable mini-grid to support the EV charging infrastructures with no dependence on the existing power system in the developing countries (especially where there is a lack of security of power supply) needs more comprehensive study.

Chapter 3 provides a thorough discussion of the various mathematical modelling stages as well as the objective equation and constraints for the implementation optimisation algorithm. The design of the transit fleet routing model, the BEB energy consumption model, the BRT transit fleet charging infrastructure model, and the estimation of transit energy demand are all covered in this chapter. The mathematical formulation for conductive charging, inductive charging, multi-terminal charging, and priority charging with respect to the transit system is also presented in this chapter. This will form the backbone of the modelling methodology for studying the bus system electrification considered in this thesis. A contextualised case study based on the Lagos bus rapid transit (BRT) is introduced in Chapter 4, which will provide the technical and operational features for applying the developed methodology. In addition, this chapter describes the Advanced Vehicle Simulator (ADVISOR) modelling tool and presents data based on Lagos BRT's current operations. The information defines the route speed, route length, terminal locations, transit schedules, route elevation, and route traffic system. The BEB energy usage per km is estimated using the ADVISOR and transit data. A PSO algorithm is introduced to provide optimised solutions to the transit network's conductive, inductive, and hybrid (conductive and inductive) charging systems. The number of chargers, charging point locations, charger power capacity, and onboard battery capacity are determined. The system's energy demand is also assessed. The considerable CO_2 emission reductions that can be achieved are also examined in this chapter. The findings of the study in this chapter can be used to promote the decarbonisation of transit networks in (mega) cities across the world and provide a basis for planners, transportation experts, and policymakers to assess the effect of switching to a low-carbon electrified BRT system.

Finally, Chapter 5 draws together the overall conclusions of the thesis and provides some recommendations for future research work.

1.6 Publications arising from the work of this thesis

1. Asaolu, A., and Galloway, S., 2020, August. Optimal design of conductive and inductive charging system for bus rapid transit network. In *2020 IEEE PES/IAS PowerAfrica* (pp. 1-5). IEEE.

2. Asaolu, A., Galloway, S. and Edmunds, C., Allocation of the inductive charging system for bus rapid transit network. In *2020 IEEE International Smart Cities Conference (ISC2)* (pp. 1-8). IEEE.

3. Optimal design of conductive and inductive charging system for bus rapid transit network (Abstract publication and presentation conference). *http://www.ieee-manchester.org.uk/wp-content/uploads/2019/11/Session-2-2-Adedayo-Asaolu.pdf*

2 LITERATURE REVIEW

The increasing population of cities globally leads to traffic congestion, increasing vehicular emission, and causes many hazards to human health. To this end, developed nations are transforming and growing investments in public transit systems that include upgrading public rail systems, trams, subways, and public transit buses. In developing countries, the increasing number of urban dwellers is expected to increase public and freight transportation demand levels in the nearest future [102]. In contrast, many developing countries cannot prioritise investment in public transit solutions such as the metro and rail systems despite facing the same challenges. While it varies from country to country, in such cases, the incumbent systems are already challenged (e.g. frequency of electricity blackouts, ageing infrastructure), and this, together with a lack of investment, means that they cannot transition at the same rate as developed nations in this regard. Hence, with less investment in heavy infrastructure, light solutions are likely to be more readily available in developing countries. On this basis, the bus rapid transit system's adoption is expected to proliferate the public transit system in these low economic countries [103].

Without change, it is also expected that the transportation sector's GHG emissions will increase to higher emission rates [104]. This increase in GHG emissions will, in turn, necessitate the need for deploying innovative approaches that can meet the growing transportation demands while addressing their environmental concerns [102] [103] [104]. The adoption of electrified transportation systems is anticipated as a promising solution that could considerably contribute to the decrease in environmental pollution [105] [33]. In this regard, this chapter presents a background on the bus transit system and a literature survey on the challenges that face the seamless adoption of electrified transport networks.

The remainder of this chapter is organised as follows: the first section covers transit systems in detail, including substantial information on the BRT system, the sustainable BRT system, and BRT components. The next sections go further into electric bus configurations, BEB charging strategies, charging technologies, and battery technologies. This chapter includes a review of the literature on battery-electric bus energy consumption modelling and the impact of EV charging on the power distribution system, which will motivate and position this thesis's work. Additionally, some interesting literature review on off-grid charging electric vehicles is included in this thesis because the developed model also estimates the transit system energy demand. This transit energy demand profile can be used as the starting point for resource modelling for the bus transit systems, as suggested for future research work. And the final section summarises the identified gaps in the work of previous authors.

2.1 The Transit System

A transit system is defined as coordinating buses and trains that run on predetermined routes and are open to the general public [106]. Unlike individual passenger transportation, public transportation is normally run on a schedule and specific routes. Trolleybuses, fast transit (metro, subway, underground, and buses), trams, trains, and urban buses are well known public transportation systems. Most public transportation systems operate on a set schedule along fixed routes with separated lanes. The urban environment is deemed favourable for transit because it provides necessary conditions for its effectiveness, such as high density and significant short-distance travel demands. Because transportation is a shared service, it might theoretically profit from economies of scale connected to high mobility demands and high densities [107]. The increased demand that makes public transportation services viable and profitable is a critical benefit of public transportation in the urban setting.

In [108], the authors carried out a cost assessment to demonstrate the transit system's advantages (i.e. metro, light rail transit LRT, or bus rapid transit BRT). The evaluation carried out in this work shows a significant reduction in passengers’ expenditures, travel time, per capita fuel usage, and CO_2 emission per passenger trip. A considerable shift from individual passage vehicles to transit mode requires the system to be flexible and relatively low cost while offering significant environmental benefits, which can only be achieved using a bus rapid transit (BRT) system [109]. The BRT provides opportunities for cities seeking efficient and cheap transit solutions that meet increasing urban growth in developing countries. While many developing countries have made plans and proposals for rail development due to its high speed capacity, these plans have not been implemented due to the high implicit costs [110] [103]. Recent studies have shown a vast increase in the adoption of a BRT system in cities across the globe because it has an efficiency level that mimics the LRT and can be implemented within a short period to reduce cost [113]–[115]. The next section presents details on the application and advantages of the bus rapid transit system.

2.1.1 The bus rapid transit system

The common transport challenge confronting most metropolitan areas can be summarised as traffic jams, pollution, delivery delays, and inadequate pedestrian facilities. A large body of research has identified the BRT system as a cheap and quick means of solving this problem (for example, Mexico City's Metrobús [116]). The BRT system has been determined to compete with expensive, sophisticated alternatives (metro, light rail, and subway), and it is both fast, frequent, and cheap [117]. The BRT often has dedicated bus lanes to help reduce congestion and offer more efficient vehicular transport solutions than private car ownership. Dedicated bus lanes can double, even triple the bus speeds and move more than four times as many passengers per hour as regular-lane traffic [111].

In [120], the authors highlight that "the BRT is part of the response to continued rapid urbanisation effects ongoing in most countries, particularly the larger cities in the developing world." Also, the study in [121] states that the BRT can deliver an excellent mass public transportation service that costs "between 4 and 20 times less than an LRT (Light Rail Transit) system and between 10 and 100 times less than an underground type system". The BRT is a transportation mode that incorporates buses and rail transit speed flexibility in terms of operation. The working system's idea is straightforward: the buses' traffic is made through a dedicated lane – this strategy makes possible a quicker, safer, and better bus service. Moreover, the BRT incorporates features mainly used in underground systems, such as off-board fare collection, platform-level boarding, and articulated vehicles.

In [109], the BRT is described as an innovative transit system that integrates the quality effectiveness of the metros system with the flexibility and relatively low cost of buses while offering significant environmental benefits. In an exceptional circumstance, the BRT systems can achieve marked levels of efficiency in terms of speed, capacity, passenger comfort, and convenience comparable to rail-based systems and, remarkably, can be built to reduce cost and construction time. Certainly, BRT can provide opportunities for cities in developing countries, where there is a growing demand for affordable transit solutions that meet the needs of increasing urban population growth and mobility demand.

In summary, the BRT is considered a viable option for alleviating traffic congestion in developing countries' cities because the capital and operating costs are relatively lower than the rail-based transit system. Another significant advantage is the interconnectivity and ability to operate on typical streets with inexpensive bus stops. The implementation period is less in comparison to rail-based systems [122].

Table 2-1 Key benefits of the bus rapid transit system (Adapted from [96])

BRT Impact	**Strategies**	**Empirical evidence**
GHG and local air pollutant emissions reductions.	1. Reduce vehicle-kilometres travelled (VKT) by shifting passengers to high-capacity BRT buses 2. Replace/scrap older, more polluting traditional vehicles. 3. Introduce newer technology BRT buses. 4. Improved driver training results in improved driving cycles, leading to reduce	1. TransMilenio BRT's implementation in Bogota, combined with new fuel quality regulations, saves about 1 million tCO2 per year [123]. 2. Mexico City's Metrobús Line 1 achieved substantial carbon monoxide reductions, benzene, and particulate matter (PM2.5) [116].

	emissions and fuel consumption.	
Reduced exposure to air pollutants.	1. Improve vehicle technologies, cleaner fuels, and reduce ambient air pollution citywide or inside the BRT buses. 2. Reduce passengers' exposure to air pollution at bus stations or inside the bus by reducing travel times.	1. In Bogota, after implementing TransMilenio (BRT), the SO_2 emissions reduce by 43%, NOx declined by 18%, and a 12% decline in the particulate matter [123]. 2. Reduction in local air pollutants, specifically particulate matter for Metrobús Line 1 in Mexico City, is expected to eliminate about 6,000 days of lost work and 12 new chronic bronchitis cases, and three deaths per year, saving an estimated USD 3 million per year [124].
Travel time savings	1. Segregated busways that detached BRT buses from mixed traffic; 2. Prepaid level boarding and high-capacity buses speed passenger boarding. 3. Traffic signal management and high-frequency bus service minimise waiting times.	1. In Johannesburg, the BRT users save an average of 13 minutes each way [125]. 2. In Istanbul, a typical Metrobüs (BTR) passenger saves 52 minutes per day [126].
Improve road safety – reductions in fatalities and crashes	1. Ease pedestrian crossings • High-capacity BRT buses reduce VKT.	1. Bogota's TransMilenio (BRT) reduces on-road crashes and injuries along the main corridors [127].

	2. Segregated bus routes decrease interaction with other vehicles (i.e. mixed traffic). 3. The BRT reduces on-the-road competition, which is expected to change drivers' behaviours by improving training.	2. On average, in Latin America, the BRTs have reduced fatalities and injuries by over 40% along their routes.
Increased physical activity	1. The spacing of BRT stations tends to require longer walking distances than all other motorised modes except Metro. 2. Higher operation speeds motivate BRT users to walk to stations.	1. The users of Mexico City's Metrobús increase their walking duration by about 2.75 minutes per day. 2. Users of the Beijing BRT walk additional 8.5 minutes daily.

Table 2-1 gives a summary of the benefits of BRT. It shows that implementing BRT systems in the cities has provided a range of benefits, including reducing travel time, reducing congestion, creating a positive environment in the cities, and improving safety. Other benefits include shifting from individual passage vehicles to public transit and improving human efficiency (gain in a working hour), which is a key consideration for this thesis's work. The Metro bus (BRT) in Mexico City reduces CO_2 by 45%, Benzene by 69%, PM 2.5 by 3%, and road accidents reduce by 80%. The BRT's introduction in Istanbul, Turkey, saved each passenger 316 hours per year, removed 80,000 individual passenger vehicles from the road, reduced CO_2 emissions by 623 tons per day, and cut the accidents rate by 64% [128]. In Johannesburg, BRT passengers save an average of 13 minutes per trip [125], and similarly, in Istanbul, BRT passengers save an average of 52 minutes per trip [126] [128].

The BRT passengers in Mexico City have a walking increase of about 2.75 minutes more per day on physical health activities. Also, in Beijing, BRT passengers have added

8.5 minutes of daily walking time. Furthermore, in terms of physical activities, the BRT users in Mexico City walk an average of 2.75 minutes additional per day than before implementing its BRT system. Similarly, as a result of the BRT system, commuters in Beijing have added 8.5 minutes of daily walking time [129]. According to the World Health Organisation, it is beneficial that adults aged 18-64 years should engage in a minimum of 150 minutes of moderate-intensity aerobic physical activity throughout the week. Alternatively, do at least 75 minutes of vigorous-intensity aerobic physical exercise throughout the week or a combination of moderate and vigorous-intensity activity [130]. It means that commuters' short distance walks to and from BRT bus stops contribute to their health.

Considering the above and with many of the same challenges identified, implementing sustainable BRT systems in developing countries' cities will form a specific focus for this thesis's work.

2.1.2 The sustainable BRT system

Transportation is the backbone of growth in developing economies [131]. However, along with this comes a significant source of environmental problems, as its share of pollutant emissions, energy consumption, and greenhouse gas emissions have grown [132]. Problems are exacerbated by vehicle travel levels rapidly outstripping existing infrastructure systems' capabilities, leading to traffic congestion and even more fuel use and air pollution than would otherwise occur. The problems are particularly acute in the developing world's largest cities (such as Lagos, Nigeria [133], Delhi and Mumbai in India [134], Nairobi in Kenya and Rio de Janeiro in Brazil [135]). Growing populations and high traffic densities with vehicles of all types mean significant congestion, slow travel speeds, human exposure to much-polluted air, and high rates of morbidity and mortality from traffic accidents [136]—the increasing desire for reforms to the current levels of car usage in most global developing countries cities needs to change. Any intervention should reflect the capacity to reduce commuter travel time, reduce the proliferation of cars and motorised trips, and reform existing often unreliable public transport to attract choice passengers from car usage to transit usage. This shift and recalibration of mode share towards efficient transit-dependent mobility patterns are considered ingredients of sustainable transportation in cities [137].

Existing historical transportation approaches are unsustainable in the long term because of:

1. the limited nature of petroleum reserves,
2. Volatility in the fossil fuel markets causes fuel/energy insecurity,
3. the negative impacts of petroleum-based emissions on air quality, and
4. levels of traffic congestion in many cities.

While there are other (equally important) issues, including secondary emissions and traffic deaths, these points above are the most relevant to this thesis's work [138].

The World Bank also defines what it refers to as the three pillars of sustainable transport as (1) the economic and financial sustainability (ensuring that transportation is cost-effective and continuously responsive to changing demands); (2) environmental sustainability (emphasis on better planning of land use and stricter management of demand, including the use of pollution and congestion charges to incentivise public transport); and (3) the social sustainability (designing transport strategies to provide social inclusivity with improved accessibility to employment, education, and health services) [139]; and (4) the mobility equity-not everyone can afford to buy a car or learn to drive . It is difficult to disagree with these points and the advantages of a sustainable BRT system continue to be important. Making the BRT sustainable requires deliberate effort from transit operators and regulating agencies to address the outlined problems.

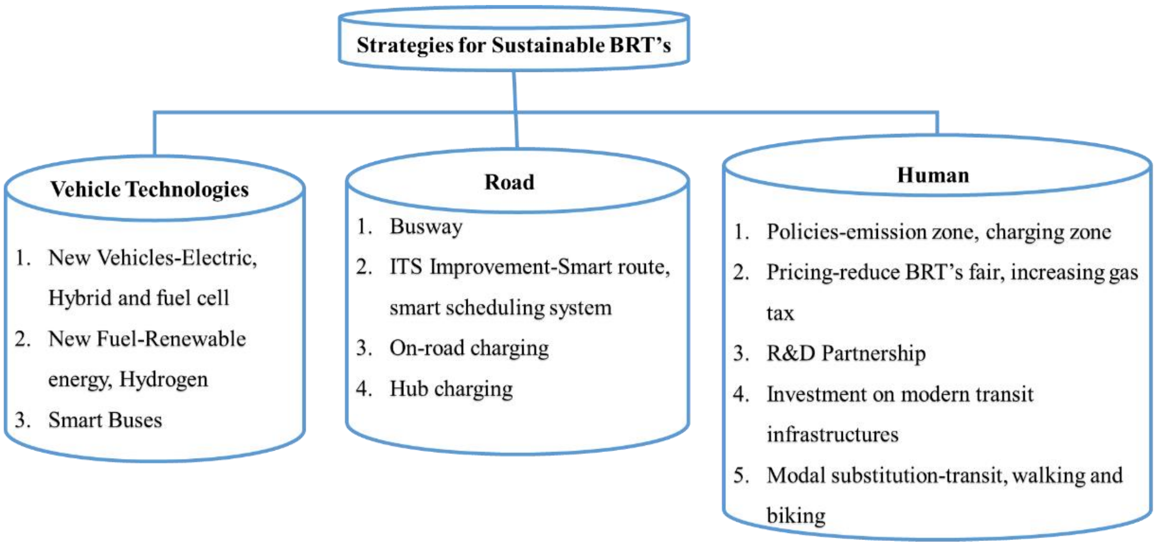

Figure 2-1 Strategies for Sustainable BRTs [137]

Figure 2-1 illustrates the strategies for transforming and implementing a sustainable BRT system. These are grouped into three categories (vehicle technologies, road, and human) based on the component of the transit system infrastructures. Integrating electric drives and renewable energy technologies into the transit system is expected to curtail the existing diesel buses' adverse environmental effects [140]–[142]. In the second category, having dedicated busways [143], [144], a smart transit scheduling system [145], and the electric bus re-charging technology that eliminates charging downtime will make the transit system perform beyond environmental sustainability but address the issues with road congestion and financial sustainability. In the third category, creating emission zones (that only permit EV drivers to use problematic congestion areas), and creating charging zones (pay to use) will reduce congestion and motivate a shift from an individual passenger vehicle to the transit mode. Also, increasing fuel tax costs and reducing transit fleet costs can reduce personal passenger vehicles' use and increase BRT's attractiveness.

This work of this thesis touches on all three of these categories. However, the primary focus is on the BRT system's electrification to support the environmental sustainability of public transportation systems. These sustainability strategies would encourage public transport usage and help manage the common congestion in the cities of many developing countries.

2.1.3 Features of BRTs

The BRT system's main components include segregated busways, bus stops, bus terminals, high-capacity buses (rolling stock), a passenger boarding platform, a real-time passenger information system, a bus route map, and the control centre (intelligent unit) branding, and bike-share facility. These identified BRTs components are further discussed below:

2.1.3.1 Segregated busway

In BRT corridors, segregated busways are meant to allow commuters to transit more quickly [146]. The busway differs from the bus lane in that the bus space is physically separated from the traffic (see Figure 2-2). A raised block/pillar separates the busway from the traffic, while a painted line separates the bus lane. Because the bus lane does not restrict traffic from entering the system, it can impair free flow and lengthen bus travel times [147].

Figure 2-2 El Metropolitano's Trunk Corridor [148]

The BRT lane is separated from other traffic using blocks in the Peru El Metropolitan's Trunk Corridor, as shown in Figure 2-2. This segregation type is provided with a dedicated and continuous lane for buses to travel against the road's block edge. The bus stops are appropriately built to provide simple access to the neighbouring streets, but as demonstrated, they limit the opportunities for bus overtaking.

2.1.3.2 Bus terminal and bus station

A bus terminal, sometimes known as a terminus, is the starting or ending point of a bus route and the location where buses stop, turn, or reverse and wait before continuing their trip back. At bus terminals, passengers board and depart from vehicles. It is also an ideal location for managing transit services [149]. The terminus is the starting point for a timetable. Terminals can be in bus stations, interchanges, bus garages, and bus stop, among other places. The terminals can begin and end at the same location or possibly in multiple locations depending on the route. A bus transit terminal may be located near other vital facilities like universities, retail malls, or hospitals. It may be part of a transportation hub or 'interchange.' A bus stop or loop on a residential street can be considered a minor terminal [150].

Figure 2-3 Bus Terminal in Oshodi, Lagos [151]

Although the terms "bus terminal" and "bus station" are sometimes interchanged, the latter is usually more accurate because some routes pass by the station without stopping. The word "bus station" usually refers to a location off the main path with only the most basic passenger amenities. A terminal might be a fully equipped bus station or a simple road intersection. In many cities, most passengers begin and conclude their journeys at bus stations, which may account for a significant amount of the money generated by operators [152].

2.1.3.3 The bus stop

A bus stop is a designated location where buses stop to allow passengers to board and disembark. Bus stops are typically built to reflect utilisation, with shelters, seating, and possibly electronic passenger information systems in high-traffic areas and a basic pole and flag in low-traffic areas. In some areas, bus stops are crowded together to form transportation hubs, allowing for interchange between routes from surrounding stops and other modes of public transportation to maximise convenience [153].

Figure 2-4 Lagos BRT Bus stop [154]

For operational purposes, there are three types of stops: scheduled stops, where the bus should stop regardless of demand; request stops (or flag stops), where the vehicle will only stop on request; and hail and ride stops, where the vehicle will stop anywhere along the designated section of road on demand [153]." Discharge/set-down only" or "pick-up only" may be the only restrictions at some stops. Some stops may be designated as "timing spots," where the vehicle will wait ahead of schedule to guarantee proper synchronisation with the schedule. Skip-stops are sometimes used to boost efficiency and decrease bus stops in dense metropolitan areas with high bus volumes. Specific stops in distance or zone-based fare collection systems can also be used to establish fare stages.

2.1.3.4 Bus depots

A depot is a transportation system's operating hub. There includes parking, bus servicing and maintenance, an administrative role, and employee facilities. A fully enclosed depot is referred to as a "garage." An operator may have one or many depots, depending on the size of its fleet and regional reach [155].

Figure 2-5 Lagos BRT Bus Depot [156]

Buses are assigned to routes, and crews are assigned to each job at the depot, dispatching buses on time and processing cash payments from drivers. These facilities also contain a signing-on office where crews report for duty and a cash office where drivers pay in revenue earned while on the job. A canteen and medical facilities for employees, off-duty personnel, backup bus drivers, and overnight lodging for crews at larger depots are probably appropriate [155]. Figure 2-5 shows a typical example of a BRT bus depot in Lagos, Nigeria.

2.1.3.5 Boarding platform

Station platforms should be level with the bus floor for quick and easy boarding, allowing wheelchairs, disabled passengers, and baby carriages to board with minimal delays. These BRT stops are distinct from street-level bus stops since stopping outside designated platforms or having standard buses stop at high-level platforms is challenging for high-floored buses [155].

Figure 2-6 A typical boarding platform for easy entry/exit [157]

As shown in Figure 2-6, the boarding platform should allow for smooth passenger entry and exit and easy entry and exit for the elderly and physically disabled.

2.1.3.6 Fare payment system

The BRT system uses a contactless off-board fare payment system like that of rail systems. Passengers enter the bus terminal by swiping their pre-loaded BRT smart card over the turnstile at the entrance, and they board the appropriate bus as soon as possible, as illustrated in Figure 2-7. Hence, using this fare payment method reduces boarding time while reducing trip time.

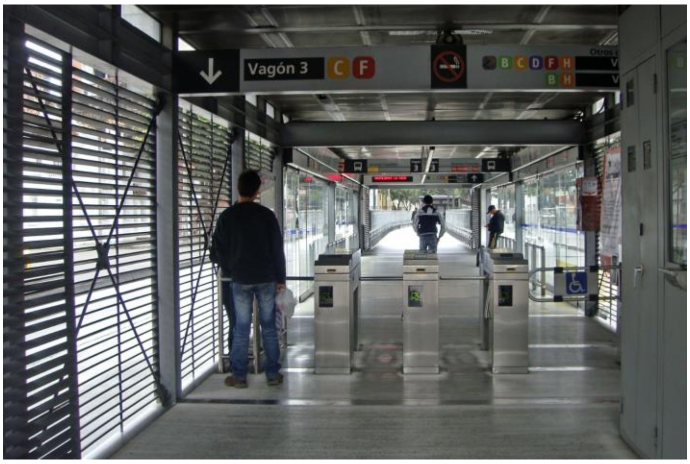

Figure 2-7 Transmilenio prepaid boarding and passenger information in Bogota (Adopted from [158]**)**

2.1.3.7 Rolling stock

The rolling stock of a BRT system is primarily articulated or bi-articulated buses with a passenger capacity of 80 to 250 people. These large vehicles can replace informal minibuses, reduce regular vehicle mileage, and reduce per capita fuel consumption and pollution associated with city commutes. To keep the system's emissions low, the buses in the BRT system must adhere to emission criteria. For compliance with the standard BRT diesel vehicles, particulate matter traps, ultra-low-sulphur diesel fuel, and selective catalytic reduction are required [159]. Particulate matter emissions from Euro IV and V authorised vehicles are lowered by twice as much, according to the efficiency level of decreasing particulate matter emissions from introducing Euro VI buses and USA 2010 emission requirements [160]. By institutionalising and maintaining compliance with these stated transportation operators' criteria, particulate matter (PM), nitrogen oxide (NOx), CO_2 emissions, air pollution, and global warming-related externalities can all be reduced.

The recent adoption of electric buses into the transit system is projected to affect the transportation system by reducing pollution significantly. The advantages of adopting battery-electric buses (BEBs) in a transportation system go even further in terms of air quality, noise reduction, and energy efficiency [161]. With sustainable BRTs in mind, greening this form of public transportation while incorporating a low-GHG solution may be an appealing choice; thus, this study investigates the advantages of electric buses and the component of electric bus transit.

2.2 Electric buses

An electric bus "can operate by different degrees of electrification that depend on the configuration of the propulsion system" [14]. Some can be continuously fed by external sources – for instance, a trolleybus powered by overhead wires. Other ones can store the electricity onboard, typically in batteries. Several electric buses fit into this category; examples include:

- **Hybrid Electric Bus (HEB)**: The Electric Motor (EM), as well as an Internal Combustion Engine (ICE), provide the traction power of this technology. In some cases, the HEB battery can also be charged using plugin technology to connect the grid [14].
- **Fuel Cell Electric Bus (FCEB):** Uses hydrogen fuel cells to generate electricity onboard during operation [162].
- **Full Battery Electric Bus (BEB):** This vehicle uses the energy stored in the bus's onboard battery to provide the electric motor propulsion [162]. Power is transferred to the battery-electric bus through electric charging systems, while regenerative braking is used to recover kinetic energy during the vehicle operation [12].

Environmental gains (no exhaust pipe emissions), better air quality, and lower total cost of ownership (TCO) are the key advantages of electric buses over diesel alternatives [163]. The lower TCO is attributed to the lower cost per kilometre of operating on electricity as compared to petrol, while the battery cost currently results in a higher average acquisition price. Because of these advantages, policymakers are setting goals to promote acceptance, such as the Netherlands' requirement that all zero-emission vehicle (ZEV) public transportation buses be sold by 2025, with a 100% ZEV fleet by 2030 [164]. Bus makers and transportation organisations signed the European Clean Bus Deployment Initiative [131] to formalise a joint commitment to promote the implementation of clean buses. Compared to internal combustion engines, hybrid electric buses, and fuel cell electric buses. Until recharging the onboard battery, the BEB's driving range is limited.

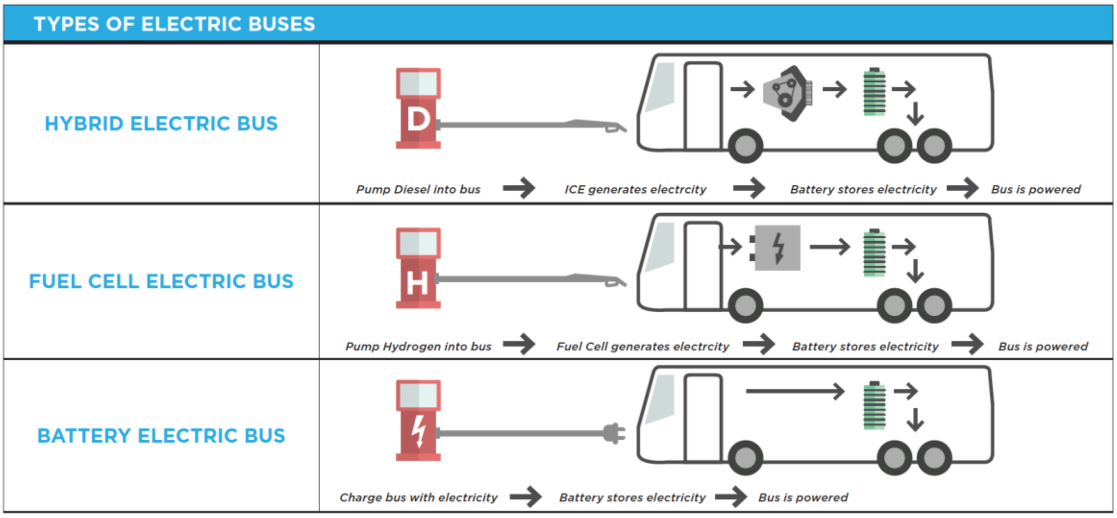

Figure 2-8 The defining components of different electric buses (Source: [12]**).**

Nonetheless, they are more efficient and environmentally friendly. Figure 2-8 shows the classification of Battery Electric Buses. A hybrid bus combines two power sources: a conventional diesel engine and an electric motor. Fuel cell electric buses are hybrid electric buses that are powered by fuel cells and batteries (s). An electric motor is used in a battery-electric bus powered by an onboard battery charged by mains electricity. Electric buses emit no tailpipe emissions, earning them the designation of "zero-emission capable." Hence, integrating BEBs into the public transit system is considered a game-changer for polluted cities in developing countries.

The configuration of the battery-electric bus includes auxiliary devices (AUX), an electric motor (EM), a transmission system (TX), and a final drive (FD), as shown in Figure 2-9. This indicates where these different elements typically reside to enable the energy for a BEB to be stored in a battery and then provided to the electric motor. Electric charging systems transmit energy to the vehicle, and regenerative braking is utilised to recover kinetic energy during operation. As indicated in Figure 2-9, the energy for a BEB is stored in a battery and then delivered to the electric motor. Lithium iron phosphate, lithium-titanate, and nickel cobalt manganese lithium-ion batteries are the three most prevalent types of batteries used in BEBs [165].

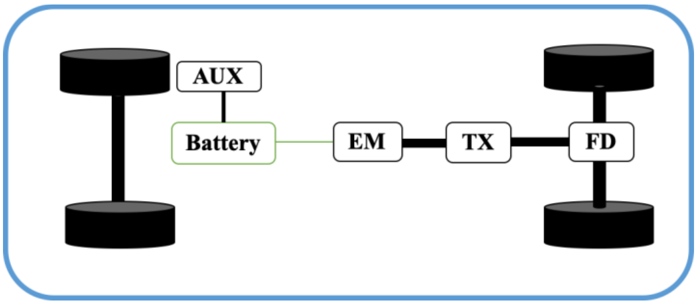

Figure 2-9 Battery Electric Bus Configuration (Adopted from [12])

Table 2.2 summarises the characteristics of popular types of BEB. The common brand BYD has produced various models. BYD manufactured most of the onboard battery-electric buses used globally in the public transit system [157]. In Europe, the most commercialised EBs are Volvo, Solaris BYD and Alexander Dennis (BYD ADL) [166].

Table 2-2 Characteristics of Electric Transit Buses

Model	Type	Battery capacity (kWh)	Range (km)
BYD ADL Enviro200EV [167]	Single-deck bus	348	250
BYD ADL Enviro400EV [167]	Double-deck bus	382	250
Enviro500EV [167]	Double-deck bus	660	400
BYD 23' Coach [168]	Single-deck bus	121	200
BYD 40' Coach [169]	Single-deck bus	352	322
BYD 60' Coach [170]	Single-deck bus	578	355
Solaris Urbino 12 [171]	Single-deck bus	145	100
Volvo 7900 [172]	Single-deck bus	76	200

Electric buses are becoming more common in public transportation fleets around the world. China was the first country to adopt electric buses, and it took a few years for other countries to follow suit. Approximately 98% of the world's electric buses are currently in operation in Chinese cities [166]. In comparison to 2017, the European electric bus industry grew by 48% in 2018. Battery-electric buses and plugin hybrids, trolleybus IMC, and fuel cell buses were among the 4,000 electric buses operating in Europe in 2019 [166]. The electric bus market in India (70,000 buses sold in 2017) has much potential. India will account for more than 10% of worldwide yearly demand for electric buses by 2025, according to Interact Analysis, which is more than Europe and North America combined. Electric buses accounted for roughly 0.5% of the overall public transit bus market in the United States at the end of 2017. Electric buses were in service in about 9% of all transportation agencies. The US government is also supporting and funding research into public transportation electrification. [173].

Table 2-3 Comparative evaluation of HEB, FCEB and DB ([12]**)**

	HEB	**FCEB**	**BEB**
Purchase Price	+50%	+200%	+100%
Maintenance Cost	More	Much More	Less
Operation Cost	Less	Much More	Much Less
Infrastructure	More	More	More
Range	Less	Less	Much less
Weight	More	More	More
Refuel Time	Less	More	More
Emissions	-20%	-75%	-85%
Energy Efficiency	Better than DBs	+150%	+450%

Electric buses are already becoming the bus of choice for many cities and public transport providers worldwide. Table 2-3 provides a comparison between *diesel buses* and *electric buses* across a range of categories. The BEBs present several advantages: the operation and maintenance costs are low, the energy efficiency is very high, and the low emissions.

Therefore, the BEBs appear as the best and most viable option for electrifying public transportation. Nonetheless, the technology still faces some challenges regarding the range, weight, and refuel time factors. In counterbalancing the limited BEB driving range, three operation conceptions have been proposed: battery swapping, wireless charging, and onboard battery charging [81] [174] [33]. In addition, the concept of charging the onboard battery of a battery-electric bus is presently under wide-ranging research and development as a necessary means for the extensive–scale adoption of electric bus fleets [175]. In this regard, two types of BEB charging–based systems have been proposed: overnight and opportunity. The difference between the two types is the trade-off in the BEB battery capacity, i.e. driving range, and the required rated power of chargers, i.e., charging time [81] [82].

BEB systems that rely solely on overnight charging require chargers that have relatively smaller power ratings. Overnight BEB chargers are installed at the bus depot/garage to provide a long time charging for a large battery capacity, compared to opportunity–based BEB. However, previous studies showed that overnight–charging BEB systems might require an increase in the BEB fleet size relative to the current diesel-based fleet to maintain the predefined operation-scheduling timetable of transit networks [82]. In contrast, opportunity–charging BEB systems use on–route high–powered chargers to provide regular and short time charging for BEBs equipped with relatively smaller battery capacity [176]. On–route charging systems use mainly automated overhead pantographic arms to charge the BEBs in the transit hub(s) (i.e., bus terminal(s)) or along the transit routes [177]. Several worldwide demonstration projects showed that on–traffic charging technologies could sufficiently charge BEBs within 4–6 minutes [177].

In contrast to other research works that focus on the adoption of individual passenger EVs. The bus transit network's electrification (especially BRTs) is considered a key component for the cities in developing countries from transportation challenges because it can reduce traffic congestion and GHG emissions, and it is often within the control of local authorities and policymakers to influence this change. Hence, the research work of this thesis will focus on the challenges enumerating the various charging options, technologies, and strategies to enhance the BEBs' driving range in the developing country context. To date, these have not been fully addressed despite the progress made internationally.

2.3 Options for BEBs charging

When dealing with BEBs, there are three main types of charging options: static, stationary, and dynamic [178] [179] [180]. These are as follows:

- Static strategy: this is usually used when the BEB will be parked for an extended period, such as overnight at a depot. The vehicles are charged during this period. This method enables a longer re-charging time. Since the chargers are designed to have charging powers in the range of 40 – 120 kW, the charging infrastructure costs are lower than other charging strategies [181]. Those vehicles normally have a regular driving range of around 300 kilometres which allows for day-to-day service like diesel buses without the need for re-charging. On the other hand, the battery's expense – due to its high capacity – significantly raises the price of such buses [182]. Since such vehicles are heavier than regular buses, they can only accommodate a small number of passengers.

- Stationary strategy: when the vehicle is stationary, the BEB is charged for a limited period. As a result, charging must be done quickly – in the range of 3 to 10 minutes [183]. As a result, charging powers range from 150 to 600 kW, and high infrastructure costs. Nonetheless, this technique allows for smaller batteries to be used in the buses and as a result, they are less costly and lighter. Furthermore, the driving range becomes nearly limitless when charging stations are strategically located along the road.
- Dynamic Charging Strategy: this charging approach allows the vehicle to be charged when it is in motion. This can be accomplished by inductive power transfer (IPT) [57] or catenary-based fast-charging systems. Although the associated infrastructure costs are substantial, the technology reduces the BEBs' onboard battery.

Table 2-4 Summary of BEB charging possibilities (Adopted from [184]**)**

Strategy	***Static***	***Stationary***	***Dynamic***
Typical application	Overnight charging at the depot	Mid-day opportunity charging due to facilities in the route	Mid-day opportunity charging due to charging lanes
Charger type	30 up to 150 kW (for buses with high range)	150/300/450 kW (fast charging)	25-150+ kW
Charging technology	Mostly plugin	Mostly pantograph Plug-in (less common)	WPT
Typical Range	100 – 300 km/day	200 – 500 km/day	100 – 200 km/day
Refuel Time	3 – 8h	3 – 10 min	10 – 15 min
Costs drivers	Needs dedicated infrastructure (e.g. depot or car park)	1 Low battery costs 2 High charging infrastructure costs 3 Medium maintenance costs	1 Low battery costs 2 Very high infrastructure costs 3 Very low maintenance costs

The features of the different BEB charging options are summarised in Table 2-4. The Static approach is widely used at the depot (overnight charging) and is the most used in developed cities with stable grid supply. The BEBs, in this case, have a large battery used during the regular operating schedule and parked at the depot overnight to charge in this situation. The possibility exists to provide co-located renewable energy (especially solar) during the daily operational schedule; *stationary* and *static* methods can be applied to developing countries and cities with power supply security challenges. The co-located renewables can help offset domestic electricity costs, improve resilience to power "black-outs," and boost green credentials because some of the power originates from low-carbon sources.

The work in this thesis will investigate the possible trade-off between charging options based on cost, BEBs battery sizes, charger location and the charger's power capacities. These features are relevant to a range of stakeholders in this setting.

2.4 Charging strategies

Electric buses typically have a shorter range than diesel buses, and a good question that municipalities, transport operators, and manufacturers are still facing is where and when to charge them. Electric buses can be recharged in three different operational scenarios presented in this section: overnight charging, Opportunity Charging, and In-Motion Charging. Each of these categories is described in the following:

2.4.1 Overnight Charging

Buses are parked at the depot after the regular schedule is completed. The bus, for instance, departs at 4 a.m. and returns at 8 p.m. The depot time is used for maintenance, cleaning, and preparation, and an electric bus can use this period to recharge its batteries. The time to fully recharge depends on the battery capacity and the power output of the transformer. Therefore, an Overnight Charging strategy uses this time in the depot to recharge the bus for operation the following day. For this strategy to work, these vehicles would need large batteries. For example, the 2018 EVOBUS eCitaro is a 12 m long Battery Electric Bus (BEB) with lithium-ion batteries with a capacity of 243 kWh that lasts in a worst-case summer scenario for 150 km [185].

2.4.2 Opportunity Charging

Opportunity charging describes operational cases in which buses are recharged at the depot and designated charging stations throughout the network. Buses do not have to drive back to the depot to recharge. Time and energy can potentially be saved. As a result, smaller batteries are needed for buses [186]. However, it is vital to schedule the buses to have sufficient energy to meet the route demand. Backup solutions for different scenarios must ensure stable operation in case of incidents, construction works, or detours. Also, recharging stations can be equipped with inductive charging pads to save time. As soon as the bus occupies the station, it is detected, and recharging is initiated.

In Eindhoven, the Netherlands, Heliox fast charging equipment was strategically delivered at the bus depot to create the most efficient and cost-effective option. Both the opportunity and overnight chargers connected with the buses automatically via a roof mounted pantograph, resulting in a robust and time-efficient charging system. Heliox provided 12 Heliox FAST DC 2x30 kW chargers with 24 separate charging stations for overnight charging. As a cost-cutting measure, the ten Heliox 300kW opportunity chargers were automatically dropped at night. Heliox's latest innovation, the SMART Switch, was used to maximise charging intervals. The SMART Switch allows charging two buses with a single charger while automatically switching from the fullest to the emptiest bus [187].

2.4.3 In-Motion Charging

In-Motion Charging enables electric buses to recharge while moving. This strategy has the advantage that no extra time for recharging must be considered during scheduled operations. When set up smart, the electric bus has access to *In-Motion Charging* that run perpetually (for example, the online electric vehicle OLEV presented in [188]). As with opportunity charging, the flexibility is restricted due to the fixed lines that must be called regularly to ensure that the state of charge (SOC) is always high enough to reach the next power lane. This strategy is usually combined with an overhead catenary power supply (a typical example of a hybrid trolleybus proposed for Berlin [189]). Some test projects worldwide equip roads with copper coils to wirelessly charge the batteries while the bus moves [178].

Table 2-5 Battery electric bus charging Strategies (Adopted from [12]**)**

Strategy	***Overnight***	***Opportunity***
Chargers capacity	typically, 30-150kw	superchargers 150+ Kw
Location	depot	terminals, on-road
Charging technologies	plug-in, pantograph	pantograph, induction
Range	100-250km/day	200-500km/day
Battery capacity	usually huge	small

Bus weight	higher bus weight and high energy consumption rate	low weight and reduce the energy consumption rate
Cost	higher battery cost lower charging infrastructure cost	lower battery cost higher charging infrastructure cost

As shown in Table 2-5, there is no standardisation for the charging strategy. Nevertheless, the recent literature suggests that opportunity charging can play a decisive role in improving the BEB's feasibility systems [190], [191]. Besides, in [163], the authors conclude that "for longer routes, opportunity charging saves 10-20% (of the Total Cost of Ownership (TCO)), as it enables a significantly smaller battery". The financial advantages combined with the enhancement of driving range and fast charging make this charging strategy the most promising. As a result, this thesis' research considers opportunity charging to ensure that battery-electric buses can be used for similar duty cycles as conventional vehicles without jeopardising the transit operational schedule.

2.5 Charging technology and charging location for Transit Electric Bus

The primary barrier to adopting and developing an electrified bus transit system globally is the lack of supporting infrastructure [192], [193]. Especially in the developing countries where the accessibility to electricity is considered limited [194] and due to cost, their circumstances do not typically support the overnight charging of large battery-sized buses commonly used in Europe and China. Generally, the cost of building onboard large capacity battery buses for overnight and depot charging is exceptionally huge. Also, there is a lack of a clear plan to deploy dedicated charging infrastructure (both conductive and inductive) at the bus terminals, which requires a considerable investment cost [195]. The trade-off between the cost of operation and charging demands is a key consideration in providing a reliable and affordable bus transit operation.

In [196], the authors present two concepts for charging the battery-electric bus; standard and fast charging. The standard charging is described as using the bus depot overnight with 'modest' charging power. The electric buses in this category are usually equipped with a high-capacity battery, which increases the bus's weight and increases bus energy consumption. These buses are scheduled to work during the bus operation hours and then retire to the bus depot for charging. The fast-charging infrastructures can be inductive (wireless) or conductive (connected). The buses are usually scheduled to charge during the daily schedule operation using inductive chargers 'on-the-fly' as they traverse along bus routes and the conductive chargers at the bus terminal during scheduled downtime [33]. The fast charging strategy supports a small onboard battery size and significantly reduces the bus's weight [194].

Using overnight depot charging provides more charging opportunities where the grid supply is reliable [185]. As mentioned previously, the grid is already challenged in developing countries, and the addition of scale loading could present further challenges to supply quality. As part of this thesis's work, on-the-fly inductive charging combined with multi-terminal conductive charging can provide easy access and effectively manage the onboard battery state of charge while reducing the burden on the incumbent grid [33]. "When determining which strategy to take, the consideration of energy usage, charging times and possibilities, operation safety, and battery lifetime should be inevitable [196]". Detailed below are the possible charging locations and charging technologies for the electric bus transit system:

2.5.1 Charging locations

An outline of the different types of charging locations is provided as background in this section. The different features are highlighted and linked to the relevant research literature in the area where appropriate.

2.5.1.1 Depot Charging

The popular charging location for electric buses is the depot. At the end of the transit buses' daily operational schedule, the buses are usually packed at the depot, usually at night. This location and time are considered the best place and duration for charging the electric buses. These overnight depots' dwell times chargers are usually configured to have low capacities [197].

A perfect environment for the depot charging of an electric vehicle is usually comparatively anticipated and follows a daily schedule with overall high mileage. These basic requirements make conveyance buses ideal candidates. A city bus covers a mean of 220 km per day [198]. Consistent with manufacturers, a battery's capacity can now last for a distance of 100 km to 300 km between charges [199]. Therefore, even today and positively soon, a city bus could manage short routes without requiring any charging infrastructure on its route. This depot charging reduces the investment required for infrastructure and minimises the operational complexity; if the vehicle must charge too often, efficient scheduling could also be difficult to plan. However, it is the most time-consuming charging strategy for electric buses. This is because charging usually happens when transit buses finish their scheduled routes or stay within the depot during the shift. The complete charge process for depot charging takes about 3-8 hours, counting on the charging infrastructure's capacity [181].

Considering the cost, charging at the depot requires the least infrastructure, as no other equipment is needed except for the depot charger. However, a big onboard battery capacity is excessively concerned because electric buses must complete their daily trip without charging. Additional increases in the battery capacity may not be so helpful because the bus becomes inevitably heavier (with a doubling of vehicle mass, energy consumption rises by 40 to 60% [200]). The overall energy consumption increases and reduces the maximum payload of the bus.

2.5.1.2 Terminal and Multi-Terminal Stop Charging

In this case, chargers are usually positioned at the start or end stops in a bus route in the terminal charging system. The chargers can be located at each terminal for a very long route with multiple terminals. The terminal and multi-terminal chargers are configured to take advantage of the stationary time between bus scheduled services [191] [201]. In the terminal charging system, the electric bus battery capacity should be sufficient to allow at least journeying between the terminals to circumvent the bus running out of energy due to external factors such as traffic conditions.

Compared with depot charging, the electric bus has a small onboard battery, and the charging is usually more frequent. The charger capacity has a higher power (mostly pantographs). Also, the battery costs are lowered due to the lower battery capacity, while infrastructure costs are higher due to several fast chargers' needs.

It is essential to ensure that the bus has enough time to recharge the onboard battery during the terminal charging because the charging duration may impact the operational bus timetable [202] [203]. Although terminal stop charging involves a considerable dwell time (typically for customer boarding), operational bus driving can be adjusted to the scheduled time during the charging procedure to accommodate possible charging delays [191].

From the grid network aspect, terminal charging avoids peak hour charging. In [181], the authors present various optimisation algorithms that can manage electric bus charging power. They make use of a range of different optimisation algorithms to explore this: Genetic algorithm [204], dynamic programming [205], exponential smoothing model [206], and locally optimal scheduling [207]. The techniques employed have been primarily applied to solve scheduling problems linked with the terminal charging of electric buses. In this work, a PSO algorithm is used to allocate charging infrastructures to electric bus transit systems in a terminal-based scenario.

2.5.1.3 Along-the-Route Charging

The along-the-route charging system means having charging infrastructure at one or more points along the bus route to charge the electric bus's onboard battery. When considering the along-the-route charging system for an electric bus transit system, a trade-off analysis of the onboard battery capacity, location of charging infrastructure, and the number of charging infrastructures is important to optimally allocate the network infrastructure [208] [33], [101]. Compared to the depot and terminal charging methods, the along-the-route method saves the onboard battery's significant expenditure cost because the battery size is relatively small. The investment in charging is the highest because numerous high capacity chargers are usually required along the route to meet the daily operational charging demand [209]. The main advantage of this charging location is the possibility to operate full-electric buses without disrupting the daily operating schedule (electric buses can be used as diesel buses); the onboard batteries will be re-charged at every charging point along the route [209], [201].

2.5.2 Charging technologies

The availability of charging infrastructures is vital for the reliability and adoption of BEBs in the public transportation system. Charging public transit BEBs are confronting higher demand for electrical energy for BEB charging and the time requirements. Considering the trade-off of these challenges to meet the transit demand, three main types of charging emerge: Plug-in charging, Pantograph charging, battery swapping, and wireless charging. Fig.2.10 shows the summary of the key charging technologies, and the detail of these charging technologies are covered in turn below.

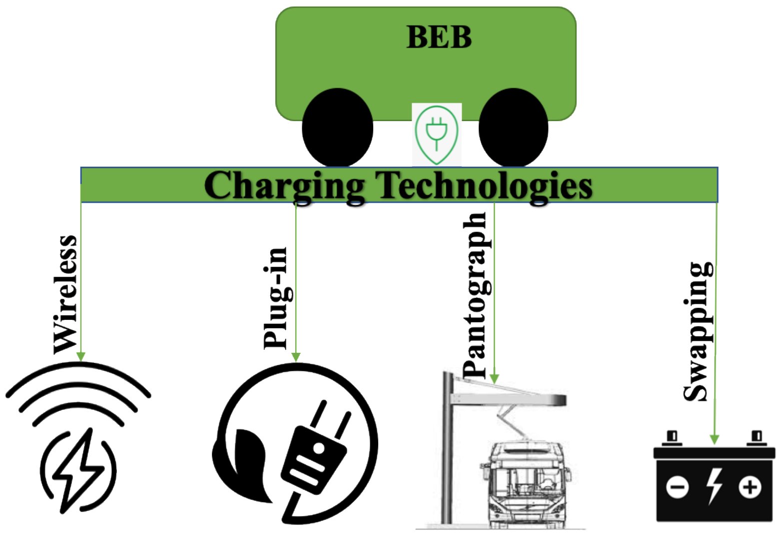

Figure 2-10 BEB Charging Technologies

2.5.2.1 Wireless charging

A wireless power transfer (WPT) system generally consists of a power supply, transmitter (primary coil), receiver (secondary coil), oscillator circuit, and matching circuit. The AC supplied by a power source is changed into low-frequency AC using an oscillator. The oscillator's output is fed into the push-pull circuit that supplies the transmitter coil. This transmitter coil is also referred to as the primary coil. This primary coil transmits this power to the receiver coil separated by a certain distance; the energy received by the secondary coil is then rectified and regulated before output to the BEB battery charger. The inductive charging system is environmentally suitable and cheap to maintain because it is not affected by water, ice, dirt, and chemicals [101]. A more detailed description of the system's power transfer mechanism and hardware configuration can be found in [210] [211] [212].

Compared to the conductive means of charging electric buses, the wireless charging system eliminates the impact of environmental conditions (such as; rain, snow, and extreme temperatures) that can cause discomfort for users when connecting an electric bus manually at the charging station. The wireless charging system also eliminates issues with the failure of power cords that can cause safety issues (risk of electrical sparking and electrical shock) [213]. The other advantages of wireless charging systems include providing fast and frequent charges while operating the BEB. This option allows for battery downscaling with the resulting benefits of lighter weight BEBs, reduction in the cost of the BEBs, energy savings resulting from the decrease in mass, and reduction of CO_2 emissions.

In [214], the authors compare the plugin charging system's energy use with the wireless charging system. The wireless charging system consumes 0.3% less energy and emits 0.5% fewer greenhouse gases. The wireless charging system is becoming increasingly common in providing an alternative charging system for public transit [213].

The three main wireless power transfer classifications commonly used for public buses are capacitive, inductive, and resonant inductive power transfer [215] [216]. The most common use is the inductive charging system. The inductive charging system is an integrated on-road charging system that charges the onboard battery remotely while the bus moves over the installed inductive cable area. The length of the inductive cable, the size of BEB's battery, and the number of transmitters installed on the road directly affect the transit system's overall performance and cost. Figure 2-11 illustrates a typical design of the inductive charging system. The wireless power receiver device is installed at the lower part of the electric bus. This wireless power receiver device remotely collects electricity from the transmitter. The wireless receiver delivers power to the BEB motor, the battery, or both, depending on the motor's power requirement and the battery state of charge [217]. When the BEB moves on a busway where no power transmitter unit is installed, the BEB motor uses the battery's power. To eliminate energy waste, the BEBs that charge via inductive means is considered to have an infra-red sensor that turns 'ON' the supply that activates the energy exchange between the transmitter and the receiver circuit. When the BEB moves away from the inductive cable, the infra-red sensor signals to turn 'OFF' the power supply [211] [101].

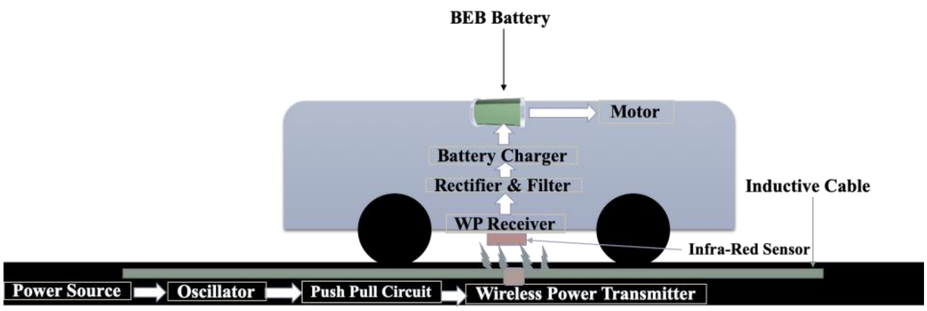

Figure 2-11 Transit inductive system (Adopted from [101]**)**

This technology's demerits include low energy transfer efficiency due to losses during coil-to-coil transfer; high installation costs, which are considerably higher than plugin charging [216]. This technology is considered the most suitable for dynamic charging possibility and works best for "along-the-route" charging locations because the onboard battery receives charge while operating the electric bus in an inductive transit route.

2.5.2.2 Plug-in Charging

'Plug-in' is a conductive charging method commonly adopted for generally charging electric vehicles and is primarily used to charge small vehicles (e.g. cars). These plug-in chargers are classified based on the supported output voltage and the rate at which they will charge a battery. Level 1 charging is the slowest and can be done with 120 volts and 15 amps AC in most wall outlets. Level 2 charging is faster and requires 240 volts and 60 amps of AC for a maximum of 22 kW. Level 3 charging is the fastest and produces more than 50 kW of power [218]. Level 1 and 2 charging can be carried out at home with the correct power adapter, and Level 2 and 3 charging are commonly carried out at fixed public charging stations [219] [220], [221]. Table 2-6 compares the characteristic of Level 1, Level 2, and Level 3 chargers.

Table 2-6 Characteristics of Level 1, Level 2 and Level 3 chargers [219] [220], [221]

Power level types	**Level 1**	**Level 2**	**Level 3**
Voltage	120V_{AC}(US), 230V_{AC}(EU)	240V_{AC}(US), 400V_{AC}(EU)	208-600V_{AC} or V_{DC}
Power range	<3.7kW	3.7-22kW	>50kW
Charging duration	11-36 hours	1-6 hours	0.2-1 hours
Charger topology	On-board	On-board	Off-board
Source supply type	1-phase	1-phase or 3-phase	3-phase
Charging type	Slow charge	Medium charge	Fast charge
Battery capacity	15-50kW	15-50kW	15-50kW

Slow charging rates are not suitable for electric buses because the battery (approx. 400 kWh) is huge, and charging could take very long, limiting trip schedules [222]. Fast charging tends to be the most convenient choice for both EBs and ETs. However, fast chargers can have some negative impacts on the BEBs battery that include heating up during charging, outsized conductors, and high voltage AC/DC converters are required. As a result of the high-power systems and short charging times, special grid operation conditions must be considered. [223] and [222] are example of research work that focuses on the grid impact of fast charging. A typical alternatives include storing energy through distributed generation in a fast-charging station to help the grid cope with the peak loads.

2.5.2.3 Pantograph charging

Conductive charging is based on energy transfer to electric vehicles by direct electric contact. The most common solution for conductive charging of electric buses is based on the usage of pantographs. A pantograph system is a type conductive charging solution that allows the electric buses to charge quickly at the terminals or stops. The pantograph system has an automatic connecting system, DC-conductive charging supply equipment, conductive rails fixed to the vehicle's roof, conductive poles, and communication systems [224]. The Automatic Connecting System controls and monitors the connection device for the conductive charger attached to the infrastructure above the vehicle [224]. The

Automatic Connecting System includes an Automatic Connecting Device, which connects or disconnects the conductive charger to the electric bus-charging interface.

These pantographs are like the ones that have been used for decades on trains and trams. There are two types of conductive chargers in electric buses, depending on where the pantograph is located: onboard and off-board [225]. In the onboard conductive charging solution, the pantograph is situated directly on the bus's roof. This roof-mounted equipment will contact the overhead supply system located at the charging station. In the case of off-board conductive charging, the pantograph is installed in the charger's overhead mast, so only a contact system is required onto the bus, reducing infrastructure cost and the bus's overall weight. Buses are charged when they arrive at the charging station, and the pantograph is extended to make electrical contact; this process is usually automated and takes several seconds. The possibility of installing onboard or off-board systems provides a high degree of flexibility. Conductive systems can transfer high power, with capacities ranging from 100 kW to 450 kW; tests are already being made with 600 kW chargers [226]. Hence, such systems make it possible to fully charge an electric bus in 4-10 minutes [218] [219].

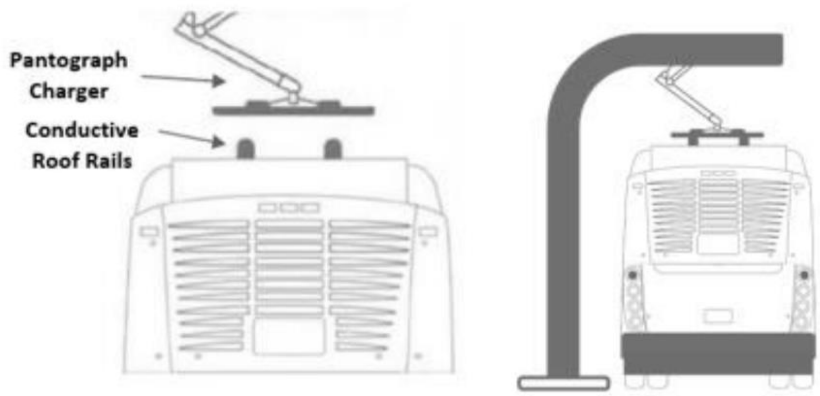

Figure 2-12 Pantograph System (Source: [227]**)**

Conductive chargers are offered by various companies worldwide, such as Siemens, ABB, and Opbrid, and have already been tested in many cities, among which Stockholm can be found [225] [226]. Some of the advantages of conductive charging are acceptable efficiency levels and lower exposure to electromagnetic fields than inductive charging systems. The main disadvantages of conductive charging technology are high maintenance costs due to the contact between the conductor and the collector, visual impact, exposure to the external environment, and vandalism.

Fig.2.12 illustrates a typical Pantograph system. The automatic pantograph charger connected to the High Voltage source contacts charging rails (Top Down: Pantograph mounted to charging station and Bottom-Up: Pantograph mounted to the electric bus). The wireless position sensors detect when the electric bus is located at the charging station and connect. High power at the rate of up to 600 kW is transferred to the onboard battery. The charging is typically about 4 to 6 minutes, making charging during layovers at route terminals and endpoints possible with the pantograph system.

2.5.2.4 The Battery Swapping Station (BSS)

A Battery Swapping Station (BSS) is where EV users can swap their discharged battery with a charged battery [228]. Hence, a large battery stockpile is needed to meet the customers' demands. It is usually assumed that the batteries are owned by the BSS and rented to customers [229], [230]. The key benefit of BSS for customers is that they can immediately have a charged battery, like petrol stations. Moreover, the BSS generally benefits EV batteries since their lives are not affected when they are not charged at fast charging levels. This is possible when the number of batteries owned by a BSS is many, and they have time flexibility to charge them. The BSS usually includes a vehicle platform, lift, alignment, equipment rollers, battery lifts, conveyor shuttles, storage racks, rails, and electrical connection alignments [231].

The main electrical components of the BSS include a distribution transformer, AC/DC chargers, battery packs, and a battery energy control module [231]. The transformer converts the grid's high voltage to a lower voltage suitable for the batteries. Since the batteries require DC energy, the AC/DC converts the AC energy from the transformer. The control module allows charging at different power levels depending on grid requirements. One of the key advantages of BSSs is that a third party might own the batteries and be responsible for swapping them with fully charged ones, monitoring their health, and retiring the batteries when they are no longer suitable. Furthermore, the BSS offers time benefits to users, like typical petrol stations, avoiding long wait times. The main limitations of BSS include standardisation of EV battery packs, acceptance of the BSS model, and the reliable estimation of battery state-of-health.

The Better Place business model, which requires customers to purchase a vehicle but leases the Better Place battery pack [230], is an example of a BSS business plan. Customers must pay a predetermined cost for up to a specified amount of miles driven per year and re-charge their cars at Better Place-provided charge stations and a network of public charging stations. Consumers would drive to the battery's limits for longer journeys and be routed to the next battery-swapping station, where robotic technology would install a new one in around 5 minutes. Better Place's idea is to separate the battery from the vehicle physically. Better Place pioneered automatic battery-switching stations, which use robots to replace a drained battery with a fully charged battery in roughly five minutes. Battery-swapping stations are preferable to chargers because they work faster; they have installed roughly 37 battery-swapping stations in Israel. Better Place can lower the price of an electric automobile and upgrade the battery as technology advances by keeping ownership of the battery. Better Place lowers the car's price, similar to how wireless phone providers discount their hardware and make money by selling minutes. It charges vehicle owners a monthly price for the battery and electricity, which is calculated based on the number of miles they travel [232], [233].

2.6 Battery Technology

The battery is the most expensive component of most battery electric vehicles [234]. Besides, they are accountable for the heavyweights of the battery-electric buses. These huge weights are due to the high energy density required to power electric vehicles. The electric bus batteries are primarily based on lithium-ion technology. The capacity of the battery is not constant throughout its lifetime. The capacity decreases progressively with the battery age. The common factors responsible for decreased capacity include charging-discharging cycles, temperature, and high Deep of Discharge (DoD) [235].

As fast charging is becoming increasingly common, slowing down the battery ageing at a high State of Charge (SoC) requires the charging current to be decreased to avoid exceeding the battery's upper limit voltage [191]. Therefore, an SoC threshold must be implemented to keep the maximum and minimum charging values in an optimal range to enhance the battery's lifetime. The maximum and minimum SoC threshold usually ranges between 20% to 80% of the battery's capacity.

Another essential factor that must be highlighted is the interaction between re-charging infrastructures and the onboard batteries' requirements. For instance, the overnight charging strategy reduces the charging frequency. On the other hand, the opportunity charging requires frequent onboard battery charging. The energy demand is usually during the daily peak, impacting the grid if the charging is not controlled. The overnight charging strategy is more suitable for developed countries where grid supply is reliable.

The opportunity charging method ensures that charging occurs when and where grid supply is present and available or with the usage of solar renewable energy sources and is seen to be appropriate for developing countries with poor grid reliability or supply security. The opportunity charging method can also be designed to lower the cost of a battery-electric bus by accommodating a reduced onboard battery size. However, a high-capacity charger must be used more frequently and quickly to recharge the buses.

It should be noted that the battery in an EV is its most expensive component, accounting for around 50% of its entire cost [236]; consequently, the affordability of EVs is directly related to the affordability of a battery. As a result, as battery costs fall, the charging infrastructure required for "small onboard batteries" and the opportunity charging model may alter.

2.7 Battery electric bus energy consumption modelling

There is a considerable body of research work addressing the analysis of energy consumption of battery electric bus fleets in the city transit networks; some of these works include [191], [237]–[239]. The transit bus's energy usage is used to forecast transit service costs. The total energy consumed by an electric bus is usually the aggregate of three loads: (1) energy consumed by the traction system to drive the vehicle, (2) energy consumed by the heating, ventilation, and air conditioning HVAC system, and (3) energy consumed by the rest of the electrical system, such as lighting or control systems. [240]. With accurate estimation under real-world traffic conditions, the schedule and the charging demand of the BEBs can be accurately defined [44]. In [239], the authors calculate the energy consumption of battery-electric buses by adding the kinetic, potential, and rotational components of the vehicle's propulsion. Consideration is given to energy loss due to frictional forces, rolling resistance, and HVAC. The combined energy output from the vehicle's onboard battery and energy obtained by regenerative braking equals the energy consumed for constant propulsion and the constant BEB regeneration efficiency. The model considered in this work did not consider the variable efficiency of vehicle propulsion and regeneration as a function of torque and rotational speed. The authors of [238] present a backward modelling method for calculating the energy consumption of a battery-electric bus. The authors investigated a particular driving cycle for city buses and the longitudinal vehicle dynamics as a function of velocity in this work. The cumulative force acting on the bus is determined by adding the aerodynamic, rolling, and climbing resistance forces and the HVAC loads.

The BEB's energy consumption models are usually defined based on the relationship between the energy consumption rate and their impact factors [241]. This energy consumption rate is mostly expressed in kWh/km when considering the modelling of electric bus transit fleets. In [242], the energy consumption estimated for 10m BEB varies from 1.6-3.2 kWh/km and 1.7-4.1 kWh/km for 12m BEB. In [243], the authors present a single-deck and double-deck BEB energy consumption average of 1.6 and 2.5, respectively. In [242], the authors quantified the double-deck intercity BEB energy consumption rate range between 2.4-4.5 kWh/km. In [244], the BEB energy consumption is given as 0.8–1.2 kWh/km, and in [195], it is estimated to be1.5 kWh/km.

Calculating the electric bus energy consumption without reflecting the high unpredictability of real-world situations is usually inaccurate [195], [243]. Moreover, overlooking uncertainty in the BEB energy consumption and actual travel time could result in over-sizing or under-sizing the BEB battery, leading to an infeasible plan for the transit system [243]. Therefore, it is essential to evaluate the BEB energy consumption based on the transit route characteristic that incorporates the uncertainty in speed profiles. Numerous works of literature have investigated the factors that influence the energy consumption of the battery-electric bus. The factors that typically affect bus fleets' energy consumption include road topography, battery weight, the weather, and load variation [239], [244]. Besides, the energy consumption of BEBs can be can also be influenced by external factors such as route traffic congestion [44]. In [245], the authors present a model of BEB that uses wireless power transfer technology. The authors estimate the energy demand between each of the stops using predefined velocity profiles in this work. Nonetheless, the authors fail to account for unpredictability in speed and uncertainty in energy demand.

In [246], the authors considered the grey relational analysis method to examine the impact of external factors on the battery-electric bus's energy consumption. The factors considered include the day of the week (weekday or weekend), weather conditions (temperature, fog, or rain), route length, the BEB HVAC, and route traffic situation. These outlined factors are modelled as numerical values using fuzzy rules. A wavelet neural network was also adopted to train these external factors and the BEB energy consumption data to develop a prediction model. The developed prediction model uses actual survey data that reflects the numerous external factors data to train the wavelet neural network. Nonetheless, most transit bus corporations do not have sufficient data to develop and operationalise the neural network model. [247] and [248] used the vehicle dynamics equation to model BEB with actual driving data for a specific route. The historical data examined are the bus drive cycles that do not consider uncertainties due to route traffic congestion.

In [244], the authors present a BEB energy consumption simulation model that integrates different operating conditions using measured data from the existing bus transit network. The auxiliary power was considered 6 kW in mild weather conditions, 14 kW in cold or hot conditions, and 22 kW in extremely cold conditions. In this work, the author estimates the gross weight of the BEB as 3750kg by assuming the number of onboard passengers to be 50. The authors in [241] considered the BEB energy consumption in a real-world traffic congestion scenario. The model considered in this work is a data-driven model that computes the route energy consumptions based on both the positive kinetic energy and the regenerative braking of the BEB. In [249], the authors present a multi-objective stochastic predictive control model for evaluating BEB energy consumption. A Markov-chain-based stochastic driver model was developed in this work to determine the BEB demand power in various speed ranges. The authors, however, did not take into account real-world driving cycles. In [250], the author computes the BEB energy consumption based on the distance between stops and the BEB average speed. This work represents the probability of traffic light stops with a binomial distribution function. The route elevation profile is used to determine the average slopes between stops. In [251], the authors use the vehicle dynamics model and support vector machine method to predict BEB driving cycle. In this work, the road slope is assumed to have the upper and lower limit of 3% and -3%, respectively. Also, the authors in [252] use the vehicle longitudinal dynamics model to estimate the power consumption of BEB. In this work, the HVAC is assumed to be constant power of 6 kW. In [195], the authors develop a model to optimise charging infrastructure for BEBs in urban settings. The authors presumed in this work that the downward sailing along the route compensates for any energy consumption increases caused by the uphill direction.

The data published by the BEBs manufacturer are usually considered as the nominal value because this data does not reflect the real-world factors that can affect the BEB energy consumption value. Field trial demonstration and simulation software with data tailored toward the specific case studies have been used to estimate the real-world value of BEB energy consumption figures for a particular BEB's transit route. In [238], the authors compared the simulated energy consumption with the energy consumption measured by Proterra using the central business district CBD driving cycle. The authors in [237] validate their model using the Standardised on-road test cycles (SORT) developed by the International Association of Public Transport.

In [253], the authors developed an algorithm that generates arbitrary driving cycles based on the original cycle characteristics of transit buses. In comparison to the original vehicle patterns, a random driving cycle is created that produces an equal speed distribution and power spectrum. This is promising in terms of providing the basis for improving the realism of driving patterns, but as the modelling approach requires an accurate driving cycle to start with might be unavailable without a real-life demonstration or at least sufficient measured data. SUMO is an open-source traffic simulation platform developed by the Institute of Transportation Systems at the German Aerospace Center (Simulation of Urban Mobility). To simulate an effective driving cycle, the SUMO needs only a few input parameters (such as the bus route and vehicle type). [254]. The SUMO is a microscopic model that allows the simulation of each vehicle as a separate entity.

Transit data, topography and GPS data and vehicle characteristics can be supplied as the model input data. The simulation output is the velocity of the targeted vehicles at any time. The authors [247] generate a driving cycle for plugin hybrid cars using a 2D simplistic SUMO version. This version of SUMO does not account for the height variations of the road. In [255], the authors introduce a 3D SUMO that incorporates topographic data as part of the input parameters. The 3D feature enhances the accuracy of the generated driving cycle. In [238], the authors examine the possibility of combining testing cycles for modelling purposes to meet up with some specific road conditions. A typical example is the Manhattan Bus Cycle (MBC) combination, and the City Suburban Cycle (CSC) is used to represent a suburban driving pattern.

Models of vehicle energy consumption can be grouped into forwarding and backward models. Backward models measure the tractive contribution required at the wheels and "function backwards" towards the engine. Alternatively, "forward models" begin with the engine and function with transmitted and reflected torque [256]. The Advanced Vehicle Simulator (ADVISOR) will simulate in both directions simultaneously [257]. The energy and signal flow in the forward-facing models are identical to the actual flows in the powertrain systems of real vehicles. The calculation starts with the energy source and progresses to the vehicle's propulsion system [256]. The models that face backwards operate in the opposite direction of the real tractive energy flow. The downstream component's energy requirements determine the energy consumed by the upstream component. The driving cycle establishes the initial energy requirement for the part immediately adjacent to the input. The simulation then continues component by component until the energy source is reached [258], [259]. The ADVISOR was first established at the National Renewable Energy Laboratory in November 1994. It was developed as an analysis tool to assist the US Department of Energy (DOE) in developing hybrid electric vehicle (HEV) technologies through the Hybrid Electric Vehicle Propulsion System contracts with Ford, General Motors, and DaimlerChrysler [257]. Its primary function is to demonstrate the system-level interactions between hybrid and electric vehicle components and their impact on vehicle efficiency and fuel economy. The authors of [234] used the ADVISOR to assess solar reflective car shells. The authors in [100] calculated the BEB's kWh/km energy consumption along particular routes using the ADVISOR model. The authors used the BEB speed profile, route topography, and auxiliary load rating in this work to improve the accuracy of the BEB energy consumption value. Nonetheless, the author neglects to account for the effect of weather-related uncertainty on the BEB energy consumption value.

Milton Keynes's demonstration project in the United Kingdom successfully converted from a diesel fleet to an electric bus transit system in 2014 [260]. There are eight buses in the fleet. The transit route is 24 kilometres long, and buses run 17 hours a day. Inductive chargers were installed to improve the range of buses, with some at the depot and others along the route for opportunity charging. When evaluating the Milton Keynes project, a comparison was made between the projected average energy usage of the buses and the five-monthly recorded energy consumption values. Extreme weather events result in a change in the auxiliary load, which increases BEB energy consumption.

Additionally, the experiment considered the effect of the driver's performance on the bus's average energy consumption. The driving demonstration demonstrates that the average energy consumption of the bus ranges between one and two kWh/mile. Additionally, it was discovered that the path topography accounted for 1-2% of the transit bus's energy consumption. Additionally, this work explores the reliability of the power charger by comparing the power drawn from the grid to the power supplied to the battery. The average performance of a charger is 78%. This study of the Milton Keynes project demonstrates that the buses' actual output is consistent with the simulated results.

The literature reviewed in this section illustrates that factors affecting bus fleets' energy consumption typically include road topography, battery weight, temperature, and load variance [239], [244]. Additionally, external factors such as route traffic congestion, which is a characteristic of a transit bus speed profile, may affect the energy consumption of BEBs [44]. As a result, it is critical to assess BEB energy consumption using transit route characteristics that account for speed profile uncertainty. As a result, this thesis develops a longitudinal dynamic model of BEBs transit and performs backward simulations using the ADVISOR software.

2.8 Stochastic EV Charging Impact and Integration of the BEB Charging demand into the Electrical Distribution System

The widespread adoption of EVs will impact incumbent power systems if left unmanaged. There would be an increase in the grid's load, resulting in an increased likelihood of overvoltage and overcurrent events, increased harmonic and reactive current, voltage imbalances, and interruptions [261]. There is already a considerable body of research work addressing these issues, and a common theme is the need to apply demand-side management to control the timing of these additional power system loads. Examples include various factors for evaluating PHEVs' impact on the distribution network, such as driving patterns, charging characteristics, charge timing, and vehicle penetration [262]. In [263], the authors explore stochastic modelling and simulation techniques to evaluate the effect of electric vehicle charging demands on the distribution network to alleviate power security problems that may emerge as a result of widespread EV adoption. Stochastic modelling was used to assess over-current and under-voltage on a three-phase delivery load flow analysis by examining driving patterns, charging characteristics, charging timing, and vehicle penetration. The Roulette wheel selection principle and Monte Carlo simulations are used in this work by introducing different uncertainties into the simulation. The author's numerical results indicate that smart charging may help mitigate power security concerns that may arise due to EV adoption. The authors, however, neglect to account for regular and hourly vehicle delivery, which would increase their model's accuracy. The authors in [264] and [265] considered the impact of uncoordinated EV charging on the grid and how coordinated charging of EVs can reduce power losses. In [265], the authors specifically look into deterministic and stochastic analyses of the potential load impacts on actual distribution circuits to investigate if controlled charging of the PEVs can potentially reduce the loading impacts. In this work, the stochastic results show that the temporal and spatial diversity of PEVs charging on the system mitigates mass overloads of any particular asset class for penetration levels in the range of 2-8%.

In [266], the stochastic approach based on a Monte Carlo simulation is applied to investigate the impact of EV charging on the load distribution system. The system considered is where both the standard charging at home and quick charge service at a public charging station are considered. In this work, the authors assumed the number of EVs to be charged in a local facility is based on the sum of local EVs owned by households in the studied area and EVs arriving from external areas. In this paper, the simulation approach is based on Monte Carlo indicates that inadequate load capacity occurs during peak hours of the day and early night-time. However, the authors fail to account for the possibility of a strategic valley filling to manage the peak hours' electric load. In [267], the authors compare the possible effect of charging electric vehicles at home and fast-charging stations on transformer loading and system bus voltage. The system considered is where the impact of the EV fast-charging stations on the distribution grid is evaluated. In this work, the stochastic charging model is applied. The result indicated that PEV charging at home has minimum impact on the distribution grid even at 100% penetration level and fast charging stations affect transformer loading and system bus voltage. This paper suggested that local energy storage and voltage conditioning devices, such as SVC (Static Var Compensator), should be used at a fast-charging station to improve system reliability.

In [268], the authors coordinate the charging of multiple plug-in hybrid electric vehicles in residential distribution grids to minimise the power losses and maximise the main grid load factor. The coordinated charging considered is one where stochastic programming is applied for 24 hours daily profile. The PHEV is taken to have 30% penetration in the case study considered, while the power losses and maximum voltage deviation for the charging period were measured. In this work, the comparative evaluation of a stochastic modelling approach and a deterministic approach reveals that a stochastic modelling approach minimises power losses and voltage deviation. In [269], the authors examine the optimisation strategy of controlled electric vehicle charging by considering the demand-side response and regional wind and photovoltaic to optimise the grid's peak-valley difference. The strategic EV-controlled charging considered is where the probability model of wind and PV power output is developed. In this work, a formal optimisation based on genetic algorithms is used to good effect to efficiently determine the start and end time of the valley price and the peak-valley price.

In [270], the authors investigate the future electric vehicle charging demand to propose an algorithm that can shift vehicle charging to absorb surplus wind generation to mitigate the increase in peak load, low voltage, and substation overloading. The model considered is when the domestic car pattern is studied by analysing the United Kingdom time of use data. A Monte Carlo simulation approach based on car departure and arrival is used to determine the car location in this work. The authors provide the basis to estimate the future impact of electric vehicle charging on the distribution transformer, especially in a scenario where the householders start charging as soon as they arrive home. However, the authors fail to account for the impact of commercial vehicles on the distribution grid. In [271], the authors propose optimal charging of electric vehicles to mitigate the distribution constraint (due to the growing uptake of EVs) by moving the charging to off-peak periods. The optimal charging considered is when electric vehicle charging is regarded as a linear optimisation problem that considers both the present and the anticipated constraints in the distribution network over a finite charging horizon. In this paper, a linear optimisation based on charging demand and vehicle arrival and departure is used with two objectives: maximising all vehicles' overall charging and minimising charging cost. The authors provide essential cost and time optimisation. The authors estimated that uncontrolled electric vehicle charging could lead to network failures at only 10 to 15 % uptake rates. The system should accommodate more than 80 % of the proposed EVs load with optimal load control.

Scientific research, international agencies, public attention, and political interest in problems associated with transportation, energy, and the environment motivate the bus transit system's electrification [101]. The power grid for public transportation is distinct from consumers', as the charging infrastructure for electric public transportation is more centralised (i.e., terminals, depots, and bus stops) [33]. As a result, charging technologies are expected to create an entirely new transportation–energy paradigm that will be incomprehensible to transit and utility operators and other stakeholders [102]. Additionally, transit bus operators have rigid bus schedules and operating logistics that must be maintained throughout the service of BEB transit systems [100]. According to [272], BEBs may stick to their scheduled operational schedules if an acceptable charging strategy is implemented.

On the other hand, the distribution network operators would have right to be concerned about the potential adverse effects of electrified bus transit networks on power grids. The authors of [174] note that charging scheduled BEBs can result in power losses and compromise the power system's stability. According to [82], incentive charging of BEBs results in voltage control problems in power distribution networks. According to [238], the BEB waiting time for charging reduces the frequency of transit services. Recent research on the smooth adoption of electrified bus transit systems includes [273], which provides a scenario-based BEB transit service scheduling method for routing BEB fleets. However, it does not consider the transit system's adherence to the BEB's operating schedule. The authors of [203] analyse a charging schedule for transit BEBs to minimise the BEB's charging cost. Nonetheless, a fixed charging and queue duration was set. The authors of [274] develop a BEB transit design algorithm to minimise charging infrastructure construction costs. The authors presume that the number of chargers is equal to the number of BEBs in this work. The authors of [81] describe how to design electrified bus transit systems using a mixed-integer linear algorithm. The size of the BEBs' onboard battery capacity has been predetermined in this work.

As part of the work of this thesis, a priority charging strategy is designed to mitigate the impact of the BEB charging on the distribution power system. This priority charging mitigates the BEB charging impact by aggerating the BEB charging demand for the scheduled operational period.

2.9 Electric Vehicles Charging Demonstration with Microgrids and Off-Grid Systems

With off-grid systems (e.g. mini-grids) playing an important role in energy provision in developing countries, it is natural to consider them as part of the literature review of this thesis. In many cases, there will be insufficient capacity available to accommodate EVs, as this was never a consideration at the design stage. However, in some cases, there are complementary benefits from considering renewable dense mini-grids with the charging issues of EV that can read across to the BEB focus of his work.

In [238], microgrids (a collection of DERs, including RES and ESS, and loads that operate locally as a single controlled entity) and their application with transportation electrifications are discussed. It is proposed in this work that increasing EV adoption would increase the microgrid's ability to promote renewable energy sources and the vehicle's efficiency in providing grid-to-vehicle services. The authors argued that electrifying the transportation system would minimise reliance on fossil fuels by increasing access to a broader range of renewable energy sources. The coordination of EV involvement in load frequency regulation in isolated microgrids MGs is discussed in [275] to minimise frequency deviances and support the microgrids' device stability. The authors added EVs to the MG to minimise frequency deviations and maintain device stability by efficient charging/discharging scheduling of EVs. When the microgrid's frequency is threatened, EVs will absorb (inject) excess (deficit) energy and act as energy storage systems. The success of the proposed plan is evaluated under a variety of operational scenarios. Additionally, this work suggested that implementing this proposed strategy would increase the overall MG operator's benefit while substantially reducing emissions, but this is not quantified.

In [276], an ‘ideal’ configuration of EV charging stations is considered by examining different energy sources to minimise device lifecycle costs while minimising environmental emissions. The EV charging stations that are being considered are those that are powered by renewable energy and diesel. The isolated microgrid is planned to meet the charging needs of electric vehicles and increase travel distance. Additionally, this work looks at grid-connected electric vehicle charging stations, which are considered the most viable alternative. The possibilities for rural areas to use electric Tuk-tuk battery charging stations are discussed in [95]. A tuk-tuk is a three-wheeled vehicle primarily used in Asia and Africa for public transportation. Wind and photovoltaic renewable energy sources and standalone battery storage are used to power the planned EV charging station. This study compared some EV charging scenarios using the HOMER framework. These comparisons are based on equipment design, energy production, and financial feasibility over a 20-year project. The system components are rated using the worst-case scenario. The simulation results indicate that the optimal operating scenario is to charge multiple vehicles consecutively when operating the station at maximum capacity for an entire day or 24 hours continuously.

The authors of [277] investigate a direct current DC microgrid for future electric vehicle charging stations using an energetic macroscopic representation and a maximum control structure. The system is a photovoltaic-based urban DC microgrid that charges plug-in electric vehicles and supplies a DC load. Additionally, the system considered the connection to the public grid. The control system is designed to obtain the maximum amount of energy possible from the photovoltaic system and regulate the power flow for the state of charge of electric vehicles and the DC load power demand. The energetic macroscopic representation (EMR) and maximum control structure are used to model the urban DC microgrid. According to the simulation results, a DC microgrid device can power five PEV chargers and a few household appliances. Additionally, the results indicated that the amount of power drawn from the public grid could be monitored and decreased by using the photovoltaic energy within the microgrid. [96] explains the design of a low-cost electric vehicle charging station using four 255-watt solar panels, batteries, a charge controller, and an inverter. The experiment lasted three months and involved a SMART Electric Drive vehicle successfully charged solely with solar energy. The proposed "Sun-Car System" offers a low-cost option for lower-income communities, such as those found on Indian reservations in the southwestern United States and Africa. It illustrates the fundamentals of using photovoltaic energy to charge electric vehicles. However, the demonstrated capacity is small, as the car needed at least eight hours of charging to gain 12 miles

[278] investigates the economics of microgrid planning algorithms in conjunction with electric vehicle charging demands to determine the most economically feasible design that maximises renewable energy use. This study uses HOMER to perform a formal optimisation based on the optimal microgrid configurations for charging systems and various EV penetration ratios. The authors of [279] discuss photovoltaic (PV) integration into low voltage (LV) grid feeders in order to meet environmental targets. The energy storage systems (ESS) within a public EV charging station regulate voltage, ensure power quality during EV charging switching events, and store and dispatch generated energy during the PV peak time (night or evening). [280] examines the design of a device that automatically switches between solar, battery, and grid electricity, with the solar generator taking precedence. The system considered is one in which an EV is connected to the charger, and the PV system cannot produce enough power to charge the EV; the battery or the utility grid will support it. While no electric vehicle is plugged in, PV energy is stored in the battery. Excess PV energy is transmitted to the electricity grid when the battery is completely charged. Grid power is used during off-peak hours to restore the battery to its optimum level if it is depleted. [281] describes an 'optimal' energy management scheme for EV integration into a microgrid that utilises an autonomous controller to schedule the charging and discharging of the EV battery for optimal energy

management. The optimal energy management scheme considered is when the electric vehicles (EVs) are connected to a charging station with a microgrid system. The peak charging and discharging schedule is determined in this work by predicting the EV's trip pattern.

As indicated in the introduction chapter, the focus of this thesis is on developing countries where the security of grid supply is already a concern. As a result, proper consideration for an energy system that can supply the energy demand of the electrified bus transit system is critical. This proposed transit-based energy system is expected to incorporate a variety of energy sources, most notably renewable energy sources such as solar and wind energy, and an energy storage system (ESS). Additionally, a grid source and a diesel generator can be added to supplement renewable energy sources (The diesel generator is considered because of the regular 'black-outs' experienced by domestic and industrial customers in developing countries [282]). As a result, the transit energy system only buys from the grid when renewable energy sources are in limited supply (i.e. when primary sources such as solar and ESS cannot meet the system's energy requirement) and sells to the grid when there is a surplus of generated energy. The diesel generator is only considered for usage in an emergency, such as when both the renewable energy source and the grid cannot supply transit demand. The use of this diesel generator is limited to reducing the system's CO_2 emissions.

2.10 Chapter summary

This chapter provides the background for the BRT focus of this thesis. An overview of the most recent studies on the modelling and simulation of battery-electric bus energy consumption is included. The published literature examines various infrastructure options and the design, implementation, and optimisation of their operational schedules and this is linked to the work of this thesis. Most notably, a summary of the literature on various strategies and technologies that can be used to promote the electrification of public transit systems in developed countries to reduce GHG emissions and congestion was also presented.

There are numerous drawbacks to adopting the bus manufacturer's nominal bus energy demand for transit system modelling. The drawbacks include one or more of the following:: 1) necessitate high-resolution speed profiles, which are difficult to obtain due to a lack of operational data and related costs; 2) ignore the difficulty and variation of detailed real-world operating conditions, such as route traffic conditions; and 3) depend on standard driving cycles, which ignore randomness in speed and energy demand volatility. The work of this thesis will incorporate five traffic flow conditions into the model to address the above concerns, thus increasing the model's accuracy. The data is focused on the volume of traffic and the road capability, with traffic conditions graded as free, move, appropriate, inappropriate, and critical. The trip time, traffic conditions, driver behaviour, and topography of the bus route will all be used to capture the effects of points 1 and 2 discretely.

Existing attempts to design charging infrastructures for BEB fleets in a transit system have not fully accounted for: (i) energy consumption at each BEB fleet charging terminal by analysing BEB energy demand and classifying the demand according to charging priority; (ii) a multi-terminal model based on inductive charging infrastructure that reduces the size of the electric vehicle's on-board battery. (iii) a hybrid solution that incorporates both conductive and inductive charging systems within a transit network in order to minimise operational downtime caused by BEB charging duration. In developing countries, transit operators and power utilities face both technical and operational challenges when integrating ready-made BEB systems. As a result, research and development efforts must be made to study these problems and develop mitigation strategies.

Thirdly, the efficient adoption of BEBs requires a multi-terminal deployment of transit bus infrastructure. As a result, these BEBs charging stations must be optimally sized to minimise capital expenditure and maximise operating profit. This profitability and expenditure study would encourage private and public investments in the electrification of public transit systems. As a result, both the government and private investors, including the BEB fleet operators, must have analytical resources available to analyse BEB charging stations and forecast financial returns based on the energy market and public transport demand. Nonetheless, the literature has included several general models for sizing charging infrastructures. However, prior to these studies, the presentation of a mathematical model converted into a computational model was unclear. Most notably, this study is focused on the electrification of bus rapid transit systems compared to the previous work presented in [105], which explored an empirical model for estimating the size of electric and hydrogen-based fuelling stations. Additionally, this study estimates the transit energy demand profile that can be extended to evaluate renewable energy systems' suitability by determining the renewable energy system's potential to electrify public transit in developing countries with an already challenged grid. This resource modelling approach is expected to differ from previous research that focused exclusively on grid integration.

3 BEB TRANSIT FLEET DESIGN AND MATHEMATICAL MODELLING

The preceding chapter presents a background and coverage of the relevant literature on electrification of BRT systems and the gaps in the literature, which involve considering various infrastructure options and the design, use, and optimisation of BEBs' operational schedules. The chapter summarises recent research on the modelling and simulation of the energy usage of battery-electric buses. The literature studies focus on various infrastructure options and their design, implementation, and optimisation of operational schedules. Notably, a literature review on different methods and innovations for promoting the electrification of public transit systems in developing countries was also addressed to minimise GHG emissions and congestion.

This chapter presents the details of the BRT system electrification modelling and the mathematical model that manages the routing and charging for BEBs that will be used in this thesis. In addition, a mathematical optimisation process for determining the critical design variables of allocation of the conductive and inductive chargers is also presented.

BRTs are designed to serve the public in densely populated metropolitan areas where traffic patterns and volumes permit service along defined routes at scheduled intervals [283]. Therefore, it is critical to guarantee that the proposed model replicates and integrates the practical elements of the standard BRT operation system while designing charging infrastructure for the electrification of BRT systems. The operational timetable for the transit network is part of the BEB's transit fleet concept. This would result in a transit network electrification model that preserves the operational requirements of the transit network. Furthermore, transit fleet data and network architecture (i.e., BEB weight, efficiency, speed profiles, route distance, and topography) influence BEB energy consumption. As a result, the output of the BEB transit fleet model and the energy consumption model is fed into the model that allocates charging infrastructure for the BEB transit network. The complete BRT transit model (Figure 3-1) aims to find the optimal configuration for an electric BRT fleet, including BEB battery capacity, location, and charger number. Furthermore, the model calculates the BEB transit energy demand profile.

Figure 3-1 provides a comprehensive visual overview of the various modelling stages for the BRT modelling that will be covered in this chapter. It starts on the left-hand side with the design of the transit fleet routing model, then the BEB energy consumption model, the modelling of charging infrastructure for the BRT transit fleets and the estimation of transit energy demand.

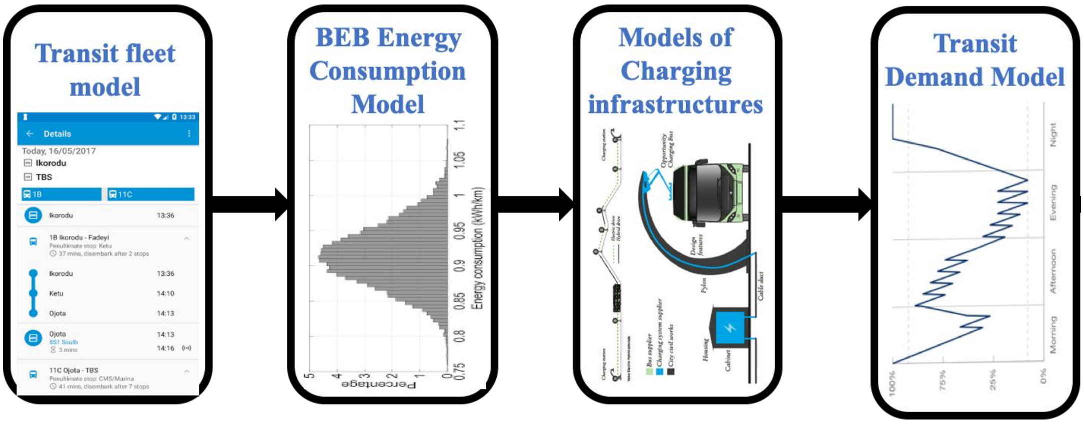

Figure 3-1: The stepwise model of the BRT electrification process

The following sections will describe each of the different feature elements shown in Figure 3.1. Firstly, the transit fleet routing model design that links the operation timetable will be detailed. Secondly, the mathematical model for the BEB energy consumption will be developed based on a longitudinal method that accounts for the dynamics. The methodology for modelling charging infrastructure for the BRT transit fleets is then developed along with the mathematical and optimisation formulations for the novel BEB charging system model, multi-terminal charging model, the integrated charging model and the BEB transit energy demand estimation. Finally, a novel mathematical model is developed to allocate multi-terminal inductive charging infrastructure to optimise power transmitter placement, inductive cable length, battery capacity, and the cost of an electrified transit system.

3.1 Transit fleet mathematical model

This section describes the mathematical modelling of the BEBs transit feet. Prior work that has influenced the approach of this thesis concerning the development of a mathematical model for the bus transit system includes the work reported in [284]. These authors present a broad and complete review of state-of-the-art models and approaches for solving public transit problems at strategic, tactical and operational levels. Also, the authors in [100] present an integrated model for optimal battery-electric bus systems configuration. The transit network operational schedule is added to the BEBs transit fleet model to preserve the transit network operational requirement. In [285], the authors propose a classification of approaches dealing with the design, frequency setting, and timetabling of transit lines and their combinations. As a result, the transit network schedule is influenced by various elements, the most important of which are transit route networks, passenger demand, transfer coordination, and fleet size. The authors of [286] put together many contributions to vehicle routing and crew scheduling, schedule optimisation, and service management for various modes of public transportation. This study demonstrates that a successful transition to electric transit systems necessitates adhering to the operation schedule.

These authors' work emphasised the importance of public timetables in meeting public transportation demands. This demand varies according to the hours of the day, the days of the week, the season, and even the year. In addittion, it represents the community's transportation needs for enterprise, industry, culture, education, social, and recreational activities. This section employs a modelling method similar to that described in [100] for determining BRT charging requirements. In contrast, this section presents a mathematical representation of the proposed bus transit timetable's proposed model in an opportunity charging scenario.

In this work, the number of electric buses is represented in the form of sets as:

$$\mathcal{B} = \{1, 2, 3, . . . , b, . . . , N_b\} \tag{3.1}$$

Where $\mathcal{B}$ is the set of buses in the transit network, b is the b-th bus in the network BEBs and N_b, is the maximum number of BEBs.

Similarly, the number of bus routes is represented in the form of sets as:

$$\mathcal{R} = \{1, 2, 3, . . . , r, . . . , N_r\} \tag{3.2}$$

Where $\mathcal{R}$ is the set of routes in the transit network, r is the *i*ndices for the r-th route and N_r, is the maximum number of routes in the transit network.

The buses are allocated to bus routes based on the bus transit operational requirements, which is mathematically represented in sets of assignments D. Each set of assignments throughout the bus operating hours is given as:

$$D = \{1, 2, 3, . . . , d, . . . , N_d\} \ \forall \ d = [b, r, S_d] \tag{3.3}$$

Where in each assignment *d*, bus *b* is scheduled for route 'r' for a prearranged scheduling period, defined as follows:

$$S_d = [t_d^s, t_d^{end}, t_d^{trip}, \ t_d^{wait}, \ N_d^{trip}] \ \forall \ d \in D \tag{3.4}$$

Where S_d is the set of the operational schedule for the assignment *d*. The $\mathrm{S_d}$ is like a typical transit timetable.cla

Figure 3-2 shows a diagram for transit bus b allocation to the route presented in (3.3) and (3.4). As depicted in the figure, the scheduled time interval for each trip assignment 'd' is defined by a start time t_d^s, and an end time t_d^{end} for a specific allocated route 'r' in minuties.

In sequence, each transit bus operates the given number of trips N_d^{trip} in a pre-quantified time, which is followed by a given waiting/dwelling time t_d^{wait} in minuties i.e., when the bus is dwelling at the bus terminal station after each trip. This waiting is considered as being available for charging time for BEBs. Notably, each bus *b* may have more than one assignment with dissimilar routes and/or schedule during the daily operating hours.

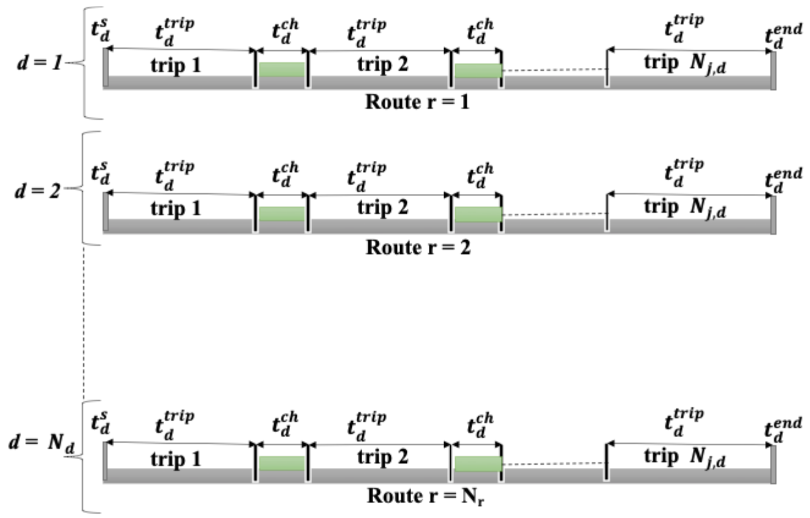

Figure 3-2 Transit schedule for assignments *d*

Additionally, it is also important to note that the allocated buses and their operation schedules for a specific route 'r' usually vary throughout the daily operation (i.e., peak versus off-peak operation); the set of assigned trips for each bus in each assignment *d* can be defined as:

$$J_d = \{1, 2, 3 \ldots, j, \ldots, N_{j,d}\} \; \forall \; d \in D \tag{3.5}$$

Where J_d is the set of trips within assignment *d* and *j* indices for the BEB trips.

The number of trips in each allocation is computed as:

$$N_d^{trip} = \frac{(t_d^{end} - t_d^{s}) + t_d^{wait}}{t_d^{cycle}} \; \forall \; d \in D \tag{3.6}$$

The cycle time for each assignment *d* is given as follows:

$$t_d^{cycle} = t_d^{trip} + t_d^{wait} \; \forall \; d \in D \tag{3.7}$$

This mathematical approach will be used in this thesis to capture the transit data and estimate the transit demand for BEBs that are operating in the transit network. It has been structured in such a way to reflect operational aspects that planners use to define when they are developing the timetable and to enable the analysis of transit data [100]. The next section presents the BEB energy consumption model.

3.2 BEB Energy Consumption Model

The BEB transit fleet's Energy Consumption Model is the second stage of electrifying the fleet, as identified in Figure 3-1. Accurate energy consumption calculation is critical for BEB scheduling and service [287]. BEBs energy consumption is necessary to determine the optimal battery and charger configuration to meet transit schedule requirements. Although manufacturers specify a nominal energy consumption rate for their BEBs, these values do not typically consider the transit network's unique characteristics, such as route topography and speed. Calculating the actual energy consumption of each direction based on the transit system's characteristics is worthwhile in this context [100].

Energy use is critical in assessing the operational strategy and cost analysis of BEBs and directly impacts the cost of fuel and greenhouse gas emissions from electric bus fleets [288]. BEB's energy use estimates are essential for planning, scheduling, and allocating transit charging stations [44]. Typically, the route topography, battery weight, temperature, and load variance all impact the energy consumption of bus fleets [239], [244]. Additionally, external factors such as route traffic congestion, which is a characteristic of a transit bus's speed profile, can affect the energy consumption of BEBs [44]. As a result, to achieve a more accurate figure for BEB consumption, it is necessary to estimate BEB energy consumption using transit route characteristics that account for the uncertainty associated with speed profiles. BEB energy consumption is an input parameter for charging facility allocation and transit energy demand modelling. Additionally, by providing a model based on route traffic classification that accurately reflects real-world scenarios. The transit operator can plan transit buses accurately, adequately scale the BEB onboard battery, and allocate charging infrastructures while preserving the BEB schedule timetable.

It was found in Chapter 2, as part of the literature review, that many of the works identified as being relevant to the work of this thesis (for example, [100], [243]) had not taken sufficient account of either the complexity and variations created by real-world operating conditions. Additionally, most of the previous authors' work failed to account for the effect of normal driving cycles, speed fluctuations, and variability in energy demand. This thesis's BEB energy consumption model considers the impact of route traffic conditions, HVAC system energy consumption, and bus route topographies. These features can assist bus transit operators in deriving greater value from this modelling work because of various traffic scenarios. This assessment is also expected to bolster the accuracy of the onboard battery sizing and charging infrastructure design.

Hence, this section presents a longitudinal dynamic BEB energy consumption model. The longitudinal dynamic method is generally based on the forces acting on the bus and the traction forces that overcome those forces to maintain the BEB velocity during the trip [250]. The traction force on the BEB in motion can be calculated using Newton's second law, which describes translational and rotational systems. This mathematical method is used to calculate the total amount of energy taken from the onboard battery of an electric bus to power the bus. The amount of energy used by the bus varies according to driving conditions. The overview of the powertrain system configuration of BEB is shown in Figure 3-3.

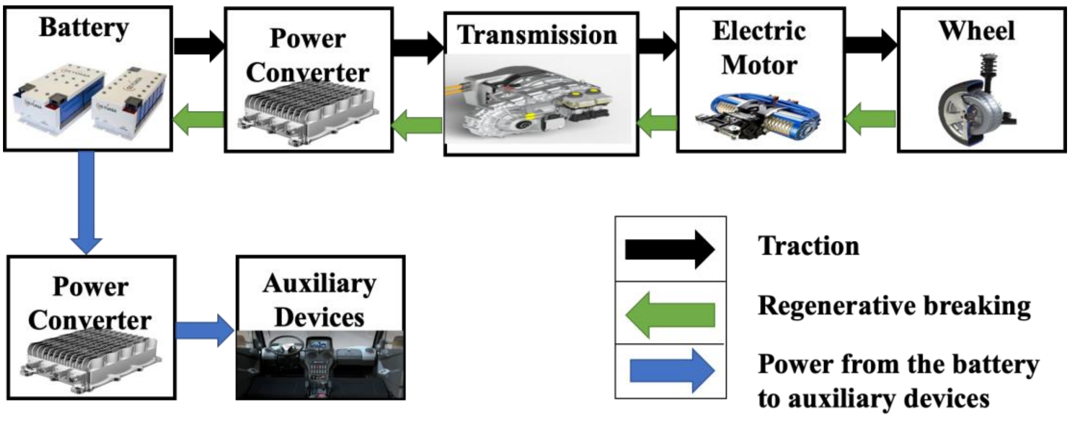

Figure 3-3 BEB Powertrain System Configuration (Adapted from [289]**)**

As shown in Figure 3-3, the BEB's primary source of energy is the battery. Traction motors can be used in either drive or regenerative-braking mode. In order to maximise performance, the bus's braking power can be captured in the regenerative-brake mode. The traction motor provides propulsion for the vehicle and recovers braking energy to charge the battery. While the traction motor is in drive mode, the electrical power produced by the motor is positive; when the motor is in regenerative-brake mode, the electrical power generated by the motor is negative. The efficiency map of a traction motor [290] is converted to a look-up table in the simulation tool, and the efficiency is calculated based on the speed and torque.

The converter acts as an ac/dc power interface between the traction motor and the battery. Converting ac to dc and dc to dc is modelled as an ideal voltage transformer with constant efficiency values. The accessory is represented mathematically as a constant power load. The transmission mechanism connects the electric motor to the vehicle dynamics. The bus transmission can be modelled in single or multiple gear ratio configurations. When a transmission with several gear ratios is modelled, an external controller controls gear shifting based on the vehicle's speed. The transmission efficiency is determined using an efficiency map and the current speed and torque values. Constant efficiency is employed in this work via the dc-dc converter—the battery powers the auxiliary devices [289], [291].

3.2.1 The longitudinal dynamic model for the BEB energy consumption

As mentioned previously, the energy consumption of a bus is usually determined by the forces acting on it and the traction force that overcomes those forces to maintain the BEB velocity during the trip [250]. The traction force on the BEB in motion can be calculated using Newton's second law, which is used to describe translational and rotational systems.

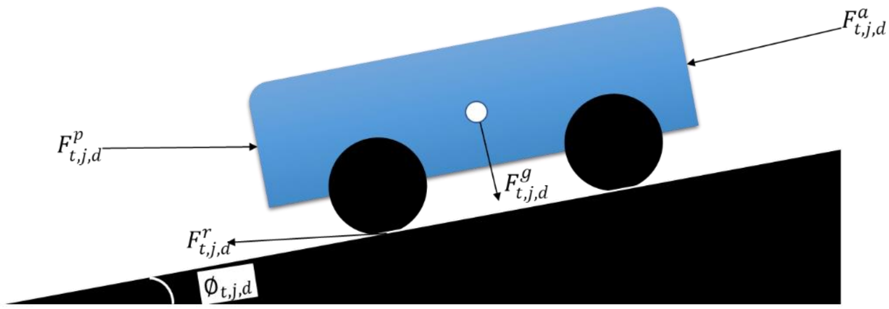

Figure 3-4 Free body diagram of a BEB in motion (Adapted from [291])

Figure 3-4 shows a free body diagram of a BEB in motion. The top and bottom rigid bodies represented are equivalent, according to Newton's second law. The main forces acting on the body are the grade force $F^{g}_{t,j,d}$, the rolling resistance force, $F^{r}_{t,j,d}$ and the aerodynamic force $F^{a}_{t,j,d}$, and $F^{p}_{t,j,d}$ represents the force supplied by the motor to propel the vehicle forward by overcoming the external resistive forces (traction force). According to Newton's second law [250], [292], the traction force is expressed as.

$$M_{t,j,d}a_{t,j,d} = F^{p}_{t,j,d} - \left(F^{a}_{t,j,d} + F^{g}_{t,j,d} + F^{r}_{t,j,d}\right) \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \qquad (3.8)$$

Where $M_{t,j,d}$, is the mass of BEB at time *t*, trip *j*, and assignment *d*, $a_{t,j,d}$ in m/s^2 is the BEB acceleration at time *t*, trip *j*, and assignment *d*, and $F^{a}_{t,j,d}, F^{g}_{t,j,d}, F^{r}_{t,j,d}, F^{p}_{t,j,d}$, is the aerodynamic, grade, rolling resistance and traction forces at time *t*, trip *j*, and assignment *d*.

Therefore, the traction force at time *t*, trip *j*, and assignment *d* is given as:

$$F^{p}_{t,j,d} = \frac{1}{2}\rho A C^{D}_{t} v^{2}_{t,j,d} + M_{t,j,d}g\cos\emptyset_{t,j,d} + C_r v_{t,j,d} M_{t,j,d} g\sin\emptyset_{t,j,d} + M_{t,j,d}a_{t,j,d} \;\; \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \qquad (3.9)$$

Where $F^{p}_{t,j,d}$ in (N) is the BEB traction force at time *t*, trip *j*, and assignment *d*, ρ is the Air density (kg/m^3), A is the BEB cross-section area (m^2), *and* C^{D}_{t}, C_r, is the drag, and rolling resistance coefficient, respectively. The $v_{t,j,d}$ in (m/s) is the BEB speed at time *t*, trip *j*, and assignment *d*, $M_{t,j,d}$ in kg, is the mass of BEB at any instance at time *t*, trip *j*, and assignment *d* g is the gravitational force (m/s^2), and $\boldsymbol{\emptyset_{t,j,d}}$ in (deg.), is the road slip angle at time *t*, trip *j*, and assignment *d*.

During acceleration, the traction force is positive. Therefore, power is transferred from the BEB battery to the wheel. The wheel and motor torque are expressed as:

$$T_{t,j,d}^{w} = F_{t,j,d}^{p} . R_{wheel} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.10}$$

where $T_{t,j,d}^{w}$ is the wheel torque and R_{wheel} , is the wheel radius.

and

$$T_{t,j,d}^{m} = \frac{T_{t,j,d}^{w}}{\eta_T} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.11}$$

$T_{t,j,d}^{m}$ represent the motor torque and η_T, is the transmission efficiency.

Respectively, their respective rotational speed is described as

$$w_{t,j,d}^{w} = \frac{v_{t,j,d}}{R_{wheel}} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.12}$$

where $w_{t,j,d}^{w}$, is the wheel rotational speed.

$$w_{t,j,d}^{m} = w_{t,j,d}^{w} \times \mathrm{GR} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.13}$$

where $w_{t,j,d}^{m}$, is the motor rotational speed, and GR is the gear ratio.

After obtaining the motor efficiency using an efficiency map, the BEB's instantaneous power consumption can be computed using the following formula:

$$P_{t,j,d}^{cons} = \frac{T_{t,j,d}^{m} . w_{t,j,d}^{m}}{\eta_m . \eta_{con}} + \frac{P_{aux}}{\eta_{con}} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.14}$$

P_{aux} is the BEB auxiliary power demand and $\eta_{con}, \eta_m,$ is the conversion and motor efficiency, respectively. The energy supply for auxiliary loads such as heating, cooling, lighting, and sound systems is referred to as auxiliary power.

This mathematical model (3.8) to (3.14) is used to estimate the total energy drawn from the electric bus onboard battery to power the bus. The energy consumed by the bus can be varied depending on the driving conditions.

The energy consumption rate is given by

$$E_{t,j,d}^{cons} = \int_{t=0}^{t=\tau} P_{t,j,d}^{cons}(t)dt \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.15}$$

The energy use per route in kWh/km is given as:

$$E_{lr}^{trip} = \frac{1}{l_r}\int_{t=0}^{t=\tau} P_{t,j,d}^{cons}(t)dt \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.16}$$

The SOC of the battery is expressed as a percentage of the total remaining battery energy capacity (100% state-of-charge means that the battery charge level is full, while 0% SOC implies that the battery charge level is empty), and this is represented as follows

$$SOC_{t,j,d} = SOC_{t-1,j,d} - \left(100 \cdot \frac{E_{t,j,d}^{con}}{E_b^{cap}} \cdot l_r\right) \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.17}$$

E_b^{cap} is the BEB battery energy capacity and l_r is the length of the route

The traction force is negative during deceleration, and the kinetic energy is transferred to recharge the battery. Thus (3.18) and (3.19) introduce the evaluation of this regenerative braking.

$$M_{t,j,d}a_{t,j,d} = F_{t,j,d}^{b} - F_{t,j,d}^{p} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.18}$$

Where $F_{t,j,d}^{b}$, is the BEB brake force at time *t*, trip *j*, during assignment *d*. The unit of this force is newton (N).

Hence, the regenerative force at any time instant in trip *j* is given as:

$$F_{t,j,d}^{reg} = S.F_{t,j,d}^{b} \quad \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.19}$$

S is the power slip ratio between friction brake and regenerative brakes. The manufacturer usually estimates the split friction and regenerative to be 60 to 40 [292].

This mathematical model shows that energy consumption is mostly determined by the forces acting on the bus and the required traction force to overcome those forces and maintain the BEB velocity during the journey. BEB's energy consumption figure is required to find the optimal battery and charger configuration to meet the transit timetable requirement. As a result, the generic roadmap for calculating BEB energy consumption is shown in this mathematical model. The advanced vehicle simulator (ADVISOR) is a commonly used tool that allows the integration of critical factors (route topography, weather conditions, passenger occupancy rate, and traffic conditions) that can improve the accuracy of a BEB battery-to-wheel energy consumption figure. As a result, the simulation example in the next chapter applied the ADVISOR modelling tool to a specific case study. The BEB energy consumption figure is estimated to be kWh/km and used as an input parameter in the novel charger allocation optimisation model proposed in this thesis, as well as to estimate the potential reduction in GHG emissions along the route under consideration.

3.3 MODELS OF CHARGING INFRASTRUCTURES

The previous section presents the procedure for evaluating the BEB transit fleet Energy Consumption figure. The BEBs energy consumption figure is one of the input parameters required for the optimum configuration of batteries and chargers to meet transit schedule requirements.

The mathematical and optimisation formulations for the novel BEB charging system model, multi-terminal charging model, integrated charging model, and BEB transit energy demand estimation are presented in this section. Moreover, a mathematical model is developed to allocate multi-terminal inductive charging infrastructure in order to optimise power transmitter location, inductive cable length, battery capacity, and an electrified transit system's cost.

3.3.1 NOVEL DESIGN OF CHARGING INFRASTRUCTURE FOR BUS RAPID TRANSIT SYSTEM

This section presents the methodology for designing charging infrastructure for the BRT transit network [33]. Also, this section gives the overview and the procedures for multi-terminal charging for the BRT transit network. The system presented in this work integrates both inductive and conductive priority charging to ensure effective energy management without disrupting the operational bus schedule.

The charging at the BEB terminals is assigned based on the priority that depends on the state of charge of the BEB battery on arrival. Priority charging is a charging strategy that is designed to address the charging challenges in the electric bus transit system. The priority charging proposed in this thesis first classified the charging need of the BEB on arrival at the bus terminal. This charging classification is based on the BEB’s computed energy demand for the next scheduled trip and the state of charge on arrival at the bus terminals where the proposed conductive charging infrastructures are located. Then a decision is made on whether the charging requirements of the BEB’s are classified as low, medium or high level charging, where this charging requirement classification is based on the calculated energy consumption expected for the next scheduled trip, the available capacity of the charger at the bus terminals and availability of on-the-road integrated inductive chargers on the route.

The term low-priority charger relates to a set of BEB’s onboard battery chargers with the lowest power capacity. The medium-priority charger relates to a set of onboard battery chargers with mid-range power capacity, and high priority chargers relate to onboard chargers with the highest power capacity. It is worth noting that the priority-charging strategy is designed to ensure that BEB’s on-board battery quickly recovers to maintain the operational timetable while aggregating the charging demand over the daily transit operation scheduled and reducing the burden of the transit BEBs charging demand on the power distribution system.

Moreover, the priority-charging model presented in this thesis also has an on-the-road integrated inductive charger. These inductive chargers are intended to be integrated into the transit system to improve the system's reliability by eliminating the impact of charging downtime. In this thesis, the allocation of the inductive charger [101] to a route is based on the length of the route, the onboard battery size of the BEB and the trade-off between the available conductive chargers and the route charging demand. This inductive charging stage occurs when the bus moves slowly or is stopped for a few minutes to pick up and drop off passengers. The BEB that can be charged inductively will contain additional equipment installed that acts as a 'pickup' device to collect electrical energy from the installed on-road power transmitters. This 'scavenged' charging will enable the topping up of the BEBs batteries to extend their range and protect the BEBs batteries from deep discharge. This proposed model is illustrated in Figure 3-6.

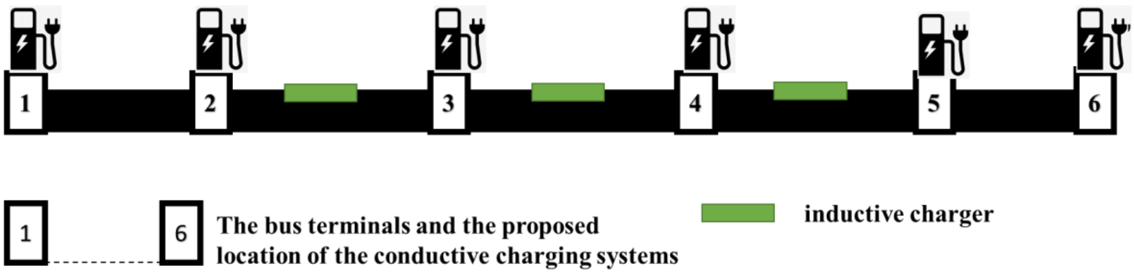

Figure 3-5 Proposed allocation of charging infrastructure for the bus transit system

The schematic diagram that illustrates multiterminal-based charging that integrated on-road inductive charger is shown in Figure 3-5. In this figure, items number 1-6 are considered the bus terminals along the BRT route. This proposed bus terminal is the location of the conductive chargers, and the green-coloured lines between some of the terminals are the proposed locations of the integrated on-road induction charger along the transit route.

The process flow diagram in Figure 3-6 illustrates the terminal-based model described above. The process starts with the daily schedule, where it is assumed that the BEBs start with a fully charged onboard battery. On arrival from the trip, the allocation of charging infrastructure is based on the process flow diagram in Figure 3-6 described as follows:

1. Given the set of BEBs ($\mathcal{B}$) assigned to a set of routes ($\mathcal{R}$) and a set of assignments (D) with a set of trips (J_d). Hence, the number of buses $b \in \mathcal{B};$ the assignment $d \in D;$ the trip $j \in J_d;$ and the time $t \in \tau$.
2. Each BEB operates on a fixed route within the BRT network, a subset of $\mathcal{R}$; this fixed route has a terminal at both ends where the BEB can use conductive chargers. Additionally, inductive chargers are allocated to the routes based on the length of the route, the onboard battery size of the BEB and the trade-off between the available conductive chargers and the route charging demand. In addition, there are multiple bus stops to load and unload passengers along each route.
3. The b-th BEB is equipped with one battery unit denoted with (E_b^{cap}) its capacity in kWh. Each of the BEB batteries is taken to be of the same size. In this work, the

BEBs batteries have a minimum (E_b^{min}) and maximum (E_b^{max}), range of the total battery energy capacity.

4. The arrival time ($t_{b,j,d}^{arr,i}$), the battery energy capacity on arrival ($E_{b,j,d}^{arr,i}$) and the battery capacity (E_b^{cap}) are logged on the arrival of the *b*-th BEB on the *j*-th trip of assignment d at the *i*-th terminal (i). The duration between the arrival and the next schedule is called the *stay or dwell time* which is the maximum time allowed for BEB charging

$$t_{b,j,d}^{wait,i} = t_{b,j,d}^{s,i} - t_{b,j,d}^{arr,i} \quad \forall b \in B \ \land \ \forall j \in J_d \land \ \forall d \ \in D \tag{3.20}$$

$$t_{b,j,d}^{ch,i} \leq t_{b,j,d}^{wait,i} \quad \forall b \in B \ \land \ \forall j \in J_d \land \ \forall d \ \in D \tag{3.21}$$

5. Then, the energy consumption of the BEB for the next scheduled trip $j + 1$ in an assignment d of the *b*-th BEB moving from terminal *i* to *i*+*n* is given as:

$$E_{b,j,d}^{i,i+n} = \int_{t=i}^{t_{=i+n}} P_{t,j,d}^{cons}\,(t)dt \quad \forall b \in B \ \land \forall j \in J_d \land \ \forall d \ \in D \land \ \forall t \in \tau \tag{3.22}$$

Here *'n'* is an integer indicating the subsequent number of terminals until the end of the scheduled trip.

6. If the $E_{b,j,d}^{arr,i}$ satisfies the next scheduled trip of the BEB energy demand, the proposed algorithm will also check capacity constraints E_b^{min}, associated with the *b*-th battery are met. If the constraint E_b^{min} is also satisfied, the charging of the BEB depends on the availability of the charging unit before the next scheduled trip $j + 1$, and the BEB charging in this circumstance is given low priority.

7. However, if the constraint E_b^{min} is not satisfied, the model verifies if the next scheduled route has a midway inductive charger that can top up the BEB battery to satisfy the E_b^{min}, constraint. With an inductive charger's availability along the route, the BEB is scheduled to charge at a low priority (depending on the charging unit's availability before the next scheduled trip). Otherwise, the BEB is allocated to be charged at a medium-priority.

8. If the $E_{b,j,d}^{arr}$, cannot meet the energy consumption demands of the next scheduled trip $j+1$ from i to i+n, the BEB is allocated for charging with high priority charging.

Thus, on the arrival of BEB at the terminal, the charging priority is selected to be high, medium, and low is expressed in the form of energy dynamics as follows:

$$Ch_{b,d,j}^{select} = \begin{Bmatrix} High & E_{b,j,d}^{arr.i} \leq E_{b,j,d}^{i,i+n} \\ Medium & E_{b,j,d}^{arr,i} - E_{b,j,d}^{i,i+n} \leq E_b^{min} \\ Low & otherwise \end{Bmatrix} \forall b \in B \wedge \forall j \in J_d \wedge \forall d \in D \quad (3.23)$$

Where $Ch_{b,d,j}^{select}$, is the charging priority selector. $E_{b,j,d}^{i,i+n}$, is the energy required for the BEB's next scheduled trip from a terminal, i to i+n. The nomenclature of high is high-priority charging, the medium is medium-priority charging, and the low is low-priority charging.

The battery energy capacity on arrival at the bus terminal is $(E_{b,j,d}^{arr,i})$, and the minimum battery capacity (E_b^{min}) is the tolerable minimum energy level that should be in the BEB onboard. In this work, the minimum energy level of the battery is expressed as 20% of the battery's state of charge. This is necessary to avoid over-draining of BEB battery to prolong the battery lifetime.

The equation (3.23) gives a simplified overview of how the priority chargers is selected at each bus terminal and ensures that each BEB uses appropriate charging priority during their recovery time at the bus terminal.

In summary, this section describes the priority-charging methodology that classifies the BEB's charging requirements upon arrival at the bus terminal. This charging classification is determined by the BEB's calculated energy requirement for the next scheduled trip, as well as the level of charge at the bus terminals. Furthermore, the priority-charging model described in this thesis includes an on-the-road integrated inductive charger. These inductive chargers are designed to be incorporated into the transit system to enhance system dependability by removing the impact of charging downtime.

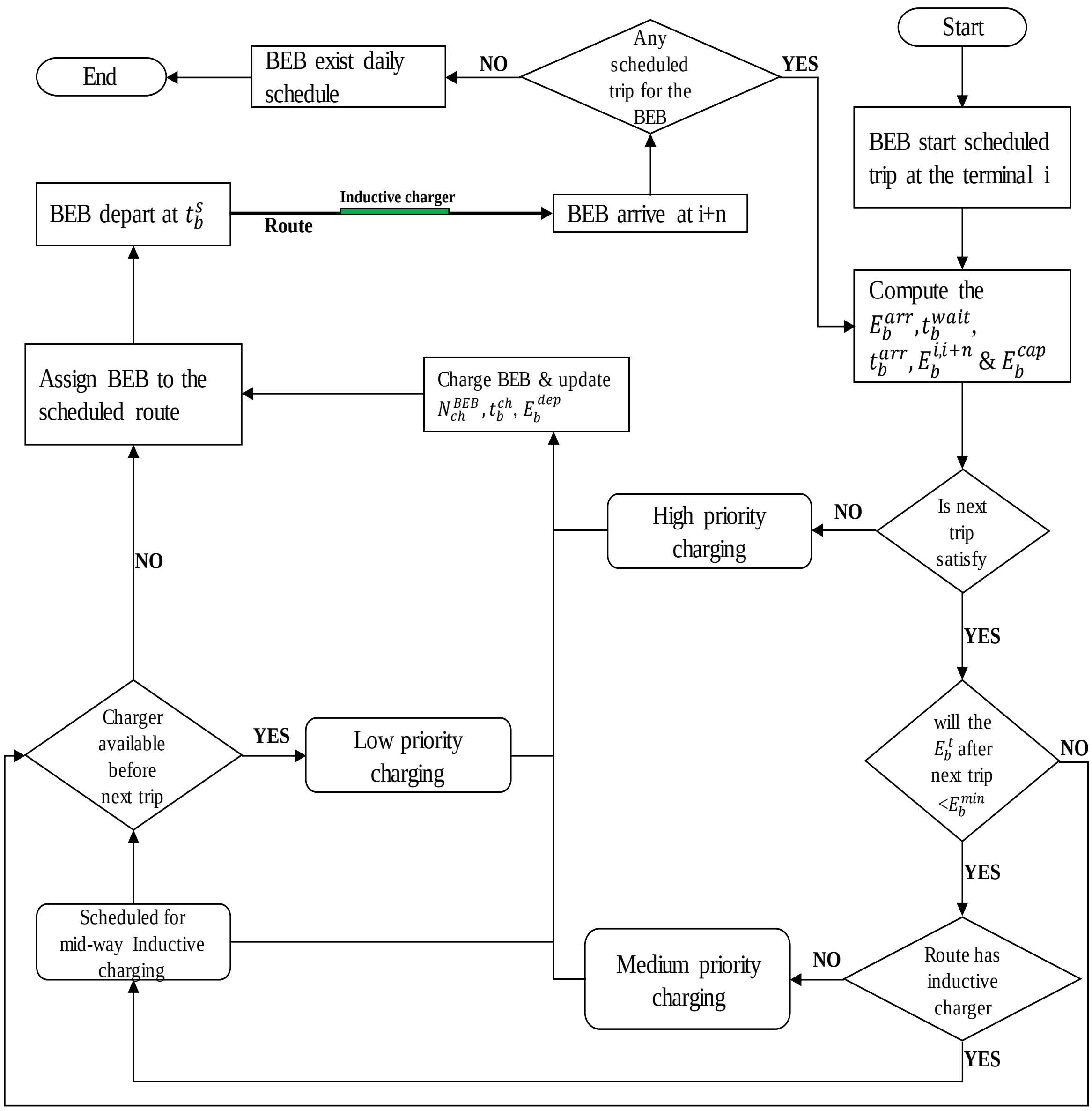

Figure 3-6 Flow chart for the terminal-based charging model

The next subsections (i.e. 3.3.1.1-3.3.1.3) give the details of the objectives equations and associated constraints based on this priority-charging model. First, an objective equation for allocating priority-charging infrastructure in the BEB transit model is given in sub-section (3.3.1.1). This objective equation is extended to represent the transit network as a multi-terminal allocation of priority-charging infrastructures in (3.3.1.2), and subsection (3.3.1.3) presents an integrated model that takes into account the allocation of both the multi-terminal priority conductive charging system and the on-road inductive system.

3.3.2 Optimisation problem for the BEB transit model's priority-charging infrastructure allocation.

This thesis is aimed to address the infrastructure need of the electrified BRT transit systems. Hence, considering a set of BEB $\mathcal{B}$ with each BEB b operates with an onboard battery capacity E_b^{cap} (kWh) that is valued at C_b^{bat} per kWh required processing a set of trip J_d. Each BEB b can process, at most, one trip j at a time. In the scheduled trip the E_b^{cap} is expected to be decreasing at the average rate of BEB energy consumption $E_{t,j,d}^{cons}$, estimated for the scheduled trip *j.* In order to prolong the battery lifespan, the BEB on-board battery is constrained by the maximum capacity ($\mathrm{E_b^{max}}$) and minimum capacity ($\mathrm{E_b^{min}}$) limits [293].

In addition, there are three categories of chargers located at the bus terminal for the purposed of charging the BEBs during the scheduled operational dwell time t_d^{wait}. These chargers are represented as low-priority chargers with power capacity $P_{(t)}^{l}$ and associated cost C_{ch}^{l}, medium-priority chargers with power capacity $P_{(t)}^{m}$ and associated cost C_{ch}^{m}, and high-priority chargers with power capacity $P_{(t)}^{h}$ and associated cost C_{ch}^{h} respectively. The charger utilisation is selected based on the state of charge on arrival $E_{b,j,d}^{arr}$ at the BEB terminal (as described in chapter 3, section (3.3.1)) and the demand for the next scheduled trip j, *in* which the product $E_{t,j,d}^{cons}$ with the length of the scheduled trip l_r. Moreover, installing these charging infrastructures is associated with a varied costs with the classified types of charging infrastructure.

Therefore, this problem formulation allows the infrastructure requirements for allocating the minimum priority-charging infrastructure in the BEB transit model to be determined-this is captured formally as:

$$Min \sum_{b\in B}\sum_{t\in T} N_b.\ E_b^{cap}.C_b^{bat} + N_{ch}^{l}.\ P_{(t)}^{l}.\propto^{l}.C_{ch}^{l} + N_{ch}^{m}.\ P_{(t)}^{m}.\propto^{m}.C_{ch}^{m} + N_{ch}^{h}.\ P_{(t)}^{h}.\propto^{h}.C_{ch}^{h} + N_{ch}^{l}.\ C_{inst}^{l} + N_{ch}^{m}.\ C_{inst}^{m} + N_{ch}^{h}.\ C_{inst}^{h} + N_b.C_b \quad (3.24)$$

- and the various terms in this equation are as follows: The first term is the cost of the BEBs battery packs ($N_b.\ E_b^{cap}.C_b^{bat}$), expressed as the product of the number of BEBs, their battery capacity, and the battery cost.
- The second term is the cost of the low-priority charging units, ($N_{ch}^{l}.\ P_{(t)}^{l}.\propto^{l}.C_{ch}^{l}$), as the product of the number of low-priority chargers, low-priority charger rated power, and the low-priority charger expenditure cost.
- The third term is the cost of the medium-priority charging units, ($N_{ch}^{m}.\ P_{(t)}^{m}.\propto^{m}.C_{ch}^{m}$), as the product of the number of medium-priority chargers, medium-priority charger rated power, and the medium-priority charger expenditure cost.
- The fourth term is the cost of the high-priority charging units, ($N_{ch}^{h}.\ P_{(t)}^{h}.\propto^{h}.C_{ch}^{h}$) as the product of the number of high-priority chargers, high-priority charger rated power, and the high-priority charger expenditure cost.
- The remaining terms describe the charger installation cost ($N_{ch}^{l}.\ C_{inst}^{l}$, $N_{ch}^{m}.\ C_{inst}^{m}$, $N_{ch}^{h}.\ C_{inst}^{h}$) for the low, medium, and high-priority charging, respectively. The charger installation cost is the product of the number of chargers and the installation cost per charger. The installation cost is considered to vary for each charging priority.

It is worth noting that the transit fleet optimisation problem aims to find the minimum cost for the transit infrastructure while optimising the charging infrastructures and the BEB onboard battery capacity. This optimisation problem is subjected to associated constraints that are given in equations 3.25 to 3.41.

For simplicity, it is assumed in this thesis that BEBs in the fleet are identical, i.e., BEBs have the same battery size to offer transit network operators flexibility to allocate the BEBs to different routes. Hence, for each BEB b at trip j, the departure ($E_{b,j,d}^{dep}$) and arrival ($E_{b,j,d}^{arr}$) battery energy capacity (from/to the bus terminal) of the BEBs on-board battery is constrained by the maximum capacity (E_b^{max}) and minimum capacity (E_b^{min}). The BEB manufacturer usually enforces limits to prolong the battery lifespan. These constraints are given as follows:

$$E_{b,j,d}^{arr} = E_{b,j,d}^{dep} - E_{t,j,d}^{cons}.l_r \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.25}$$

$$E_{b,j,d}^{arr} \geq E_b^{min} \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \tag{3.26}$$

$$E_{b,j,d}^{dep} \leq E_b^{max} \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \tag{3.27}$$

Here (3.25) gives the trip arrival energy state of each BEB on arrival at the bus terminal as the difference between the state of energy of the battery on departure and the trip consumption rate with distance. Therefore, the BEB battery size is constrained by the capacity limits of the onboard bus battery as follows:

$$E_b^{min} \leq E_b^{cap} \leq E_b^{max} \quad \forall b \in B \tag{3.28}$$

At the BEB arrival at the bus terminal, the bus is expected to charge before the next trip *j+1*. The charging equation is expressed as follows:

$$E_{b,j+1,d}^{dep} = E_{b,j,d}^{arr} + E_{b,j,d}^{ch} \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \tag{3.29}$$

The energy gain during the charging with low-priority chargers is given as:

$$E_{b,j,d}^{ch,l} = \eta_{ch} \times \int_{t=0}^{t=t_{b,j,d}^{ch,l}} P_{(t)}^{l}\, dt \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.30}$$

The energy gain during the charging with medium-priority chargers is given as:

$$E_{b,j,d}^{ch,m} = \eta_{ch} \times \int_{t=0}^{t=t_{b,j,d}^{ch,m}} P_{(t)}^{m}\, dt \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.31}$$

The energy gain during the charging with high-priority chargers is given as:

$$E_{b,j,d}^{ch,h} = \eta_{ch} \times \int_{t=0}^{t=t_{b,j,d}^{ch,h}} P_{(t)}^{h}\, dt \quad \forall b \in B\, \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.32}$$

The charging power is constrained by the minimum and maximum capacity of the specified charger. The constrained equation for the minimum and maximum capacity of the low-priority, medium-priority and high-priority charger is given by:

$$0 \leq P^{\iota} \leq P^{\iota}_{max} \tag{3.33}$$

$$P^{\iota}_{max} \leq P^{m} \leq P^{m}_{max} \tag{3.34}$$

$$P^{\iota}_{max} \leq P^{h} \leq P^{h}_{max} \tag{3.35}$$

Respectively, the summation of the energy used by all BEBs that charge at a particular terminal can be described as follows:

$$\sum_{j}^{n}(E^{ch,l}_{b,j,d} + E^{ch,m}_{b,j,d} + E^{ch,h}_{b,j,d} \leq P^{total}_{(t)} \, . \, t^{ch,total}_{b,j,d}) \ \forall b \in B \ \forall j \in J_d \wedge \forall d \in D \wedge \forall t \in \tau \tag{3.36}$$

$$\sum_{t \in T}(P^{l}_{(t)} + P^{m}_{(t)} + P^{h}_{(t)} = P^{total}_{(t)} \ \forall t \in \tau \tag{3.37}$$

$$\sum_{j}^{n}(t^{ch,l}_{b,j,d} + t^{ch,m}_{b,j,d} + t^{ch,h}_{b,j,d} = t^{ch,total}_{b,j,d}) \ \forall b \in B \ \forall j \in J_d \wedge \forall d \in D \tag{3.38}$$

When the BEB arrives at any designated BEB terminals, and it receives a charge, the constraints are given as:

$$E^{arr}_{b,j,d} + E^{ch,l}_{b,j,d} \leq E^{max}_{b} \ \ \forall b \in B \ \forall j \in J_d \wedge \forall d \in D \tag{3.39}$$

$$E^{arr}_{b,j,d} + E^{ch,m}_{b,j,d} \leq E^{max}_{b} \ \ \forall b \in B \ \forall j \in J_d \wedge \forall d \in D \tag{3.40}$$

$$E^{arr}_{b,j,d} + E^{ch,h}_{b,j,d} \leq E^{max}_{b} \ \ \forall b \in B \ \forall j \in J_d \wedge \forall d \in D \tag{3.41}$$

The $\propto^{\iota}$, $\propto^{m}$ and $\propto^{h}$, are the probability variables for low-priority, medium-priority, and high-priority charging, respectively. In equations 3.42 to 3.49, the details of these probability variables are given.

The value of $\propto^{\iota}$, $\propto^{m}$ and $\propto^{h}$ are is based on the possible numbers of the trips in the transit network schedule. With the short distance attributed to low-priority or low power charger within the dwelling time at the bus terminal, the medium-priority for median distances and the high-priority for the far distances.

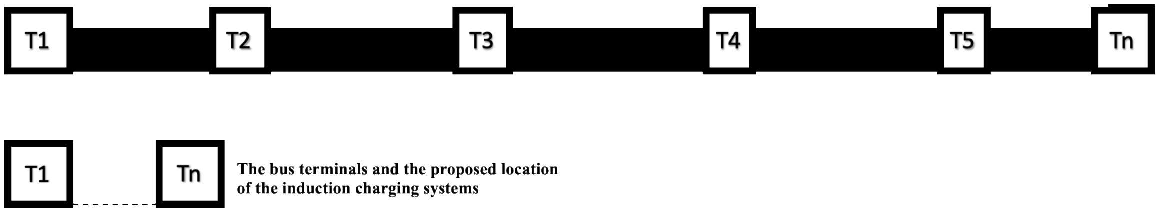

Figure 3-7 Multi-terminal route based charging model

Using Figure 3-7 to show how the values of $\propto^{\iota}$, $\propto^{m}$ and $\propto^{h}$ are calculated: Assuming that some BEBs will travel from T_1 to T_2, T_2 to T_3, T_3 to T_4, T_4 to T_5, or vice versa. Because the trips occur between two terminals and span a short distance, the energy consumed is proportionate to the distance travelled, resulting in low kWh consumption that may be recovered with a low-priority charger during the dwell period.

Similarly, if BEBs are scheduled to go from T_1 to T_3, T_2 to T_4, T_3 to T_5, or vice versa, the BEB will require more energy to recover appropriately; thus, the BEBs are charged using the medium-priority charger.

Furthermore, if BEBs are scheduled for a long trip, such as from T1 to T4, without being charged the entire journey. The BEBs will be charged using a high-priority charger in order for them to recover quickly within the allotted dwell period.

Hence, a mathematical model is developed to calculate the proposed value of $\propto^{\iota}$, $\propto^{m}$ and $\propto^{h}$ using Figure 3-7 as an example. The (3.42) combines all the transit routes in the network. The (3.43) is the proportion of BEBs that used low priority chargers, (3.44) is the proportion of BEBs that used medium-priority chargers and (3.45) is the proportion of BEBs that used high priority chargers.

$$T = \begin{vmatrix} T_{11} & T_{12} & \cdots & T_{1n} \\ T_{21} & T_{22} & & T_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ T_{m1} & T_{m1} & & T_{mn} \end{vmatrix} \tag{3.42}$$

$$\propto^{\iota} = \frac{n(T^{l})}{n(M) - n(D)} \tag{3.43}$$

Where $n(T^{l})$ is the number of possible routes with the distance that require a low-priority charger, $n(M)$ is the total number of routes combined in a transit schedule system that is represented with matrix (T) shown in (3.42), and $n(D)$ are diagonal elements of the matrix in (3.42).

Similarly,

$$\propto^{m} = \frac{n(T^{m})}{n(M) - n(D)} \tag{3.44}$$

$$\propto^{h} = \frac{n(T^{h})}{n(M) - n(D)} \tag{3.45}$$

Where,

$$n(T^{l}) = n(T_{mn+1}, T_{m+1n}, T_{m+1n+2} \dots \dots . T_{m+5n+4} \dots) \tag{3.46}$$

$$n(T^{m}) = n(T_{mn+2}, T_{m+1n+3}, T_{m+2n} \dots \dots . T_{m+5n+3} \dots) \tag{3.47}$$

$$n(T^{h}) = n(T_{mn+3}, T_{mn+4}, T_{mn+5} \dots \dots . T_{m+5n+2} \dots) \tag{3.48}$$

It is also a constraint that a BEB can only use one type of charger during the bus terminal's waiting time.

Therefore,

$$\propto^{l} + \propto^{m} + \propto^{h} = 1 \quad \propto \in [0, 1] \tag{3.49}$$

This section described the optimisation model of the multi-terminals priority charging strategy and the associated constraints. The implementation of this optimisation algorithm and the result of a simulation example is presented in the next chapter. The following section considered an integrated model that added an on-road inductive charging system to the multi-terminal priority-charging present in this section.

The introduced problem is based on optimising the infrastructure needs for the electrification of the BRT system. The developed mathematical formulation helps quantify the charging infrastructure needed to meet the electrified BEB demand as it services the various routes in the timetable. The solution to this problem will provide the necessary infrastructure needed to optimise the investment cost (least assets) for the BEB transit system.

This mathematical formulation only considers a priority-charging conductive single terminal case; the next subsection extends these optimisation parameters for the multi-terminal transit system.

3.3.3 Optimisation problem for the allocation of the priority-charging infrastructure in a multi-terminal transit model

The proposed BEB transit system multiterminal charging configuration is the design of chargers at the major bus stop (called the bus terminal). The terminal is where the buses stop for 10-30 minutes at the end or start of a scheduled trip to off-board and onboard passengers. This waiting time is considered as the charging duration to avoid disruption of the BEB operational schedule. A transit network usually has many terminals strategically positioned to distribute buses to meet customer demand effectively. Hence, the multiterminal priority charging strategy proposed in this thesis is aimed to allocate priority charging infrastructures to meet the transit BEBs charging demand by positioning adequate resources at each BEB terminal. An example that illustrates this is shown in Figure 3-5, which shows six terminals transit network where charging infrastructures would be allocated.

The objective equation for the multi-terminal charging model is expressed,

$$Min \sum_{i=1}^{n} \sum_{b \in B} \sum_{t \in T} N_b.\ E_b^{cap}.C_b^{bat} + N_{ch}^{l}.\ P_{(t)}^{l}.\propto^{l}.C_{ch}^{l} + N_{ch}^{m}.\ P_{(t)}^{m}.\propto^{m}.C_{ch}^{m} + N_{ch}^{h}.\ P_{(t)}^{h}.\propto^{h}.C_{ch}^{h} + N_{ch}^{l}.\ C_{inst}^{l} + N_{ch}^{m}.\ C_{inst}^{m} + N_{ch}^{h}.\ C_{inst}^{h} + N_b.C_b \tag{3.50}$$

It is noted that (3.50) is similar in structure to (3.24) that provides the infrastructure requirements for allocating the minimum priority-charging infrastructure in the BEB transit model; the only difference is the fact that (3.50) is applied across the whole transit network system (i.e., all the terminals in the transit network).

Here

$$C_{ch}^{l} = c_f^{l} + c.p_{(t)}^{l} \tag{3.51}$$

$$C_{ch}^{m} = c_f^{m} + c.p_{(t)}^{m} \tag{3.52}$$

$$C_{ch}^{h} = c_f^{h} + c.p_{(t)}^{h} \tag{3.53}$$

The cost components C_{ch}^{l}, C_{ch}^{m} and C_{ch}^{h} are considered to have two components; the fixed cost (c_f^l, c_f^m, and c_f^h)charged for using either low priority, medium priority, and high priority, as described in (3.51) to (3.53), respectively. These fixed costs are considered varied with the charger's priority. The lowest cost is allocated as a fixed cost for the lowpriority charger and the highest for the high-priority charger. This fixed cost is only charged once per charging, and it is used to enforce the use of an appropriate charger (i.e., BEB that needs to charge with low priority should not consider high priority). The other component of the charging cost (i.e.,$c.p_{(t)}^{\iota}$, $c.p_{(t)}^{m}$, and $c.p_{(t)}^{h}$) is the cost of energy per kWh. This cost is varied with the capacity of the charger, and hence, the objective function (3.50) can now be expressed as follows:

$$
\begin{aligned}
Min \sum_{i=1}^{n} \sum_{b \in B} \sum_{t \in T} & N_b.\ E_b^{cap}.C_b^{bat} + N_{ch}^{\iota}.\propto^{\iota}.\left(c_f^{l} + c.p_{(t)}^{\iota}\right) \\
& + N_{ch}^{m}.\propto^{m}.\left(c_f^{m} + c.p_{(t)}^{m}\right) + N_{ch}^{h}.\propto^{h}.\left(c_f^{h} + c.p_{(t)}^{h}\right) \\
& + N_{ch}^{l}.\ C_{inst}^{l} + N_{ch}^{m}.\ C_{inst}^{m} + N_{ch}^{h}.\ C_{inst}^{h} + N_b.C_b
\end{aligned}
\tag{3.54}
$$

This section described the optimisation model of the multi-terminals priority charging strategy and the associated constraints. The implementation of this optimisation algorithm and the result of a simulation example is presented in the next chapter. The following section considered an integrated model that added an on-road inductive charging system to the multi-terminal priority-charging present in this section.

3.3.4 Optimisation problem for the allocation of the priority integrated charging model

In this section, the transit electrification system considered is the multi-terminal allocation of charging infrastructure for a bus transit system where both conductive and inductive charging systems are employed. This approach is considered with the aim to reduce the cost of investment and makes the operational service reliable by optimising the charging station infrastructure: charger-operating capacities, the onboard battery capacity, location of inductive transmitters, length of inductive cables and the numbers of chargers. This section presents the mathematical model that integrates conductive and inductive charging infrastructure for the multi-terminal BRT system (Figure 3-5).

The objective equation for the integrated charging model is expressed as:

$$Min \sum_{i=1}^{n} \sum_{b \in B} \sum_{t \in T} N_b.\ E_b^{cap}.C_b^{bat} + N_{ch}^{\iota}.\propto^{\iota}.P_{(t)}^{\iota}.\left(c_f^{l} + c.p_{(t)}^{\iota}\right) + N_{ch}^{m}.\propto^{m}.p_{(t)}^{m}.\left(c_f^{m} + c.p_{(t)}^{m}\right) + N_{ch}^{h}.\propto^{h}.p_{(t)}^{h}.\left(c_f^{h} + c.p_{(t)}^{h}\right) + N_{ch}^{l}.\ C_{inst}^{l} + N_{ch}^{m}.\ C_{inst}^{m} + N_{ch}^{h}.\ C_{inst}^{h} + N_b.C_b + N_b.C_{WPR} + N_{WPT}.T_{cap}.C_{WPT} + \sum_{i=1}^{N} C_{cable}(d_i^e - d_i^s) + N_{ch}^{ind}.\ C_{inst}^{ind} \tag{3.55}$$

In addition, the various terms in this equation are as follows:

- The first term is the cost of the BEBs battery packs ($N_b.\ E_b^{cap}.C_b^{bat}$), expressed as the product of the number of BEBs, their battery capacity, and the battery cost.
- The second term is the cost of the low-priority charging units, ($N_{ch}^{\iota}.\ P_{(t)}^{\iota}.\propto^{\iota}.\left(c_f^{l} + c.p_{(t)}^{\iota}\right)$), as the product of the number of low-priority chargers, low-priority charger rated power, and the low-priority charger expenditure cost.
- The third term is the cost of the medium-priority charging units, ($N_{ch}^{m}.\ P_{(t)}^{m}.\propto^{m}.\left(c_f^{m} + c.p_{(t)}^{m}\right)$), as the product of the number of medium-priority chargers, medium-priority charger rated power, and the medium-priority charger expenditure cost.
- The fourth term is the cost of the high-priority charging units, ($N_{ch}^{h}.\ P_{(t)}^{h}.\propto^{h}.\left(c_f^{h} + c.p_{(t)}^{h}\right)$) as the product of the number of high-priority chargers, high-priority charger rated power, and the high-priority charger expenditure cost.
- The fifth terms describe the charger installation cost ($N_{ch}^{l}.\ C_{inst}^{l}$, $N_{ch}^{m}.\ C_{inst}^{m}$, $N_{ch}^{h}.\ C_{inst}^{h}$) for the low, medium, and high-priority charging, respectively. The charger installation cost is the product of the number of chargers and the

installation cost per charger. The installation cost is considered to vary for each charging priority.

- The $N_b.C_b$, C_{WPR} is the numbers of BEB, cost of each BEB, and cost of wireless power receiver respectively.
- The term $N_{WPT}.T_{cap}.C_{WPT}$ describe the cost of the wireless power transmitters- where $N_{WPT,}$ T_{cap}, C_{WPT} is the number, capacity and cost of wireless power transmitters, is the respectively.
- The term $C_{cable}(d_i^e - d_i^s)$ is used to describe the cost of the inductive cables.
- And the N_{ch}^{ind}. C_{inst}^{ind} represent the cost of installing the inductive chargers.

It is worth noting that all the inductive transmitters considered in this work are of identical power capacity. The duration for the inductive charging for the *b-th* BEB on the *j-th* trip in *d-th* assignment is represented with $t_{ch(b.j.d)}^{ind}$ which is equivalent to the time for the BEB to travel distance ($d_{ind(b,j,d)}^{trav}$) as shown in Figure 3-8. The figure illustrates the location of the inductive chargers between two BEB terminals; the BEB is considered to receive a charge at the start of the trip, and the on-road inductive charger top-up the BEB onboard battery while moving on the part of the route that has an integrated on-road inductive charger.

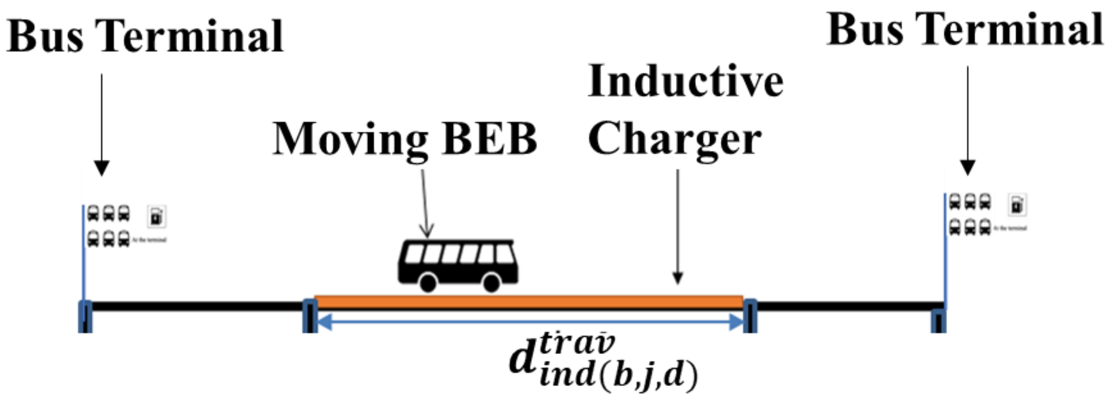

Figure 3-8 Model of two-transit terminal

Here, the charge added to the BEB battery as it passes across the inductive charger is proportional to the time the BEB takes to travel above the transmitter.

Hence, the energy gain is a result of the inductive charging depends on the distance covered with the inductive cable (represented with $d_{ind(b,j,d)}^{trav}$ in Figure 3-8), the time to travel the distance $d_{ind(b,j,d)}^{trav}$ represented with $t_{ind(b,j,d)}^{trav}$ and the power capacity of the inductive charger P_{ch}^{ind}. In a route that is equipped with an inductive charging system between terminals (as shown in Figure 3-8), the BEB battery energy level after the travelling distance $d_{ind(b,j,d)}^{trav}$ is expressed as:

$$\frac{dE\ (t_{ind(b,j,d)}^{trav})}{dt} = -P_{use(b,j,d)}^{ind} + P_{ch}^{ind}\left(t_{ind(b,j.d)}^{trav}\right) \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.56}$$

Where $P_{use(b,j,d)}^{ind}$ is the rate of consumption when the *b-th* BEB on the *j-th* trip in *d-th* assignment has travelled the distance $d_{ind(b,j,d)}^{trav}$ in the time $\left(t_{ind(b,j,d)}^{trav}\right)$ and $P_{ch}^{ind}$is the energy supply to the battery at the time $t_{ind(b,j,d)}^{trav}$ that is required to travel a distance $d_{ind(b,j,d)}^{trav}$. Then integrating (3.56) gives

$$E_{ind(b,j,d)}^{arr} - \int_{t=0}^{t=t_{ind(b,j,d)}^{trav}} P_{use(b,j,d)}^{ind}\, dt + \int_{t=0}^{t=t_{ind(b,j,d)}^{trav}} P_{ch}^{ind}\, dt \ \leq\ E_b^{max} \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.57}$$

Where $E_{ind(b,j,d)}^{arr}$ is the energy capacity in the BEB battery at the start of inductive charging.

Hence, equation 3.57 can be rewritten as:

$$E_{ind(b,j,d)}^{arr} - E_{ind(b,j,d)}^{use} + E_{ind(b,j,d)}^{rec} \ \leq\ E_b^{max} \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.58}$$

$$E_{ind(b,j,d)}^{gain} = E_{ind(b,j,d)}^{rec} - E_{ind(b,j,d)}^{use} \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.59}$$

$$E_{ind(b,j,d)}^{use} \ \leq\ E_{ind(b,j,d)}^{gain} \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.60}$$

$$E_{ind(b,j,d)}^{gain} \ \leq\ E_{ind(b,j,d)}^{rec} \quad \forall b \in B\ \forall j \in J_d \wedge \forall d \in D \tag{3.61}$$

In order to calculate the length of the inductive cable, let the starting and ending points of the inductive cable of the i_{th} power transmitter be d_i^s and d_i^e, respectively. The inductive cable length of the i_{th} power transmitter is expressed as $d_i^e - d_i^s$, as shown in Figure 3-9. This expression should satisfy the following:

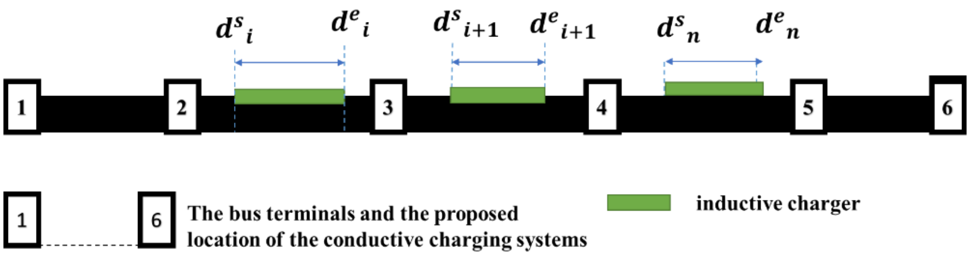

Figure 3-9 Allocation of inductive cable length

$$d_i^e > d_i^s \;\; for\; i = 1, \dots\dots, N \tag{3.62}$$

$$d_i^e < d_{i+1}^s \;\; for\; i = 1, \dots\dots, N-1 \tag{3.63}$$

Another constraint is the number of wireless power transmitters (N_{WPT}). The number of power transmitters can be expressed as the transit energy ratio to the power transmitter's installed capacity as given in (3.64). This energy ratio is evaluated by subtracting the energy demand of the conductive chargers from the transit system energy demand and dividing by the transmitter's power capacity.

$$N_{WPT} \geq \frac{1}{T_{cap}} \left\{ \sum_{j=1}^{n} \int_{t_1}^{t_j} P_{use}(t)dt - \sum_{j}^{n} E_{b,j,d}^{ch,l} + E_{b,j,d}^{ch,m} + E_{b,j,d}^{ch,h} \right\} \;\; \forall b \in B \; \forall j \in J_d \wedge \; \forall d \in D \wedge \; \forall t \; \in \tau \tag{3.64}$$

This section has presented the multi-terminal priority charging optimisation model in combination with an on-road inductive charging. This integrated model is considered a trade-off option for the infrastructure need of a BEB transit system. The simulation work present in the next chapter compared these models while considering various charging scenarios.

3.4 Design of Inductive Charging System for Bus Rapid Transit Network

Generally, BEBs are more financially expensive than diesel buses [2], and the conventional charging system limits the driving range [81]. The charging systems that support long driving distances are still in the early phases of development and very expensive [14]. Moreover, the schedule for BEBs needs to consider a variety of parameters about the energy system [81],[14]. Mitigating these issues while observing the operational bus schedules and the adequate provision for trip demand energy need to be considered. Different strategies have been proposed in the literature, and the common theme includes charging and battery swapping [100] and repurposing infrastructure [295]. Under a battery swapping system, the BEB can replace its depleted battery pack with a full one within a few minutes. The drained battery packs are then recharged at the station and later swapped for other arriving BEBs [295],[296]. However, the battery swapping system requires a significant extra investment and depot investment [297]. Hence, most of the research work on BEBs has been concentrated on the optimal sizing of battery and charging infrastructures to satisfy the BEBs' transit operation plan [81],[82],[298]. Specifically, the authors in [299] develop an optimisation model for charging station design in fully electric transport networks. Moreover, in [298] a Spatio-temporal optimisation model for determining the best deployment methods for the BEB system, is presented.

The wireless charging technology implies transmitting energy from a power transmitter to the BEB that charges on-road during its motion over the inductive cable. The improvements in wireless power transfer (WPT) technologies have aided various commercial applications. The application of WPT is common in small electronic devices such as mobile phones and small personal devices [300], [301], [302]. WPT technology can charge the batteries in such equipment without a wired connection [302]. Recently, the WPT has applications in the charging of electric vehicles [302]. In 2006, a team of MIT scholars introduced a resonant coupler that transmits a considerable quantity of power at a low frequency for a mid-length distance [10]. The authors in [11] developed the commercial applications of WPT for charging vehicles in parks and garages. Hino Motors and Showa Aircraft in Japan developed inductive coupling wireless power transfer to an electric bus in 2009. In [13], the authors examine the power transmitter's allocation for the on-line electric vehicle (OLEV). This work (ref [13]) considered the trade-off between battery size and the positions of power transmitters on a circular route. However, the authors fail to account for the multi-terminal bus transit system with the bus terminals as the charging transmitter's primary location. The authors also fail to consider the impact of route traffic situations.

In this section, a new mathematical model is developed to allocate multi-terminal inductive charging infrastructure to optimise power transmitters' location, the length of the inductive cable, battery capacity, and the electrified transit system cost. The formulated optimisation model minimises capital cost while considering the system operational constraints imposed by the transit system.

3.4.1 The BRT inductive charging system overview

The inductive charging system is an integrated on-road charging system that charges the BEB battery remotely while the bus moves over the installed inductive cable area. The length of the inductive cable, the size of BEB's battery, and the number of transmitters installed on the road directly affect the transit system's overall performance and cost.

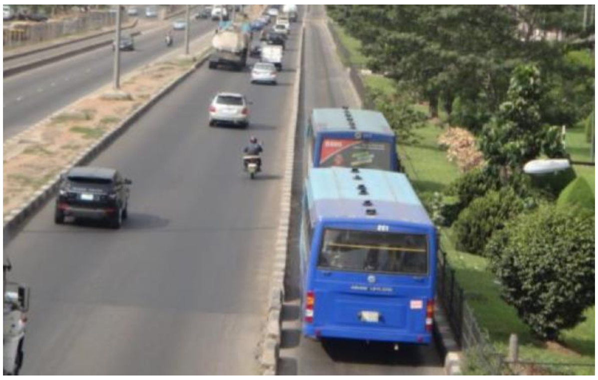

Figure 3-10 BRT route with buses

The focus of this work is to introduce the BRT network inductive charging system design problem. This design problem is illustrated with a mathematical model used to evaluate the optimal combination of the inductive transit system's critical design parameters (i.e. battery size, length of the inductive cable, and the power transmitters' allocation) as shown in Figure 3-11.

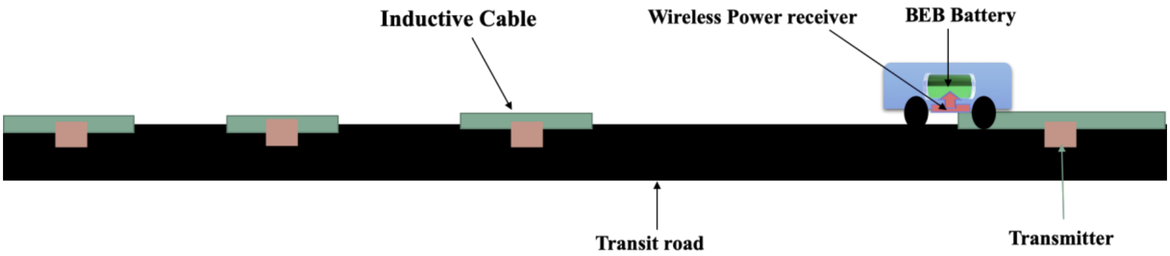

Figure 3-11 Design of the BEB inductive transit system

3.4.2 Wireless Charging System

WPT system generally consists of a power supply, transmitter (primary coil), receiver (secondary coil), oscillator circuit and matching circuit [210]. The A.C. supplied by a power source is changed into low-frequency A.C. using an oscillator. The oscillator's output is fed into the push-pull circuit that supplies the transmitter coil. This transmitter coil is also referred to as the primary coil. This primary coil transmits this power to the receiver coil that is separated by a certain distance; the power received by the secondary coil is then rectified and regulated before output to the BEB battery charger [305], [306]. The inductive charging system is environmentally suitable and cheap to maintain because water, ice, dirt and chemicals do not affect them. A more detailed description of the system's power transfer mechanism and hardware configuration can be found in [211], [212], [301], [305], [306].

The wireless power transfer technology enables the motor to obtain power remotely while the vehicle is on track, eliminating the need for the vehicle to idle while the battery is recharged. As a result, the BEB does not need a large battery. The downside of wireless power transfer charging systems (i.e. inductive chargers) is the high initial investment. Compared to the existing plug-in electric vehicle infrastructure, inductive chargers need a significant initial investment to install the power transmitters. However, the smaller battery size and improved running time achieved by eliminating the vehicles' recharging downtime can compensate for this initial expense. Specifically, there is a trade-off between battery capacity and power transmitter allocation. If the vehicle has a large battery, fewer transmitters are needed. However, a vehicle with a small battery may need more frequent recharges, necessitating the installation of additional transmitters. Given that the battery and power transmitter costs account for a sizable portion of the inductive charging transit system's overall investment cost, it is vital to investigate this trade-off.

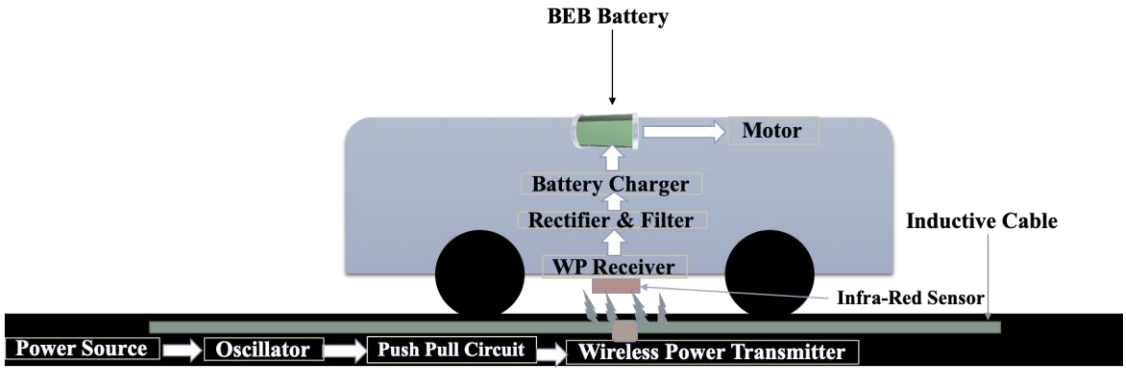

Figure 3-12 Proposed BRT inductive charging system

In this work, the BEB is considered to operate on a road with an installed power transmitter. As shown in Figure 3-12, the wireless power receiver device is deemed to be installed at the lower part of the BEB bus. This wireless power receiver device remotely collects electricity from the transmitter. The wireless receiver delivers power to the motor or the battery, or both, depending on the motor's power requirement and the battery charging level [12]. When the BEB is moving on a busway where no power transmitter unit is installed, the motor in the BEB uses the power from the battery. To eliminate energy waste, the BEBs that charge via inductive means is considered to have an infra-red sensor that turns 'ON' the supply that activates the energy exchange between the transmitter and the receiver circuit. When the BEB moves away from the inductive cable, the infra-red sensor sends the signal to turn 'OFF' the power supply [211].

3.4.3 Mathematical optimisation model

This optimisation model aims to minimise the total cost of the electrified transit system; this includes BEB cost C_{BEB}, inductive charger cost (the receiver C_{WPR} and the transmitter C_{WPT}), battery cost C_{bat} and the inductive cable cost C_{cable}, as follows

$$Min(N_{BEB}.C_{BEB} + N_{BEB}.C_{WPR} + N_{BEB}.B_{cap}.C_{bat} + n.T_{cap}.C_{WPT} + \sum_{i=1}^{n} C_{cable.}(d_i^e - d_i^s)) \quad (3.66)$$

The first term in (3.66) represents the cost of BEBs for the number of BEBs N_{BEB}. The second expression refers to the price of Wireless power receivers. The wireless power receivers ($WPRs$) are devices mounted beneath BEBs that accept electricity from the transmitters and use it to charge the BEB's onboard battery. The received power is delivered to the motor or the battery, or both. The power transferred to the motor or the battery depends on the motor's power requirement and the battery state of charge; hence, each BEB operating on the BRT route is equipped with a WPR. The third term is the battery cost multiplied by the number of BEBs operating on the BRT route. There are N_{BEB} BEBs, each with a single identical battery. The battery's cost is proportional to its maximum capacity, which is specified by the decision variable B_{cap}. The fourth term denotes the transmitter's cost. Each transmitter unit is connected to an inductive cable; hence, if a transmitter unit is installed, there is a cost for the transmitter and the inductive cable. There are *n* transmitter units; thus, the terms describing the cost of the transmitter are multiplied by *n*. It is worth noting that the cost of the cable increases linearly with the cable's length. As a result, the cost of each cable unit is denoted by the $C_{cable.}(d_i^e - d_i^s)$. As a result, the fifth term represents the total cost of the cables.

The BEBs operate on a fixed route with multiple terminals and stops to load and unload passengers. The BEBs considered in this work are identical and operated according to the operational schedule or timetable set by the transit operators. For a given BEB, the rate of using energy is represented by the power used over the operational time ($P_{use}(t)$), and the energy via charging is given as the power gain for the charging duration $P_{gain}(t)$.

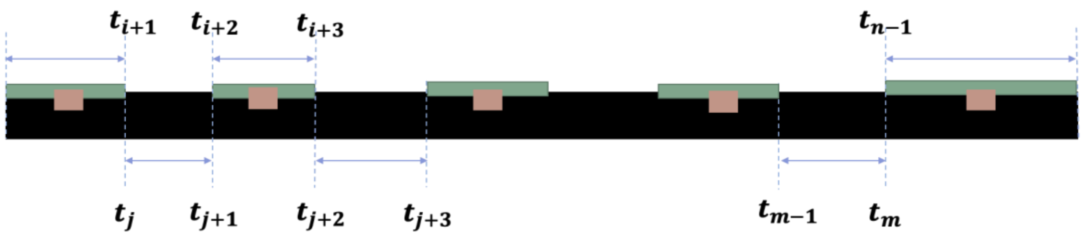

Figure 3-13 Mathematical model transit inductive system

Consider the situation in which a BEB is about to leave an area that has a power transmitter. In this modelling concept, the BEB is located at d_i^e as shown in Figure 3-14, and the time at which the BEB is at this location is symbolised by t_{i+1} as shown in Figure 3-13. The battery's state of charge at this point is expressed by the equation given in (3.67). Once the BEB begins going along a route without a transmitter, the energy in the battery is used at the rate of $P_{use}(t)$, i.e., the BEB's power consumption rate at time *t*.

$$E_{t_{i-i+1}} = \int_{t_i}^{t_{i+1}} P_{gain}(t)dt - \int_{t_i}^{t_{i+1}} P_{use}(t)dt \tag{3.67}$$

Here $E_{t_{i-i+1}}$ represents the energy received while the BEB is moving from t_i to t_{i+1} as shown in Figure 3-13. The received energy is considered higher than the energy used.

$$P_{gain}(t) > P_{use}(t) \tag{3.68}$$

When the BEB reaches the transmitter's starting point at a time t_{i+2}, the total energy consumption from the point t_j to point t_{j+1}, is calculated by integrating $P_{use}(t)$ over t_j and t_{j+1}. This number should be more than the minimum charge level E_{min}; thus, we can state the following constraint:

$$E_{t_{i-i+1}} - \int_{t_j}^{t_{j+1}} P_{use}(t)dt \geq E_{min} \tag{3.69}$$

If the BEB continues to travel from point t_{i+2}, the charge level will increase since it is now moving on the path equipped with a transmitter, and the battery is receiving energy wirelessly from the transmitter. $P_{gain}(t)$, is the quantity of charge added to the battery is proportional to the time spent by the BEB moving over the transmitter. As a result, the motor consumes charge at the rate of $P_{use}(t)$, while the BEB adds charges at the rate of $P_{gain}(t)$. When the battery charge level reaches its maximum, i.e., E_{max}, the pickup device's power is disconnected to protect the battery from overcharging. As a result, at any point along the BEB transit route, the charge level in the onboard battery is given as:

$$E_{t_{i-i+1}} - \int_{t_i}^{t_{i+1}} P_{gain}(t)dt - \int_{t_i}^{t_{i+1}} P_{use}(t)dt + \int_{t_j}^{t_{j+1}} P_{use}(t)dt \leq E_{max}$$

$$for\ i = 1, \dots\dots, n-1\ and\ for\ j = 1, \dots\dots, m-1$$

In this work, the cost of battery per BEB accounts for a substantial portion of the transit system's electrification total investment cost. The battery capacity (B_{cap}) is considered as one of the critical decision variables of the objective equation. This battery capacity (B_{cap}) is expressed as the function of the transit system energy dynamics as

$$B_{cap} \geq \sum_{i=1}^{n} (\int_{t_i}^{t_{i+1}} P_{gain}(t)dt - \int_{t_i}^{t_{i+1}} P_{use}(t)dt) + \sum_{j=1}^{m} \int_{t_j}^{t_{j+1}} P_{use}(t)dt \quad (3.70)$$

Another constraint is the number of wireless power transmitters, N_{WPT}. The number of power transmitters can be expressed as the transit energy ratio to the power transmitter's installed capacity as given in (3.71).

$$N_{WPT} \geq \frac{\left\{\sum_{i=1}^{n} \int_{t_i}^{t_{i+1}} P_{use}(t)dt) + \sum_{j=1}^{m} \int_{t_j}^{t_{j+1}} P_{use}(t)dt\right\}}{T_{cap}} \quad (3.71)$$

Also, consider the starting point and endpoint of the inductive cable of the i_{th} power transmitter be d_i^s and d_i^e, respectively. The inductive cable length of the i_{th} power transmitter is expressed as $d_i^e - d_i^s$, as shown in Figure 3-14. This expression should satisfy (3.72) and (3.73).

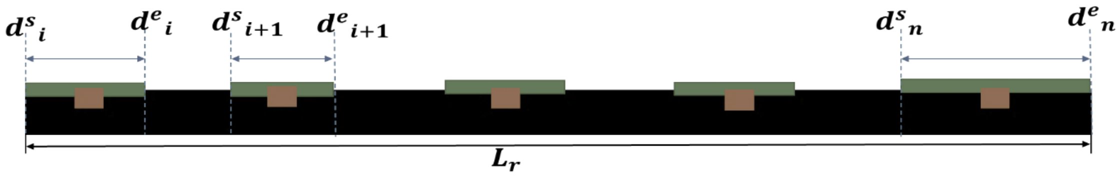

Figure 3-14 Allocation of inductive cable

$$d_i^e > d_i^s \;\; for\ i = 1, \dots \dots, n \quad (3.72)$$

$$d_i^e < d_{i+1}^s \;\; for\ i = 1, \dots \dots, n-1 \quad (3.73)$$

$$\sum_{i=1}^{n} (d_i^e - d_i^s) < L_r \quad (3.74)$$

The section looks at a multi-terminal inductive base model of BEB's transit charging infrastructure. The mathematical optimisation model examines the provision of inductive charging infrastructure, including battery sizes, transmitter position, and inductive cable length. With the trade-off analysis of the component of an inductive transit system, the next chapter gives a simulation example that explores several scenarios that maximise the utilisation of the inductive charging infrastructure while minimising the infrastructure cost.

3.5 Chapter summary

First, section 3.1 presents the transit fleet routing model related to the operating timetable. The operational schedule for the transit network is fed into the BEBs transit fleet model. This fleet routing model would result in transit network electrification parameters that meet the operational needs of the BEB transit system.

Second, in section 3.2, the mathematical model for BEB energy consumption is described based on a longitudinal technique that accounts for dynamics. The energy consumption model is used to determine the BEBs' energy consumption in kWh/km using transit fleet data and network topology data (i.e., BEBs weight, efficiencies, speed profiles, and routes distance and elevation profile). Therefore, the output of the BEBs transit fleet model and the energy consumption model and operational needs are incorporated into the BEB transit system’s proposed novel charging infrastructure model.

Section 3.3 presents the technique for modelling charging infrastructure for BRT transport fleets and the mathematical and optimisation formulations for the novel BEB charging system model 3.3.2, multi-terminal charging model 3.3.3, and integrated charging model 3.3.4. The integrated charging model is a multi-terminal charging infrastructure allocation strategy using conductive and inductive charging methods for a bus transit system. This approach has been considered to cut the cost of investment and increase the reliability of the operational service by optimising the charging station infrastructure. At the same time, examine the trade-off of the charger-operating capacities, onboard battery capacity, number of conductive priority chargers and number of inductive chargers. In summary, the general aim of the three objectives of the optimisation problem introduced in this section is to minimise the electrification expenditure cost of bus transit networks while considering different charging options.

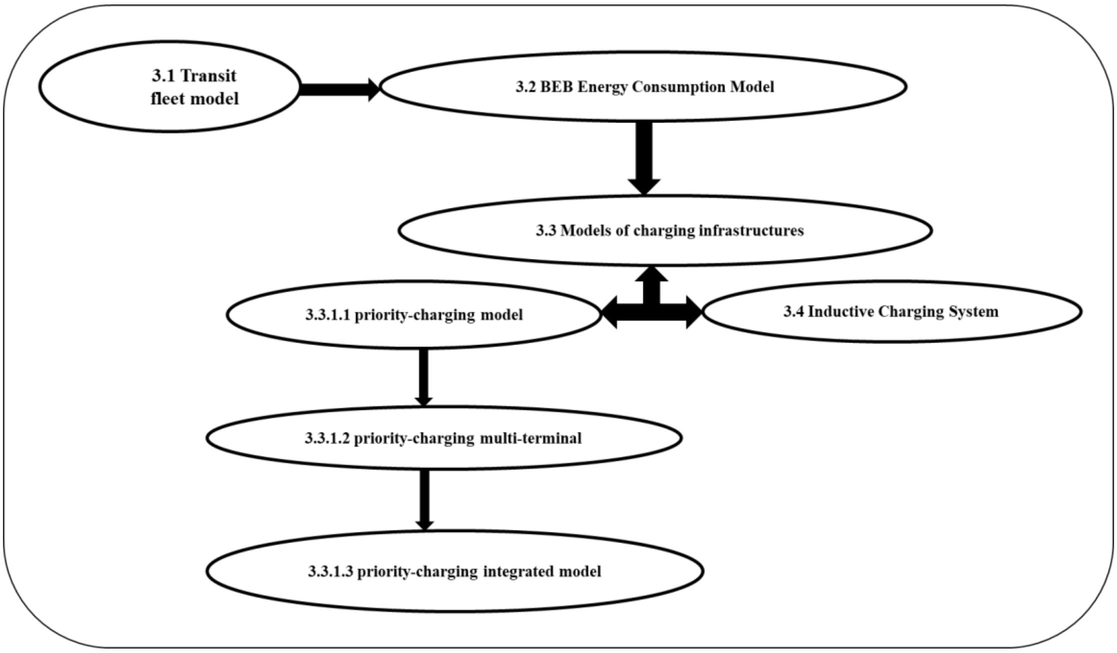

Figure 3-15 Summary of BEB transit fleet design and mathematical modelling

Finally, in section 3.4, a mathematical model for assigning multi-terminal inductive charging infrastructure is presented to optimise power transmitter location, inductive cable length, battery capacity, and the cost of an electrified transportation system. The inductive charging system is an integrated on-road charging technology that charges the BEB battery while the bus moves through the inductive cable route. The overall efficiency and cost of the transit system are directly influenced by the length of the inductive cable, the size of BEB's battery, and the number of transmitters deployed on the road. The summary of the sections covered in this chapter is given in Figure 3-15.

The simulation study in the next chapter looked at these models while considering various charge scenarios.

4 BEB Transit fleet electrification numerical Case Studies

4.1 Introduction

The numerical case studies shown in this chapter used the optimisation model described in Chapter 3 and analysed the several modelling options described in Chapter 3. First, a simulation is performed to determine the average power consumption of BEBs given a classified traffic situation and speed profile for a particular case study. Then, a novel charging optimisation tool is developed to demonstrate how multiple charging strategies can be optimally employed to study essential factors of the transit system: such as the trade-offs between alternative charger designs, charger locations, battery sizes, and cost.

In order to estimate the average power requirement of the BEB, simulation tools and algorithms are developed to evaluate the power consumption of BEBs travelling on defined driving cycles. The BEB power requirement simulation is accomplished using the 'Advanced Vehicle Simulator' (Advisor), an open-source software application tool developed for the US Department of Energy by the National Renewable Energy Laboratory [30]. Numerous authors and international laboratories have proven its accuracy [31], [32].

The derived energy requirements figures are combined with transit data to define the system's performance requirements. The systems under consideration involve designing novel charging infrastructures for the BEB transit system to minimise charging costs and downtime. Additionally, the inductive charging simulation system that optimises the location of power transmitters, the length of the inductive wire, battery capacity, and the cost of the electrified transit system is also studied. The developed optimisation model minimises capital costs while considering the transportation system's operational constraints. Moreover, the GHG emission reduction is estimated. This study aims to determine whether such systems are financially reasonable the extent to which this can, contribute to direct transport GHG emission reduction programmes in developing nations, and improve transit infrastructure and alleviate congestion in emerging cities.

The BEB transit fleet optimisation model developed is based on the particle swarm algorithm PSO. Figure 4-1 shows the overview of the simulation work present in this chapter. The figure shows that the Advisor modelling tool simulates the BEB energy consumption and estimates the GHG emission figure. The PSO optimisation is used to allocate charging infrastructure, trade-off the transit system components and optimise for the minimum cost of infrastructure configuration. It utilises the three proposed priority charging models described in Chapter 3 and the proposed inductive charging model as the bases for studying the BEB fleet electrification.

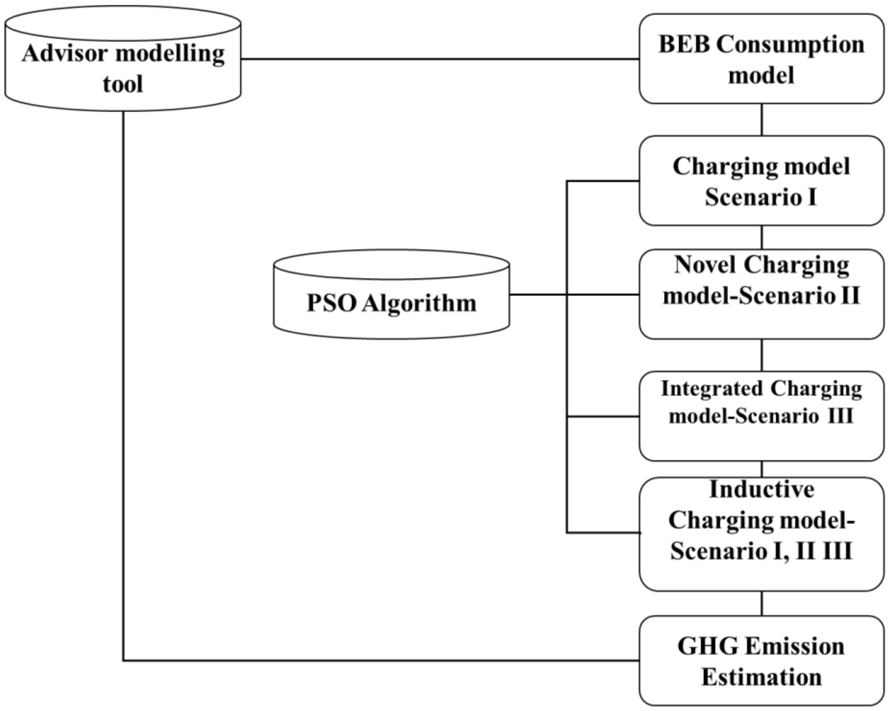

Figure 4-1 Modelling elements and simulation overview

The Lagos BRT case study is considered because both the Lagos state government and the federal government of Nigeria have been eager to adopt measures to alleviate traffic congestion, promote transit use, and significantly reduce CO_2 emissions along this route. Nonetheless, the technique used in this study could be used to examine the electrification of road transit systems in other comparable countries.

This is examined in detail in this thesis, and up-to-date data was gathered from a reputable sources, including the Lagos Metropolitan Area Transport Authority (LAMATA) and PRIMERO Transport Services Limited [307]. This simulation tool and method also employed national traffic statistics, road length data, and driving cycle profiles. Valuable data was gathered from the websites of BEB manufacturers (examples include BYD ADL), and some cost estimates were made using the relevant project as a baseline.

The remainder of this chapter begins with a summary of the case study. The Advanced Vehicle Simulator (ADVISOR) modelling tool and BEB energy consumption simulation, are discussed in detail. The novel method for BEB charging simulation (Scenario I, II, III and IV) is then provided.

4.2 Overview of Lagos Bus Rapid Transit-Case study

Lagos is the most populated city in Nigeria and Africa, with 21 million inhabitants [308]. The rapid growth in Lagos's population (the current estimated growth rate is 6%) generates increasing travel demand, longer trip distances, more trips by car and more car ownership, all of which add to more traffic congestion and pollution in Lagos city [309].

BRT is a sustainable transit system that can compete with and supplement rail systems in providing high-quality transport services. It is a high-quality bus-based transit system that offers fast, comfortable, and cost-effective urban mobility through segregated right-of-way infrastructure and rapid, reliable and frequent operations [31]. The BRT system's unique advantages over the metro systems include lower operating and capital costs, higher flexibility, and short implementation time. These benefits have made BRT predominant in developing countries with insufficient funds for public infrastructure.

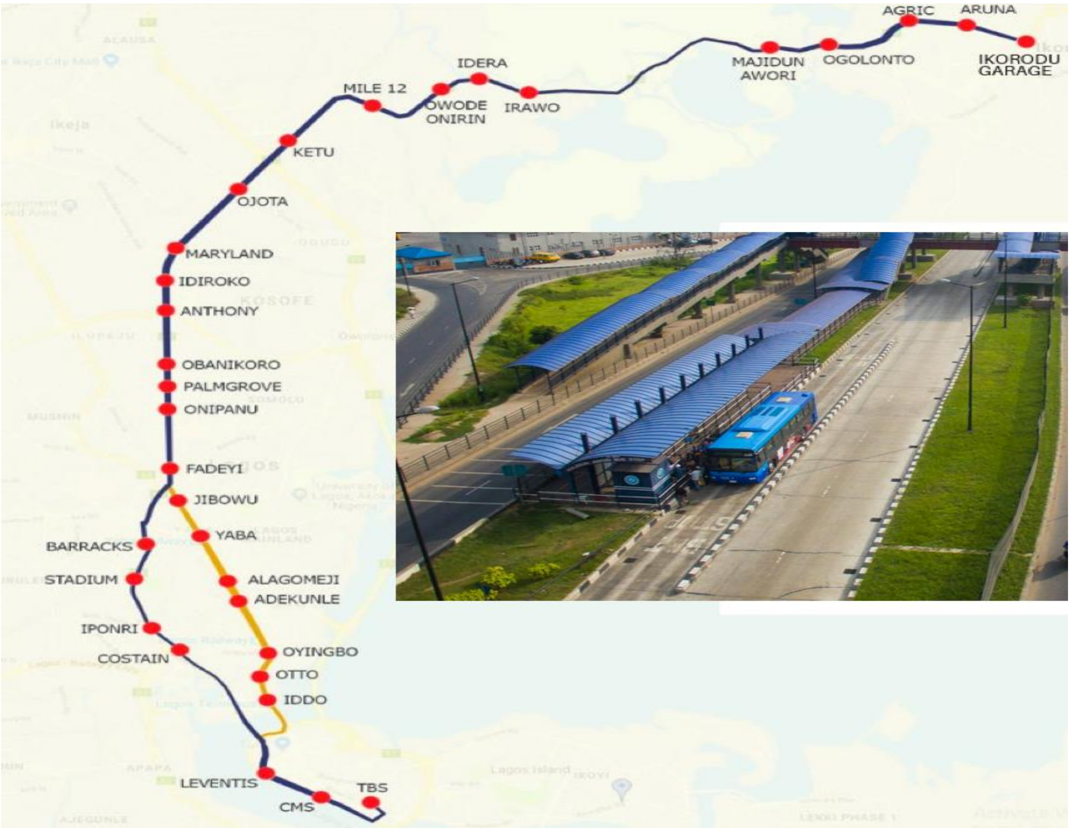

Figure 4-2 Lagos BRT route with the location of bus stops (Source: PRIMERO)

The Lagos BRT scheme is on the Ikorodu-TBS passageway in the Lagos metropolis. This route is one of the busiest and most essential routes with high passenger traffic. The Ikorodu-TBS passageway cuts across seven local government areas and leads to the major Lagos Central Business District (CBD). The route is divided by a median and has several intersections, which are traffic signalised. The route from Ikorodu provides one of the main principal links within Lagos State, linking the exterior settlement of Ikorodu to Lagos Island and other intermediate settlements. The entire BRT Scheme is 38km long, running from Ikorodu to TBS, as shown in Figure 4-2. The transit system is equipped with Electronic Ticketing and Intelligent Transport System. The Lagos BRT currently has 44 bus shelters in both directions, six terminals, 19 intersections, two bus depots with a maintenance bay, an automatic washing bay, administrative offices, a fuel dump, and other appurtenances smooth operation of the system [310] [311].

Primero Transport Services Limited (PTSL), a private company that took over the transit operations in November 2015, manages the Lagos BRT scheme. PTSL has added 434 buses to the transit operations from Ikorodu to TBS and has shuttled over 101 million commuters from November 2015 to date [310]. Since its inception, the BRT scheme in 2008 has conveyed over 400 million passengers [310]. The BRT Operates 16 hours every day from 6:00 am to 10:00 pm. The transit operation schedule is divided into two shifts, with 8 hours of driving per shift (AM & PM). In 2020, pre-covid, the government planned to extend the busway to Oworonshoki-Apapa, Ota-CMS, TBS-Berger, Berger-Iyana Ipaja-Ikotun and Jbowu-Iddo [310] with some delays still in place.

The greening of the Lagos BRT system is an attractive option to reduce pollution and promote policies that can eliminate driveway congestion. Therefore, given its relevance, the data used for this work is for the Lagos BRT network.

4.3 BEB Energy Consumption Simulation

A mathematical analysis based on the longitudinal dynamic is provided in Chapter 3. This section presents the simulation of this mathematical model, which is based on the ADVISOR simulation tool. As a result, this section briefly explains the ADVISOR modelling tool in relation to the energy consumption simulation. In addition, the details of vehicle specification modelling, energy storage system and driving cycles, as well as HVAC and route elevation, were provided. It is worth noting that the BEB energy consumption figure is a vital input parameter in the charging infrastructure allocation. Hence, the BEB energy consumption simulation presented in this section is an essential step in designing and simulating charging infrastructure for the BEB transit system.

4.3.1 The Advanced Vehicle Simulator (ADVISOR)

A study that investigates transit route-based BEB energy consumption and GHG emission is carried out as part of the work of this thesis; because the simulated BEB energy consumption figure is one of the model's input parameters that allocates charging infrastructure for the BEB transit network. The transit fleet routing model design, which links the route and operation circumstances, is provided in Chapter 3, along with the mathematical model for the BEB energy consumption, which is based on a longitudinal method that accounts for dynamics. Hence to simulate this developed model based on the route characteristic of the case study, an ADVISOR simulation tool is adopted.

The National Renewable Energy Laboratory's Advanced Vehicle Simulator (ADVISOR) was first created in November 1994 [312]. It was created as an analysis tool to assist the US Department of Energy (DOE) in developing hybrid electric vehicle (HEV) technologies through the Hybrid Electric Vehicle Propulsion System contracts with Ford, General Motors Daimler Chrysler. Its primary function is to demonstrate the system-level interactions between hybrid and electric vehicle components and their impact on vehicle efficiency and fuel economy[257], [312].

The National Renewable Energy Laboratory developed ADVISOR in the MATLAB/Simulink environment. ADVISOR offers an easy-to-use, scalable, robust, and supported research kit for advanced vehicle modelling to the vehicle engineering community. It is primarily used to measure the fuel efficiency, output, and emissions of vehicles equipped with alternative technologies such as fuel cells, batteries, electric motors, and internal combustion engines operating in hybrid (multiple power source) configurations. It is particularly adept at quantifying the relative change that can be anticipated due to technology adoption compared to a baseline scenario [257], [312], [313].

The previous study has demonstrated the value of the ADVISOR modelling tool. For example, the authors of [314] present the ADVISOR software's design, explain its combined backward–forward computation approach, and demonstrate its accuracy, speed, and adaptability. [315], gives a practical overview of ADVISOR, including the layout of the graphical user interface (GUI), the program's capabilities and limits, and power source modelling options. Additionally, [316] detailed ADVISOR's battery modelling capabilities and indicated that a resistance-capacitance model is preferred for vehicle simulations. The authors of [317] used Simulink tools to model a hybrid drive train for a postal service delivery vehicle. The authors of [318] used the ADVISOR tool to analyse a basic vehicle used for studying hybrid fuel cell/battery passenger cars. Furthermore, the authors of [319] altered the parallel block diagram in ADVISOR to create a simple electric vehicle. The vehicle required controls and components that were not included in the software. The simulation and data analysis tools were found to be convenient and helpful in establishing the capabilities of their design. Using the ADVISOR model, the authors in [100] computed the BEB's kWh/km energy usage along specific routes. The authors improved the accuracy of the BEB energy consumption value by using the BEB speed profile, route terrain, and auxiliary load rating in this work. Nonetheless, the author fails to consider the impact of weather-related uncertainty on the BEB energy consumption value.

As a result, the usage of ADVISOR in this work is in a competitive context and distinct from past research. This work incorporates five traffic flow conditions that mimic the case study situation into the model in order to compare the impact of traffic conditions on the BEB energy consumption figure and to improve the model's accuracy. The data focuses on traffic volume and road capacity, with traffic conditions classified as free, move, appropriate, inappropriate, and critical. The matching average speed profile from the ADVISOR database was used to select this graded traffic condition.

4.3.2 The Advanced Vehicle Simulator (ADVISOR) structure and capabilities

ADVISOR was written in MATLAB/Simulink. MATLAB is a simple-to-use matrix-based programming environment for performing calculations, while Simulink is used to graphically model complex structures using block diagrams [257]. The software uses an iterative calculation approach to produce outputs of a vehicle's velocity and energy consumption at all moments during a simulation. ADVISOR is the only simulation engine that integrates backwards and forwards simulation features.

In the Forward-facing approach, the vehicle simulators provide a driver model that considers the necessary speed and the current speed while developing acceptable throttle and brake commands (often through a PI controller). The throttle command is then converted into engine (and/or motor) torque and energy consumption rate. The engine's torque is fed into the transmission model, converting it to the transmission's efficiency and gear ratio. The computed torque is then transmitted forward through the drivetrain in the vehicle's physical power flow direction until it reaches the tire/road interface as a tractive force. The forward-facing method is very useful when creating hardware and running extensive control simulations. Because forward-facing models deal with quantities that can be measured in a real-world drivetrain, such as control signals and true torques. The fundamental drawback of the forward-looking strategy is its slow simulation speed. Drivetrain power calculations are based on vehicle states, which include computed drivetrain component speeds via integration. Higher-order integration strategies with small time steps are thus required to achieve robust and accurate simulation results. As a result, forward-facing simulation for analysing BEB energy consumption figures can be excessively time-consuming [257].

In contrast to the forward-facing technique that starts with a driver model, the required vehicle velocity drives the backwards-facing approach. A driver model is not included in the backwards-facing method. The force needed to accelerate the vehicle through the time step is derived directly from the speed trace of the simulated driving cycle. The simulation calculates the torque and speed of drive train components required to overcome the vehicle's inertial forces and achieve the target velocity. The calculation is performed backwards, beginning at the tire/road interface and finishing at the energy source. The backwards-facing technique is unsuitable for researching control systems due to the lack of throttle and brake information. A pure backward method is unsuitable for analysing best-effort performance since the backwards-facing model implies that the vehicle achieves the requisite speed trace (i.e., acceleration tests). ADVISOR can effectively take advantage of improved battery and component models while retaining a comparably rapid simulation speed by merging the forward- and backwards-facing approaches [320].

The user interacts with a succession of graphical user interface (GUI) windows to enter various vehicle characteristics and drive cycle requirements and evaluate their impact on vehicle performance, energy consumption, fuel economy, and emissions. The vehicle input screen, the simulation setup screen, and the results screen are the three primary GUI screens in ADVISOR. Figure 4-3 and Figure 4-4, illustrate examples of these screens. The user builds a vehicle of interest on the vehicle input screen (Figure 4-3) by selecting options from drop-down menus. Each list contains many pre-programmed items for use in the vehicle. By altering the attributes of each part, the user can easily construct new components. ADVISOR's revolutionary vehicle design and simulation are more accessible by this functionality [1] [320].

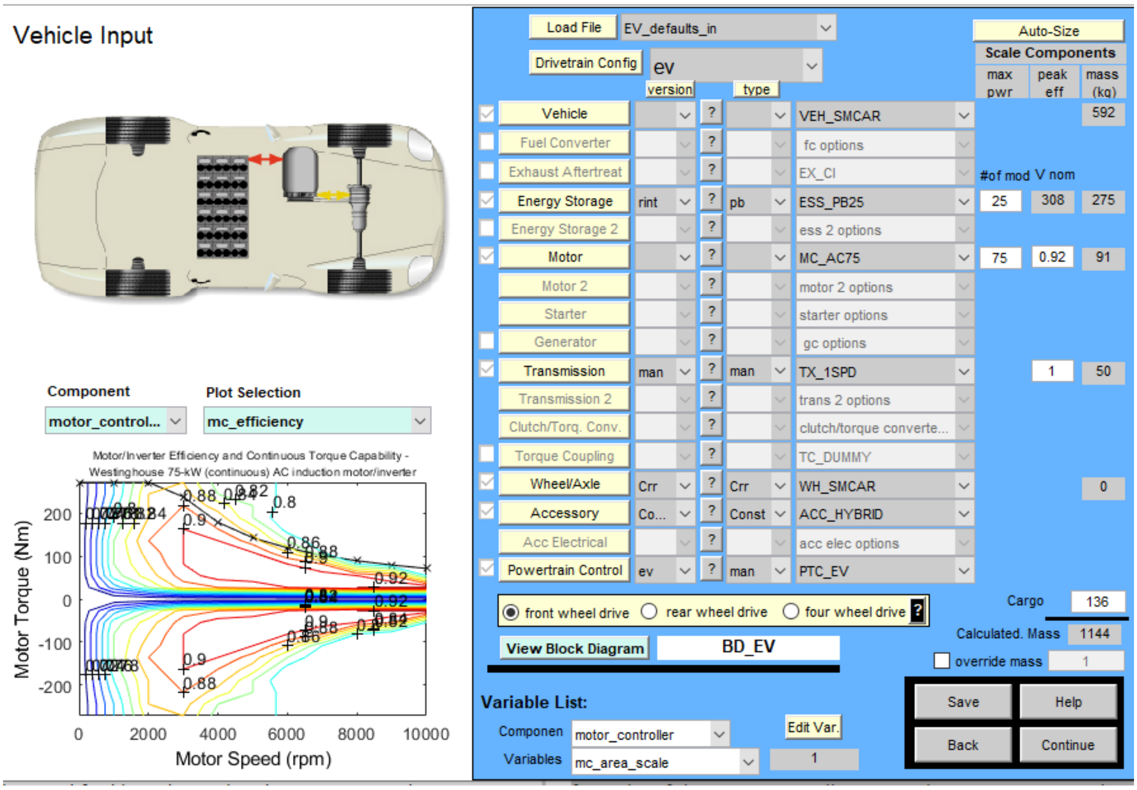

Figure 4-3 ADVISOR vehicle input window

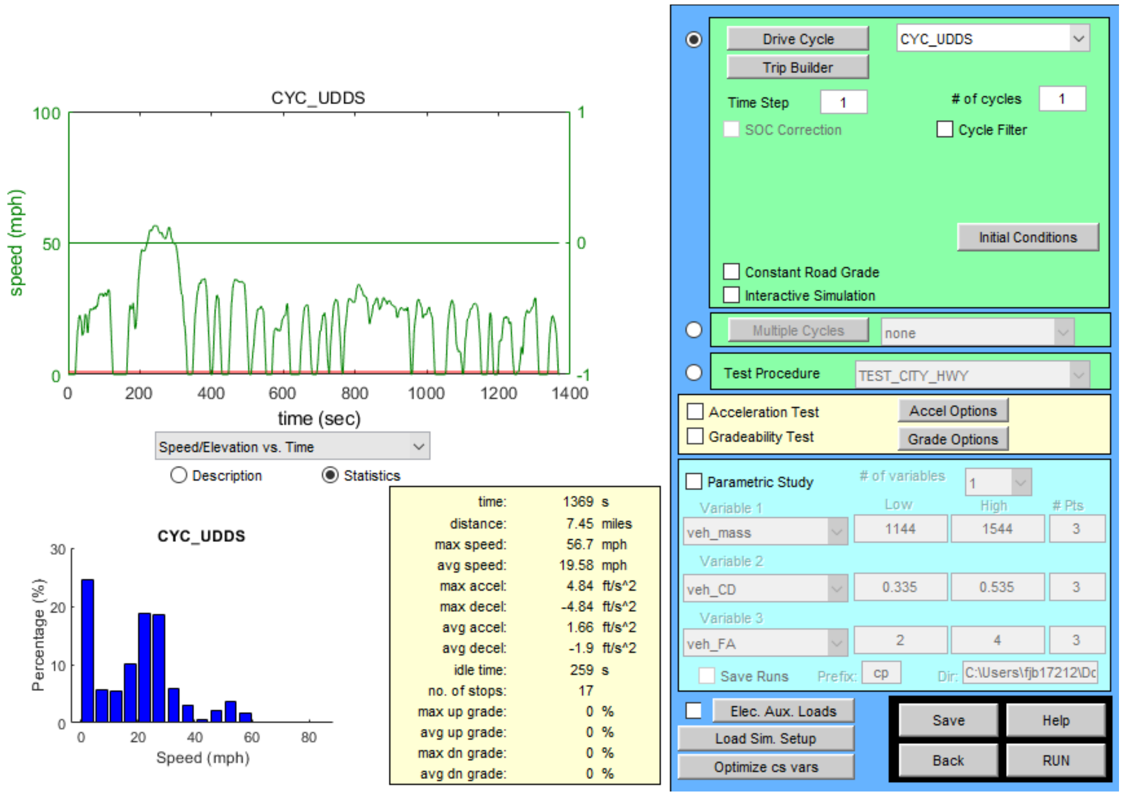

Figure 4-4 ADVISOR simulation setup window

The user defines the drive cycle settings for the event over which the vehicle is to be modelled in the simulation setup screen (Figure 4-4). The results screen (Figure 4-5) displays fuel economy and emissions and detailed charts of time-dependent outputs for reviewing vehicle performance. The user can choose from a variety of output options related to speed and torque, energy usage, emissions, battery charge level, Etc., and up to four plots can be displayed simultaneously [257].

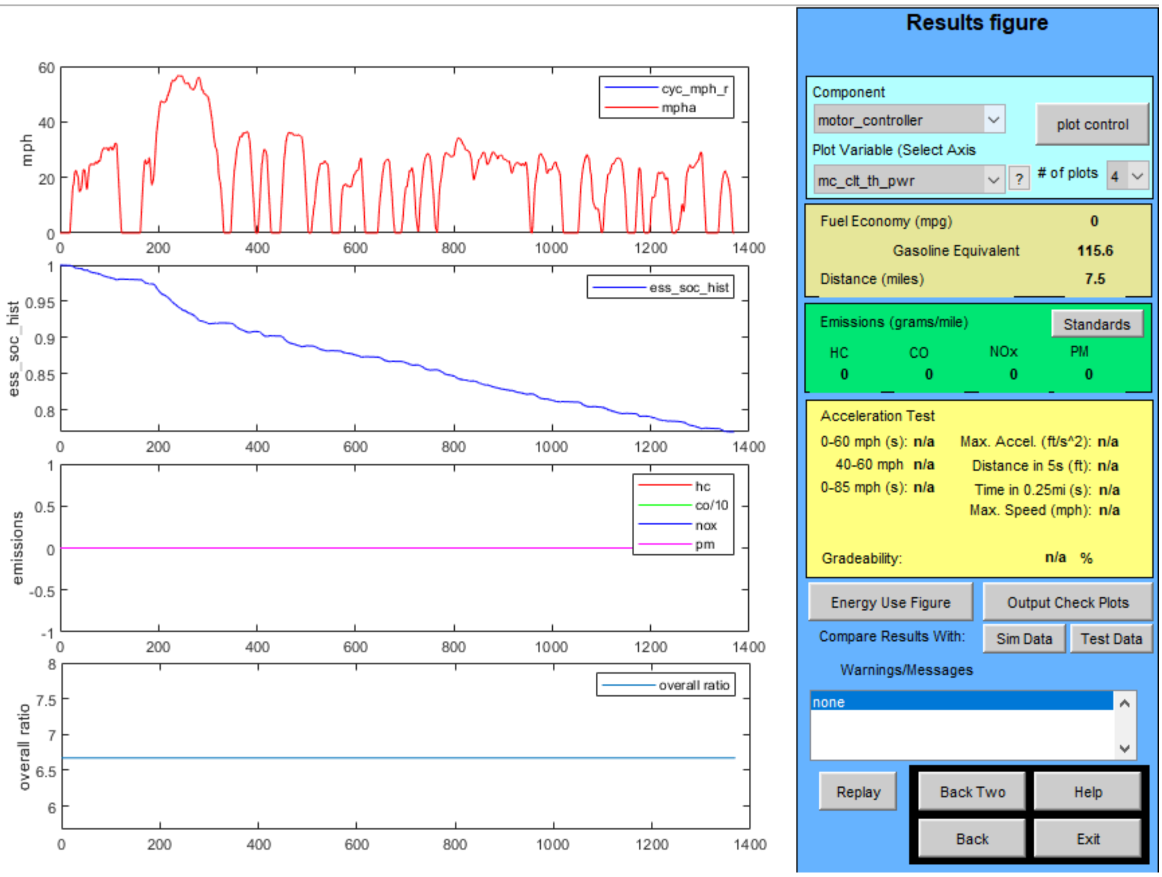

Figure 4-5 ADVISOR results window

4.3.3 ADVISOR BEB energy consumption simulation

In this work, The ADVISOR is used to compute the BEB energy consumption for the Lagos BRT case study using the BEB parameters given in Table 4-1, the BEB speed profile, route topography, trip duration, and the corresponding traffic flow conditions. Hence the next section presents the BEB energy consumption simulation relevant to the case studies for this thesis Advisor's database has a sizable number of regular vehicle types, including light and heavy-duty vehicles equipped with conventional or all-electric drivetrains. The user chooses components such as motors, batteries, vehicle mass, and additional electric loads to mimic a particular vehicle's performance, fuel economy, and emissions.

4.3.3.1 Vehicle design

The advisor vehicle input interface for vehicle design allows the user to pick and customise the drive train configuration to emulate the real-world counterpart. This work uses the ADVISOR vehicle input interface to pick a default EV, and the BEB parameters are entered, as shown in Table 4-1.

All BEBs are assumed to be the same size and capacity in this work. The current bus specification for the Lagos bus rapid transit network is 12m, with a total capacity of 80 passengers with up to 40 seats. It is worth noting that the passage capacity is used to compute the cargo mass in kg. This mass is computed using the global average body mass of 62kg [320].

Table 4-1 BEB Parameter (Source: BYD ADL Enviro200EV)

Vehicle Parameter	Value
Vehicle type	Pure electric
Dimensions	~12m
Gross Veh. Weight	18700kg
Passenger capacity	80 (40 seats)
Electric motors	2×90kW
Battery system	lithium iron phosphate 348kWh
Charging system	dual plug 2×40kW AC
Operational range	Up to 160 miles
Aux. Power	About 15kW
SOC_b^{max}, SOC_b^{min}	80%, 20%

4.3.3.2 Battery selection

The energy storage capacity is based on the battery capacity values on the specifications of the BYD ADL Enviro200 EV. The lithium-iron-phosphate battery capacity of the BYD ADL Enviro200EV pure electric bus is 348kWh [321]. The lithium ion battery is selected as the battery for this simulation because the ADVISOR does not have a lithium-iron-phosphate battery option. On the other hand, lithium-ion batteries have a higher energy-to-weight ratio than other chemistries used in electric vehicles (such as nickel-metal hydride or lead-acid) [322]. In ADVISOR, the default lithium-ion battery pack is made up of 25 modules, each with a capacity of 6 Ah. The battery pack's nominal voltage is 267 V, and capacity in kilowatt-hours may be determined using the formula kWh=AhV. According to this kilowatt-hours computation, the default lithium-ion battery model in ADVISOR has a capacity of around 1.6 kWh. As a result, the energy storage capacity input variable ("ess_cap_scale") must be changed to the desired capacity. In this study, a 348kWh capacity is used to keep the BYD ADL Enviro200 EV in its real-world form.

4.3.3.3 Driving Cycle

The prime objective of the BEB energy consumption simulation is to replicate the proposed case study's real-world conditions (i.e. Lagos BRT). As a result, the ADVISOR was precisely set by employing specific driving cycles that mimicked the Lagos route traffic condition. This traffic situation is classified into five categories that are based on the ratio (v/c) of traffic volume (v) to road capacity (c). These traffic conditions are free, move, appropriate, inappropriate and critical [286], [323], [324]. Although, the Lagos BRT BEBs prototype covered in this thesis operates on a designated fixed-route known as Transit-Way. The Transit-Way separates bus lanes from other traffic with concrete walls, as illustrated in Figure 4-2; nonetheless, these lanes are not absolute. For instance, there are instances when buses connect with other buses on the opposite side of the road. As a result, the speed profile is not always consistent throughout the journeys. In order to evaluate the impact of the traffic conditions on the BEB's energy consumption figure, the speed profiles for different Levels of service LoS (*i.e., (v/c) values- The vehicle road capacity is the maximum number of vehicles that can go through a particular point on the road for a specific period under the prevailing roadway, traffic, and control conditions* [325]). Quality of service involves quantitative procedures to characterise operational requirements within a traffic stream. Level of service(LoS) is a quality measure describing operating conditions within a traffic stream, usually in terms of such service measures as speed and travel time, freedom to manoeuvre, traffic interruptions, and comfort and convenience [325]) are considered. The five-speed profiles classification for Lagos BRT's route are *free*, *move*, *appropriate*, *inappropriate* and *critical conditions* that correspond to <0.6, <0.9, <1.1, <3.1 and >3.1, LoS respectively. The Advisor database lists driving cycles that can be adopted for various simulation purposes. The driving cycles selected for this work are classified based on the average speed. The corresponding average speed used for free, move, appropriate, inappropriate, and critical traffic conditions are 33km/h (Figure 4-6), 21 km/h (Figure 4-7), 18km/h (Figure 4-8), 12km/h (Figure 4-9), and 7km/h (Figure 4-10). As shown in the Figures, the average speed of the BEB's driving cycles decreases with the increasing traffic congestion. It is worth noting that the corresponding average speed used for this simulation is based on the estimation that is focused only on Lagos, Nigeria, traffic scenarios [326]–[331].

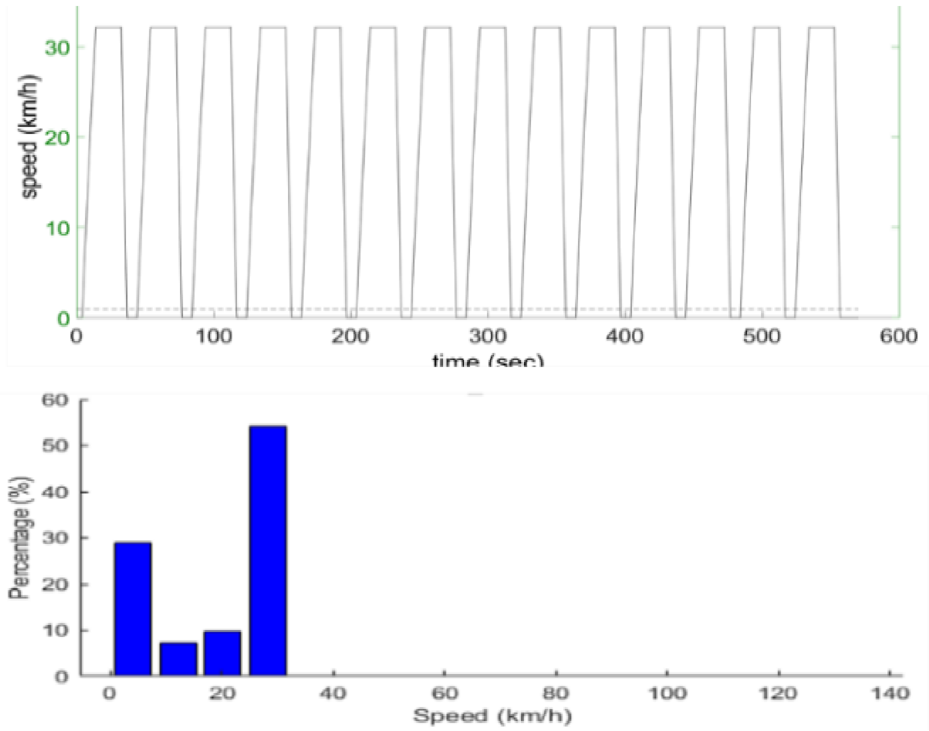

Figure 4-6: Free traffic (average speed: 33km/h)

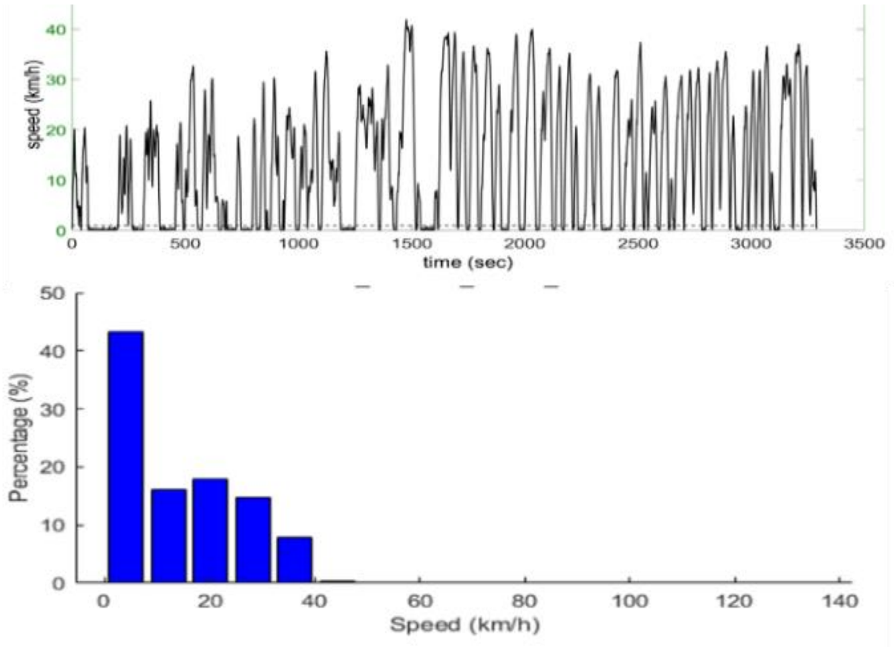

Figure 4-7 Move traffic (average speed: 21km/h)

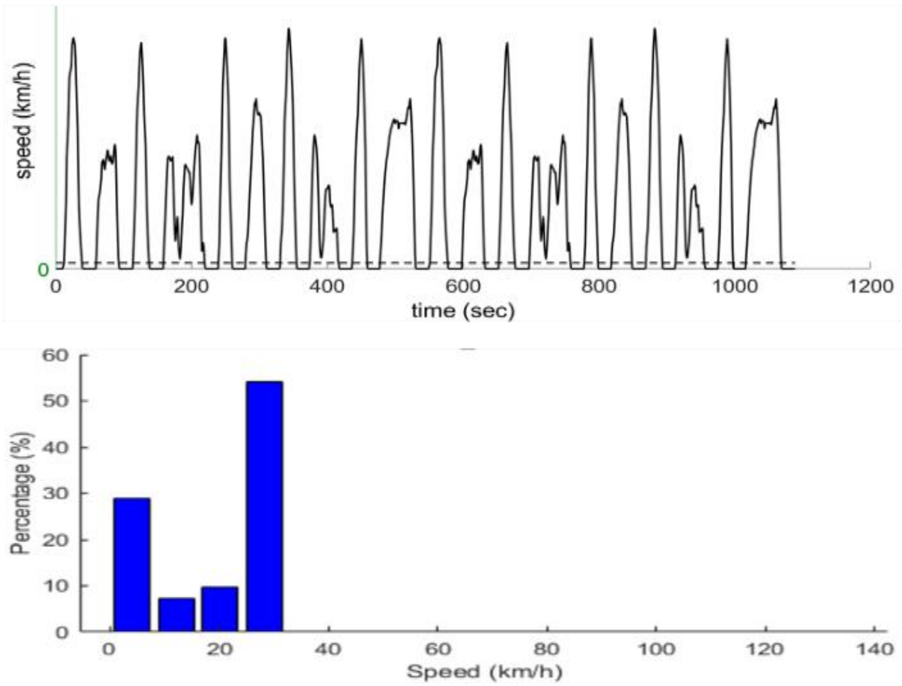

Figure 4-8: Appropriate traffic (average speed: 18km/h)

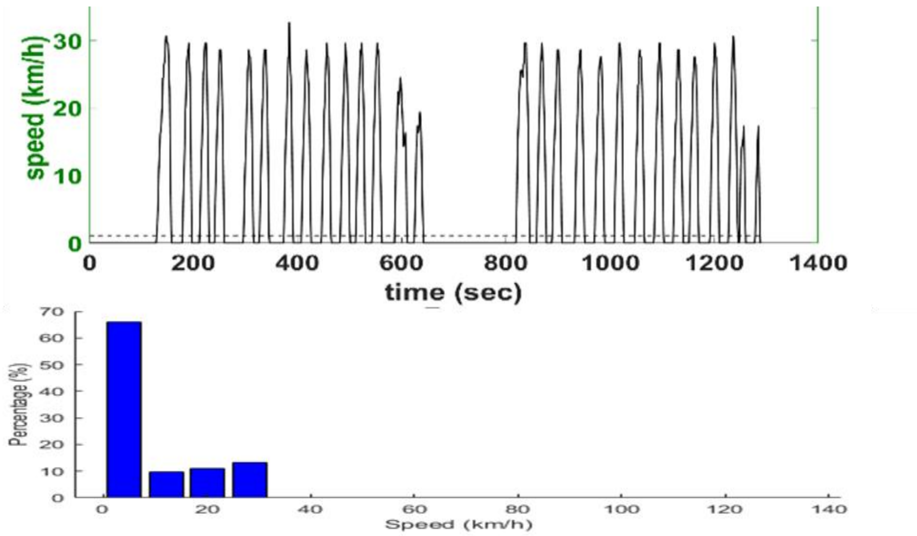

Figure 4-9: Inappropriate traffic (average speed: 12km/h)

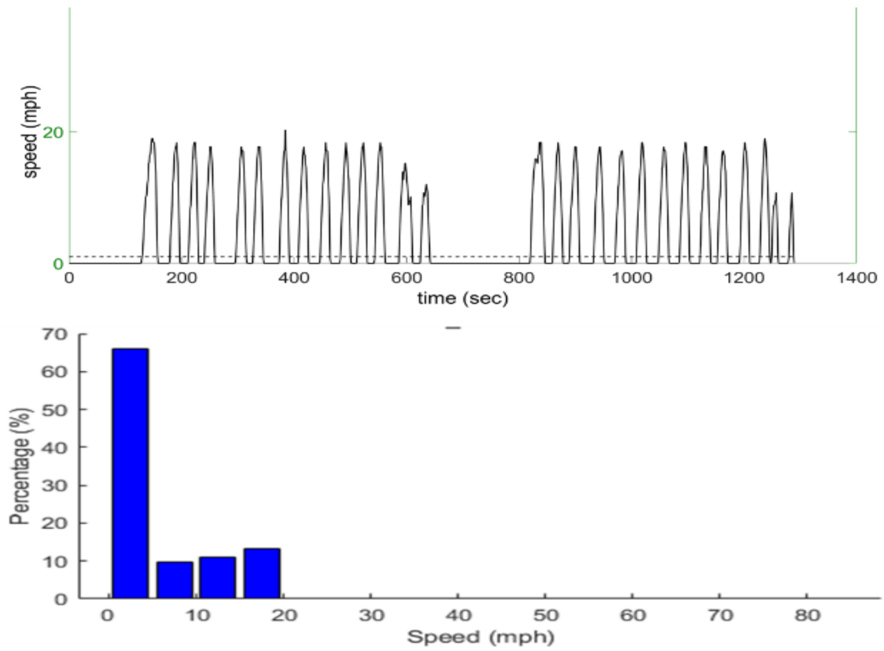

Figure 4-10 Critical traffic (average speed: 7km/h)

4.3.3.4 Other input parameters

The heating, ventilation, air conditioning (HVAC) and route topography are two more input characteristics taken into account to improve the simulation's accuracy. The rated power of the HVAC system and auxiliary systems (i.e., light, sound, and mechanical systems) is assumed to be 15kW [10], which is the worst-case scenario imaginable given the case study's average ambient temperature (> 20 degrees Celsius). The value is inputted into ADVISOR by modifying the default value of *Elect_Aux_Loads.*

Figure 4-11 depicts the route topography for this case study (i.e., the Lagos BRT route topography). The accuracy of the BEB energy consumption figure is improved by mimicking route topographies. As a result, this is entered into the ADVISOR by changing cyc_elevation_init table.

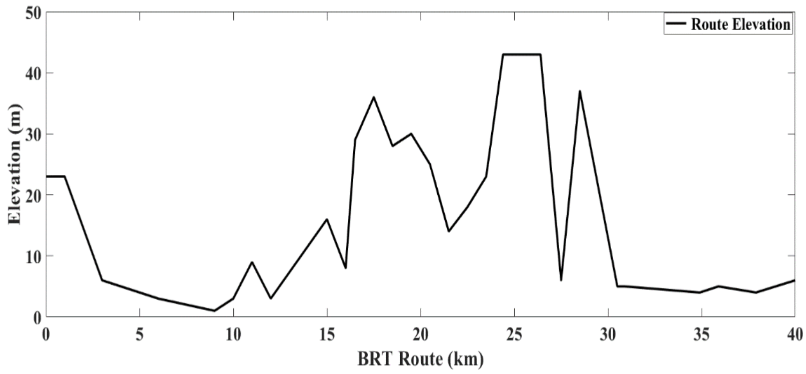

Figure 4-11 The route elevation profile [332]

4.3.4 Simulation results

Individual driving cycles used in this simulation are shorter than the case study transit route to simulate the case study route length. Several driving cycles are simulated in succession. The simulated number of cycles is determined by the multiple selected driving cycles that are equivalent to the proposed length of the case study considered (40km).

The ADVISOR simulations' primary outputs are displays of the velocity profile, State of Charge, emission, and energy consumption as a function of time. The top plots (i.e. Label-I) show the input drive cycle versus the BEB's real simulated velocity. The second (i.e. Label-II) graphs show the energy storage system's State of Charge. The third graph (i.e. Label-III) depicts the BEB's GHG emissions, while the fourth one (i.e. Label-IV) depicts its energy use. These profiles accurately predict how the BEB will perform on the specified course. The BEB's energy consumption is calculated using this simulation. The output represents the energy consumed between the battery pack and the vehicle driving train. As a result, this approach is referred to as BEB Electricity-Tank-to-

Wheel, and the details of the five scenarios simulated result is given Table 4-2. As earlier presented, this table compare the BEB energy consumption simulation result for the five categories of studied traffic situations (i.e., *free* (Figure 4-6), *move* (Figure 4-7), *appropriate* (Figure 4-8), *inappropriate* (Figure 4-9) and *critical* (Figure 4-10).

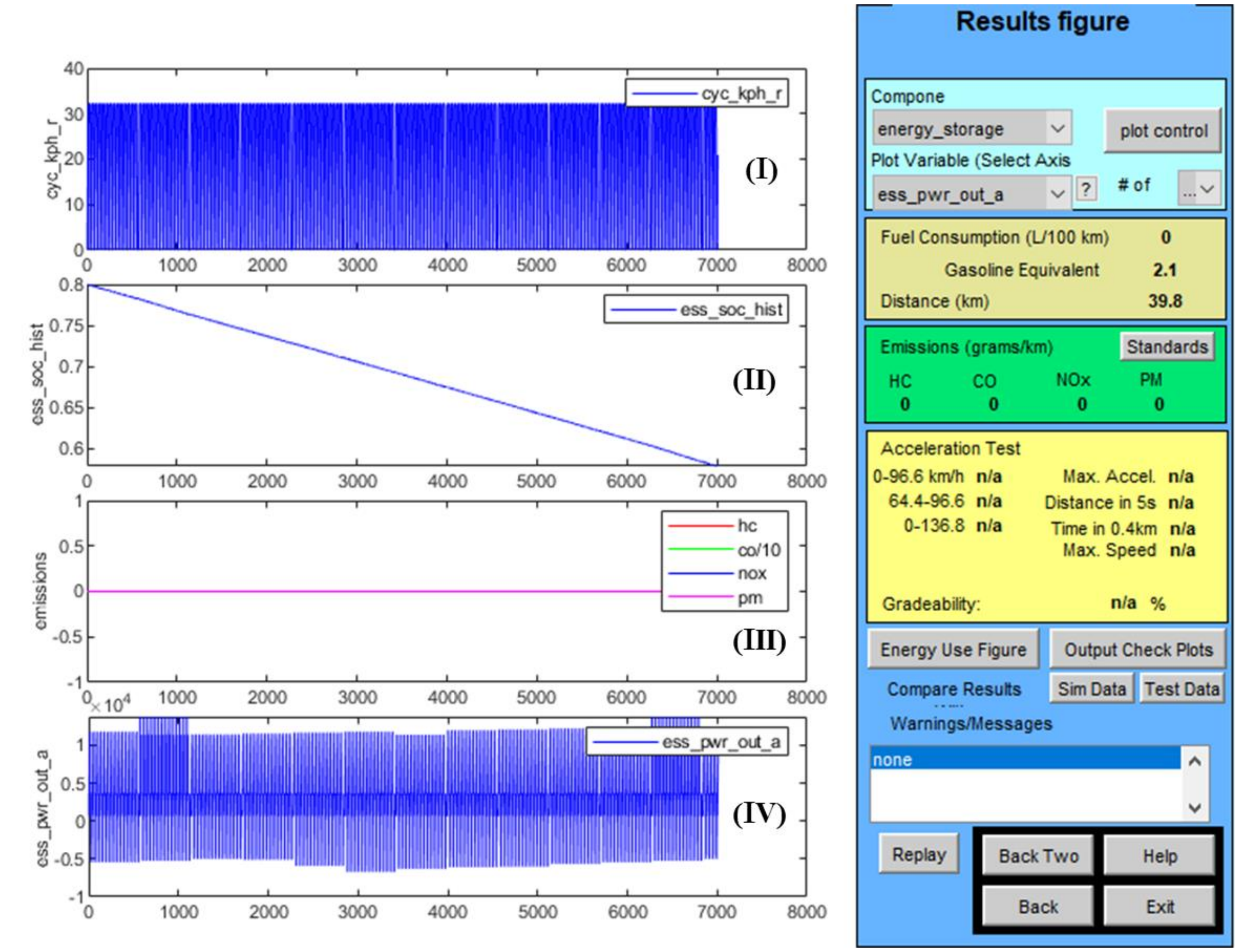

Figure 4-12 Result (Free traffic)

The Figure 4-12 is the simulation result for the free traffic scenario. The figure is labels (I)-(IV); (I) is the speed profile, (II) shows the BEB state of charge (SoC), (III) shows the BEBs emission profile, and (IV) is the BEBs power consumption profile. The power consumption profile is the BEB battery's power to drive the BEB and supply the auxiliary loads. In contrast, the negative power represents the recovered power during deceleration. The kWh/km results presented in Table 4-2 represent the average BEB power consumption simulated for the 40 km route considered as the case study.

Table 4-2 Average BEBs Energy Consumption Based on Traffic Flow classification

Parameters	Traffic condition				
	Free	move	Appropriate	Inappropriate	Critical
v/c	<0.6	<0.9	<1.1	<3.1	>3.1
kWh/km	1.05	1.54	1.88	2.22	2.95
Period(hr)	23-5	10-15 22-23	5-7 21-22	9-10 16-17	8-9 17-21

Table 4-2 shows Lagos traffic characteristics (free, move, appropriate, inappropriate and critical) and the average energy consumption rate for the studied transit system under different traffic conditions. Auxiliary power is regarded to be a constant value. The model does not attempt to account for the uncertainty associated with weather conditions. The energy usage figures in Table 4-2 are an average for the driving cycle. The average energy consumption of the transit system is required from the transit operator's assessment in order to standardise their BEBs route energy demand. As indicated in Table 4-2, the average energy usage under free traffic conditions (the BEB is likely to make a few stops) is 1.05kWh/km. The critical traffic scenario consumes the most energy at 2.95kWh/km. The BEBs' energy usage increases when the route traffic situation worsens, as the BEBs take longer to traverse each kilometre.

4.3.5 Discussion and Summary

The simulated energy consumption analysis reflects the impact of roadway level of service on the average traffic speed to simulate different real-world traffic conditions. Five different traffic scenarios have been presented to quantitatively assess the parameters that affect the energy consumption of BEBs in different real-world traffic. The case studies indicate that different traffic scenarios (i.e., *free*, *move*, *appropriate*, *inappropriate* and *critical* traffic) might have different energy consumption figures due to the BEB speed and trip time variation, and these have been generated to be the reference of conditions on the Lagos BRT. The numerical studies also reveal that traffic conditions could affect the energy consumption figures by increasing the BEB energy consumption by about 180% of its value in critical traffic situations due to lower speed values and longer trip duration at high traffic conditions. The evaluated BEB energy consumption figure is part of the input parameter for the developed optimisation model for the allocation of charging infrastructures for the BEB transit system. Hence, the next section presents the detail of the simulation BEB Transit Charging Infrastructures.

4.4 Simulation BEB Transit Charging Infrastructures

The previous section presents the procedure for evaluating the BEB transit fleet Energy Consumption figure. The BEBs energy consumption figure is one of the input parameters required for the optimum configuration of batteries and chargers to meet transit schedule requirements.

The mathematical and optimisation formulations for the novel BEB charging system model, multi-terminal charging model, integrated charging model, and BEB transit energy demand estimation are described in the third chapter. A mathematical model is also developed in Chapter 3 to allocate multi-terminal inductive charging infrastructure in order to optimise power transmitter placement, inductive cable length, battery capacity, and the cost of an electrified transit system.

Based on these mathematical models in chapter 3, in this section, simulation tools are developed using a PSO algorithm to optimally determine the numbers, locations, power capacity, and costs while considering alternative scenarios and charging strategies, as well as the trade-offs among these output parameters in the designing of charging infrastructures for the BEB transit system.

The PSO approach is simple to implement and can rapidly converge to a good solution. It uses only primitive mathematical operators and does not require any gradient information about the function to be optimised. It is faster, cheaper, and more efficient than other optimisation methods. Furthermore, it requires few initial parameters and is highly suited to solving non-linear, non-convex, continuous, discrete, integer variable problems [333]–[335]. The optimisation equations in this work are not linear and non-differential, and the case studies studied have limited data. As a result, the PSO algorithm is the ultimate pick for solving this optimisation problem. The appendix contains information on the PSO approach, including a brief introduction and PSO fundamental modelling ideas.

4.4.1 PSO Modeling

The optimisation problems formulated in this thesis are nonlinear programming problems with the objective of:

Solve for $\vec{x}$ which optimises $f(\vec{x})$

Subject to:

$$\boldsymbol{g_i(\vec{x}) \leq 0, i = 1, 2, \ldots\ldots, m} \quad (4.8)$$

$$\boldsymbol{h_i(\vec{x}) = 0, i = 1, 2, \ldots\ldots, p} \quad (4.9)$$

$$lb_i \leq x_i \leq ub_i, i = 1,2, \ldots\ldots n \quad (4.10)$$

Where $\vec{x}$ is the denotes the solutions vector $\vec{x}$ = $[x_1, x_2, \ldots\ldots\ldots, x_n]^T$, m is the total number of inequality constraints, and p is the total number of equality constraints (in both cases, constraints could be linear or nonlinear). In the relevant literature on evolutionary optimisation, it is usual to convert equality constraints to inequalities of the form:

$$\boldsymbol{|h_i(\vec{x})| - \epsilon \leq 0} \quad (4.11)$$

Where ϵ is the permissible tolerance (a very small value), this enables us to focus exclusively on inequality constraints. A similar transformation is achievable when only equality constraints are involved. However, this type of modification is uncommon since, when utilising evolutionary algorithms, it is typically easier to deal with inequality constraints (for example, using exterior penalty functions [15]) than it is with equality constraints.

```
Define nvar, ub, lb
Define objective function and constraints (O)
Define t_max , w_max , v_max , v_min , c_1, c_2, nop
Define t_max , w_max , v_max , v_min , c_1, c_2, nop
for ( k = 1 to nop) do
    X_i(k) ← Generate random particle position
    Intialise V_i(k) randomly
    Calculate O_i(k)
    PBEST(k)(i) = X_i(k), PBEST O_i(k) = O_i(k)
    if O_i(k) < GBEST O_i(k)
        GBEST(k)(i) = X_i(k), GBEST O_i(k) = O_i(k)
    end if
end for
for ( t = 1 to t_max ) do
    for ( k = 1 to nop) do
    calculate O_i(k)
    if O_i(k) < PBEST O_i(k)
    PBEST X_i(k) = X_i(k), PBEST O_i(k) = O_i(k)
    end if
end for
Calculate w(t) = w_max − t(w_max − w_min)/t_max
for ( k = 1 to nop) do
    V_i(k) ← update velocity of the ith partile
    X_i(k) ← update postion of the ith partile
    if O_i(k) < PBEST O_i(k)
        update PBEST X_i(k) = X_i(k), PBEST O_i(k) = O_i(k)
        end if
    if O_i(k) < GBEST O_i(k)
        update GBEST X_i(k) = X_i(k), GBEST O_i(k) = O_i(k)
        end if
end for
Output GBEST
```

Figure 4-13 Pseudocode of the PSO algorithm

Assuming F denotes the feasible area and S denotes the whole search space, it should be obvious that F⊆S. For an inequality constraint that satisfies $g_i(\vec{x}) = 0$, hence F is active at $\vec{x}$. At all points of F, all equality constraints h_i (independent of the value of $\vec{x}$ used) are considered active.

4.4.1.1 The modelling approach

The PSO algorithm used in this research is depicted in Figure 4-13. The technique is essentially a straightforward PSO implementation, with three notable exceptions: the way velocity is determined, the turbulence operator and the mechanism used to handle restrictions. These points are covered in considerable detail in the following subsections.

4.4.1.2 Calculating Velocity

The expression proposed by the authors in [336] is used to determine the velocity of a particle:

$$\boldsymbol{V_{id}} = \boldsymbol{\omega} \times \boldsymbol{V_{id}} + \boldsymbol{c_1} \times \boldsymbol{rand_1}() \times (\boldsymbol{p_{best,id}} - \boldsymbol{x_{id}}) + \boldsymbol{c_2} \times \boldsymbol{rand_2}() \times (\boldsymbol{g_{best,id}} - \boldsymbol{x_{id}}) \quad (4.12)$$

where V_{id} is the velocity of the *id* dimension, c_1 and c_2 are two values randomly generated in the range [1.5,2.5] (this range are empirically determined), $rand_1()$ and $rand_2()$ refer to functions that return a random value in the range [0.0, 1.0], is the inertia weight, which in this case takes a randomly generated value in the range [0.1, 0.5] (this range was determined empirically), *pbest* is the best position of the current particle found so far, and *gbest* is the best position of the best particle found so far.

4.4.1.3 The Turbulence Operator

Turbulence is defined as a change in the travel velocity of a particle. This alteration occurs across all dimensions (i.e., across all choice variables), allowing the particle to migrate to an entirely isolated location (something much more difficult to achieve by the mere use of the velocity adjustment formula described above). This method perturbs the swarm in order to prevent particles from becoming trapped in local optima. The turbulence operator behaves probabilistically, considering the current generation and the overall number of iterations required. The objective is to have a substantially higher possibility of perturbing the particle's trajectory at the start of the search. This probability will decline over time as we advance in the search.

Turbulence can be viewed as a mutation operator, and it is defined as follows:

$$\boldsymbol{temp} = \boldsymbol{current_{generations}} / \boldsymbol{total_{generations}} \quad (4.13)$$

$$prob_{turbulence} = temp^{1.7} - 2.0x(temp) + 1.0 \quad (4.14)$$

where $temp$ is used as a temporary variable, $current_{generations}$ is the current generation number, $total_{generations}$ denotes the total number of generations and $prob_{turbulence}$ denotes the likelihood of employing the turbulence operator to impact the trajectory of a particle. The values for this expression were determined empirically through a series of studies.

4.4.1.4 Handling Constraints

The technique proposed in this thesis to handle constraints is applied when selecting a leader [337], [338]. The fitness function is modified slightly so that the particle with the highest fitness value wins when two viable particles are compared. If one of the particles is deemed infeasible and the other is deemed feasible, the feasible particle becomes the winner. If both particles under consideration are infeasible, the particle with the lowest overall violation of constraints (normalised by the maximum violation of each constraint attained by any particle in the present population) prevails. The objective is to choose the particle closest to the feasible region as a leader, even if it is infeasible.

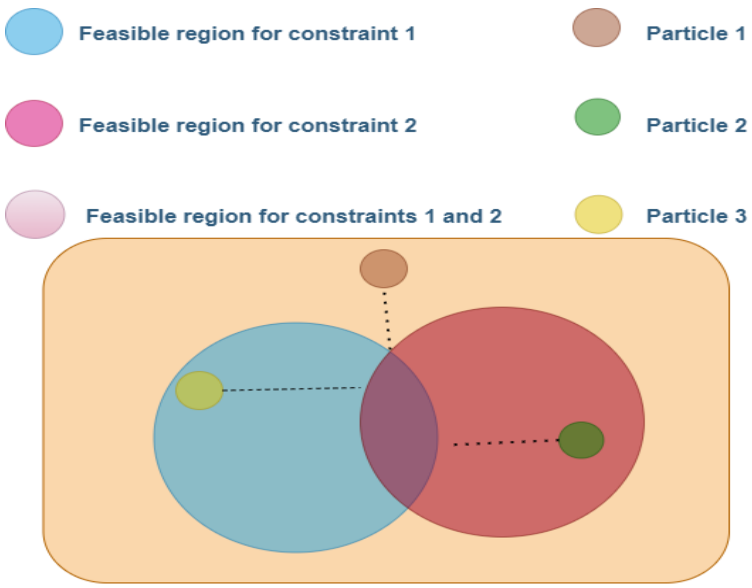

Figure 4-14 Graphical representation explains the constraint-handling mechanism incorporated into our PSO algorithm (Adapted from [339]).

To better understand this concept, consider three particles and two constraints scenario presented in [339]: particle one breaches the first constraint in 30 units and the second in 40 units. Particle 2 does not violate the first constraint but does violate the second constraint by 100 units. Finally, particle 3 breaches the first constraint by 130 units, but not the second. Additionally, the largest violation of the first restriction is 200, whereas the largest violation of the second constraint is 120. Thus, particle 1's fitness is 30/200+40/120=0.48333. Particle 2 has a fitness of 0+100/120=0.83333. Particle 3 has a fitness of 130/200+0=0.65000. Thus, particle 1 has higher fitness than particle 2 and particle 3 (remember that a smaller value indicates that the particle is closer to the feasible region in this case), even though this particle violated both of the problem's constraints. In contrast, the other two particles violated only one of them. Figure 4-14 illustrates this behaviour graphically.

4.4.2 Transit fleet electrification simulation studies

Chapter three presents the design and the mathematical modelling that includes the optimisation model for the BEB transit fleet. The modelling considers diverse BEB’s charging configurations, including studying the use of both the conductive and inductive charging infrastructure and the design of the novel alternative multi-terminal priority charging model. Each of these modelling attributes is used as a planning objective for the BEB transit system optimisation problem.

In this section, each of these modelling objections is demonstrated as a BEB charging configuration scenario. These studies shows the trade-off between the cost, location of the charging infrastructures, the charging duration, on-board battery size, and the transit operation schedule. The first scenario illustrates the trade-off between the chargers' three possible capacities (i.e. 50kW, 200kW, and 400kW) and the optimised battery sizes and the cost.

The second scenario is the novel priority charging strategy that considers allocating the high-priority, medium priority and low priority chargers at each BEB terminal based on the state of charge on arrival. The detail of this strategy is illustrated in the flow diagram in Figure 3-6. In this work, the high priority chargers are configured to have a maximum capacity of 400kW. The medium priority chargers are considered to have a maximum capacity of 200kW, and the low priority chargers are configured to have a maximum capacity of 50kW. These different capacities chargers are considered because of the nature of the schedule in a bus transit system, i.e. buses are usually scheduled to different routes, resulting in different energy demand and charging needs. As a result, to manage the impact of of the BEB charging demand on the grid while maintaining the operational bus schedule, the use of different capacity charges based on the charging priority need of the bus is to aggregate the charging demand over daily operational hours and to avoid unnecessary peak that can impact the grid while ensuring that the transit operational schedule is met.

The third scenario is the novel priority charging strategy that integrates both the conductive and inductive chargers. The allocation of the conductive chargers at the bus terminals is based on the charging strategy described in the second scenario. The addition of strategic placement of inductive chargers to the system illustrates the trade-off in cost, battery size, and infrastructure need for the transit network. These inductive charges are considered located near major bus stops. Because the vehicles slow down as they approach the stations and then eventually stop to offload and load passengers - these allow a short but sufficient time to 'top-up' the BEB battery, and several buses can be charged simultaneously.

The case study considered is the Lagos BRT system, as described in section 4.2. The first part of this study evaluates the BEB average energy consumption value, already presented in section 4.4. This BEB energy consumption figure is part of the input parameter for evaluating the BEB charger configuration. Each of these BEB charging configuration scenarios is a model with the PSO algorithm (the detail of the PSO algorithm is presented in section 4.5).

4.4.2.1 BEB Transit data and model input parameters

As presented in section 4.2, the BRT route is about 40km long, running from Ikorodu to TBS. The Lagos BRT currently has 44 bus shelters in both directions, six terminals, 19 intersections and two bus depots [4] [5]. Primero Transport Services Limited (PTSL), a private company that took over the transit operations in November 2015, manages the Lagos BRT scheme. PTSL has added 434 buses to the transit operations from Ikorodu to TBS and has shuttled over 101 million commuters from November 2015 to date. It operates 16 hours every day from 6:00 am to 10:00 pm [4].

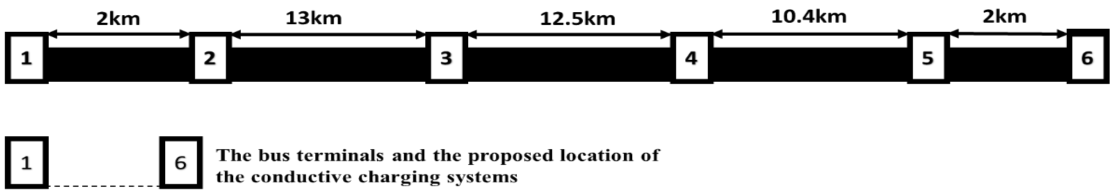

Figure 4-15 Lagos transit network showing bus terminals (Source: LAMATA)

Table 4-3 presents the details of the service lines with the average cycle time. The route has 29 bus stops and six terminals. The terminals' locations are Ikorodu, Agric, Mile 12, Moshaladhi, CMS and TBS, respectively. This data, combined with the cycle time, the BEB energy consumption figure and the bus transit schedule data, are used as input parameters for the optimisation model. The multi-terminal characteristic of the Lagos BRT is shown in Figure 4-15. From the figure, the total distance of the transit network is about 40km.

Table 4-3 Route distance and runtime (Source: LAMATA)

Route Distance and Runtime			
Starting point	End point	Length Km	Runtime
IKORODU	ARUNA	1	0:04:00
ARUNA	AGRIC	1	0:01:30
AGRIC	OWUTU IDIROKO	1	0:03:00
OWUTU IDIROKO	OGOLONTO	2	0:03:00
OGOLONTO	MAJIDUN	1	0:02:30
MAJIDUN	AJEGUNLE	3	0:08:00
AJEGUNLE	IRAWO	1	0:03:00
IRAWO1	IDERA	1	0:01:40
IDERA	OWODEO	1	0:02:00
OWODEO	MILE12	1	0:02:30
MILE12	KETU	3	0:05:00
KETU	OJOTA	1	0:03:11
OJOTA	NEW GARAGE	0.5	0:02:16
NEW GARAGE	MARYLAND	1	0:02:20
MARYLAND	IDIROKO	1	0:01:50

IDIROKO	ANTHONY	1	0:02:25
ANTHONY	OBANIKORO	1	0:02:30
OBANIKORO	PALMGROOVE	1	0:01:18
PALMGROOVE	ONIPANU	1	0:02:15
ONIPANU	FADEYI	1	0:03:42
FADEYI	MOSHALASI	0.9	0:01:00
FADEYI	BARRACKS	2	0:05:00
MOSHALASI	BARRACKS	1.1	0:03:00
BARRACKS	STADIUM	1	0:01:30
STADIUM	IPONRI	2	0:03:00
IPONRI	COSTAIN	0.4	0:01:00
COSTAIN	LEVENTIS	4	0:05:30
LEVENTIS	CMS	1	0:04:00
CMS	TBS	2	0:04:00
Total Travel Time & Length		38	1:25:57
Number of Terminals: **6**			
Number of Depot: **2**			
Average Speed: **45Km/h**			
Average Passenger volume: **116,000 per day**			

Other input parameters for the case study considered in this work are shown in Table 4-3. Detailed data of the Lagos BRT transit data is provided in Appendix A.

Table 4-4 Modelling and simulation parameter (Adapted from [245], [340], [100])

Input Parameters	Value
Number of BEBs	400
Cost of battery per kWh (£)	250
Cost of inductive Cable per meter (£)	50
Cost of BEB (£)	100,000
Cost of wireless power receiver (£)	2,000
Cost of wireless power transmitter per kWh (£)	200
Transmitter capacity (kW)	500
Power of conductive chargers (low, medium & high priority) (kW)	50, 200, 400
Cost of charger installation (low, medium & high priority) (£)	5,000, 15,000 & 30,000
fixed cost (c_f^l, c_f^m, and c_f^h) charged for using either low, medium and high priority, respectively	£0.0, £1.0 & £2.0
Charging cost (c) is the cost of energy per kWh (£)	0.2
Cost of charger installation of inductive transmitter(£)	30,000

It is also worth noting that all the inductive chargers are configured to have the same capacity of 500kW. The inductive chargers' location and the length of the inductive cables are to be obtained from the optimisation result. However, the approach considered in this work gives priority for the inductive chargers to be located near major bus stops where possible. Because the vehicles slow down as they approach these stops and then eventually stop to offload and load passengers - these allow sufficient time to 'top-up' the BEB battery, and several buses can be charged simultaneously. The inductive chargers are considered necessary because of the following reasons:

As shown in Figure 4-15, the Lagos BRT network has six terminals, with each terminal in the modelled case will have charging infrastructures that BEB can use at the start and the end of a scheduled trip. The chargers at the terminals are designed with various capacities, and the capacities are allocated based on the BEB energy demand and the power capacity of the charging infrastructures. The BEBs will be subject to the high, medium and low priority charging described previously. The high priority chargers in this study are set to a maximum capacity of 400kW. Chargers with a maximum capacity of 200kW are called medium capacity, while those with a maximum capacity of 50kW are considered low capacity.

4.4.2.2 BEB energy consumption

The Lagos BRT network's current bus specification is 12m with up to 80 total passengers with up to 40 seats [341]. While there is some generational variation in the existing bus fleet for the Lagos BRT, with different buses being purchased at different times, in this work, all the BEB are assumed to be of the same size and capacity. This is largely for ease of modelling characterisation. In this work, the equivalent electric drive considered is the BYD ADL Enviro200EV pure electric, zero emission single deck bus from BYD and Alexander Dennis [167]. This *BEB energy consumption* modelling associated with the modelled vehicles have already been presented in section 4.3.4 using the ADVISOR modelling tool. The evaluated value of 1.88kWh/km for the 'appropriate traffic' is considered as the input parameter for the optimisation model (see Table 4-2).

4.4.3 Charging infrastructure simulation studies

The simulation research presented in this section is based on the mathematical analysis of charging infrastructure allocation to the electric bus transit network system presented in chapter 3, section (3.3.1). The proposed analysis is based on the design and modelling of multi-terminal charging infrastructure to meet the charging demand of the bus transit network system. The simulation model considered different scenarios that include fixed charger capacities (scenario I). The second scenario is the simulation priority charging (scenario II). Also considered is a model that integrates both inductive and conductive priority charging (scenario III) to ensure effective energy management without disrupting the operational bus schedule. In the fourth scenario (scenario IV)), only inductive charging infrastructure is investigated for comparison. The inductive model determines the best position and length for the inductive cable, as well as the lowest infrastructure cost. The optimisation problem is made up of the objective functions and constraints given in section (3.3.1) of chapter 3.

4.4.3.1 Scenario I – Simulation of fixed terminal charger capacity

In this case, the transit optimisation problem assumes that all six terminals have the same charger capacity. The simulation model allocates a sufficient number of charging infrastructure to each bus terminal in the most efficient way possible. This charging infrastructure allocation is based on the mathematical model presented in chapter 3, section (3.3.1) and implemented using the PSO optimisation method. The derived BEB energy consumption figure (Table 4.2 in section 4.1), as well as transit data such as route length, transit schedules, and cycle duration, were used as input parameters. In addition, the estimated cost value in Table 4-4, the number of buses, and the charger's capacity are also input parameters for the simulation model. Additionally, the model generates results for the optimal battery size and the cost associated with different types of chargers considered in this scenario.

In this scenario, a comparative evaluation of simulation studies of three different types of chargers is classified based on their power capacities. The charger capacities are 400kW, 200kW and 50kW, respectively, as shown in Table 4-5. The results show that the whole transit network system in the case studies requires about 47 chargers of 400kW capacity, and each BEB will require an onboard battery of 96kWh. At 200kW, the transit network needs to have 76 chargers, and the optimal onboard battery is evaluated to 126kWh. Charging with 50kW chargers requires 116 charges, and an onboard battery capacity is estimated to be 164kWh.

Table 4-5 Simulation result for the scenario I

Variables	Terminals						Result Summary		
	1	2	3	4	5	6	Total	Battery Size (kWh)	Optimal Cost (£)
No of 400kW conductive chargers	7	6	9	10	9	6	47	96	51,070,720
No of 200kW conductive chargers	10	12	14	14	14	12	76	126	53,782,480
No of 50kW conductive chargers	18	20	20	20	20	18	116	164	56,980,608

In this scenario, the optimal cost for each charger capacities classification is shown in Table 4-5, with the lowest value of £51,070,720.00 associated with the 400kW chargers.

It shows that a fast charger can benefit the cost of installation. Without the loss of generality, it is important to indicate that fast charging can negatively impact the grid if not properly managed and promote the BEB on-board battery's ageing [343].

4.4.3.2 Trade-off Analysis (Scenario I)

This study has shown the impact of onboard battery reduction with varied transit charger configurations on the related costs. This first scenario presents the trade-off between the chargers' three possible capacities (i.e. 50kW, 200kW, and 400kW) and the optimised battery sizes and the cost, as shown in Table 4-5.

According to the findings, the entire transport network system will require approximately 47 charges of 400kW capacity each, with each BEB requiring a 96kWh onboard battery. In addition, when considering a 200kW charger for the transit network, it is determined that it will require 76 chargers. The optimum onboard battery capacity of the BEB is estimated to be 126kWh. The onboard battery capacity is estimated to be 164kWh while charging with 50kW chargers, and the transit network requires about 116 units' charges. In this scenario, the optimal cost for each charger capacities classification is shown in table 5.3, with the lowest value of £51,070,720.00 associated with the 400kW chargers.

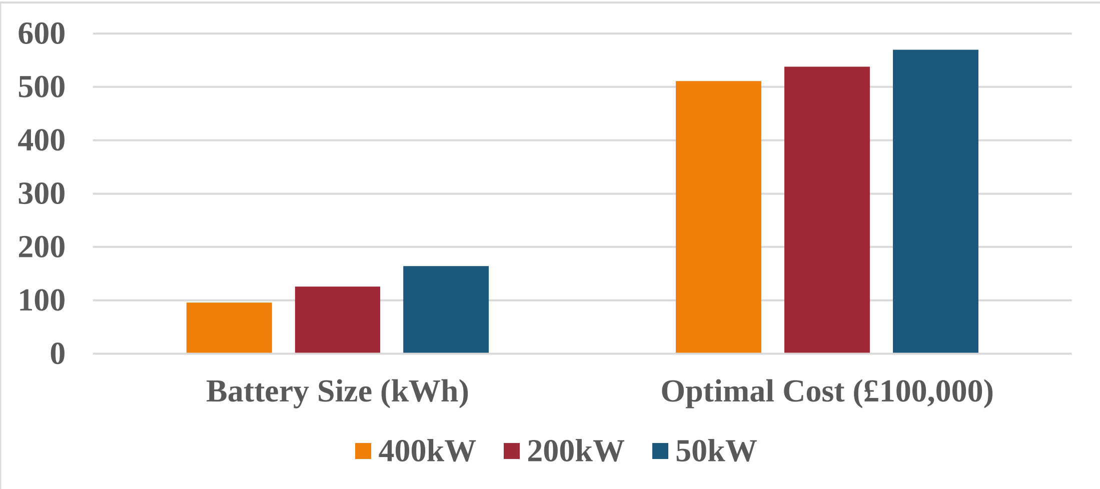

Figure 4-16 Scenario I, trade-off analysis

As illustrated in Figure 4-16, having many low-capacity chargers may be financially costly and inefficient than having fewer, higher-capacity ones (as seen in the situation of 400kW and 50kW configurations). This inefficiency is caused by long charging durations that are inconvenient for bus transit schedules. In order to fulfil transit schedules, the number of charging facilities increases, as does the cost.

Furthermore, the greater capacity charger demonstrates that the BEB onboard battery can be swiftly recharged. As a result, a lower on-board battery capacity is possible with high-capacity chargers. Furthermore, because there are fewer charger units and a smaller BEB onboard battery, the investment cost is cheaper than low-capacity chargers requiring more charging points and BEBs with a large onboard battery. For example, this simulation result shows that implementing 400kW is estimated to be £5,909,888.00 less expensive than implementing 50kW in this case study.

4.4.3.3 Scenario II- Simulation of priority charging strategy

The modelling of the multiterminal BEB transit system in this scenario is based on priority charging set up at the bus terminal. The terminal is where buses halt for 10-30 minutes at the end or beginning of a scheduled trip to allow passengers to off-board and on-board. This waiting period is considered the charging duration to prevent disrupting the BEB operational timetable. A transportation network typically has multiple terminals strategically placed to adequately distribute buses to meet passenger demand. As a result, the multiterminal priority charging approach proposed in this thesis aims to allocate priority charging infrastructures to meet the charging demand for transit BEBs by positioning adequate resources at each BEB terminal.

The charging infrastructure allocation of high (H), medium (M), and low (L) priority chargers are based on the mathematical model (objective equation and constraints) described in chapter 3, section (3.3.1.2) and is implemented using the PSO optimisation method. The input parameters include the derived BEB energy consumption figure (Table 4.2 in section 4.1) and bus transit data such as route length, transit timetables, and cycle duration. Also, the estimated cost value in Table 4-4, the number of buses, and the charger's capacity are part of the input parameters for the simulation model. Moreover, the model gives results for the optimal battery size and the optimal cost.

This allocation of high-priority, medium-priority, and low-priority chargers at each BEB terminal is based on charge condition on arrival. The flow diagram Figure 3-6 depicts the strategy in full depth. The high-priority chargers in this study are set to a maximum capacity of 400kW. Chargers with a maximum capacity of 200kW are termed medium-capacity, while those with a capacity of 50kW are considered low-capacity.

In this scenario, the model considered the use of three different chargers capacities strategically, as described in chapter 3 and illustrated in Figure 3-6. This strategy is considered to efficiently manage the transit energy demand and mitigate the power grid's transit demand impact because the power demand at every point in time depends on the total capacities of the operating chargers. For example, if 18 BEBs arrive at the terminal for charging at the same time, and all of the chargers are 400kW, the charger demand will be (400kW ×18 = 7,200kW). However, utilising the proposed priority charging technique, the total demand will be (400kW ×1 + 200kW ×6 +50kW ×11 = 2,150kW), relieving the grid of approximately 5,050kW of immediate demand. Although a lower number of 400kW may be sufficient to meet the charging demand, BEBs will be forced to queue in this situation. This condition was depicted in scenario-I above, so the following subsection compares the behaviour of terminal one in scenarios-I and II.

Table 4-6 Simulation result for priority charging (Scenario II)

Variable		Terminals					
		1	2	3	4	5	6
No of conductive chargers	H	1	1	3	3	3	1
	M	6	6	6	8	7	8
	L	11	9	9	9	9	9
Total no. of terminal chargers		18	16	18	20	19	18
Optimal Cost (£)	47,338,900.00						
Optimal battery capacity (kWh)	64						

The optimisation model generates the optimal cost for the bus transit infrastructure needs to be £47,338,900.00. Table 4-6 shows the result per terminal—the optimal onboard battery capacity in this scenario is 64kW. It is worth noting that the result charger allocation simulation across the terminals is different because the terminal's demand is based on the distance travelled by bus and the varying operational schedule.

4.4.3.4 Comparison of charging behaviour of Scenario I and II

This study demonstrates the charging of ten BEBs using the charger allocation result from the optimisation algorithm. In this case study, a comparative evaluation of priority and the fixed capacity charging of BEB is carried out at terminal one. The priority charging of ten BEBs is compared with 50kW, 200kw, and 400kW capacity chargers. The result is shown in Figure 4-17.

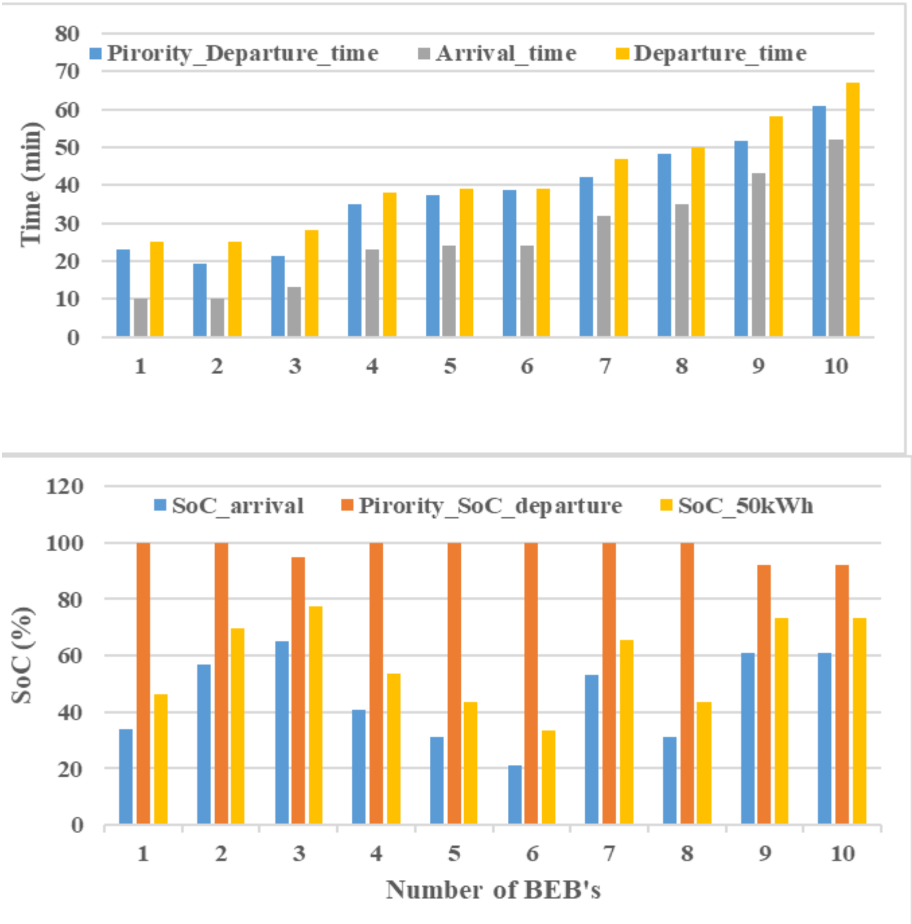

Figure 4-17 Charging duration (min) and SoC (%) of BEBs priority and non-priority (50kW) scenarios

Figure 4-17 shows the arrival time and departure time and the BEB on-board battery state-of-charge on arrival and the state-of-charge (SoC) on departure for both priority and fixed capacity (50kW) scenarios. The fixed capacity of 50kW charger’s capacities specify that none of the BEBs can receive charge to total capacity before departure within the maximum schedule duration of 15minute (dwell time). However, some of the BEB may be able to meet the next scheduled trip demand. For example, the 10th BEB in the Figure

4-17 could meet the demand of the next scheduled trip depending on the trip distance. However, it could be difficult to achieve an optimal BEB schedule (like the existing diesel buses) using the 50kW capacities chargers in most cases. In the priority scenario, seven out of the ten BEBs charged to their full capacities while the remaining three received energy sufficient for the next scheduled trip. These three BEBs cannot be fully charged because they receive a charge at a medium or low priority that depends on their battery capacity on arrival; however, the received energy is sufficient to keep the transit schedule going without delay.

Figure 4-18 shows the arrival time and departure time, the BEB on-board battery state-of-charge on arrival, and the state-of-charge (SoC) on departure for both priority and non-priority (200kW) set-ups. The non-priority scenario of 200kW charger's capacities shows that 5 of the 10 BEBs can receive charge to total capacity before departure within the maximum schedule duration of 15minute. However, the remaining 5 BEBs that arrived at the charging station with relatively low SoC did not charge to the total capacity. Although the received energy may be adequate to meet the next trip demand in some cases, this is not always the case since some BEB with a deficient state of charge may be unable to gain enough energy for the next scheduled trip.

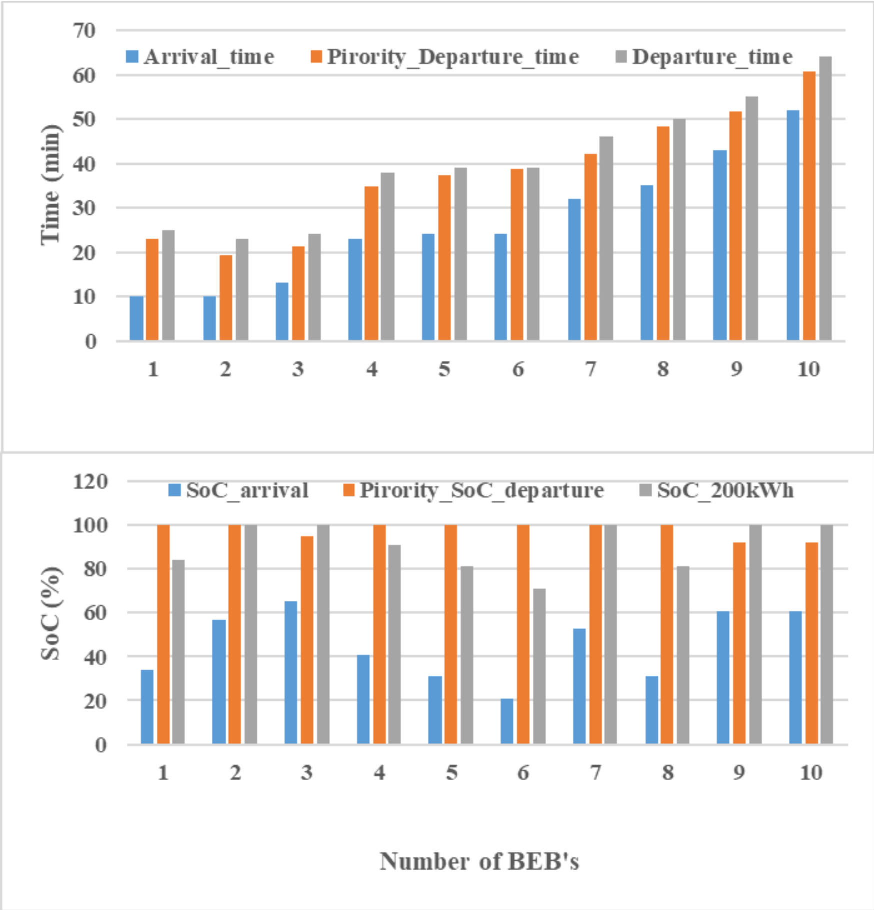

Figure 4-18 Charging duration (min) and SoC (%) of BEBs priority and non-priority (200kW) scenarios

In the priority scenario, seven out of the ten BEBs charged to their full capacities while the remaining three received energy sufficient for the next scheduled trip. These three BEBs cannot be fully charged because they are receiving a charge at a medium or low priority that depends on their battery capacity on arrival. However, the received energy is sufficient for the next transit scheduled trip. Compared to the priority charger with the non-priority 200kW chargers, the priority configuration systems are cheaper and ensure that all the buses are accurately planned to receive charges to meet scheduled trips without any operational delay. In addition, a minimum number of buses can be operated, similar to the diesel bus transit system.

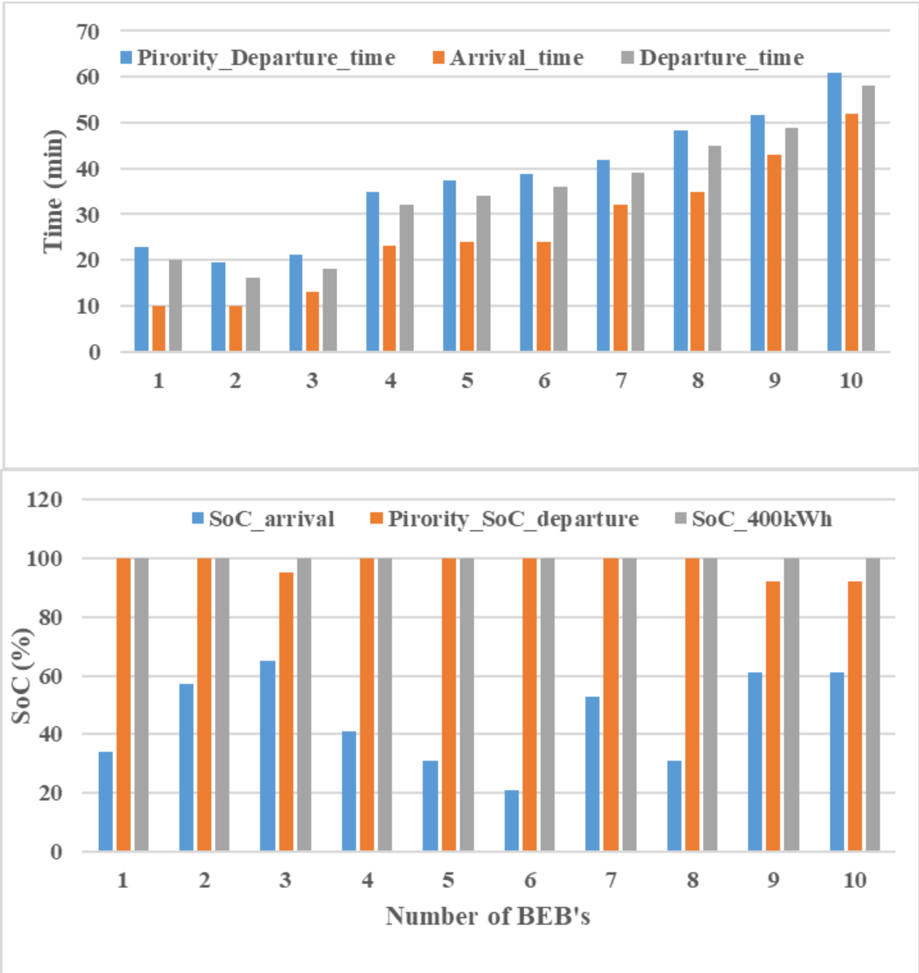

Figure 4-19 Charging duration (min) and SoC (%) of BEBs priority and non-priority (400kW) scenarios

Also, Figure 4-19 shows the arrival time and departure time and the BEB on-board battery state-of-charge on arrival and the state-of-charge (SoC) on departure for both priority and non-priority (400kW) scenarios. The non-priority 400kW charger's capacities specify that all the BEBs received a charge to total capacity before departure within the maximum schedule duration of 15minute (dwell time). However, compared to the novel priority-charging charging strategy proposed in this work, the use of several high-capacity chargers simultaneously could negatively impact the grid and distribution network infrastructure [344]. The priority charging strategy proposed in this thesis reduces the demand from the grid while charging several BEBs simultaneously. Hence, it potentially mitigates the valley and peak effect on the grid [344] and reduces the impact of BEBs' charging demand on the distribution network and the grid because the peak load could be shifted as priority-charging spreads the transit demand for the duration of the operational bus schedule.

Moreover, the cost of providing these proposed charging infrastructures (priority chargers) is cheaper than the needed investment cost for providing the 400kW capacities chargers.

4.4.3.5 Scenario III-Simulation of the multi-terminal integrated charging model

The simulation of the transit electrification system considered in this scenario is the multiterminal allocation of charging infrastructure for a bus transit system that uses conductive and inductive charging techniques. This simulation approach demonstrates the cost-benefit trade-off and improves operational service reliability by optimising charging station infrastructure: charger-operating capacities, on-board battery capacity, the position of inductive transmitters, length of inductive cables, and the number of chargers. This simulation is based on the mathematical model and objective equation described in chapter 3, section (3.3.1.3)-equations (3.55) - (3.65).

The PSO optimisation method is used to implement this mathematical model. Input parameters included the computed BEB energy consumption figure (Table 4-2 in section 4.1), as well as transit data such as route length, transit timetables, and cycle duration. In addition, the simulation model takes into account the estimated cost value in Table 4-4, the number of buses, and the charger's capacity. The model gives findings for the optimum battery size, total infrastructure cost, and the number of different types of chargers considered in this scenario.

Table 4-7 Simulation result for the integrated model (scenario III)

Variable		Terminals					
		1	2	3	4	5	6
No of conductive chargers	H	1	2	2	3	3	1
	M	6	6	6	6	6	5
	L	8	10	8	9	8	10
Locations of the inductive transmitter (500kW)		0	0	1	1	1	0
Locations of inductive cable (m)				7900-9039	20425-21526	31630-32852	
Optimal Cost (£)	44,377,000.00						
Optimal battery capacity (kWh)	33						

It is worth noting that inductive charges should be located near major bus stops. Because the vehicles slow down as they approach the stop and then eventually stop to offload and load passengers - these allow a short but sufficient time to 'top-up' the BEB battery, and several buses can be charged simultaneously.

The optimisation model generates the optimal cost for the bus transit infrastructure required in this scenario to be £44,377,000.00. The result per terminal is shown in Table 4-7; the ideal onboard battery capacity, in this case, is 33kWh. The optimisation result shows that inductive chargers were only allocated to terminals 3, 4, and 5 of the transit network because these positions are associated with 13 km, 12.5 km, and 10 km (Figure 4-15), respectively. Compared to terminals 1 and 2, where the BEB travel distance is about 2km and can be completed without recharging the BEB on-board battery. In addition to cost-saving, this integrated model also reduces the size of the onboard battery of the BEB, as shown in (Table 4-7). Hence, reducing the cost and the weight of the BEBs. As a result, it minimises BEB energy usage per km.

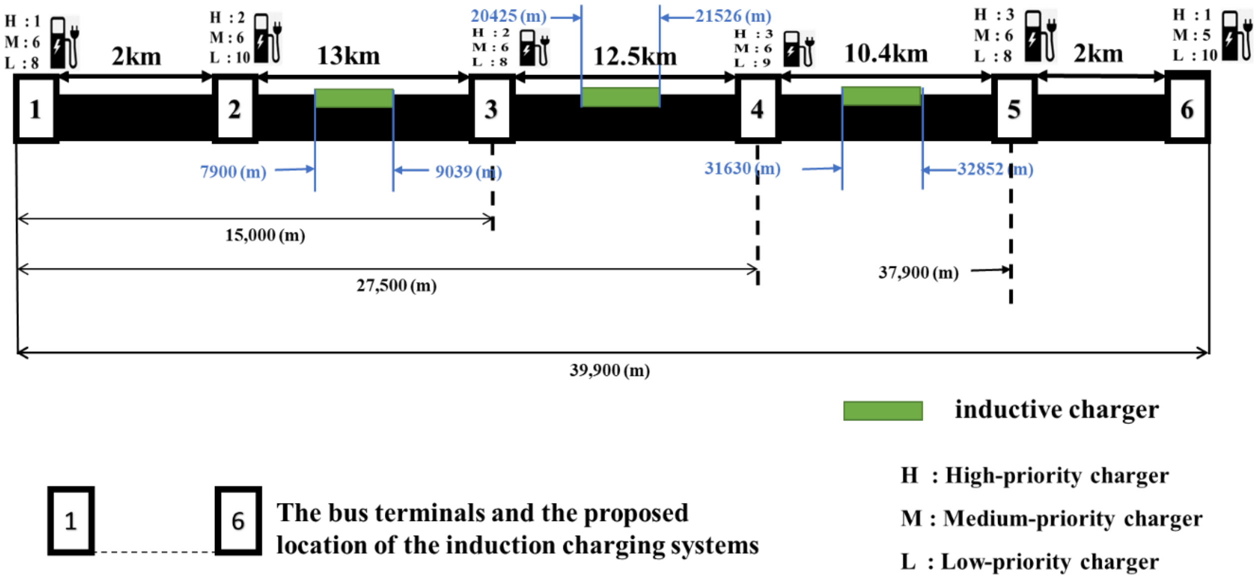

Figure 4-20 Optimal design Lagos BRT network electrification

The summary of the optimal design (i.e. the result) of the novel priority charging strategy for Scenario III that integrates both the conductive and inductive chargers for the Lagos BRT network is shown in Figure 4-20. This figure gives an overview of the simulation result that can be implemented for this case study. Moreover, it can be inferred that this framework demonstrates that large, expensive onboard batteries are unnecessary and that recharge periods can be reduced. This allows BEBs to be utilised in the same cycle as conventional diesel buses without compromising the system's effectiveness.

4.4.3.6 Scenario IV- Simulation of inductive charging

This scenario's transit electrification simulation is based on utilising inductive charging infrastructure for a bus transit system. This simulation approach demonstrates the cost-benefit trade-off and increases operational service reliability by optimising charging station infrastructure: onboard battery capacity, inductive transmitter position, and inductive cable length. The mathematical model and objective equation provided in chapter 3, equations (3.67) - (3.74) are the frameworks for this simulation studies.

Table 4-8 Simulation result for the inductive charging model (scenario IV)

Variable	Terminals					
	1	2	3	4	5	6
Locations of inductive cable (m)	0-660	2120-2980	14120-15400	26120-28381	38020-38983	39120-39480
Optimal Cost (£)	52,155,184.98					
Optimal battery capacity (kWh)	24					

This mathematical model is implemented using the PSO optimisation method. The input parameters include the computed BEB energy consumption figure (Table 4.2 in section 4.1) and bus transit data such as route length, transit schedules, and cycle duration. Furthermore, the simulation model considers the estimated cost value in Table 4-4, the number of buses, and the capacity of the charger. The model provides results for the optimal battery size, overall infrastructure cost, and length with inductive cable locations.

The optimisation model generates the optimal cost for the bus transit infrastructure needs to be £52,155,184.98. Table 4-8 shows the optimal locations and the length of the inductive cable. The optimal onboard battery capacity in this scenario is 24kWh. It should be noted that the inductive simulation in this section is intended to be used as a comparison tool with alternative charging models that have been suggested, primarily to examine the financial impact of each scenario. The following chapter gives a comprehensive framework for the simulation of an inductive transit system.

4.4.3.7 Trade-off Analysis (Scenario I, II, III, &IV)

Figure 4-21 depicts the optimal battery sizes and costs in various charging scenarios explored in this work. This chart illustrates the trade-off between the BEB's battery configuration and the optimal cost for the proposed electrified bus transportation system. As shown in Figure 4-21, the lowest cost is related to the smallest on-board battery BEB except for scenario IV, which considers an inductive only system, and this cost is associated with a longer length of the inductive wire, which could be a trade-off if the number of buses increases.

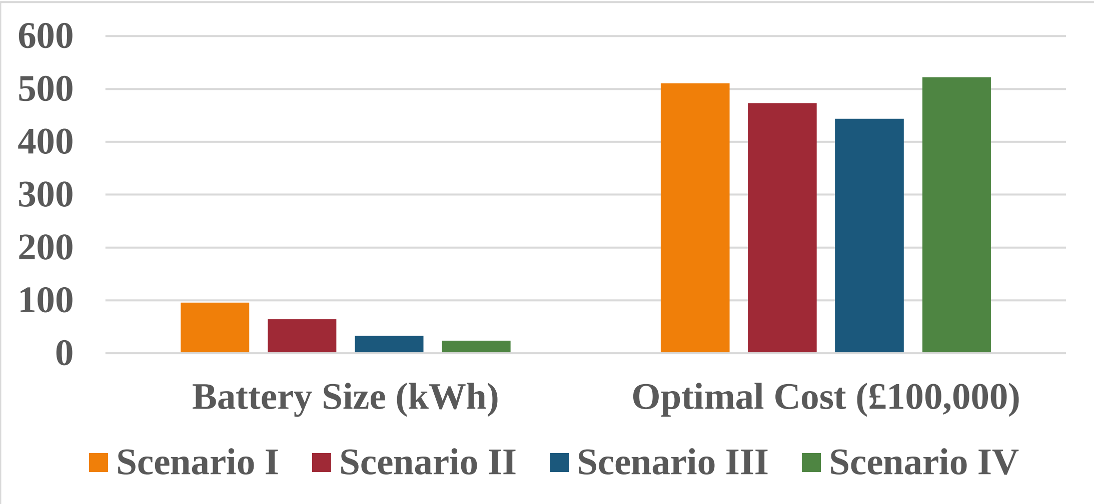

Figure 4-21 Trade-off analysis of Scenario I, II, III & IV

In summary, having a robust charging infrastructure can lower the cost of electrifying bus transit systems. Scenario III, in which the system integrates conductive and inductive charging techniques, demonstrates that investing in charging infrastructure is more advantageous than increasing on-board BEB battery capacity.

As a result, increasing the number of BEB fleets could offset the cost of charging infrastructures because numerous BEB can use the same charging infrastructures, particularly on-the-fly-inductive chargers. This, of course, excludes some installation fees and any complications that may develop as a result.

4.4.4 Transit charging demand profile

The power consumption of onboard battery chargers and the available charges are utilised to calculate the demand profile of the charging process. BEBs begin to use chargers one by one as demand progressively rises with varying SOCs, and the aggregated power demand curve begins with low demand. Figure 4-22 illustrates the aggregated power demand curve from around 6 a.m. to 10 p.m. These demand profiles are calculated based on the daily bus schedule and charging demand for the priority and non-priority charging scenarios. Most BEBs are expected to begin their daily schedules with a charged battery; hence, charging buses after their daily operations may be appropriate, resulting in a demand profile that extends to roughly 11 p.m. through overnight charging.

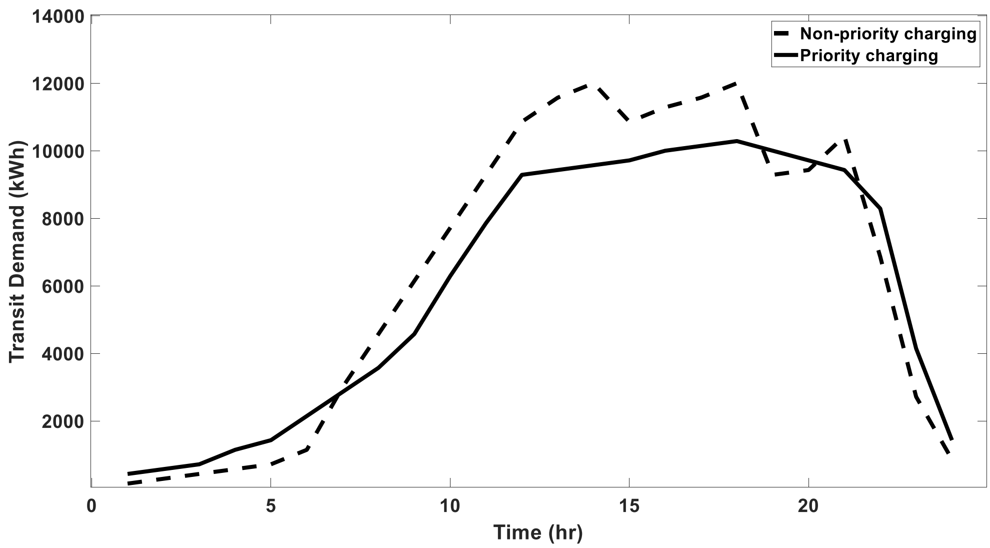

Figure 4-22 BEB charging demand profile

Furthermore, because not all buses begin service at the same time, the transit operational schedule data has an impact on the demand profile (see Appendix A). This operational schedule data is utilised to calculate and determine when the BEB will need to charge, how much charge is required, and how much charging time is available. The total energy consumed for charging is estimated to be 142880 kWh. This estimate is based on the amount of energy consumed per kilometre and the type of charger utilised during each recovery time.

Priority charging may not have a substantial impact on overall charging demand. Because it evenly distributes peak demand and minimises the impact of charging transit buses on the grid and power distribution infrastructures.

4.4.5 Summary and discussion

This work proposed designing the multi-terminal base model of BEB's charging infrastructure for the transit network. In this work, both inductive and conductive chargers are considered to manage the transit network's charging demand. The charging infrastructure allocation is based on the PSO algorithm that is used to find the minimum allocation value per terminal.

The priority (scenario II) method for preferential charging is introduced in this work and is compared with the non-priority (scenario I) model. The result shows that scenario II saves cost and is a key for energy management for the BEB transit network. Combining the conductive and inductive charger (scenario III) in this model helps keep the BEB batteries from being deep discharge. This priority strategy also lowers the cost of having a large, expensive conventional onboard battery, reducing the overall weight of the BEBs and contributing to the BEBs using less energy per km. This work's priority charging system has the potential to be developed into an efficient, affordable energy management system that aggregates energy usage over the operational schedule time as shown in Figure 4-22. This priority charging strategy also reduces the power infrastructure investment because the model ensures that minimum energy is used from each terminal at every time.

Through the investigation of Scenarios I, II, III and IV, it is found that charging BEBs in the Nigerian city of Lagos's BRT network can be accomplished using an opportunity charging method that does not affect the operational bus timetable. During their stay at the BEB's terminal, all BEBs are scheduled to charge. This research focuses on underdeveloped countries with unreliable networks that make overnight charging of large energy storage systems difficult and sometimes impossible.

It is worth noting that preliminary studies have shown that using different charging capacities at different terminals along the route could not meet the transit network's demand. The transit timetable made it clear that each terminal had a different schedule for each bus, which resulted in varying energy demand and, consequently, different recovery times. As a result, having different chargers at different transit network terminals will cause disruptions in the BEB transit schedule.

4.5 Chapter Summary

This chapter's numerical case studies are based on the optimisation model provided in Chapter 3. First, a simulation is performed to evaluate the average power consumption of BEBs given a defined traffic situation and speed profile. Then, a novel charging optimisation tool is created to demonstrate how diverse charging techniques may be advantageous to investigating key transit system elements such as the trade-offs between alternative charger designs, charger locations, battery sizes, and cost.

The chapter describes how ADVISOR modelling works before simulating various traffic scenarios (i.e., free, move, appropriate, inappropriate, and critical traffic) based on BEB speed and trip time variation using the Lagos BRT as a case study. The results show that the average BEB energy consumption per km ranges from 1.05 to 2.95kWh and that traffic conditions can impact energy consumption figures up to 180 %.

The evaluated BEB energy consumption figure is part of the input parameter for the developed optimisation model that uses the PSO algorithm. As a result, a brief overview of the PSO algorithm is provided.

The numerical study compares several charging choices such as varied charging capabilities, priority charging, and integrated charging. The results suggest scenario I, fast chargers are less expensive for powering transport fleets. However, the impact of this charger on the grid is not investigated. The numerical study of priority charging reduces costs and optimises energy use for BEBs in the transit network. The combination of the conductive and inductive chargers in this model helps to keep the BEB batteries from being overdrawn and reduces costs because the BEB optimal battery size is small compared to other proposed models.

5 BEB Transit fleet electrification numerical Case Studies (2)-inductive charging and carbon emissions savings

5.1 Introduction

This chapter continues the numerical studies presented in the previous chapter (Chapter 4). The work presented in this chapter is explicitly based on the simulation of a case study of an inductive charging system simulation and a case study of estimating carbon emission savings for the transit bus system. Hence, this chapter's numerical case studies is based on the optimisation model provided in Chapter 3.

5.2 Case Study of inductive charging simulation

The simulation of the inductive charger allocation for the bus transit system is detailed in this section. This inductive charging infrastructure allocation sought to optimise power transmitter placement, inductive cable length, battery capacity, and the cost of an electrified transit system.

Three different scenarios based on the case studies are discussed in this section. The first scenario envisions adding an inductive charging system to the current Lagos BRT system, with inductive chargers primarily located at the bus terminal. In the second scenario, the optimal design of inductive chargers at six equal-distance locations along the Lagos BRT transit network route is investigated. The third scenario looks into the possibility of having four inductive charger locations. These three scenarios are compared using the optimisation parameters (i.e. cost, the battery size, length and the location of the inductive cable and power transmitters).

A state of charge analysis that depicts battery depletion and recovery rate, as well as a sensitivity analysis that investigates the impact of the trade-off between; the BEB's on-board battery capacity and the number of bus terminals, transmitter numbers, inductive cable length, and inductive cable length, are also presented.

5.2.1 Introduction

As described in chapter 3 (section 3.4), the inductive charging system is an operated on-road charging technology that charges the BEB battery while the bus moves through the inductive cable region. The length of the inductive cable and the size of BEB's battery directly influence the overall performance and cost of the transit system and the number of transmitters deployed on the road. The novel mathematical model for the allocation of inductive charging infrastructure is established in (3.4.1) to optimise the position of power transmitters, the length of the inductive cable, battery capacity, and the cost of an electrified transit system. The stated optimisation model (3.66) minimises capital cost while taking into account the transportation system's operating constraints. The simulated system improves accuracy by adding BEB energy usage based on route factors. This designed problem is demonstrated with a mathematical model that is used to determine the best combination of crucial inductive transit system design characteristics (i.e. battery size, length of the inductive cable and the allocation of the power transmitters)

The described particle swarm optimization (PSO) algorithm (in section 4.5) is used to determine the optimal transit system cost, cable length, battery size, number of transmitters, and total cost. This cost includes the BEB cost, inductive charger cost (the receiver and the transmitter), battery cost, and the inductive cable cost, as illustrated with the objective equation (3.66) and the associated constraints in equations (3.67-3.74).

The inductive-based simulation present in this section is based on the Lagos BRT case study described in (4.1). As shown in Figure 4-15, the transit system has six terminals located at various points (2km, 15km, 27.5km, 37.9km, and 40km) within the 40km route transit system. Because the vehicles slow down as they approach the bus terminals and then stop to offload and load commuters, these are considered the locations for inductive charges. These allow a short but sufficient time to 'top-up' the BEB battery, and several buses can be charged simultaneously.

This thesis investigates the optimal values of the optimisation parameters (i.e. battery size, length of the inductive cable and the allocation of the power transmitters and the cost) based on the bus terminals. In addition, the trade-off of these optimisation factors was investigated further. Three scenarios are addressed in this study. The first scenario considers introducing an inductive charging system to the existing Lagos BRT system, with the bus terminal illustrated in Figure 4-15 serving as the primary location of the inductive chargers.

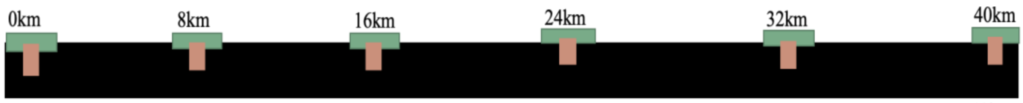

Figure 5-1 Redesigned transit system (Scenario II)

The second inductive charging scenario investigates the optimal configuration of the inductive chargers at six equal-distance locations from each other along the Lagos BRT transit network route Figure 5-1. The third scenario investigates the possibility of having four locations for the inductive chargers Figure 5-2. These three scenarios are compared using the optimisation parameters (i.e. cost, the battery size, length and the location of the inductive cable and power transmitters). Moreover, this thesis further investigates the trade-off between the possible number of bus terminals (i.e. location of power transmitters), numbers of transmitters, inductive cable length and the on-board battery capacity of the BEB for the Lagos transit system.

Figure 5-2 Redesigned transit system (Scenario III)

5.2.2 Data and input parameters

In addition to the data in Figure 4-15, Figure 5-1, Figure 5-2 and

Table 4-3 presented. The additional input parameters considered for this case study is shown in Table 5-1. The BRT line, which runs from Ikorodu to TBS, is approximately 40 kilometres long, as shown in section 4.2. There are 44 bus shelters in both directions, six terminals, 19 intersections, and two bus depots on the Lagos BRT [4] [5]. Table 5.1 also shows the details of the service lines as well as the average cycle time. There are 29 bus stops and six terminals along the route. Ikorodu, Agric, Mile 12, Moshaladhi, CMS, and TBS are the terminal locations. This data, along with the cycle time, BEB energy usage, and bus transit schedules, is used as input to the optimisation model.

Table 5-1 BEB Parameter (adopted from [101])

Input Parameters	Value
Number of BEBs	100
Cost of battery per kWh (£)	125
Cost of inductive Cable per meter (£)	20
Length of the transit route (m)	40,000
Cost of BEB (£)	50,000
Cost of wireless power receiver (£)	1,000
Cost of wireless power transmitter per kWh (£)	100

Transmitter capacity (kW)	500

5.2.3 Inductive charging simulation studies

The optimal cost of the transit system, cable length, battery size, the number of transmitters, and total cost are all determined using a particle swarm optimization (PSO) algorithm. The total cost includes the BEB cost, inductive charger cost (the receiver and the transmitter), battery cost, and inductive cable cost. The objective equation described in (3.66) reflects the details. The PSO algorithm operated in this case study using 200 iterations and 1000 particles; the key optimisation results for the three scenarios investigated are listed in Table 5-2. The simulations converge in about 15seconds, and the simulation results obtained from the PSO implementation for allocating the inductive chargers for the Lagos BRT electrification model are shown in Table 5-2.

The simulation result for the scenario 1 – inductive charging at terminals (Figure 4-15 Lagos transit network showing bus terminals (Source: LAMATA)) gives an optimal solution that indicates that the total cost is £5,619,550 and the optimal battery size is 26kWh. Scenario 2 – inductive charging at equidistant locations on the route considered is when each inductive charger proposed for the Lagos BRT transit system is at an equal distance Figure 5-1. The results suggest that a smaller onboard battery of 16kWh capacity should be sufficient for each BEB running on the proposed inductive transit route due to the equidistant location of the inductive transmitters, resulting in a shorter inductive cable and hence a lower total cost in comparison to the first scenario.

In the third scenario (Figure 5-2), the optimal cost is the lowest as a result of using four transmitters at equal distances from each other. Hence, some savings on the transmitters cost in comparison to scenarios II & I. This optimisation result is shown in Table 5-2 and is aimed to support the transit operator in considering the various trade-offs between the parameters when investigating the electrification of transit routes—in addition, using the model to determine the appropriate position and length of inductive cable required for the specific transit route.

Table 5-2 Result of allocation of inductive simulation

Variable	Scenarios		
	I	II	III

Total cost (£)	5,619,550	5,501,450	5,492,200
Battery Size (kWh)	26	16	22
Number of Power Transmitter	6	6	4
Total length of cable (m)	4034	3691	2140
Position 1 of Transmitter with cable (m)	0-340	0-220	0-221
Position 2 of Transmitter with cable (m)	1980-2580	7980-8700	13280-13760
Position 3 of Transmitter with cable (m)	14998-15820	15986-16700	26580-27180
Position 4 of Transmitter with cable (m)	27484-28080	23980-24700	39360-40080
Position 5 of Transmitter with cable (m)	37882-38720	31982-32700	
Position 6 of Transmitter with cable (m)	39282-40120	39481-40080	

5.2.3.1 State of charge analysis of electrified BRT inductive model

Figure 5-3, Figure 5-4 and Figure 5-5 depict the SoC of the on-board battery of the BEB along the Lagos BRT transit route using the inductive charging model. It should be noted that the onboard battery SOC is calculated using the linear model proposed in [345], [346] and [217]. This state of charge analysis is based on the battery depletion and recovery rate as it travels along the transit route. The battery's state of health is not considered in the SOC calculation, as proposed in [317], because for this initial design assessment, the BEBs would have new batteries. Figure 5-3 (scenario I) indicates that the BEB on-board battery is fully charged at the start of the scheduled trip and the SoC drops to 65% before recovery to 80%. Also, a full recovery of the BEB onboard battery SoC occurs at 4717 seconds toward the end of the trip. This reduces to 66% before another full recovery occurs as a result of another inductive transmitter located about 2km from the 5th transmitter. Therefore, it is observed that the 1st and 6th transmitter's location are not optimal for this bus. Thus, it is important to investigate how to maximize the use of the inductive charger along the transit route across the fleet.

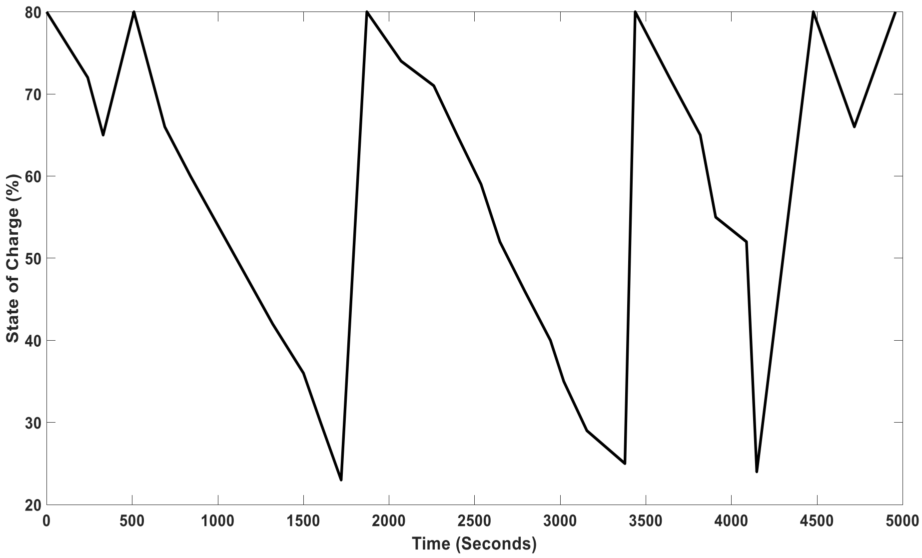

Figure 5-3 Scenario I- State of charge analysis

The inductive power transmitters are set at an equal distance from one another in the second scenario, which takes into account six different locations. Because the battery SoC changes between the set maximum SoC of 80 % and the set minimum SoC of 20 %, as illustrated in Figure 5-3, the locations maximise the BEB on-board battery capacity compared to the scenario I. Hence led to the consideration of a smaller onboard battery and reduced cost.

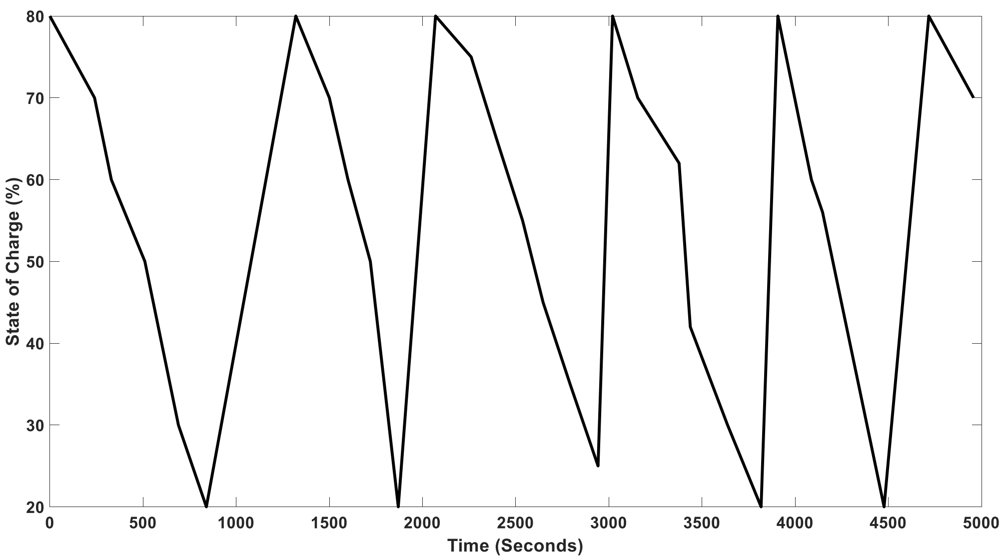

Figure 5-4 Scenario II- State of charge analysis

In the third scenario, the location of the inductive chargers is at four points along the transit route, and the system optimally maximises the use of the onboard battery; as shown in Figure 5-4, the battery SoC changes from 80% to 20%. Hence a small onboard battery reduces cost, as shown in Table 5-2.

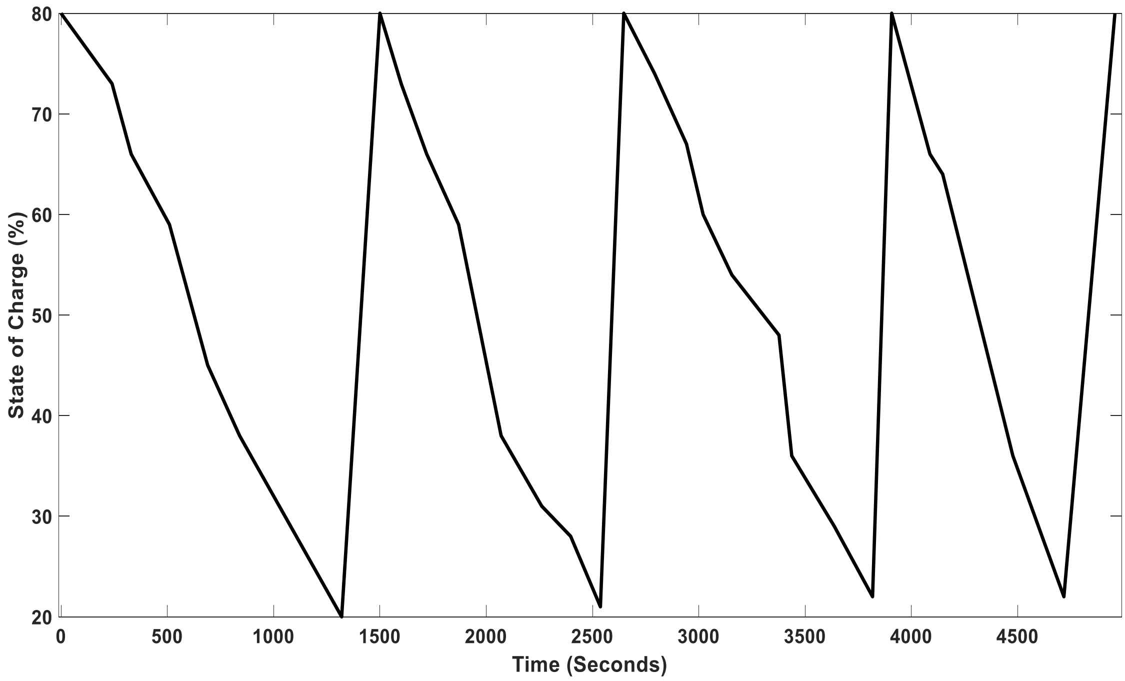

Figure 5-5 Scenario III- State of charge analysis

5.2.3.2 Sensitivity analysis of inductive charging case study

The results of the different inductive charging scenarios show the trade-off between the available number of bus terminals (i.e. location of power transmitters), numbers of transmitters, inductive cable length and the on-board battery capacity of the BEB for the Lagos transit system. To further investigate the impact of the trade-off between the BEB's onboard battery capacity and the number of bus terminals, transmitter numbers, inductive cable length, and inductive cable length, a sensitivity analysis is presented in this section using the developed optimisation model.

As demonstrated in the three scenarios considered in this simulation work, the varied equidistance locations of the inductive charger can significantly impact the cost of infrastructure. Hence, sensitivity analysis is considered to investigate different locations for allocating power transmitters and inductive cables within the transit network. This study varied the numbers of the power transmitter within the Lagos bus transit network between 3 and 9, as shown in Figure 5-6 and Table 5-3. As shown in Table 5-3, the number of bus terminals is usually the same as the number of the power transmitter except for the circumstance where three transmitters are considered because the transmitter's capacity is proportional to the length of the inductive cable. The total length of the inductive cable for the four terminals transit is 2140m. The three-terminal configuration needs an inductive cable length of 2141m; hence a terminal location requires two power transmitters of 500kW (making four power transmitters due to the constraints imposed on the inductive cable length).

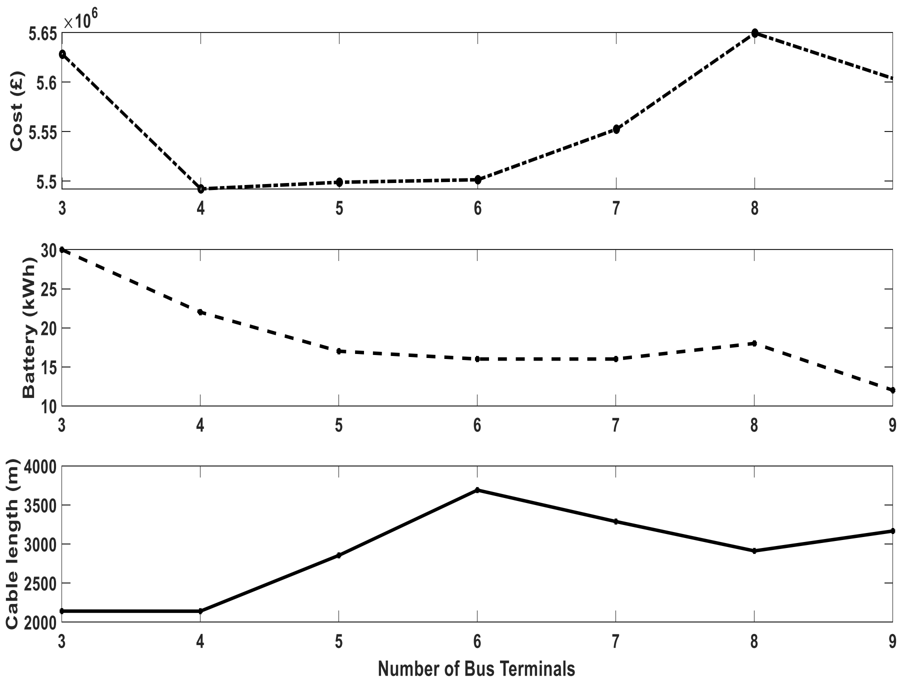

Figure 5-6 Sensitivity analysis at different number of terminals

In considering the varied location of power transmitters (Bus Terminals), as shown in Figure 5-7. The three-terminal configuration requires a sizeable onboard battery capacity of 30kWh compared to other configurations in the transit system simulation. Because three-terminal configurations require that each transit BEB have a huge battery capacity, increasing cost, the cost keeps increasing proportionally with an increase in the number of BEBs. The four-terminal configurations show that an optimum transit electrification cost can be achieved with a 22kWh onboard battery, an inductive cable length of 2140m, and four power transmitters. As shown in Figure 5-6, the cost keeps increasing progressively on increasing the terminal configuration to 5, 6, 7 and 8. Using nine terminals configuration led to decreased cost because the design requires a small on-board battery capacity (i.e. 12kWh) BEBs for the transit operation.

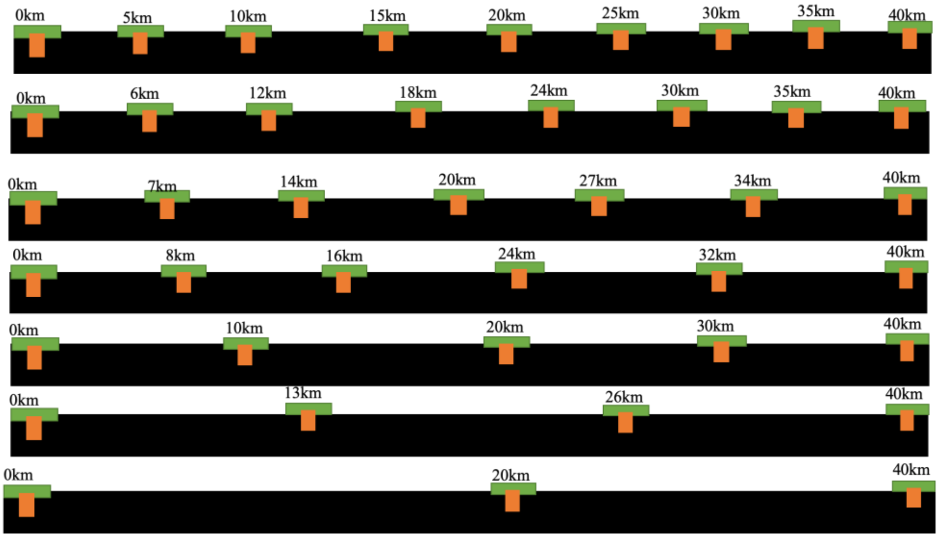

Figure 5-7 Alternative configurations of inductive chargers for Lagos BRT network

This sensitivity analysis result can help the transit company consider the trade-offs between the parameters and cost and decide based on their need.

Table 5-3 Sensitivity analysis of the multi-terminal configuration of inductive charging transit design

Variable	Terminals						
	9	8	7	6	5	4	3
Total Cost (£)	5,603,600	5,649,600	5,552,500	5,501,450	5,498,900	5,492,200	5,628,196
Battery Size (kWh)	12	18	16	16	17	22	30
Number of Power Transmitter	9	8	7	6	5	4	4
Total length of Cable (m)	3167	2912	3288	3691	2855	2140	2141
Position 1 of Power Transmitter with cable	0-190	0-220	0-221	0-220	0-340	0-221	0-460
Position 2 of Power	4980-5580	5690-6280	6680-7280	7980-8700	9980-10580	13280-13760	19980-20940

Transmitter with cable							
Position 3 of Power Transmitter with cable	9985-10580	11402-11980	13280-14000	15986-16700	19980-20580	26580-27180	39360-40080
Position 4 of Power Transmitter with cable	14980-15580	17085-17680	20007-20580	23980-24700	29984-30580	39360-40080	
Position 5 of Power Transmitter with cable	19980-20579	22786-23260	26702-27280	31982-32700	39360-40080		
Position 6 of Power Transmitter with cable	24988-25570	28604-29060	33380-33978	39481-40080			
Position 7 of Power Transmitter with cable	30046-30580	34282-34760	39495-40080				
Position 8 of Power Transmitter with cable	35063-35580	39502-40080					
Position 9 of Power Transmitter with cable	39480-40080						

Each column in Table 5-3 presents the result for each configuration investigated. The optimal battery capacity follows the optimal cost, the number of power transmitters, and then inductive cable length and position.

5.2.4 Discussion and Summary

The work presented in this section considers the design of a multi-terminal inductive base model of BEB's charging infrastructure for the transit network in Lagos, Nigeria. The solution is obtained using a PSO algorithm that seeks to find the minimum allocation of charging resources to meet the requisite route demands. The optimisation model developed for this research makes a significant contribution by optimally allocating inductive chargers and forms the basis of a practical approach in the design of inductive charging system for the bus transit network; this is in the provision of inductive charging infrastructure that allocates battery sizes, location of the transmitter, and the inductive cable's length.

When comparing the original location, Figure 4-15, with the bus terminal's equal distance locations (Figure 5-1), the result shows that more savings can be achieved if the inductive chargers are located equidistant from each other. The option in Figure 5-2 (scenario III) shows that having four terminals in the Lagos transit system can give an optimal trade-off between the bus charging terminal and the onboard battery's size.

The inductive charger's location at the bus at the significant stops maximises the use of the inductive charging infrastructure. Positioning the charging infrastructure at an equal distance from each other, as shown in the example of Lagos infrastructure, reduces cost. In this case, the battery size required is smaller. This study's allocation of inductive charging infrastructure is a cost-cutting method that saves money in the short and long run.

5.3 A case study of carbon emissions savings of electrified BRT system

In section (4.2), the BEB energy consumption simulation result for the five categories of studied traffic situations (i.e., free, move, appropriate, inappropriate and critical). The power consumption profile represents the power supplied by the BEB battery to drive the BEB and supply the auxiliary loads. This simulation produced values for buses' energy consumption when powered by electricity. In this section, an additional simulation is performed to estimate the energy consumption of the diesel equivalent of the BEB bus in five categories of studied traffic situations. The findings are utilised to compute the BEB buses' emission savings compared to the diesel equivalent. It is worth noting that these energy consumption estimates represent the energy consumed between the diesel-fuel tank/battery pack and the vehicle drive train (i.e. tank-to-wheel). Table 5-4 shows the tank-to-wheel electricity and diesel consumption in various traffic scenarios.

Table 5-4 Comparison of Diesel bus and BEB GHG emission (gCO_2/km)

Parameters	Traffic condition				
	Free	move	Appro	Inappro	Critical
kWh/km of electricity	1.05	1.54	1.88	2.22	2.95
Litre/km of diesel	0.17	0.25	0.30	0.35	0.47
BEB Emission (gco2/km)	269	394	481	568	755
Diesel bus emission (gco2/km)	459	675	810	945	1269
BEB Vs Diesel bus GHG Saving (gco2/km)	190	281	329	377	514

The diesel engines produce approximately 2.7kg of CO2 emission per litre of diesel fuel consumed [348] [349]. Using the UK government 2019 figure for carbon emission per kWh of electricity on the average energy fuel mix is 0.256kg CO_2 [350],[351].

These GHG figures for diesel and electricity per km must be updated based on the energy consumption estimates for the BEB and diesel bus values from the simulated case study.

Hence

$$\left(\frac{KgCO_2}{Km}\right)_{Diesel\ Bus} = \frac{2.7KgCO_2}{L} \times \frac{ADVISOR\ simulated\ L}{Km} \tag{5.1}$$

Similarly;

$$\left(\frac{KgCO_2}{Km}\right)_{BEB} = \frac{0.256KgCO_2}{kWh} \times \frac{ADVISOR\ simulated\ kWh}{Km} \tag{5.2}$$

The figure for CO_2 emission comparing diesel and BEB bus at different traffic scenarios is also given in Figure 5-8.

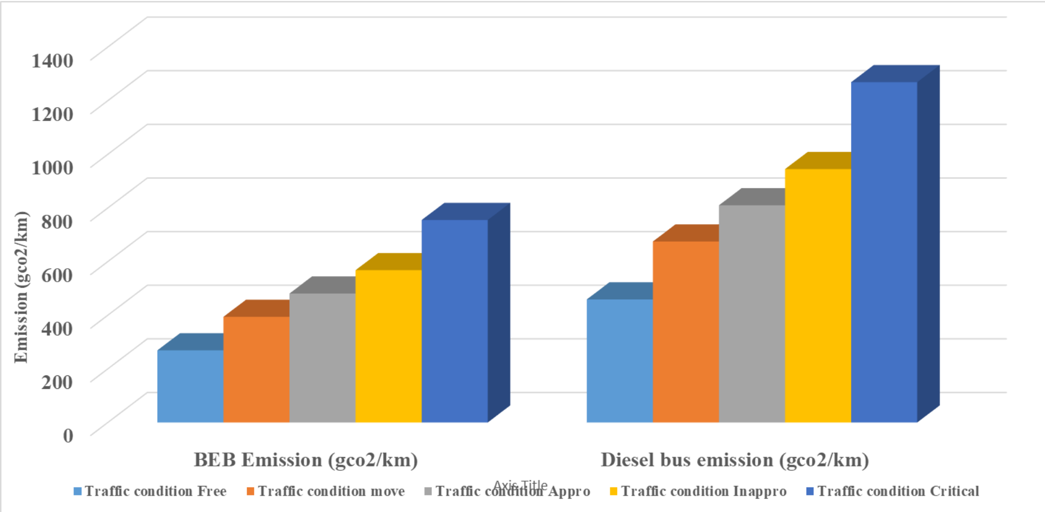

Figure 5-8 Comparison of Diesel bus and BEBs GHG emission at different Traffic Condition

In Table 5-4 the comparison of Diesel buses and BEBs GHG emission figures at different Traffic conditions based on the Lagos BRT route is presented. The deployment of BEBs along this route is expected to reduce GHG emission by 190gCO_2/km (≈ 41%) for a free traffic situation, 281gCO_2/km (≈ 42%) for a move traffic situation, 329gCO_2/km (≈ 41%) for an appropriate traffic situation, 377gCO_2/km (≈ 40%) for inappropriate traffic situation, and 514gCO_2/km (≈ 41%) for a critical traffic situation. Also, Figure 5-8 illustrates the comparison of the Diesel bus and BEBs GHG emissions under different Traffic Conditions.

Table 5-5 BEBs GHG emission saving figures at different Traffic Conditions

No of BEBs	**Traffic condition/Emission savings (tCO2)/Year**				
	Free	move	Appro	Inappro	Critical
100	1335	1974	2311	2648	3611
200	2669	3948	4622	5296	7221
300	4004	5922	6933	7945	10832
400	5339	7895	9244	10593	14442
500	6673	9869	11555	13241	18053

1000	13346	19738	23110	26482	36105

A transit bus travels about 43,647miles (70,243km) in a year [352]. Hence, the deployment of 100 BEBs in the Lagos transit route could save up to 33611 tCO_2 per year in a critical traffic situation.

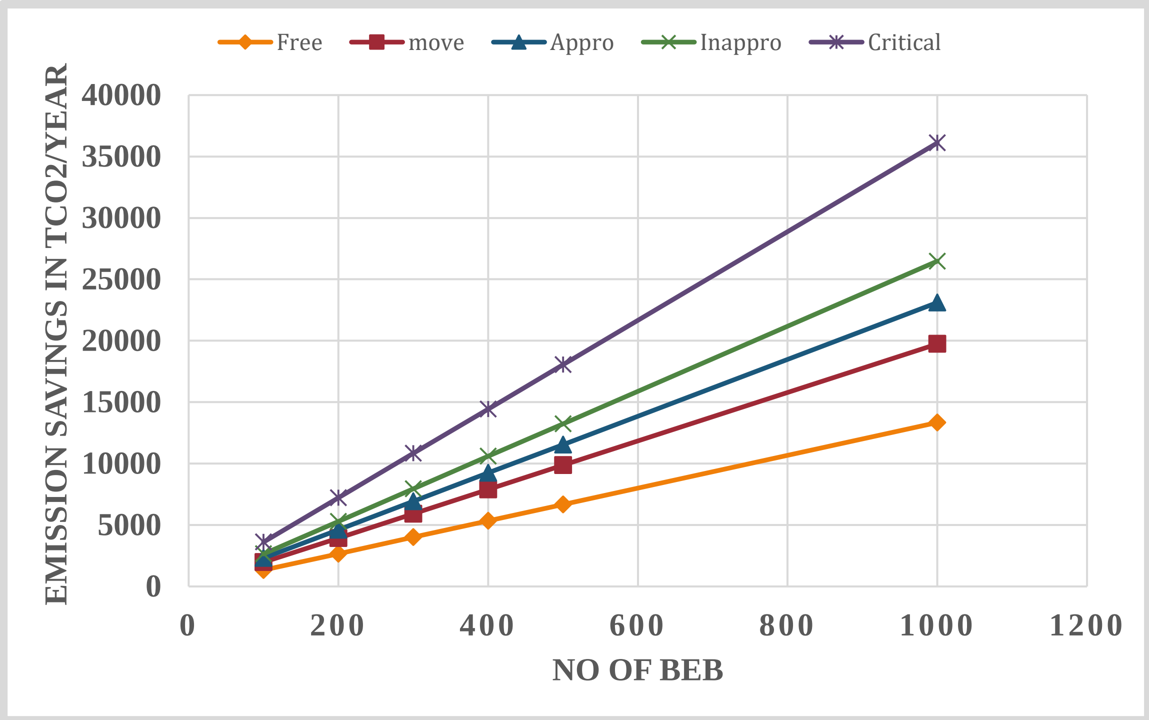

Figure 5-9 Comparison of (100 to 1000 BEBs) Diesel bus and BEBs GHG emission (tCO_2 per year) at different Traffic Conditions

As a result, the emission savings figure over a year at various BEB adoption rates (i.e. 100 to 1000 units) is evaluated using the differences between the diesel bus emission and BEB emission values for an average anticipated km journey in one year. Table 5-5 has these estimated values, which are depicted in Figure 5-9 using the Lagos BRT as a case study.

5.3.1 Discussion and Summary

Assuming that the Lagos BRT system operates an average of 200 buses concurrently on a daily schedule. If these 200 buses are replaced with BEBs, the impact will reduce

GHG emissions by 2669 tCO2 to 7221 tCO2 per year. Realistically, the Lagos BRT network could operate 400 concurrent buses to satisfy busy daily demands. Using 400 BEBs will reduce passenger waiting time [376] and reduce GHG emissions by 5339 tCO2 to 14442 tCO2 per year. Moreover, taking into account the future development of the BRT system in Lagos as well as the adoption of an electrified transportation system that uses around 1000 BEBs at the same time, GHG emissions could be reduced by 13346 tCO2 to 36105 tCO2 per year.

Additionally, electrified BRT that utilises BEB can increase bus travel speed and service while maintaining reasonable fares. The non-electric vehicle could be zone-restricted to promote mode transfer and collect revenue to finance the electrified BRT. These emission savings could also be accomplished by establishing emission and pricing zones along public transportation corridors. In [2], the author estimates that it takes about 100 electric cars to accomplish the same environmental relief as can be gained from a single 18m battery-electric bus. At current occupancy rates for cars, passengers' full busload can take more than 40 cars off the road [353]. When the BEB is operated at a higher travel speed, the electrified BRT system could significantly attract private vehicle users to switch modes of transport. Some private vehicle users would switch to the proposed electrified-BRT system because the new buses with smooth drive, low noise, and air conditioning are significantly more comfortable than the existing diesel buses.

In developing countries, the authors in [54] analysed Malaysia's policies encouraging public transportation usage and discovered that, in addition to journey duration, age, gender, car ownership, travel cost, and household income all have a role in influencing an individual's mode choice. However, the essential measures favouring public transportation are shorter trip times between homes and public transportation stations and fare subsidies. In general, the proportions of private car users who switch to BRT vary significantly depending on various circumstances. In summary, apart from traffic management, shifting from individual passenger vehicles to public transit fleet is considered a tool to reduce the significant quantity of GHG emissions and reduce traffic congestion in cities [354], [355],[356].

In summary, this research compares BEB energy consumption and GHG emission savings under various traffic circumstances. This study looks at how the energy consumption of electric buses varies depending on route features, speed profile, and traffic situations. The simulated energy consumption study reflects the impact of roadway level of service on the average traffic speed to replicate diverse real-world traffic situations. Five different traffic scenarios were presented to examine the parameters influencing BEB energy consumption in real-world traffic and estimate the GHG emission savings figure.

The result indicates that the deployment of BEBs in the Lagos, Nigeria BRT route could significantly save about 13tCO_2 to 36tCO_2 for each BEB deployed per year. Generally, the impact of electrified full BRT in Lagos, Nigeria, would reduce travel time and reduce GHG emissions.

5.4 Chapter Summary

This chapter research work investigates the use of multi-terminal inductive chargers as BEB's charging infrastructure for the Lagos BRT system. The result shows that positioning the charging infrastructure at an equal distance reduces cost.

This research also evaluates the potential GHG emission savings for adopting BEB in the Lagos BRT. The results show that deploying BEBs along the Lagos, Nigeria BRT route might reduce CO2 emissions by 13tCO2 to 36tCO2 per BEB deployed per year.

6 Conclusions and future work

6.1 Thesis Conclusions

The growing population of cities around the world is producing traffic congestion, increasing automotive emissions, and posing a number of health risks. For that purpose, developed countries are reforming and increasing their investments in public transportation networks, such as public rail, trams, subways, and public transit buses. The growing urban population in developing countries is predicted to boost public and freight transportation demand in the near future. On the other hand, many developing countries lack the ability to prioritise investment in public transportation systems such as the metro and rail systems, although they are facing similar issues. While it varies between countries, incumbent systems in such circumstances are already challenged (e.g., frequent power outages, ageing infrastructure). This, along with a lack of investment, means that they will not be able to shift at the same rate as developed countries in this regard. As a result, in the case of developing countries, less investment-intensive 'infrastructure lite' alternatives are more likely to be accessible. On this premise, implementing the bus rapid transit system through staged electrification of existing bus fleets is predicted to be a particularly relevant area for decarbonising the public transportation system in these low-income nations.

It is also projected that, if nothing changes, the transportation sector's GHG emissions will rise to higher levels. As a result of the growth in GHG emissions, creative techniques continue to be required to accommodate rising transportation demands while addressing environmental issues. The implementation of electric transportation networks is expected to be a potential solution that will assist in significantly reducing pollution and help support the delivery of GHG targets.

In this regard, the research work of this thesis presents a novel method of charging the transit BEB with the goal of meeting the need in developing societies where the grid cannot readily support overnight charging of large onboard BEB batteries, as is common in developed countries (such as Europe and China), by developing a novel charging method that can support cheap BEB (i.e. BEB with small onboard BEB battery). The common practice in transit systems is using the battery-electric bus (BEB) with a battery capacity of 200-500kWh. The required charging duration for this type of BEB is usually long, and the frequently adopted charging strategy is overnight charging. This strategy is considered to avoid disruption of the operation schedule of the transit network, and it fits with a reduced bus service overnight and with lower electricity system utilisation (off-peak). However, overnight charging is described as a strategy requiring the transit system to have many extra fleet buses or battery swapping systems that bring demands for substantial additional investment—for example, the 40ft K9 BYD's iron-phosphate batteries BEB cost about $600k. A single BEB has a battery capacity of 324kWh, and the maximum range is estimated to be 250km (155miles), and it requires about 2-3hour charging duration using an 80kW charger. The implication of using this conventional 40ft bus in a transit network includes enormous investment, especially in a situation where there are inadequate funds like in most developing countries.

This research work offers solutions that supplement BEB charging in a transit network without disrupting the operational schedule and minimises the initial investment cost by scaling the BEB battery capacity for the need of the transit system. This is distinct from other authors' work that focuses on overnight charging and the impact of the charging on the power system. This work also promotes the design of a specific BEB that precisely meets the transit network's need by specifying the battery size. Furthermore, promoting the BEB design can receive charge through inductive and conductive charging methods. This research is also applicable to the optimal design of the charging facility that integrates both conductive and inductive charging facilities into the transit network system. In the power network industries, it enhances the management of the transit network demand. It could be used as a tool by transit operators to design capability for addressing BEB scheduling on day-ahead timescales.

In Chapter 2, an overview of the most recent battery-electric bus energy consumption modelling and simulation was provided. The design, implementation, and optimisation of operational schedules for various infrastructure options are examined in this literature review. This also included a review of various methods and technologies for promoting the electrification of public transportation networks to reduce carbon emissions and congestion. . The literature study points out some shortcomings in predicting energy demand for transit system modelling, such as ignoring the variation of detailed real-world operational variables such as route traffic. The work of this thesis was guided by the existing literature in BEB and transport modelling to purposefully address the BRT transport problems to be considered. It builds upon this to address some of the gaps identified in existing published research. For example, integrating five traffic flow characteristics into the modelling activities improves the overall BRT model's representation.

Prior attempts to design charging infrastructures for BEB fleets in a transit system have not completely accounted for (i) a multi-terminal model based on charging infrastructure that reduces the size of the electric vehicle's onboard battery (ii) a hybrid approach that uses both conductive and inductive charging technologies to reduce operational downtime induced by BEB charging. Point (i) being applicable in the developing country case as mentioned previously and (ii) as a supporting ‘opportunistic’ addition that can provide a trade-off between centralised and distributed charging infrastructure. As a result, and guided by the literature, this thesis developed a priority charging model and investigated the trade-offs between various charging methodologies.

Chapter 3 tackles some of the intricacies of the BRT system electrification modelling and develops the mathematical model that coordinates the routing and charging for BEBs. A mathematical optimisation approach for determining the critical design variables of conductive and inductive charger allocation is described. This chapter provides an in-depth look at the various modelling stages as well as the implementation infrastructure optimisation algorithm. The design of the transit fleet routing model, the mathematical model of BEB energy consumption, and the mathematical modelling of charging infrastructure for BRT transit fleets are all covered in detail in this chapter. The overall simulation modelling, arising from the different parts of the framework of the governing model, will be presented and utilised in subsequent chapters based on the various mathematical models and features developed here.

Chapter 4 begins to consider some of the numerical case studies in relation to the BEB transport modelling of this thesis. Based on traffic conditions and speed profile, the average power consumption of BEBs is determined. A novel charging optimisation tool, developed as part of the work of this thesis, is utilised to show how different charging strategies may favourably impact key transit system elements. This includes trade-offs between alternative charger designs, charger locations, battery sizes, and cost. In this thesis, a particular emphasis is placed on the developing country case, and the case study of Lagos BRT in Nigeria is explored in-depth. Current data acquired from trustworthy sources such as the Lagos Metropolitan Area Transport Authority (LAMATA) and PRIMERO Transport Services Limited are used to characterise the study problems.

The following list of features provides the main conclusions arising from the investigation of the various scenarios and case studies that were simulated:

I. BEB energy consumption simulation: - the case studies result indicates that including the different classified traffic scenarios (i.e., free, move, appropriate, inappropriate and critical traffic) provides different energy consumption figures due to BEB speed and trip time variations. Other published work failing to account for this added value is demonstrated through this activity. The numerical studies also reveal that traffic conditions affect the overall BEB energy consumption figure, which can be as much as 180% of its expected value in critical traffic situations. This percentage increase is usually due to lower speed values and longer trip duration in high traffic conditions.

II. Transit fleet electrification simulation studies - Scenario I (Simulation of fixed terminal charger capacity): - a comparison of three types of chargers is classed in this scenario based on their power capacities (400kW, 200kW, and 50kW, respectively). The findings of the studies conducted demonstrate that BEB onboard batteries can be recharged quickly with a higher capacity charger. While this is not fully unexpected, it does confirm that fewer charger units are needed, and smaller BEB onboard batteries can be used even when external BEB and route influences are included. Thus, the investment cost is cheaper overall as compared to the use of low-capacity chargers that require more charging points and BEBs with a large onboard battery.

III. Transit fleet electrification simulation studies - Scenario II (Simulation of priority charging strategy): - this second scenario is based on a novel priority charging strategy that allocates high priority, medium priority, and low priority chargers at each BEB terminal based on the state of charge on arrival. The high priority chargers in this scenario are set to a maximum capacity of 400kW. Chargers with a maximum capacity of 200kW are termed medium-capacity, while those with a capacity of 50kW are considered low-capacity. The priority charging technique presented in this thesis minimises grid demand while simultaneously charging several BEBs. As a result, it can lessen the impact of BEBs' charging demand on the distribution network and the wider grid and potentially support DSM (mitigate the grid's valley and peak effect). Again it is highlighted that such features are attractive to many network operators in developing countries where supply and demand imbalance outages are much more common than in European networks. In addition, the cost of constructing the proposed charging infrastructures (priority chargers) is less than the cost of constructing 400kWh capacity chargers. Finally, the priority charging system described in this thesis forms the basis of a low-cost energy management system (EMS) that can support the minimisation of energy consumption in the short and long run. Furthermore, it lowers the cost of power infrastructure because the concept spreads out energy consumption over the transportation system's daily timetable.

IV. Transit fleet electrification simulation studies - Scenario III (Simulation of the multi-terminal integrated charging model): - This scenario considers a novel priority charging technique incorporating conductive and inductive chargers. It can be inferred that scenario (III), which lowers the optimal cost of bus transit system electrification by a significant amount, also illustrates that investing in charging infrastructure is preferable to increasing onboard BEB battery capacity. Furthermore, the more BEBs there are, the less expensive it gets because charging infrastructure, particularly on-the-fly inductive chargers, can be shared. The findings of some of the work on novel priority charging modelling and simulation have been published in the IEEE PES/IAS Power Africa, 2020.

V. The transit electrification simulation for this scenario IV is based on a bus transit system using inductive charging infrastructure. The simulation approach optimises charging station infrastructure and improves operational service reliability by displaying the cost-benefit trade-off. According to the optimisation model, the optimal cost for bus transit infrastructure is £52,155,184.98. In this circumstance, 24kWh of onboard battery capacity is optimal. As a result, the BEB will be less expensive.

VI. This thesis proposes the design of a multi-terminal inductive base model of BEB's charging infrastructure for the Lagos Nigeria transport system. The solution is obtained using a PSO algorithm that aims to discover the minimum possible size of the BEB onboard battery, the length of the inductive cable and the location of inductive power transmitters to meet the required route demands in three possible scenarios. The first scenario considers an inductive charging system for the existing Lagos bus rapid transit system, as illustrated in Figure 4-23, with the identified significant bus stops (i.e. bus terminals) considered the primary location of the inductive chargers. The second scenario investigates the optimal configuration of the inductive chargers at six equal-distance locations from each other along the Lagos BRT transit network route Figure 5-1. The third scenario investigates the possibility of having four equal-distance locations for the inductive chargers Figure 5-2.

The simulation result for the first scenario yields an optimal solution, indicating that a 26kWh onboard battery would be sufficient to meet the transit route's requirement. The second scenario reveals that for each BEB running on the proposed inductive transit route, a smaller onboard battery with a capacity of

16kWh should suffice. In the third scenario, the optimal cost is the lowest as a result of using four transmitters at equal distances from each other.

When comparing the original location Figure 4-15 (scenario I) to the equal distance scenario II, the result shows that significant savings can be achieved if the inductive chargers are placed at equal distances from each other. The option in Figure 5-2 (scenario III) illustrates that having four terminals in the Lagos transit system can provide an appropriate trade-off between the inductive charger locations and the size of the onboard battery. The placement of the inductive charger at major stops maximises the utilisation of the inductive charging infrastructure. The cost of charging infrastructure is reduced when it is placed at an equal distance from each other, as seen in the case of Lagos infrastructure, because the battery size required is smaller. Moreover, the state charge and sensitivity analysis carried out in this thesis also support the simulation result. The allocation of inductive charging infrastructure provided in this thesis is a cost-cutting method that saves short-and long-term costs. The state of charge and sensitivity analysis were performed to back up the simulation's results. The findings of some of the work on inductive modelling and simulation have been published at the IEEE International Smart Cities Conference 2020.

VII. A comparative case study of carbon emissions savings of the electrified BRT system is conducted based on the Lagos BRT case studies. Estimates are provided for the potential reduction in GHG emissions arising from moving a BEB delivered version of the BRT. In varied traffic situations, the consumption of diesel and electric buses was compared with the associated GHG emission figure. The results show that deploying BEBs along the Lagos, Nigeria BRT route might save 13 to 36 tons of CO_2 per BEB deployed per year. Furthermore, assuming that Lagos BRT operates an average of 400 BEBs every schedule, GHG emissions are predicted to be reduced by 5339 tCO2 per year to 14442 tCO2 per year.

The benefit of an electrified transportation sector would be for EVs to have a considerable share of road transportation demand. Although, this depends on overcoming considerable obstacles. The most significant include the expensive cost, primarily due to the batteries; the limited range; the lengthy battery recharge times; and the lack of public charging infrastructure. This thesis developed a strategy for electrifying public transportation systems that offers excellent prospects for solving transportation electrification hurdles.

First, the small onboard battery allows for significant cost savings while investing in charging infrastructure. The replacement of existing diesel buses with BEBs can also result in considerable reductions in GHG emissions. This, together with a future substantially decarbonised electricity supply network, opens up the possibility of a nearly completely decarbonised road transportation sector. Second, the hub-based charging proposed in this work can encourage mini-grids and energy sources that enable energy diversification, ensuring energy supply stability and the widespread use of carbon-free energy sources. Third, by proposing the necessary infrastructure for effective transit BEB charging. Although, a considerable improvement would be required to support the additional power demand for electrifying transportation.

In general, efforts are being undertaken to solve Nigeria's current energy shortfall. The separation of distribution industry is a key endeavour to improve competition by dividing distribution businesses into network and supply businesses. As part of sweeping power sector reforms in 2013, the Nigerian government privatised 11 electricity distribution firms and six generating companies to boost capacity, extend access to electricity, and improve transmission. Additionally, the Renewable Energy Master Plan, which was introduced in 2011, aims to increase the proportion of renewable energy in the nation's energy mix by at least 13% by 2015, 23% by 2025, and 36% by 2030. Although the country's present generating capacity is estimated to be 5 GW, Nigeria is thought to have a potential solar energy output of over 427 GW. A Power Purchase Agreement worth $2.5 billion was signed in 2016 between the nation and 14 independent power producers for the construction of solar power plants around the nation, which are projected to increase the grid's capacity by roughly 1.1 GW. These projects are, however, at a standstill because of some problems, including pricing structures and uncertainty about the ability of the present transmission system to handle the extra electricity output. Smaller micro-grid initiatives have the most significant promise, according to industry experts.

Hydroelectric energy accounts for around 20% of the country's installed capacity. According to studies, there is a possibility for 11,500 MW of capacity in significant hydropower plants and up to 730 MW in small hydropower projects.

Onshore wind power generation in Nigeria has enormous potential. A 100 MW wind power project, is currently in the works, and offshore wind resources are being assessed and mapped. Off-grid solar power systems are increasingly being used to replace more expensive diesel generators around the country, both for commercial and industrial uses.

Hence, emerging nations' increasing interest in low-carbon solutions, such as investment in renewable energy resources and EV adoption. The conversion of the Lagos BRT system to an electric system is crucial for boosting mass passenger transportation in the city while also developing low-emission transportation alternatives. Furthermore, Nigerian grids are deficient, with voltage-sensitive to the connection on the new load. The existing capacity is insufficient to meet home and industrial demand. The total available capacity in 2019 is 3.7GW, while peak demand is 8.25GW [98]. According to a recent National Bureau of Statistics estimate, Nigerians only get 6.8 hours of energy each day from the national grid [99].

In this scenario, the findings of this research are critical for addressing charging infrastructures that will support transport electrification with little to no reliance on the existing power system, as well as providing guidance for the deployment of energy solutions that will meet transit energy demand.

6.2 Future Work

1. The work of this thesis explored the electrification of the rapid bus system as an alternative to individual cars; shifting from individual cars to transit buses will reduce congestion and GHG emission and improve safety. This work makes extensive use of a novel method developed for allocating charging infrastructures for the transit system by integrating both conductive and inductive chargers.

   As identified in Chapter 1, this thesis focused on applications in developing countries for the decarbonisation of transport where the security of the grid supply is already challenged. Hence, there is a need to propose solutions to meet the energy demand, in this case of the bus transit systems, that account for these grid issues while encouraging the integration of various sources of energy supply (most especially renewable energy sources). In the African case, the local energy system is anticipated to comprise increasing solar energy sources, the energy storage system (ESS), the existing grid, and backup diesel generators.

This proposed bus transit energy system is hoping to consider solar energy system as the primary source of energy; this solar renewable energy system is characterised by intermittence that necessitates the integration of the ESS. Moreover, the grid in developing countries is considered weak and not dependable, especially for an effective public transit system. Therefore, the transit energy system only considers buying from the grid when the primary sources (i.e. the solar and ESS cannot meet the system energy demand) and selling to the grid when there is a surplus generated energy. The diesel generator is only considered to minimise the system's Co_2 emission in an emergency need.

The proposed operation of the transit energy system that may be considered for future study is illustrated in Figure 6-1. Connected to the solar energy source is the PV converter that tracks the maximum power point of the generated solar energy. The central controller is considered to perform the function of both the power converter and energy management system that control various chargers. An intelligent bidirectional hybrid power converter controls the ESS, the interconnected grid and the diesel generator, as shown in Figure 6-1.

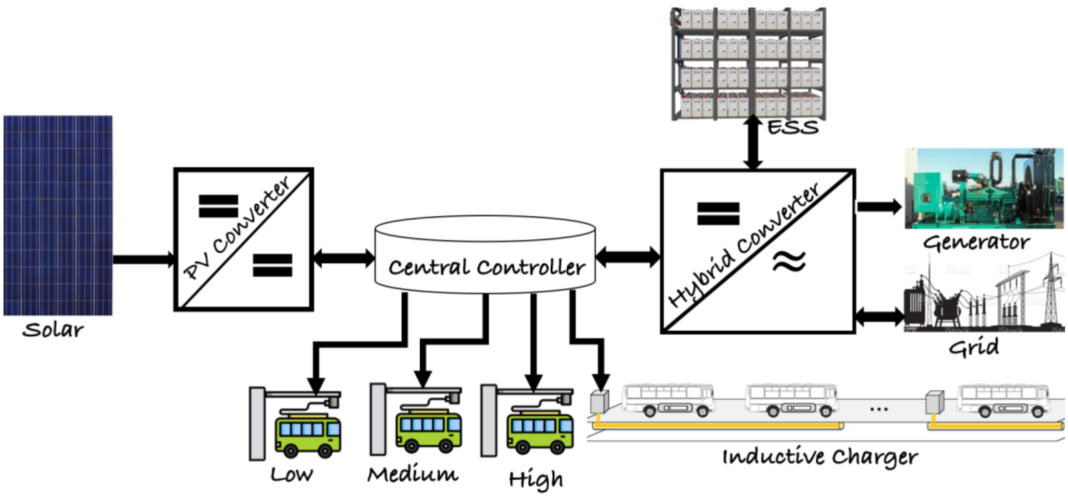

Figure 6-1 Proposed Terminal Based Transit Energy System

In addition, the modelling of this future proposed work is expected to extend to the multi-terminal allocation of the transit energy system, as illustrated in Figure 6-2.

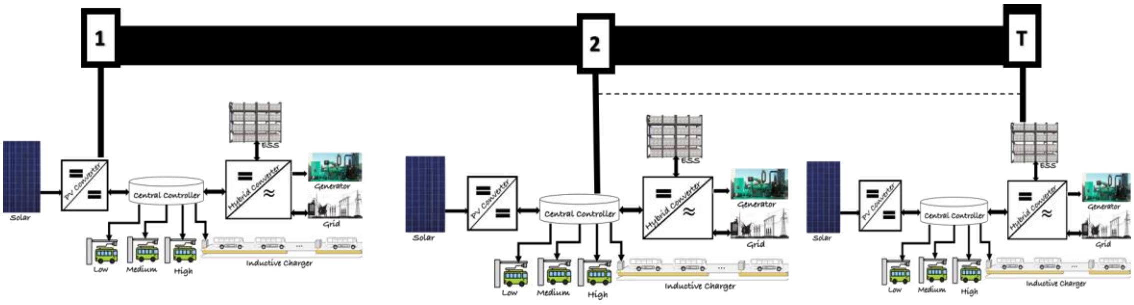

Figure 6-2 Proposed Multi-terminal Based Transit Energy System

The proposed renewable resource is expected to cater charging demand of the charging model proposed in this work. This solution is considered because the security of grid supply is already challenged. Besides supporting challenged grids, it reduces pollution from both transport and power generation points of view. Hence, this introduces a mathematical problem that needs to be formulated in the form of an optimisation model for sizing various components of the proposed transit energy system to minimise the cost while optimally sizing the system components.

As a result, it is envisaged that industry, academia, and the government will examine bus transit electrification as a feasible option for more sustainable transportation. Governments and funding organisations are also urged to recognise and promote the potential benefits of an electrified bus transit system.

2. The key determinant of BEB's operational strategy and cost analysis is energy consumption. The BEB energy consumption figure might be a crucial factor in calculating the fuel cost and greenhouse gas emissions for fleet buses, which could have significant economic and ecological implications. An accurate estimation of the BEB energy consumption figure is also essential for its development, deployment, and necessary charging infrastructure. One of the critical variables

affecting the BEB energy consumption figure is the speed profile, which should be available to accurately assess the BEB energy consumption figure. This speed profile has been considered in this thesis, along with other parameters such as route topography, weather, traffic, and passenger occupancy rate.

In this thesis, the passenger rate considered is a full bus load, which is typically the case for the Lagos BRT considered in this thesis. However, it would be beneficial if future research work could consider scenarios of more representative use cases, such as variations in bus loading, traffic congestion, and charger capacity along the route length, as well as over the course of the day and also annual variations.

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8 APPENDICES

8.1 Appendix A: PSO Algorithm

Particle swarm optimisation (PSO) is a stochastic optimisation technique that focuses on swarm intelligence. It was introduced in 1995 by Eberhart and Kennedy [357], [358]. PSO simulates the social behaviour of animals such as insects, herds, birds, and fish. These swarms work cooperatively to hunt food, and each swarm member modifies its search behaviour in response to its own and other swarm members' learning experiences. The core design principle of the PSO algorithm is closely linked to two studies: One is an evolutionary algorithm; similar to evolutionary algorithms, PSO operates in a swarm mode, which enables it to simultaneously scan a large part of the solution space for the optimised objective function.

Meta-heuristics are high-level strategies for employing heuristics to solve a wide variety of problems Examples include complex scheduling problems, space allocation problems, and clustering problems [359]. In contrast to heuristics, they do not require any problem-dependent heuristic expertise. One of their key advantages is that they avoid making bold conclusions about the problem instead of treating it as a black box [360] [361]. They sample the problem's search space, which is too large to explore exhaustively, in order to find optimal solutions. Meta-heuristics are a subclass of Soft Computing approaches that permit incomplete or inaccurate solutions. This comes at the cost of inaccuracy when selecting the ideal solution to a given problem. The tremendous complexity of some issues and the failure of exact approaches explain the adoption of such problem-solving procedures that quickly find optimal or near-optimal solutions. Numerous algorithms have been created in the field of meta-heuristics, with the majority of them being inspired by nature. Several of the most popular is Simulated Annealing [362], which mimics the annealing mechanism in physics. Genetic Algorithms [363] which are inspired by evolutionary theory. Differential Evolution [364], which incorporates evolutionary principles into differential equations, Ant Colony Optimization (ACO) [365], which is inspired by ant swarm intelligence, and Particle Swarm Optimization (PSO) [366].

The PSO has seen many revisions in the literature recently. Importantly, this algorithm has varied versions. Recently, the PSO algorithm models have incorporated many transfer functions to solve binary issues [367]. These functions use the velocity values to flip a binary bit. The larger the velocity vector, the more likely it is that the binary bit will flip [368], [369] [367].

Numerous multi-objective versions of PSO have been proposed to address multi-objective issues in the literature. In [370], the authors proposed the most extensively used method, in which non-dominated solutions (Pareto optimum solutions) were stored and developed during the optimisation process using an index. The archive's global best solution was chosen for each iteration, as all solutions in the archive are considered solutions to a multi-objective optimisation problem. A grid technique was applied in the archive to increase the solutions' heterogeneity [371]. Additionally, there are methods for increasing diversity, such as crowding distance [372]. Another often-used strategy is ranking and boosting previously obtained non-dominated solutions using non-dominated sorting in the PSO [373]. Additionally, there are algorithms that aggregate objectives in the literature [374].

Numerous functions for managing constraints are available in the literature [375], [376]. These functions are occasionally used with the goal function to penalise particles that breach constraint violations. Some of these functions apply the same penalty to particles regardless of the severity of the infraction. In this context, such functions are referred to be barrier functions. Additionally, there exist functions that penalise particles based on the gravity of their violation. These functions are crucial when addressing problems characterised by dominating infeasible zones, as PSO iterates through a large number of infeasible solutions [377].

In [378], the authors proposed a dynamic version of PSO for solving situations with quickly changing objectives. The fundamental purpose is to prevent PSO from converging on a solution in order to track changes in the objective function(s) [378]. Additionally, robust PSOs [379], [380] and robust MOPSOs [381], [382] have been proposed to handle problems involving uncertainty in the literature.

8.1.1 PSO Basic Modelling Concepts

The PSO algorithm was inspired by the flocking behaviour of birds in nature, as previously stated. Each particle is seen as a solution to a specific optimisation problem in this method. It's made up of two vectors: one representing the position and the other representing velocity. The values of all the variables in the problem are stored in the position vector. The position vectors of the particles will be two-dimensional if the problem has two parameters. In an n-dimensional search space, where n is the number of variables, each particle has total freedom of movement. The particle's location is tracked using the second vector (velocity). This vector specifies the quantity and direction of each dimension's and particle's step size [383].

At each optimisation step, the following equation is used to update the location of particles [384]:

$$\overrightarrow{\mathbf{X_i(t+1)}} = \overrightarrow{\mathbf{X_i(t)}} + \overrightarrow{\mathbf{V_i(t+1)}} \tag{8.1}$$

Where $\overrightarrow{X_i(t)}$ denotes the position of i_th particle at t_th iteration and $\overrightarrow{V_i(t)}$, denotes the velocity of i_th particle at t_th iteration. This equation demonstrates how simple it is to update position using the velocity vector as the primary variable. The velocity vector is defined as follows [383]:

$$\overrightarrow{\mathbf{V_i(t+1)}} = \mathbf{w}\overrightarrow{\mathbf{V_i(t)}} + \mathbf{c_1 r_1}\left(\overrightarrow{\mathbf{P_i(t)}} - \overrightarrow{\mathbf{x_i(t)}}\right) + \mathbf{c_2 r_2}\left(\overrightarrow{\mathbf{G(t)}} - \overrightarrow{\mathbf{x_i(t)}}\right) \tag{8.2}$$

where $\overrightarrow{X_i(t)}$ denotes the *i_th* particle's position during the t_th iteration, $\overrightarrow{V_i(t)}$ denotes the *i_th* particle's velocity during the t_th iteration, *w* denotes the inertial weight, c_1 denotes the individual coefficient, c_2 denotes the social coefficient, $r_1 r_2$ denote random numbers in the range [0, 1], $\overrightarrow{P_i(t)}$, denotes the best solution obtained by the ith particle.

As defined in (4.7), the velocity vector is composed of three parts. The first element, $w\overrightarrow{V_i(t)}$, preserves the trend of the present velocity. This factor is multiplied by a value for the inertia parameter w. The bigger this parameter's value, the more likely it is that the prior velocity will be maintained. In the next part, $c_1 r_1 \left(\overrightarrow{P_i(t)} - \overrightarrow{x_i(t)}\right)$, simulates the individual intelligence of a bird by memorising and employing each particle's best answer thus far. The vector $\overrightarrow{P_i(t)}$, is changed after each iteration in case the *ith* particle identifies a more efficient solution. By adjusting c_1, the effect of this variable on the final velocity value can be enhanced or lowered. Due to the stochastic nature of PSO, this parameter is multiplied by a random value in the range [0, 1] to generate randomised behaviour. By and large, the second component preserves a bias towards the particle's best solution thus far, the so-called "personal best". The third part, $c_2 r_2 \left(\overrightarrow{G(t)} - \overrightarrow{x_i(t)}\right)$, replicates the social intelligence of a flock of birds by storing and utilising the optimal solution obtained by all particles in $\overrightarrow{G(t)}$. This means that contemplating the optimal solution for the swarm draws all particles to a single spot. Additionally, this component's impact can be adjusted via c_2 [379], [381].

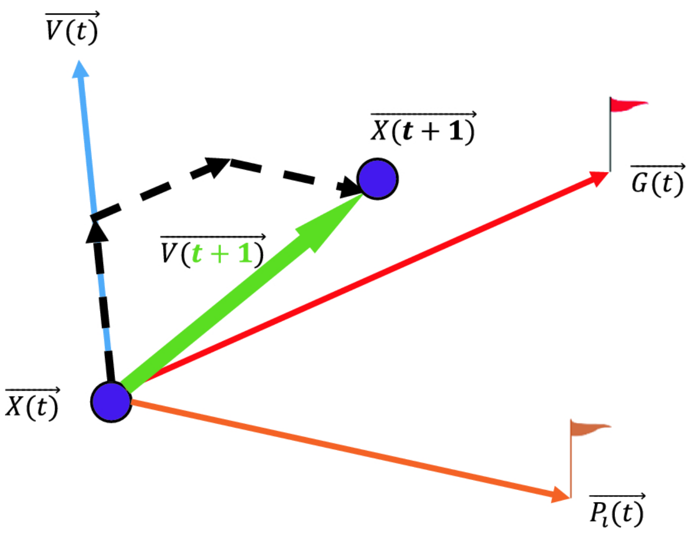

Figure 8-1 In PSO, each particle considers its prior velocity, personal best, and global best to define its current velocity and position (Adopted from [386]).

The three Cartesian components can be used to describe the next position of a particle. This principle is illustrated in Figure 8-1. This illustration explains how each particle determines its current velocity and position by comparing it to its prior velocity, personal best, and global best. The position immediately following is significantly reliant on the random integers generated by r_1 and r_2. In Figure 8-1, it is assumed that the particle considers 50% of its current velocity, 40% of the global best, and 40% of the personal best [385]. c_1 and c_2 are, in reality, multiplied by random numbers. The values of w, c_1, and c_2 must be known in order to identify the zone in which a particle can move. In the most generally used PSO variant, the value of w drops linearly from 0.9 to 0.4 in relation to the number of iterations [386]. Additionally, the c_1 and c_2 parameters are set to 2. Due to the difficulties of illustrating the different places of particles when the inertial weight is changed, this paragraph illustrates probable locations when *w=1*, *w=0.5*, and *w=0*. Fig. 2 illustrates the new places that the particle could take in this form.

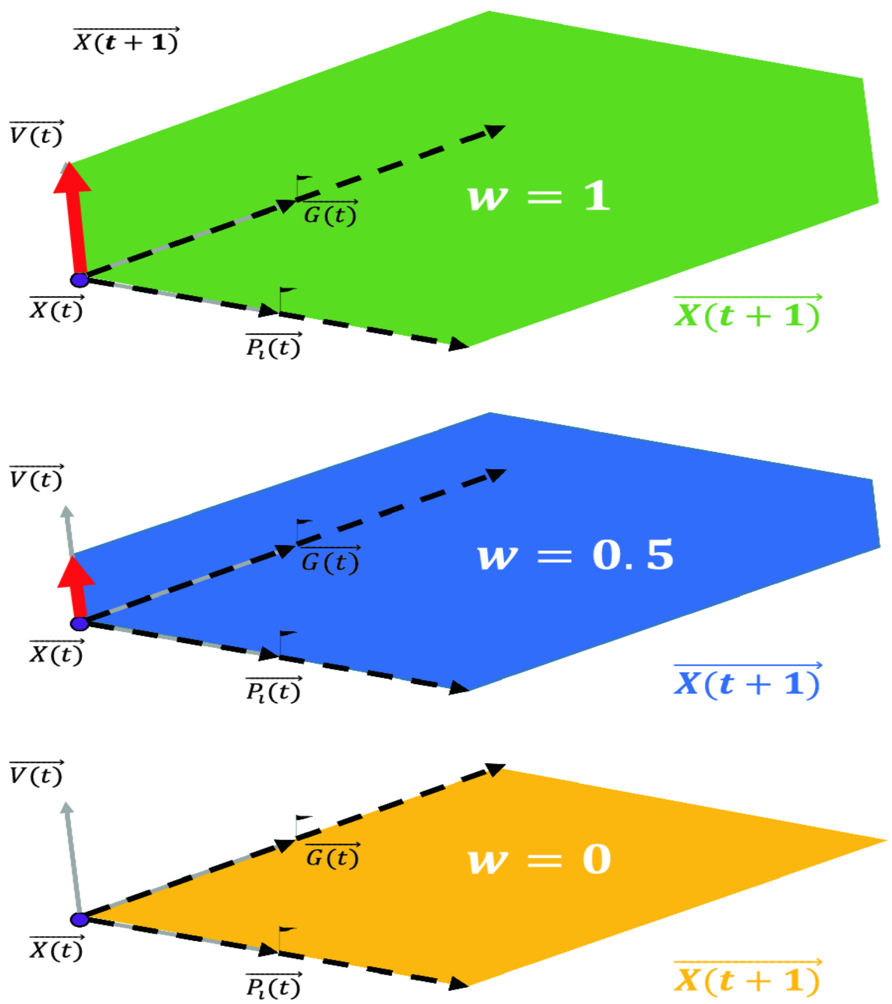

Figure 8-2 The inertial weight's (*w*) effect on the velocity vector in PSO (Adopted from [386]).

The vectors toward the personal and global bests can be any length between 0 and twice their respective distances. This is due to the fact that both c_1 and c_2 have been multiplied by a random number between 0 and 1 [386]. As a result, the range of these two parameters is unlimited inside the range [0,2]. When the value is 0, the component is ignored by the particle. When the variable's value equals 2, it is considered twice as large. This is why the vectors in Figure 8-2 have been multiplied by two. Due to the fact that the lower and upper bounds of c_1 and c_2 remain constant, the greatest and minimum distances to personal and global bests are equal, as illustrated in Figure 8-2. However, as illustrated in this image, the inertial weight is adjusted. As illustrated in Figure 8-2, when the inertial weight is 0, the particle's next position is somewhere between its current location and its personal and global bests. Due to the fact that the algorithm searches locally within the region defined by the current location, personal best, and global best, the PSO model incorporates exploitation and local search. Indeed, when both c_1 and c_2 are set to 1, just the local search is conducted. This principle is illustrated in Figure 8-3.

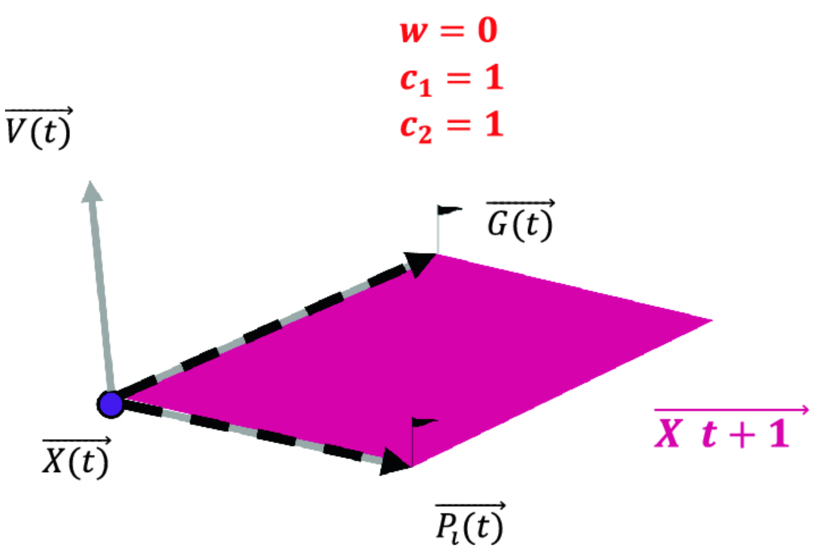

Figure 8-3 When w=0, c_1 =1 and c_2 =1, exploitation and local search performance in PSO (Adopted from [386]).

Exploration is maximised, and global search performance increases correspondingly to both of these parameters' values. This is depicted in Figure 8-4. As demonstrated, the particle has a proclivity for travelling outside the region indicated by the global or local bests. As a result, discovery and global search are enabled. It is worth mentioning that both personal and global bests are updated continuously. As a result, the shaded area in Figure 8-4 shows the area of the next position. c_1 =1 and c_2 =1, exploitation and local search performance in PSO.

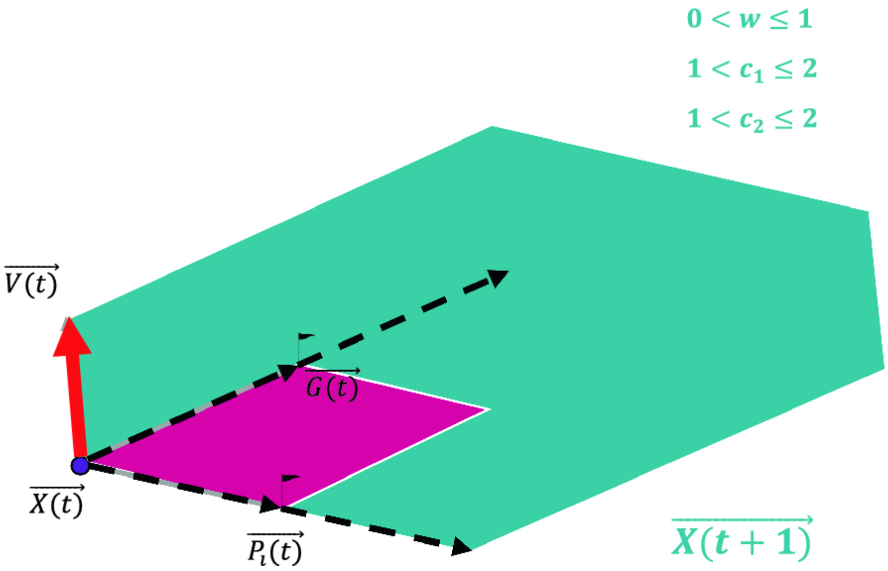

Figure 8-4 Exploration and global search rise proportionately to *w*, c_1 and c_2 values (Adopted from [386]).

The PSO algorithm is based on these simple concepts and is used to find the optimal global solution to a given optimisation issue. It begins with a population of randomly picked solutions. It then continues the steps below till the end condition is met:

1. Determination of each particle's objective value

2. *w*, c_1 and c_2 are updated. If both c_1 and c_2 remain constant, just w is altered.

3. Managing personal and global records

4. Determine the velocity vector for each particle using Eq. 8.1.

5. Determine the next position of each particle using Eq. 8.2.

The final optimum for the optimisation problem will be the best solution obtained by the entire swam at the conclusion of the optimisation process [333], [383]–[385], [386].

8.2 Appendix B: Supplementary Data for Case Study

8.2.1 Average Lagos BRT driving (minutes)

S/n	Service Lines	Average Cycle time (min)
1	Ikorodu-Mile12	76
2	Ikorodu-Fadeyi	132
3	Ikorodu-TBS	164
4	Aruna-TBS	160
5	Agric-Mile12	66
6	Agric-Fadeyi	127
7	Agric-TBS	159
8	Agric-Maryland	99
9	Agric-Costain	157
10	Ogolonto-TBS	189
11	Irawo-TBS	177
12	Idera-TBS	176
13	Owode-Ikorodu	72
14	Mile12-Fadeyi	82
15	Mile12-TBS	139
16	Ketu-Ikorodu	102
17	Ketu-Fadeyi	69
18	Ketu-TBS	126
19	Ojota-Ikorodu	90
20	Ojota-Fadeyi	69

21	Ojota-TBS	125
22	Maryland-Ikorodu	115
23	Maryland-Fadeyi	67
24	Maryland-TBS	117
25	Anthony-Ikorodu	124
26	Fadeyi-TBS	74
27	Barracks-Ikorodu	140
28	Barracks-Mile12	85
29	Barracks-TBS	69
30	Costain-Ikorodu	165
31	Costain-Mile12	105
32	Leventis-Ikorodu	207
33	Leventis-Mile12	149
34	CMS-Ikorodu	204
35	CMS-Mile12	139
36	CMS-Fadeyi	62

8.2.2 Lagos BRT weekdays operational Schedule

Route 14 — **Weekdays**
Vehicle working 61

[pull-out trip] | from: Majidun BRT | departure: 04:14 | towards: Ikorodu_Terminus | arrival: 04:24 | [empty running]

Route 14					
Ikorodu	04:30	07:18	10:06	13:12	16:18
Ketu	|	|	|	|	|
Anthony	|	|	|	|	|
Ikorodu	|	|	|	|	|
Barracks	|	|	|	|	|
Stadium	|	|	|	|	|
Iponri	|	|	|	|	|
Costain	|	|	|	|	|
Leventis	05:43	08:31	11:22	14:28	17:29
CMS/Marina	05:47	08:35	11:26	14:32	17:33
TBS	05:51	08:39	11:31	14:37	17:38
TBS	06:05	08:53	11:45	14:51	17:52
Ketu	|	|	|	|	|
TBS	|	|	|	|	|
Owode Onirin	06:45	09:33	12:35	15:41	18:46
Idera	06:47	09:35	12:37	15:43	18:48
Irawo	06:48	09:36	12:38	15:44	18:49
Majidun Awori	06:57	09:45	12:47	15:53	18:58
Majidun Ogolonto	07:00	09:48	12:49	15:55	19:00
Agric	07:03	09:51	12:53	15:59	19:04
Aruna	07:05	09:53	12:54	16:00	19:06
Ikorodu	07:08	09:56	12:58	16:04	19:10

[pull-in trip] | from: Ikorodu_Terminus | departure: 19:11 | towards: Majidun BRT | arrival: 19:21 | [empty running]

8.2.3 Lagos BRT Saturday operational Schedule

Route 14 — **Saturday**
Vehicle working 61

[pull-out trip] | from: Majidun BRT | departure: 05:46 | towards: Ikorodu_Terminus | arrival: 05:56 | [empty running]

Route 14					
Ikorodu	06:00	09:02	12:04	15:06	18:08
Ketu	|	|	|	|	|
Anthony	|	|	|	|	|
Ikorodu	|	|	|	|	|
Barracks	|	|	|	|	|
Stadium	|	|	|	|	|
Iponri	|	|	|	|	|
Costain	|	|	|	|	|
Leventis	07:15	10:17	13:19	16:21	19:23
CMS/Marina	07:20	10:22	13:24	16:26	19:28
TBS	07:25	10:27	13:29	16:31	19:33
TBS	07:33	10:35	13:37	16:39	19:41
Ketu	|	|	|	|	|
TBS	|	|	|	|	|
Owode Onirin	08:27	11:29	14:31	17:33	20:35
Idera	08:29	11:31	14:33	17:35	20:37
Irawo	08:31	11:33	14:35	17:37	20:39
Majidun Awori	08:41	11:43	14:45	17:47	20:49
Majidun Ogolonto	08:44	11:46	14:48	17:50	20:52
Agric	08:49	11:51	14:53	17:55	20:57
Aruna	08:51	11:53	14:55	17:57	20:59
Ikorodu	08:55	11:57	14:59	18:01	21:03

[pull-in trip] | from: Ikorodu_Terminus | departure: 21:04 | towards: Majidun BRT | arrival: 21:14 | [empty running]

8.2.4 Lagos BRT Sunday operational Schedule

Route 14 **Sunday**

Vehicle working 61

[pull-out trip] | from: Majidun BRT | departure: 05:46 | towards: Ikorodu_Terminus | arrival: 05:56 | [empty running]

Route 14

Ikorodu	06:00	09:06	12:12	15:18	18:24
Ketu	|	|	|	|	|
Anthony	|	|	|	|	|
Ikorodu	|	|	|	|	|
Barracks	|	|	|	|	|
Stadium	|	|	|	|	|
Iponri	|	|	|	|	|
Costain	|	|	|	|	|
Leventis	07:15	10:21	13:27	16:33	19:39
CMS/Marina	07:20	10:26	13:32	16:38	19:44
TBS	07:25	10:31	13:37	16:43	19:49
TBS	07:35	10:41	13:47	16:53	19:59
Ketu	|	|	|	|	|
TBS	|	|	|	|	|
Owode Onirin	08:29	11:35	14:41	17:47	20:53
Idera	08:31	11:37	14:43	17:49	20:55
Irawo	08:33	11:39	14:45	17:51	20:57
Majidun Awori	08:43	11:49	14:55	18:01	21:07
Majidun Ogolonto	08:46	11:52	14:58	18:04	21:10
Agric	08:51	11:57	15:03	18:09	21:15
Aruna	08:53	11:59	15:05	18:11	21:17
Ikorodu	08:57	12:03	15:09	18:15	21:21

[pull-in trip] | from: Ikorodu_Terminus | departure: 21:22 | towards: Majidun BRT | arrival: 21:32 | [empty running]

8.2.5 Lagos BRT Corridor Lanes