Chapter 5
Fast-Charging Infrastructure for Transit Buses

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Nomenclature

BS	Battery swap
CC	City Center
DC	Depot charger
DER	Distributed energy resource
EB	Electric bus
ESS	Energy storage system
EV	Electric vehicle
FC	Flash charger
HF	High frequency
LD	Long distance
LF	Low frequency
LV	Low voltage
SD	Short distance
SoC	State-of-charge
SU	Suburban
TC	Terminal charger

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Sets and Indexes

i Index for stops
j Index for trips
k Index for buses
r Index for routes

Index of the First Element in a Set

end Index of the last element in a set
I^r Set of all stops in route r
J^r Set of all trips in route r
K^r Set of all buses in route r
R Set of all routes
H Set of all available on-route charger types

Variables

d_r^s Average distance between stops on route *r*
L_r Length of route *r*
N_r^s Number of stops in route *r*
d_r^d Average daily distance between stops on route *r*
H_r Operating hours of route *r* (time difference between first and last buses of the day)
T_r Average duration of route *r*
N_r^t Daily number of trips for route *r*
bs_r Binary variable indicating battery swap depot existence in route *r*
bd_r Binary variable indicating bus depot existence in route *r*
$b_{k,r}$ Capacity of battery on bus *k* on route *r*
$x_{i,h,r}$ Binary variable indicating presence of on-route charger type *h*, at stop *i*, in route *r*
$e_{i,j,r}$ Energy charged at stop *i*, during trip *j*, in route *r*
d_{year} Number of days in a year
n_r^{bus} Number of buses deployed to route *r*
F_r^b Frequency of buses is route *r*
$E_{i,j,k,r}$ Battery SoC at stop *i* during trip *j*, on bus *k*, in route *r*
$\overline{B}$ Upper bound for the batteries' SoC
$\underline{B}$ Lower bound for the batteries' SoC
$\overline{E}_h$ Maximum charge capacity of on-route charger type *h*
$\overline{E}_{DC}$ Maximum charge capacity of the depot charger

5.1 Introduction

Electrification of buses is widely recommended to reduce greenhouse gas (GHG) emissions from conventional fossil fuel buses. There are a number of challenges to achieve high-performance charging infrastructures for electric buses (EBs). Time to charge EB during the daily trips should be minimum to reduce waiting time and passengers' trip time. There are a number of challenges that face the transition of electric bus fleet, including planning charging stations, adopting fast- and ultrafast-charging stations, and possible business models of swapping battery in EBs to avoid waiting time to charge on-route [1]. The deployment of electric buses in different regions, such as Europe, reflected challenges including infrastructure planning, marketplace, pricing, charging infrastructure, and business models [2]. The performance of charging infrastructure is evaluated with a number of performance measures, such as cost, time, mobility, and social factors. The optimization of charging infrastructures is essential to achieve profitable transportation electrification [3]. The charging stations are interfaced with the grid, where charging demands affect the grid performance. Hence, the study of charging station interface to the grid is critical to meet charging demand profiles and grid performance [4]. The expansion of transportation electrification and charging infrastructures requires proper analysis of grid impacts to balance charging load profiles with grid condition [5]. The deployment strategies and planning of fast-charging stations should consider electrification load profiles [6]. The coupling between transportation electrification and grid condition will support the planning of large-scale charging stations [7]. The charging performance could be enhanced with different strategies such as prediction of charge ahead of time [8]. The overall performance of electric buses could be enhanced with smart charging capabilities where coordination between buses and stations, among buses, and stations, and the grid could provide enhanced performance [9]. There are a number of bus charging technologies which are available in the market, such as the technologies from ABB [10]. The different deployment strategies opened the door for implementation projects in different regions, city centers, urban areas, suburban areas, and remote communities. To achieve successful installation projects of charging infrastructures, the requirements should be analyzed in terms of energy storage, mobility demand, and social factors [11]. And the bus route planning should also be considered as an integral part of the charging infrastructure. Case study is analyzed for bus electrification in Porto [12] and in London [13]. To reduce the impacts on the grid, renewable energy sources, such as solar and wind, are widely used and integrated with charging stations in large-scale stations and small-scale stations in parking lots [14]. The scheduling of bus routes should be planned properly to optimize the overall transit performance whether by adopting central charging strategies with battery swapping or by charging on-routes [15]. Computational intelligence techniques could be utilized to enhance energy management of electric bus charging performance with deep learning techniques where selection of nearest station based on battery state could be optimized [16]. Stochastic learning techniques are also utilized to improve energy management of electric bus charging and the overall performance [17]. In order to have better understanding of different techniques and strategies for the planning of electric bus deployment and charging infrastructure, it is important to provide analysis using bus transit and charging infrastructure models. This chapter will present possible models and associated parameters for electric bus charging with different strategies and scenarios.

5.2 Electric Bus Charging Models

There are a number of EB charging styles that can be selected based on different trips, regions, technologies, and techno-economic preferences. Figure 5.1 shows a public transit network with possible charging models for EB, which include on-route charging using flash charger, bus terminal charging, or overnight charging in bus depot. Also battery swapping could be implemented in selected charging stations.

The buses are parked in the depots when they are not in service. Buses usually stop for longer periods and can have longer charging time. Fast or ultrafast charging will be implemented in charging station on-route via flash charging.

The depot charger (DC) is used to charge buses when they are out of service and parked at the depot, which is usually off-route. The power rate of DC is typically in the power range from 50 to 100 kW, which are usually used for slow charging, that is, overnight or when they are out of service. The terminal charger (TC) is typically installed for on-route charging at main terminals. Buses stay a few minutes at the TC station. The rated power of TC is ranging from 500 to 600 kW. TC is commonly connected to high-voltage power grid. The flash charger (FC) is used for on-route fast charging at regular bus stops. FC has a rated power ranging from 400 to 500 kW,

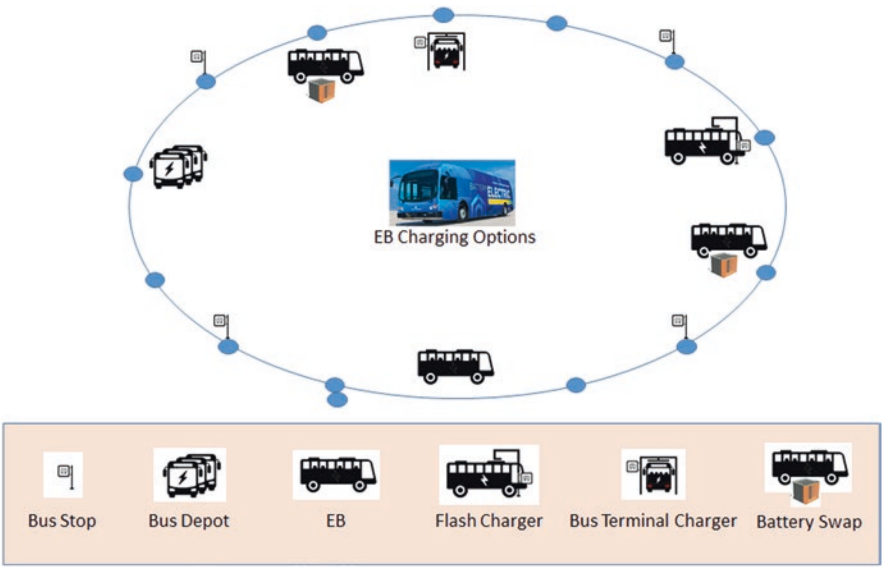

Fig. 5.1 Electric bus charging on-route

which is connected to low-voltage (LV) power grid. Batteries are commonly used with FC to reduce load spikes on the LV grid. Bus stop at regular stops for a few seconds; hence, fast charging is required.

d_r^d is the average daily distance on route r, which is calculated based on total operating hours per day, trip average time, and trip average distance. It is defined using Eq. 5.1:

$$d_r^d = \frac{H_r}{T_r} \cdot L_r = N_r^t \cdot L_r \tag{5.1}$$

d_r^s is the average distance between stops for route r, which is calculated based on the total distance on route r, defined as L_r, and number of stops on route r, based on Eq. 5.2:

$$d_r^s = \frac{L_r}{N_r^s - 1} \tag{5.2}$$

The proposed EB charging infrastructure planning mechanism is based on defining number of scenarios where different combinations of charger types on a given route can serve number of buses on the same route. The selection of the best charger type is based on optimization model in view of performance measures, which are defined in the following section.

5.3 Performance Measures

The performance of the bus transit network is evaluated based on multiple performance measures, as described in Table 5.1.

KPI-C	Cost	KPI-C1: Capital cost of charging infrastructure
		KPI-C2: Cost of daily trips
		KPI-C3: Cost of daily energy back to grid (V2G)
KPI-T	Time	KPI-T1: Average time of daily trips
		KPI-T2: Average charging time of daily trips
		KPI-T3: Total delay time for daily trips
KPI-B	Battery	KPI-B1: Battery lifetime
KPI-I	Charging infrastructure	KPI-I1: Energy not served for charging buses
		KPI-I2: Total daily energy back to the grid (V2G)
		KPI-I3: Reliability of charging infrastructure
KPI-S	Social	KPI-S1: Mobility density per day
		KPI-S2: Area coverage index
KPI-R	Risk	KPI-R1: Risk value of not reaching charging station in normal condition
		KPI-R2: Risk value of not reaching charging station in abnormal condition

Table 5.1 Specifications of routes for the case study

	Route A	Route B	Route C
Number of trips (per day)	7	14	16
Number of stops (per trip)	70	80	75
Total number of stops (per day)	350	800	1200
Trip length (km)	25	20	15
Bus size (m)	18	24	24
Average consumption (kWh/km)	1.8	2.2	2.2

The proposed performance measures include cost measures related to capital and operating costs associated with charging infrastructures. Time factors are considered as part of the overall performance of charging infrastructures, including charging time, trip time, and delay time in each trip. The performance of charging infrastructure is also monitored and optimized in terms of energy not served to charge incoming buses, total energy back to the grid (in different peak times), and the reliability of the charging infrastructure. Social factors are considered in terms of mobility density per day and area coverage index to ensure equity for reduced delays in different regions. The risk factors are also monitored in terms of the risk of the bus not being able to reach the next charging station with empty battery in normal and abnormal conditions.

5.4 Case Study

To understand the proposed modeling of charging infrastructures for transit buses, case studies are illustrated in this section. Table 5.1 shows specifications for the case study represented by three different routes. Route A has 7 trips per day, route B has 14 trips per day, and route C has 16 trips per day. The case study shows different parameters for the three routes in terms of stops per trip, stops per day, trip length, bus size, and average energy consumption per Km.

The understanding of the routes is used to analyze the techno-economic specifications of the chargers in each route. Table 5.2 shows different charger classifications, models, rated power, maximum charging time, capital cost of the charger, operating cost of each charger, and lifetime of the charger. These parameters are used to analyze and optimize charging infrastructure in terms of defining charger model, type, size, and location with respect to bus stops. The different scenarios will be optimized in view of key performance indicators defined in Table 5.1.

The selection of batteries for the electric buses will influence the selection of charging infrastructure specifications. Table 5.3 shows different techno-economic parameters defined for batteries of electric buses, including capital cost of the battery, operating cost, lifetime, and state-of-charge upper and lower limits. These battery parameters will be used to analyze and optimize battery selection within charging infrastructures.

Table 5.2 Techno-economic specifications of chargers

	DC	TC		FC	
Charger classification	Depot	On-route		On-route	
Model	Standard	Slow	Fast	Slow	Fast
Rated power (kW)	50	400	600	400	600
Maximum charging time	5 h	3 min		10 s	
Capital cost (EUR)	100 k	290 k	310 k	320 k	320 k
Operating cost (EUR/year)	120	2100		2100	
Lifetime (years)	20	20		20	

Table 5.3 Techno-economic specifications of batteries

Capital cost (EUR/kWh)	250
Operating cost (EUR/year)	–
Battery lifetime (years)	5
State-of-charge upper boundary (%)	90
State-of-charge lower boundary (%)	10

The proposed charging infrastructures for transit buses are useful and comprehensive to enable detailed analysis of different deployment strategies and operational scenarios based on user requirements and target performance. Optimization methods could be used to maximize profits and the overall performance of charging infrastructures for transit buses.

5.5 Summary

This chapter presented detailed models for charging infrastructure to support electrification of transit buses. Different routes are defined in terms of trips, bus technologies, charging technologies, battery technologies, and performance measures. Case study specifications for routes, chargers, and battery technologies are defined as basis for the analysis of charging infrastructures for transit buses.

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