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Strategies for deploying zero-emission bus fleets: Route-level energy consumption and driving range analysis

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Introduction

Today, the vast majority of transit buses operating in cities are powered with internal combustion engines (ICEs). They mostly burn diesel or compressed natural gas (CNG) and can be a significant source of air pollutant emissions. These emissions are harmful to human health and are of greatest concern when they occur in close proximity to populations, for example at stops or stations with high levels of bus activity. The risks are especially potent for cities operating older fleets or that are located in regions without stringent air pollutant emission standards for heavy-duty engines.

In recent years, battery electric buses have emerged as a viable option for public transit operators and authorities seeking to improve the environmental performance of their fleets.[1] These buses have zero tailpipe emissions of harmful air pollutants. Furthermore, when charged using low-carbon electricity sources, electric buses can deliver deep fuel life-cycle greenhouse gas (GHG) emissions reductions relative to conventional diesel and CNG buses. Even in areas with relatively carbon-intense electricity grids, electric buses can still have lower GHG emissions on a life-cycle basis than conventional diesel and CNG buses.[2]

Transitions to zero-emission battery electric bus fleets require careful planning in order to ensure that the new technologies can be incorporated into existing operations

1 Bloomberg New Energy Finance, "Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO_2," (2018), https://assets.bbhub.io/professional/sites/24/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf.

2 Tim Dallmann, Li Du, and Ray Minjares, *Low-Carbon Technology Pathways for Soot-Free Urban Bus Fleets in 20 Megacities* (ICCT: Washington, DC, 2017), https://theicct.org/publications/low-carbon-technology-pathways-soot-free-urban-bus-fleets-20-megacities.

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cost-effectively with minimal disruptions to service.[3] Battery electric buses introduce unique operational considerations with respect to charging strategies and driving range that are not typically encountered with diesel and CNG buses. Parameters such as passenger load, accessory power consumption, and battery degradation can affect the performance of battery electric buses. These parameters can vary across routes, by time of day, seasonally, and throughout the lifetime of the bus and battery. An understanding of how these parameters impact electric bus energy consumption and driving range is needed to make informed decisions regarding bus technology selection, charging infrastructure development, and deployment strategies.

This paper is the second in a series describing the development of tools and methods to perform route-level analysis to support electric bus deployments. The goal of this work is to develop and apply analytical tools to support the decision-making of transit bus operators pursuing transitions to zero-emission bus fleets and to identify the least-cost approaches for widespread procurement and deployment of these technologies. The first paper presented methods for using real-world operational data from existing fleets to develop representative drive cycles for individual routes.[4] As a case study, the methods were applied to data from the Bengaluru Metropolitan Transport Corporation (BMTC), the largest public operator of urban transit buses in the city of Bengaluru (commonly referred to as Bangalore), the capital of the state of Karnataka, India. This second paper builds on that work by developing methods for estimating route-specific energy consumption for electric buses using vehicle simulation software. These methods are then used to evaluate the performance of a representative electric bus technology operating on 29 BMTC routes that are under consideration for initial electric bus deployments. By doing this, we demonstrate how these route-level modeling tools can be used to investigate the impacts of different parameters on electric bus energy consumption and driving range, and to assess the suitability of electric bus technology options for individual routes.

In the next section, we present the methods developed to estimate the energy consumption of transit buses using vehicle simulation software. After that, we give an overview of the process we used to select BMTC routes for initial consideration for electric bus deployment, and of how we developed representative duty cycles for these routes. Finally, we apply the vehicle simulation approach for the selected BMTC routes to demonstrate how results can help evaluate the effect of important parameters on electric bus energy consumption and assess route-specific driving range and electric bus replacement ratios.

Route-level energy consumption modeling methodology

Energy consumption is a key determinant of the total cost of ownership (TCO) of a vehicle, particularly its operational cost; vehicle performance, such as driving range; and the environmental impacts of a vehicle, such as GHG emissions. The simulation of energy consumption is necessary in the absence of real-world energy consumption data. When planning for a new fleet of electric buses, energy simulation is useful to compare technologies and operational strategies to reveal which technology would perform best and at the lowest cost.

To estimate the energy consumption and performance of city transit electric buses, we used vehicle simulation software combined with standardized drive cycles developed from real-world driving data collected from BMTC's current fleet of diesel buses.

3 National Academies of Sciences, Engineering, and Medicine, *Guidebook for Deploying Zero-Emission Transit Buses* (Washington, DC: The National Academies Press), https://doi.org/10.17226/25842.

4 Lingzhi Jin et al., *Strategies for Deploying Zero-Emission Bus Fleets: Development of Real-World Drive Cycles to Simulate Zero-Emission Technologies along Existing Bus Routes*, (ICCT: Washington, DC, 2020), https://theicct.org/publications/zev-bus-fleets-dev-drive-cycles.

Vehicle simulation software

We estimated the energy consumption of diesel and battery electric buses using the Autonomie vehicle simulation tool.[5] Autonomie is a state-of-the-art, physics-based vehicle simulation tool developed by Argonne National Laboratory and has been used by university and industry research groups to assess the effects of vehicle technologies on efficiency and emissions. The tool allows the user to evaluate the powertrain and vehicle performance of both electric and conventional internal combustion vehicles, flexibly allowing for selection of different powertrain configurations, component models, and drive cycles.

The Autonomie architecture includes a vehicle propulsion controller that imitates the driver of the vehicle and exercises high-level control over the vehicle's shifting, propulsion, and braking based on the speed and power demands imposed by the drive cycle. The vehicle propulsion architecture (VPA), which represents the physical construct of the vehicle, includes the powertrain systems and their low-level controllers. The VPAs for diesel and battery electric buses are shown in Figure 1. Each block represents a specific component of the powertrain, and the connections between components depict energy transfer interactions between the simulated components. For example, the battery electric architecture consists of an energy storage system, electric machine and inverter, a single-speed transmission, a final drive, a DC-DC converter, and electric accessories.[6]

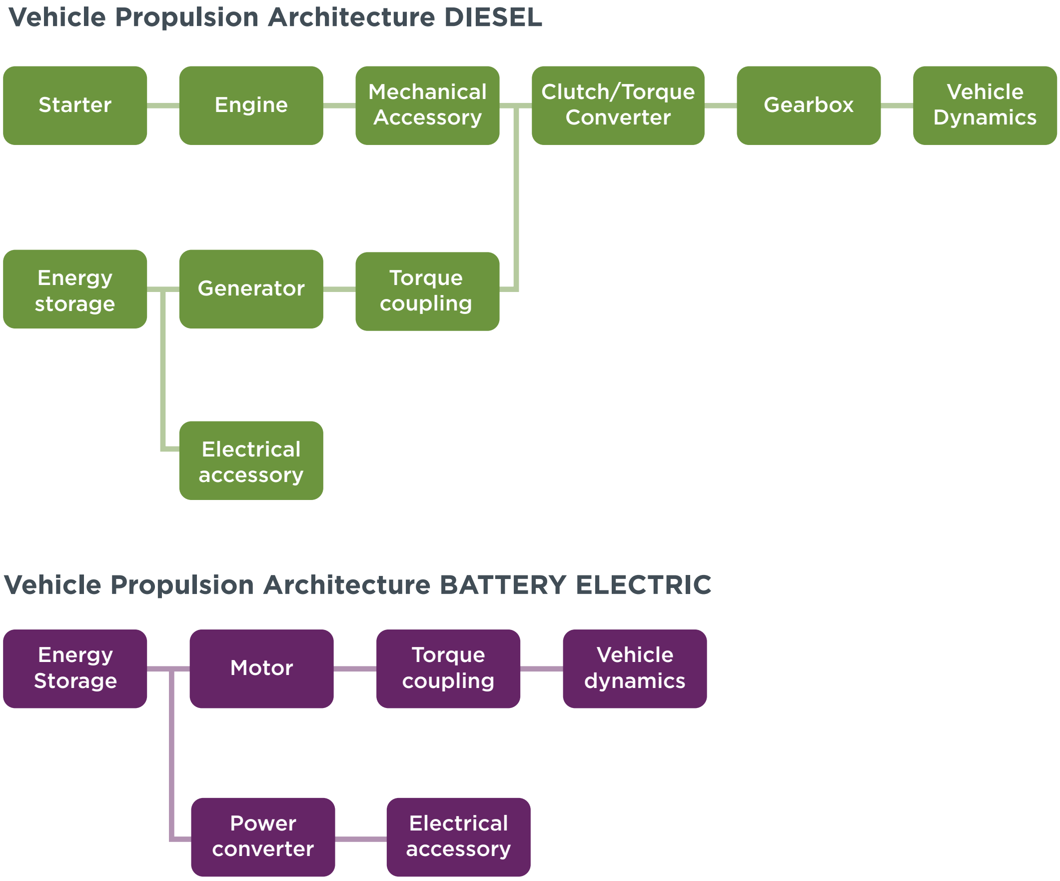

Figure 1. Vehicle propulsion architecture for diesel (top) and battery-electric (bottom) buses.

5 "Autonomie," Argonne National Laboratory, accessed January 15, 2021, https://www.autonomie.net.

6 For further details on the specific characteristics and applications of the Autonomie model, please refer to the publications listed here: https://www.autonomie.net.

Input data and modeling assumptions

We constructed a conventional, 12-m ICE transit bus configuration based on diesel-powered bus models currently operating in the BMTC fleet. A battery electric, depot-charging, 12-m transit bus configuration was constructed based on battery electric bus models available in the Indian market. We parameterized the Autonomie component models illustrated in Figure 1 to reflect the technical characteristics of the buses subject to analysis and used energy consumption maps to model the performance of ICE and electric motors over the entire range of operating conditions. The battery package was modeled based on an equivalent circuit consisting of a number of modules in parallel, with each module consisting of a number of battery cells in series. The single battery cell consists of a resistance-capacitance circuit. The model accounts for open-circuit voltage, internal resistance, and the impact of temperature in power rates and battery state of charge (SOC). The diesel bus model has a manual 6-speed transmission. A single gear transmission transfers power from the electric motor to the wheels in the electric bus model.[7] Table 1 shows a summary of major input parameters and key efficiency characteristics for the diesel and battery electric bus models.

We used a generic Autonomie driver model with a distance compensation feature capable of following speed profiles and made no structural changes.[8]

Table 1. Diesel and battery electric bus specifications.

Bus technical specification	Diesel bus	Battery electric bus
Length (m)	12	12
Curb weight (kg)	11,300	13,100
Gross vehicle weight (kg)	16,200	18,000
Frontal area (m^2)	8.4	8.4
Aerodynamic drag coefficient	0.65	0.65
Tire rolling resistance (N/N)	0.008	0.008
Wheel radius (m)	0.49	0.49
Engine / E-Motor peak power (kW)	243	300
Transmission gear ratios	8.17/4.65/2.79/1.81/1.25/1	Motor-to-axle ratio: 15.5
Rear axle ratio	6.17	
Mechanical accessory power (kW)	7	0
Electrical accessory power (kW)	1	8
Battery capacity (kWh)	N/A	322

Besides the technical specification of the bus models, other variables can have a significant impact on energy consumption. In particular, passenger load and use of air conditioning (AC) vary continuously during operation, depending on passenger demand and ambient temperature conditions. As these variables are stochastic in nature, we simplified the analysis by running simulations under the passenger load assumptions listed in Table 2 and the AC power consumption assumptions listed in Table 3. Our modeling simplified accessory load to a constant power demand over the test cycle. Note that we assumed that the power consumption of other vehicle accessories, such as interior and exterior lighting, coolant pump, steering, and braking, remain constant

7 Some electric bus models have a different powertrain architecture with no differential, in which the rear axle has two electric motors independently connected to the driven wheels with fixed-ratio single-speed gearboxes. Other potential architectures could feature a 2-speed transmission.

8 Vehicles with a higher power-to-weight ratio will better keep up with the speed-time trace of the simulated cycle and will cover more distance than less powerful vehicles. With distance compensation, the driver covers the same distance regardless of the vehicle configuration, allowing for proper comparison of energy consumption in units of kWh/km.

during operation. In order to compare the diesel and battery electric buses, we simulated both bus types using the same passenger load and accessory loads.

Table 2. Passenger load assumptions.

Condition	Number of passengers	Weight of passengers (kg)
Empty (0%)	0	0
Half capacity (50%)	40	2,450
Full capacity (100%)	80	4,900

Table 3. Air conditioning system power consumption assumptions.

Condition	Total accessory power consumption (kW)
AC off	4
AC on	8

Model calibration and validation

To ensure that the assumptions generated reasonable simulation results, we refined the models. We calibrated the diesel bus model based on fuel consumption values measured by BMTC. Since the electric buses have not yet been deployed in the city, we lacked in-use data to calibrate the model and instead based the electric bus model on electric energy consumption of similar battery electric buses deployed in Santiago, Chile, and in the United States.[9]

Accessory power demand

The accessories of a transit bus include heating, ventilation, and air conditioning systems (HVAC), cooling fans, air compressors, water pumps, and alternators, among others. The power demand of the accessories of urban buses will vary depending on environmental and operational conditions. For example, the frequency of bus stops will affect air compressor operation to open and close the doors; the route and traffic situation will affect power required for steering and braking systems; and weather conditions, such as temperature and relative humidity, will affect the operation of HVAC systems. Because accessory power demand varies based on bus route, time of the day, and season of the year, we made a simplifying assumption and modeled the energy consumption of the accessories as a single, constant power demand over the duration of the simulated routes. We performed a literature review of measured or modeled values for total accessory power demand for standard (around 12-m) transit buses. Table 4 summarizes our findings in units of power (kW) and/or distance-specific energy consumption (kWh/km).

9 Ministerio de Transportes y Telecomunicaciones, Gobierno de Chile, "Certificación Características Funcionales y Dimensionales Buses Transporte Público Urbano en Santiago. Consumo - Eficiencia Energética Buses Transporte Público Urbano Ciudad de Santiago - Resultados Buses Motor Eléctrico" (2020), https://www.mtt.gob.cl/archivos/5597.
"Bus Research and Testing Center," Penn State College of Engineering accessed January 15, 2021, http://altoonabustest.psu.edu/home.

Table 4. Literature review on urban bus accessory power demand.

Reference	Accessory power demand	Accessory energy consumption
Raab et al. (2019)[a]	—	0.14–0.29 kWh/km (cooling) 0.49–0.75 kWh/km (heating)
MIEM (2013)[b]	—	0.26 kWh/km
Gao et al. (2019)[c]	—	0.23 kWh/km
IEA (2018)[d]	—	0.2–0.4 kWh/km
Rothgang (2015)[e]	—	0.28 kWh/km
Gao et al. (2016)[f]	3.1–3.7 kW (no HVAC)	—
Miranda et al. (2017)[g]	7.1 kW	0.22 kWh/km
Gao et al. (2017)[h]	3.75 kW	—
Göhlich et al. (2014)[i]	6 kW	—
Kivekas et al. (2018)[j]	4 kW	—
Vepsäläinen et al. (2019)[k]	2–7kW	—
Khan and Clark (2010)[l]	7.5kW	—

[a] Andreas F. Raab et al., "Implementation Schemes for Electric Bus Fleets at Depots with Optimized Energy Procurements in Virtual Power Plant Operations," *World Electric Vehicle Journal* 10, no. 1(2019), https://doi.org/10.3390/wevj10010005.

[b] Ministerio de Industria, Energía y Minería (MIEM), "Informe: Pruebas de Campo Bus 100% Eléctrico. Montevideo, Uruguay" (2014), http://www.eficienciaenergetica.gub.uy/informes/-/asset_publisher/hJhvph6TjO1U/content/informe-pruebas-de-campo-100-electrico.

[c] Zhiming Gao et al., "Evaluation of Electric Vehicle Component Performance over Eco-Driving Cycles," *Energy* 172 (2019): 823–39, https://doi.org/10.1016/j.energy.2019.02.017.

[d] International Energy Agency, "Global EV Outlook 2018" (Paris: IEA, 2018), https://www.iea.org/reports/global-ev-outlook-2018.

[e] Susanne Rothgang et al., "Battery Design for Successful Electrification in Public Transport," *Energies* 8, no. 7 (2015): 6715–37, https://doi.org/10.3390/en8076715.

[f] Dawei Gao et al., "Development and Performance Analysis of a Hybrid Fuel Cell/Battery Bus with an Axle Integrated Electric Motor Drive System," *International Journal of Hydrogen Energy* 41, no. 2 (2016): 1161–69, https://doi.org/10.1016/j.ijhydene.2015.10.046.

[g] P.E.V. de Miranda et al., "Brazilian Hybrid Electric-Hydrogen Fuel Cell Bus: Improved On-Board Energy Management System," *International Journal of Hydrogen Energy* 42, no. 19 (2017): 13949–59, https://doi.org/10.1016/j.ijhydene.2016.12.155.

[h] Zhiming Gao et al., "Battery Capacity and Recharging Needs for Electric Buses in City Transit," *Energy* 122 (2017): 588–600, https://doi.org/10.1016/j.energy.2017.01.101.

[i] Dietmar Göhlich, Alexander Kunith, and Tu-Anh Ly, "Technology Assessment of an Electric Urban Bus System for Berlin," *WIT Transactions on The Built Environment,* 138 (2014): 137–149, https://www.witpress.com/elibrary/wit-transactions-on-the-built-environment/138/26132.

[j] Klaus Kivekas et al., "City Bus Powertrain Comparison: Driving Cycle Variation and Passenger Load Sensitivity Analysis," *Energies* 11, no. 7 (2018): 1755, https://doi.org/10.3390/en11071755.

[k] Jari Vepsäläinen et al., "Computationally Efficient Model for Energy Demand Prediction of Electric City Bus in Varying Operating Conditions," *Energy* 169 (2019): 433–43, https://doi.org/10.1016/j.energy.2018.12.064.

[l] ABM Siddiq Khan and Nigel Clark, "An Empirical Approach in Determining the Effect of Road Grade on Fuel Consumption from Transit Buses," *SAE International Journal of Commercial Vehicles* 3 (2010): 164–80, https://doi.org/10.4271/2010-01-1950.

We gave particular focus to the HVAC systems, which represent a significant share of the accessory power demand. In 2019, Vepsäläinen et al. estimated input HVAC power as a function of ambient temperature based on a 2016 study by Lajunen and Tammi.[10] We adapted these estimates and combined them with the results of our literature review to estimate total accessory power demand as a function of ambient temperature, as shown in Figure 2. This chart can be used to estimate seasonal variations of bus accessories' energy consumption in a given city, or to estimate energy consumption for cities with different average ambient temperatures. For example, given our focus on the city of Bangalore, we assume an average temperature of 25 °C that results in an average power demand of about 8 kW.[11]

10 Jari Vepsäläinen et al., "Computationally Efficient Model for Energy Demand Prediction of Electric City Bus in Varying Operating Conditions," *Energy* 169 (2019): 433–43, https://doi.org/10.1016/j.energy.2018.12.064.

11 See "Bengaluru Climate," Climate-Data.org, Accessed January 22, 2021, https://en.climate-data.org/asia/india/karnataka/bengaluru-4562/.

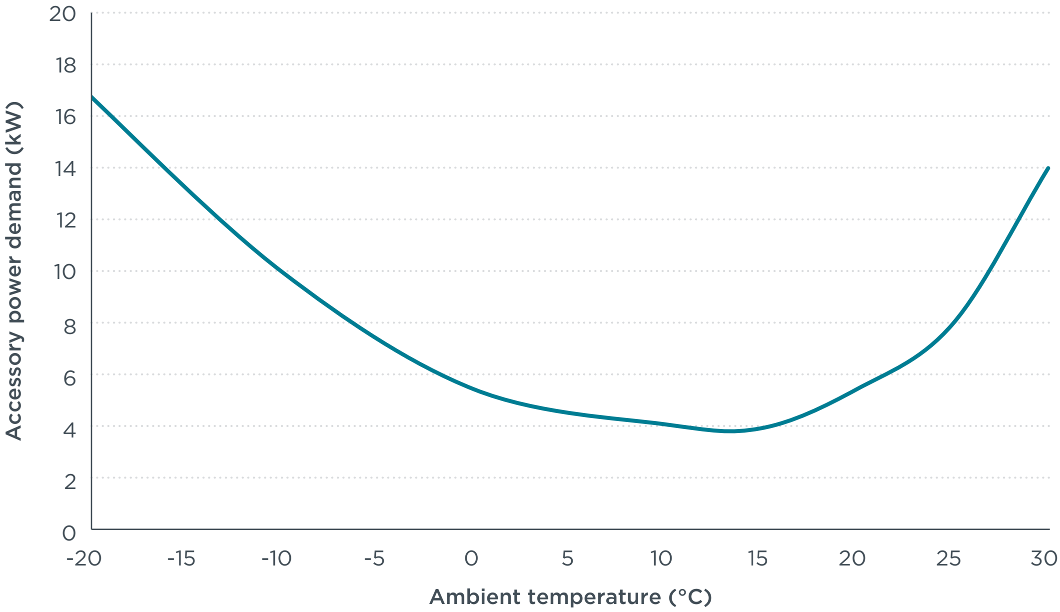

Figure 2. Accessory power consumption as a function of ambient temperature. Adapted from Klaus Kivekäs et al., "City Bus Powertrain Comparison: Driving Cycle Variation and Passenger Load Sensitivity Analysis," *Energies* 11, no. 7 (2018): 11, 1755, https://doi.org/10.3390/en11071755, and Antti Lajunen and Kari Tammi, "Energy Consumption and Carbon Dioxide Emission Analysis for Electric City Buses," in *International Electric Vehicle Symposium and Exhibition*, Montreal, Canada (2016): 1–12.

We conducted simulations to estimate the sensitivity of energy consumption to local ambient temperature. Figure 3 shows the percentage increase in distance-specific energy consumption (in units of kWh/km) as a function of temperature for two selected BMTC routes. Extreme temperatures can have a significant effect on energy consumption and vehicle range. Henning et al. evaluated the effects of changes in ambient temperature based on operational data that U.S. transit agencies have made available.[12] Figure 3 adds these results as a reference.

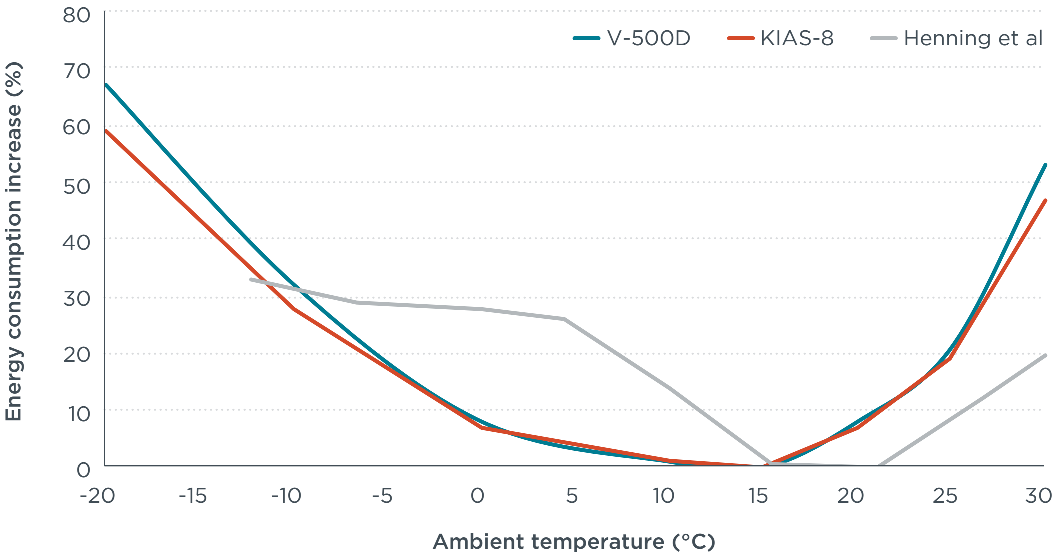

Figure 3. Energy consumption increase as a function of ambient temperature.

12 Mark Henning, Andrew R. Thomas, and Alison Smyth, "An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses," *Urban Publications* 0 1 2 3 1630 (2019), https://engagedscholarship.csuohio.edu/urban_facpub/1630.

Energy audits

Energy audits are an effective way to identify the sources of the energy efficiency advantages of electric buses over their ICE counterparts. We used vehicle simulation to calculate and disaggregate the energy distribution according to the various losses and loads.

Figure 4 shows the energy audit in distance-specific energy consumption units of kWh/km for both propulsion technologies running over the same test cycle, passenger load, and ambient temperature conditions.

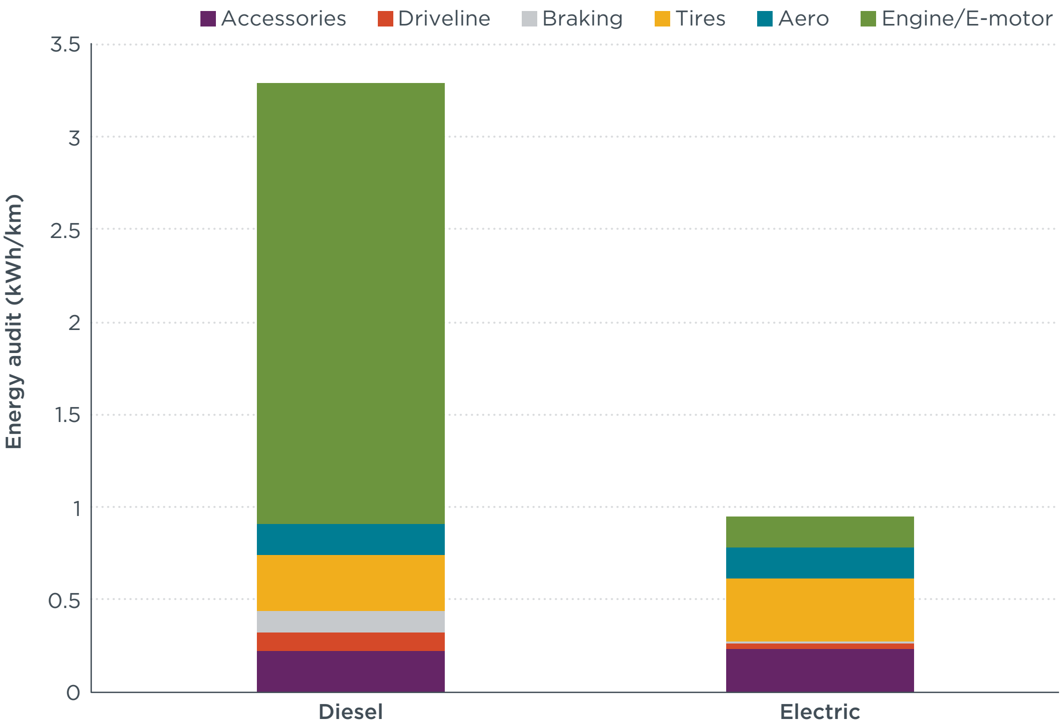

Figure 4. Energy audit in absolute units for diesel and electric buses over the World Harmonized Vehicle Cycle-India cycle with 50% passenger load and AC on.

In Figure 4, the height of the bars represents the total energy demand over the cycle. The electric bus consumes about 29% of the energy consumed by the diesel bus, which can be explained by examining the individual losses at the component level:

» Electric motors have significantly higher efficiency than ICEs. For the diesel bus, the engine comprises the largest share of energy losses at about 70% of the total energy used, while the electric system losses for the electric bus are about 20%.[13]

» Electric buses have kinetic energy recovery systems that allow them to recover a fraction of the braking losses. Braking losses are larger on vehicles driving with heavier payloads and those that typically travel in urban, stop-and-go driving patterns, so the efficiency advantage of electric buses would be greater under these conditions.

» The driveline losses include all moving parts that allow the transmission of power from the prime mover (engine/motor) to the wheels. Diesel engines' speed-torque characteristics require the use of multi-gear transmissions to keep the engine operating at the proper speed. Electric motors have a "flatter" torque-versus-speed characteristic that allows for a simplified driveline and lower driveline energy losses.

13 For a detailed energy audit of diesel engines, see Arvind Thiruvengadam et al., *Heavy-Duty Vehicle Diesel Engine Efficiency Evaluation and Energy Audit* Morgantown: West Virginia University, 2014), https://theicct.org/sites/default/files/publications/HDV_engine-efficiency-eval_WVU-rpt_oct2014.pdf.

» Rolling resistance losses are about 10% higher for the electric bus, which carries the additional weight of batteries and therefore suffers an energy penalty compared to diesel buses.

» Aerodynamic drag losses are about the same for the diesel and electric buses, as we assumed the same aerodynamic shape for both technologies, and aerodynamic losses are independent of the mass of the vehicle.

» The accessory losses are similar because the same accessory power demand assumption was made for both technologies. However, we note that the availability of high-voltage electric power onboard the electric bus enables the use of all-electric vehicle accessories. These accessories offer opportunities to reduce energy use when compared to accessories that are mechanically connected to the engine in a diesel bus. For example, while electric accessories can operate only when needed, engine-driven mechanical accessories impose a continuous parasitic demand. Also, because electric accessories have more flexible speed control, they can run at speeds independent of the engine speed. This optimizes energy consumption.

Figure 5 shows the same energy audit as Figure 4 but in relative (%) units to identify areas of technology improvement. For example, for the diesel bus, engine efficiency technologies would prove key to reducing fuel consumption. The second largest energy use comes from the tires, so using low rolling-resistance tires would enhance efficiency. For the electric bus, tire losses and accessory power demand are the largest components of the audit. Low rolling-resistance tires and high-efficiency accessories, including HVAC, would improve performance. Vehicle lightweighting would increase the efficiency of both technologies.

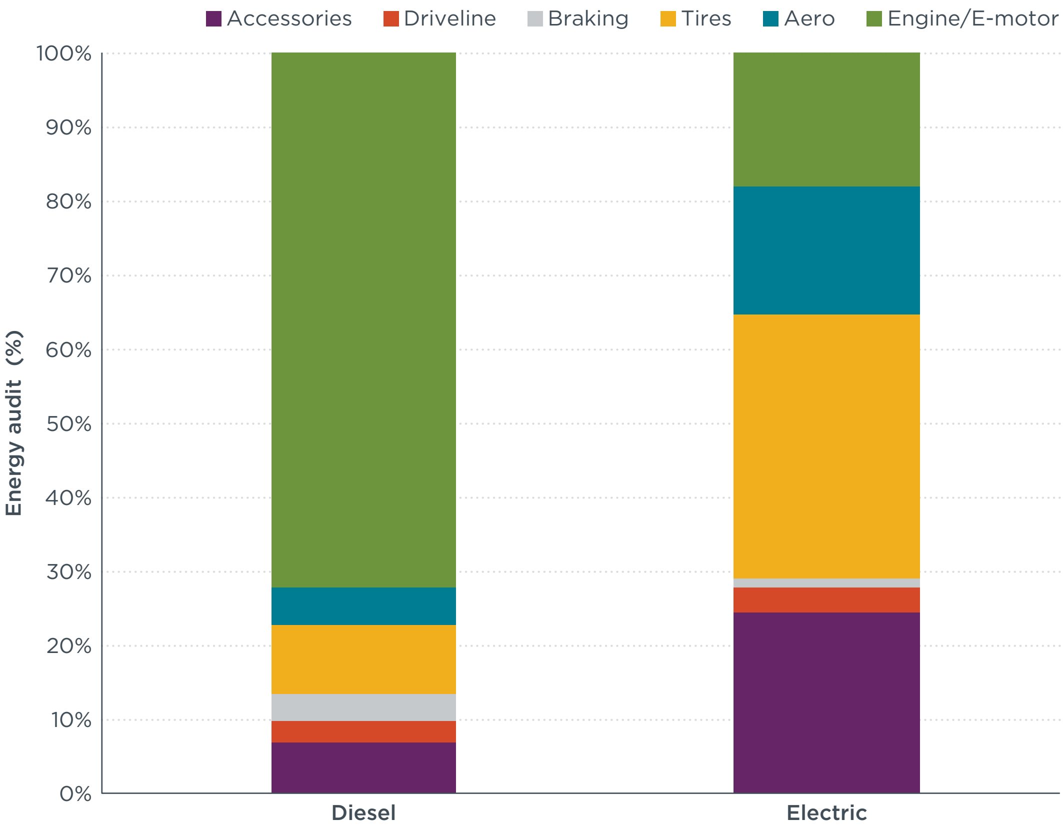

Figure 5. Energy audit (relative) for diesel and electric buses over the World Harmonized Vehicle Cycle-India cycle, with 50% passenger load and AC on.

Model limitations

Simulation results might differ from real-world or experimental data due to a number of simplifying assumptions. For example, the generic models we use for both electric motor and battery might deviate from actual components. Similarly, control algorithms are generic, not specific. External conditions such as ambient humidity, temperature, and pressure are static in the modeling and thus not identical to what is experienced in real-world operation. Many factors affect the range of a bus, including temperature, passenger load, weight of bus, driver habits, HVAC usage, and topography. We do not account for real-world energy losses associated with changing rolling resistance coefficients due to road surface changes or tires not operating at correct pressures, or wind effects, including the influence of headwind yaw angle on drag.

BMTC route selection and drive cycle development

BMTC's plan for 2030 envisions the completion of a transition to a 100% electric bus fleet by that year and procurement of only electric buses from 2023 onward.[14] It also targets the deployment of 1,500 electric buses by 2023. Despite the rapidly reducing cost differential between electric and ICE-powered buses, electric buses have not yet reached TCO parity with ICE buses in India. Therefore, BMTC adopted a phase-wise approach for electric bus induction, where the initial deployment would focus on routes that offer TCO closest to diesel buses. This section gives an overview of the process for screening routes to prioritize initial electric bus deployments and the development of representative drive cycles for selected routes.

The Government of India selected BMTC to receive a subsidy for procurement of 300 electric buses under its Faster Adoption and Manufacturing of Electric (and hybrid) vehicles (FAME) scheme. This selection created an opportunity to support BMTC in identifying the initial set of routes for electric buses.

We applied the vehicle simulation approach described above using detailed drive cycles developed for BMTC to support route selection for electric buses under a gross cost contract (GCC) model of procurement. We used energy simulation modeling to check that electric buses can deliver diesel-equivalent performance along routes prioritized by BMTC and to specify for these routes the number of electric buses and the charging strategy required to match existing diesel bus performance.

The key operational aspects impacting electric bus implementation can broadly be categorized into depot, route, and schedule characteristics, and these have multiple sub-components, as listed in Table 5. As of January 2021, BMTC owned 6,574 diesel buses (5,715 non-AC and 859 AC buses). The number of buses operating on a given day are colloquially referred to as the number of schedules for the day: A normal weekday for BMTC would have schedules for 6,161 buses (5,423 non-AC and 738 AC buses), and the rest of the buses would either be under scheduled maintenance or resting at depots to be used as spares in case of breakdowns. These buses are served by 43 depots; six of these serve AC buses, and the rest are earmarked for non-AC buses. The city has a total of 2,263 routes, and 101 of these provide AC bus services.

BMTC stopped its operations between March and May 2020 due to the COVID-19 pandemic-induced hard lockdown and subsequently incrementally resumed operations in line with increasing travel demand. By January 2021, economic activity had resumed significantly, and BMTC was operating 5,268 daily schedules—86% of its pre-COVID-19

14 Chiranjeevi Kulkarni, "BMTC Plans to Buy 11k Electric, BS VI Buses in 5 yrs," *Deccan Herald*, December 12, 2019, https://www.deccanherald.com/city/bengaluru-infrastructure/bmtc-plans-to-buy-11k-electric-bs-vi-buses-in-5-yrs-784779.html.

peak. BMTC is expected to reach 100% of pre-pandemic operations toward the end of 2021 or early 2022.

Working with BMTC, we developed a deployment strategy for 400 AC and 400 non-AC buses to improve the preparedness of BMTC to procure both types of services. We performed the analysis using pre-pandemic operations data to be relevant for the peak service volume and travel demand that BMTC serves.

Table 5. Key operational aspects and sub-components influencing the assessment of routes for initial electric bus deployments.

Depot choice	Route and schedule choice
• Space constraints for parking, charging, and maintaining buses • Availability of power infrastructure • Feasibility of (re)development of the depot for electric bus needs	• Number of buses per route • Vehicle utilization (daily kilometers operated) of buses on the route • Speed profile • Passenger demand profile • Revenue potential • Daily hours of operation • Match of vehicle schedules with charging and crew schedules

We evaluated the following aspects while prioritizing them for electric bus deployment:

» **Current operational practices:** BMTC owns and operates its services in-house. Therefore, it has traditionally managed operations with depots as the primary unit and treated routes and schedules as subsets to the depot of operation. Even if some routes have buses scheduled from multiple depots, the buses' parent depots perform the operations and maintenance management. This practice is in contrast to other international examples (e.g., London and Singapore), where the public transport authorities plan for routes and outsource their operations to external operators, who are also in charge of depot development and management.

» **Space constraints and life of infrastructure:** In urban bus operations, depots are typically a more significant constraint than routes and schedules because of the limited land available for public transport and the challenges associated with establishing the necessary electricity and charging infrastructure for buses in high-density Indian cities with limited electric mobility penetration. Additionally, the charging and power infrastructure that needs to be set up for electric buses typically lasts up to 30 years. Hence depots, which have set long-term charging needs, are preferred over routes and schedules that are typically more flexible and can be allocated between depots. Furthermore, route layouts are typically modified over time according to evolving travel needs and infrastructure developments in a given city.

Since BMTC owns the depots and has traditionally treated them as a key unit of operations, we adopted a depot-first approach to develop a deployment strategy for electric buses. We then considered route and schedule selection.

Approach for selection of depots and routes for electric buses

We selected the initial set of depots, routes, and schedules for electric bus deployment using a combination of quantitative and qualitative indicators. Figure 6 presents an outline of our process for selecting depots and routes. We made vehicle technology selections, including for length of bus, typical daily range of operation in kilometers, and AC, before operational planning decisions because these aspects must be specified in the tender documents and have long-term implications on the service delivered and

TCO. The depots and routes we selected for these vehicle types are based on the key variables listed in Figure 6.

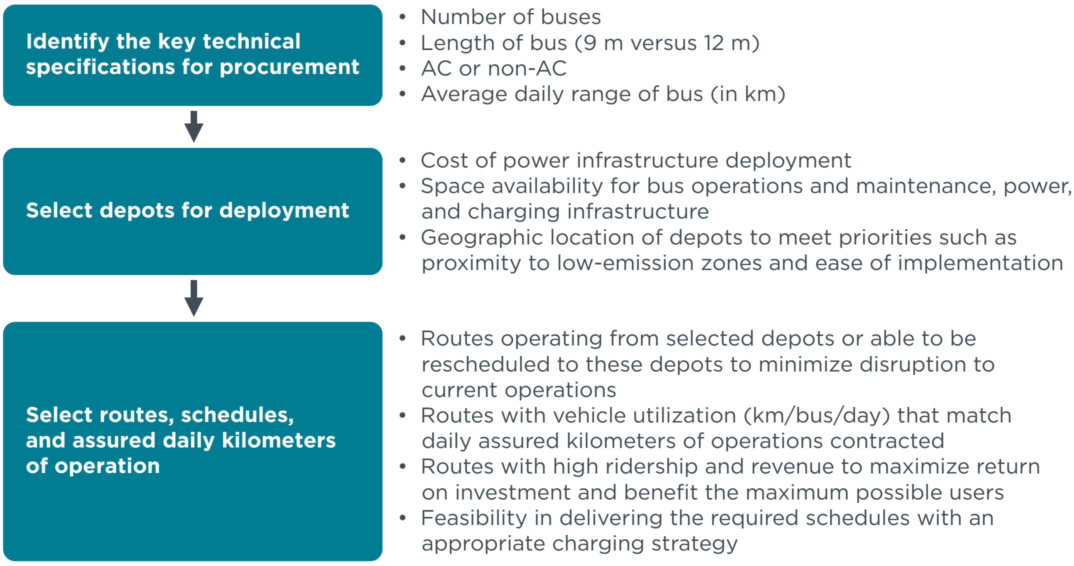

Figure 6. Key stages and criteria to identify electric bus deployment specifications.

Depot selection

All depots were scored on a scale of 1 to 5 for each of the three criteria listed in Figure 6. We determined the scores for cost of power infrastructure and space availability on a relative scale based on available quantitative data, while the scores for geographic location were determined through qualitative assessment provided by the operations, engineering, and planning departments of BMTC. We assigned the scores on cost of power infrastructure such that the depot with the least cost received a score of 5, and the depot with the highest cost was assigned a score of 1; the rest were assigned ratings of 2, 3, and 4 based on their relative cost compared to the highest and lowest cost depots. In the case of space availability, we assigned depots with the maximum space a 5, those with the least space a 1, and the rest based on their own relative space availability.

We determined the qualitative assessment of the geographic location based on the strategic significance of the depot (i.e., its proximity to the city center and whether it serves routes along key corridors of the city), the difficulty in relocating existing diesel buses to other depots, and infrastructure readiness. We assigned these scores based on the perceived ratings for different depots offered by different heads of the departments of BMTC. A total of 13 depots scored 12 or more out of the maximum possible score of 15. Figure 7 presents the locations of all BMTC depots on the Bangalore map and their relative scores. Each depot is labeled with its depot number in the figure, and the size of each circle indicate the depot scores, as provided in the legend.

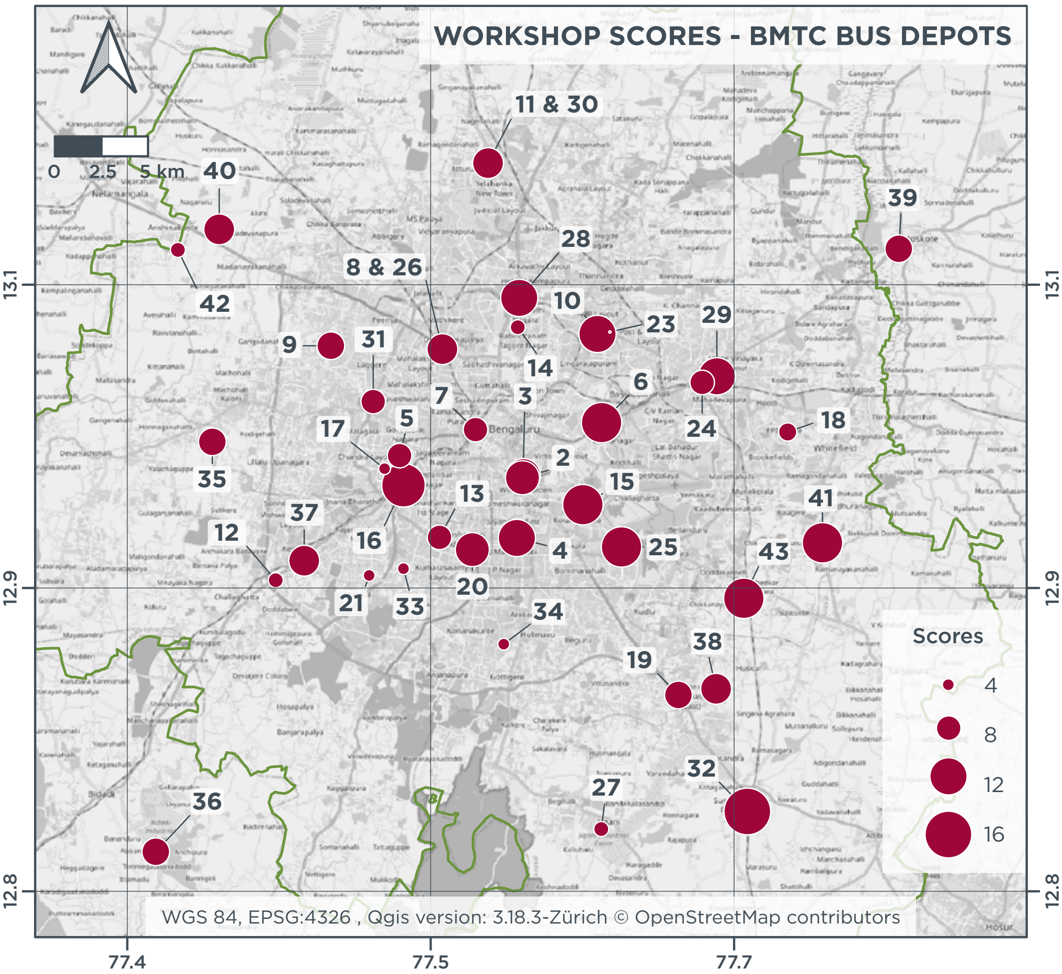

Figure 7. Locations of BMTC depots and their relative suitability for electric bus deployment.

BMTC currently has six depots exclusively operating AC buses; the rest operate non-AC buses. While the depots can be used interchangeably for both AC and non-AC management, the analysis considered depots with both types of buses because the rationales for currently using these depots for AC/non-AC diesel buses, such as minimizing dead-mileage for the routes in each service type, would also hold true for electric buses. We performed a selection process for both AC and non-AC buses to help BMTC identify the preferred depots according to the service type they choose. We further analyzed the four AC and four non-AC depots with the highest scores and assumed a per-depot capacity of 100 buses to receive 400 AC and 400 non-AC buses.

Route and schedule selection

We analyzed the schedules of all the routes currently operating out of the eight selected depots to identify the routes offering the best conditions for deployment of electric buses, as outlined in Figure 6. All schedules with at least 180 km of daily vehicle utilization were selected to match the expected daily vehicle range and contractual payment constraints that come with the gross cost contract (GCC) mode of procurement preferred by BMTC. Manufacturers of vehicle models currently available in the market report to deliver this range with one overnight charge or through a combination of overnight charge and one intermittent charge during the day, which can be accommodated into the current BMTC schedules.

Under the GCC mode of procurement, BMTC faces the challenge of providing an assured daily kilometer of payment for the next decade, even as its fleet-wide average daily vehicle utilization has dropped from 225 km per day to 200 km per day over the past decade. Hence, we selected 180 km as a reasonable assured kilometer of service to be contracted, and we selected routes that can deliver an aggregated range more than this over the next decade for electric bus deployment. However, we observed that some of the buses operating on the selected routes meeting this operational requirement currently originate from depots not shortlisted for electric bus deployment. The recommendation is therefore that these routes be served from depots selected for electric buses and that the remaining routes be served by diesel buses from other depots. Such an arrangement would allow for the operation of 400 AC and 400 non-AC bus schedules every day for the selected depots and the assured kilometer of 180 per day. Figures 8–10 present the key corridors of the city served by the three categories of routes selected for deployment:

» **Airport (suburban) AC routes,** presented in Figure 8, currently have a daily utilization of more than 300 km per bus per day due to the suburban nature of operations and because the airport is located to the north of Bangalore.

» **Urban AC routes** presented in Figure 9 originate from the selected depot and have a vehicle utilization of 150–225 km per bus per day such that their fleetwide average is still higher than 180 km.

» **Urban non-AC routes** from the selected four depots can deliver the committed daily range of 180 km and are presented in Figure 10.

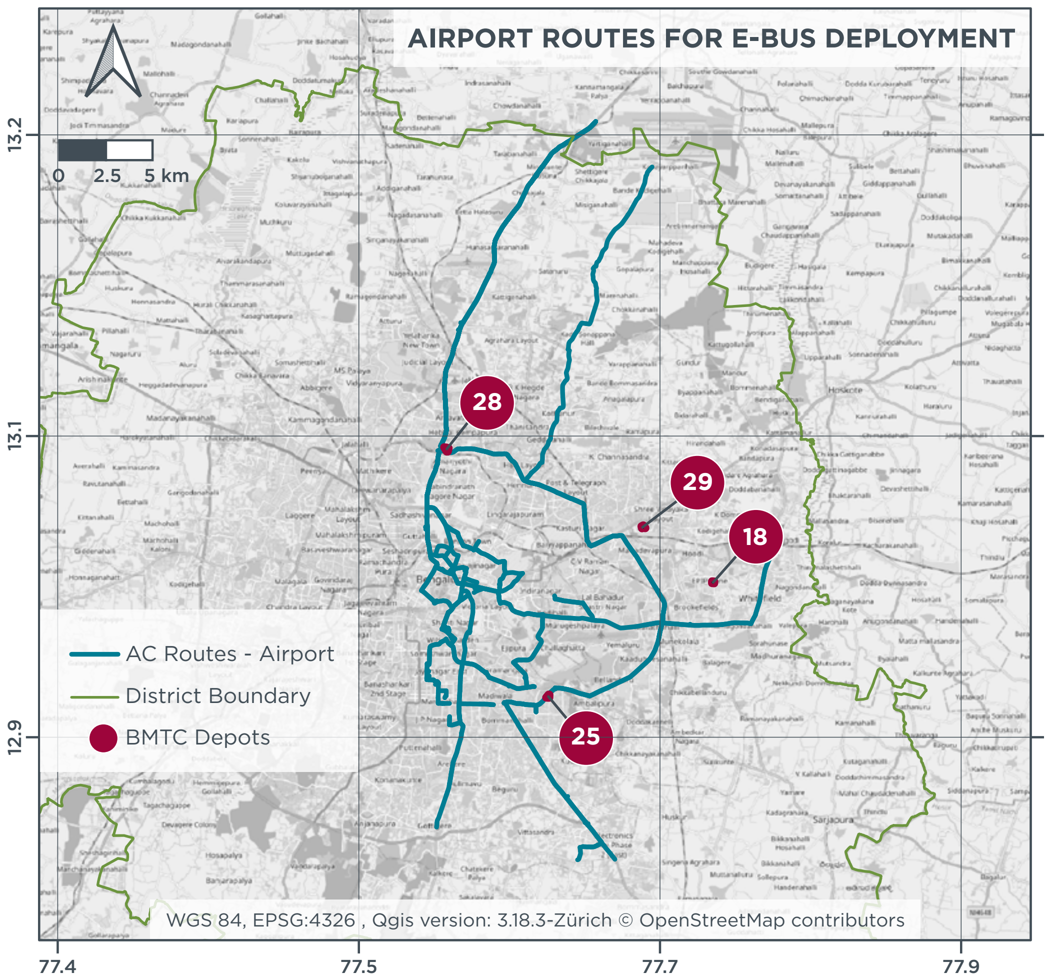

Figure 8. BMTC airport AC routes under consideration for initial electric bus deployments.

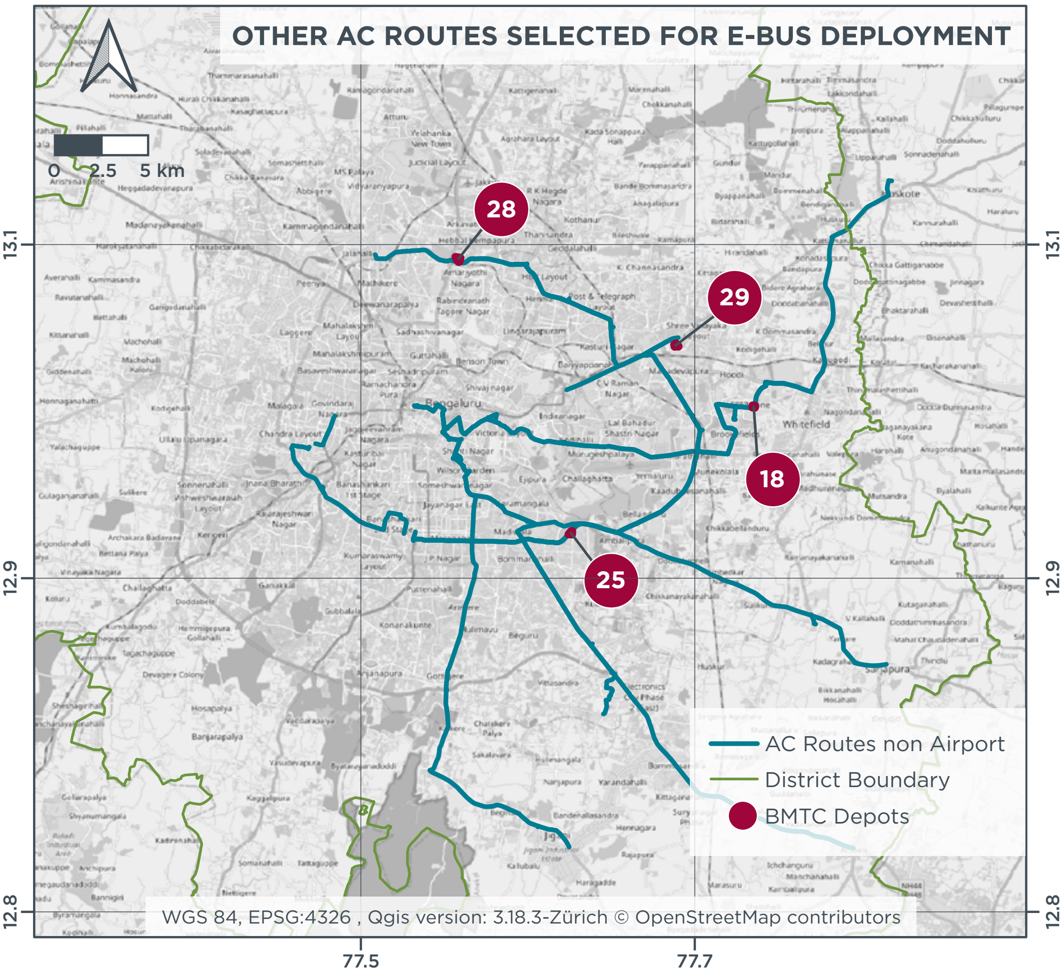

Figure 9. BMTC urban AC routes under consideration for initial electric bus deployments.

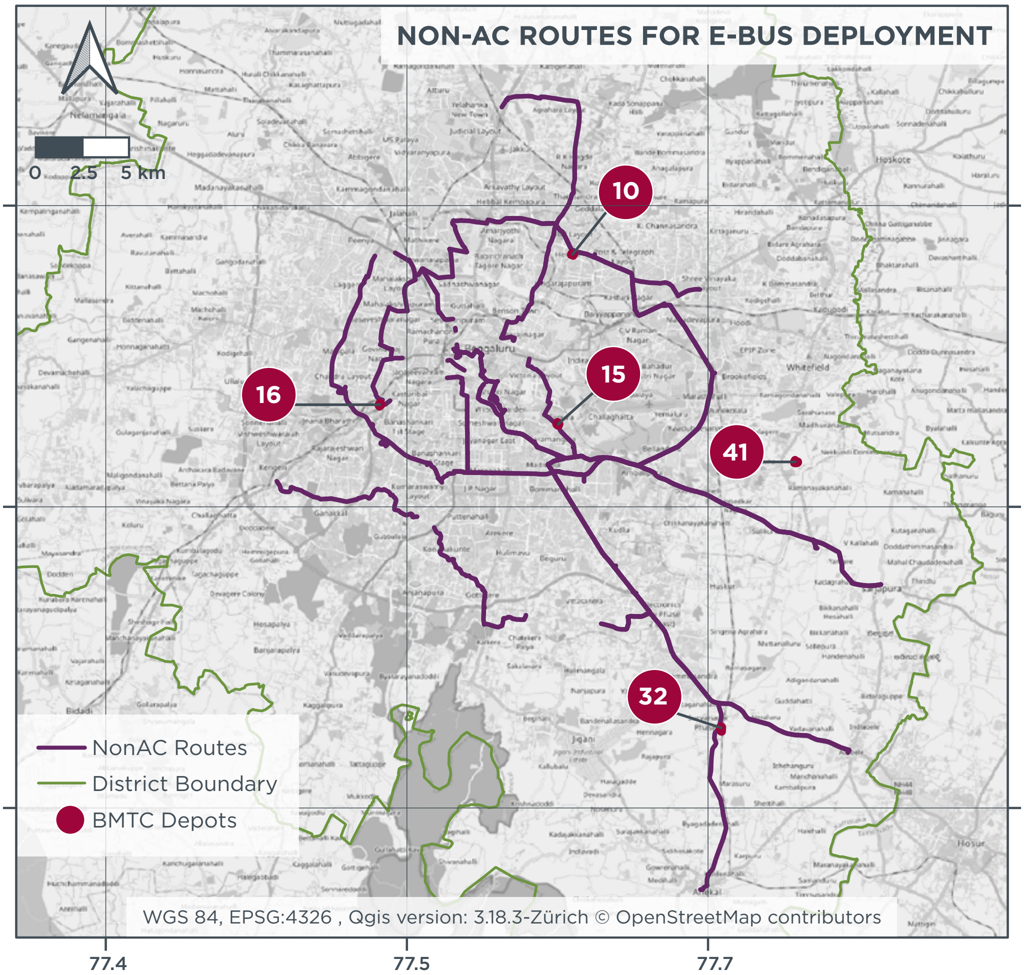

Figure 10. BMTC non-AC routes under consideration for initial electric bus deployments.

Drive cycle development

For our initial assessments, we focused on detailed route-level analysis of 29 of the routes identified in the initial screening described above. These routes were selected from the airport AC and urban AC routes identified for initial allocations of electric buses shown in Figures 8 and 9. Characteristics of these routes are summarized in Table 6 (see Table A1 for the complete list of routes selected for this analysis). These routes cover the majority of key corridors served by BMTC and are also served by non-AC buses, which makes the drive cycle development exercise representative of the overall BMTC network.

Table 6. Summary of characteristics of routes selected for initial electric bus deployments.

Route type	Route length (km)	# buses	Trips/ day	Utilization (km/day/ bus)	Average speed (km/h)	Stops/km	Idle time (%)
Urban AC	30 (25–49)	12 (4–78)	91 (31–632)	188 (175–227)	32.5 (12.6–43.3)	0.56 (0.34–1.52)	25 (15–37)
Airport AC	55 (35–74)	6 (4–18)	47 (28–137)	381 (299–407)	28.4 (14.7–40.6)	0.47 (0.28–1.10)	24 (14–32)

Note: For each characteristic, the median value for each route type is presented, followed by the range in parentheses.

For each of these routes, we collected and analyzed real-world operational data using methods presented in a previous publication, in order to develop representative drive cycles for use in vehicle simulations.[15] A summary of the approach to drive cycle development is presented in Figure 11.

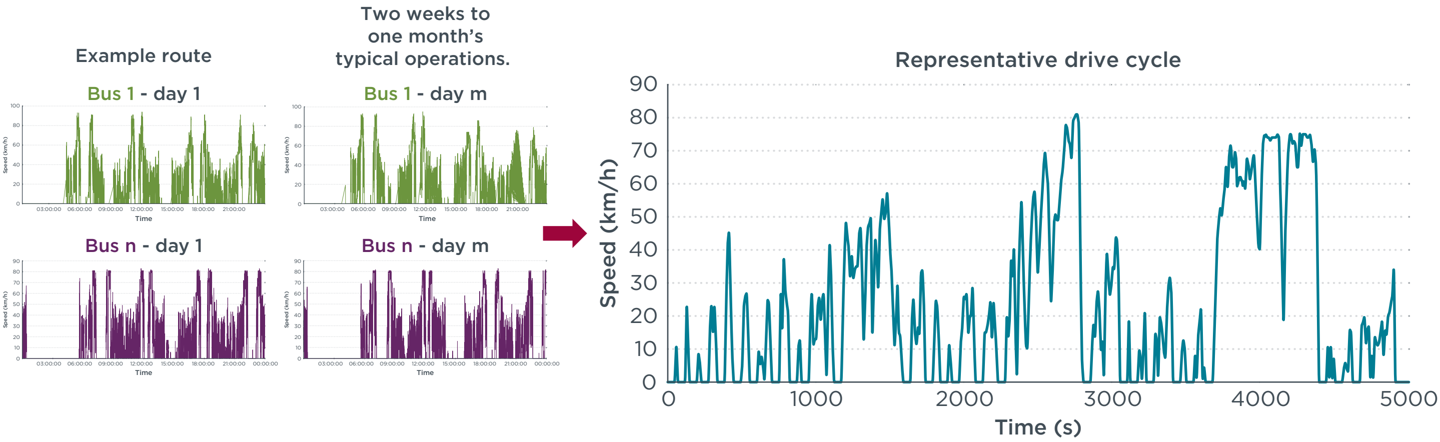

Figure 11. Illustration of a drive cycle developed for a route from real-world operational data.

BMTC route-level energy consumption modeling results

We applied the vehicle simulation approach using detailed drive cycles developed for 29 individual BMTC routes to estimate the energy consumption of electric buses operating on these routes under a variety of assumed operating conditions. This analysis provides information about the expected performance of a representative electric bus and thus offers insight to further refine BMTC's strategy for initial electric bus deployments. Our aim was to estimate the energy consumption and range of an electric bus on each route; compare the results to the diesel fleet operating today; and examine the impacts of parameters, such as passenger load and accessory power consumption. Furthermore, we explored how simulations of these types can support electric bus implementation through optimization of technology selection and charging strategy development.

For each of the 29 routes considered here, we performed nine separate simulations, for a total of 261 individual model runs. Table 7 summarizes the modeling scenarios. The following sections detail the results of these simulations and their implications for electric bus deployments in the BMTC system.

Table 7. Modeling scenarios for vehicle simulations.

Vehicle technology	Accessory power consumption (kW)	Passenger load
12-m diesel bus – AC	8	0%, 50%, 100%
12-m electric bus – non-AC	4	0%, 50%, 100%
12-m electric bus – AC	8	0%, 50%, 100%

Comparing electric and diesel bus energy consumption

Energy consumption results for all modeling scenarios are presented in Figure 12. For each box plot, whiskers indicate the minimum and maximum energy consumption across the 29 routes for each set of modeling conditions. The top and bottom of each box indicate 75th and 25th percentile values, respectively, and median values are shown with a horizontal line (see Tables A2–A4 for more detailed energy consumption modeling results).

15 Lingzhi Jin et al., *Strategies for Deploying Zero-Emission Bus Fleets.*

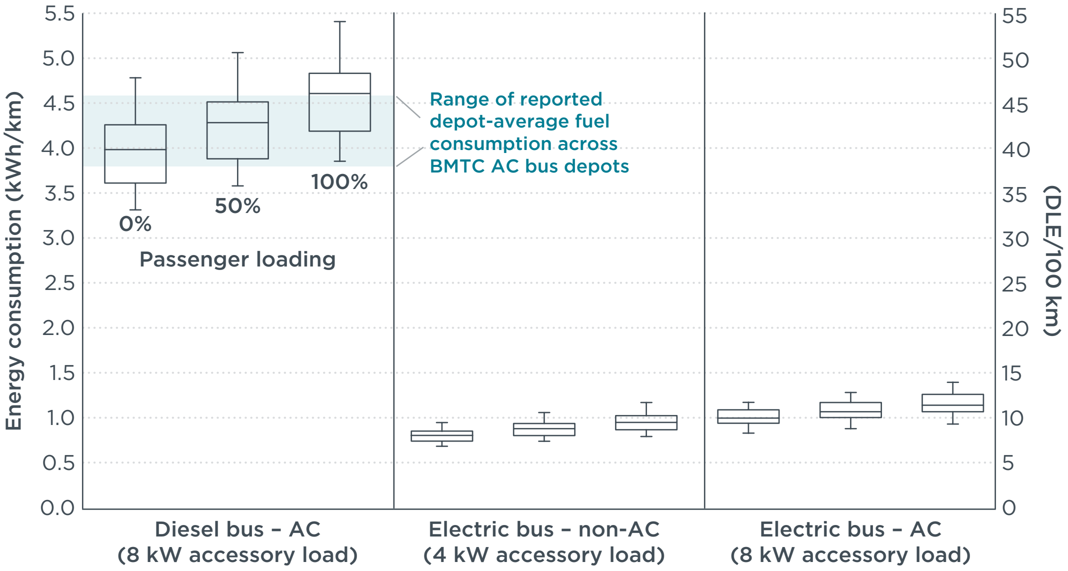

Figure 12. Energy consumption estimates for all modeling scenarios. The right axis shows fuel consumption in terms of the energy equivalent of a liter of diesel fuel, referred to as diesel liter equivalent (DLE).

For diesel buses, the median energy consumption ranged from 40.0–46.3 diesel liter equivalent (DLE)/100 km (3.98–4.61 kWh/km) depending on passenger load assumptions.[16] For each passenger load condition, the variation in the maximum and minimum diesel energy consumption across the 29 routes was about 15 DLE/100 km (1.5 kWh/km). This variation is attributable to the differences in physical characteristics of the routes and driving conditions, as captured in individual route driving cycles.

The variation in energy consumption across routes exceeds the variation attributable to passenger load. Relative to the 0% load condition, energy consumption increased by 2.1–3.6 DLE/100 km (0.21–0.36 kWh/km) for the 50% load condition and 5.0–7.2 DLE/100 km (0.50–0.72 kWh/km) for the 100% load condition; these are average increases of 7% and 15%, respectively. We note that simulated energy consumption of diesel buses increases approximately linearly with vehicle weight, which means that these results could be used to interpolate energy consumption for other passenger load conditions.

On average, estimates of energy consumption for diesel buses simulated on airport route drive cycles were lower than estimates for buses on urban route drive cycles. The average energy consumption estimated for airport routes was approximately 15% lower than that of urban routes across the different passenger load conditions.

Results presented in Figure 12 show the significant efficiency benefits of battery electric buses relative to the baseline diesel AC bus operating in the BMTC system. The median energy consumption for the electric bus ranged from 0.80–1.14 kWh/km across the different passenger load and accessory power consumption conditions. Across all model runs, the maximum estimated energy consumption was 1.39 kWh/km, and the minimum was 0.68 kWh/km. For similar accessory power consumption and passenger load conditions, energy consumption for battery electric buses was on average 25% of the energy consumption of diesel buses. The reduced energy demand of battery electric buses was fairly consistent across the 29 routes, ranging from 23%–28% of the energy consumption of diesel buses.

16 For diesel buses, DLE/km fuel consumption results were converted to kWh/km units using the lower heating value of 9.95 kWh/L.

The electric bus energy consumption values estimated for the 29 BMTC routes are generally comparable to real-world energy consumption data reported for initial testing and deployments of similar battery electric bus technologies. The International Council on Clean Transportation previously evaluated energy consumption data collected during test track evaluations of 12-m electric bus models from three manufacturers at the Altoona Bus Research and Testing Center.[17] In the Altoona test program, buses are tested over three drive cycles, respectively representative of suburban/commuter, medium-speed urban, low-speed urban driving conditions. The average energy consumption for the tested electric buses ranged from 0.9–1.4 kWh/km across the different drive cycles. Similarly, a recent review of the performance of low-carbon buses in 16 Chinese cities reported an average energy consumption for 12-m electric buses of 1.14 kWh/km over a 1-year monitoring period.[18] Finally, preliminary data is becoming available for initial electric bus deployments in Indian cities. Energy consumption data for 12-m electric buses reported by Kolkata (0.94 kWh/km), Hyderabad (0.98 kWh/km), and Pune (1.09 kWh/km) are consistent with our simulation results for BMTC routes.[19]

Effect of passenger load on electric bus energy consumption

Figure 13 shows the effects of passenger load assumptions on estimated energy consumption for battery electric buses. Box plots show results across the three different passenger load conditions. Results for airport and urban routes are presented separately. The top panel of the figure translates energy consumption results to driving range estimates. The range estimates show how far a bus operating on each route can travel on a single charge, assuming a 258-kWh usable battery capacity (i.e., 20% reserve state of charge [SOC]).

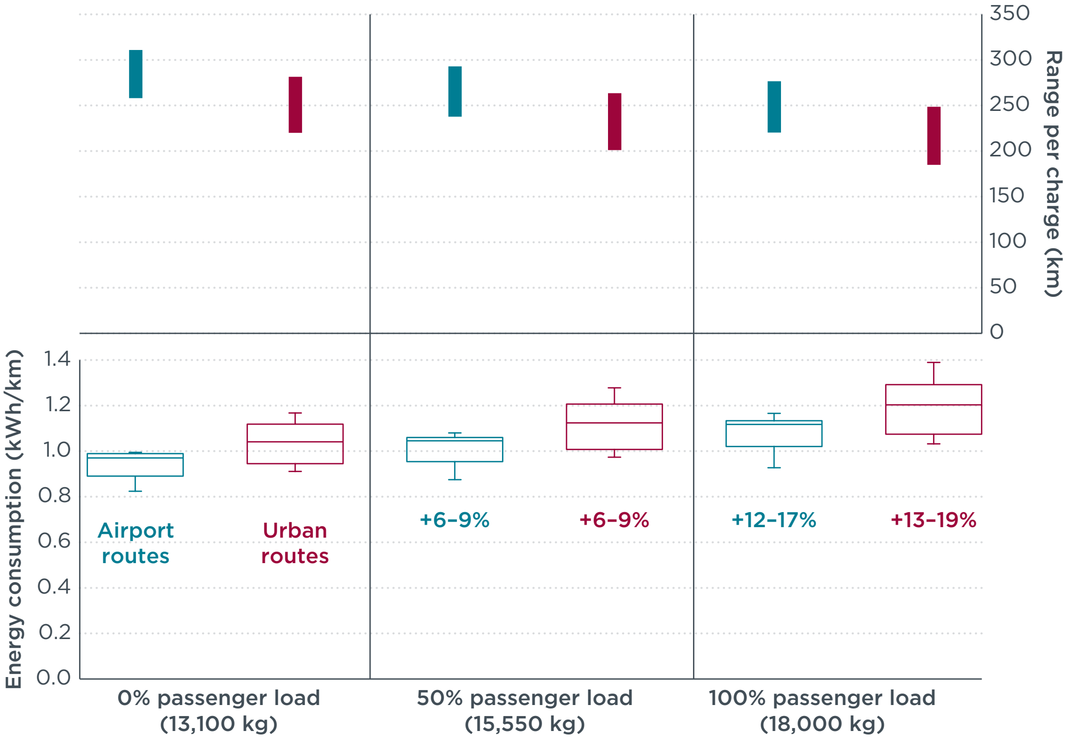

Figure 13. Impacts of passenger load assumptions on energy consumption and electric bus range estimates. An 8-kW accessory power consumption is assumed (i.e., AC on). Range calculations assume a 322-kWh battery capacity and a 20% reserve SOC (i.e., 258-kWh usable capacity). Percentages indicate change in energy consumption estimates relative to the 0% load scenarios.

17 Tim Dallmann, Li Du, and Ray Minjares, *Low-Carbon Technology Pathways for Soot-Free Urban Bus Fleets in 20 Megacities* (ICCT: Washington, DC, 2017), https://theicct.org/publications/low-carbon-technology-pathways-soot-free-urban-bus-fleets-20-megacities.

18 Asian Development Bank, "Sustainable Transport Solutions: Low-Carbon Buses in the People's Republic of China" (2018), https://www.adb.org/publications/sustainable-transport-solutions-peoples-republic-china.

19 Data collected by project team in consultation with local operators.

The results shown in Figure 13 demonstrate that passenger load can have a considerable impact on electric bus energy consumption and range. Simulations indicate a 6%–9% increase in energy consumption for the 50% condition relative to the 0% condition for both airport and urban routes. For the 100% passenger load condition, energy consumption is estimated to increase by 12%–17% (airport routes) and 13%–19% (urban routes) relative to the 0% condition. As was the case with the diesel bus simulations, electric bus energy consumption increases approximately linearly with simulated vehicle weight, allowing for interpolation-based estimates of energy consumption for other assumed passenger load conditions. Over the three passenger load conditions, energy consumption estimates for buses modeled over urban route cycles were on average higher than estimates for buses modeled on airport route cycles (0.94–1.09 kWh/km for airport routes vs. 1.04–1.20 kWh/km for urban routes).

The estimated driving range per charge is inversely proportional to energy consumption. For example, routes with more demanding driving conditions and high passenger load and accessory power consumption have higher estimated energy consumption values and faster battery charge depletion, which lead to lower range estimates. Less demanding routes and operating conditions, meanwhile, yield lower energy consumption estimates and thus greater range per charge. For the set of simulations considered here, range per charge varied from 201–293 km for 50% passenger load conditions and from 185–277 km for 100% passenger load model runs. On average, the range for electric buses operating on airport routes is approximately 10% greater than the range estimated for buses on urban routes.

Effect of AC power consumption on electric bus energy consumption

Figure 14 shows how accessory power consumption assumptions affect the estimated energy consumption of battery electric buses operating on BMTC routes. Box plots show results for the two different accessory power consumption levels investigated in our simulations—4 kW and 8 kW. The 8-kW accessory load represents the extra power demand due to operation of the AC system, assuming an ambient temperature of about 25 °C. Results for airport and urban routes are presented separately. The top panel of the figure translates energy consumption results into range per charge estimates, assuming a 258-kWh usable battery capacity (20% reserve SOC).

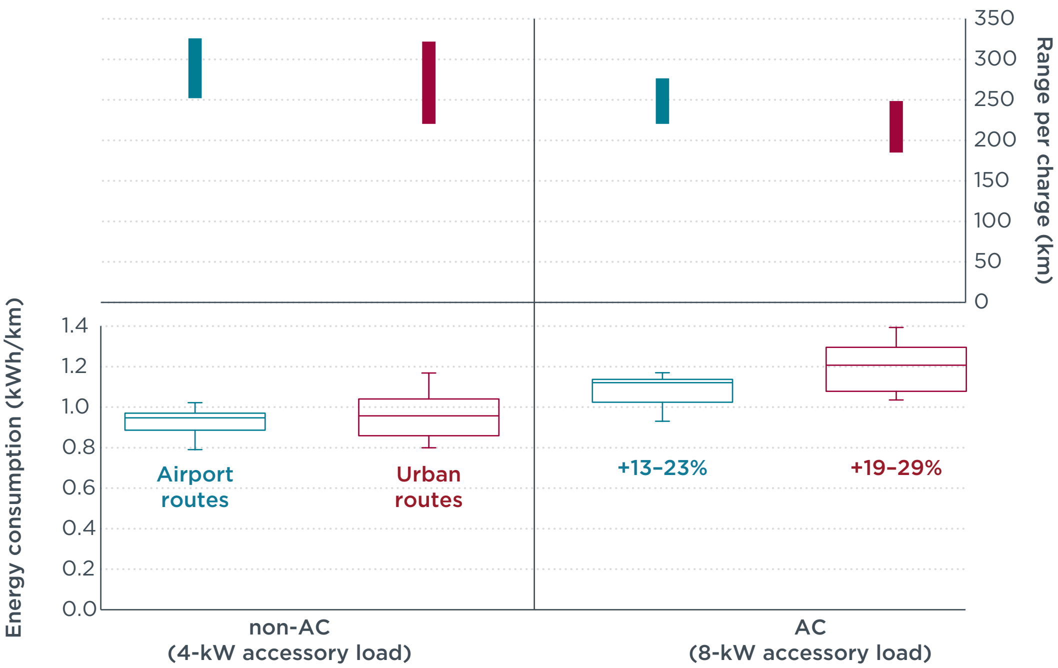

Figure 14. Impacts of accessory load on energy consumption and electric bus range estimates. 100% passenger load conditions are assumed. Range calculations assume a 322-kWh battery capacity and a 20% reserve SOC (i.e., 258-kWh usable capacity). Percentages indicate the change in median energy consumption estimates relative to the 4-kW accessory load scenario.

As discussed earlier, the extra power load associated with running AC systems can have significant impacts on energy consumption and range. Results presented in Figure 14 show an increase in energy consumption of 13%–23% for airport routes and 19%–29% for urban routes when a 8-kW AC load is assumed. This increase translates into a reduction in driving range of 31–53 km for electric buses on airport routes and 35–73 km for buses on urban routes when AC systems are in use.

Electric bus driving range assessment

In addition to the variables covered above, additional variables can impact range, including the degradation of the battery over time and the extent to which the battery is allowed to be depleted during normal operations. Considering these variables using the route-level modeling approach presented in this paper can help operators optimize the selection of electric bus technologies and charging strategies for individual routes.[20] Such planning can help reduce the risk of disruptions to service delivery with electric bus transitions by ensuring that the selected battery capacity and charging schedule are sufficient to meet the requirements of a given route or service schedule. Furthermore, capital and operating costs of electric bus deployments can be minimized by optimizing technology selection for the characteristics of a given route.

In this section, we give examples of how route-level energy consumption simulation results, when combined with operational data, can be used to help operators evaluate the suitability of electric bus technology options. We use a 12-m, 322-kWh, depot-charging electric bus as an example. Similar analysis can be extended to cover alternative electric bus options, provided that route-level energy consumption modeling results are available.

20 Other parameters such as driving style can also impact electric bus range but are more difficult to capture in the modeling framework presented in this paper. Future work should aim to incorporate these parameters into the route-level modeling approach.

Driving range is one of the most important design parameters to consider when choosing between electric bus technology options. Operators should be confident that an electric bus will be able to deliver sufficient range to cover existing service schedules under the range of expected climatic and driving conditions and throughout the useful lifetimes of the bus and battery. A conservative approach to electric bus planning would focus on the minimum projected driving range. The ability of a fleet of electric buses operating along a given route to meet operational performance requirements in the most challenging conditions, would be a good indication that the electric fleet can replace an existing fleet of diesel or natural gas buses on a 1:1 basis.

Figure 15 gives an example of how route-level energy consumption simulation results can be used to evaluate the impacts of different parameters on electric bus driving range for two representative routes in the BMTC system. The KIAS-8 route, shown in blue, services the Kempegowda International Airport and had the lowest modeled electric bus energy consumption of the 29 routes considered in the analysis. The V-500D route, shown in red, is an urban route and has the highest modeled energy consumption. These two routes therefore represent the two extremes of driving range estimates for the 29 BMTC routes.

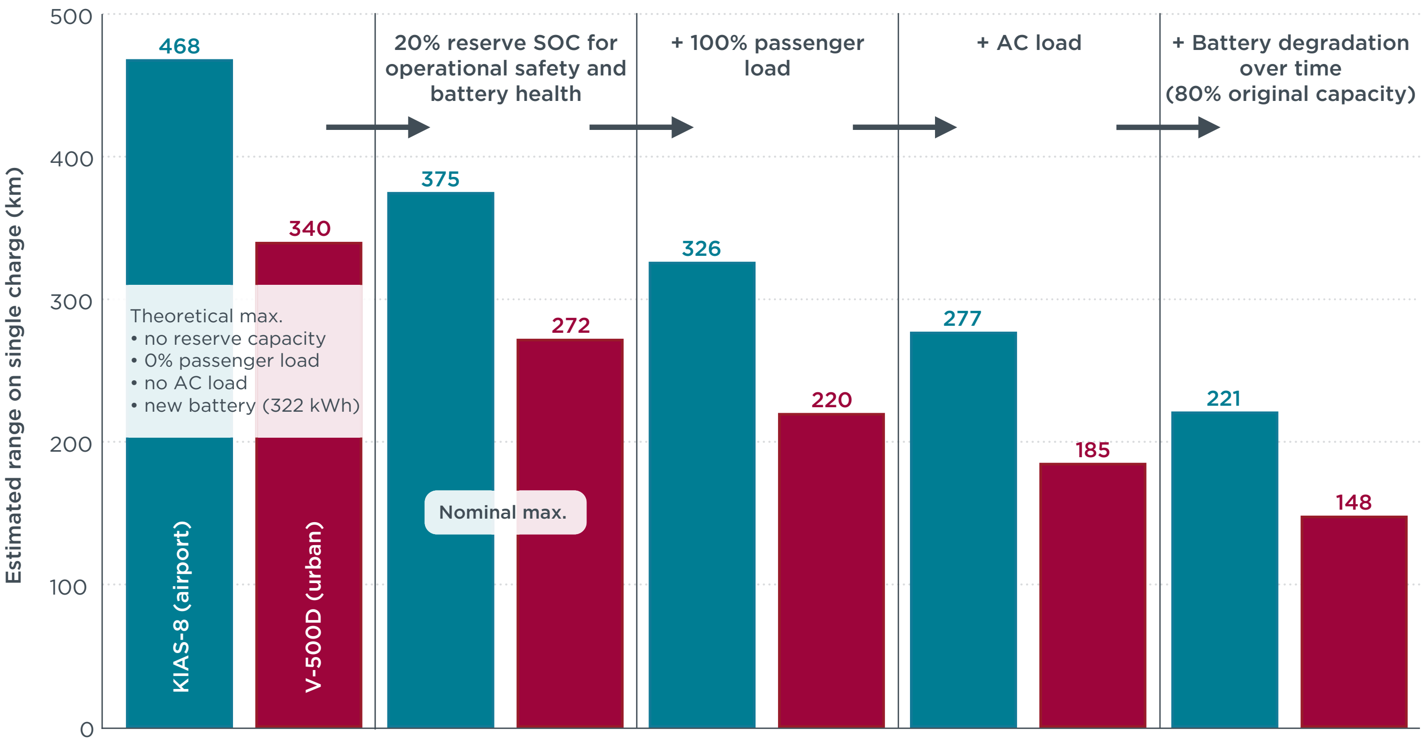

Figure 15. Impacts of key variables on estimated driving range for electric buses operating on selected BMTC routes.

The leftmost bars of Figure 15 show the theoretical maximum driving range estimates for electric buses operating on each route. For this case, we assume an empty bus with no AC accessory power load and a full battery capacity of 322 kWh. The range per charge is thus 468 km for the KIAS-8 route and 340 km for the V-500D route. The difference in driving range between the two routes reflects the impacts of drive cycle on energy consumption.

In real-world electric bus operations, the entire amount of energy stored in the battery is not available for use. Some reserve capacity should be maintained to account for any deviations from expected operations and to ensure drivers can safely return buses to charging locations. Furthermore, manufacturers recommend against depleting batteries completely and suggest that operators maintain a minimum reserve battery SOC of typically 10%–20% of the battery's nameplate capacity.[21] The second bar shows how a conservative assumption of a 20% reserve SOC impacts range estimates for the two routes. Even before considering other variables, this assumption reduces the nominal maximum range on each route by 20%.

We described above how passenger load and AC use can impact driving range. Here, under the most challenging operational conditions of 100% passenger load and 8-kW accessory power load, nominal maximum range is reduced from 375 km to 277 km for buses on the KIAS-8 route and from 272 km to 185 km for buses operating on the V-500D route. For this example, we have focused on the impacts of AC power load. For applications of these tools in regions with colder climates, the impacts of heating systems should also be considered.

Finally, the usable battery capacity diminishes over time as batteries degrade. To maintain performance levels, battery packs can be replaced. In this example we assume that the maximum degradation in capacity before a battery would be replaced is 20%, i.e., an aged battery will have 80% of the capacity of a new battery pack. The rightmost bars of Figure 15 show what can be considered the worst-case estimates of electric bus driving range for the two routes with an aged battery under challenging operating conditions and with a conservative reserve SOC assumption. Under these conditions, we estimate a range of 221 km for the airport route and 148 km for the urban route.

Importantly, in most applications, electric buses operating on these routes would be expected to have a greater driving range than what is shown in the most conservative scenario. However, considering the worst-case scenario as the design range will help operators select the best technology for a given route.

The next step in this assessment is to compare modeled electric bus driving range with the daily operations for each BMTC route. Figure 16 shows how the current average daily utilization (average kilometers traveled per bus per day) for buses servicing each of the 29 routes compares to range estimates for battery electric buses. Battery electric bus range estimates are shown for new (filled circles) and aged (hollow circles) battery conditions and reflect 100% passenger load conditions with an 8-kW accessory power load.

21 Dustin Grace, "Understanding Range: Clarity behind the Calculations," *Proterra*, September 20, 2018, https://www.proterra.com/understanding-range-clarity-behind-the-calculations/. Dana Lowell, "Electric Bus 101: Economics, Politics, Myths & Facts," M. J. Bradley & Associates, May 2019, https://www.mjbradley.com/sites/default/files/EVIElectricBus101FINAL15may19.pdf.

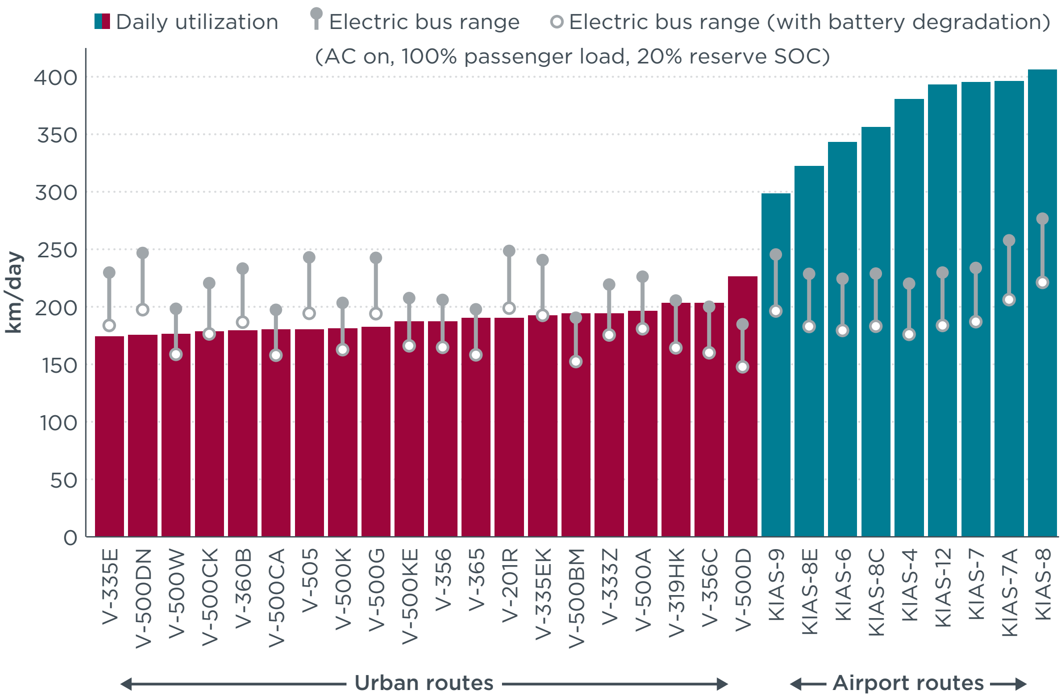

Figure 16. Estimated range under new and aged battery conditions by route compared to average route-level daily utilization of the existing diesel fleet.

In general, the routes can be divided into three groups, depending on the relationship between electric bus range and daily utilization and whether this relationship changes as batteries degrade over time. The first group includes those routes where electric bus range on a single, full charge exceeds daily utilization under all scenarios. For these routes, the electric bus should be able to provide diesel-equivalent performance throughout its entire useful life. Six of the routes considered here meet these criteria, and all are among the routes with the lowest estimated electric bus energy consumption.

The second group consists of routes where electric bus range exceeds daily utilization for new battery conditions, but where battery degradation leads to range estimates that fall below daily utilization at the end of the battery's useful life. Eleven of the routes fall into this category. New electric buses servicing these routes should be able to provide diesel-equivalent performance, but the findings indicate that these buses should be monitored over time to ensure that battery degradation does not lead to range deficiencies. For most of these routes, the range estimates under the aged battery conditions fall short of current utilization levels by less than 30 km, indicating that minor operational changes may be sufficient to offset the impacts of range degradation.

For the remaining 12 routes, electric bus range on a single charge is less than current utilization levels under all scenarios. The majority of these are airport routes, where daily service schedules are longer and buses travel between 300 km and 400 km on average per day. This level of utilization exceeds estimated electric driving range on a single charge in all cases and means that the modeled electric bus, when paired with an overnight depot charging strategy, would not be sufficient to replace the existing service provided by diesel buses. The comparison shows that alternative electric bus technologies, such as extended range options with larger battery capacities, or more frequent charging throughout the day (e.g., opportunity charging), may be better suited for airport routes and longer urban routes.

The example shown in Figure 16 assumes that each electric bus is charged at the depot overnight and completes its daily service schedule without further charging during the day. However, for many BMTC routes, schedules are set such that there might be opportunities to accommodate an additional midday charging period for electric buses.

Midday charging, even if only for a short period, would effectively extend the daily range of an electric bus and in some cases may make the electric bus options viable for selected routes.

The impacts of allowing for a short midday charging period are explored in Figure 17, which shows a comparison of route daily utilization and estimated electric bus range similar to those presented in Figure 16. In Figure 17, electric bus range estimates reflect an additional midday charging period, which adds 50 kWh of energy to the battery.[22] For urban routes, incorporating midday charging into service schedules reduces uncertainty related to the effects of battery degradation. With the additional range provided by the assumed midday charging period, estimated electric bus range exceeds daily utilization for nearly all urban routes, even when assuming 20% battery degradation. For airport routes, this level of midday charging is not sufficient to provide adequate driving range to cover existing service schedules. More detailed assessment of schedules for these routes would be needed to determine whether additional periods could be used to extend the amount of time available for charging throughout the day.

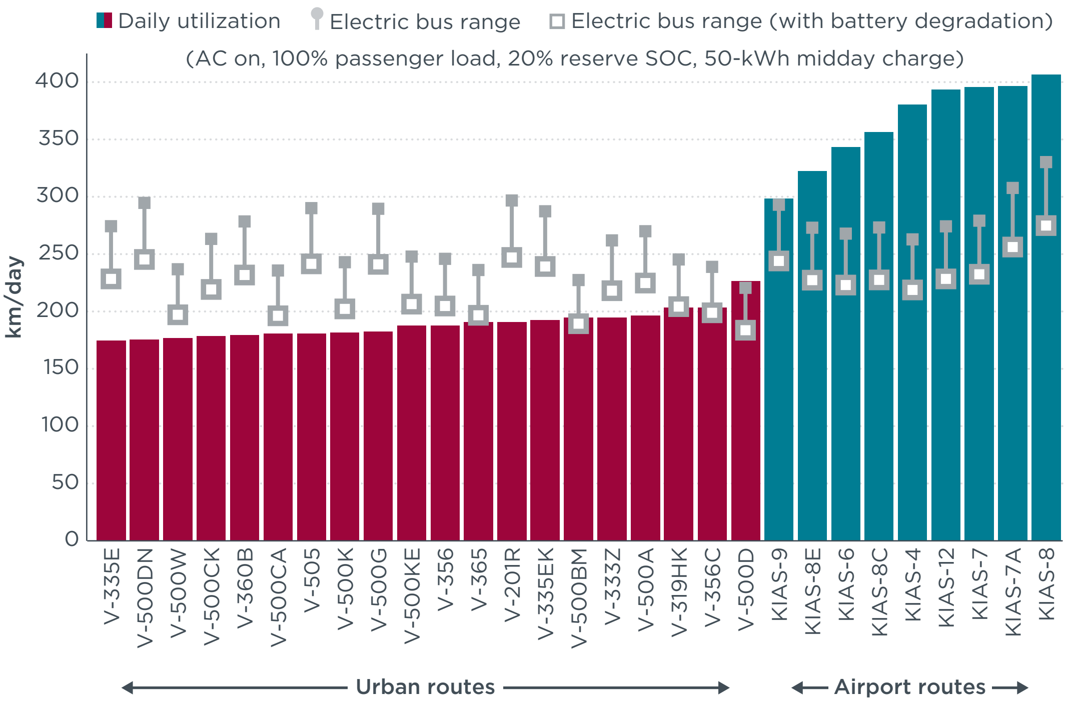

Figure 17. Estimated range under new and aged battery conditions by route with midday charging, compared with average route-level daily utilization of the existing diesel fleet.

Table 8 summarizes the findings of the comparison of electric bus driving range with current daily utilization levels for each route. It shows the number of routes which fall into each of the categories identified above under the different charging scenarios.

Table 8. Number of BMTC routes grouped based on estimated range and utilization.

Route category	Overnight charging only	Overnight + midday charging
Electric bus range > daily utilization	6	17
Electric bus range > daily utilization (new battery) **Electric bus range < daily utilization (aged battery)**	11	2
Electric bus range < daily utilization	12	10

22 This equates to approximately 35–45 minutes of charging using an 80-kW charger.

Replacement ratio

Having shown how electric bus driving range estimates from energy consumption modeling can be compared against operational data, here we combine these parameters into a single value we refer to as the replacement ratio This metric can be used as a design parameter for electric bus planning and to inform evaluations of technology options.

The replacement ratio estimates the number of electric buses needed to maintain existing service levels and indicates the likelihood that the existing fleet servicing a given route can be replaced on a 1:1 basis with a selected electric bus technology. It is calculated as the current daily utilization (in kilometers traveled per day) for a bus operating on a given route, divided by the estimated daily range of an electric bus. Replacement ratios can be grouped into three categories:

» Replacement ratio > 1: Daily utilization exceeds driving range. Additional electric buses beyond current fleet levels would likely be needed to maintain scheduled service. Alternative technology options and charging strategies that can deliver a 1:1 replacement should be considered.

» Replacement ratio ~1: Electric bus driving range is comparable to daily utilization. The existing fleet can be replaced with electric buses on a 1:1 basis.

» Replacement ratio < 1: Electric bus driving range exceeds daily utilization. This means that while the route can be electrified on a 1:1 basis, cost savings could likely be realized by optimizing technology selection, such as by considering buses with lower battery capacity.

Figure 18 shows the estimates of the replacement ratio for a 322-kWh, depot-charging electric bus operating on each of the 29 BMTC routes. For each route, we present a range in replacement ratio. The upper end of the range represents the replacement ratio when only overnight depot-charging is used. The lower end of the range reflects an operational strategy which accommodates an additional 50-kWh midday charging period. In both cases, we calculate results assuming the most conservative modeling conditions with respect to passenger load, accessory power consumption, battery degradation, and reserve SOC assumptions.

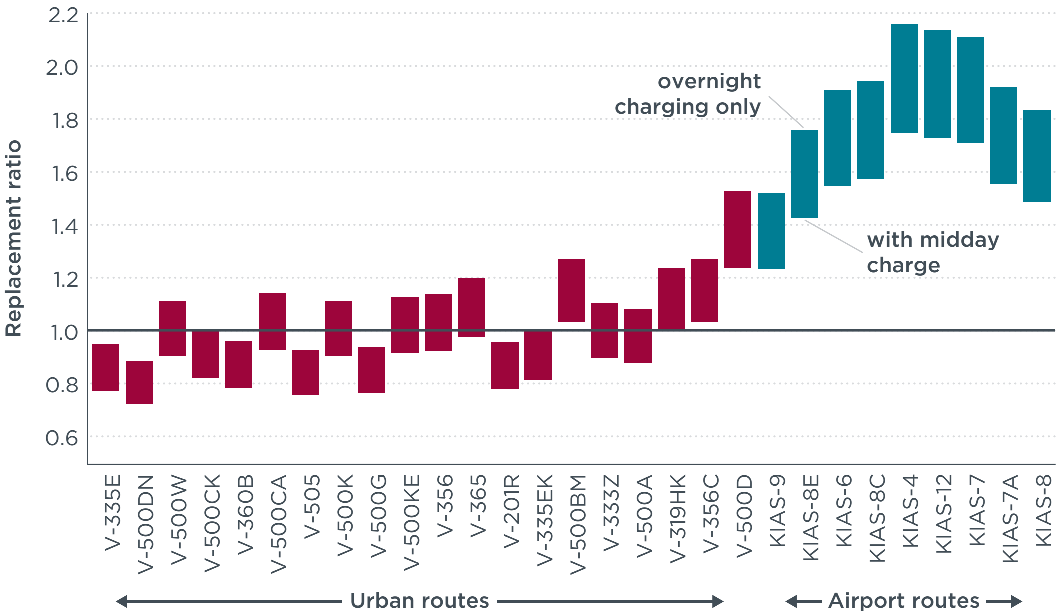

Figure 18. Electric bus replacement ratio estimates for 29 BMTC routes.

Replacement ratio results reiterate the finding presented above that the modeled electric bus technology appears to be well-suited for urban routes, especially if a short midday charging period is incorporated into service schedules. For these conditions, replacement ratios are less than 1 for 17 out of 20 urban routes. For the remaining three routes, replacement ratios are slightly greater than 1, indicating the selected technology could likely support 1:1 replacement of the existing fleet with minor operational changes, such as a slightly longer midday charging period.

The replacement ratios estimated for airport routes are greater than 1 in all cases, and additional electric buses would likely be needed to maintain service levels. The higher replacement ratios for these routes indicate that larger batteries, alternative zero-emission electric bus technologies (i.e., hydrogen fuel cells), or longer allocations of time for charging throughout the day should be considered. In cases where replacement ratios are greater than 1, a TCO assessment can be applied to inform decision-making on route electrification. For example, the relative cost of alternative electric bus technology options capable of delivering a 1:1 diesel replacement ratio (e.g., range-extended buses) can be compared against the cost of purchasing additional buses.

Conclusions and recommendations for future work

This paper presented a methodology for performing route-level energy consumption and performance modeling for electric buses using vehicle simulation software. The methodology was applied to estimate the energy consumption and driving range of a 12-m, 322-kWh, depot-charging electric bus model for 29 BMTC routes under consideration for initial deployments of electric buses. The modeling approach was used to investigate the influence of several parameters, such as passenger load and accessory power consumption, on energy consumption and driving range. Results for each route were compared against operational data to evaluate the suitability of the modeled electric bus option for 1:1 replacement of the existing diesel fleet on each route.

Energy consumption modeling results demonstrated the significant efficiency benefits of electric buses compared to similar diesel options. Energy audits performed using the standardized World Harmonized Vehicle Cycle-India drive cycle showed that an electric bus uses 29% of the energy of a comparable diesel bus. The efficiency benefits came primarily from the use of electric motors instead of ICEs and through kinetic energy recovery systems which recover braking losses. Simulations performed using representative drive cycles for individual BMTC routes indicated efficiency benefits for electric buses that surpassed those shown in the energy audits: For the 29 routes, electric buses were estimated to use between 23% and 28% of the energy per kilometer of a similarly sized diesel bus.

Our simulations for the selected BMTC routes indicated that energy consumption can increase by between 12% and 19% for a full bus relative to an empty bus. With an assumed AC load of 4 kW, energy consumption for an electric bus was estimated to increase by 13%–29%. In both cases, the increased energy consumption in the more demanding operating conditions reduced the driving range of the electric bus. Other parameters related to the operationally defined reserve SOC and battery degradation over time also served to limit the driving range of electric buses and should be considered when evaluating electric bus technology options and charging strategies.

Comparisons of the estimated electric bus driving range with current BMTC diesel bus operations found that the modeled electric bus technology delivered sufficient range to match or exceed daily kilometers traveled on most urban routes. Allowing for a short midday charging period further increased the suitability of the modeled technology and offset some of the impacts of battery degradation on driving range. With midday charging included, the replacement ratio for most urban routes was less than or equal to 1, indicating that this technology and charging strategy can allow for 1:1 replacement of existing diesel buses. In contrast, for the airport routes considered here, which are characterized by longer daily service schedules, estimated electric bus driving range was less than current daily utilization rates and replacement ratios were greater than 1 in all cases, indicating that an investigation of alternative charging strategies or electric bus technologies is needed to identify the most cost-effective path to electrification.

A key focus of future work should be to add additional electric bus charging options to the modeling framework. This work highlighted a single option to showcase the development of the modeling methods and analytical approach. Adding data for other options, like opportunity charging buses, will be important to further extend the utility of this approach. Furthermore, we identified a number of areas where vehicle simulation modeling could be refined and improved, including through the consideration of other parameters which affect electric bus energy consumption, such as driver style. With the growth of electric bus fleets, more real-world performance data is becoming available. Such data, especially if collected in the city for which the modeling approach is applied, can help refine vehicle simulation input parameters and validate the modeling approach. Finally, the route-level analysis approach should be extended to incorporate results into a framework for evaluating the TCO of electric bus options for individual routes to help identify the most cost-effective technology option and charging strategy and to optimize zero-emission electric bus deployment strategies.

APPENDIX

Table A1. Characteristics of routes selected for initial electric bus deployments.

Route	Route type	Route length (km)	# buses	Trips/day	Utilization (km/day/bus)
V-335E	Urban	28	78	632	175
V-500DN	Urban	30	4	33	176
V-500W	Urban	30	5	44	177
V-500CK	Urban	29	12	94	179
V-360B	Urban	35	60	428	180
V-500CA	Urban	27	58	547	181
V-505	Urban	31	9	87	181
V-500K	Urban	38	27	248	182
V-500G	Urban	35	4	31	183
V-500KE	Urban	45	6	46	188
V-356	Urban	29	15	129	188
V-365	Urban	25	17	147	191
V-201R	Urban	27	12	115	191
V-335EK	Urban	39	11	82	193
V-500BM	Urban	30	4	38	195
V-333Z	Urban	35	4	37	195
V-500A	Urban	36	24	189	197
V-319HK	Urban	49	6	64	204
V-356C	Urban	29	5	46	204
V-500D	Urban	31	54	450	227
KIAS-9	Airport	35	15	128	299
KIAS-8E	Airport	67	5	28	323
KIAS-6	Airport	56	6	47	344
KIAS-8C	Airport	74	5	30	357
KIAS-4	Airport	55	9	69	381
KIAS-12	Airport	49	6	60	394
KIAS-7	Airport	50	4	32	396
KIAS-7A	Airport	50	4	33	397
KIAS-8	Airport	67	18	137	407

Table A2. Energy consumption modeling summary statistics (kWh/km).

Technology	Passenger load	Urban routes (n=20)				Airport routes (n=9)			
		Mean	Median	Min	Max	Mean	Median	Min	Max
Diesel – AC (8-kW accessory load)	0%	4.17	4.12	3.80	4.78	3.52	3.52	3.31	3.93
	50%	4.46	4.41	4.06	5.06	3.80	3.81	3.58	4.22
	100%	4.77	4.71	4.37	5.41	4.10	4.11	3.85	4.52
Electric – non-AC (4-kW accessory load)	0%	0.80	0.82	0.68	0.95	0.79	0.80	0.69	0.85
	50%	0.88	0.90	0.74	1.06	0.86	0.88	0.74	0.94
	100%	0.96	0.97	0.80	1.17	0.93	0.95	0.79	1.02
Electric – AC (8-kW accessory load)	0%	1.04	1.02	0.91	1.17	0.94	0.97	0.83	1.00
	50%	1.12	1.10	0.98	1.28	1.01	1.05	0.88	1.08
	100%	1.20	1.17	1.04	1.39	1.09	1.12	0.93	1.17

Table A3. Energy consumption modeling summary statistics (DLE/100 km).

Technology	Passenger load	Urban routes (n=20)				Airport routes (n=9)			
		Mean	Median	Min	Max	Mean	Median	Min	Max
Diesel – AC (8-kW accessory load)	0%	41.9	41.4	38.2	48.1	35.3	35.4	33.3	39.5
	50%	44.8	44.3	40.8	50.9	38.2	38.3	36.0	42.4
	100%	47.9	47.3	43.9	54.4	41.2	41.3	38.7	45.4
Electric – non-AC (4-kW accessory load)	0%	8.0	8.3	6.9	9.5	7.9	8.1	6.9	8.5
	50%	8.8	9.0	7.5	10.6	8.6	8.8	7.4	9.4
	100%	9.6	9.8	8.0	11.8	9.3	9.5	7.9	10.3
Electric – AC (8-kW accessory load)	0%	10.4	10.2	9.2	11.8	9.5	9.8	8.3	10.0
	50%	11.2	11.0	9.8	12.9	10.2	10.5	8.8	10.9
	100%	12.0	11.8	10.4	14.0	10.9	11.3	9.4	11.8

Note: DLE = diesel liter equivalent.

Table A4. Fuel efficiency results for diesel bus simulations (km/L).

Technology	Passenger load	Urban routes (n=20)				Airport routes (n=9)			
		Mean	Median	Min	Max	Mean	Median	Min	Max
Diesel – AC (8-kW accessory load)	0%	2.39	2.42	2.08	2.62	2.83	2.83	2.53	3.00
	50%	2.23	2.26	1.97	2.45	2.62	2.61	2.36	2.78
	100%	2.09	2.11	1.84	2.28	2.43	2.42	2.20	2.58

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