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Planning the adoption of battery electric buses in Transjakarta: Route-level energy consumption, driving range, and total cost of ownership

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Summary

Transitioning from fossil-fueled buses to battery electric buses (e-buses) for public transport presents a significant challenge for bus operators. Transjakarta, the largest bus transit system in Indonesia, is planning to operate e-buses on all its routes by 2030. The energy consumption and operational range of e-buses vary within the transport system, as driving dynamics, terrain, and operational demands are unique to each route. Energy consumption and operational demands impact costs, which are of particular concern to transit operators. This study provides a detailed energy consumption, range, and cost analysis for routes served by 12 m buses that are slated for electrification in the Transjakarta BRT system. It provides recommendations on which routes are preferable to be electrified first and explores which cost factors can be modified to increase the competitiveness of e-buses on a cost per kilometer basis. To accurately model the total cost of ownership (TCO) for each route, we use a proprietary route development tool, a computational simulation tool, and route-level range analysis.

Key findings of the study are:

» Energy consumption modeling shows that e-buses are 4–5 times more efficient than diesel buses certified to Euro III-equivalent standards operating in the evaluated routes.

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- The range analysis suggests that Route 1 and Route 13 can be operated by a 324 kWh 12m e-bus without mid-day charging or major operational changes, even as the battery ages.
- For Route 5 and Route 2A, e-buses may need additional charging during daily operations or a higher battery capacity, which would imply a higher capital cost and present vehicle weight challenges.
- The e-bus TCO can be competitive with conventional bus technology by extending the duration of e-bus contracts to 15 years. This will reduce the TCO per km by 23%–25% compared to diesel buses operating under a 7-year contract.

Introduction

The city of Jakarta has become a leader in public transit bus electrification in Indonesia, with PT Transportasi Jakarta (Transjakarta), the country's largest bus transit system, successfully operating 30 electric buses (e-buses) on selected routes in 2022. At the national level, the Ministry of Transport has announced goals to expand the electrification program to 10 provincial capitals and 10 other Indonesian cities and reach 90% of new bus procurement by 2030.[1]

The Jakarta Special Capital Region (Daerah Khusus Ibukota or DKI) provincial government plans to expand its public transportation and its transition to electric vehicles as part of its efforts to reduce economy-wide emissions 50% by 2030.[2] As a signatory of the C40 Cities Fossil Fuel Free Streets Declaration, Jakarta has joined 34 other cities in committing to zero-emission road transport (C40, 2019). Alongside these commitments, the DKI Jakarta government has formally set a target to operate 100% e-buses by 2030 through Transjakarta. [3] To help meet this goal, Transjakarta procured more e-buses by the end of 2023, reaching 100 units in operation[4].

Transjakarta cooperates with several third-party bus operators to service their routes. In 2019, around 4,415 buses operated on regular and rapid-transit routes, consisting of articulated buses (18 m), single buses (12 m), maxi-buses (12-13.5 m), and microbuses. The current fleet consists of diesel, compressed natural gas (CNG), and battery electric buses.[5]

Through presidential decrees, the national government aims to provide incentives, policies, and supporting regulations to accelerate the uptake of battery electric vehicles.[6] In April 2023, The Ministries of Industry and Finance announced direct

1 Ministry of Transportation, "Future Indonesia Towards Zero Emission Buses [presentation]," TUMI E-Bus Workshop: Indonesia E-Bus Roadmap & Financing Strategy, (2022), https://itdp-indonesia.org/2022/11/tumi-e-bus-workshop-indonesia-e-bus-roadmap-financing-strategy/.

2 DKI Jakarta Province Governor Regulation 90/2021. Climate Resilient Regional Low Carbon Development Plan. https://peraturan.bpk.go.id/Home/Details/184664/pergub-prov-dki-jakarta-no-90-tahun-2021.

3 DKI Jakarta Province Governor's Decree No 1053/2022. Guidelines for the Acceleration of Battery-Based Electric Motorized Vehicles in Transjakarta Transportation Services. https://jdih.jakarta.go.id/uploads/default/produkhukum/KEPGUB_NO._1053_TAHUN_2022.pdf.

4 Transjakarta, "Transjakarta dan DAMRI Bersinergi Genapkan Target Pengoperasian 100 Bus Listrik Transjakarta and DAMRI Synergize to Achieve the Target of Operating 100 Electric Buses," December 2023, https://transjakarta.co.id/transjakarta-dan-damri-bersinergi-genapkan-target-pengoperasian-100-bus-listrik/.

5 Additional information on the Transjakarta fleet can be found in Adhi Triatmojo, Ahmad Safrudin, Francisco Posada, Mega Kusumaningkatma, and Ray Minjares, *Evaluation of factors that affect total cost of ownership in support of Transjakarta's electric bus adoption plans*, (Washington, DC: ICCT, 2023), https://theicct.org/publication/indonesia-ebus-costs-april23/.

6 Presidential Regulation No 55/2019. Acceleration of the Battery Electric Vehicle Program for Road Transportation. https://peraturan.bpk.go.id/Home/Details/116973/perpres-no-55-tahun-2019.

financial incentives for procuring 138 e-buses and reduced the value added tax for e-buses complying with a minimum local manufacturing content of 40%.[7]

Integrating e-buses into existing public transit systems requires appropriate planning to ensure a smooth transition in each of the serviced routes. The transition from a diesel to an electric public transit bus system poses challenges for city authorities and bus operators due to operational differences and cost uncertainty. One of the most important operational differences of e-buses is their operational range, which is affected by battery capacity, energy consumption, driving behavior, and route characteristics. Another factor that affects e-bus adoption is their higher initial procurement costs compared to conventional diesel buses. However, e-buses can also offer the potential for operational and maintenance cost savings, which, over their contractual lifetime, can make them competitive compared to diesel buses.

This study assesses and compares the operational and economic performance of diesel and electric buses on specific Transjakarta routes. This route level analysis, the first of its kind concerning e-buses in Indonesia, can serve as a more accurate tool for decision makers in Transjakarta other cities to assist in achieving public transit electrification goals.

This study assesses 12-meter single buses operating in the Transjakarta Bus Rapid Transit (BRT) system. The operational analysis evaluates the buses' electric range and individual driving dynamics for each of the routes studied. In addition, the analysis evaluates the total cost of ownership (TCO) for each bus, including capital and operational costs, in addition to individual route energy consumption, over a predefined period. Data for this analysis was provided by Transjakarta and complemented with the International Council on Clean Transportation's (ICCT) own data on e-bus costs.

The results of this study are being presented in two reports, a consultancy report to Transjakarta and a public version which does not contain information deemed confidential by Transjakarta (e.g., operational cost of maintenance per km).

Background: Transjakarta bus system

Transjakarta is a regionally owned enterprise public transit bus operator in the DKI Jakarta Province. Since 2004, Transjakarta has managed the region's BRT system, along with its feeder bus routes and microtrans (Figure 1). The BRT system is integrated with rail, light-rail, and commuter transit, which are connected throughout its 13 corridors (trunk routes). Due to the large number of commuters traveling to the DKI Jakarta Province from the Greater Jakarta area, daily ridership in the Transjakarta system can reach up to 0.8 million passengers per day.[8]

7 Nadya Zahira, "Bus Listrik Juga Dapat Subsidi Kendaraan, Begini Syarat Mendapatkannya [Subsidy for Electric Bus is Available, Here is How to Get It]," *Katadata*, March 7, 2023, https://katadata.co.id/ira/berita/640690e2593f1/bus-listrik-juga-dapat-subsidi-kendaraan-begini-syarat-mendapatkannya.

8 Iqbal Muhtarom, "Diminta Alih Usaha Ternak, Pengusaha Arang di Lubang Buaya Memilih Pindah [Number of Transjakarta Users Reach 800 Thousand Passengers per Day], *Tempo*, October 20, 2022, https://metro.tempo.co/read/1647425/jumlah-pengguna-transjakarta-tembus-800-ribu-penumpang-per-hari.

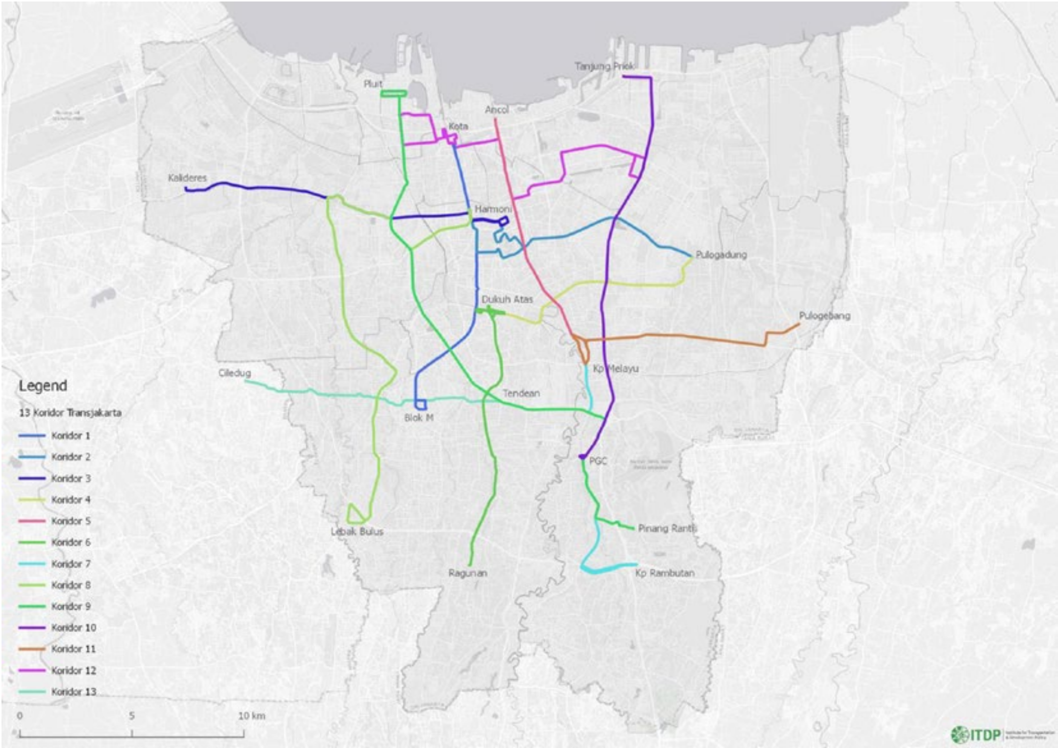


Figure 1. Map of Transjakarta BRT System.[9]

Buses operating in the Transjakarta system are a mix of those owned by the enterprise and those owned-and-operated by third parties. Third-party bus operators, who are awarded gross cost contracts to provide service on Transjakarta routes, are paid based on the operational performance (km driven) and price rate (IDR/km) for their services. Bus operators are responsible for bus purchases, operation, and maintenance, as well as for providing depots. Bus operators must meet certain minimum service levels determined by Transjakarta and the DKI Jakarta government. Transjakarta owns some of the depots for diesel buses currently in operation, however third-party bus operators have their own depots, including depots for the 30 e-buses currently operating in Transjakarta routes.

Transjakarta electrification plans

Transjakarta aims to operate a 100% e-bus fleet by 2030, with annual targets shown in Figure 2.[10] The transition began with a pretrial phase, conducted from 2019–2020, which then continued with the pilot phase that has been carried out from 2021–2022. As of the end of 2022, 52 e-buses were in operation[11] and 46 additional e-buses have

9 Institute for Transportation and Development Policy, "Support for E-mobility Transition in Jakarta," (2021), https://itdp-indonesia.org/publication/support-for-e-mobility-transition-in-jakarta/.

10 Data was shared by Transjakarta officials during the National Workshop on Accelerating Battery-Electric Vehicle Adoption 2022 in Indonesia. International Council on Clean Transportation. "Accelerating Battery-Electric Vehicles: Indonesia National Workshop – International Council on Clean Transportation," November 1, 2022. https://theicct.org/event/indonesia-workshop-sep22/.

11 Wasti S. S. and Ambaranie N. K. M., "Transjakarta Operasikan 52 Bus Listrik di 3 Rute [Transjakarta Operates 52 e-buses on 3 Routes]," Kompas, August 23, 2023, https://megapolitan.kompas.com/read/2023/08/23/17153251/transjakarta-operasikan-52-bus-listrik-di-3-rute.

been contracted and deployed by the end of 2023 resulting in total of 100 e-buses.[12] Transjakarta is planning to procure another 200 e-bus to fulfil its target to operate 300 e-buses by the end of 2024.[13]

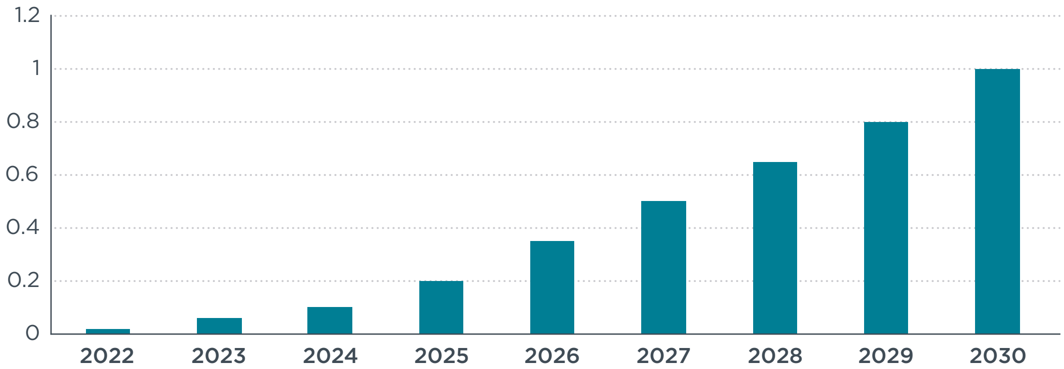


Figure 2. Transjakarta e-bus target, 2022–2030.

Route-level operational and cost analysis

This study analyzes the operational range and total cost of owning and operating an e-bus in each of the routes targeted for electrification. The operational range of e-buses depends on battery size and capacity, passenger loading time, battery degradation, and energy consumption. The TCO model estimates the capital cost of the vehicle and charging infrastructure, energy consumed, maintenance, and staffing. The size of the batteries and the charging infrastructure, which affect capital costs, define the operational range of the battery. Thus, the energy consumption values, range analysis, and charging strategy are incorporated into the TCO model to provide a detailed assessment of the costs incurred in electrifying a specific route for each type of bus.

Methodology

This study evaluates the operational and economic aspects of a transition to electric from diesel buses in Transjakarta routes. Because Transjakarta is currently focused on procuring standard 12-meter e-buses, this study focuses on four BRT routes that are serviced by this type of bus: routes 1, 5, 13, and 2A.

Operational range and management of the battery state-of-charge are challenges for transitioning to e-buses. Key parameters such as daily distance, passenger loading time, topography, and air conditioning affect the energy consumption of e-buses and should be considered during operational planning. This study assesses the energy consumption of an e-bus on each of the four routes, which are typically serviced by diesel buses, through simulations that use the characteristics of each route.

Energy consumption estimations can help bus operators choose the optimal battery size and charging strategy for each route. It can also help define an electrification

12 Transjakarta, "Transjakarta dan DAMRI Bersinergi Genapkan Target Pengoperasian 100 Bus Listrik [Transjakarta and DAMRI Synergize to Achieve the Target of Operating 100 Electric Buses]," December, 2023, https://transjakarta.co.id/transjakarta-dan-damri-bersinergi-genapkan-target-pengoperasian-100-bus-listrik/

13 Fransiskus Wisnu Wardhana Dany, "Transjakarta Tambah 200 Bus Listrik pada 2024 [Transjakarta To Add 200 E-Buses in 2024]," Kompas, December 25, 2023, https://www.kompas.id/baca/metro/2023/12/25/transjakarta-tambah-200-bus-listrik-tahun-2024.

schedule that prioritizes the most appropriate routes. The methodology of the analysis is divided into three stages, illustrated in Figure 3.

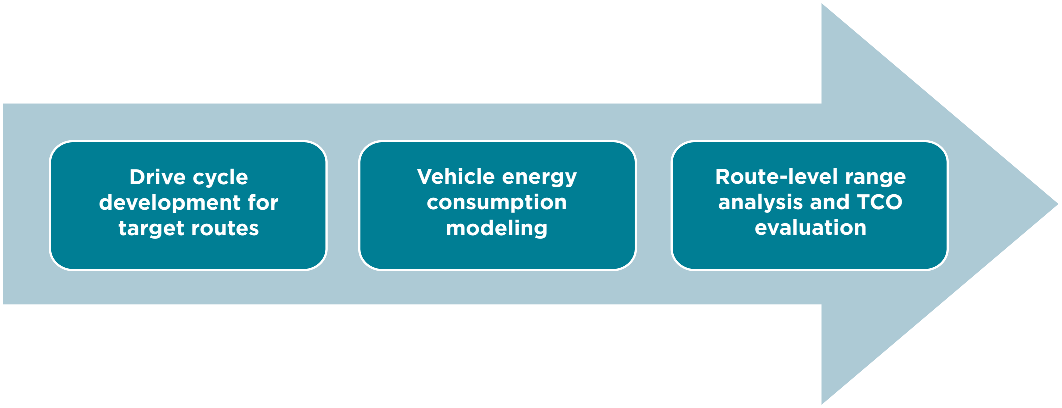


Figure 3. Stages of route-level TCO analysis.

First, a drive cycle is developed for each of the target routes using data collected from global positioning systems (GPS) to represent the key driving behavior parameters of the routes (e.g., average speed, average acceleration, stops per km, etc.) Next, the drive cycle is used to estimate energy and fuel consumption for both diesel and electric bus technology. Finally, the route-level TCO estimates the capital expenditure and operational costs over a predefined time for the buses on each route.

Route development tool: GPS data collection, data preparation, and drive cycle development

To create a simulation that accurately represents real-world performance, access to real-world operational data that captures existing operating buses must be obtained. GPS tracking and other intelligent transport systems can be used to capture fleet performance data. In this study, we use three steps to create a representative route-level cycle: data collection, data preparation, and drive cycle development (Figure 4). This study uses a drive cycle development methodology developed by ICCT and described in detail in a previous paper.[14]

14 Lingzhi Jin, Oscar Delgado, Ravi Gadepalli, and Ray Minjares, *Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes*, (Washington, DC: ICCT, 2020), https://theicct.org/publication/strategies-for-deploying-zero-emission-bus-fleets-development-of-real-world-drive-cycles-to-simulate-zero-emission-technologies-along-existing-bus-routes/.

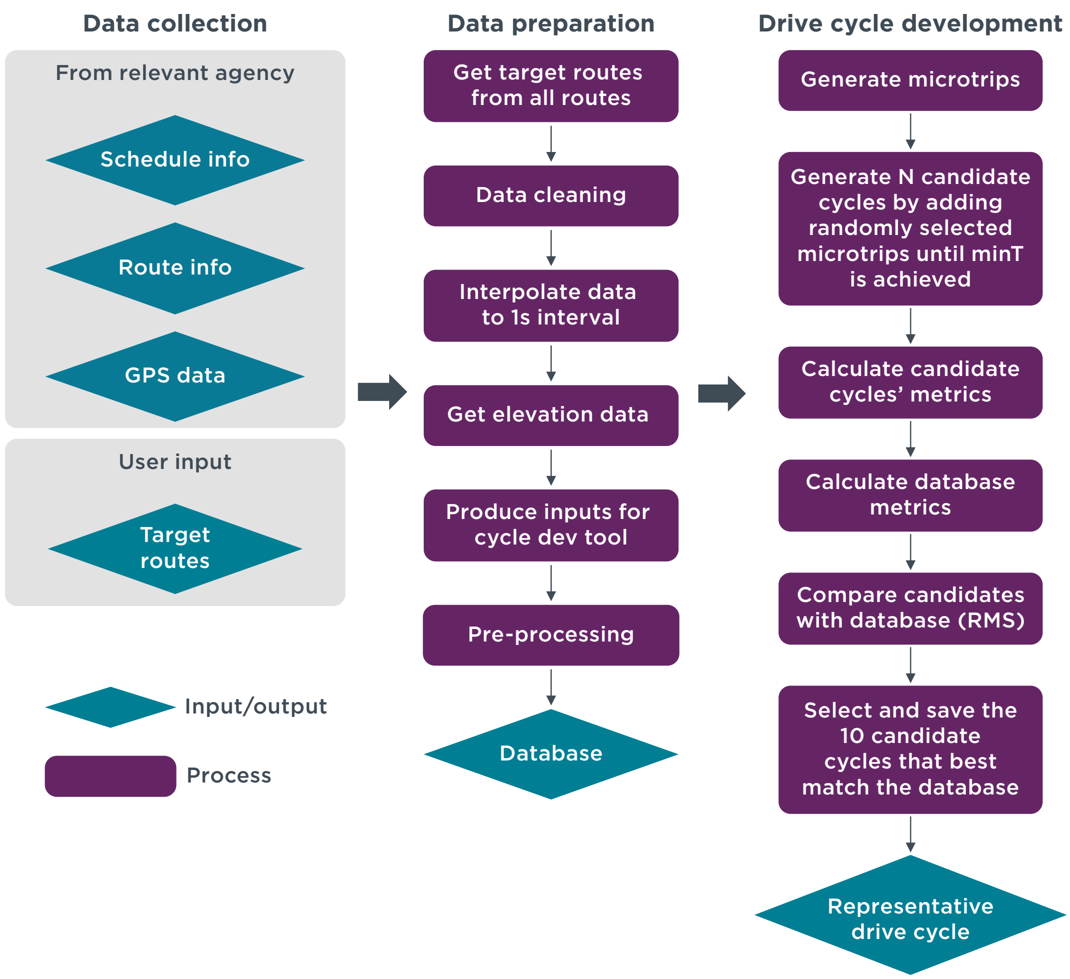


Figure 4. Route development analysis workflow.

Data collection

The development of representative drive cycles requires GPS data collection and processing to generate representative drive cycles for the routes studied. Second-by-second GPS data is captured by data-logging units installed in diesel buses operating on Transjakarta BRT routes. GPS data is collected for 5–10 working days per bus per route, depending on bus availability. Data collected include coordinates and time, which are later cleaned and processed to extract bus speed and acceleration data for each route. Data required for route development are:

» GPS-based vehicle tracking data which includes: bus identifier; route identifier; date; time (at 1 second intervals); latitude; longitude; speed; and elevation

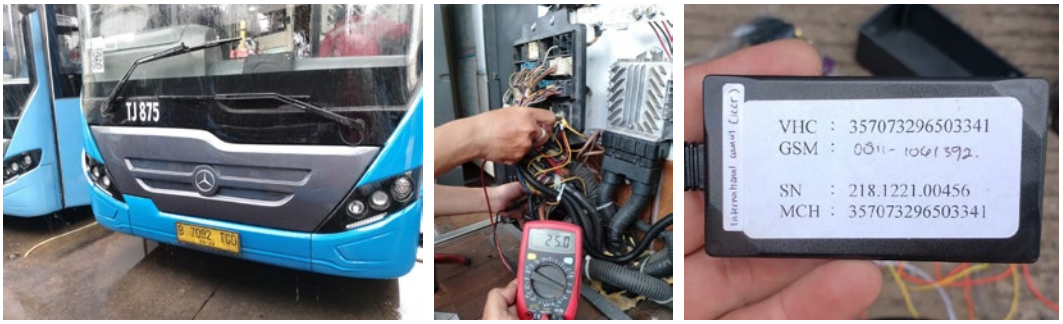
» Bus schedule information

» Total length of each route

» Latitude and longitude of bus stops

» Total number of buses serving each route

In this study, GPS data was collected by INDOGPS, a GPS service provider in Indonesia. The GPS device used was able to collect 1-second interval data during bus operation and store the data in a cloud web service at the end of each day. Figure 5 illustrates the GPS installation process. GPS data was collected from 20 buses during a total of 33 days of operation.



(a) (b) (c)

Figure 5. GPS system installation: (a) Bus picture; (b) Electrical panel; (c) GPS device.

Data preparation

Data preparation ensures data contained in the cycle development are complete and valid. It involves data cleaning (removing days without data, duplicated data, invalid data, etc.) and data interpolation when the data gathering frequency is lower than the desired 1 second interval. If elevation data not available from the GPS device, the Google Elevation API service was used to capture elevation based on latitude and longitude data to calculate road grade.

Drive cycle development

ICCT's previously developed methods were applied to the GPS data collected to develop drive cycles for each target route. The drive cycle is defined as a speed profile over time that represents the driving dynamics (speed, acceleration, stops, and road grade). Drive cycle development informs a range of analytical tools that can shape decisions around technology selection for a given route, inform decisions on the minimum technology specifications for vehicles, and reveal the infrastructure and investments necessary to support the technology selected.[15]

Drive cycle development involves several steps. First, data is separated into multiple micro-trips. Second, a user-defined number of micro-trips sequences are generated (candidate cycles). Finally, the original database is compared to candidate cycles using five metrics: average driving speed, standard deviation of driving speed, characteristic acceleration, average positive road grade, and standard deviation of road grade. The candidate cycle with parameter values closest to those of the original long cycle will be selected as final drive cycle. Figure 6 provides an example of a drive cycle, consisting of speed versus time, for Route 1.

15 Jin, Delgado, Gadepalli, and Minjares, *Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes*.

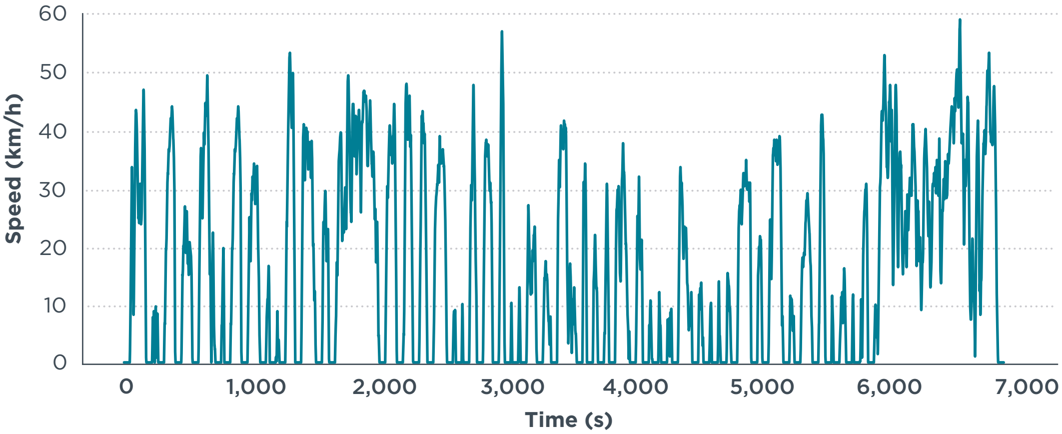


Figure 6. Drive cycle development for Route 1.

The use of drive cycles in computational models can predict the potential performance of e-buses on specific public transit routes without investment in expensive and complex pilot studies. Therefore, the development of drive cycles is a recommended first step in e-bus deployments and can be used to better plan for piloting e-bus models in real world operation.[16]

Energy and fuel consumption

Energy and fuel consumption is one of the main determinants of e-bus operational range, costs, and performance. Simulation of this variable is necessary when actual operational data is not available. This study estimates the energy and fuel consumption of buses using Siemen's AMESIM vehicle simulation software to analyze the impact of different routes in the Transjakarta BRT system on e-bus energy consumption.[17]

The software was used to model the energy consumption of 12-meter diesel and electric buses. Drive cycles that were developed for this study were used to ensure the energy consumption data accurately predicts the operational needs of the future e-bus fleets. The analysis compares the effective driving range of the e-buses against the utilization needs and would estimate if any additional charging strategy or bigger battery capacity is needed in certain routes.

The model approximates the actual behavior of the input components from the drive cycle (average speed, stops per km, road grade, etc.) and technical parameters (battery capacity, motor power, etc.). The technical parameters used, which reflect the buses currently operating on Transjakarta routes, can be found in the appendix.

Passenger load affects the weight of the bus during operation, which consequently affects energy consumption. Therefore, this study uses a simulation considering three scenarios: an empty bus, a bus at half capacity, and a bus at full capacity was created. To evaluate the power demand for accessories, the use of air conditioning is considered, assuming an annual average temperature in Jakarta of 26.4°C.[18]

16 Jin, Delgado, Gadepalli, and Minjares, *Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes.*

17 Siemens, Simcenter Amesim software, https://plm.sw.siemens.com/en-US/simcenter/systems-simulation/amesim/.

18 Jakarta average temperature data was collected from Climate Data website: https://en.climate-data.org/asia/indonesia/jakarta-special-capital-region/jakarta-714756/.

Route-level range and total cost of ownership analysis

The TCO analysis compares the total cost of owning and operating an e-bus and diesel bus for the selected routes targeted for electrification. E-buses have a higher acquisition cost than diesel buses but lower operating and maintenance costs.[19] This analysis compares the cost of each bus technology in the selected route over the bus lifetime, including the net present value of the sum of capital expenditures, in addition to costs associated with the operation and maintenance of buses and their infrastructure, annualized over the contract service period.

The outputs of the energy consumption evaluation in the previous step are used here to inform the fuel and electricity costs for each of the routes evaluated. At the same time, the calculated energy consumption informs the operational range of the e-bus for each route.

The TCO components used in this study are listed in Table 1. The methodology applied here is based on the public transit bus methodologies developed in a previous ICCT study and adjusted for Transjakarta case.[20]

Table 1. Main components and inputs of the total cost of ownership analysis.

Main components	Inputs
Fleet information	Fleet size and ownership terms
Capital costs	Bus purchase price, infrastructure cost, bus residual/scrappage value
Operations and maintenance	Annual vehicle kilometer traveled, fuel/energy consumption, fuel/electricity price, and vehicle maintenance cost
Midlife costs	Engine overhaul or battery replacement costs
Staff	Driver, fare checker, technician, and operator
Financial assumptions	Loan term, interest rate, down payment, and discount rate

Note: This study does not include indirect overhead or accidental costs.

Some inputs for the TCO analysis come from a recently published report describing a high level TCO comparison of diesel and e-buses in Transjakarta.[21] For this route level analysis, additional data for each route was included to have an accurate comparison:

» Total number of buses running on each of the route

» Total distance traveled per day per bus (km)

» Total days planned as available per year

» Total days available per year

» Operating hours of each route (hours)

Table 2 lists the values used for the main components of the TCO input for the buses analyzed in Transjakarta routes. It is important to note that these values are dynamic and may vary according to the macroeconomic climate, market conditions, and regulations throughout the year. In this study, we compare battery electric buses with

19 Triatmojo, Safrudin, Posada, Kusumaningkatma, and Minjares, *Evaluation of factors that affect total cost of ownership in support of Transjakarta's electric bus adoption plans*.

20 Joshua Miller, Ray Minjares, Tim Dallmann, and Lingzhi Jin, *Financing the transition to soot-free urban bus fleets in 20 megacities*, (Washington, DC: ICCT, 2017), https://theicct.org/publication/financing-the-transition-to-soot-free-urban-bus-fleets-in-20-megacities/.

21 Triatmojo, Safrudin, Posada, Kusumaningkatma, and Minjares, *Evaluation of factors that affect total cost of ownership in support of Transjakarta's electric bus adoption plans*.

diesel buses certified to the Euro III standards, as this is the most common diesel single bus that runs on Transjakarta routes.

Table 2. Main components for TCO analysis.

Input	Unit	Diesel Euro III	Battery electric	Source
Bus purchase price	IDR/Bus	2,594,715,750[a]	5,500,000,000[b]	LKPP e-catalogue (Diesel) and MoIA reg.40/2021 (Electric)
Fuel/energy price	IDR/DLE or IDR/kWh	6,800[c]		MEMR Ministerial Decree
Infrastructure maintenance	IDR/Annual		9,250,000[d]	ITDP, 2021 (Electric, recalculated by ICCT)
Infrastructure costs	IDR/Bus		703,333,333[e]	Confidential for diesel. Electric infrastructure cost from ICCT e-bus TCO databases
Bus maintenance	IDR/km			Confidential
Staff costs	IDR/km			Confidential
Midlife costs	IDR		908,992,320[f]	ICCT Estimate

Note: Filled boxes contain confidential information.

a. E-Katalog 5.0, "Mercedes Benz Bus Besar (O 500 U 1726 A/T) (Laksana Cityline 37 Seats) (Thermoking Tk- 1100 With Airpurifier) (Bus Low Entry) Off The Road," https://e-katalog.lkpp.go.id/katalog/produk/detail/1286810?lang=id&type=general.

b. Ministry of Home Affairs Regulation 40/2021, "Amendment to Regulation of the Minister of Home Affairs Number 1/2021 Concerning Calculation of the Basis for Imposition of Motorized Vehicle Tax and Transfer Fee of Motorized Vehicles in 2021," https://peraturan.bpk.go.id/Home/Details/185922/permendagri-no-40- tahun-2021.

c. MEMR Ministerial Decree No 37.K/HK.02/MEM.M/2022, "Concerning Special Assigned Fuel Oil Type," https://jdih.esdm.go.id/storage/document/SALINAN%20KEPMEN%2037%20TAHUN%202022%20TTG%20JBKP.pdf.

d. Institute for Transportation and Development (ITDP), "Support for E-mobility Transition in Jakarta," (2021), https://itdp-indonesia.org/publication/support-for-e-mobility-transition-in-jakarta/. Price was recalculated by the ICCT, but ITDP served as reference (2.5% cost of maintenance from charging station capital costs).

e. The price of the infrastructure cost for e-buses are based on 150 kW depot charger and the cost of upgrading grid connection.

f. To maintain conservative midlife cost estimates for the electric bus, the average battery price in 2020 for lithium-ion battery which is 157 US$/kWh[22] has been considered for battery replacement.

The TCO of an e-bus and diesel bus is compared for each route to determine which routes are preferable for electrification based on economic performance. An analysis of TCO per km is also performed to reflect longer e-bus contract durations of 15 years and compared to the existing e-bus contract duration of 10 years, and diesel bus contract duration of 7 years. The fuel used for the diesel bus has a biodiesel blend of 20% (B20).

Results

Route-level drive cycles

As described above, ICCT obtained GPS data collected March–May 2022 from four Transjakarta routes serviced by 12-meter buses:

» Route 1: Kota-Blok M, main BRT route

» Route 5: Ancol-Kp.Melayu, main BRT route

» Route 13: Tendean-Puri Beta, main BRT route

» Route 2A: Pulogadung-Rawa Buaya, mixed BRT and non-BRT route

22 Eamonn Mulholland, *Cost of electric commercial vans and pickup trucks in the United States through 2040*, (Washington, DC: ICCT, 2022), https://theicct.org/sites/default/files/publications/cost-ev-vans-pickups-us-2040-jan22.pdf.

Maps of these routes and the associated drive cycles are shown in Figure 7.

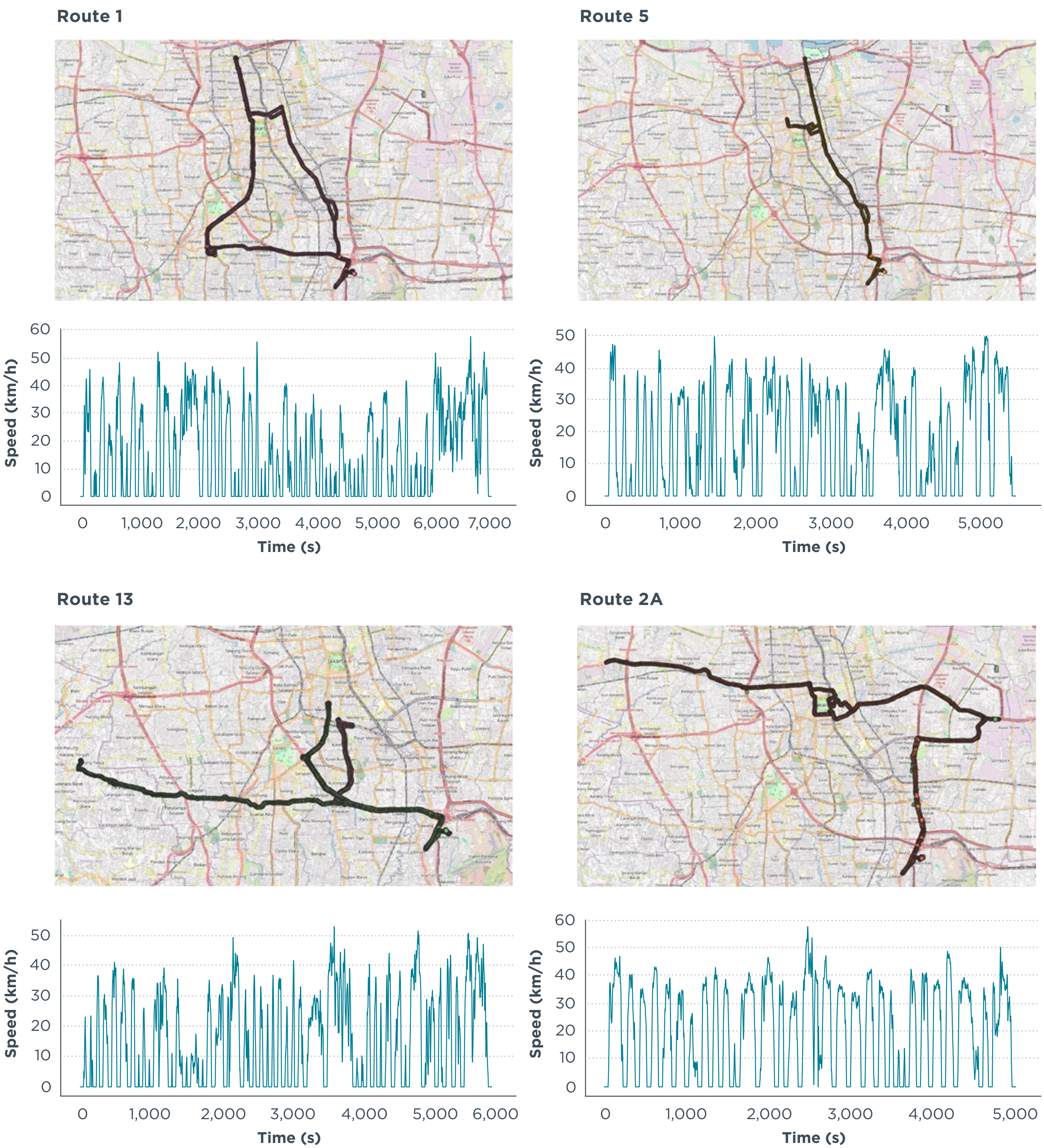


Figure 7. GPS route identified and its drive cycles.

The drive cycle metrics that have the strongest effect on fuel consumption are:

» Average speed (km/h): The average bus speed including idle time during stops in the route

» Average driving speed (km/h): The average bus speed excluding idle time

» Average stop duration: The average duration of a bus not moving in a single stop

» Percentage of idle time: The total percentage of a bus not moving while the vehicle is on in a single drive cycle duration. Idle time is calculated when the bus speed reaches zero during the operational time

» Kinetic intensity: A measure of how much stop-and-go is in a cycle, or the ratio between acceleration and speed.[23] This ratio provides an indication of the energy available for regeneration, which can help identify drive cycles where regenerative braking technology would offer economy improvements.[24]

Table 3 presents the result of the drive cycle characterization analysis.

Table 3. Key drive cycle parameter results per route.

Cycle	Duration (s)	Duration (min)	Distance (m)	Average speed (km/hr)	Average driving speed (km/h)	Maximum speed (km/h)	Number of stops	Stops per km	Average stop duration (s)	Share of idle time	Kinetic intensity
Route 1	6,937	115.62	29,095	15.10	23.56	57.60	53	1.82	47.00	36%	1.61
Route 5	5,,774	96.23	23,596	14.71	23.22	52.80	45	1.91	47.02	37%	1.92
Route 13	5,020	83.67	27,587	19.78	27.87	57.20	31	1.12	46.97	29%	1.12
Route 2A	5,454	90.90	25,422	16.78	24.95	50.00	38	1.49	47.00	33%	1.44

The drive cycle characterization results show that buses operating on Route 1 and Route 5 have the most idle time. These routes, which are two of the busiest in the Transjakarta system and operate outside dedicated BRT corridors, likely face traffic congestion. This higher idle time could lead to higher energy consumption. High kinetic intensity is also identified in Route 1 and Route 5, which could favor regenerative breaking in e-buses for energy efficient operation.

Energy consumption analysis

Comparison of the energy consumption of diesel buses with e-buses

Figure 8 shows the estimated energy consumption comparison for each route analyzed, considering 0%, 50%, and 100% passenger loading. Diesel buses and e-buses were simulated based on the technical specifications described in the appendix. The fuel consumption (diesel liter equivalent (DLE)/km) are converted into energy consumption (kWh/km) to give a better comparison in the figure (1 DLE/km B20 biodiesel = 9.69 kWh/km).[25] The simulation also assumes air conditioning is constantly in operation while buses are servicing the routes.

23 Characteristic acceleration measures the inertial work to accelerate and/or raise the vehicle per unit mass per unit distance over the cycle. Aerodynamic speed measures the ratio of the average cubic speed to the average speed and characterizes the impact of aerodynamic resistance on vehicle fuel usage. See Jin, Delgado, Gadepalli, and Minjares, *Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes*.

24 Michael O'Keefe, Andrew Simpson, Kenneth Kelly, and Daniel Pedersen, "Duty cycle characterization and evaluation towards heavy hybrid vehicle applications (SAE Technical Paper 2007-01-0302)," SAE International, (2007), https://doi.org/10.4271/2007-01-0302.

25 U.S. Department of Energy. "Fuels Properties Comparison," retrieved January 10, 2023, https://afdc.energy.gov/fuels/properties.

The energy consumption modelling was applied to the four routes analyzed. Differences in modeling results are mainly due to the unique slope, number of stops and accelerations, and average speed for each of the routes. Figure 8 shows a box plot of energy consumption for both diesel and e-buses in target drive cycles under different loading conditions. Median energy consumption for diesel buses servicing Routes 1, 13, 2A, and 5 are 4.5, 4.49, 4.94, and 4.6 kWh/km, respectively, and 0.97, 1.05, 0.96, and 0.97 kWh/km for e-buses.

The results highlight the energy efficiency benefits of e-buses. Energy consumption values for e-buses are 76%–80% lower than those of diesel buses. This improvement matches the results of a California Air Resources Board study which showed the energy efficiency ratio between electric and diesel buses is about 3.5 at highway speeds (38 mph or 61 km/h) and 5 to 7 times this when operating at lower speeds in inner city routes (13 mph or 21 km/h), where idling and coasting loses from conventional engines are highest.[26]

This analysis reflects real world energy efficiency data captured from e-buses piloted by Transjakarta since 2022. Our energy consumption values for the e-buses, which range from 0.92 kWh/km to 1.14 kWh/km, closely match real-world energy consumption data captured by Transjakarta during the e-bus pilot program in 2022, which range from 0.9 to 1.0 kWh/km.[27]

It is important to note that the modeling result can differ from actual energy consumption data because of external conditions such as temperature, humidity, and wind drag. Energy losses due to changes in road surfaces or tires are also not accounted for. Additionally, differences in driving performance of different operators is not studied in the energy consumption analysis, but the variability is included in the GPS data and drive cycle determination, as buses are operated by different drivers over the study period.

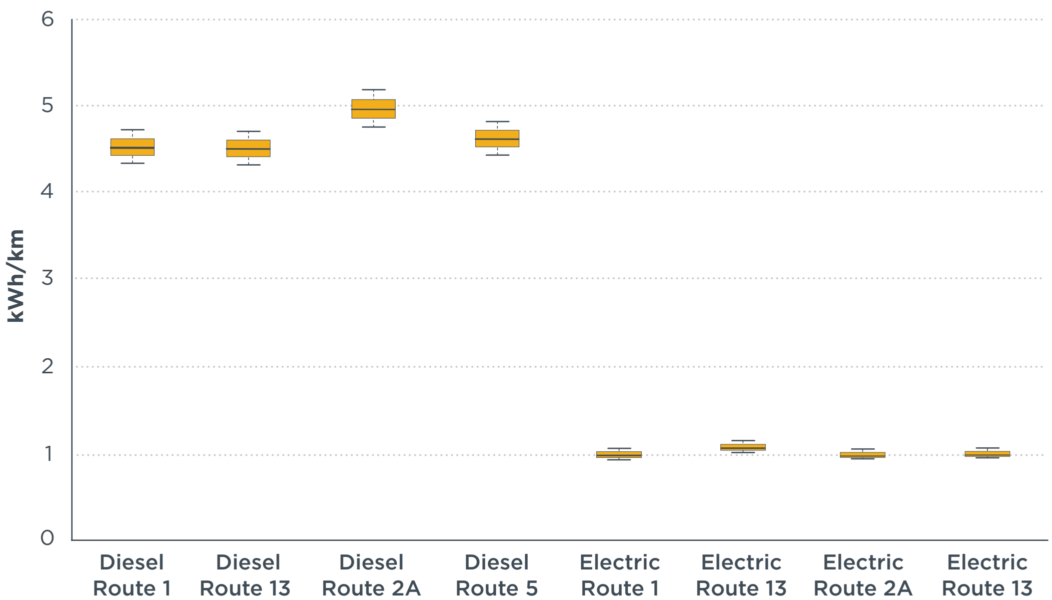


Figure 8. Comparison of energy consumption of a diesel and electric bus on four Transjakarta routes. The boxplot on each route represents passenger loads of 0% (bottom limit), 50% (middle), and 100% (upper limit).

26 California Air Resources Board, "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles," (2018), https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf.

27 Data collected by ITDP research in 2022-2023 as part of TUMI Project.

Impact of passenger load on energy consumption and electric range

Figure 9 shows the impact of passenger load on energy consumption and electric range on Transjakarta BRT routes. The boxplot below shows the energy consumption and range of e-buses in three passenger load conditions: full load (100%), half load (50%), and empty (0%).[28] The energy consumption results affect the range estimates of e-buses, based on a 324-kWh battery, with battery charge reserve of 20%. Each boxplot represents the results for all four routes tested.

Passenger load can significantly impact on energy consumption and electric range. Our results indicate that a full passenger load will increase the energy consumption of an e-bus up to 13% (1.07 kWh/km), while a half load increases it by 4% (0.98 kWh/km), compared to an empty load (0.94 kWh/km).

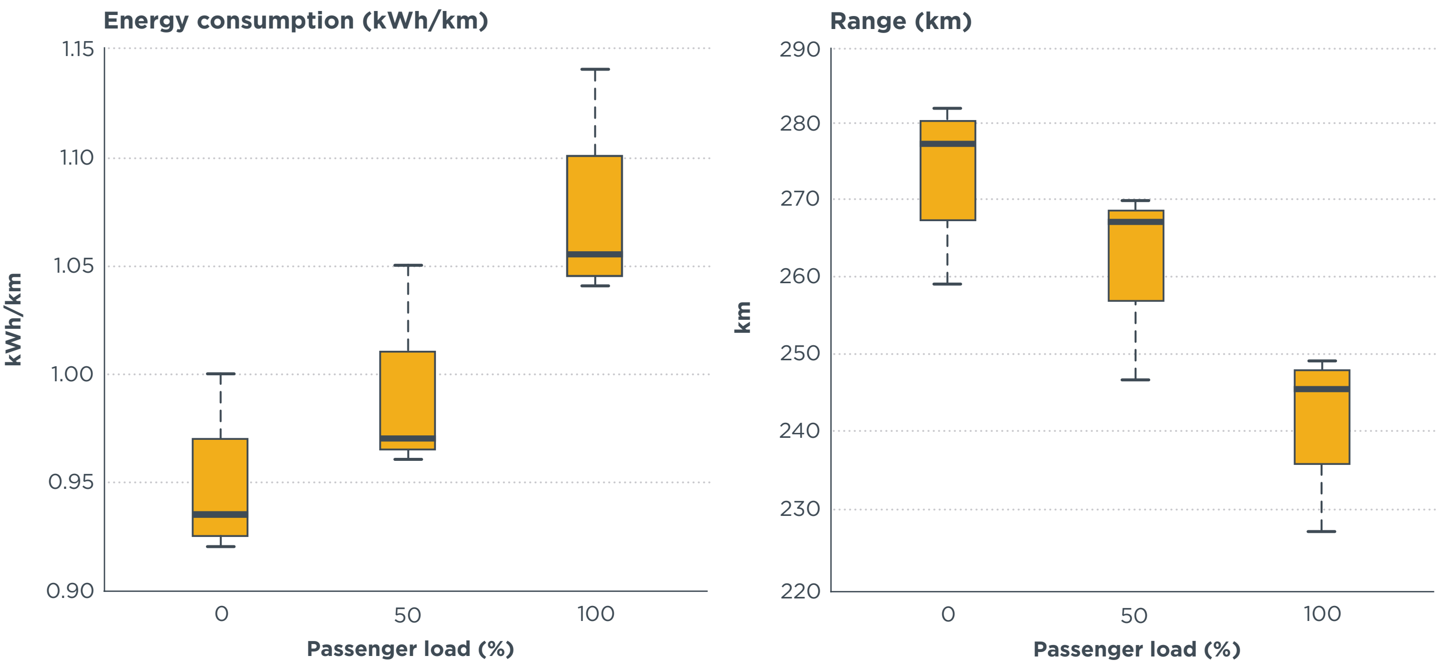


Figure 9. Effect of passenger load on energy consumption and electric range.

Based on the analysis, electric range will decrease as passenger load increases. With an empty load, an e-bus can reach up to 273 km on average, while a full passenger load will reduce the electric range up to 32 km (241 km), and a half load will reduce range by 11 km (262 km). This result is inversely proportional to energy consumption, which is affected by the driving conditions on each route, as explained in the drive cycle results section.

Evaluation of electric range under different operating conditions

The variables that impact electric range are energy consumption, battery degradation, and battery technical reserves (20% of battery capacity). Figure 10 presents the operational range modeling results for a 12 m standard electric bus operating on the selected routes with different passenger loads. The results suggest that, if starting the day with a full battery, at the beginning of battery life with 100% passenger loading, the e-bus will be able to meet the ranges required for the three routes' daily operation with a full passenger load. The exception is Route 2A, which has a longer daily

28 A full passenger load contained 50 passengers and a half load contained 25 passengers.

distance and operates outside a BRT route. However, in an average situation with 50% passenger loading, e-buses servicing all four routes will be able to meet the required daily range. Battery degradation can significantly impact all routes but will have the least impact for buses servicing Route 1 with 50% passenger load.

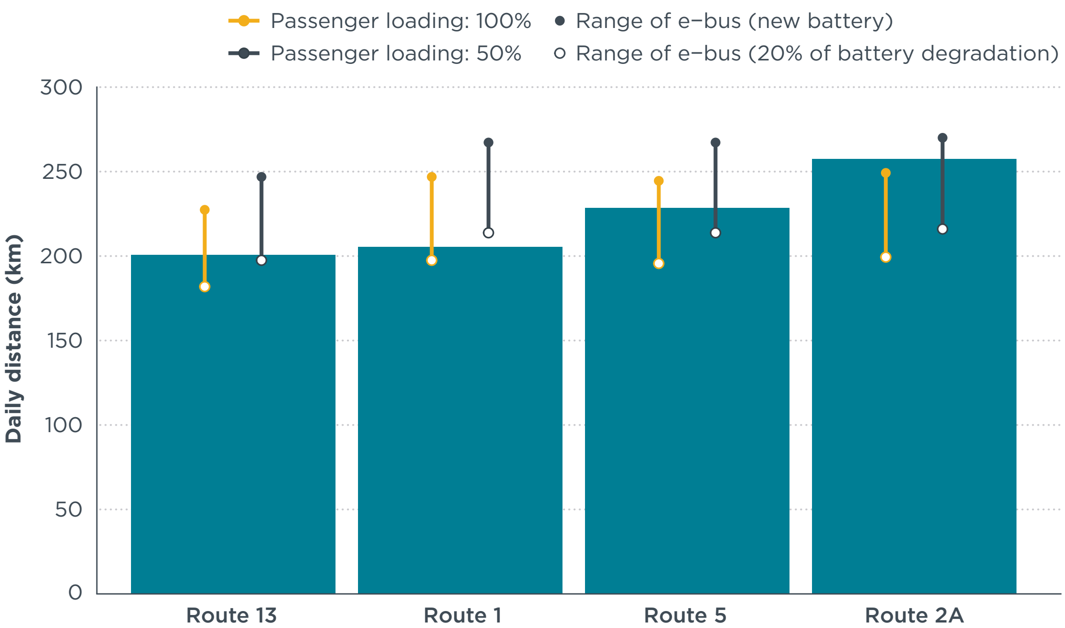


Figure 10. Electric range of buses operating on selected routes with varying passenger loads. Daily distances for each route were calculated from GPS data.

Several operational strategies could be applied to address range issues due to battery degradation over time. For example, buses could charge mid-day, particularly on demanding routes, when batteries start to degrade. Buses with new batteries could also be chosen to operate on the most demanding routes, Route 5 and Route 2A.

In summary, Route 1 and Route 13 are the preferred routes to electrify early because the range of the 12m 324 kWh battery e-bus exceeds the daily range required and will meet the operational need till the end of the battery useful life. E-buses deployed in Route 5 and Route 2A will need additional midday charging to cover their daily operation.

Battery capacity can also be sized for the range requirement of a particular route, meaning shorter routes may be serviced with a smaller and cheaper battery. In this study, the 324-kWh bus can serve Route 1 at 100% passenger capacity for the entire useful life of the battery. It may be possible to find a bus with a smaller battery that would cover a large portion of the useful life and complement operational requirements with mid-day charging at a lower capital cost. The identification of routes which may be candidates for this operational strategy would require additional analysis.

Route-level TCO analysis

The route-level analysis estimates the TCO of a diesel and electric 12 m low-deck bus with air conditioning installed and operating with a full passenger load.
The TCO estimate is broken down into seven categories: vehicle acquisition, infrastructure acquisition, fueling/energy cost, maintenance cost, engine overhaul or battery replacement costs, staff cost, and other taxes and fees, as detailed in the methodology section.

The TCO calculation is based on the current Transjakarta contract duration of 7 years for a diesel bus. The 7-year TCO for an e-bus does not include battery replacement (midlife) cost since the battery will be replaced in the 9th year of battery lifetime. E-buses with contract durations of 10 and 15 years are also presented and compared with current diesel bus contract. Energy consumption costs for each of the routes (1, 5, 13, and 2A) is based on 100% passenger loads for e-bus (1.05, 1.06, 1.14, and 1.04 kWh/km, respectively) and for diesel bus (0.49, 0.5, 0.48, and 0.53 DLE/km), respectively.

As shown in Figure 11, the TCO difference between a diesel and e-bus with a 7-year contract duration ranges from 19% to 23% in favor of conventional diesel buses. Route 13 has the lowest TCO difference, and Route 5 has the highest, compared to diesel baseline. Route 2A has the second lowest TCO/km difference, but it was determined in the range analysis that this Route will require additional charging or a higher battery capacity to match diesel operational range.

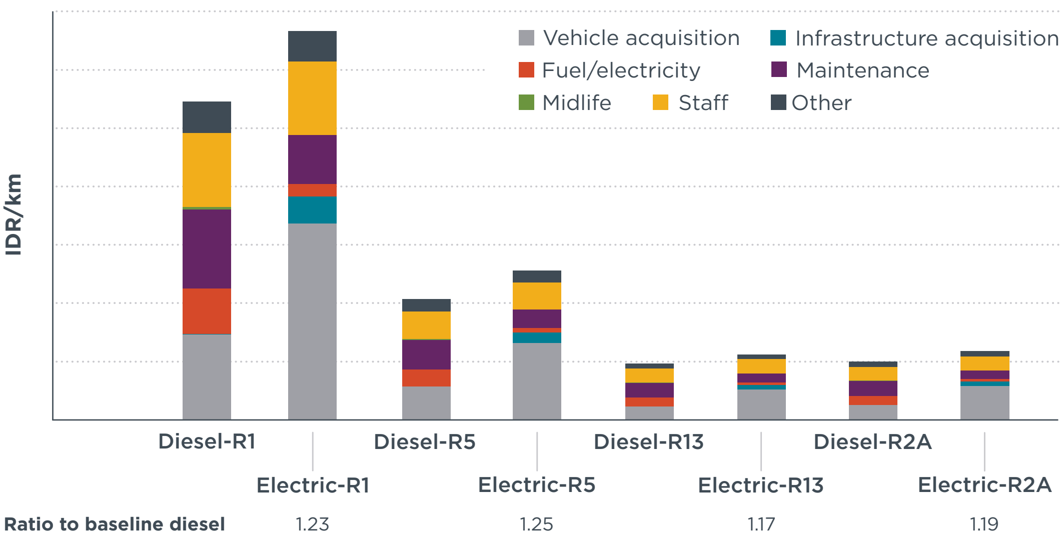


Figure 11. Route-level total cost of ownership of a diesel and electric bus, assuming a contract duration of 7 years. Costs do not include indirect overhead or accidental costs.

Figure 12 shows the TCO per km of operation, which is derived by applying the annual vehicle kilometer traveled as determined by GPS data, to the TCO calculation. Values in the TCO/km figures represent the same diesel and bus difference as in the TCO calculation result. The ratio between diesel and e-bus remains the same, in favor of diesel, as shown in the absolute TCO figure above.

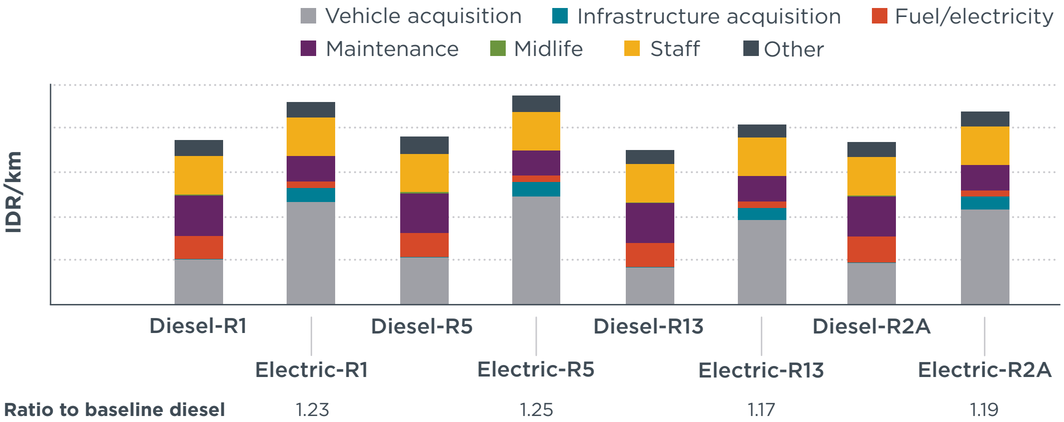


Figure 12. Route-level TCO of a diesel and electric bus per km traveled, assuming a contract duration of 7 years. Costs do not include indirect overhead or accidental costs.

Total cost of ownership per km with longer contract duration

Cities that have incorporated thousands of e-buses in their fleets have incentivized this technology by offering contracts that are 4–5 years longer than those offered for conventional buses. For example, Bogotá and Santiago offer contracts of 14 and 15 years, respectively, for operators offering battery-electric bus service, while diesel bus services are typically set at 10 years.[29]

The current contract length for buses operating in DKI Jakarta Province is 10 years for e-buses and 7 years for diesel. For some of the routes studied, the TCO per km can be lower for e-buses compared to diesel with an extended 10-year contract, and all of them will be lower than diesel when contracts are extended to 15 years (Figure 13).

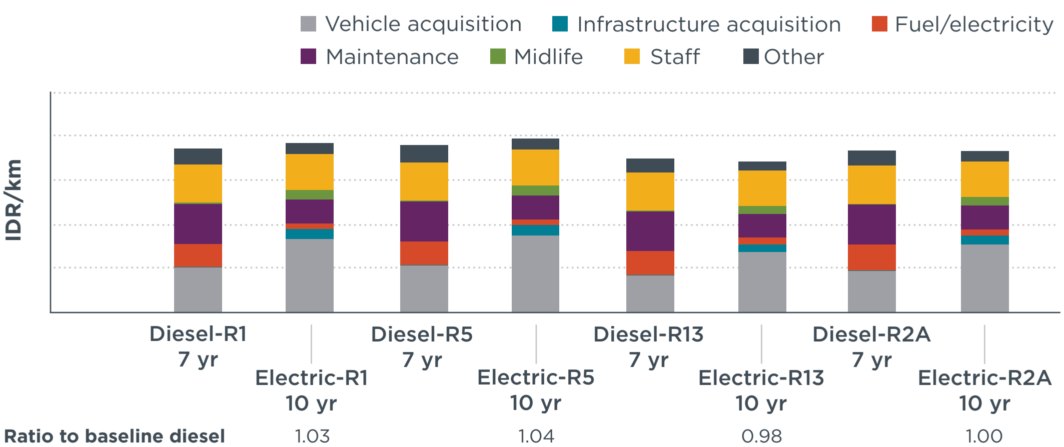


Figure 13. Route-level TCO per km travelled, assuming a contract duration of 7 years for diesel buses and 10 years for e-buses. Costs do not include indirect overhead or accidental costs.

Extending the contract duration to 10 years for e-bus helps to reduce their TCO/km compared to diesel buses, even when including battery replacement cost in the 9th year of ownership (Figure 14). Based on the modeling, a lower cost of ownership per

29 Yihao Xie, Francisco Posada, Adhi Triatmojo, Mega Kusumaningkatma, and Ahmad Safrudin, *Guidelines for Electric Bus Procurement in Jakarta*, (Washington, DC: ICCT, 2023). https://theicct.org/publication/asia-pacific-hvs-guidelines-jakarta-bus-jan23/.

km can be seen for e-buses servicing Routes 13 and 2A, although buses servicing Route 2A will require additional charging during the day to accommodate its high daily mileage.

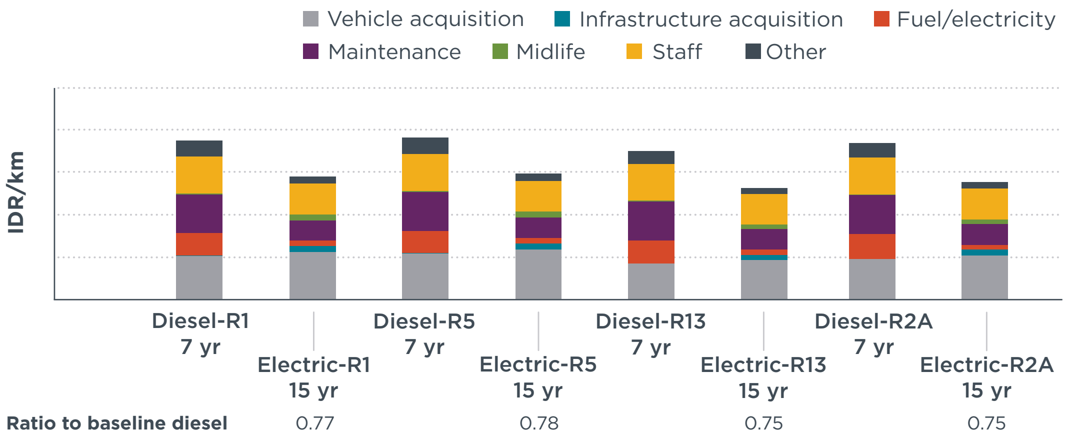


Figure 14. Route-level TCO per km travelled, assuming a contract duration of 7 years for diesel buses and 15 years for e-buses. Costs do not include indirect overhead or accidental costs. Shaded boxes contain confidential information.

Extending the bus contract duration to 15 years, while keeping the diesel bus contract duration at current levels (7 years) results in positive TCO/km results for the e-bus. The cost reduction through using e-bus fleets in the routes are ranging from 23% to 25%. The extension of contract durations to 15 years for e-buses are a common practice globally. The reduced TCO/km values in earlier years of ownership allows for saving in advance to pay for the cost of battery replacement.

Figure 15 shows a comparison of contract duration for BEBs. Extending the contract to 15 years will reduce the TCO/km by 36%–37% if compared to e-bus with a 7-year contract duration. It also suggests that the benefit is mostly independent of route characteristics.

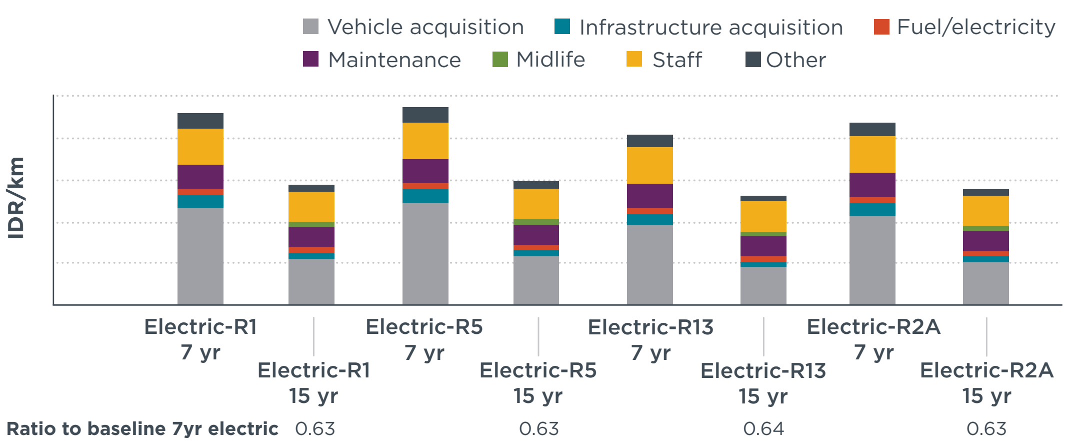


Figure 15. Comparison of the TCO per km for e-buses with a 7-year and 15-year contract duration. Costs do not include indirect overhead or accidental costs.

Conclusions and recommendations

This study assessed the operational viability of transitioning from diesel buses to e-buses on specific routes in the Transjakarta bus system. Simulation software was used to estimate the energy consumption and e-bus range for four routes. **Results of the range analysis suggest that Routes 1 and 13 can be operated by a 324 kWh 12 m e-bus without major operational adaptation.** Meanwhile, e-buses servicing Routes 5 and 2A may need additional charging or higher battery capacity batteries, which would have cost and weight impacts.

The TCO for each of the routes was also evaluated. If comparing diesel and e-buses with the same contract duration, the TCO difference of using e-buses is unfavorable by 19%–23. When the comparison is done between the current 7-year contract length for diesel buses and a 10-year contract for e-buses, the TCO/km for e-buses becomes more competitive, although still slightly higher than diesel buses (only Route 13 presents a lower TCO for e-buses under this scenario). **Extending the e-bus contract duration to 15 years results in a TCO per km 23-25% lower than for a diesel bus at 7 years, even after including the additional costs of battery replacement.** Extending contracts to 15 years for e-buses is a common practice in Latin American countries and allows bus operators to optimize operational cost savings in the earlier years of ownership and cover the cost of battery replacement.

It is important to analyze the possibility of transitioning to e-buses for use in Transjakarta BRT routes, since each route presents different driving dynamics and operational challenges for e-buses. **Route-level TCO analysis can be one of the most cost-effective methods to help identify and address e-bus operational and economic challenges for individual routes, particularly in advance of e-bus pilot projects**. **Expanding this type of analysis to other Transjakarta serviced routes will be beneficial to bus operators in planning their transition to 100% e-bus fleets.**

Appendix: Bus specifications

Parameter	Diesel bus	Electric bus
Total length (meter)	12	11.94
Total height (meter)	3.3	3.4
Total width (meter)	2.472	2.5
Wheelbase (meter)	5.95	6.1
Curb weight (kg)	13840	13760
Gross vehicle weight (kg)	16000	16000
Rear axle ratio	5.875	4.484
Transmission gear ratio	26.2	n/a
Seated passenger capacity	24	24
Standing passenger capacity	26	26
Tire size	295/80	275/70
Tire radius	22.5	22.5
Battery manufacturer		BYD
Battery model		Conductive
Battery nominal voltage (V)		540
Battery chemistry		LFP
Battery capacity (kWh)		324
Battery capacity (Ah)		600
Number of packs		1
Motor manufacturer		BYD
Motor model		PMSM
Motor location		Axle
Motor power – Nominal (kW)		150
Motor power – Peak (kW)		180
Motor torque (Nm)		800