FEBRUARY 2023

ZEBRA

ZERO EMISSION BUS
RAPID-DEPLOYMENT ACCELERATOR

# Operational analysis of battery electric buses in São Paulo

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**Acknowledgments:** Technical study developed for São Paulo Transportes S/A (SPTrans) as part of the ZEBRA initiative (Zero Emission Bus Rapid-deployment Accelerator). Funding for this work was generously provided by P4G, iCS (Instituto. Clima e Sociedade), and TUMI (Transformative Urban Mobility Initiative). The authors are grateful to Simão Saura Neto and SPTrans' engineering team, Paulo Lima and Transwolff's team, and BYD Brazil for the discussions and data provided.

**ZEBRA:** The ZEBRA (Zero Emission Bus Rapid-deployment acceleration) initiative is co-led by C40 Cities and ICCT and supports the transition to zero emission buses in Latin American cities, including the city of São Paulo.

This report was originally published in Portuguese in November 2022 and titled "Análise operacional de ônibus elétricos a bateria em São Paulo".

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## 1. INTRODUCTION

Several cities around the world have electrified their urban bus fleets to reduce the negative effects of pollutant emissions on the environment and on the health of the population. The city of São Paulo has advanced in this direction, having started operating a pilot fleet of battery electric buses in 2019. This report evaluates the operational performance of 2 of the 18 electric buses in this pilot project, monitored by telematics equipment.

In 2018, Law No. 16,802 was approved in the city of São Paulo. It requires that bus transit operating companies gradually reduce emissions of air and climate pollutants from their fleets. The pilot project is part of the city's effort to improve the environmental performance of its urban buses and adapt its public transportation system to the current legislation. In addition to generating zero tailpipe emissions, electric buses offer great potential to reduce emissions of climate pollutants across the energy life cycle due to the high percentage of electricity generated from renewable sources in Brazil.

São Paulo has the largest bus fleet in the country and one of the largest in Latin America, with approximately 14,000 vehicles, over 98% of which run on diesel (São Paulo Transportes, 2022). The small share of alternative transportation technologies consists of 201 trolleybuses and the 18 battery electric buses of the pilot project.

Since January 2021, the operation of two electric buses has been monitored by telematics equipment, which collects data on their position, the performance of their electric motors, and their energy consumption in real time. This report presents an exploratory analysis of these data. It evaluates the performance of the electric buses monitored over time and under different operating conditions, in addition to analyzing the charging strategies adopted.

The next section presents a literature review, identifying the main factors that influence the energy consumption of battery electric buses. Section 3 contextualizes the electrification of transit buses in the city of São Paulo. Section 4 presents the telematics data used in this study and assesses the operational performance of the monitored buses. Section 5 concludes the study.

## 2. LITERATURE REVIEW

Diesel buses are still widely used in public transport. They emit greenhouse gases and pollutants that are harmful to human health (Bakker & Konings, 2018). Zero-emission alternatives, such as battery electric buses, are now available and gaining market share in different countries. In addition to helping to reduce atmospheric pollution by not generating exhaust emissions, these alternatives have better energy performance compared to conventional technologies (Lajunen & Lipman, 2016; Zhou, Wu, et al., 2016).

Brazil, which predominantly uses renewable sources to generate electricity, is considered ideal for the adoption of electric buses (Correa et al., 2019). However, the implementation of these buses on a larger scale still faces barriers, such as the buses' high cost and limited range. The high price is due mainly to the costs of some parts of electric buses (especially the battery) and to their production being on a smaller scale (Bakker & Konings, 2018; Lajunen, 2014).

Range of electric buses is a barrier because it is shorter than that of equivalent internal combustion vehicles. Vehicle range results from the balance among several variables, including capacity, weight, volume, and cost. Batteries with smaller capacities can reduce costs and increase energy efficiency because they are lighter (Lee et al., 2021). Larger batteries, besides having higher costs, add weight and volume to buses, which can reduce their passenger capacity (Bakker & Konings, 2018). As buses generally travel known, fixed, and recurring routes, it is possible to modify typical routes (Wenz et al., 2021) or to adopt strategies in choosing technology and routes to achieve greater operational efficiency (Papa et al., 2022).

One of the main advantages of battery electric buses, compared to conventional buses, is their low energy consumption, which reduces their operating costs significantly (Feng & Figliozzi, 2013; Hellgren, 2007). Lajunen (2014) points out that the energy consumption of electric vehicles can be up to five times lower than the consumption of diesel buses considering equivalent operation. In a previous study, the ICCT ran simulations for some bus routes in the city of São Paulo, and the estimates indicated that the energy consumption of electric battery buses would be 28% of the consumption of diesel buses (Eufrásio et al., 2022).

Studies with internal combustion vehicles have shown that energy consumption is influenced by factors belonging to the following categories: travel, weather, vehicle, roadway, traffic, and driver (Ahn et al., 2002; Zhou, Jin, & Wang, 2016), as depicted in Figure 1. Together, these categories encompass variables such as speed, acceleration, weight carried, and outside temperature. De Abreu e Silva et al. (2015) point out that the main variables that impact the energy efficiency of electric buses are the model and weight of the vehicle, the average speed of operation, road grade greater than 5%, and the characteristics of the routes. Wang et al. (2020) add the relevance of driving styles, weather factors, schedules (night or day operation) and days of the week (weekend or weekday operation) in their analyses of energy consumption.

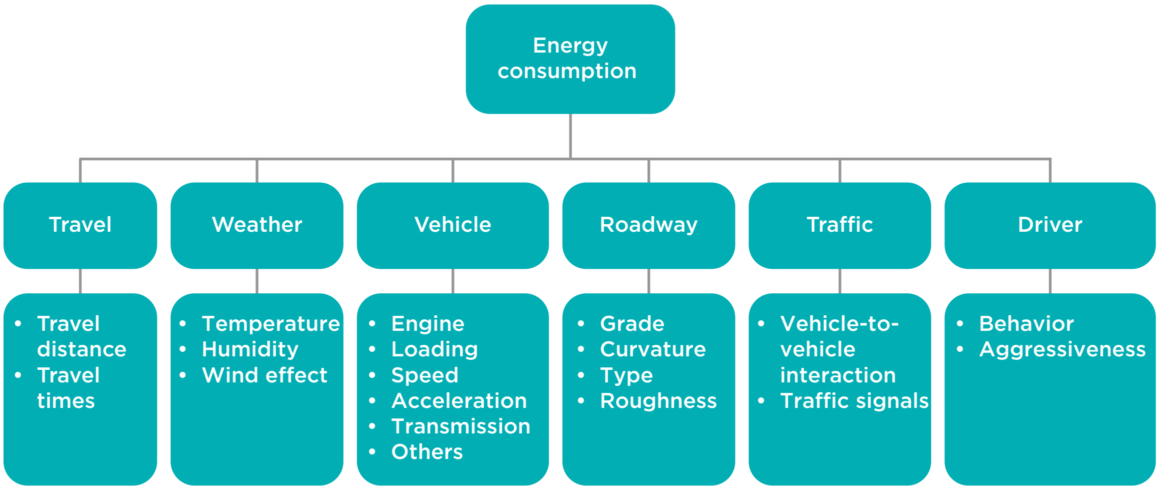


**Figure 1.** Factors that influence the energy consumption of a vehicle (adapted from Zhou, Jin, & Wang, 2016)

De Abreu e Silva et al. (2015) report that, for urban buses, higher speeds are more associated with fewer stops and fewer acceleration and deceleration events than they are with a higher cruising speed. In general, higher commercial speeds favor the energy performance of urban buses. The authors point out that increasing the distance between bus stops, despite contributing to reducing energy consumption, reduces accessibility, which can negatively affect the passenger experience and reduce demand.

Some strategies may facilitate operation at speeds that favor lower energy consumption, such as the implementation of bus-only lanes (Hu et al., 2012). Evaluating the case of battery electric buses in more detail, Fiori et al. (2021) observed that a 13% saving in energy consumption could be achieved, depending on the speed adopted. Wang et al. (2020) observed 19.5% higher energy performance when applying an optimal speed strategy.

Driving style and traffic conditions influence speed variation, acceleration and deceleration patterns and, consequently, energy efficiency (Wang et al., 2020). Perrotta et al. (2014) conclude that more aggressive behavior in traffic leads to worse performance and a lower potential for regenerating energy during braking, which increases energy consumption by up to 14%.

Regenerative braking technology consists of recovering part of the energy used by the vehicle through braking events. This mechanism, present in battery-powered electric buses, is essential for reducing energy consumption. In their simulations, Kusuma et al. (2021) obtained a reduction in energy consumption of nearly 15% when using regenerative braking strategies. In a pilot test carried out in Buenos Aires, 43% of the energy consumed was recovered with this type of braking (Maio et al., 2021).

The slope of the route also has a major effect on vehicle energy consumption and regenerative braking performance (Bian & Qiu, 2018). Sagaama et al. (2020) demonstrate that negative slopes favor energy recovery by electric vehicles, while values are close to zero when the uphill slope is greater than 8%.

Some studies analyze the effect of temperature and weather conditions on the performance of electric buses. Wang et al. (2020) point out that electric vehicles are less energy efficient in warmer seasons. However, Chikishev (2021) observes that a large part of the variation in energy consumption with temperature is due to the use of auxiliary equipment, such as air conditioning, which can increase consumption by up to 14%. Gao et al. (2019) estimate that 20% to 25% of the energy is consumed by auxiliary equipment in battery electric buses. A field test conducted in Uruguay found a 21% increase in energy consumption of electric buses with the use of air conditioning (Uruguay, 2013).

Table 1 presents information on the energy performance of battery electric buses used in public transport in different regions. Considering cases in which the bus size was similar to the one analyzed in this study (12 m), it was found that the average consumption varied between 0.86 kWh/km and 1.26 kWh/km. As discussed above, energy performance depends not only on the technological characteristics of the bus but also on operating conditions. Climate conditions, driving style, and driving cycle (route, frequency of stops, elevation) are some of the factors that explain variations in energy consumption. These variations are expected even for the same bus operating on a specific route.

**Table 1.** Energy performance of battery electric buses implemented in the public transport system of different regions

| Operation monitored | Features of the monitored buses | Energy consumption | Reference |
|---|---|---|---|
| **Montevideo, Uruguay 11/2013 to 12/2013** | 2 BYD K9 buses (12 m)<br>324 kWh battery | Average of the buses: 1.26 kWh/km<br>Impact of air conditioning + 21% (test with internal temperature of 20ºC and external temperature of 29.4ºC) | Uruguay (2013) |
| **Buenos Aires, Argentina 05/2019 to 03/2020** | 2 Yutong ZK6128BEVG buses (12 m)<br>324 kWh battery | Lowest monthly average: 0.91 kWh/km<br>Highest monthly average: 1.12 kWh/km<br>Impact of air conditioning: + 9.3% (maximum monthly percentage observed) | Maio et al. (2021) |
| **Santiago, Chile 11/2017 to 10/2018** | 2 BYD K9FE buses (12 m) | Average of the buses: 1.006 kWh/km | Galarza (2020) |
| **Long Beach (CA), United States 01/2019 to 12/2019** | 10 BYD 2017 6120 LGEV buses (12 m)<br>324 kWh battery (original) but 360 kWh total capacity (supplement) | Highest annual average: 1.26 kWh/km<br>Lowest annual average: 1.14 kWh/km | Eudy & Jeffers (2020) |
| **Shenzen, China 01/2019 to 12/2019** | 6,053 buses (13 models, from BYD and NJGD, from 6.8 m to 12 m).<br>67% of the fleet: BYD K8 (10.5 m) | Lowest monthly average: 0.86 kWh/km<br>Highest monthly average: 1.08 kWh/km<br>Energy consumption in summer is 19.3% higher than in other seasons | World Bank (2021) |

## 3. THE ELECTRIFICATION OF BUSES IN THE CITY OF SÃO PAULO

Through Law No. 16,802/2018, the city of São Paulo amended an article of its Climate Change Law (Law No. 14,933 of 2009), defining new targets for reducing emissions of fossil carbon dioxide ($CO_2$), particulate matter (PM), and nitrogen oxides ($NO_x$). The law establishes that tailpipe emissions of fossil $CO_2$, PM, and $NO_X$ be reduced by 50%, 90%, and 80%, respectively, in 10 years; it also establishes that tailpipe emissions of fossil $CO_2$ be eliminated and that $NO_X$ and PM emissions be reduced by 95% at the end of 20 years. Despite setting targets only for tailpipe emissions, the law determines that the choice of technology must prioritize the reduction of fossil emissions in the life cycle of the energy source, within acceptable costs.

Public transport services in São Paulo are made possible through 15-year bidding contracts, signed in 2019 between city hall and private companies. The contracts establish annual targets for reducing pollutant emissions, thus adding other obligations to the 10 and 20-year targets established by Law No. 16,802/2018.

A contractual requirement is the submission of fleet replacement plans to SPTrans, the city's transit authority, demonstrating how each bus operator intends to meet the emissions reduction targets. The plans were presented in 2020 and relied mainly on the adoption of battery electric buses in the following years. However, the Covid-19 pandemic brought several challenges to this technological transition. Some contractual conditions were made more flexible. The purchase of new vehicles was prohibited during the emergency, and the average age of the fleet increased temporarily from 5 to 7 years (Portaria da Secretaria Municipal de Mobilidade e Transportes nº 81/2020). Even in this scenario, the city has reiterated its commitment to the transition to a cleaner fleet. The city government included in its program of goals the intention to deliver 2,600 electric buses by the end of the current mayor's term, in 2024 (São Paulo, 2021).

Seeking to adapt the bus transport system to current legislation, SPTrans conducted several tests with battery electric buses between 2014 and 2018. In October 2018, the municipality launched, in partnership with manufacturer BYD, the pilot project that added 18 battery electric buses to the Transwolff fleet between 2019 and 2021. The selected route was 6030-10 (Unisa–Campus 1/Terminal Santo Amaro), which is operated by basic buses every day of the week and is about 30 km long. Its route is shown in Figure 2. The average distance between bus stops on this line is 388 meters.

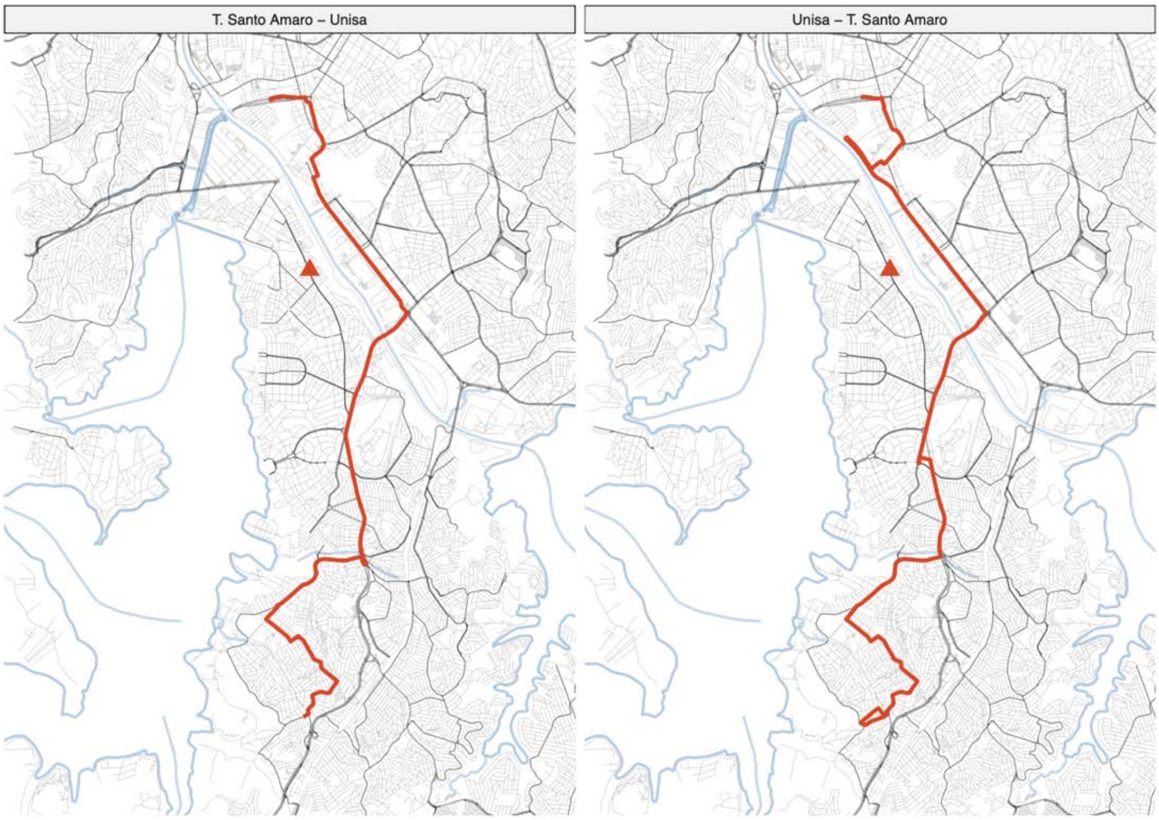


**Figure 2.** Route of line 6030-10 and indication of the garage (represented by the triangle)

The electric buses in the pilot project were produced by BYD in partnership with Caio and Marcopolo, two Brazilian bus manufacturers. Of the 18 buses, 12 have bodies from Caio and 6 have bodies from Marcopolo. The buses are of the padron type, 12.9 m long, but their designed capacity of around 80 passengers had to be restricted due to weight limitations. From 70 to 72 passengers are transported depending on the body of the bus. Therefore, in terms of passenger capacity, the buses are more similar to the basic model; however, in terms of comfort and accessibility, they are equivalent to the padron. There is a small difference in weight between the vehicles: one weighs 14,750 kg, and the other, 14,937 kg.

To reduce the capital cost of the project, the bus operator purchased the vehicles without the batteries. These were leased for the service life of the bus (15 years) with monthly payments. BYD owns all batteries and is responsible for their proper operation throughout the project. The buses are recharged at the Transwolff garage, mainly at night and during off-peak hours (the peak hours are between 5:30 pm and 8:30 pm in the city of São Paulo).

# 4. EVALUATION OF THE BUS OPERATIONS

This study analyzes operating data from two Transwolff battery electric buses that belong to the São Paulo pilot project fleet detailed in the previous section. The two buses analyzed have BYD chassis. One has a Marcopolo bodywork and the other has a Caio bodywork. Both are anonymized throughout this report.

Data were collected with a telematics device installed on each bus, the Geotab GO9. The method of collection used by the device does not adopt a fixed frequency. For each variable, new observations are recorded only when relevant variation is detected. In this way, storage is optimized and the collection maintains high accuracy since critical values are not lost and intermediate values can be estimated from interpolations. Technical details of the device and more information about the method of collection are presented in Appendix I.

The collection took place in real time from January 21 to December 31, 2021. Days with less than 50 km of operation by bus (which represent 10.5% of the observations) are excluded from the sample.[1] The variables analyzed were constructed based on GPS and energy data. This section analyzes the operational performance and energy consumption of the monitored buses, in addition to the charging strategy adopted.

## 4.1 OPERATIONAL PERFORMANCE

Table 2 presents a summary of the operation of the two electric buses monitored and Figure 3 displays a histogram showing the distribution of distances covered daily.

**Table 2.** Daily operation of the buses monitored (January, 2021 to December, 2021)

| Bus | Number of days | Daily distance (km) Average [min.–max.] | Number of trips per day (round trip)[a] Average [min.–max.] | Daily duration of the operation (hours)[b] Average [min.–max.] | Speed (km/h)[c] Average [min.–max.] |
|---|---|---|---|---|---|
| **1** | 325 | 177.1 [50.6–261.0] | 5.0 [1–7.5] | 12.6 [4,3–18.2] | 14.1 [6.3–18.3] |
| **2** | 291 | 166.1 [52.8–261.2] | 4.7 [1–7.5] | 12.2 [4.0–22.2] | 13.6 [4.4–17.4] |

a. Number of trips obtained from the GPS data of the actual operation and the data of the planned bus route. Information made available by SPTrans (data from General Transit Feed Specification, GTFS2).

b. Daily time with the ignition on.

c. The average speed was calculated by dividing the distance traveled per day by the daily operational time.

1 Days with low recorded mileage, considered outliers, may be those in which the bus was inoperative due to a technical problem or scheduled maintenance.

2 Retrieved October 7, 2022, from http://www.sptrans.com.br/desenvolvedores/.

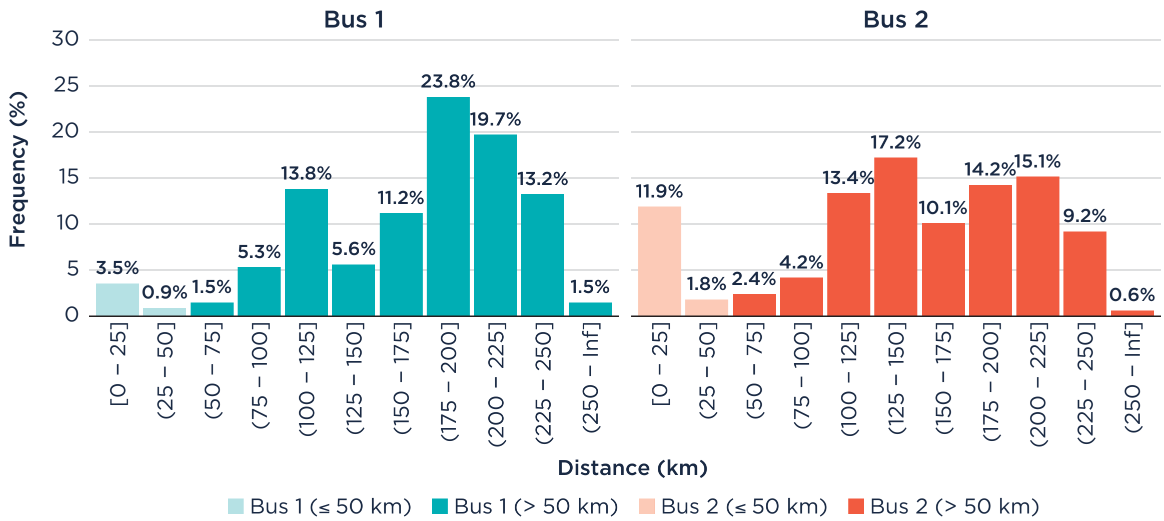


**Figure 3** – Daily distances covered by the buses. The days when the distance covered was between 0 km and 50 km, highlighted in lighter colors, were excluded from the sample analyzed in the study.

As can be seen in Table 2, the average daily distance traveled by Bus 1 is 177.1 km and by Bus 2 is 166.1 km. The maximum daily distance is 261.2 km. Concerning the distribution of distances, Figure 3 shows that Bus 1 traveled between 100 km and 250 km on 87.3% of the days observed, while Bus 2 operated on the same range on 79.2% of the days. Buses on the same route can cover different daily distances, as the number of vehicles in operation can vary throughout the day. At peak hours, for example, there are usually more buses in service.

Table 2 also shows that each bus on the 6030-10 route makes an average of 5 trips per day. On some days, the buses completed 1 to 7.5 trips. Regarding the duration of operation, the ignition of the buses remains switched on for just over 12 hours a day on average; however, hours in operation can range from 4 to 22.2 hours. The average speed is 14.1 km/h for Bus 1 and 13.6 km/h for Bus 2.

### 4.2 ENERGY PERFORMANCE

As discussed in the literature review (section 2), the energy consumption of electric buses is influenced by several technical and operational factors. Technical factors include characteristics such as engine power, vehicle weight, and battery capacity. Operational factors, on the other hand, refer to variables associated with vehicle use—speed, gross transported weight, use of air conditioning and external temperature, use of other accessories, traffic jams, and driving style—as well as characteristics of the bus route, such as the number of scheduled stops and the elevation profile.

At this stage of the study, exploratory analysis is carried out to characterize the behavior of energy consumption and verify its correlation with other variables, without establishing cause-and-effect relationships. Table 3 presents energy performance indicators of the two battery electric buses monitored.

**Table 3.** Energy performance of the buses monitored (January, 2021 to December, 2021)

| Bus | Net energy per day (kWh)[b, f] Average[a] [min.–max.] | Daily energy consumption (kWh/km)[c] Average[a] [min.–max.] | Energy regenerated per day[d] Average[a] [min.–max.] | Energy consumed daily in idle period[e] Average[a] [min.–max.] |
|---|---|---|---|---|
| **1** | 224.40 [58.9–340.4] | 1.19 [0.94–1.94] | 40.7% [29.0%–49.2%] | 9.6% [0%–40.2%] |
| **2** | 224.35 [79.6–320.7] | 1.27 [0.99–2.29] | 38.6% [17.2%–48.1%] | 11.9% [0%–35.4%] |

a. The averages displayed are weighted by the daily distance covered.

b. Net energy is equal to the total energy spent by the battery to power the bus minus the total energy generated by regenerative braking over the day.

c. Energy consumption is calculated by dividing the net energy by the distance traveled.

d. The regenerated energy share is the energy recovered by regenerative braking divided by the total energy spent by the battery over the day.

e. The idle period refers to the moments when the bus is stopped (speed equal to zero) with the ignition on.

f. The average gross energy consumed per day (not discounting the regenerated energy) can be calculated by equation. $\frac{\textit{ENet Energy}}{\textit{1-\% Regenerated Energy}}$ The average is 379.8 kWh for Bus 1 and 366.4 kWh for Bus 2 (average weighted by the daily distance traveled).

Table 3 shows that the average daily net energy is 224.4 kWh for Bus 1 and 224.35 kWh for Bus 2, with a maximum of 340.4 kWh. The battery capacity of these buses is 324 kWh; however, part of this capacity is not usually accessed during actual operation due to the technical reserve. This reserve is indicated both to ensure that drivers can return to charging points safely and to preserve battery health and prevent rapid degradation. Manufacturers recommend that batteries not be completely discharged and that 10% to 20% of the state of charge be maintained in reserve (Grace, 2018; Lowell, 2019).

Table 3 also displays information on energy consumption per kilometer. On average, Buses 1 and 2 consume 1.19 kWh/km and 1.27 kWh/km, respectively. However, there is a wide range of values for this variable: between 0.94 and 1.94 kWh/km for Bus 1 and between 0.99 and 2.29 kWh/km for Bus 2. It is important to point out that the consumption measured by the telematics device considers only the inputs and outputs of the battery, and can be used to estimate the vehicle's range. However, this value is different from paid energy consumption, which includes charging losses. The energy calculated in the electricity bill includes the energy lost from the output of the electricity system to the charger and from the charger to the bus battery[3].

In the city of São Paulo, measuring energy consumption is part of the approval process for battery electric buses. Currently, the Standardized On-Road Test Cycle (SORT) is used for such measurement, more specifically the 2017 E-SORT protocol. Appendix II provides more details and the SORT test results for Transwolff BYD buses. As it is standardized, the test makes it possible to compare the energy performance and range of bus technologies, brands and models. In actual operation, however, different performances from those obtained in the test are expected due to the variation in operating conditions.

Table 3 also shows the percentage of energy recovered with regenerative braking. The average share of regenerated energy is 40.7% for Bus 1 and 38.6% for Bus 2, with values varying between 17.2% and 49.2%. Also, part of the energy was consumed during the idle period—9.6% for Bus 1 and 11.9% for Bus 2.

Table 4 shows the portion of monitored days in which the net energy was greater than the usable capacity of the battery, considering a technical reserve of 10% and 20%. In the two scenarios of technical reserve analyzed, there are days when the energy consumed was greater than the usable capacity of the battery. This is possible by performing intermediate recharges throughout the operation.

**Table 4.** Share of days when the energy consumed was greater than the usable capacity of the battery, considering scenarios of technical reserve (total battery capacity: 324 kWh)

| Scenario | Usable capacity of the battery (kWh) | Share of days when energy consumed was greater than usable capacity |
|---|---|---|
| **Battery technical reserve of 10%** | 291.6 | Bus 1: 3.4%<br>Bus 2: 4.5% |
| **Battery technical reserve of 20%** | 259.2 | Bus 1: 17.5%<br>Bus 2: 21.3% |

3 Losses vary with the configuration of the vehicle's electrical system and the charging infrastructure. There is still little research on energy losses in electric bus battery recharging. A study carried out by the ICCT in 2022 on battery electric trucks assumed charging losses of 15% (RAGON et al., 2022).

### 4.2.1. EVOLUTION OF ENERGY CONSUMPTION

Figure 4 presents the relationship between the daily distance covered and the energy consumption on the same day.

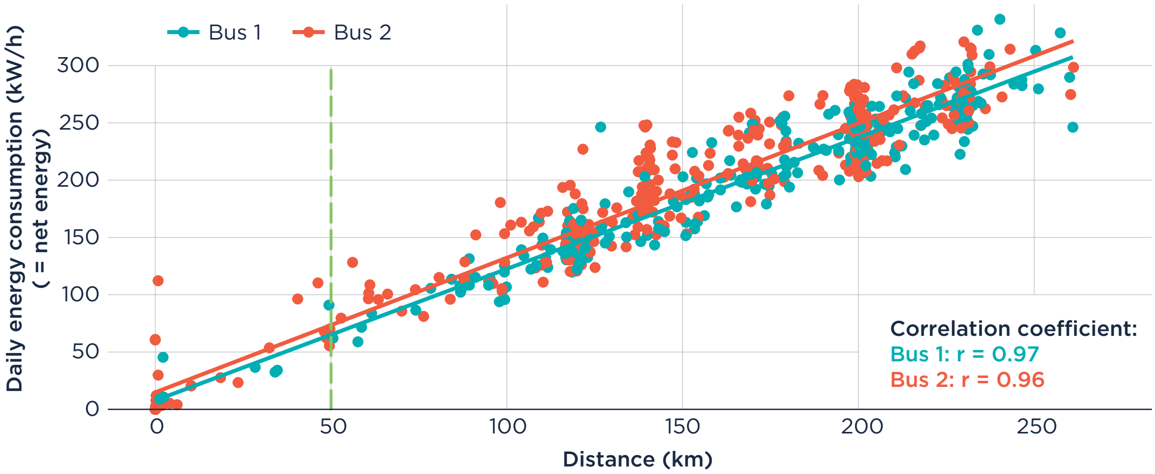


**Figure 4.** Relationship between energy consumption and daily distance

Coefficients close to 1 show a strong positive correlation between the variables, and energy consumption increases with greater distances. Observations to the left of the red dashed line point to daily distance traveled of less than 50 km and, as described earlier, have been excluded. On those days, the bus may have remained on for maintenance work, consuming energy, but with low mileage recorded. Keeping these observations would generate days with high levels of energy consumption per kilometer but would not be representative of the operation.

Figure 5 shows a histogram with the distribution of the daily energy consumption per kilometer. Days with low mileage are excluded from the sample.

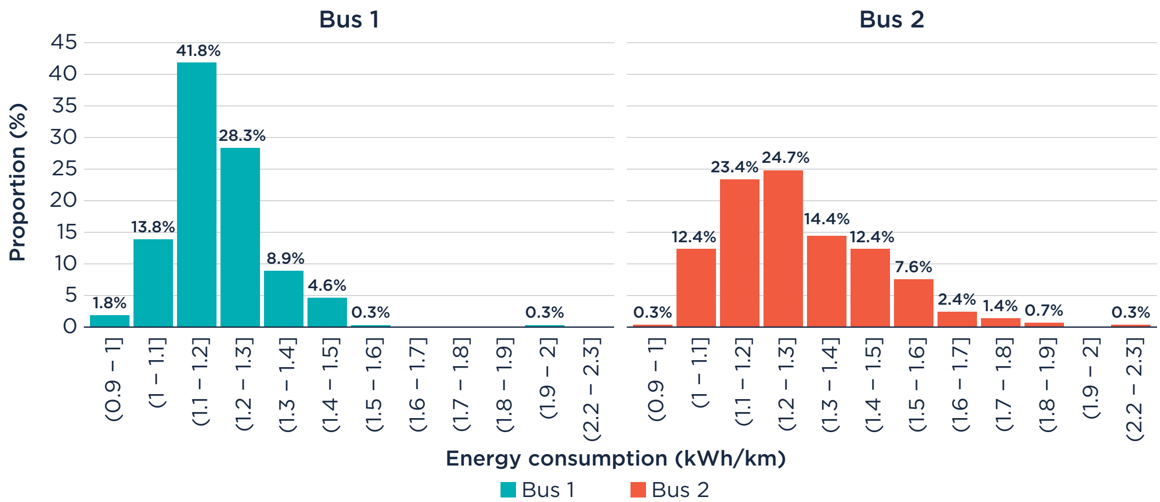


**Figure 5.** Daily energy consumption per kilometer

Bus 1 consumed less than or equal to 1.3 kWh/km on 85.7% of the days. The energy consumption of Bus 2 was within this range on 60.8% of the analyzed days. Days with over 1.5 kWh/km are less frequent for Bus 1 (0.6% of observations versus 12.4% for Bus 2). Figure 6 shows a box plot[4] of the daily energy consumption per kilometer of each bus for each month.

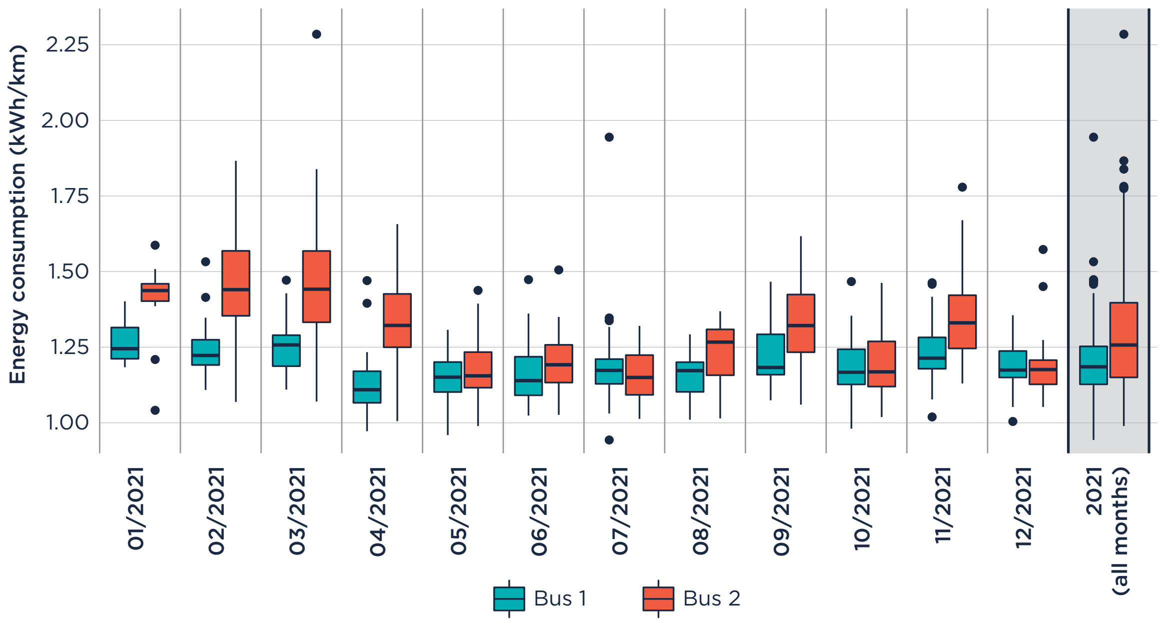


**Figure 6.** Daily energy consumption per kilometer over the monitored months, aggregated for 2021

4 The box plot represents the variation of the observed data, which makes it possible to analyze its dispersion and amplitude by quartiles graphically. Quartiles divide the ordered sample into four parts. The box is limited by the first and third quartiles, that is, 25% to 75% of the sample. The central line represents the median, the central value of the sample. The outliers are the individual points.

A lower average consumption can be seen from May onward, with a slight increase in August, September, and November. The season is one of the factors that influence energy consumption behavior. In the winter months, from June to August, temperatures tend to drop, and lower consumption of air conditioning is expected. A higher consumption pattern is observed mainly from January to April. Temperature and other relevant factors are discussed below.

In this study, it was not possible to obtain a variable that represented the load transported per bus. SPTrans made available the number of passengers transported per day, as shown in Appendix III; however, this information possibly is insufficient to represent the transported load. For the analysis of energy consumption, it is also important to consider the duration of passengers' commuting. Unfortunately, this study did not have access to information on the route and duration of passengers' commuting, nor on the variation in bus occupancy throughout the day, so this relationship is worthy of further analysis.

### 4.2.2. AMBIENT TEMPERATURE

This subsection explores in more detail the relationship between the temperature and energy consumption of buses. The analyzed buses are equipped with air conditioning, whose consumption tends to be higher on warmer days. To analyze the behavior of energy consumption in different climatic conditions, temperature information was collected from a meteorological station close to the route on which the buses operate, made available by the Brazilian National Institute of Meteorology (INMET).[5] Figure 7 shows the evolution of maximum and average daily temperatures in the period analyzed. Figure 8 shows the relationship between the average daily energy consumption and the daily maximum temperature.

5 Meteorological information collected at a station in the Interlagos neighborhood was used. The database contains hourly information on temperature, atmospheric pressure, precipitation and humidity, among other climate data. Data retrieved from https://portal.inmet.gov.br/dadoshistoricos.

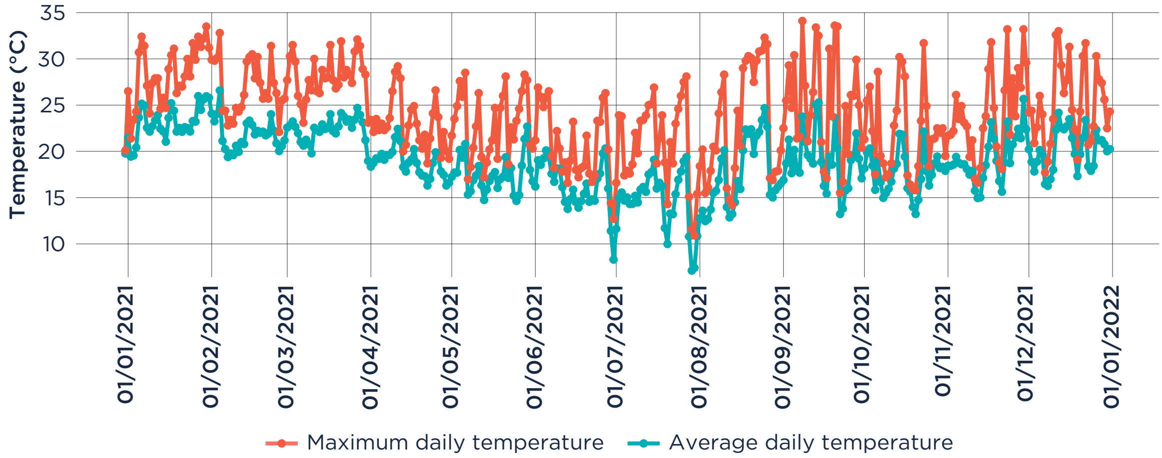


**Figure 7.** Daily maximum and average temperatures throughout 2021

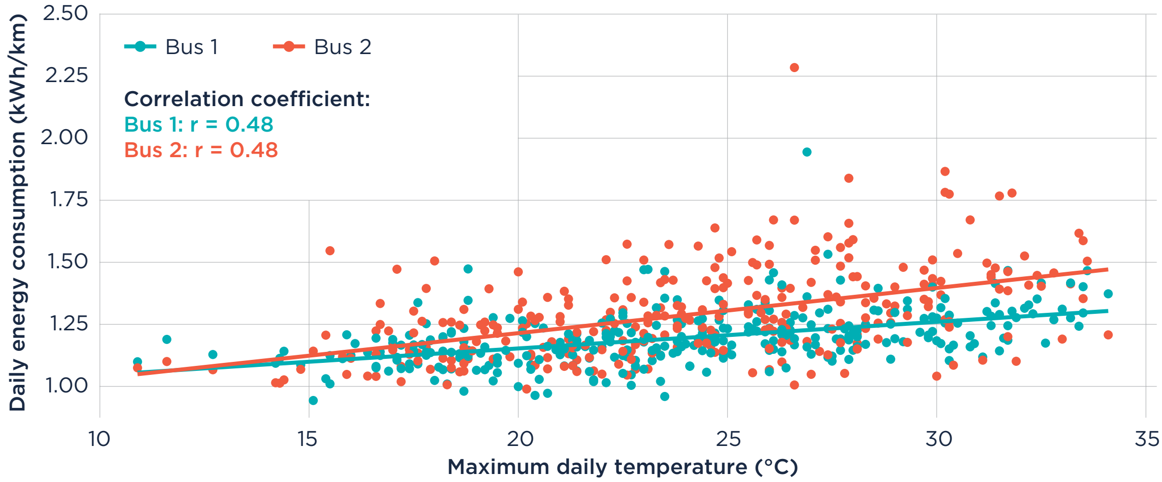


**Figure 8.** Relationship between daily energy consumption per kilometer by maximum daily temperature (in Celsius)

Note in Figure 8 that energy consumption per kilometer tends to be higher on days with higher maximum temperatures. Bus 2 tends to have higher consumption levels at higher temperatures than Bus 1. If this behavior is a consequence of differences in air conditioning systems, the air conditioning in Bus 2 is likely less energy-efficient than the one in Bus 1. Technical specification data is needed to draw further conclusions. However, in addition to the technical characteristics, other factors that were not controlled for may justify a higher energy consumption of the air conditioning, such as the weight carried, the temperature set, and even the frequency of door opening.

### 4.2.3. AVERAGE SPEED

Speed also influences energy consumption. Figure 9 presents a scatterplot of daily energy consumption and average operating speed.

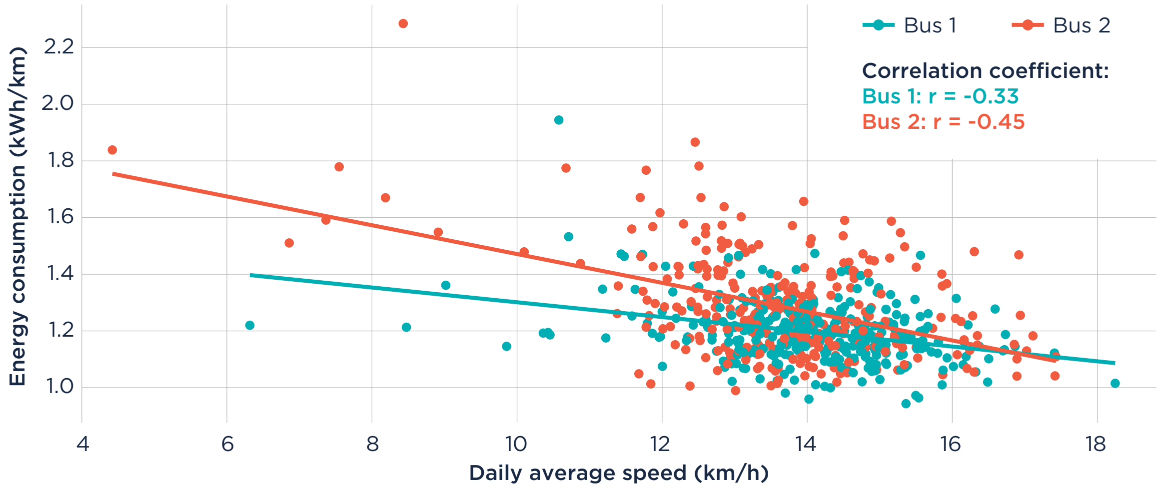


**Figure 9.** Relationship between daily energy consumption (kWh/km) and average operating speed (km/h) for each bus

Figure 9 indicates that, in this sample, average speed is negatively correlated with daily energy consumption. As discussed in the literature review (section 2), the low commercial speeds of urban buses are more associated with acceleration and deceleration events than with a lower cruising speed. Thus, higher speeds may indicate fewer acceleration oscillations and, consequently, lower consumption. The two monitored buses operate on the same line; therefore, they travel the same route. Although the bus stops are the same, variations in average speed can occur due to congestion, variations in demand, driving style, and frequency of passenger pick up and drop off.

It is important to emphasize that the average daily speeds vary little in the sample, with values between 12 km/h and 16 km/h on most days. In addition, the low correlation coefficient indicates a weak correlation. However, speed is not isolated from other variables. This analysis only displays a general trend, limited to the observed sample, and does not establish a causal relationship between speed and energy consumption.

### 4.2.4. REGENERATIVE BRAKING

Electric buses have a regenerative braking system that makes it possible to recover the kinetic energy generated during braking, which is converted into electrical energy and stored in the batteries. Because it depends on the frequencies and intensity of accelerations and decelerations, the performance of this system is directly related to characteristics of the route and driving, such as road grade, number of scheduled stops, the distance between stops, and driving style. These characteristics impact acceleration oscillations and thus the amount of energy regenerated by braking. Drivers accustomed to driving diesel buses need a period of adaptation to draw greater efficiency from electric vehicles.

Figure 10 shows a histogram of the daily percentage of energy regenerated by each bus. This percentage is calculated as the energy recovered during braking over the total energy consumed in a day.

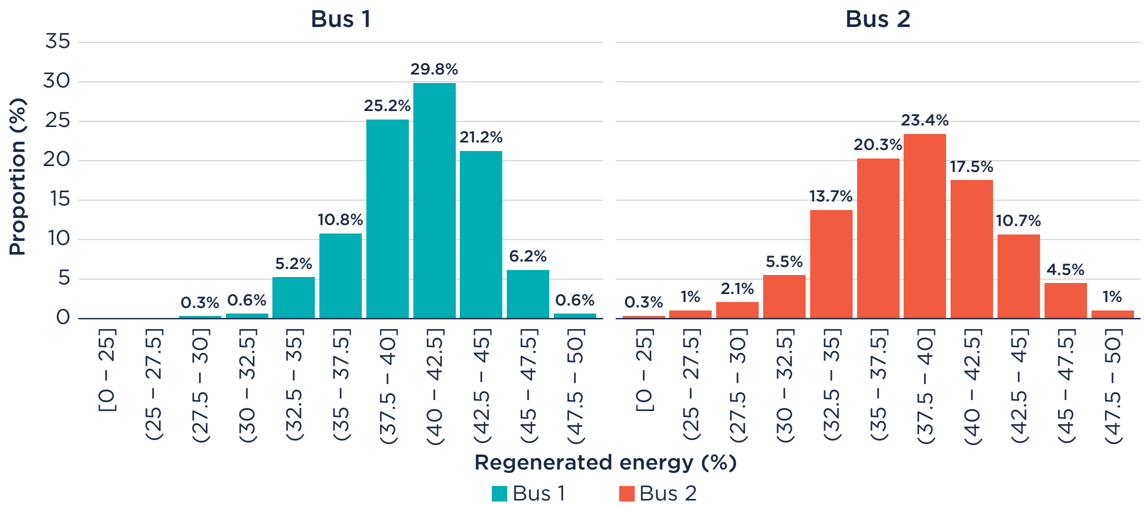


**Figure 10.** Distribution of the daily regenerated energy percentage

Figure 10 shows that the buses have a regenerated energy rate greater than 30% on most days monitored (99.7% for Bus 1 and 96.5% for Bus 2). Bus 1 had higher regeneration percentages in general: between 40% and 50% on 57.9% of its days, in contrast to 33.7% of the days monitored for Bus 2. Figure 11 displays a box plot per month and per vehicle, representing the distribution of the daily percentage of energy regenerated over the monitored months.

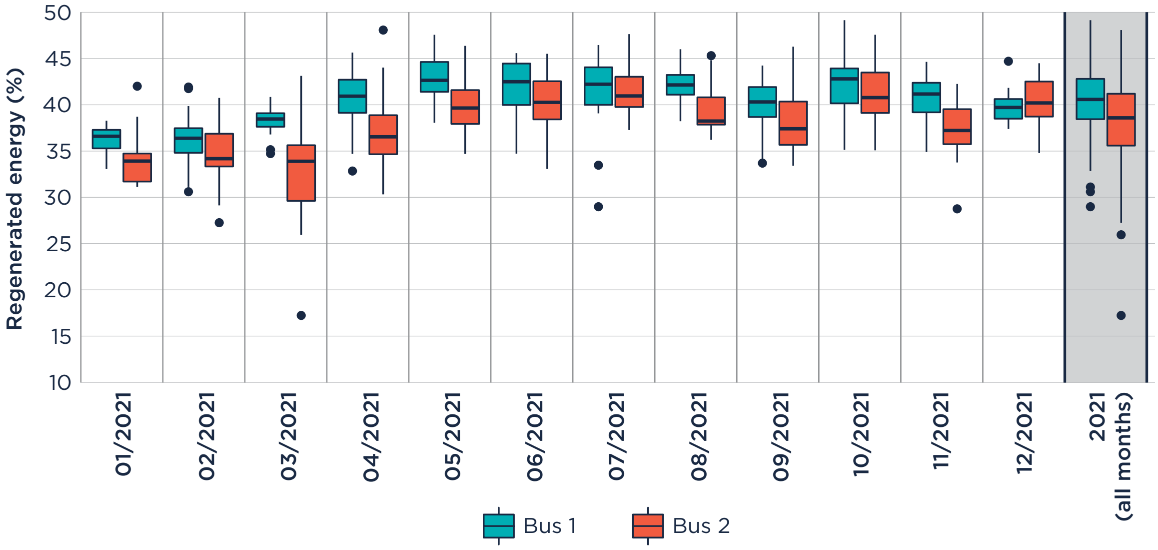


**Figure 11.** Distribution of daily energy regenerated by braking in each monitored month, aggregated for 2021

The results indicate that Bus 1 has higher percentages of regeneration in most months. There is a general increase in regeneration over time, which may reflect driver adaptation to operating electric vehicles and to regenerative braking.

### 4.2.5. ENERGY CONSUMPTION IN IDLE TIME

The idle period corresponds to the moments when the bus has the ignition on but with zero speed. This period includes stops for boarding and disembarking passengers, at traffic lights and in general operations, excluding times when the bus is off, which happens mainly in the garage. Energy consumption during idle time is mainly due to use of accessories, including the air conditioning and heating system, ventilation and lighting, among others. Figure 12 shows a histogram with the distribution of the percentage of energy consumption per day in the idle period.

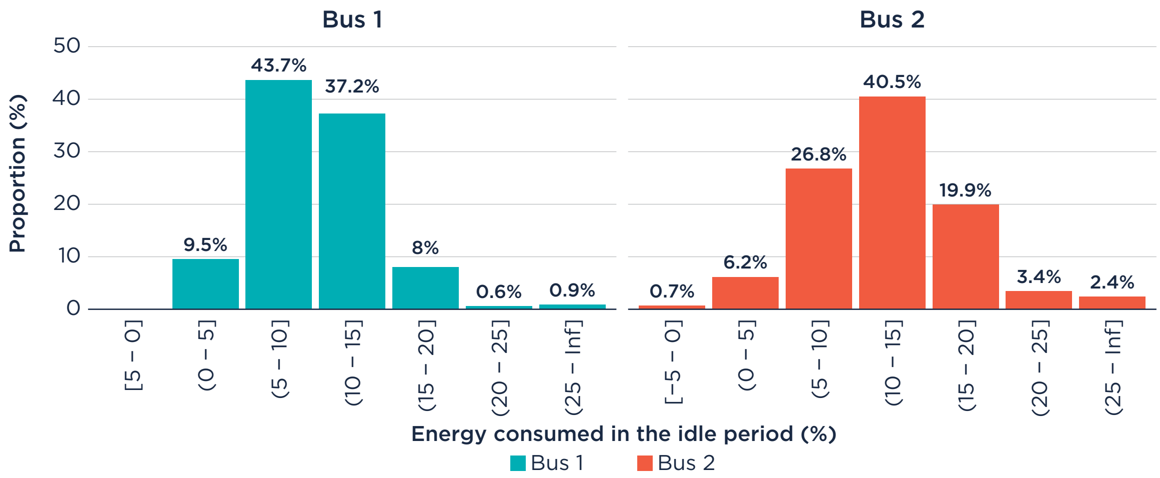


**Figure 12.** Distribution of the percentage of energy consumed per day in the idle period by the two monitored buses

The energy consumed during the idle period ranged from 5% to 15% on most monitored days (80.9% for Bus 1 and 67.3% for Bus 2). Proportionally, Bus 2 exceeded 15% of the energy consumed at idle times for more days (25.7% against 9.5% for Bus 1).

Air conditioning, one of the main drivers of energy consumption of accessories, is greatly influenced by ambient temperature. Figure 13 relates the daily maximum temperature to the percentage of energy consumed in the idle period.

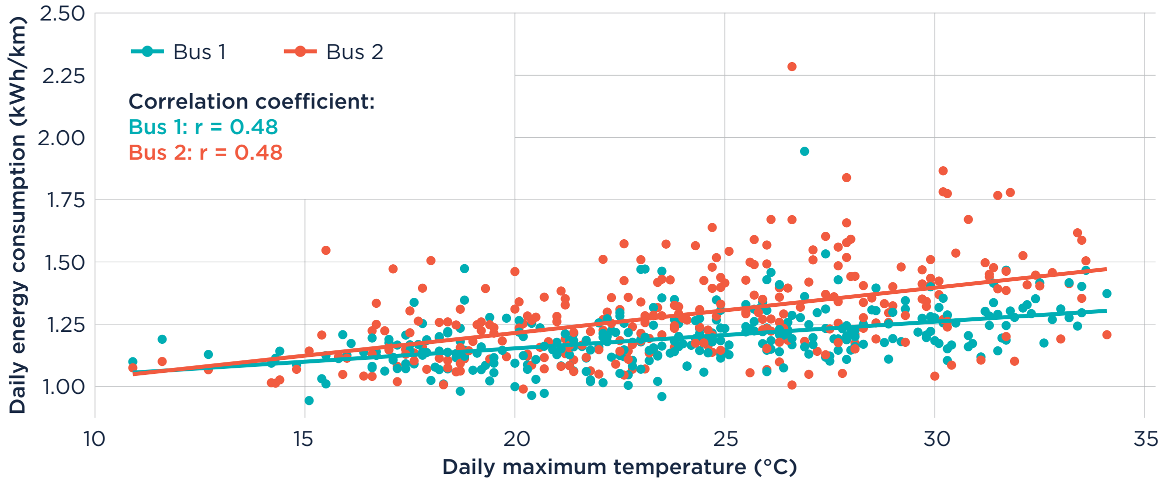


**Figure 13.** Relationship between maximum daily temperature and percentage of energy consumed during idle periods by the monitored buses

There is a weak positive correlation between the variables, that is, there is a slight tendency to observe greater energy consumption during idle periods on days with higher maximum temperatures. This behavior is likely related to the use of air conditioning.

The power demand of auxiliary equipment depends on operating and environmental conditions. For example, the power required for air conditioning varies with the ambient temperature and the frequency with which the doors are opened and closed. Thus, in general, the power required by accessories varies by bus line, time of day, and climate conditions. Figure 14 shows the distribution of power consumption during the idle periods of the monitored buses.

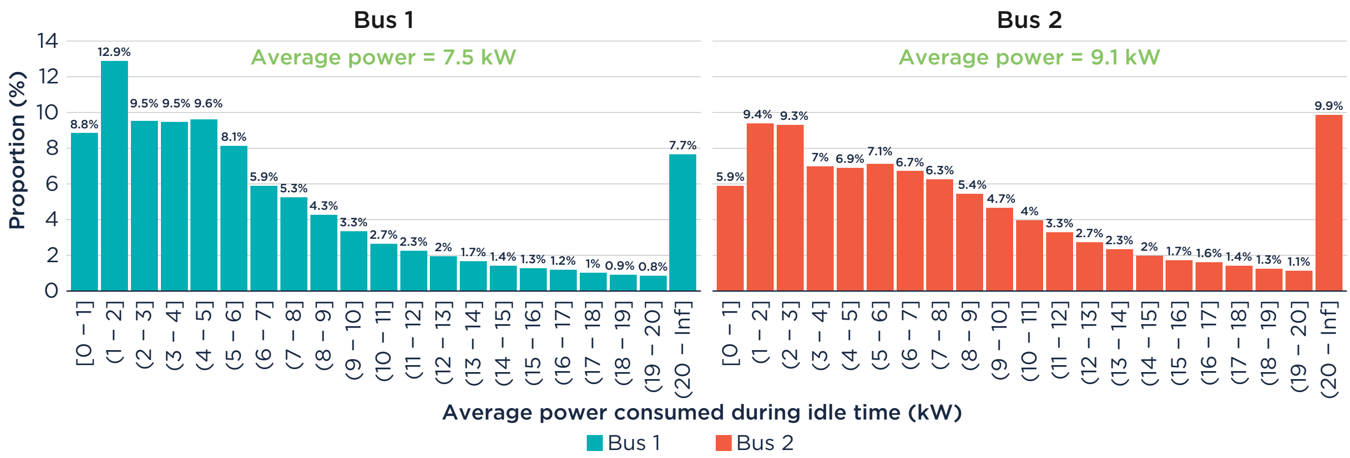


**Figure 14.** Distribution of power consumption (in kW) during idle time

A significant part of the observed values is between 0 kW and 8 kW (75.9% for Bus 1 and 67.7% for Bus 2). The average power consumed in the idle period by Bus 1 is 7.5 kW and, by Bus 2, 9.1 kW. A 2021 ICCT study on the relationship between the external temperature and power demand from accessories estimated that, for temperatures between 15ºC and 30ºC, auxiliary equipment demands power between 4 kW and 14 kW (Dallmann et al., 2021). The study highlighted that the demand tends to be significantly higher on days with extreme temperatures.

### 4.2.6. RANGE

One of the main concerns of bus line operators when replacing their diesel-run fleet with battery electric buses is range, that is, the distance these vehicles can travel on a full charge. The range of electric buses depends on the capacity of the battery (in kWh) and energy consumption (kWh/km). Consumption, in turn, varies with environmental and operational conditions, such as external temperature, transported weight, number of stops and driving style, as discussed earlier. Therefore, variations in range are expected even when analyzing only one bus line. Figure 15 shows range estimates considering the daily energy consumption per bus. The technical reserve, important for battery health and operational safety, is indicated by the manufacturer. Three technical reserve scenarios are considered: 10%, 15%, and 20%.

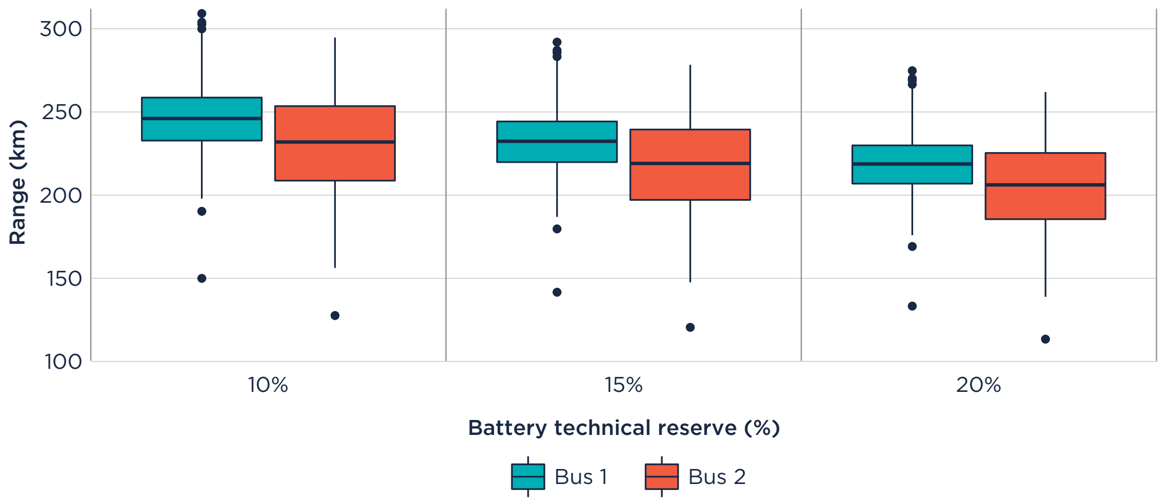


**Figure 15.** Range estimates for three battery technical reserve scenarios (10%, 15%, and 20%)

The figure shows a significant range variation even for the same bus operating on a single route. Considering a battery technical reserve equal to 20%, the estimated range for Bus 1 varies between 175.9 km and 264.3 km, while for Bus 2, it varies between 138.9 km and 262 km (disregarding outliers). The median ranges in this scenario of 20% battery reserve are equal to 218.7 km and 206.2 km for Buses 1 and 2, respectively.

The planned average daily distance on a working day for route 6030-10 is 188 km, according to data from the SPTrans cost spreadsheet (São Paulo Transportes, 2022). For the 20% technical reserve, the estimated range was greater than or equal to the average daily planned distance in 83.9% of the analyzed days. However, single-route buses do not necessarily cover the same distance over a day. The frequency of departure of buses tends to vary, and there may be a greater number of vehicles in operation during peak hours and, therefore, different distances traveled.

In the case of routes used more intensively, the range of electric buses may be less than the planned daily mileage. This does not necessarily prevent the adoption of electric buses on that route, whose operation can be made possible with intermediate recharges throughout the day, which increases its daily range. However, the operation does not always allow for more recharges than at night, due to either the impossibility of returning the vehicle to the garage or the lack of additional recharge points or even the need for greater availability of the vehicle during the day. In addition, costs may vary depending on the recharge time. For the analyzed case, the cost of electricity is higher at peak hours (i.e., between 5:30 pm and 8:30 pm in the city of São Paulo). The charging strategy adopted is analyzed below.

## 4.3 BUS CHARGING STRATEGY

The charging strategy is essential to ensure that the vehicle can travel the required distance and, consequently, define the operational planning of electric buses. The monitored vehicles are charged in the garage of the operating company using 80 kW chargers. Table 5 and Table 6 show, respectively, a summary of charging events monitored by bus and by type (night or intermediate).

**Table 5.** Charging characteristics of the monitored buses (January, 2021 to December, 2021)

| Bus | Number of rechargesa | Number of recharges per day Average [min.-max.] | Total energy recharged per day (kWh) Average [min.-max.] | Time per day charging (hours) Average [min.-max.] | Night charging (between 8 pm and 4 am) |
|---|---|---|---|---|---|
| **1** | 583 | 1.86 [1 – 5] | 222 [0.4 – 469.3] | 3.6 [0.01 – 9.4] | 71.4% |
| **2** | 463 | 1.67 [1 – 5] | 219.3 [0.4 – 440.8] | 3.8 [0.01 – 8.9] | 73.8% |

a. As described in section 4, days on which the buses traveled less than 50 km were excluded from the sample.

**Table 6.** Recharging by type (January, 2021 to December, 2021)

| Recharge type | Number of recharges | Energy recharged per charging event (kWh) Average [min.-max.] | Portion of the battery recharged Average [min.-max.] | Recharge duration (minutes) Average [min.-max.] | Proportion of recharges up to 100% charge |
|---|---|---|---|---|---|
| **Night time (20h – 4h)** | 758 | 137.6 [0.1 – 290.1] | 43.0% [0% – 87.8%] | 134.5 [0.3 – 402.4] | 75.9% |
| **Intermediate (4h – 20h)** | 288 | 90.7 [0.01 – 221.1] | 28.3% [0% – 72.6%] | 99.3 [0.3 – 433.2] | 61.1% |

Table 5 shows that, on average, both buses recharge more than once a day. Over 70% of such recharges take place at night (between 8 pm and 4 am). The total energy recharged per day averages 220 kWh for both vehicles, and the average daily recharge time is 3.6 hours for Bus 1 and 3.8 hours for Bus 2.

Analyzing recharges by type in Table 6, night recharges present a greater energy input on average (137.6 kWh for night recharges and 90.7 kWh for intermediate recharges). Thus, the percentage of recharge is also higher for night recharges, on average 43%, while for intermediate recharges, it is 28.3%. As a result, overnight recharges are also longer, with an average duration of 134.5 minutes versus 99.3 minutes for intermediate recharges. Furthermore, 75.9% of overnight recharges charge the battery up to 100%, while the same happens in 61.1% of intermediate recharges.

Figure 16 shows more information about the recharge strategy adopted during this monitoring. In the first panel, the height of the bars indicates the frequency of recharges by the start time of the charging events. The second and third panels display box plots with the percentages of charge available (SoC - state of charge) at the beginning and end of the charging events, respectively.

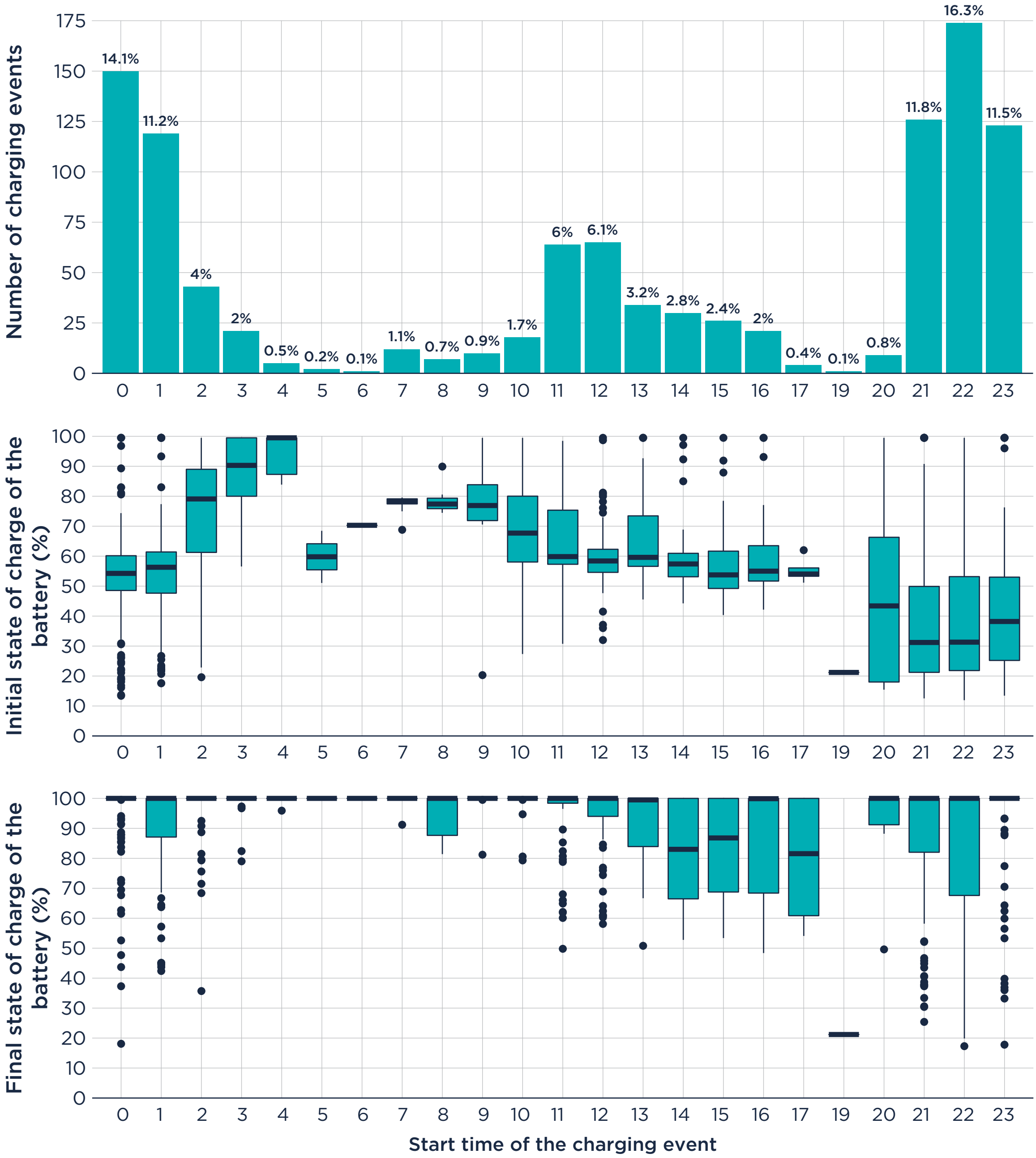


**Figure 16.** Battery charging strategy. The top panel displays the number of charging events per start time. The last two panels show the distribution of the percentage of energy available in the battery, also according to the start time of the charging event.

As the first panel indicates, most charging events start between 8 pm and 1 am. There is also a significant number of recharges starting at 11 am and 12 pm. However, they are less frequent than at extreme times of the day. The second panel shows that overnight recharges tend to start when the battery is emptier than what is observed in intermediate recharge events.

In addition, the operator maintains a technical reserve in the battery, as recommended by the manufacturer, which is necessary for battery health and operational safety. Most recharges (91.9%) start with a SoC above 20%, and only 8.1% start with a SoC between 12% and 20%. There is still a significant number of recharges, mainly intermediate ones, starting with a SoC of more than 50% (59.4%).

The bottom panel shows that batteries are charged to 100% in more than 70% of the recharges. This indicates that the operator seeks to fully charge the batteries of the two buses when possible.

## 5. CONCLUSION

Over the last few years, the city of São Paulo has been committed to improving the environmental performance of its transport system. In addition to the approval of Law No. 16,802/2018, which established emission reduction targets for urban buses, the city government committed to including 2,600 electric buses in its fleet by 2024. The pilot project launched by SPTrans in partnership with BYD enabled the implementation of 18 battery electric buses in the fleet, operated by the company Transwolff since 2019. The results of the pilot project can help guide the next steps of the technological transition in the city.

This report analyzed the performance of two electric buses from the pilot project's fleet. They were monitored throughout 2021 for operating data and energy consumption. The analyses presented here seek to characterize the performance of buses over time under different operating conditions, but do not establish cause-and-effect relationships between the variables, nor do they quantify the impact of each variable.

There is a significant variation in energy consumption over time for the same bus and between the analyzed buses. The average consumption is equal to 1.19 kWh/km for one bus and 1.27 kWh/km for the other, but the daily averages varied between 0.94 kWh/km and 2.29 kWh/km on the analyzed days. Although there are technical differences between the monitored vehicles (body models are different), both have the same chassis and battery model, and their curb weights are close (with a difference of about 1%). The significant variation of values for the same bus demonstrates the impact of operating conditions on energy consumption. Importantly, the consumption measured by the telematics devices does not include energy losses in recharging, which are accounted for in paid consumption.

The use of air conditioning on buses increases energy consumption, especially on hot days. In general, the buses showed higher consumption on days with higher maximum temperatures. In addition, one of the buses tends to consume more energy at higher temperatures than the other, indicating a possible difference in the performance of the air conditioning equipment.

Payload is another relevant factor; however, detailed data on the number of passengers transported per trip and their routes were not available for this analysis. No clear correlation was observed between average daily consumption and the total number of passengers carried per day. Further investigation of this relationship with more disaggregated data is suggested.

The relationship between average speed and energy consumption was also evaluated. In general, on days when the monitored buses had higher average speeds, they also consumed less energy. Urban buses tend to have low average speeds due to the high frequency of stops throughout the day to pick up and drop off passengers. The acceleration oscillations throughout the operation are also influenced by traffic jams, which influence average speed. Therefore, higher speeds may be associated with fewer acceleration and deceleration events and thus lower energy consumption.

Regenerative braking is also impacted by the frequency and intensity of acceleration and deceleration oscillations. For the two monitored buses, the average daily percentage of energy regenerated by braking ranged from 17.2% to 49.2%, with an average value equal to 40.7% for one bus and 38.6% for the other. An increase in regeneration over time was observed, which may have been influenced by drivers better adapting to the technology.

Driving style is another factor that affects energy consumption. This study did not have access to the drivers' shift schedules, so it was not possible to analyze driving style more comprehensively. However, the analysis of regenerative braking can provide indications about driver adaptation to the new technology. Further studies on this topic are recommended.

Finally, regarding the charging strategy, the monitored buses are recharged mainly at night, especially between 9 pm and 2 am. A significant number of recharges start between 11 am and 1 pm. However, these are less frequent and less intense. On average, there is more than one charging event per day and generally, the operator tries to charge the battery fully.

Although the study only monitors two buses, the collected data provide accurate and detailed information on energy consumption and operation efficiency. The results are compatible with values found in other studies on cities that already operate large-scale electric bus fleets.

It should be noted that these results are limited to the two buses analyzed. Thus, the same bus will not necessarily have a similar energy performance if operating in different conditions. Variations in energy consumption are expected even for a bus that runs on a single route, as operating conditions vary throughout the operation – such as gross weight, traffic jams, weather conditions, and driving style. Being able to monitor these variations is helpful in the operational management of the bus fleet.

In addition to generating no exhaust emissions, battery electric buses tend to have low operating costs compared to conventional technology. Therefore, maximizing the use of these vehicles brings greater financial gains, in addition to the climate and health benefits associated with reduced emissions. Consequently, this type of monitoring represents an even more important tool as it follows the evolution of the energy performance and range of such vehicles, bringing more predictability and safety to the operation.

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# APPENDIX I: OPERATION OF THE TELEMATICS DEVICE

The two Transwolff battery electric buses analyzed in this study have been monitored since January 2021 by telematics (GO9 devices from Geotab). The devices collect data such as position, distance traveled and battery charge in real time, which are made available on a digital platform. This information not only makes it possible to monitor vehicle performance and detect technical problems but can also be used to calibrate simulations.

The telematics device is connected directly to the vehicle's on-board diagnosis (OBD) input, extracting data from the controller area network (CAN) output. This input communicates with the vehicle's engine control unit (ECU) and allows access to data from the sensors of each of its components. A representation of the data collection and storage mechanism is provided in Figure 17.

## Telemetry mechanism

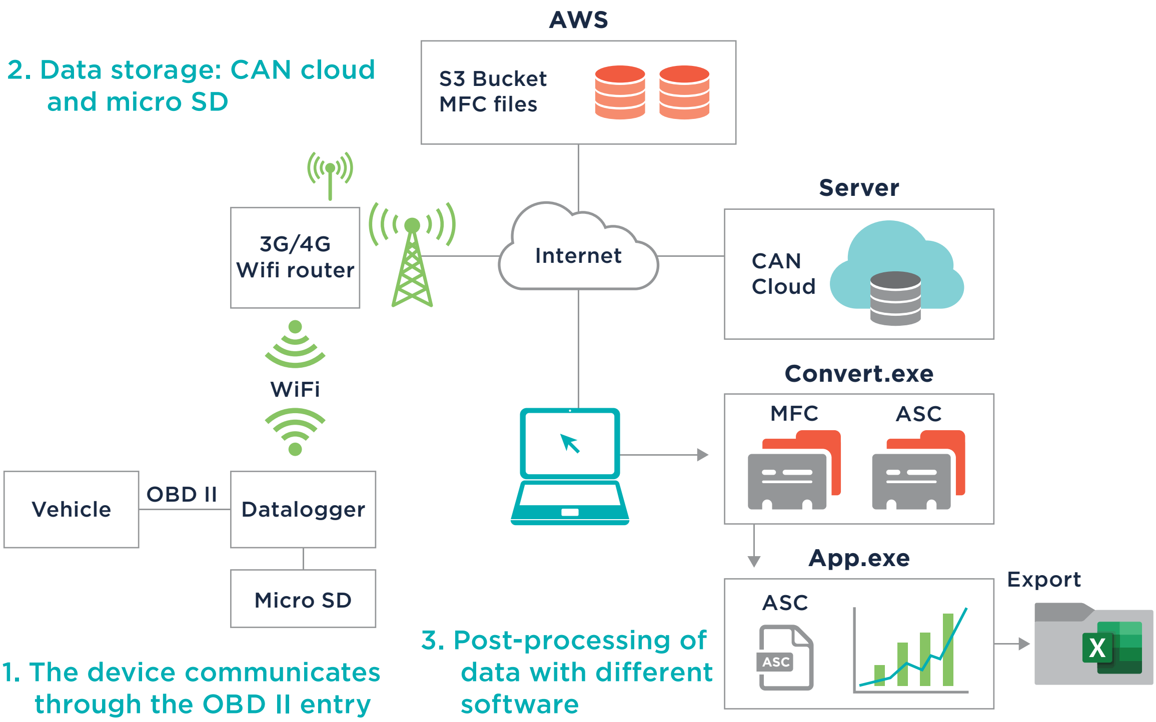


**Figure 17.** Data collection and storage structure for monitored electric vehicles

*Source:* Helmer Acevedo, "Mecanismo de telemetria," unpublished internal communication (Washington, DC: ICCT, 2022).

Datasets are collected by the device and transmitted to the digital platform using a curve algorithm patented by Geotab, which in turn uses the Ramer-

Douglas-Peucker algorithm. This method registers new observations when the device detects a relevant variation in the variable analyzed, according to the pre-established margin of error. Thus, the device does not collect data with a fixed frequency but ensures that critical values are recorded, collecting fewer data points. With this, data storage is optimized and yet it is possible to create a predictive curve to estimate intermediate data (Cawse, 2022). A comparison between collecting all points with this approach and collecting curve critical points is illustrated in Figure 18.

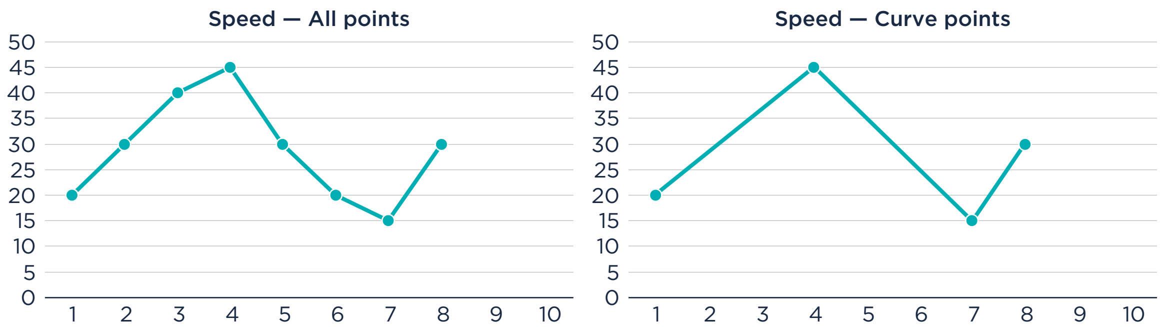


**Figure 18.** Collecting all speed data points versus collecting critical points (curve points). Adapted from Cawse (2022).

## APPENDIX II: SORT TEST RESULTS

The approval process for battery electric buses in São Paulo includes the SORT test (Standardised On-Road Test Cycle), a protocol developed by the *Union Internationale des Transports Publics* (UITP) to measure the fuel consumption of buses in a standardized and reproducible way. In 2017, the scope of the SORT test was expanded to include electric buses, called E-SORT (UITP, 2022). The test protocol includes three cycles: SORT 1 is the urban cycle; SORT 2 is the mixed cycle; and SORT 3 is the suburban cycle. SPTrans required that battery electric buses reach a minimum range of 250 km in the test.

Transwolff's BYD bus test was conducted in 2020 and the results are shown in Table 7. For the test, the weight of the vehicle was 16.675 kg. This value corresponds to the bus loaded with half the total passenger capacity. During the test, auxiliary equipment (such as air conditioning) remained off.

**Table 7.** SORT test results on a BYD bus from Transwolff (test performed in September, 2020)

| | Energy consumption (kWh/km) | Maximum range (km) |
|---|---|---|
| **SORT 1 (Urban cycle)** | 0.9353 | 267.4 |
| **SORT 2 (Mixed cycle)** | 0.8588 | 291.2 |
| **SORT 3 (Suburban cycle)** | 0.8589 | 291.2 |

The SORT test makes it possible to compare bus models in terms of performance on energy consumption and range, which is very relevant for the choice of technology since it considers controlled test conditions. This direct comparison is not possible in actual operation, where buses operate on lines which differ in terms of route, elevation profile, number of stops, level of traffic jam, weight carried, driving style, and weather. Because of this, different energy consumption values from those observed in the SORT test are expected in real operation scenarios.

## APPENDIX III: PASSENGERS TRANSPORTED BY BUS PER DAY

One factor that influences the energy consumption of a vehicle is the load it carries. The number of passengers transported per day is monitored by SPTrans, which made this dataset available for the two buses analyzed in this study from January to September 2021. Bus 1 carried, on average, 388.9 passengers per day, while Bus 2 carried 361.5 passengers. Figure 19 shows a histogram with the distribution of the number of daily passengers per bus in the analyzed period. Figure 20 shows the relationship between the average energy consumption and the number of passengers transported per day.

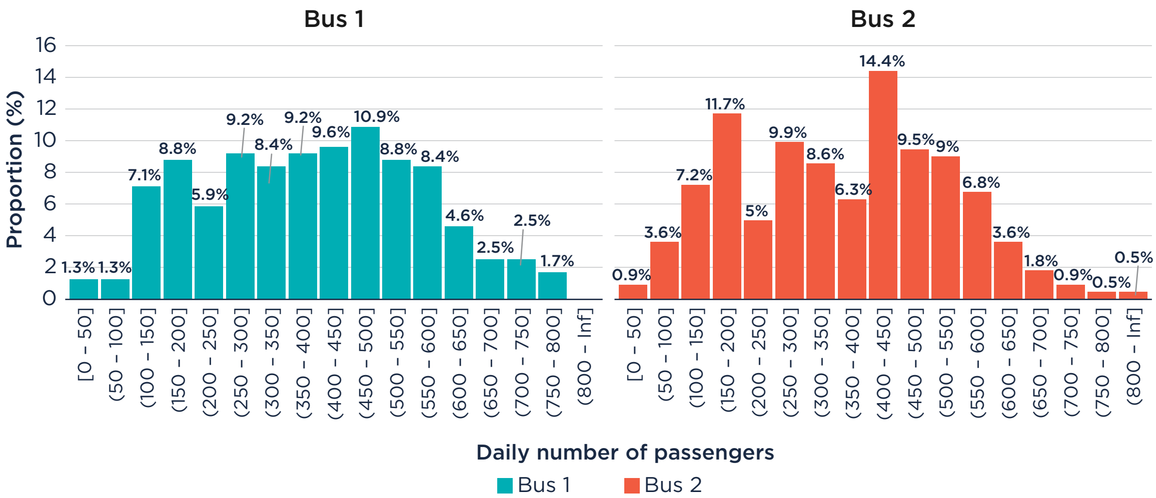


**Figure 19**. Distribution of the number of passengers transported per day by each bus from January to September, 2021

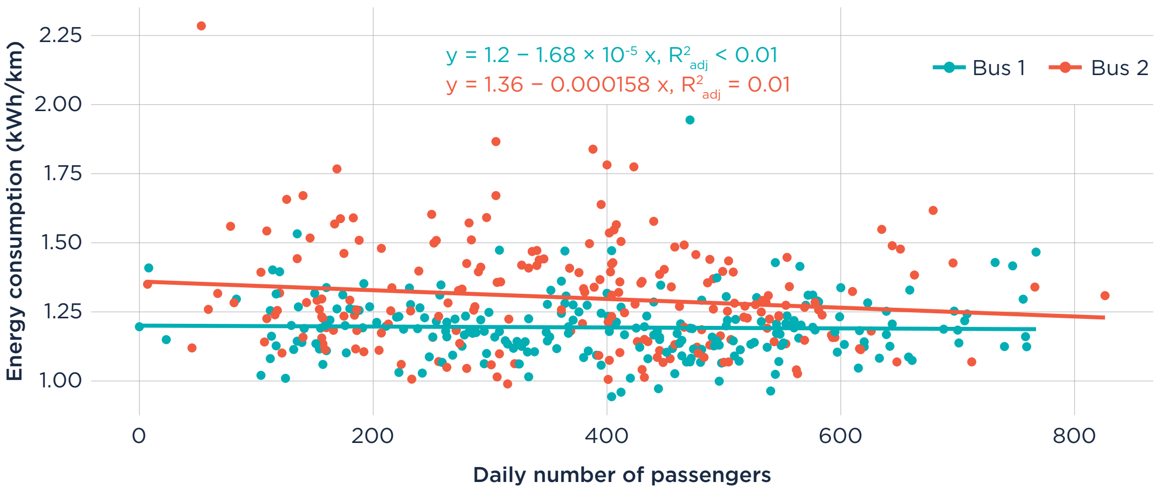


**Figure 20.** Relationship between energy consumption and the daily number of passengers

The low coefficient indicates that there is no correlation between energy consumption and the daily number of passengers on buses. However, this result does not indicate that the variable is irrelevant. First, the relationship between the variables may not be evident because the effect of other variables is not isolated. Additionally, this behavior can be a limitation of the available data. Due to the boarding and disembarking throughout the operation, it is important to consider how long the passengers were transported. Bus occupancy variation data could also represent this information. Unfortunately, this additional information was not available. It is suggested that this analysis be explored in future studies.

A previous ICCT study estimated the energy consumption of battery electric buses and diesel buses on some routes in the city of São Paulo (Eufrásio et al., 2022). Energy consumption was simulated in three scenarios: 0%, 50%, and 100% passenger occupancy. The simulations showed that the transported load has a significant impact on energy consumption, with an average increase of 16.9% in consumption when comparing the fully occupied bus with the empty bus.

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