

# IMPACT OF URBAN TRANSPORT ELECTRIFICATION: AN APPROACH USING SYSTEMS DYNAMICS

## 1 INTRODUCTION

The transport sector is a major consumer of fossil fuels, responsible for 16.2% of GHG emissions in 2020 (Ritchie, 2021). Passenger vehicles account for around 45% of this share (Rietmann et al., 2020), and decarbonizing this subsector is crucial to mitigating climate change (Manzoli et al., 2022). Electric vehicles (EVs) are seen as key to fossil fuel-free public transport (Borén, 2020), improving air quality and energy efficiency when powered by renewables (Wolking et al., 2018).

In Brazil, the sector emitted 196 Mt of CO<sub>2</sub> in 2019, largely due to combustion-engine vehicles. Public transport accounted for 29% of trips in 2016, with buses representing 20% (SEEG, 2020; ANTP, 2018). Technological advances, such as hybrid engines, have reduced emissions (Usman et al., 2023; Suki et al., 2022), with G7 countries showing benefits from green innovation.

Electric buses are expanding globally, with 600,000 in operation—12% in China—while South America lags, though Santiago leads regionally with 10% of its fleet (IEA, 2018; LABMOB, 2022). This study investigates the environmental impact of electrifying urban passenger transport in Brazil through a system dynamics model to analyze scenarios with electric buses. The method enables understanding of complex systems and supports policy design (Serman, 2018). The article is structured into six sections: introduction, framework, method, model development, results, and final considerations.

## 2. THEORETICAL FRAMEWORK

### 2.1 Electric Vehicles

Air pollution and greenhouse gases from fossil fuels have driven the development of cleaner, more efficient transport, such as electric vehicles (EVs) and alternative fuels (Carranza et al., 2022). Adoption has been encouraged worldwide through technological advances, greater range and speed, and government incentives like tax breaks, subsidies, and special access (Liu & Ial, 2020).

EVs date back to 1834, with fuel cells appearing in 1839. Hybrids emerged in 1898 with Ferdinand Porsche's model, but interest declined by 1930 due to battery limitations (Rizet, Cruz & Vromant, 2016). The 1970 oil crisis revived projects, fuel cells gained relevance with NASA's Apollo program, and in 1997 Toyota launched the Prius (Hung & Lim, 2020; Castro, 2019).

Today, EVs are central to transport decarbonization. Their adoption has grown exponentially, with projections of 26.4 million units on U.S. roads by 2030 (EEI, 2022).

Electric vehicles (EVs) are efficient, less polluting alternatives for mobility, gaining global prominence (Neto et al., 2017). They play a key role in reducing carbon emissions and improving urban air quality, with plug-in hybrids (PHEVs) also showing potential (Zhao et al., 2021). Replacing gasoline cars with EVs can further lower environmental impacts, especially when combined with renewable energy and carbon capture (Shen et al., 2023).

The electrification of transport is central to sustainable urban systems (Zeng et al., 2024), as EVs limit the negative effects of mobility on the environment (Lin et al., 2023). Electromobility is expected to be crucial for future ecological mobility, cutting greenhouse gases and local air pollution, an especially relevant benefit in densely populated cities (Jianwei et al., 2019; Jianwei et al., 2021).

### 2.2 Impacts of electrification of urban transport

Urban transport is essential for sustainable urban development but also generates significant externalities. While other sectors reduce CO<sub>2</sub> emissions, transport emissions are expected to rise due to freight expansion (ITF, 2015). In large cities, transport is the main source of harmful gases such as CO, CO<sub>2</sub>, HC, and NO<sub>x</sub>, which damage both the environment and human health (Falco, 2017; Ye et al., 2021; Liyang et al., 2020; Samaranayake et al., 2014; Wang et al., 2016).

CO<sub>2</sub>, though naturally present, intensifies the greenhouse effect and global warming (MMA, 2020; IEA, 2020). Air pollution also increases public health costs (MMA, 2017). Electrifying public transport reduces oil dependence and emissions (Yu et al., 2018). Despite fewer buses compared to cars, their long operating times and stop-and-go routines lead to high fuel use (Lin & Zhang, 2019; Liu et al., 2019).

Diesel buses worsen pollution, while electric buses cut energy consumption by up to 72.9% and offer zero-emission alternatives (Bi et al., 2015; Bi et al., 2018). Their global adoption grows, led by China's policies (Dallmann, 2019; Asian Development Bank, 2018). In Brazil, São Paulo has begun this transition but counts only 100 units (Venditti, 2022). Calculating emission factors per kilometer is vital to assess CO<sub>2</sub> levels, with diesel variants still dominant. The environmental costs of fossil fuel use remain central in climate change debates and IPCC reports (Siqueira et al., 2019; Lopes et al., 2018; Ülengin et al., 2018).

### **3 RESEARCH METHOD**

The method is a logical sequence of steps to achieve specific objectives (Appolinário, 2016; Matias-Pereira, 2019). This study applies the System Dynamics (SD) approach to analyze the insertion of electric vehicles. SD supports decision-makers in testing policy solutions and incorporates stakeholder knowledge to better understand system behavior (Thompson et al., 2016; Scott et al., 2016). It was chosen for its capacity to model nonlinear feedback processes, represented through cause-consequence diagrams that reveal variables and causal relationships (Correia de Araujo et al., 2019; Chen et al., 2021).

As a systems thinking tool, SD enables investigating, analyzing, and predicting system behavior, clarifying complex problems (Ghaffarzadegan & Rahmanda, 2020). It allows detailed modeling of interrelations among internal and external factors, combining qualitative and quantitative analyses of system dynamics over time (Jiao et al., 2015).

#### **3.1 Formulation of the dynamic hypothesis**

This step explains the causes of the problem through a cause-and-consequence diagram, where causal loops highlight system variables, their links, and the polarity of feedbacks (Sterman, 2000). Model evaluation tests ensure the hypothesis aligns with real behavior (Lane, Munro & Husemann, 2016). Such behavior aims to neutralize disturbances that move the system from its goal (Sterman, 2000; Ford, 1999). In this study, the hypothesis assumes that including electric buses reduces CO<sub>2</sub> emissions and benefits the environment.

### **4 DEVELOPMENT OF THE DS MODEL**

Urban mobility in Brazil faces challenges from population growth, insufficient infrastructure, and the shift toward private transport since the 1990s, which intensified congestion (Carvalho, 2016). The first phase of the model identifies key elements: bus fleet size, vehicle characteristics (energy source, capacity, CO<sub>2</sub> emissions), transport logistics (distance, passengers per route), emissions data, costs, fuel prices, and ticket values. Data were provided by a transport association in Rio Grande do Sul. For analysis, a line with 14 routes and 43 vehicles was selected, with detailed logistics presented in Table 1.

**Table 1** - Transport Logistics

Route	Distance	Turns	QtOn	DT	OF	TPT
A	30 km	72	20	2160 km	108 km	40
B	28km	36	14	720 km	52 km	30
W	25 km	20	14	500km	35 km	30
D	28 km	18	11	504 km	46 km	30
E	12 Km	10	6	120 Km	20 Km	10
F	48 Km	10	8	480 Km	60 Km	40
G	59 Km	20	10	1180 Km	118 Km	40

Legend: TP =Terminal stopped time; DT = total distance; DO -= bus distance

Table 2 presents the bus models used in the simulation, serving to characterize the research scenarios. Although the city has more vehicle types, only three models from the chosen route were considered.

**Table 2** – Models used

Model	Year	Consumption (km/l)	Fuel	P.S.	FOOT
VW/MPOLO TORINO GVU	2007	2,549	Diesel S10	44	24
M.BENZ/COMIL DOPPIO A	2016	3,583	DIESEL B12	83	40
SVELTOMIDI	2011	2,609	DIESEL B12	58	30

Source: <https://www.comilonibus.com.br/site/veiculos/detalhe/linha-urbano/produto-svelto#/dados-tecnicos>.

Caption: PS – People sitting; PE – People standing.

The average energy efficiency of conventional urban buses ranges from 2.549 to 3.583 km/l. Data on performance and consumption were provided by the local transport association, considering only working days. Most vehicles use B13 diesel, a biodiesel petroleum blend, while some rely on pure S10 diesel (ANP, 2020; Dreier et al., 2018).

#### 4.1 Development of an environmental model for the electrification of urban transport

To estimate CO<sub>2</sub>, vehicle approval and failure rates were determined annually using opacity tests, following CONAMA Resolution 418/2009 and IBAMA Instruction No. 6/2010. These rates, along with yearly fuel consumption per mileage, supported the calculations. Figure 4 summarizes the procedures for estimating emission factors, expressed in grams/km. The CO<sub>2</sub> values refer only to exhaust emissions from fuel combustion, excluding full life-cycle impacts. Factors for diesel vehicles were obtained from the National Inventory, ANFAVEA, CETESB, PROCOVE, ANTP, PETROBRAS, CBCS, and SEEG.

Emission factors for heavy diesel engines, defined by CETESB and IBAMA under ABNT standards, are measured by pollutant mass per unit of work. Vehicle pollution is classified as local, affecting nearby populations, or global, impacting the planet; CO<sub>2</sub>, though natural, is a major GHG and the focus of this model (Ipea, 2020). Studies indicate that burning one liter of diesel emits between 2.6 and 3.87 kg of CO<sub>2</sub> (ANFAVEA; BEN, 2020), with 3.2 kg as the average reported by Ipea. This research simulates 2.6 kg per liter as the base factor, rising to 3.87 kg in worst-case scenarios (IPEA, 2018; ANTT, 2020). Fuel consumption values were drawn from ANFAVEA, ANTT, IPEA, and URBS, while current averages came from the regional transport association, consolidated in Table 4.

**Table 3** - Consumption per km

Reference	Minimum (Km/l)	Maximum (Km/l)
ANFAVEA (2020)	2.23	3.18
ANTT (2020)	2.19	3.23
IPEA (2018)	2.24	3.19
URBS (2018)	2.27	3.17
Average value	2,215	3.19

Source: ANFAVEA (2020); ANTT (2020); IPEA (2018); URBS (2018).

According to Cuellar et al. (2018), several cities already use electric buses, motivating their inclusion in the studied region's transport system. Three BYD models—D9W, D9A, and D11B41820—were selected to meet local demand without harming service. BYD, whose

mission is to reduce fossil fuel dependence through battery and EV technology, supplies 100% electric chassis for the Brazilian market, with bodies produced by local partners. Each unit can cut emissions equivalent to 33 cars, is safe and quiet, and may reduce operating costs by up to 70% (BYD, 2021). Table 5 details the models' characteristics.

The simulation considered lithium iron phosphate batteries, noted for safety, durability, efficiency, and low environmental impact, with replacement every 4 years (Manzolini et al., 2022). These batteries, averaging 224 kWh, yield consumption of 1.12 kWh/km, consistent with tests in Brazil showing 1.04–1.59 kWh/km (BYD, 2020; Liu et al., 2016; Nordelof et al., 2019). Studies informed future consumption, with autonomy near 200 km, 14 lithium batteries per bus, and recharge in about four hours (Guenther & Padilha, 2016; Du et al., 2019). Charging was modeled at 30–40% capacity, restricted to weekdays.

CO2 emissions for electric and hybrid buses were based on well-to-wheel analysis (Wu & Zhang, 2017), considering Brazil's hydro-dominated energy matrix. Historical factors ranged from 108.23 tCO2/GWh (2015) to 43.68 tCO2/GWh (2018) (SEEG, 2019). Hybrid buses emit 1.35–1.4 gCO2/km, while purely electric average 132.4 gCO2/km, versus 272.7 gCO2/km for hybrids (Lajunen, 2014; Zhang et al., 2014; Muncrief et al., 2012).

The model also assessed CO2 reductions as energy equivalents: generating 1 GWh emits ~477 tCO2 in gas plants, 623 in oil, and 667 in coal. Thus, avoided emissions from electric buses can be expressed as significant energy savings (SEEG, 2019).

The model has two input streams for the stock variable *EmissionCO2*. The "Diesel Emission" flow captures diesel fuel use, with the auxiliary "Diesel Consumption" determined by: number of diesel buses (*BusDiesel Quantity*), monthly distance traveled (*DistanciaTravelled*), fuel efficiency (*Km/lDiesel*), and CO2 generated per liter (*GerPerLitro*).

The second input stream stores the electrical share of simulations, separating hybrid buses' battery and combustion use. Emissions are based on CO2 generation from thermoelectric plants (Zhou et al., 2016). These variables feed the *EmissionCO2* stock, enabling simulation of scenarios and calculation of the impact of electric bus adoption. Table 4 presents the main equations.

**Table 4 – Environmental Model Equations Model**

1.	$QuantityBusDiesel = TotalBus * PerBusDiesel$
2.	$HybridDiesel = (HybridBusQuantity * (DistanceTravelled * "Km/l Diesel")) - (HybridBusQuantity * (PerElectric * (DistanceTravelled * "Km/l Diesel")))$
3.	$DieselSpent = (QuantityBusDiesel * (DistanceTravelled * "Km/l Diesel")) - (QuantityBusDiesel * (PerDiesel * (DistanceTravelled * "Km/l Diesel")))$
4.	$CostLitroDiesel = VarCostDiesel * 2.99$
5.	$Transport Cost = (LiterDiesel Cost * (DieselSpent + HybridDiesel)) + Maintenance Cost$

Source: Prepared by the Author (2024).

## 5 RESULTS ANALYSIS

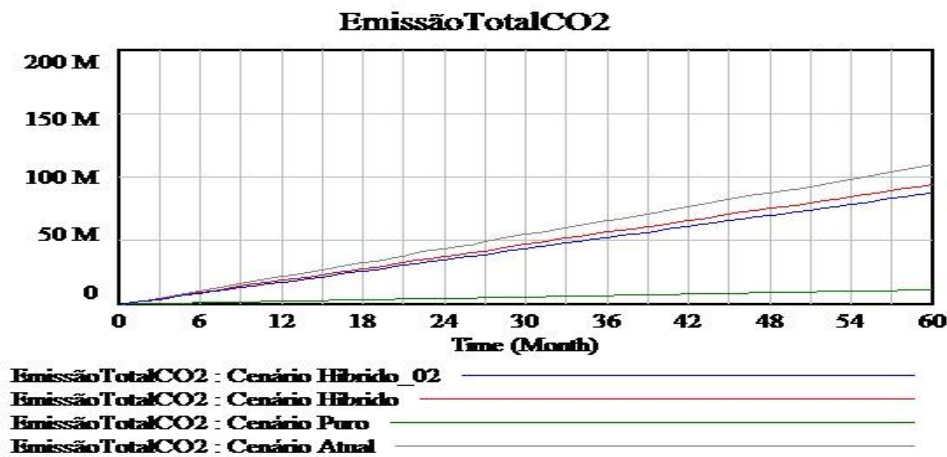
To simulate the proposals, four scenarios were defined: (i) **Current** – urban transport without electric buses; (ii) **Hybrid 30%** – buses with batteries supplying 30% of engine energy; (iii) **Hybrid 50%** – batteries supplying 50%; and (iv) **Pure** – fully electric buses. Simulations were run in Vensim (2022) with a 60-month horizon, chosen to capture seasonal passenger flows.

Decisions from the results may support partial or total EV adoption to reduce CO2. The models were designed for simplicity, enabling managers to test different scenarios. Model validity was checked by comparing simulated and real behavior (Simonetto et al., 2016; Pidd, 1998), ensuring representativeness despite inherent limitations (Alves, 2019; Sommerville, 2015).

The first analysis assessed CO2 reduction from urban transport electrification, assuming annual fleet renewal of 6%. After 60 months, the **pure scenario** cut emissions by up to 110,000

tons, while **hybrid scenarios** achieved 96,000–98,000 tons. Even the current scenario showed reductions due to biodiesel use. These results confirm the relevance of EV adoption (Janovec & Koháni, 2019) and reinforce that electric buses significantly replace fossil fuels and lower GHG emissions, supporting environmental preservation (Santana & Sampaio, 2021).

**Figura 1.** CO<sub>2</sub> Reduction



The CO<sub>2</sub> reduction from electric buses can be expressed as equivalent electricity generation. Purely electric buses represent about 230 GW in natural gas plants, while hybrids reach 201–205 GW—comparable to a large city’s annual consumption (São Paulo Energy Ranking, 2021). In coal plants, reductions equal 164 GW for pure electric and 143–146 GW for hybrids, highlighting the environmental importance of electrification.

The study analyzed the electrification of urban transport in Brazil, focusing on electric buses as a strategy to cut GHG emissions. Using system dynamics, it showed: (i) **CO<sub>2</sub> reduction**, electric buses significantly lower emissions, making electrification an effective mitigation measure; (ii) **Scenarios**, hybrid and pure electric options reveal distinct impacts, broadening understanding of outcomes; (iii) **Energy equivalence**, emission cuts parallel large-scale electricity generation, stressing the need for renewable sources; and (iv) **Environmental impact**, EVs reduce air pollution and are key to global sustainability efforts.

## 6 FINAL CONSIDERATIONS

The study presented an approach for the insertion of electric vehicles, which reinforces the importance of electrification of public transport, and presents an effective strategy to face the environmental challenges associated with urban mobility in Brazil. Through the application of systems dynamics, the study provides a detailed understanding of the interrelationships between the various factors that influence the transport system and how they may be affected by the introduction of electric vehicles.

The results obtained from the simulation model show that replacing internal combustion buses with electric buses can result in a significant reduction in CO<sub>2</sub> emissions, contributing to the improvement of air quality and the mitigation of climate change. An analysis of different scenarios, including the adoption of hybrid and electric buses, provides valuable insights into possible transition trajectories towards a more sustainable transport system. The equivalence between the generation of electrical energy and the reduction of CO<sub>2</sub> emissions emphasizes the need to ensure that the electricity used in electric buses comes from renewable sources to maximize environmental benefits. The article reinforces the need for public policies and investments in infrastructure that support the electrification of urban transport.

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