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# **Sao Paulo Bus System: Transitioning to electric fleet**

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## **Sao Paulo Bus System: Transitioning to electric fleet**

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## **Sao Paulo Bus System: Transitioning to electric fleet**

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# Abstract

This study analyzes the electrification of São Paulo's bus fleet through a principal-agent model, addressing the dynamics between concessionaires and the municipal government. Unlike traditional centralized models found in the literature, this method captures the distinct incentives of both parties, offering a more practical basis for public policy design. The analysis evaluates the effectiveness of São Paulo's current subsidy policy, which covers the price difference between electric and diesel buses, subsidizing approximately 72% of electric bus acquisition costs, comparing it with alternative scenarios of subsidized percentage. The results indicate that the payoff of the current policy is close to the optimal payoff – with 100% subsidy – when compared to the alternative no-subsidy scenario, achieving a value R\$ 151 million higher than the no-subsidy scenario and only R\$ 13.6 million lower than the optimal case. Sensitivity analyses reveal that municipal budget constraints and externality pricing critically influence policy outcomes. Although the study demonstrates the effectiveness of the approach adopted by São Paulo, investments in the electrical grid infrastructure and supply constraints, which may impact implementation feasibility, were not considered. This research contributes a new methodological perspective to the literature and offers practical insights for urban mobility policymakers.

Keywords: Bus Fleet Electrification, Agent-Principal Framework, Public Transportation Sustainability.

# Resumo

Este estudo analisa a eletrificação da frota de ônibus de São Paulo por meio de um modelo de agente-principal, abordando a dinâmica entre concessionárias e governo municipal. Diferentemente das abordagens tradicionais encontradas na literatura, de modelos centralizados, este método captura os incentivos distintos de ambas as partes, oferecendo uma base mais prática para o desenho de políticas públicas. A análise avalia a eficácia da atual política de subvenção de São Paulo, que cobrindo a diferença de preço entre ônibus elétricos e a diesel, subvenciona aproximadamente 72% dos custos de aquisição de ônibus elétricos, comparando-a com cenários alternativos de percentual subvencionado. Os resultados indicam que o payoff da política atual está próximo do payoff ótimo - de subvenção de 100%, quando comparado com a alternativa sem subvenção, alcançando um valor R\$ 151 milhões maior do que o cenário sem subvenção e apenas R\$ 13,6 milhões inferior ao caso ótimo. Análises de sensibilidade revelam que restrições orçamentárias municipais e precificação das externalidades influenciam criticamente os resultados das políticas. Embora o estudo demonstre a eficácia da abordagem adotada por São Paulo, não foram considerados investimentos na infraestrutura da rede elétrica e restrições de oferta, que podem impactar a viabilidade da implementação. Esta pesquisa contribui com uma nova perspectiva metodológica para a literatura e oferece insights práticos para formuladores de políticas em mobilidade urbana.

Palavras-chave: Eletrificação de Frotas de Ônibus, Modelo de Agente-Principal, Sustentabilidade no Transporte Público.

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# List of abbreviations and acronyms

DB	Diesel bus
EB	Electric bus

# Executive Summary

The city of São Paulo, with its extensive public transportation network, faces significant challenges in its quest for sustainable urban mobility solutions. Among the primary issues is the high emission of pollutants, particularly nitrogen oxides (NO<sub>x</sub>), particulate matter, and carbon dioxide (CO<sub>2</sub>), from the diesel bus fleet. To address this, the City of São Paulo has implemented a bus fleet electrification program aimed at reducing these emissions and contributing to a cleaner and healthier environment. However, the transition to a 100% electric fleet faces obstacles such as the high upfront costs of electric buses and the need for charging infrastructure.

The central problem addressed in this dissertation is how to optimize the terms of concession contracts between the municipality and public transportation companies, considering budgetary constraints and the necessary incentives to effectively encourage fleet electrification. The relevance of this issue is reflected in the growing pressure for cities to adopt stricter environmental policies, alongside economic considerations related to the high initial costs of green technologies. Current solutions include subsidies for the purchase of electric buses, but these approaches have been criticized for their efficiency and long-term impact.

The proposed solution in this study is the use of an optimization model based on the agent-principal framework, where the relationship between the municipality (principal) and the concessionaires (agents) is considered in a more realistic manner, focusing on financial and environmental incentives. This model takes into account both the internal costs of the concessionaires and external costs such as environmental externalities. By optimizing the parameters of the contracts, the proposal aims to determine the ideal subsidy amount that maximizes benefits for both the concessionaires and the municipality, balancing financial and environmental concerns.

The context for the proposed solution is São Paulo's public transportation system, which is operated through concession contracts with private companies. These contracts are periodically adjusted to incorporate environmental incentives and targets, such as CO<sub>2</sub> emission reductions. The analysis in this dissertation uses an integer programming model to calculate the impact of different subsidy levels, taking into account variables such as operational costs, vehicle acquisition, charging infrastructure, and transportation-related externalities.

The evidence obtained points to the fact that the current subsidy policy, which covers approximately 72% of the cost of electric buses, yields a similar result to the optimal solution. This results in significantly higher net payoff compared to the no-subsidy scenario, while sensitivity analyses show that the fleet electrification process could be accelerated with adjustments in the policy, such as relaxing municipal budget restrictions.

The practical implications of this work are clear: to accelerate the transition to an electric fleet and optimize public resources, the terms of the concession contracts need to be adjusted, considering both financial costs and environmental benefits. Practical prescriptions include maintaining the subsidy model but with adjustments to maximize efficiency, such as introducing a more flexible subsidy cap and considering externalities in public policy decisions. However, for these prescriptions to be successfully implemented, efficient collaboration between the municipality and the concessionaires is crucial, and continuous monitoring should be carried out to assess the implementation of the policy and adjust parameters as needed, especially in the face of potential constraints related to the supply of electric buses and charging infrastructure.

This work contributes to understanding how public policies can be structured to encourage the adoption of sustainable technologies in urban transportation, offering a solution that effectively balances economic, environmental, and operational needs.

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# 1 Introduction

The municipality of São Paulo, with an area of approximately 1,521 km<sup>2</sup> and 11.6 million inhabitants, has a complex public transport network due to its vast urbanized area and high population density. Over the past decades, São Paulo has faced significant challenges in managing its urban mobility, with periods of expansion and modernization, especially in the 1980s, 1990s, and 2000s. This process was driven by demographic and economic growth, resulting in a transport network that includes buses, subway, and trains.

São Paulo's municipal bus system, one of the largest and most complex in the world, comprises about 1,340 lines, recording an average of 9.8 million boardings per day (São Paulo, 2015b). This system is operated by private companies contracted through concession by São Paulo Transporte S.A. (SPTrans), which is subordinated to the Municipal Secretariat of Mobility and Transport (SMT). The bus network is organized into three main subsystems: the structural subsystem, the regional articulation subsystem, and the local distribution subsystem.

The structural subsystem caters to high demand and is designed to integrate different regions of the city through exclusive bus corridors, facilitating faster and more efficient travel. This subsystem connects peripheral areas to major urban and commercial centers, improving accessibility. On the other hand, the regional articulation subsystem is responsible for meeting the internal demands of each region, feeding into the structural subsystem. Finally, the local distribution subsystem addresses local level demands, ensuring passengers can easily access the main transport axes.

Among the current challenges of the transport system, the transition to a more sustainable system is a central goal for the municipality. This includes electrifying the bus fleet to reduce air pollution and urban noise. São Paulo has been implementing plans to encourage this transition by offering subsidies and other incentives to bus concessionaires. These subsidies are designed to make viable the acquisition of electric buses, which currently have a higher initial cost compared to diesel buses. Additionally, investments are being made in charging infrastructure to support the operation of electric buses.

Adopting cleaner and more efficient technologies in public transport not only helps improve air quality and reduce noise pollution but also brings long-term economic benefits. Electric buses have lower maintenance and operating costs compared to diesel vehicles, which can result in significant savings for concessionaires and the city hall. Effective public policies, government support, and a continuous commitment to sustainability are crucial for the success of these initiatives.

In this regard, the São Paulo Municipal Government, through Law No. 16.802/2018, set a 20-year deadline for a 100% reduction in CO<sub>2</sub> emissions and a 95% reduction in NO<sub>x</sub> and

particulate matter emissions. These targets have been incorporated into the concession contracts resulting from bids 001/2015-SMT-GAB, 002/2015-SMT-GAB, and 003/2015-SMT-GAB for the public passenger transport service, which are currently in force (São Paulo, 2015a).

Moreover, the financial resources to cover the subsidies will preferably come from loans from development and promotional banks taken by the City Hall, which generally have access to cheaper credit than the concessionaires. For 2024, out of the estimated R\$ 5.9 billion for subsidies, R\$ 2.5 billion will come from the National Development Bank (BNDS), R\$ 2.5 billion from the Inter-American Development Bank and the World Bank, R\$ 750 million from federal public banks, and R\$ 165 million from the municipal budget (Diário do Transporte, 2023)

In the literature, the Fleet Replacement Problem is usually approached, methodologically, as a central planner's problem, considering all costs, either internal or external, in a single maximization operation. It was not found an approach like the one proposed by the present study, which considers a principal-agent problem, where concessionaires (agents) are concerned with internal costs, and the Municipal Government (principal) with external costs, regulated by a contract that provides subsidies and penalties, as well as remuneration for the services provided.

The concessionaire evaluates, based on the effective price of the electric bus (market price minus the subsidy), the total gain it will incur for each fleet composition over time, subject to budget constraints. The gains account for revenues and operating costs, as well as the costs of acquiring vehicles and chargers, along with the revenue from selling used buses. Concretely, the concessionaire's trade-off lies in paying more for electric buses and charging infrastructure to achieve lower operational costs or opting for lower acquisition costs with diesel buses while facing higher operational expenses.

From the public sector's perspective, the payoff considers operating costs (which are the counterpart of the concessionaires' revenues), subsidy costs, and environmental costs. In principle, increasing the subsidy amount could lead to a higher payoff if it accelerates fleet electrification to the point where the reduction in environmental costs offsets the additional subsidy expense.

Given the economic incentives, the analysis aim to determine the optimal parameters for the concession contract that the Municipal Government should establish. Specifically, what should be the subsidized amount for the acquisition of electric buses. This study chose to consider all revenue and cost parameters as deterministic throughout the operational period of the bus transportation system to keep the computational treatment of the problem viable.

Moreover, all the analyzed literature models the Fleet Replacement Problem as an integer programming problem, solving it with the CPLEX algorithm, by IBM. In this study the same approach will be made, both to dialogue with the literature and because it's a well-established commercial algorithm.

## 2 Literature Review

Currently, many cities around the world are introducing EBs to improve urban air quality, reduce carbon emissions, and potentially lower operational costs. In this context, many governments have already set targets for fleet electrification: Paris aims to operate only electric buses by 2025, Los Angeles by 2030, the state of California aims to have zero emissions by 2040, while Toronto aims to have 50% of its fleet with zero emissions between 2028 and 2032 (PELLETIER et al., 2019).

However, there are still significant barriers to the widespread adoption of these vehicles. The biggest challenge for EBs is the high upfront cost compared to DBs. To address this issue, new business models such as battery leasing, joint procurement, and bus sharing have emerged, mainly in North America and Europe. Additionally, uncertainty about the residual value of buses, driven by the battery lifespan, is another difficulty (Bloomberg New Energy Finance, 2018).

Analyses indicate that EBs will reach upfront cost parity with DBs around 2030, with the reduction in battery costs. However, increased demand could accelerate this parity to the mid-2020s. Electric buses already have much lower operating costs and can be cheaper in terms of total cost of ownership (TCO) than conventional buses today (Bloomberg New Energy Finance, 2018).

Also, a study from Goldman Sachs (Goldman Sachs, 2024) estimates an average 9% decrease in battery prices in real terms, as shown in Figure 1.

As a result, numerous studies on the Fleet Replacement Problem have emerged in the literature, addressing the optimization of the energy transition of bus fleets, which are currently predominantly diesel-powered, to alternative technologies, mainly electric.

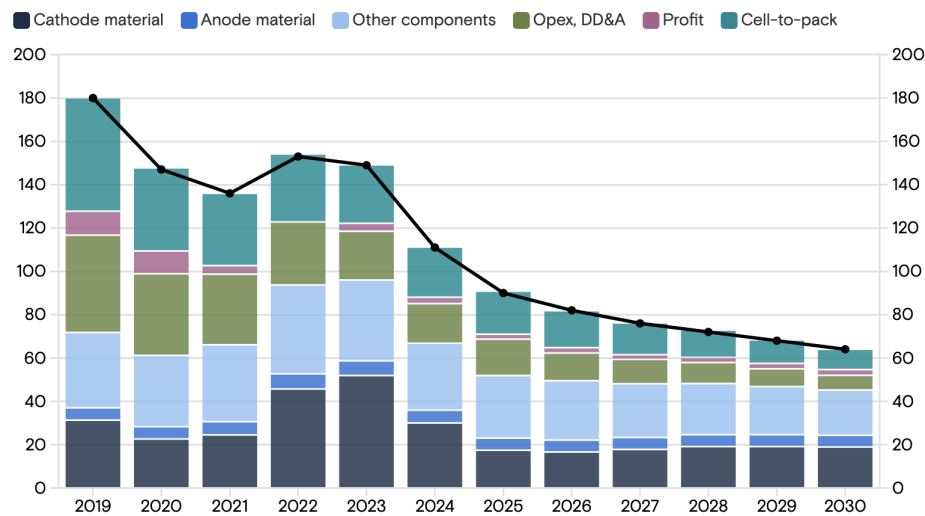
(LI; CASTELLANOS; MAASSEN, 2018) analyzes the electrification programs of 22 worldwide, and explores strategies to overcome the financial and operational barriers to transitioning urban bus fleets to electric vehicles. The study highlights that grants—whether public, private, or in-kind—are the most common means of addressing the higher upfront costs of electric buses. In addition to these trends, innovative approaches such as involving utility companies and bus manufacturers to provide training and infrastructure funding, and leasing models for buses and batteries to reduce initial costs and reallocate risks, are proving impactful.

The research also identifies emerging funding mechanisms, such as soft loans and green bonds, which are being used by cities like Curitiba and Tianjin to finance electric buses. Contractual innovations, including concessions and tailored maintenance agreements, facilitate risk-sharing among stakeholders, ensuring smoother technology adoption.

(FENG; FIGLIOZZI, 2014) studies the Fleet Replacement Problem of diesel buses to

## Battery prices forecast to continue to fall

Global: average battery pack prices (US\$/kWh)



Source: Company data, Wood Mackenzie, SNE Research, Goldman Sachs Research  
2024-2030 are forecasts

**Goldman  
Sachs**

Figure 1 – Forecast for battery prices

hybrid buses, using data from King County (Seattle, USA). The article uses variables such as government subsidies, maintenance costs, fuel prices, and pollution-related costs. Through sensitivity analysis, it is found that the subsidy must be equal to or greater than 63% of the purchase price for the choice of hybrid buses to be optimal.

(ISLAM, 2018) develops a model similar to the previous one, considering the alternative between one type of hybrid bus and one type of electric bus, in addition to restrictions on annual emissions and the need for infrastructure investment for electric buses. The data used is from the Chicago transport system. It considers the Life-cycle costs (LCC), which includes not only operation but also the environmental impact of production.

On the other hand, (PELLETIER et al., 2019) complements the models by simultaneously considering emission targets over time, vehicle purchase and salvage decisions, and different EB technologies with different infrastructure requirements, as well as alternatives such as natural gas. Using data from a bus operator in France, the study concludes that EBs are the optimal choice, regardless of the technology, for small buses, while for regular-sized buses, natural gas technology can be a good intermediary until electric battery prices decrease enough. It is worth noting that hybrid buses are not used in optimal solutions even as intermediaries.

(ZHOU; ONG; MENG, 2023) develops a general model considering three internal cost components (purchase, operation, and salvage) and four external ones (air pollution, noise, contribution to climate change, and battery recycling). The decision variables are the purchase and sale by type and age of vehicles, as well as infrastructure investment, with transport demand, budget, and energy demand constraints. The impact of interventions such as purchase subsidies,

diesel taxes, or DB taxation is also considered. Using data from the Singapore transport operator, the results suggest that opportunity-charging technologies (performed during operation, e.g. in bus stations) are preferable to overnight-charging (in parking lots). The study also found no impact from DB taxation, but a 10% diesel tax seems to be appropriate. Furthermore, in the analyzed context, the efficiency of subsidies, that is, the sum of operator and external benefits over the spent value, decreases with the subsidized amount, being less than 1 for 10% or more of the purchase price.

All the approaches above consider the total costs, including externalities, to be borne by the operator of the system. (ARIZCUREN-BLASCO; MARTIN-GARCIA; RUIZ-RUA, 2023) divides them between operator/concessionaire and government. However, the authors do not solve a Fleet Replacement Problem, but instead analyze only the net present value of replacing one DB for one EB. They do argue that externalities should be discounted to present value using a rate different from the financial rate, namely a social discount rate. This is because the value of social benefits should not depend heavily on the period in which they are obtained. For example, the preserved health of a person today should hold the same value as the preserved health of a person five years from now. Consequently, the social discount rate is expected to be lower than the financial rate. For the present study, the baseline case uses the same rate for social and financial purposes, but a sensibility analysis on social discount rate for the externalities is made.

At the federal level, the National Public Transport Agency (ANTP) published a reference document in 2023 on the calculation methodology and parameters for the costs of electric bus transport services (ANTP, 2023). It also presents reference values for the parameters, which were found through market consultation.

## Nomenclature

$a_0^\theta(t)$	Quantity of new buses of type $\theta$ acquired in period $t$
$a^I(t)$	Quantity of new electric chargers acquired in period $t$
$B(t)$	Budget available in period $t$
$E^\theta(t)$	Energy consumption/km by bus of type $\theta$ in period $t$
$I(t)$	Quantity of electric chargers owned in period $t$
$i$	Age of the bus, in years
$i_{max}$	Maximum age permitted by contract, in years
$j$	Annual inflation rate
$km^\theta(t)$	Kilometers traveled in a month by a bus of type $\theta$
$MT_i^\theta(t)$	Maintenance cost/km by bus of type $\theta$ and age $i$ in period $t$
$P^I(t)$	Price of a charger in period $t$
$P_i^\theta(t)$	Market price of a bus of type $\theta$ and age $i$ , in period $t$
$P^b(t)$	Market price of EB batteries in period $t$
$Penal(t)$	Penalty stipulated in the contract for not meeting the emission reduction target, in period $t$ .
$P2^\theta(t)$	Remuneration parameter for maint. & energy of bus of type $\theta$ in period $t$
$P3^\theta(t)$	Remuneration parameter for capital investment of bus of type $\theta$ in period $t$
$P4^\theta(t)$	Remuneration parameter for investment in $TR^\theta$ of bus of type $\theta$ in period $t$
$q_i^\theta(t)$	Quantity of fleet buses of type $\theta$ and age $i$ in period $t$
$r$	Financial discount rate
$s_i^\theta(t)$	Quantity of buses of age $i$ and type $\theta$ salvaged in period $t$
$sub(t)$	Amount subsidized for EB acquiring in period $t$
$T_c$	Timeframe of the concession contracts
$T_s$	Timeframe of the study, used to evaluate the objective functions.
$TR^\theta$	Technical reserve, additional quantity of spare buses
$\alpha$	Bus/charger ratio
$\theta$	Bus type, Diesel or Electric

### 3 Methodology

The study aims to analyze the relevant factors in contracts between the City Hall and the concessionaires, especially the optimal subsidy conditions to maximize the payoff of the municipality. This payoff considers both financial costs and the socio-environmental impact of the urban bus transportation system. Therefore, the payoff function depends not only on the subsidy policy,  $Sub$  (decision variable), but also on the fleet composition  $F$ .

$$\max_{Sub \in Pol_{Sub}} PO(Sub, F) \quad (3.1)$$

In the concession model, the direct definition of the fleet composition is a decision of the concessionaires, who respond to economic incentives to maximize profit, subject to budget constraints. As discussed in the literature, especially in (ZHOU; ONG; MENG, 2023), this decision is influenced by the value of the subsidies, such that  $F$  is a function of  $Sub$ :  $F = F(Sub)$ . Thus, the problem of maximizing public payoff becomes:

$$\max_{Sub \in Pol_{Sub}} PO(Sub, F(Sub)) \quad (3.2)$$

Thus, the problem can be decomposed into two subproblems: (P1) the concessionaire's decision on the fleet composition to maximize profit, given the value of the subsidy; and (P2) the Municipal Government's decision on the subsidy value to maximize public payoff, considering the expected response from subproblem (P1). Put in another way, chronologically, the Municipal Government solves P2 forecasting the response to P1, finding the optimal policy ( $Sub^*$ ), and given its decision the concessionaire in turn solves P1, finding the fleet which retrieves most gains for it ( $F^*(Sub^*)$ ). Scheme shown in Figure 2. The present model considers all parameters as exogenous, and known beforehand by all parts involved, so predictions are met.

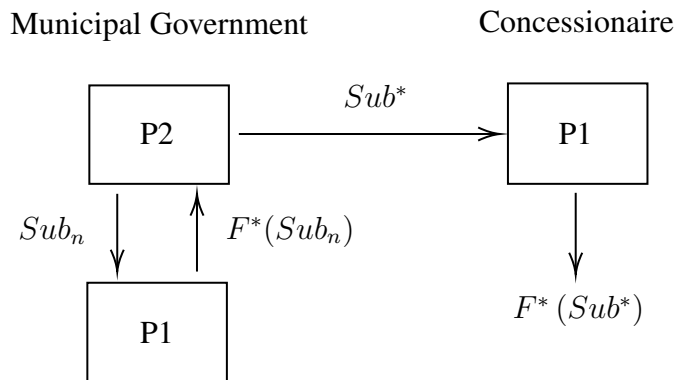


Figure 2 – Model scheme

For a detailed explanation of the current policy, that defines the baseline case modeled below, please refer to Appendix A.

Also, this modeling considers that the municipality's payoff is equal to the society's, which is in fact what the government should be optimizing. For a brief discussion on a possible correction of values and its potential impact on the study's result, refer to Appendix B.

### 3.1 P1: Fleet Composition

The goal of the concessionaire is to maximize the present value of its earnings. To achieve this, the concessionaire decides each period on the purchase and salvage of vehicles and investment in infrastructure, subject to a budget constraint. These decisions, made each period, determine the transition of the fleet state to the next period. The fleet state is characterized by the composition of buses (type of technology, age), existing infrastructure, and available budget.

To find the optimal policy for each period, this work utilizes the CPLEX algorithm, by IBM, to solve the integer programming problem. This is common practice in the literature.

The fleet composition is defined as  $F = [Q, I, B]$ , where  $Q$  is the matrix of quantities  $q_i^D(t)$  of ODs and  $q_i^E(t)$  of EBs of age  $i$ ,  $i = 0, 1, 2, \dots, i_{max}$ , for  $i_{max}$  maximum age accepted in the contract for fleet vehicles and  $t = 0, 1, \dots, T_s$ ;  $I$  is the vector of available infrastructure in each period, in terms of number of chargers; and  $B$  is the vector concessionaire's budget available for acquiring new buses in each period.

The decision variables are  $A = [a_0^D(t), a_0^E(t), a^I(t)]$ , for  $t = 0, 1, \dots, T_s$ , the quantities acquired of new ODs, EBs, and chargers, respectively; and  $S = [s_i^D(t), s_i^E(t)]$ , for  $i = 1, 2, \dots, i_{max}$  and  $t = 0, 1, \dots, T_s$ , the quantities of ODs and EBs of age  $i$  salvaged.

As of the timeline, the problem is modeled as such:

- A fleet state at the beginning of period  $t$  is given.
- Acquisition and salvaging are actions taken at the beginning of period  $t$ , such that their related costs and revenues are also accounted for at its beginning, but the fleet is only updated in period  $t + 1$ , modeling the time to deliver the vehicles.
- Revenues and costs related to the operation are considered to be taken at the end of the period.

To calculate the objective function, first it is necessary to define the revenues and costs that are part of it.

### 3.1.1 Revenues and Costs

The bus acquisition cost for each period, in Equation 3.3, takes into account the market price and quantities of new buses of type diesel or electric acquired, and subtracts the amount subsidized.

$$C_a(t) = P_0^D(t) \cdot a_0^D(t) + P_0^E(t) \cdot a_0^E(t) - sub(t) \quad (3.3)$$

Also, the concessionaire needs to have sufficient charging infrastructure, as to support its electric fleet. This cost is modeled similar to the bus acquisition cost, but it's entirely backed by the concessionaire, with no subsidy, as in Equation 3.4

$$C_I(t) = P^I(t) \cdot a^I(t) \quad (3.4)$$

Each EB will also eventually have to have its battery replaced. It is considered that they have an 8-year life expectancy, so for every EB of age 8 there may be an additional cost for battery change, as shown in the Equation 3.5. Since the maximum age is 12, that is the only battery change needed for each bus. As stated in the introduction, all the parameters were modeled to be deterministic, even though, in this case, the 8-year value is only expected.

$$C_b(t) = P^b(t) \cdot q_8^E(t) \quad (3.5)$$

As of operational costs, they consist of two components: energy and maintenance. They are accounted for per kilometer traveled by each vehicle. It is assumed that labor costs are the same regardless of the vehicle's technology and, therefore, will not be considered in the study. Equation 3.6 shows that operational costs are proportional to the number of buses in the fleet, where the parameter  $\gamma_i^\theta(t)$  is the maintenance and energy costs per kilometer per bus multiplied by the kilometer traveled per month.

$$C_o(t) = \sum_{\theta \in \{D,E\}} \sum_{i=0}^{i_{max}} \gamma_i^\theta(t) \cdot q_i^\theta(t) \quad (3.6)$$

Where:

$$\gamma_i^\theta(t) = 12 \cdot (MT_i^\theta(t) + E^\theta(t)) \cdot km^\theta \quad (3.7)$$

The revenue formula is defined in the concession contracts for each vehicle technology. It is structured to compensate for each cost component (maintenance, energy, labor, capital, and technical reserve) and to approximately ensure a defined return rate. In Equation 3.8, the portion related to operational labor was not considered, as it does not vary with vehicle technology.

$$R_o(t) = \sum_{\theta \in \{D,E\}} \left( \beta^\theta(t) \sum_{i=0}^{i_{max}} q_i^\theta \right) - k \sum_{\tau=0}^t sub(\tau) \quad (3.8)$$

Where:

$$\beta^\theta(t) = 12 \cdot \left( \frac{1}{1 + TR^\theta} (P2^\theta(t) \cdot km^\theta + P3^\theta) + \frac{TR^\theta}{1 + TR^\theta} \cdot P4^\theta(t) \right) \quad (3.9)$$

The factor dependent on the subsidy in Equation 3.8 was established to compensate for the portion of the capital investment that was not made by the concessionaire, and therefore should not be remunerated. The parameter  $k$  was calibrated so that this compensation is approximately achieved.

$TR^\theta$  is the technical reserve required for type- $\theta$  buses. It refers to the surplus number of buses the concessionaire must have available to ensure service continuity in adverse events, such as the need for vehicle maintenance.

From the contracts, the terms  $P2$ ,  $P3$  and  $P4$  specified in Equation 3.9 are the remuneration parameters for maintenance & energy, capital investment and technical reserve investment, respectively.

Moreover, revenue may be realized through salvaging used vehicles. Equation 3.10 calculates the salvaging revenue in period  $t$  from the market prices for buses of type  $\theta$  and age  $i$ , and quantity salvaged.

$$R_s(t) = \sum_{\theta \in \{D,E\}} \sum_{i=1}^{i_{max}} 0.8 P_i^\theta(t) s_i^\theta(t) \quad (3.10)$$

The 0.8 multiplier was inserted to reflect sales costs. It may include income taxes and failed sales, and its value was estimated prudentially, not calculated.

Finally, the amount in the concessionaire's cash or cash equivalents will yield at the rate  $r$ . Considering that acquisitions and salvaging are done at the beginning of the period, the yield of the period is approximately calculated in Equation 3.11

$$R_c(t) = (B(t) + R_s(t) - C_a(t) - C_i(t)) \cdot r \quad (3.11)$$

### 3.1.2 Gain and Objective Function

The Gain Function is the sum of revenues and costs.

$$G(t) = R_o(t) + R_s(t) + R_c(t) - C_a(t) - C_i(t) - C_b(t) - C_o(t) - C_p(t) \quad (3.12)$$

And the Objective Function is the net present value of  $G(t)$  until period  $T_s$ .

$$OF(F, A, S) = \sum_{t=0}^{T_s} \frac{G(t)}{(1+r)^t} \quad (3.13)$$

Note that the sum limits for  $t$  are 0 and  $T_s$ , instead of  $T_c$ , with  $T_s$  considerably higher than  $T_c$ . This was chosen to reflect the fact that the concessionaire may choose to replace its fleet slower than the contract's limit. If the limit of full electrification in  $T_c$  periods is respected for all subsidy policies, the comparison between scenarios is trivial.

### 3.1.3 Boundary Conditions

The boundary conditions in this integer problem consist in the non-negative, intertemporal, infrastructure and budget constraints.

All the decision variables are non-negative, since there cannot be a negative quantity.

$$q_i^\theta(t), a_0^\theta(t), s_i^\theta(t) \geq 0 \quad (3.14)$$

The fleet is replaced over the periods, but the integer problem is solved at once, so there may be constraints to account for the intertemporal changes. The quantity of type  $\theta$  in period  $t + 1$  is equal to its quantity one year newer in period  $t$  plus the amount bought, minus the amount salvaged. Moreover, all the vehicles bought are new, and as they reach their maximum age, they must be salvaged.

Fleet:

$$q_0^\theta(t+1) = a_0^\theta(t), t = 0, 1, \dots, T_s \quad (3.15a)$$

$$q_{i+1}^\theta(t+1) = q_i^\theta(t) - s_i^\theta(t), t = 0, 1, \dots, T_s; i = 0, 1, \dots, i_{max} - 2 \quad (3.15b)$$

$$q_{i_{max}}^\theta(t) = s_{i_{max}}^\theta(t), t = 0, 1, \dots, T_s \quad (3.15c)$$

Infrastructure:

$$I(t+1) = I(t) + a^I(t), t = 0, 1, \dots, T_s \quad (3.16)$$

Budget:

$$B(t+1) = B(t) + G(t), t = 0, 1, \dots, T_s \quad (3.17)$$

The charging infrastructure is proportional to the EB fleet size by a coefficient of  $\alpha$ , depending on the time it takes to fully charge a vehicle, and the time available to do so.

$$I(t) \geq \alpha \sum_{i=0}^{i_{max}} q_i^E(t) \quad (3.18)$$

Also, there budgetary constraints regarding the amount of cash available to the concessionaire for acquiring buses and charging infrastructure, and the limit value of subsidy the Municipal Government can spend each period.

Concessionaire's budget:

Considering there's an initial budget  $B_0$ , and that the amount available for acquisition in  $t$  is equal to  $B(t) + R_s(t)$ , the constrains are:

$$B(0) = B_0 \quad (3.19a)$$

$$B(t) \geq C_a(t) + C_i(t) - R_s(t) \quad (3.19b)$$

$$B(t) \geq 0 \quad (3.19c)$$

Subsidy limit:

The municipality is also limited in its ability to provide subsidies due to budgetary and credit constraints. Given an annual budget of  $B_M$ , adjusted for annual inflation  $j$ , and the function  $f_{pol}(t, a_0^E(t))$ , which returns the subsidy amount in period  $t$  for the acquisition of  $a_0^E(t)$  units of EBs under the chosen policy, we have:

$$sub(t) = \min[B_M \cdot (1 + j)^t, f_{pol}(t, a_0^E(t))] \quad (3.20)$$

The form of  $f_{pol}(t, a_0^E(t))$  is determined by the subsidy policy chosen by the municipality, as explained in the following section. It suffices to note that it is increasing monotonically in  $a_0^E(t)$ .

Equation 3.20 limits  $sub(t)$  to the adjusted budget, without limiting the choice of  $a_0^E(t)$  by the concessionaire, that might choose to acquire additional buses without subsidy, if the lower operational costs are worth it.

Lastly, there is a full electrification target to be achieved until the end of the concession, in  $T_c = 15$  years, and there is a credible intention that the next concession will already require a full EB fleet. So if the concessionaire does not have enough EB at this point, it will not be able to participate on the contracts. This is a high enough cost to be considered a constraint. That means that at period  $T_c - 1 = 14$ , all DBs left must be salvaged, and replaced by EBs, in time to fully electrify the fleet at  $T_c$ .

In conclusion, P1 is solved by finding the fleet electrification schedule that maximizes the concessionaire's present value of gains, given the subsidy policy determined by the municipality beforehand. There's no limit on number of bus acquired, though there is a limit on amount of subsidy for each period.

## 3.2 P2: Subsidy Decision

Given the space of possible subsidy policies  $Pol_{Sub}$ , the concessionaire will adopt an acquisition and salvaging policy that will lead to a fleet planning. Given  $Sub \in Pol_{Sub}$ :

$$F^*(Q(0), I(0), B(0), A^*(Sub), S^*(Sub)) \equiv F^*(Sub) \quad (3.21)$$

Where  $A^*(Sub)$  and  $S^*(Sub)$  are the vectors of optimal acquisition and salvaging decisions, respectively, given the policy chosen, to solve P1 for the concessionaire. The municipality decision problem then is to determine  $Sub$  that solves (3.2).

The municipality's payoff function accounts for internal costs, such as subsidies and concession remuneration, and external costs, such as environmental and welfare costs.

For subsidy costs, considering  $sub(t)$  as the total subsidy in period  $t$ , the cost to the municipality will as stated in Equation 3.22

$$C_{Sub}(t, F^*(Sub)) = sub(t) = \min[B_M \cdot (1 + j)^t, f_{pol}(t, a_0^{E,*}(t))] \quad (3.22)$$

The calculation of  $f_{pol}(t, a_0^E(t))$  is defined by  $Sub$ , which can be a percentage of the purchase value,  $f_{pol}(t, a_0^E(t)) = p \cdot P_0^E(t) \cdot a_0^E(t)$ , or the price difference between DB and EB,  $f_{pol}(t, a_0^E(t)) = (P_0^E(t) - P_0^D(t)) \cdot a_0^E(t)$ , for example. Also,  $f_{pol}(t, a_0^E(t)) = 0, \forall t > T_c$ , i.e. the subsidy policy is only valid to the current contracts, with no subsidies in the next concession period.

For this study, it is based on either a percentage of acquisition cost or the current municipal policy, which is the price difference between electric and diesel buses, with an upper limit of 85% of EB's price.

For concession remuneration, defined in (3.8), the municipality pays the concessionaires for the service provided. It also deduces from this remuneration in period  $t$  the amount of  $k \sum_{\tau=0}^t sub(\tau)$ , which balances the return given the subsidy received, so  $R_o(t) = R_o(t, Sub)$

Thus, in P2 the remuneration is based on the optimal fleet resulting from solving P1.

$$C_R(t, F^*(Sub)) = R_o^*(t, Sub) \quad (3.23)$$

This study follows the methodology and data from the "EU Handbook on external costs of transport" (European Commission et al., 2020). External costs of transport refer to the difference between social costs (i.e., all costs to society due to the provision and use of transport infrastructure) and private costs of transport (i.e., the costs directly borne by the transport user). The externalities considered are local air pollution, noise pollution, and contribution to climate change. For the evaluation of both air and noise pollution, the authors adopt the damage cost approach, considering health impacts (physical or psychological), as well as damage to material and natural assets. On the other hand, the contribution to climate change is assessed using the avoidance cost approach, as potentially catastrophic events, such as polar ice cap melting and abnormally intense storms, cannot be well incorporated into the damage cost approach. In this case, cost estimates are used to avoid GHG emissions that would lead to a 1.5 to 2 degrees Celsius increase in average global temperature.

The willingness-to-pay (WTP) data in (European Commission et al., 2020) are estimated in Euro for European Union countries; however, the study itself suggests a methodology to convert the values with income-based adjustments.

$$WTP_{PS} = WTP_{SS} \left( \frac{I_{OS}}{I_{SS}} \right)^\varepsilon \quad (3.24)$$

Where  $WTP_{PS}$  is the transferred WTP,  $WTP_{SS}$  is the WTP at the study site,  $I_{OS}$  and  $I_{SS}$  are income at the other and study sites, and  $\varepsilon$  is income elasticity of WTP. Income is defined as PPP-adjusted GDP/capita.

From the coefficients obtained in (European Commission et al., 2020), environmental costs can be calculated using the following formula:

$$C_{amb}(t, F^*(Sub)) = \sum_{\theta=D,E} \left[ \left( (c_{air}^\theta(t) + c_{CC}^\theta(t)) \cdot pkm^\theta + c_{noise}^\theta(t) \cdot km^\theta \right) \sum_{i=0}^{imax} q_i^\theta(t) \right] \quad (3.25)$$

Where  $c_{air}^\theta(t)$  and  $c_{CC}^\theta(t)$  account for the cost of air pollution and the contribution to climate change per passenger-kilometer traveled; and  $c_{noise}^\theta(t)$  represents the cost of noise generation per kilometer traveled.

Finally, the goal is to optimize (maximize) the sum of the present value of the payoff in  $T_s = 40$  periods ( $T_s \gg T_c$ ), which is defined as minus the sum of costs:

$$PO(Sub) = \sum_{t=0}^{T_s} - \frac{(C_{Sub}(t, F^*(Sub)) + C_R(t, F^*(Sub)) + C_{amb}(t, F^*(Sub)))}{(1+r)^t} \quad (3.26)$$

### 3.3 Optimization

For the solution of P1, this studies utilizes the CPLEX algorithm, which is an optimization solver that efficiently solves linear programming (LP), mixed-integer programming (MIP), and quadratic programming (QP). It employs the Simplex method for LP, the Barrier method for large-scale problems, and Branch-and-Bound with cutting planes for MIP. The algorithm follows a structured workflow: problem formulation, preprocessing to reduce complexity, solving LP relaxations, applying integer search methods for MIP, and post-processing to refine the solution.

It is worth noting that all the functions and restrictions stated for P1 are linear, but for Equation 3.20, which cannot be directly used as a constraint in solving with CPLEX. However, using auxiliary variables, this constraint can be expressed in a linear form.

Let  $M = 10^{15}$ ,  $L1 = B_M \cdot (1 + j)^t$ , and  $a1 = f_{pol}(t, a_0^E(t))$ . Equation 3.20 is equivalent to:

$$sub(t) - L1 \leq 0 \quad (3.27a)$$

$$sub(t) - a1 \leq 0 \quad (3.27b)$$

$$sub(t) - (L1 - M \cdot (1 - aux1)) \geq 0 \quad (3.27c)$$

$$sub(t) - (a1 - M \cdot (1 - aux2)) \geq 0 \quad (3.27d)$$

$$aux1 + aux2 = 1 \quad (3.27e)$$

Where  $aux1$  and  $aux2$  are binary variables (0 or 1). Since  $M$  is larger than any possible value of  $sub(t)$ , it is straightforward to see that, if  $L1 \leq a1$ , then it must be so that  $aux1 = 1$  and  $aux2 = 0$ :

$$sub(t) - L1 \leq 0 \quad (3.28a)$$

$$sub(t) - a1 \leq 0 \quad (3.28b)$$

$$sub(t) - L1 \geq 0 \quad (3.28c)$$

$$sub(t) - (a1 - M) \geq 0 \quad (3.28d)$$

So all constraints are respected, implying  $sub(t) = L1$ . Similarly, if  $a1 \leq L1$ ,  $aux1 = 0$  and  $aux2 = 1$ , so  $sub(t) = a1$ .

For P2, there is no analytical formula for Equation 3.26, and since evaluating fleet replacement is computationally expensive, a more appropriate methodology should be used. Thus, to solve P2 optimization problem, a space of  $n$ , equally spaced from range 0 to 1, proportions  $p$  for price subsidy is tested, in addition to the current policy.

# 4 Data

## 4.1 Transportation System

Information on the bus transportation system in the city of São Paulo primarily comes from SPTrans itself, either from its reports or documentation for the concession. All monetary values below have been adjusted by the accumulated IPCA from the publication date until 03/08/2024.

In this study, a standard fleet consisting solely of Padron-type vehicles was chosen, as it is a model manufactured and sold in both technologies (diesel and electric). No differentiation on DB technology is made (Euro V, Euro VI, etc)

For the study, the financial discount rate ( $r$ ) considered is the contract target IRR of 9.1% yr. Also, whenever it is necessary to update prices yearly, the 2% annual inflation rate ( $j$ ) is used.

For  $km^\theta$ , considered equal for both types, based on Annex 3.1 of the Concession Bid Document (São Paulo, 2015a), the average number of Padron buses contracted by line and subsystem, as well as the average distance traveled per vehicle per month is as shown in Table 1. The study considered the number for the Structural Subsystem.

Subsystem	Number of Lines	Fleet	Fleet/Line	km/Month	km/Month/Bus
Structural	111	1,388	13	9.087.488	6.549
Regional Articulation	113	1,149	10	7.532.649	6.554

Table 1 – Number per line and monthly mileage. Prepared by the author.

From the SPTrans Citizen Information System (e-SIC), it is possible to estimate the bus fleet composition of a concessionaire utilizing Padron-type buses, both diesel and electric. Table 2 show the total number of vehicles by model year. Data obtained on 08/12/2024.

From Table 2, for the total fleet of 100 buses, it is considered as initial condition as in Figure 3, giving  $q_i^D(0)$ ,  $i = 0, 1, \dots, 12$ , and totalizing 100 buses. Initially, no EBs are owned.

$E^\theta(0)$  and  $MT_0^\theta(0)$  are calculated based on the methodology applied in Annex 4 of the Concession Bid Document, using current values for Diesel S10 (Petrobras, 2024), maintenance costs from (REBOUÇAS; ROZENFELD; DELGADO, 2022), and energy prices presented by Enel. Table 3 show the results. These parameters are adjusted for inflation throughout the periods  $t$ .

Moreover, maintenance costs are expected to rise at a compound rate of 5% per year of vehicle age. This is a prudential value, since no specific studies were found.

Year\ Type	ePadron	Padron	Total	Total (%)
2007	-	1	1	0,02%
2009	-	11	11	0,24%
2012	-	87	87	1,91%
2013	-	141	141	3,10%
2014	-	457	457	10,04%
2015	-	130	130	2,85%
2016	-	360	360	7,91%
2017	-	109	109	2,39%
2018	-	299	299	6,57%
2019	-	697	697	15,31%
2020	-	918	918	20,16%
2021	-	316	316	6,94%
2022	-	275	275	6,04%
2023	-	651	651	14,30%
2024	102		102	2,24%
Total	102	4452	4554	100,00%

Table 2 – Bus system Padron-type fleet composition.



Figure 3 – Modeled initial bus fleet.

For battery replacement prices, from (ZHOU; ONG; MENG, 2023), the expected battery

Type	Fuel/Energy			Maintenance	Total
	Consumption l(kWh)/km	R\$/l(kWh) adjusted	R\$/km	R\$/km	R\$/km
Diesel	0.644	5.95	3.83	0.80	4.63
Electric	1.25	0.656	0.82	0.61	1.43

Table 3 – Maintenance and energy costs. Prepared by the author.

cost in April/22 was USD 133,000.00. Considering the exchange rate at the time (US\$1.00:R\$4.92) and the Brazilian inflation in the period, the battery price ( $P^b(0)$ ) used is R\$ 720,000.00/battery. Following (Goldman Sachs, 2024), the prices are updated at a real rate of -9% yr.

The acquisition and resale prices shown in Table (4) were calculated based on the reference values present in the joint ordinance SMT/SF No. 2, dated November 30, 2023, and the depreciation table present in (KONAI et al., 2024).

Age	Diesel	Electric	Post-depreciation
$P_0^\theta(0)$	774,579.26	2,825,649.53	100.0%
$P_1^\theta(0)$	682,404.33	2,489,397.24	88.1%
$P_2^\theta(0)$	596,426.03	2,175,750.14	77.0%
$P_3^\theta(0)$	517,418.95	1,887,533.89	66.8%
$P_4^\theta(0)$	443,833.92	1,619,097.18	57.3%
$P_5^\theta(0)$	375,670.94	1,370,440.02	48.5%
$P_6^\theta(0)$	314,479.18	1,147,213.71	40.6%
$P_7^\theta(0)$	259,484.05	946,592.59	33.5%
$P_8^\theta(0)$	210,685.56	768,576.67	27.2%
$P_9^\theta(0)$	167,309.12	610,340.30	21.6%
$P_{10}^\theta(0)$	130,903.90	477,534.77	16.9%
$P_{11}^\theta(0)$	99,920.72	364,508.79	12.9%
$P_{12}^\theta(0)$	75,908.77	276,913.65	9.8%

Table 4 – Price (R\$) by age. Prepared by the author.

For updating values, for DBs the inflation rate is used, for EBs the battery price is segregated and updated separately, and for the remaining portion the inflation rate is used.

The remuneration factors as defined in Table 5, according to the terms of the concession contracts and its 7th amendment regarding the remuneration of the electric fleet.

Considering a concessionaire that currently has no infrastructure for charging ( $I_0 = 0$ ), the initial mean cost for acquiring chargers ( $P^I(0)$ ), according to the reported by Public Transport National Association (ANTP) (ANTP, 2023) is R\$310,000.00/charger.

Also, following the parameters of (ANTP, 2023), for overnight charging there's available

Type	P2	P3	P4	k
Diesel	1.5653	22,427	18,119	-
Electric	1.1435	57,440	51,662	0.978%

Table 5 – Remuneration coefficients

time to charge two buses for each charger, giving  $\alpha = 0.5$

For emission target, since emission is proportional to DB quantity, and the study fleet has 100 buses, EB target is simply  $100 - 100 \cdot (\text{Reduction Target})$ , rounded to nearest integer.

Finally, the budgetary constraint parameters are given as follows:

#### Concessionaire's Budget

The initial cash available for acquiring new buses ( $B(0)$ ) is considered to be sufficient to buy 10 EBs.

#### Subsidy Limit

The municipality announced in 2024 sufficient budget to subsidize 2,600, equivalent to approximately 21.7% of the total fleet of around 12,000. Considering the current policy of subsidizing around R\$ 2,000,000.00 per electric Padron bus, the initial subsidy constraint to a 100-bus fleet ( $B_M$ ) is estimated in R\$ 40,000,000.00.

## 4.2 Environmental Impact

According to data provided by SPTrans (SPTrans, 2024), in the reference set used, the number of passengers transported annually in the structural subsystem would be approximately:

Subsystem	Passengers/month	Passengers/year
Structural	17,383,187	208,598,244
Regional Articulation	14,586,710	175,040,520

Table 6 – Number of passengers transported. Prepared by the author.

As a prudential value for calculating  $pkm^\theta$ , it is considered that each passenger travels 7.5 km per travel. Thus, according to the methodology adapted from (European Commission et al., 2020),  $c_{air}^\theta(t)$ ,  $c_{noise}^\theta(t)$  and  $c_{CC}^\theta(t)$  are given by each column of Table 7, respectively:

Type	Pollution (R\$/pkm)	Noise (R\$/km)	Climate Change (R\$/pkm)
Diesel	0.004	0.3021	0.0203
Electric	0.0013	0.2309	0.00

Table 7 – Environmental cost. Prepared by the author.

## 5 Results

The following are the results for the baseline case, using standard values for revenues, costs, and constraints. P1 and P2 are solved for different subsidy policies to determine the optimal policy from the municipality's perspective, which solves P2.

Subsequently, robustness and sensitivity analyses are conducted: for electrification target, price ratio, municipal budget, technical reserve value, and EB's operational costs in P1; and for externality cost and social discount rate in P2.

### 5.1 Baseline Case

In the results for P1, as shown in Figure 4, it is possible to see that even in the scenario without subsidies, the final electrification target is achieved. However, the 50% target is only met starting from a 30% subsidy on the price of the EB.

An interesting point to note is that the greatest advancement in electrification does not occur with full subsidies but rather with a subsidy of around 70%. Beyond this level, the electrification timeline starts to increase again. As the results suggest, the concessionaires prefer to wait for subsidized acquisitions rather than bearing the full cost of part of the acquisitions themselves. Given the municipal budget constraint for subsidies, higher subsidy percentages result in longer timelines. Figure 5 supports this analysis, showing that only subsidized acquisitions occur.

Figure 6 shows the median age of the fleet vehicles, for 0%, 70% and 100% subsidy policies. As full electrification is achieved, the optimal solution seems to be letting the fleet age until the maximum age permitted, and then restarting the cycle.

Calculating the objective function value of P2 for different subsidy policies, the results presented in Figure 7 are obtained. The horizontal lines represent the price-difference policy, which features a variable subsidy percentage.

The result of P2, the argument that maximizes its objective function, corresponds to the policy that maximizes Total Payoff. In the baseline case, this is the policy with a 100% subsidy.

However, some results are worth noting:

1. The total financial cost—comprising the subsidy cost and compensation—i.e., the monetary amount disbursed by the municipality, does not vary significantly with the policy. This was expected since the parameter  $k$  for EB compensation was specifically designed to offset the subsidized values at the same return rate as stipulated in the contracts.
2. Observing only the externality costs, there is a maximum at a 65% subsidy. This occurs

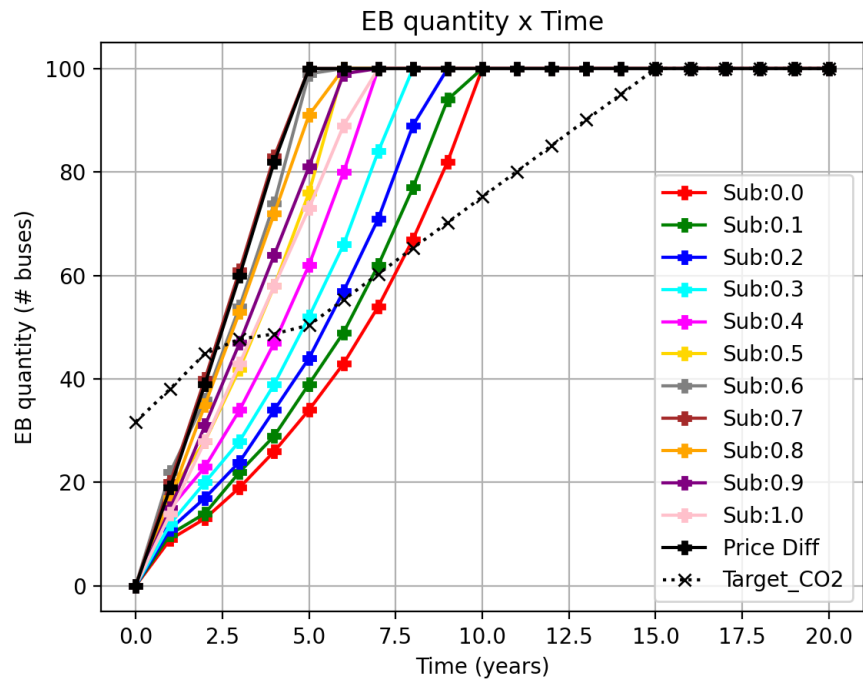


Figure 4 – Baseline: Electric fleet development

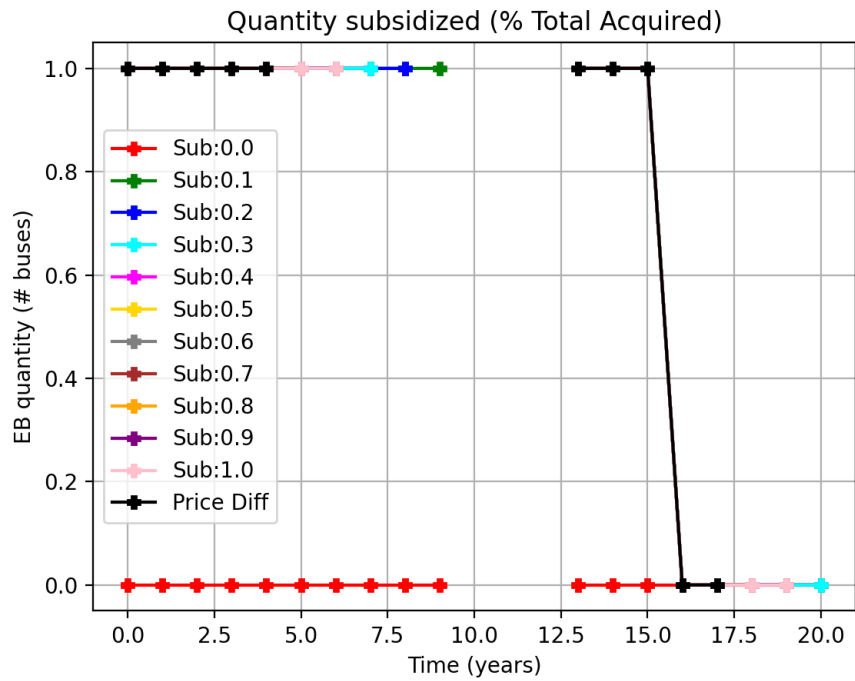


Figure 5 – Baseline: Proportion of acquisitions subsidized

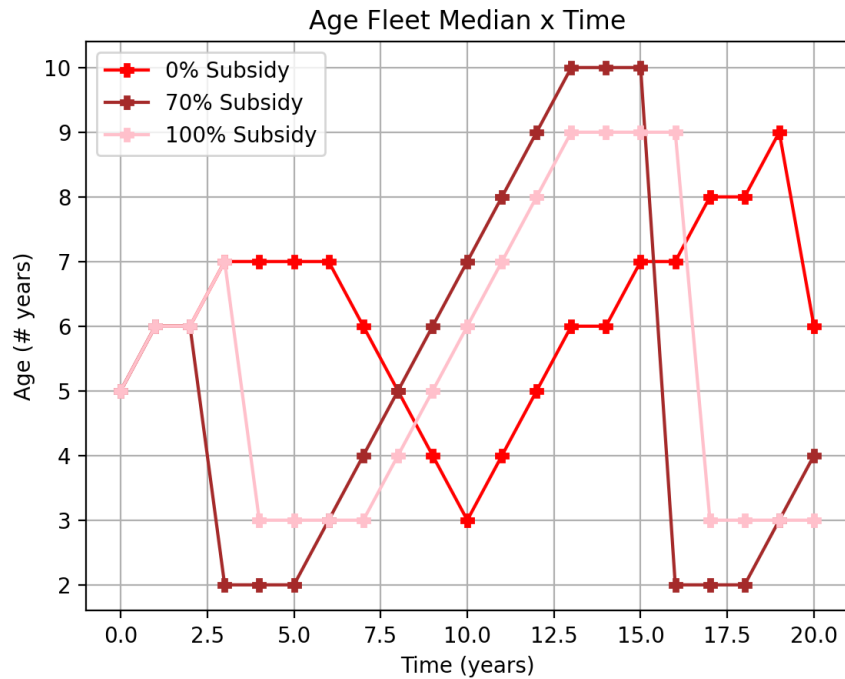


Figure 6 – Baseline: Median age

because, as seen in the P1 solution, the budget constraint can delay electrification beyond a certain subsidy percentage.

3. In present value, the current subsidy policy yields a payoff about R\$ 151 million higher than no-subsidy policy, while R\$ 13.6 million lower than the optimal solution.

The externality cost minimum at 65% subsidy is not enough to offset the slight decrease in total financial costs observed at higher subsidy levels. However, it opens the possibility of changes in the P2 solution under sensitivity analysis scenarios for externality values.

## 5.2 P1: No electrification target

Although the total electrification target was comfortably achieved for all scenarios in the baseline case, indicating that the 100% restriction within 15 years is not active, one might question whether the deadline for subsidies influenced the outcome, that is, the fact that municipal support is only provided for acquisitions made within the 15-year period.

As an analysis, the case in which there is no time limit, neither for total electrification nor for receiving the subsidy, is examined. Figure 8 presents the same values as the baseline case, showing that there is no impact.

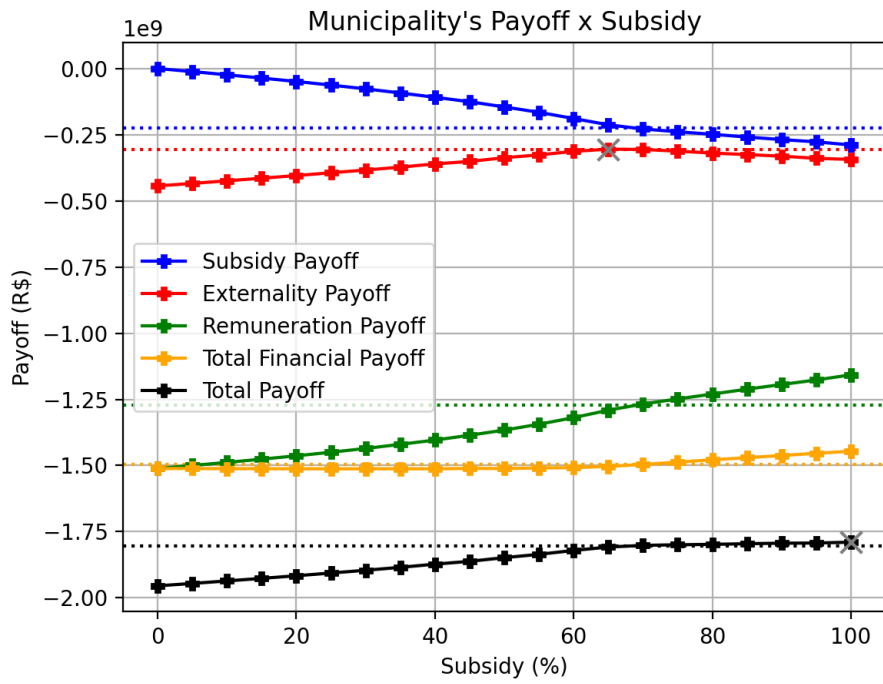


Figure 7 – Baseline: Municipal payoff

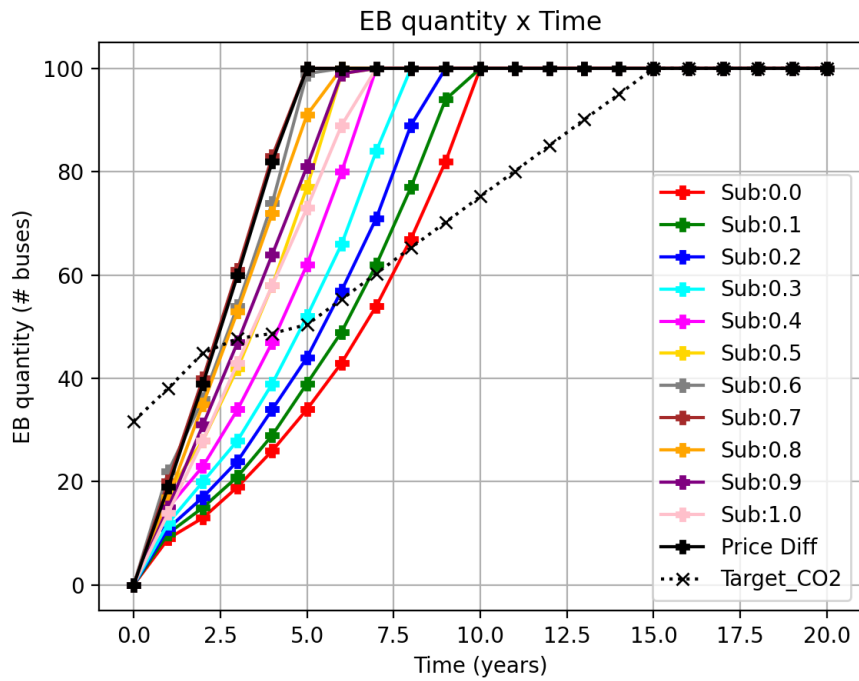


Figure 8 – No target: Fleet development

### 5.3 P1: Constant price ratio

Here, the hypothesis of no cost reduction of EBs compared to DBs is analyzed, keeping the price ratio constant. In comparison to the baseline case, it is expected to find something analogous to the income effect, where the quantity purchased changes due to the limitation of available budget, but also to the substitution effect, where the concessionaires may prefer to delay acquisition to take advantage of lower prices in the future.

Figures 9 to 11 show the quantity acquired per year, both for the baseline case and the case of constant ratio, at different subsidy levels. While it is clear that the decrease in the price of EBs over time in the baseline case allows for earlier purchases, there is no sign of a "substitution effect", meaning there are no periods where the acquisition in the baseline case is less than in the constant ratio case — except in the last periods, indicating the early reach of electrification. It does not seem that there is a postponement of purchases in anticipation of lower future prices.

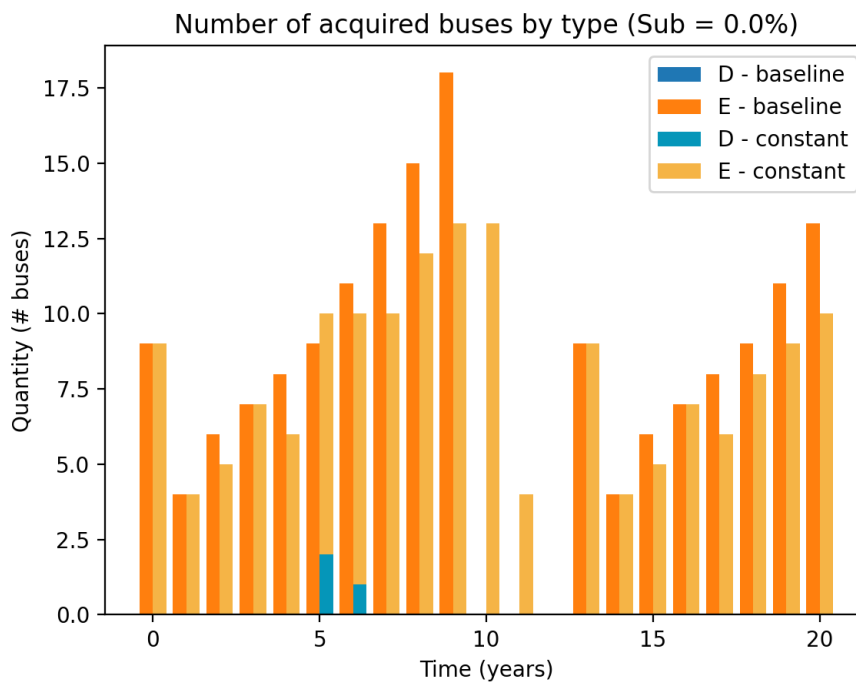


Figure 9 – 0.0% subsidized: Quantity acquired

## 5.4 Sensibility Analysis

### 5.4.1 P1: Municipal Budget

The limitation of the municipal budget appears to be a critical parameter for accelerating electrification, as evidenced in the baseline case, where concessionaires prefer to make acquisitions only with the receipt of subsidies, even if it delays purchases.

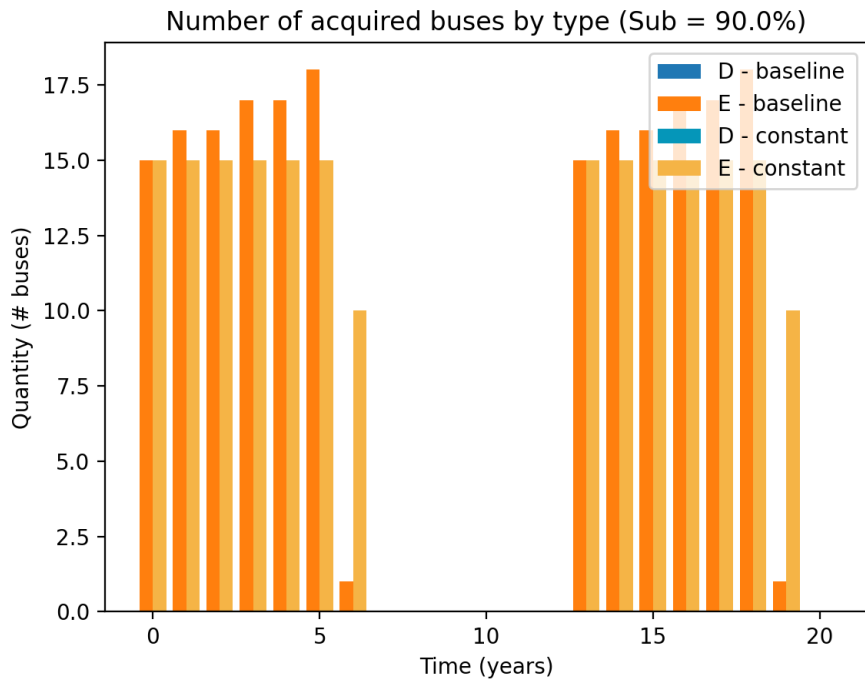


Figure 10 – 90% subsidized: Quantity acquired

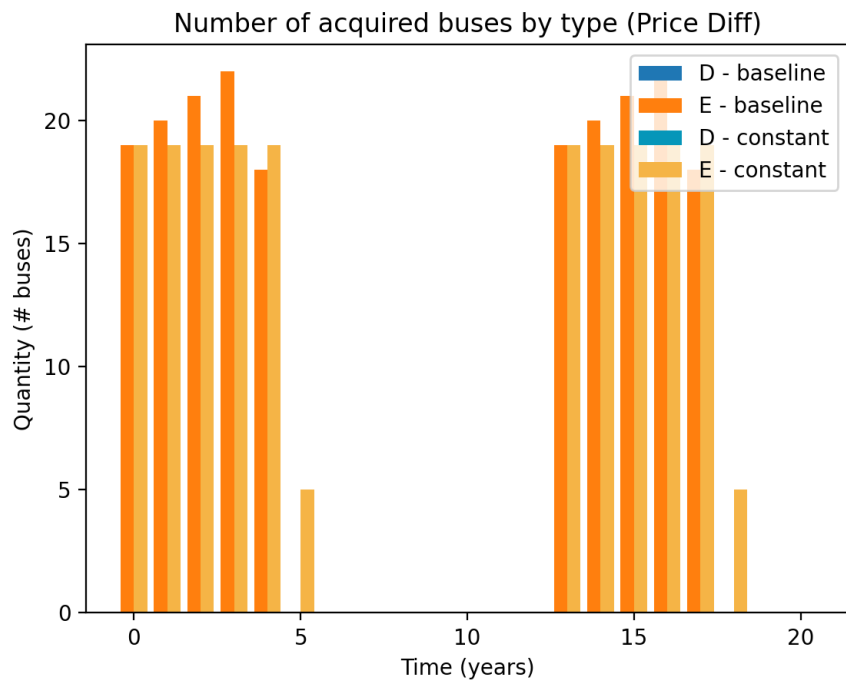


Figure 11 – Price-difference subsidized: Quantity acquired

In the baseline case, the most significant acceleration of fleet replacement is observed with a 70% subsidy, which is very close to the price-difference-based formula currently in contracts. Full subsidies, on the other hand, perform worse than a 50% subsidy.

Figure 12 illustrates a 30% reduction in the municipal budget available for subsidies. The subsidy percentage with the fastest electrification shifts to 60%. For percentages below this level, where the budget limit is not active and cost trade-offs dominate, the acquisition rate remains unchanged. It is noteworthy that while full subsidies are faster than no subsidies, they achieve total electrification within the same timeframe (10 years).

In Figure 13, the scenario of a 140% increase in the municipal budget is presented—a substantial amount. Only from this point onward does the 100% subsidy scenario conclude faster than the others, though it remains closely aligned with the 80% and 90% subsidy scenarios.

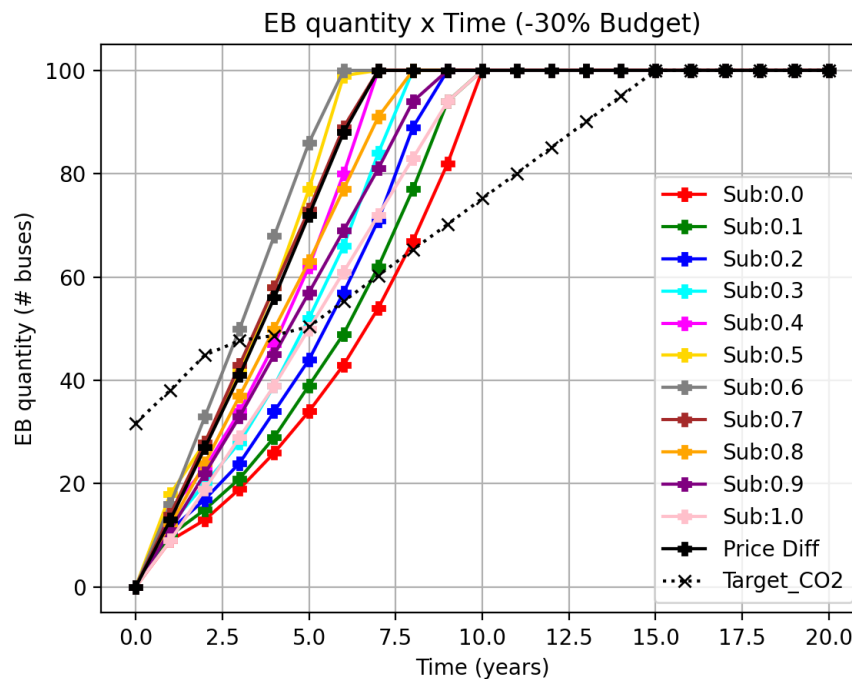


Figure 12 – -30% Budget: Fleet development

#### 5.4.2 P1: Technical Reserve

The current contracts stipulate a technical reserve of 8% for DBs, with no different values specified for EBs. In other words, for every 100 buses in operation, the concessionaire must have 8 additional buses for technical needs.

For EBs, however, another factor to consider is the vehicles' range, which may require earlier returns to the garage for recharging. For this reason, (ANTP, 2023) recommends a value of 20% for electric buses.

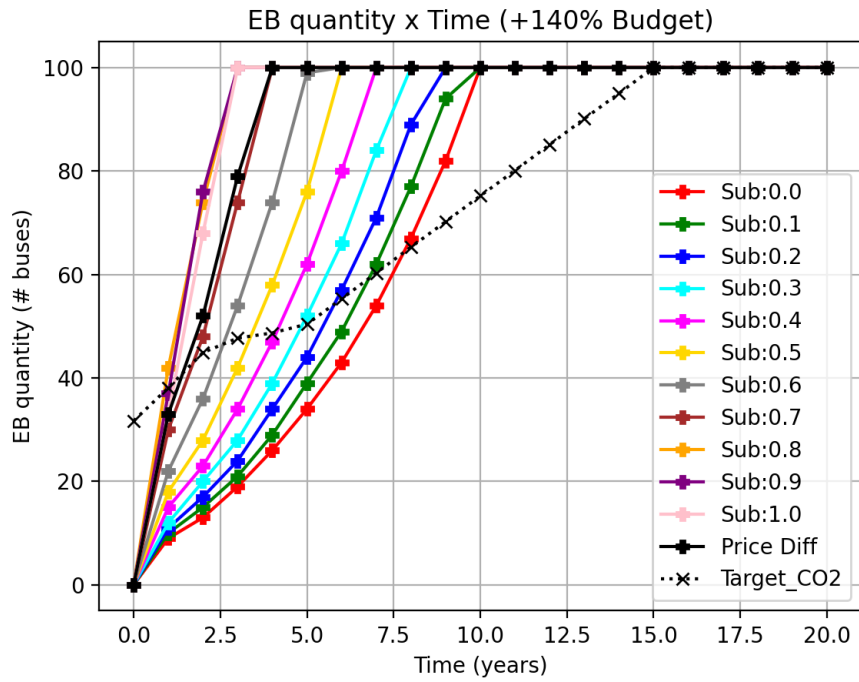


Figure 13 – +140% Budget: Fleet development

Although the contract formula provides compensation for capital investment in the technical reserve, higher values also require a larger budget for vehicle acquisition. In the following, we compare the current and recommended values, shown in Figures 14 and 15, respectively.

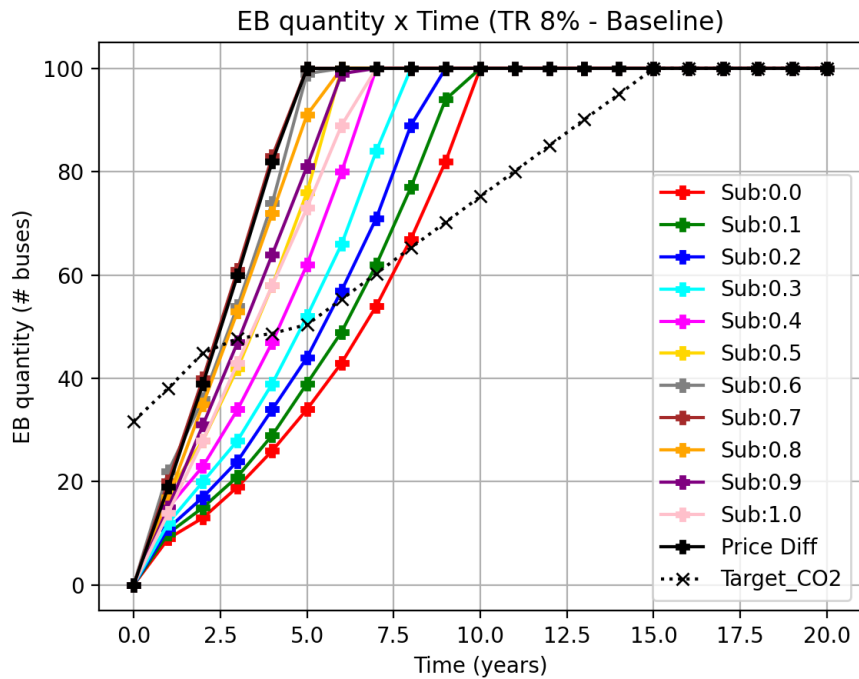


Figure 14 – TR 8%: Fleet development

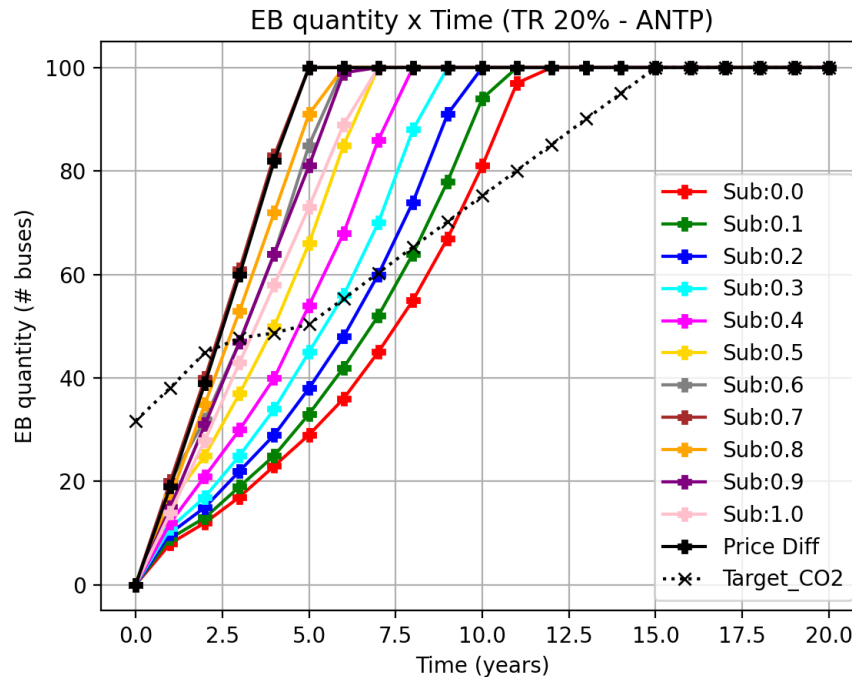


Figure 15 – TR 20%: Fleet development

As observed, the higher requirement generally has the effect of delaying electrification. However, this effect is seen only at lower subsidy levels (below 60%), where the electrification timeline is extended by one year, except in the no-subsidy scenario, which is delayed by two years. Nevertheless, the complete electrification target is still achieved in all scenarios.

#### 5.4.3 P1: EB's operational costs

The baseline case is calculated based on operational cost estimates from SPTrans and ANTP, which, in the presented methodology, also reflect the concessionaires' expectations. However, as this is a new technology that has not yet been implemented at the proposed scale in Brazil, these values are subject to errors.

Figure 16 shows, for the no-subsidy scenario, different maintenance and energy cost scenarios for EBs. For comparison purposes, the 15-year electrification restriction was not considered.

What is observed is that, although some effect is noted, it is only after an increase of 245% (or more than tripling) that the total electrification timeline is compromised. At a 270% increase, DBs become more advantageous, and electrification does not occur.

#### 5.4.4 P2: Externality cost

The externality costs used were derived from the study by (European Commission et al., 2020), published by the European Union Publication Office, based on data from European coun-

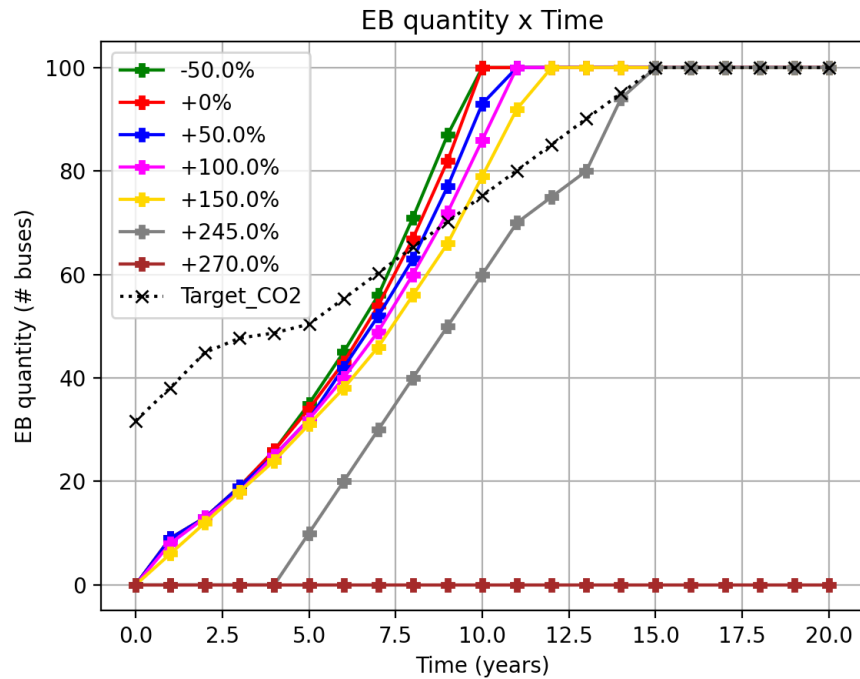


Figure 16 – Operational costs: Fleet development

tries. However, the costs of pollution, noise and greenhouse gas emission are highly dependent on the technological context, energy matrix, urban density, and the specific methodology chosen for calculation. Therefore, it is necessary to perform a sensitivity analysis on these values.

Figure 17 presents the scenario with a 50% increase in externality costs. With higher absolute values for these costs, the variation between a 65% and 100% subsidy is sufficient to offset the reduction in financial costs, shifting the P2 solution to 70%.

In Figure 18, however, it is observed that the result alteration occurs only after a 30% increase in the monetary cost of externalities and does so abruptly.

Overall, accepting the calculation methodology proposed by (European Commission et al., 2020), it is expected that the costs are likely overestimated in reality, as Brazil — and São Paulo specifically — has a cleaner energy matrix and lower urban density than European countries.

#### 5.4.5 P2: Social discount rate

Following the argument of (ARIZCUREN-BLASCO; MARTIN-GARCIA; RUIZ-RUA, 2023) on the use of social discount rate, Figure 19 illustrates the limiting scenario of a zero social discount rate. Since the most significant impact of electrification occurs in the early periods, which are less affected by the discount rate, the externality cost graph retains its shape but with higher values. The optimal point for externalities remains at a 65% subsidy. However, the overall optimum (the P2 solution) shifts to 75%, which is much closer to the current policy.

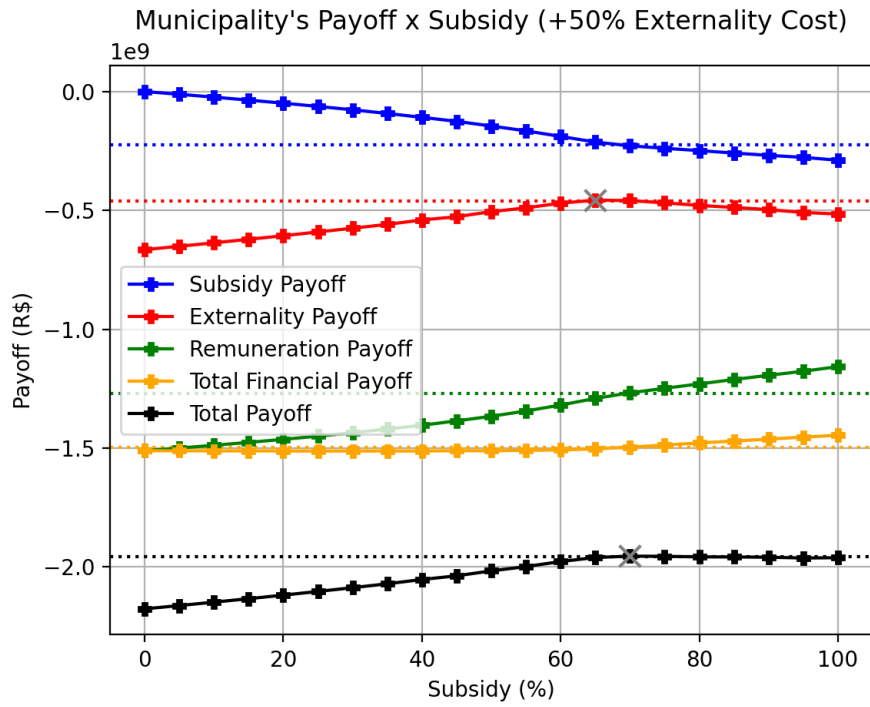


Figure 17 – +50% Externality Cost: Municipal payoff

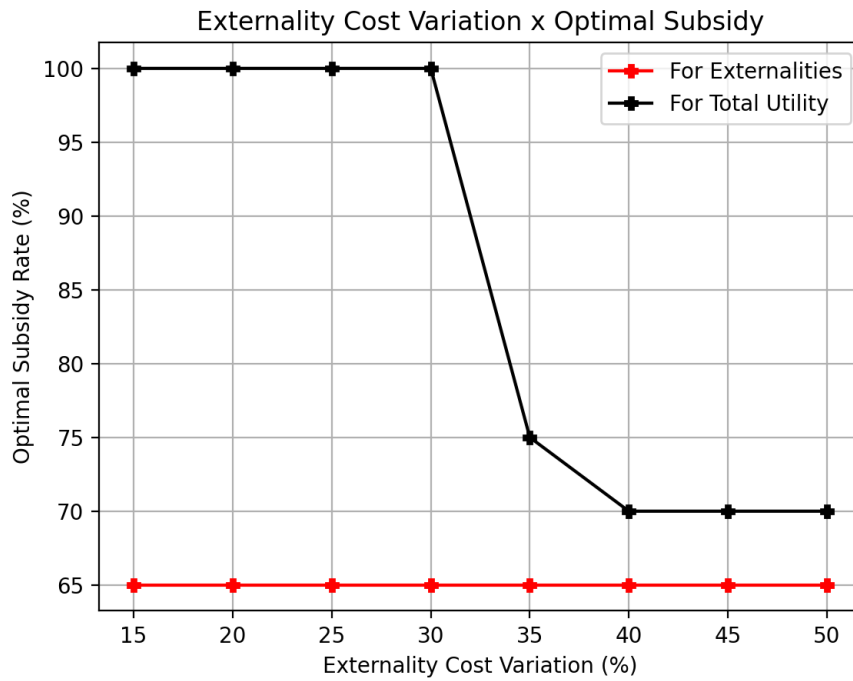


Figure 18 – Externality costs: Sensibility analysis

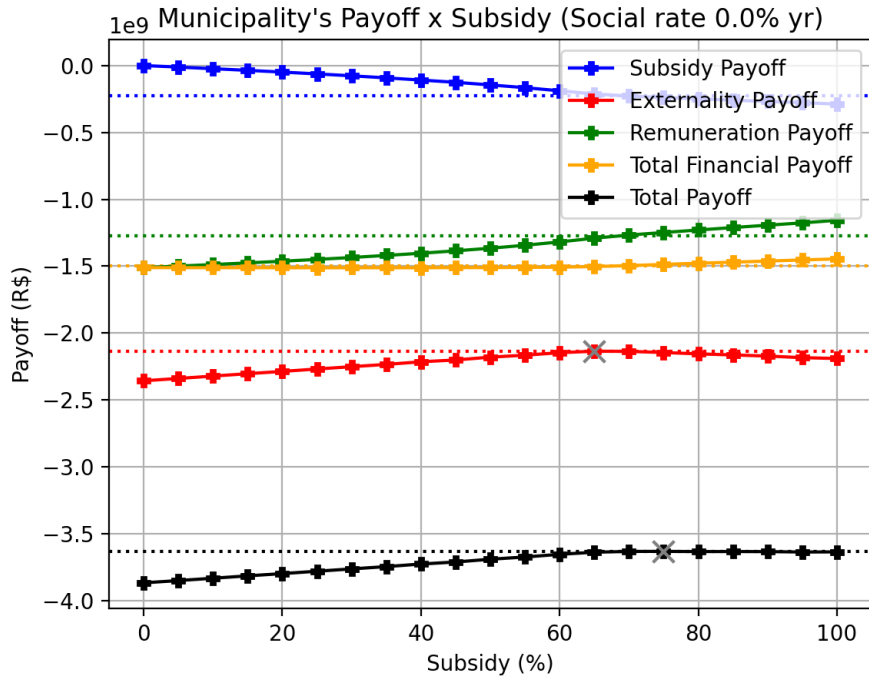


Figure 19 – Social rate 0%: Municipal payoff

Figure 20 presents the optimal subsidy rate for various social discount rates, ranging from 0% to 9% per year (below the financial rate), considering both total payoff (P2) and externality costs alone. It is noted that, indeed, the externality optimum does not change, and although lower social discount rates lead to smaller P2 solutions, the result proves to be quite robust at 100%.

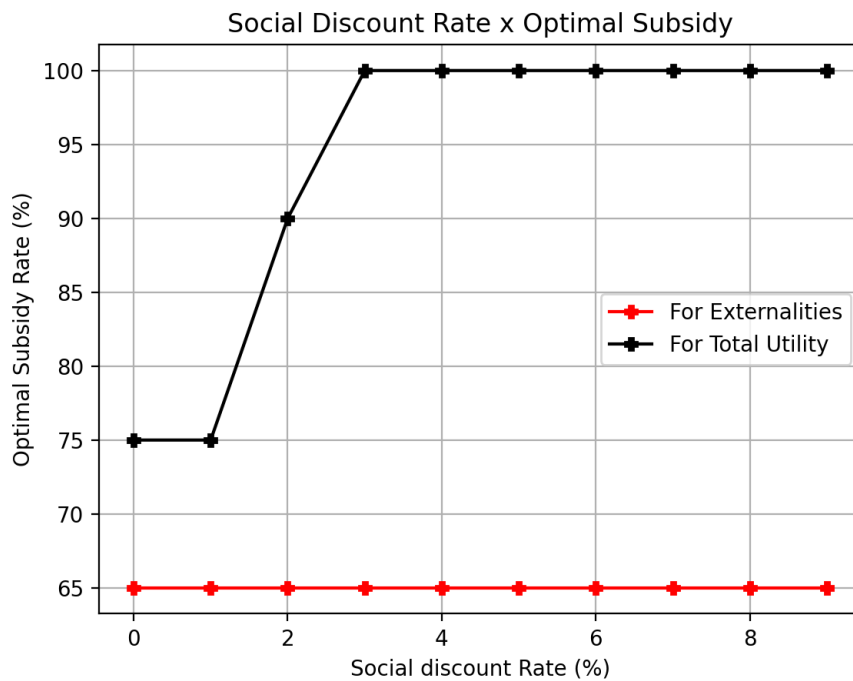


Figure 20 – Social rate: Sensibility analysis

## 6 Conclusion

The transition of São Paulo's bus fleet to electric vehicles marks a transformative step toward sustainable urban mobility. This study introduces an agent-principal framework to address the fleet replacement problem, a perspective not found in the existing literature. Unlike traditional approaches that model the problem from a central planner's viewpoint, this study differentiates the roles of concessionaires (agents) and the municipal government (principal), capturing the distinct incentives and constraints each party faces. This methodological innovation provides a more realistic and actionable understanding of policy impacts.

The analysis highlights that São Paulo's current subsidy policy, covering the price difference between EBs and DBs, which equates to approximately 72% of electric bus acquisition costs, is highly effective and close in payoff value to the identified optimal subsidy level of 100%. The current policy achieves a payoff R\$151 million higher than a no-subsidy scenario and only R\$13.6 million lower than the optimal case. Furthermore, the baseline case revealed that subsidies significantly accelerate fleet electrification, with a 30% subsidy ensuring faster progress toward interim targets, such as 50% electrification, compared to no subsidies.

The study also underscores the diminishing returns of higher subsidies, such as 100%, due to budget constraints and concessionaires' strategic reliance on subsidized acquisitions. Sensitivity analyses demonstrated that factors like municipal budget limitations and operational cost variations critically influence electrification timelines. For instance, a 30% budget reduction shifted the most anticipated electrification to a subsidy of 60%, while a 140% increase facilitated faster electrification even at 100% subsidy.

Additionally, the study's externality analysis reinforced the current policy's payoff, with environmental and societal benefits peaking at a 65% subsidy. While the current approach is slightly suboptimal in quantitative terms, its simplicity and transparency provide non-quantifiable benefits, such as ease of justification and stakeholder buy-in.

However, key caveats remain. The study did not address supply-side constraints, such as manufacturing capacity for electric buses or the need for significant investments in São Paulo's electric grid to support expanded charging infrastructure. These factors will be critical in shaping the feasibility and pace of electrification.

In conclusion, São Paulo's current policy demonstrates a commendable balance between fiscal responsibility and sustainability goals. The innovative agent-principal approach introduced in this study provides valuable insights for refining public policies and contract designs. By addressing identified constraints and leveraging this framework, São Paulo can further cement its leadership in transitioning to cleaner, more efficient public transportation systems.

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# Appendix

## APPENDIX A – Current Policy

The policy chosen by the Municipality aimed to make minimal changes to the economic logic of the existing concession contracts, refraining from interfering with each concessionaire's responsibility to decide on investments while also avoiding imposing significantly higher costs than those projected at the time of the bidding process.

The electrification program for the São Paulo Municipal fleet involves:

- **Municipal Law 14.933/2009:** Climate Change Law;
- **Municipal Law 16.802/2018:** Establishes sustainability goals for public transportation;
- **Circular Letter DP/SCS nº 035/22 (SPTrans):** Prohibits the acquisition of new diesel buses;
- **Ordinance SMT/SF nº 02:** Defines the subsidy value and rules;
- **Concession Contract Addendum:** Includes remuneration for electric buses; and
- **Credit Acquisition:** R\$ 5.9 billion from national and international banks.

Annually, the Municipality estimates the market prices for electric and diesel buses for each fleet model, determining the subsidy amount for each electric bus purchased by concessionaires as the difference between the values of electric and diesel buses, capped at 85% of the value of electric buses.

Concessionaires place orders for the vehicles and request the subsidy amount from the Municipality, which verifies whether the concessionaire has the necessary infrastructure, such as chargers for electric buses. If all conditions are met, the Municipality transfers the subsidy amount. These reference prices are updated annually.

The annual remuneration of the concessionaires is adjusted to account for the reduced capital investment resulting from the subsidy. Based on current prices, the subsidy covers approximately 72% of the cost of an electric bus. Additionally, the investment in garage infrastructure with chargers is the sole responsibility of the concessionaires, while the Municipality leverages its ability to secure lower-cost financing from national and international institutions to fund this subsidy.

The penalties defined in the contract are severe and the electrification schedule is already delayed, partly due to the time spent negotiating the contract terms. In an informal conversation with municipal government officials, it was found that there is no expectation for now that the

penalty clauses will be enforced. Therefore, they were not considered in this study, although the target line is shown for comparison purposes.

Moreover, it is de facto assumed, although not officially confirmed, that the subsidy policy will only last until the end of the current contracts.

## APPENDIX B – Effect of Marginal Cost of Public Funds

The Marginal Cost of Public Funds (MCPF) is defined as the total cost to society of raising an additional unit of public revenue, typically through taxation. In this study, the MCPF concept may be used to correct the municipality's payoff for this additional cost, since ultimately all public funds have their origin in taxation, even if indirectly. One might argue that considering the MCPF could alter this study's results.

In the recent literature, (MATTOS; CARDIM; POLITI, 2018) have estimated the MCPF for Brazilian municipalities, using the model proposed by (DAHLBY, 2011):

$$MCPF_{\tau} = \frac{1}{1 + \tau\eta} \quad (\text{B.1})$$

Where  $\tau$  is the tax rate and  $\eta = \frac{\partial \ln(\text{Tax Base})}{\partial \tau}$ , the elasticity of the tax base with respect to the tax rate.

The elasticity is estimated in -0.016, resulting by Equation B.1 in a maximum value for MCPF of 1.016 ( $\tau = 1$ ), which is just slightly above 1.

Moreover, this correction should be applied to the municipality's subsidy payoff, but also to the remuneration payoff, both public expenditures financed ultimately by taxation. Since the sum of the two (total financial payoff) presents a slight increase from around 65% subsidy and above, applying the MCPF would reinforce this increase, consolidating the result of optimality in 100% subsidy. To illustrate, Figure 21 shows the estimated scenario of 1.016 MCPF.

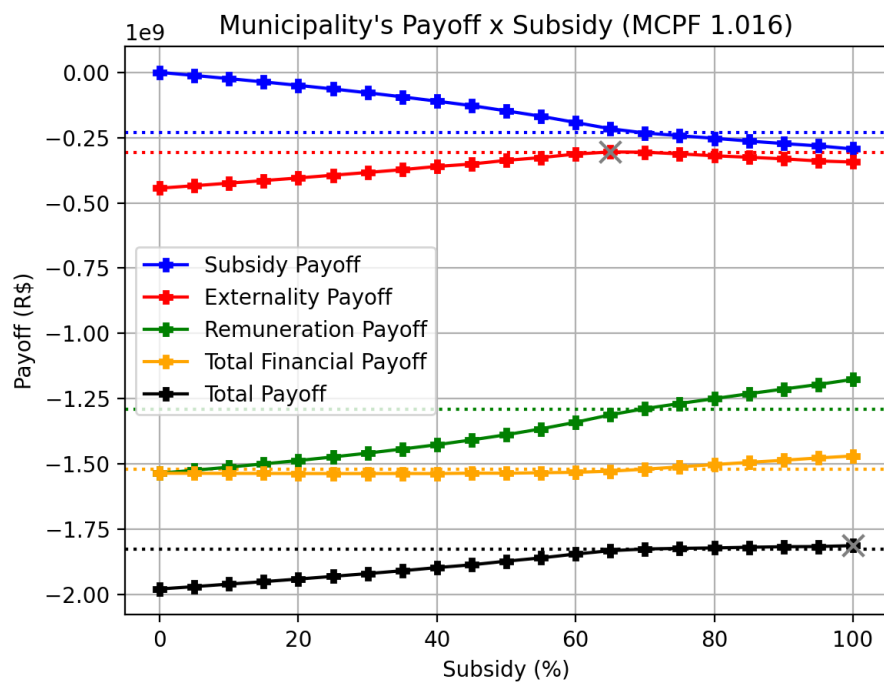


Figure 21 – MCPF: Municipal payoff