System dynamics to analyze scenarios of electric cars insertion in Brazilian cities

Dinâmica de sistemas para analisar cenários de inserção de carros elétricos em cidades brasileiras

Dinámica de sistemas para analizar escenarios de inserción de coches eléctricos en ciudades brasileñas

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Abstract

Objective: This paper aims to present and analyze the use of system dynamics to analyze the impact of electric cars on Brazilian cities.
Methodology: A simulation model was developed with the purpose of being used to predict population growth in any Brazilian region based on the logic of stocks and flows. The model was created to specify an environmental impact analysis system, considering CO2 emissions from different types of vehicles and fuel sources. The financial model takes into account the cost of recharging electric vehicles during peak and off-peak periods.
Originality: The originality consists of assessing the importance of expanding the use of EVs in the country to promote sustainable development and reduce harmful emissions. The EV20 scenario predicts a cost reduction of around 118 trillion reais with the introduction of electric cars, reducing maintenance costs and saving citizens money.
Results: The study confirms that the introduction of electric cars will reduce the amount of CO2 released into the atmosphere. The research used computer modeling and variables such as the number of cars and their average CO2 emissions, allowing the model to be proposed for empirical studies in other cities.
Theoretical and methodological contributions: The model, as well as its applicability method, although similar studies are found in the literature, notably abroad, contribute to the evolution of knowledge for the Brazilian reality, contributing to its implementation in a comprehensive manner.
Executive contributions: The model developed is open and can be expanded to any Brazilian city. Since the environmental impact of battery use was not measured and the possibility of using hybrid electric cars was not analyzed, it is proposed, in the executive applicability, to address these elements and increase the time horizon analyzed.

Keywords: Electric cars, System dynamics, Sustainability

Resumo

Objetivo: Este artigo pretende apresentar e analisar o uso da dinâmica de sistemas para analisar o impacto dos carros elétricos nas cidades brasileiras.
Metodologia: Foi desenvolvido um modelo de simulação, com o propósito de pode ser utilizado para prever o crescimento populacional de qualquer região brasileira com base na lógica de estoques e fluxos. O modelo foi criado para especificar um sistema de análise de impacto ambiental, considerando as emissões de CO2 de diferentes tipos de veículos e fontes de combustível. O modelo financeiro leva em conta o custo de recarga de veículos elétricos durante os períodos de ponta e fora de ponta.
Originalidade: A originalidade consiste na avaliação da importância de expandir o uso de VEs no país para promover o desenvolvimento sustentável e reduzir as emissões nocivas. O cenário EV20 prevê uma redução de custos da ordem de 118 trilhões de reais com a inserção dos carros elétricos, diminuindo os custos de manutenção e economizando dinheiro dos cidadãos.
Resultados: O estudo confirma que a inserção de carros elétricos reduzirá a quantidade de CO2 lançada na atmosfera. A pesquisa usou modelagem de computador e variáveis como o número

de carros e suas emissões médias de CO2, permitindo a proposição do modelo para estudos empíricos em outras cidades.
Contribuições teóricas e metodológicas: O modelo, bem como seu método de aplicabilidade, embora encontra estudos similares na literatura, notadamente do exterior, contribui na evolução do conhecimento para a realidade brasileira, contribuindo à sua implementação de forma abrangente.
Contribuições executivas: O modelo desenvolvido é aberto e pode ser expandido para qualquer cidade brasileira. Como não se mediu o impacto ambiental do uso da bateria e não se analisou a possibilidade de usar carros elétricos híbridos, propõe-se, na aplicabilidade executiva, abordar estes elementos, e aumentar o horizonte de tempo analisado.

Palavras-chave: Carros elétricos, Dinâmica de sistemas, Sustentabilidade

Resumen

Objetivo: Este artículo tiene como objetivo presentar y analizar el uso de la dinámica de sistemas para analizar el impacto de los automóviles eléctricos en las ciudades brasileñas.
Metodología: Se desarrolló un modelo de simulación, con el objetivo de utilizarlo para predecir el crecimiento poblacional en cualquier región brasileña a partir de la lógica de stocks y flujos. El modelo fue creado para especificar un sistema de análisis de impacto ambiental, considerando las emisiones de CO2 de diferentes tipos de vehículos y fuentes de combustible. El modelo financiero tiene en cuenta el coste de cargar los vehículos eléctricos durante las horas punta y valle.
Originalidad: La originalidad consiste en valorar la importancia de ampliar el uso de vehículos eléctricos en el país para promover el desarrollo sostenible y reducir las emisiones nocivas. El escenario EV20 prevé una reducción de costes de alrededor de 118 billones de reales con la inclusión de los coches eléctricos, reduciendo los costes de mantenimiento y ahorrando dinero a los ciudadanos.
Resultados: El estudio confirma que la inclusión de coches eléctricos reducirá la cantidad de CO2 liberado a la atmósfera. La investigación utilizó modelos informáticos y variables como el número de coches y sus emisiones medias de CO2, lo que permitió proponer el modelo para estudios empíricos en otras ciudades.
Contribuciones teóricas y metodológicas: El modelo, así como su método de aplicabilidad, a pesar de encontrar estudios similares en la literatura, principalmente extranjera, contribuye para la evolución del conocimiento de la realidad brasileña, contribuyendo para su implementación integral.
Contribuciones ejecutivas: El modelo desarrollado es abierto y extensible a cualquier ciudad brasileña. Como no se midió el impacto ambiental del uso de baterías y no se analizó la posibilidad de utilizar autos eléctricos híbridos, se propone, en la aplicabilidad ejecutiva, abordar estos elementos, y ampliar el horizonte temporal analizado.

Palabras clave: Coches eléctricos, Dinámica de sistemas, Sostenibilidad

1 INTRODUCTION

Electricity is used for the most diverse purposes, and in situations where its supply is interrupted, the importance of systems capable of automating the process of restoring it becomes evident (Ehsani et al., 2021). Issues involving strategy for the economy, telecommunications, transportation, and industrial activities, among others, exist only through electric power (Kucukoglu, Dewil & Cattrysse, 2021).

To mitigate the effects of global warming caused by greenhouse gas emissions, governments are actively promoting the development of sustainable energy and green industries, as well as the reduction of carbon emissions. In response to this trend, electric vehicles have been listed as an important development goal for the automotive industry (Chen et al., 2019).

The world energy matrix is composed of various primary sources, among which are oil, natural gas, coal, uranium, hydraulic energy, solar energy, wind energy, and energy from biomass. However, despite this diversity, the consumption of fossil fuels, which are non-renewable resources, prevails over the others (Goel & Rathore, 2021). The burning of fossil fuels causes damage to the environment, such as the emission of large amounts of carbon dioxide (CO2), contributing to global warming and, consequently, increasing the greenhouse effect. A good part of climate change comes from generation, handling, and use of this energy (Bhatti Mohan & Mingh, 2021).

The transportation sector contributes substantially to poor air quality which has been associated with billions of years of lives lost in Northern China and India (Guerra, 2019). Switching from gasoline to electric cars would improve local air quality and reduce one of the main harmful impacts associated with internal combustion vehicles (Sanguesa et al., 2021). While the effect on overall pollution and fossil fuel consumption depends on power generation, the replacement of conventional vehicles with electric vehicles could also support efforts to move away from fossil fuels (Albatayneh, Assaf & Jaradat, 2020).

For Sanguesa (2020), the automotive industry has become one of the most important industries worldwide, not only economically, but in research and development. More and more technological elements are introduced into vehicles to improve passenger and pedestrian safety.

Furthermore, there are more vehicles on the roads, allowing us to get around quickly and comfortably. However, this led to a dramatic increase in air pollution levels in urban environments (i.e. pollutants such as PM, nitrogen oxides (NO X), CO, sulfur dioxide (SO 2), etc.).

For Zhang et al. (2022), in the coming years, EVs will play a very important role in smart cities, along with shared mobility, public transportation, etc. Therefore, more efforts are required to facilitate the charging process and improve batteries. The main disadvantage of EVs is their range. However, researchers are working on improved battery technologies to increase autonomy and decrease charging time, weight, and cost. These factors will ultimately determine the future of EVs.

2 SEARCH METHOD

This study employs the system dynamics method to gain a better understanding of hiring inbreeding faculty. Using System Dynamics assists the decision maker to adopt and recommend the policy solutions simulated in the system dynamics model(s) (Thompson, Howick & Belton, 2016). The model can be enriched by the local knowledge of the stakeholders and they will also develop a detailed understanding of how the system works and evolves (Scott, Cavana & Cameron, 2016).

System dynamics was chosen to model the nonlinear dynamics of critical feedback processes. The dynamic behavior of the model could be captured through cause-consequence diagrams (Sahin et al., 2019). The cause-consequence diagram facilitates the identification of the main factors of the variables and their corresponding causal relationships (LU et al., 2017). For Ghaffarzadegan and Rahmanda (2020), system dynamics can be understood as a tool for systems thinking, and is used to investigate, analyze and predict the behavior of a system and overcome complexities in explaining problems and solutions.

SD allows the decision maker to model in detail the interrelationships between different factors in the system and external factors. This method focuses on developing qualitative and quantitative models of complex situations, as well as studying the dynamics in the behavior of systems over time (Jiao et al., 2015). Sterman (2000) separates into five stages the application of this methodology.

The first step consists of identifying the problem and aims to objectively define the problem to be solved and the objectives of the model. System dynamics models feature problem solving by updating all variables with positive and negative feedback and time delays that structure interactions and control at smaller intervals. The problem was structured using a cause and consequence diagram, and this diagram is a basic map of the problem structure with all its components and their interaction. From this diagram, a stock and flow diagram was subsequently developed. For Reddy et al. (2019), this diagram is used to analyze the empiricism of the model through computer simulation.

For Kirkwood (2013), the development of the cause-consequence diagram is necessary to enable the modeler to efficiently describe the essential elements of the system and the interactions between them, integrating two forms of feedback, i.e., negative (equilibrium) and positive (reinforcement) feedback loops. For the development of the diagram, the variables to be considered need to be identified. Since SD models are developed to compare fixed and dynamic systems, the models are restricted to a simple view of the inbreeding system in a higher education institution.

In the second step it is important to develop the dynamic hypothesis to explain the problem's cause. It is necessary to use the cause and consequence diagram (causal loop) created in the previous step. The Causal Loop highlights the system variables, links between these variables, and polarity associated with causal links to distinguish between positive feedback loops and negative feedback loops (Sterman, 2000). Lane, Munro, and Husemann (2016) state that to describe the dynamic hypothesis it is necessary to conduct tests to evaluate the model. In this study, this test was used to verify the adherence of the dynamic hypothesis to the actual behavior of urban transport in the city studied.

The model testing and verification step are necessary before using the model for scenario analysis and decision-making (Sterman, 2000). The approach implemented to evaluate the model is composed of dimensions of analysis, calibration, and verification tasks. Initially, the analysis dimension was conducted using the unit verification function of the Vensim software.

The second step, the evaluation step, was fulfilled from the model calibration, and for Zare et al. (2019), this step refers to the procedure of comparing, adjusting, and evaluating the modeling results to obtain a match between observed or actual data and simulated behaviors and structures.

The third step evaluates the planning time horizon and uncertainty aspects of the model, and the modeling results were used to estimate the accuracy of the model performance.

The fourth step is to ensure that the model is suitable for the task through model validation. Typically, this step involves a series of tests to gain confidence in the model based on internal and external consistency (Martis, 2006), and discussions with stakeholders involved in the modeling process.

For Ford (2019), evaluation is the comparison of the results achieved by the study through the agreement of the model with the real system. To Darabi and Hosseinichimeh (2020), the evaluation aims to confirm whether or not the simulated modeling was able to replicate the behavior of real action, thus conferring credibility in using the model to simulate policies, contribute to decision-making, and always on the path of system improvement. The evaluation process through simulations stimulated the increasing evolution of the analyses, allowing the perception of issues that would not be observed otherwise. After completing the model evaluation, the model's confidence levels increase, allowing one to evaluate the results obtained and choose the best scenario for a given strategy to be applied.

The fifth stage consists of relating the formulation of potential strategies and the evaluation of simulated results. It requires the identification of scenarios, i.e., alternative strategies, and the analysis and discussion of the simulated results generated by the model for each scenario over time (B'erard, 2010). The process of model development among experts and stakeholders through five stages allows for the improvement of DS model performance. Thus, the simulation model aims to compare different scenarios of “fictitious” actions, predict the future behaviors of the system under consideration, and make recommendations (Sterman, 2000).

3 IMPACT OF THE INSERTION OF ELECTRIC CARS

With economic growth and urbanization, the transportation sector has become an important driver of CO_2 emissions (Xiao et al., 2017). The sector accounts for a significant proportion of total emissions, 32.9% in the United States, 17.7% in Japan, and 8.6% in China in 2012 (IEA, 2020). In Brazil, in the year 2019, the transportation sector emitted about 196 Mt CO_2, an increase of one percent compared to the previous year (SEEG, 2020).

This is due to the use of a transportation network composed mostly of vehicles powered by combustion engines. More specifically, in the passenger transport sector, according to the report prepared by the National Association of Public Transport (ANTP), in the year 2016, of the total number of trips made by the population, 29% were made through public transport sector, of which, 20% used municipal buses as a means of transport (ANTP, 2018).

CO_2 emissions originate from the burning of fossil fuels (Miskolczi et al., 2021), thus, several strategies and instruments for carbon emission reduction are designed and implemented in buses to mitigate CO_2 emissions from urban transport, such as electric-powered engines (Lonan & Ardi, 2020; Nemoto et al.,2021; Zhang et al., 2021; Juvvala & Sarmah, 2021; Hu et al., 2021).

For Lima et al. (2019), the association of the use of public transportation with the replacement of fossil fuels by electricity is one of the alternatives that presents itself as the most promising. Petzhold (2013) pointed out that the use of these vehicles reduces the environmental impact caused by internal combustion models since the electric modal practically does not emit pollutants (Petzhold, 2013).

The electrification of urban transportation has been used for decades, but the technologies that are used today add new features to the modal (Ghorbanzadeh et al., 2018). The models developed could be applied to any city in Brazil. Knowing that there is a difference in car buying behavior in capital and non-capital cities (Silvestre, 2021), it was decided to develop two modeling logics. The first logic is applied to capital cities, while the second logic is applied to non-capital cities.

The growth in interest related to electric transportation is increasingly progressive, whether in the private or public sector (Campatelli et al., 2014). According to the IPEA (2016), about 85% of the Brazilian population lives in urban centers, with only 36 cities having more than half a million inhabitants, in addition to 40 consolidated metropolitan regions, in which more than 80 million people live. Given this scenario of rapid urbanization and metropolization, the pressure on urban infrastructure is increasing (Ciciola et al., 2016). Therefore, they must undergo considerable transformations to create sustainable living conditions for their inhabitants.

With the constant technological evolution, it has become feasible to join the technology of pure electric cars, being considered one of the most suitable when it comes to electric transport due to its versatility and adaptability to the existing roads (Rogge, Wollny & Sauer, 2015).

For Sebastini (2014), the growth of factories specializing in large-scale electric vehicle manufacturing has increased. However, as each region has a certain technology, factories are required to adaptat to the local technology.

The total internal energy available in Brazil grew by 1.4%, reaching 294 Mtoe. The increase is associated with the advance in the supply of renewable energy, such as wind and solar. The supply of electrical energy advanced by 2.3% reaching the value of 14.9 TWh (Ben, 2021, p. 7). Table 1 shows the comparative supply of energy in the last two years.

Table 1
Energy Supply

Values in Mtep	2018	2019
Internal energy supply	289,9	294
Final Consumption	257,4	259,4
Losses	32,4	34,6
Losses (%)	11,2%	11,8%

Source: Adapted from Ben (p. 7, 2021).

In Brazil, different sources of energy generation are used. The internal distribution of energy is shown in Table 2. The leading source is petroleum and its derivatives. Among the first three types of generation are two renewable sources, namely biomass from sugarcane and hydroelectric power.

Table 2
Energy Supply

Type of generation	Repartição (%)	Type
Oil and derivatives	34,4	Não renovável
sugarcane biomass	18	Renovável
Hydraulics	12,4	Renovável
Natural gas	12,2	Não renovável
Firewood and Charcoal	8,7	Renovável
Other Renewables	7	Renovável
Mineral coal	5,3	Não renovável
Uranium	1,4	Não renovável
Other non-renewable	0,6	Não renovável

Source: Adapted from Ben (p. 20, 2020).

In 2019, final consumption in Brazil showed a drop of 0.8% when compared to 2018. From the National Energy Balance conducted by the Energy Research Company (EPE, 2020), the energy consumption matrix by source can be observed, with 2019 as the base year (Table 3). In 2018, diesel oil was the main fuel consumed, accounting for 17.2% of the total energy consumed. 2019 saw a drop in the matrix/total share of 0.4%, losing the top position to electricity, which accounted for 18.1% of energy consumption. Diesel is the fuel capacity causing the highest pollution levels, characterizing it as harmful to the environment (EPA, 2016). The main energy consumption by the source is shown in Table 3.

Table 3
Energy consumption by source.

	2018	2019
Diesel oil	17,2%	16,8%
Electricity	16,6%	18,1%
sugarcane bagasse	12,5%	12,9%
firewood	7,1%	6,9%
Natural gas	7,0%	6,9%
Gasoline	7,3%	6,9%
Ethanol	5,2%	7,0%

Source: Adapted from Ben (p. 22, 2020).

The increase in ethanol production from 5.2% to 7.0% in 2019 is associated with the final price policy at the gasoline pump (EPE, 2020). Gasoline has reduced its share by 0.4% of the total. According to the EPE (2020), the reduction in gasoline consumption is due to the drop in Brazilian economic activity, and the increase in ethanol consumption was justified by more competitive prices for this fuel.

The transport sector consumes 32.7% of the energy generated in the country, followed by the industrial sector, representing 30.4%, seen in Table 4. It is the second consecutive year that the transport sector surpasses industry in energy consumption, and combined, these two sectors account for approximately 63% of the country's energy consumption.

Table 4.
Energy use by sector.

Sector	Quantity (Mtep)	%
Transport	82,88	32,7
Industry	77,70	30,4
Energy Sector	28,49	11,2
Residences	25,90	10,3
non-energy use	14,24	5,5
services	13,21	5,1
farming	12,69	4,9

Source: Adapted from Ben (p. 25, 2020).

When compared to 2018, the sector that varied the most in energy consumption was the service sector, with +3.4%, followed by the transport sector (+3.3%) and agriculture and livestock (+2.8%). The industrial sector had its consumption reduced (-2.7%). Given this study, the model presented in Figure 1 was developed. It is a model based on the stock and flows logic, where it is possible to predict the population growth of any Brazilian region.

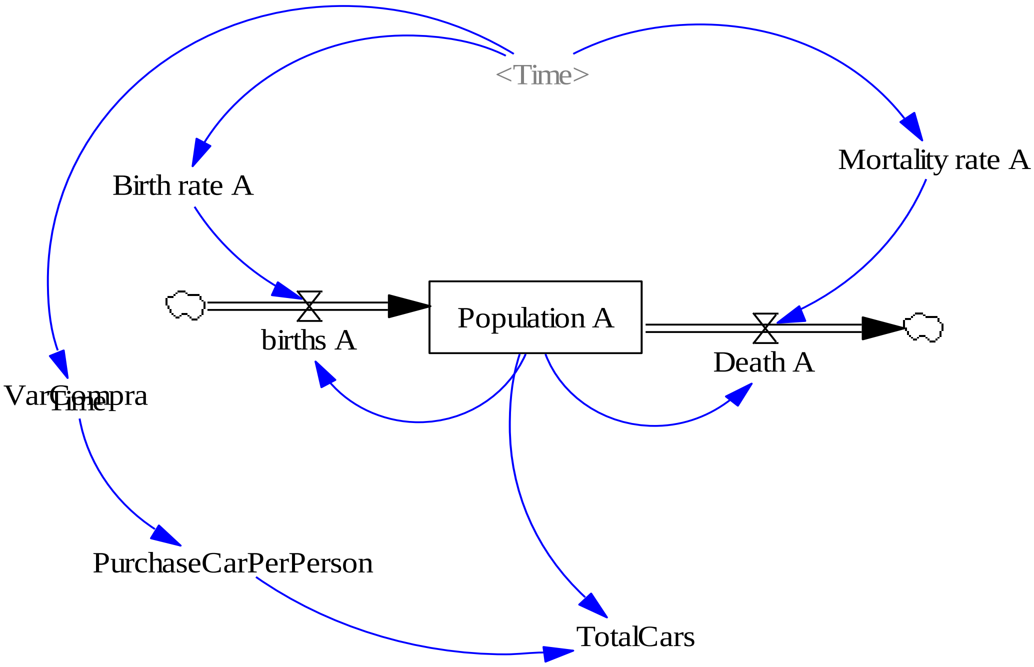

Figure 1: Car-buying behavior.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

The stock variable called "**Population A**" receives its value from the interaction between the flows "**Births A**" and "**Deaths A**". In turn, the flows are fed by the information coming from the auxiliary variables "**Birth A**" and "**Death A**", which are the birth and death rates stipulated by IBGE. Once the population of the simulated region was calculated, a variable was generated to store the total number of registered cars. This variable is called "**TotalCars**". The interaction of the monthly purchase variation with the purchase per person results in the total sum of cars used in the simulation.

To analyze the population growth behavior of the region, one has to understand the rate of annual births and deaths. To support the data entry on these two rates, the projections platform of the Brazilian Institute of Geography and Statistics (IBGE) was used. The projections of the rates involving the size of the Population of Brazil and the Units of the Federation are elaborated based on information about the components of demographic dynamics coming from demographic censuses, household surveys by sampling, and administrative records of births and deaths investigated by IBGE. The projection values of the rates that influence the inhabitants and variables of the model cited above are shown in Table 5.

Table 5

Data model purchasing behavior.

Variable	0-11	12-24	25-37	38-49	50-60
Birth	0,001069	0,00988	0,00973	0,00958	0,0094
Mortality	0,000621	0,000628	0,000638	0,000647	0,000656
Var Purchase			0.00125% ao mês		
PurchasePerPerson			Aumento de 0,021% ao mês		

Source: Adapted from DENATRAN (2021), IBGE (2022), and INMETRO (2022).

Regarding the environmental impact, emission factors must be computed to evaluate the level of CO2 emissions. The emission factor for each vehicle is computed from the mileage done by each car. Figure 2 presents the model that will be used to simulate the insertion of electric cars. The model developed is based on the stock and flow logic, and has input values from the previously presented model. For this, the shadow type variable **"TotalCombustion"** was used, which passed to the model the value of internal combustion cars. The environmental model has six stock submodels and each submodel presents the emission accumulation by category. The emission accumulation of the categories is added up in the variable called **"EmissionTotal"**. The data used in the variables will be exposed below.

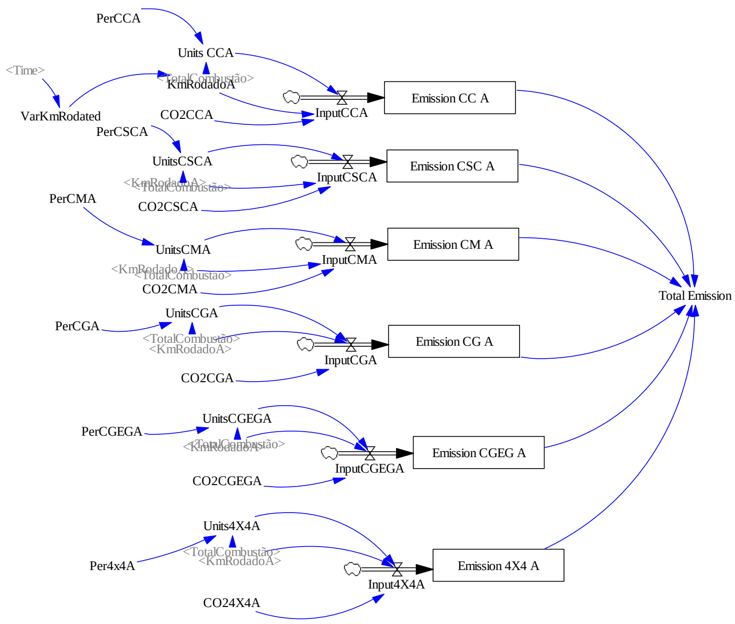

Figure 2: CO2 emission from EC.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

To develop the computer model that will simulate the cars consumption, data from the Anuário Estatístico de Transportes version 2010-2020, Associação Brasileira do Veículo Elétrico (ABVE), Departamento Nacional de Trânsito (DENATRAN), Empresa de Pesquisa Energética (EPE), Instituto Brasileiro de Geografia e Estatística (IBGE), Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO), and Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG) were used.

The model variables were quantified. Regarding the cars that were initially used, they were separated by categories defined in the tables of the Brazilian Labeling Program (PBE) available on the INMETRO website (2021). Among the categories, there are several models. The category with the greatest diversity of models is that of four-wheel-drive vehicles, followed by medium-sized vehicles. Table 6 shows the categories used and the data used to quantify the model. It is noteworthy that the category that emits the most carbon dioxide is the “4x4”, while the category with the least impact on the environment is the “subcompact”.

Table 6
Vehicle data by category.

Categoria	Qt	CO2 G/D	Km/l C_E	Km/l C_GD
Compacto	73	104 g/km	8,7	12,7
SubCompacto	21	96 g/km	9,2	13,1
Médio	91	108 g/km	7,9	12,4
Grande	61	127 g/km	7,5	8,8
Extra Grande	88	149 g/km	6,7	8,9
4x4	129	175 g/km	11	15,4

Source: Adapted from DENATRAN (2020) and INMETRO (2020).

Seeking to understand the behavior of cities in Brazil, the capital of the State of Rio Grande do Sul, Porto Alegre, with 1,409 million inhabitants, and the city of Santa Maria with 277,309 inhabitants (IBGE, 2020) were used as models. The idea of using these two distinct cities is to understand the urban traffic behavior of a large city or capital and of an ordinary Brazilian city. Table 7 presents the vehicle data of the two cities.

Table 7
Vehicles by type/classification.

TYPE	PORTO ALEGRE	SANTA MARIA
Automóvel	628422	112983
Caminhão	16838	2012
Camionete	45678	14623
Camioneta	56858	8099
Moto	99061	27910
Motoneta	12015	5664
Total	890467	171426

Source: DENATRAN (2022).

Only cars were used in the study. Table 8 represents the quantity per category for each city. To carry out the division by category, we used data from DENATRAN (2022) and INMETRO (2020). Each category received a weight (in percentage) according to the registration of vehicles in the government's databases. The data are approximate since to know the exact value it would be necessary to have access to the registration of all vehicles in the studied cities, however, this data is not yet available for free access.

Table 8
Type of vehicle by city.

TYPE	PORTO ALEGRE	SANTA MARIA
Automóvel	628422	112983
Caminhão	16838	2012
Camionete	45678	14623
Camioneta	56858	8099
Moto	99061	27910
Motoneta	12015	5664
Total	890467	171426

Source: Adapted from DENATRAN (2022) and INMETRO (2022).

The value used for the mileage traveled annually was based on the report released by the Environmental Company of the State of São Paulo (CETESB, 2022), which indicates that a vehicle in the city of São Paulo travels, on average, 15 thousand km per year. For the simulation, the total value of the city of São Paulo was defined for Porto Alegre and 50% of this value for the city of Santa Maria. The values referring to the average mileage may be altered if a more precise study on urban mobility in the cities is published.

Regarding the financial model, initially, the fuels used by the selected cars in the simulation were mapped. It was found that three types of fuel supply the cars: gasoline, ethanol, and diesel.

For the study of the equivalent CO2 emissions of electric vehicles, the efficiency of different categories, for example, Subcompacts, Compacts, Sedan, and SUVs, were surveyed. Based on this, the energy required by such models to travel 15,000 km/year during a useful life of 10 years was estimated with the same considerations used in combustion vehicles.

Besides the equivalent emission caused by the energy consumption of the mentioned sources, it is important to consider the emissions caused by the battery production of EVs. Estimating that such production generates about 254 kg CO2/kWh (Romare & Dahllöf, 2017), it is possible to estimate the total equivalent emission. With this, for these models, the emission from the battery production varies between 4 and 24 Tons of CO2, depending on the autonomy of the vehicle.

Table 9
The energy required for the electric car models used in the simulation.

Carro Elétrico	Categoria	Eficiência [kWh km]	Bateria [kWh]	Energia Necessária [kWh]
Chery Eq	Subcompacto	0.13	32	19123
Renault Zoe R110	Compacto	0.16	41	23653
VM E-Up	Compacto	0.17	16	25263
Nissan Leaf	Compacto	0.16	36	24545
VM E-Golf	Médio	0.17	32	25263
Tesla Model X	Médio	0.22	95	33529
Tesla Model S	Grande	0.22	95	29687

Source: Parente et al. (2020); Bento (2021)

Using the values in Table 9 it is possible to identify for each vehicle the proximity of the numerical values of the number of pollutant emissions among the energy sources, except for thermoelectric generation, which has much higher values than the other sources. Furthermore, according to Table 11, it is worth mentioning that vehicles with the same efficiency, such as VME-Up! and VME-Golf, for example, but with different battery capacities, have very different emission levels, which can be justified by the direct proportion between the battery capacity and the amount of CO2 emitted in its manufacture.

To define/set the number of electric cars in the simulation, the variable **"PerElectric"** was generated. In turn, the variable **"PerCombustion"** will represent the total amount of cars powered by internal combustion. The values of both variables can vary according to the will of the person responsible for the simulation. It is used to modify each simulated scenario. After separating the percentages, the total of each type of vehicle will be stored in the auxiliary variables **"TotalCombustion"** and **"TotalElectric"**.

The variable **"ConsumptionElectricCar"** stores the average amount of energy used to run one kilometer. Once the average GW per kilometer is computed, its value is connected to the **"QuantityRecharge"** variable. In turn, this variable receives its input value through the multiplication of the **"ConsumptionElectricCar"** variable by **"KmRodadoA"**. With this, it is already possible to check the amount of energy consumed by the simulated electric cars. The auxiliary variable **"EnergyConsumed"** stores the total GW used.

To compute the cost of the recharges it was necessary to understand the cost of peak and off-peak energy. In the peak consumption period, the value of the energy and demand charges can be up to three times the value of the tariff charged during the other hours of the day. This increase in tariffs occurs mainly as an incentive argument for not consuming electricity at peak times. This behavior is stored in the variables **"VarCostGWhEnd"** and **"CostGWhEnd"**. The off-peak period comprises the day when electricity consumption is lowest, that is, the maximum capacity of the power transmission lines is far from being reached. During this period, electricity and demand charges are not increased. The behavior of off-peak consumption is stored in the following variables: **"VarCostGWhOffPeak"** and **"CostGWhOffPeak"**. Thus, the recharge cost is stored in the variable **"CostRecharge"** through the interaction of the previously mentioned variables.

To measure the cost of fuel for cars powered by internal combustion, the variable **"SupplyCost"** was developed, where the interaction between the variables: **"TotalGasoline"**, **"CostGasoline"**, **"TotalEthanol"**, **"CostEthanol"**, **"TotalDiesel"** and **"CostDiesel"** is simulated. The variable **"CostInfrastructure"** is responsible for measuring the cost of electric infrastructure, and charging was used in three levels as shown in Table 10. The charging tier for electric cars is driven by the maximum amount of electricity made available by the charger, as it will affect the speed of recharging. The type, usage, and capacity of the battery also affect the speed of recharging, which ranges from 30 minutes to 20 hours. According to the International Energy Agency (IEA, 2020), the types of recharging need to be distinguished by considering the voltage and current level (direct or alternating).

Table 10.
Types of charging according to the recharge level.

Nível	Uso típico	Tensão/voltagem e tipo de corrente	Autonomia por hora de recarga
Nível 1	Residências e locais de trabalho	127 V Corrente alternada	3km a 8km
Nível 2	Residências, locais de trabalho e locais públicos	220-240 V Corrente alternada	10km a 96km
Nível 3	Locais públicos	Pode atingir até 600 V Corrente alternada ou contínua	96km a 160km

Source: Adapted from FGV Energia (2017).

Figure 9 presents the cost model of the insertion of electric cars. The data regarding energy and infrastructure costs were collected from an energy concessionaire in the studied region, where the value of each GW was computed. For the data related to internal combustion vehicles, government databases such as ANP (2021) and Petrobras (2021) were used.

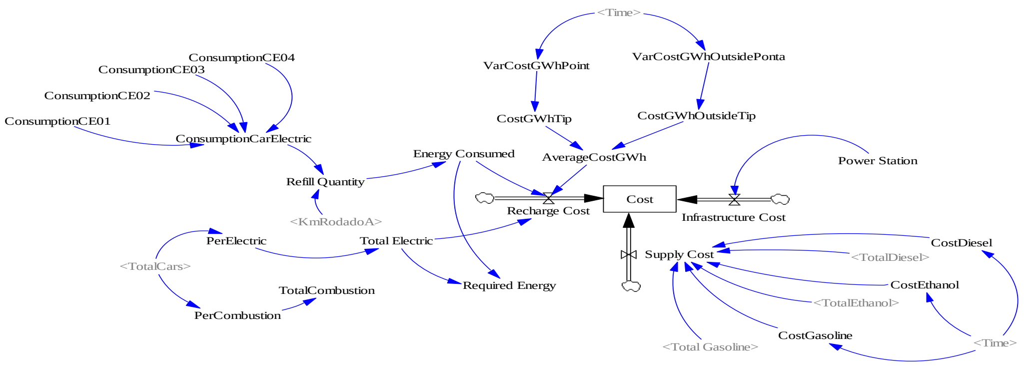

Figure 3: Cost of EVs.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

Considering the reality of Brazilian cities, where cars cover an average of 20 kilometers per day in a small city and 48 km in the capital, using a car with a 350 kWh battery and slow charger in the garage becomes cheaper after 80,000 kilometers. This means that cars with higher battery capacity should only be considered for cities with a daily average of over 120 kilometers.

To compute the CO2 emission to generate the energy that will fuel the electric cars, the submodel shown in Figure 10 was developed. The stock variable called **"ElectricMotorGeneration"** quantifies the total CO2 generated for further input with the generation of the combustion cars. The variable **"GenerationCO2GW"** is composed of the average CO2 emission to generate electricity in thermoelectric power plants (Coal, Gas, and Diesel). This variable will enable the decision maker to understand how much CO2 is generated to generate 1GWh.

The auxiliary variable **"TotalGW"** aims to insert into the model the total gigawatts used by the electric motors, that is, how many monthly GW were necessary to supply the energy demand that made possible the urban transportation of the simulated region. The auxiliary **"QuantityRecharge"** retains the value of the monthly recharge totals; the variable **"BatteryDuration"** comprises the maximum distance reached by the battery until the next recharge, and the variable **"RunningDistance"** inserts into the model the number of kilometers traveled monthly by the routes of the simulated cars. Multiplying these variables will yield the number of GWs used per month, and the **"Losses per Recharge"** variable will make it possible to verify the lifetime of the battery since it loses capacity with each recharge according to the study by El-Saadawy (2020).

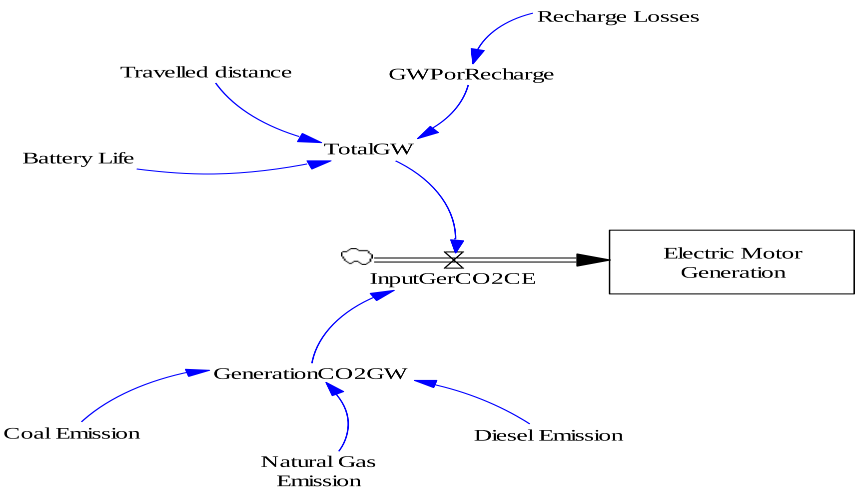

Figure 4: Generation of CO2 as Energy.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

The evolution of emissions by primary energy sources follows the same trend as the generation of each of these sources. Between 2019 and 2020, monthly emissions from natural gas power plants decreased by 31% and those from petroleum products decreased by 51%. On the other hand, emissions from coal-fired plants decreased by only 5%. Despite the greater participation of natural gas in GHG emissions from electricity generation, the energy sources that emit the most per unit of energy produced are petroleum products or mineral coal. Chart 1 shows the emission factor for each source given in terms of tons of CO2 and per GWh of electricity produced in 2016. Within terms of GHG emissions, this emission factor can be evaluated as an indicator of the efficiency of electricity generation by fossil sources. Energy can be generated from different sources, each with different costs and characterized by a factor that indicates the number of tons of CO2 that are released into the atmosphere to produce a given amount of electricity. This data will be used to determine the equivalence of energy that can be generated from the reduction of CO2 emissions by internal combustion vehicles.This section presented the data used to run the simulation that will be presented in the next section.

4 ANALYSIS OF THE EVs MODEL EXPERIMENT

The planning by scenarios presents itself as a tool that enables the evaluation of future alternatives related to electric vehicles. Under this logic, the scenarios provide an environment that enriches the debate on critical issues related to the future of transportation and enables the population to make risk decisions with greater clarity. They also allow the identification of alternatives for public policies related to the environmental theme, promoting the development and analysis of new options given the changes in the energy and transportation sector (Marcial & Grumbach, 2020).

According to the International Energy Agency (IEA), the number of electric vehicles (EVs) will increase from 2 million units in 2016 to 56 million by 2030 (IEA, 2017). In this context, understanding the system-wide trade-offs of replacing ICE vehicles with EVs is paramount and requires a life-cycle perspective (Ellingsen et al., 2017). Regarding the goal of scenario analysis as it relates to the study, three scenarios were generated. Initially, the CEV0 scenario will represent the current behavior of cars registered by DENATRAN, in which case less than one percent of the total cars are electric. To insert and enable the analysis of the behavior of the insertion of the electric cars two scenarios were generated. The CEV10 scenario will insert ten percent of electric cars in the sixty months, where the behavior is based on the purchase of cars by category, and the goal is to insert the equivalent behavior of vehicle consumption of the population under study. The most optimistic scenario, which inserts twenty percent of electric cars, was generated with the same proposal seeking to bring to the model equivalence of the real behavior and presenting greater validity to the results of the system dynamics simulation.

After defining the two scenarios for model experimentation, the simulations were run on the Vensim simulator (VENTANA SYSTEMS, 2022) on a computer with a Pentium Core i5 processor and 8 GB of RAM memory. The simulation execution time was around hundredths of a second. The time horizon simulated in the experiment was sixty months; however, the configuration of this variable is up to the designer/user, as it depends on the analysis to be done.

Figure 5 shows the accumulation of emissions from the simulated cars. This first simulation used capitals as the behavior to be analyzed. As the model developed was based on the stock logic in which the totals were considered for each year, it was noticed that the three scenarios accumulate more than 950 million tons of CO_2; however, the insertion of electric cars reduces the total accumulation. This premise corroborates with the study by Holmberg and Erdemir (2019), which cites the fruits of decades of dedicated research into all-electric vehicles powered by electric batteries, which are paving the way for a much cleaner and more sustainable transportation future.

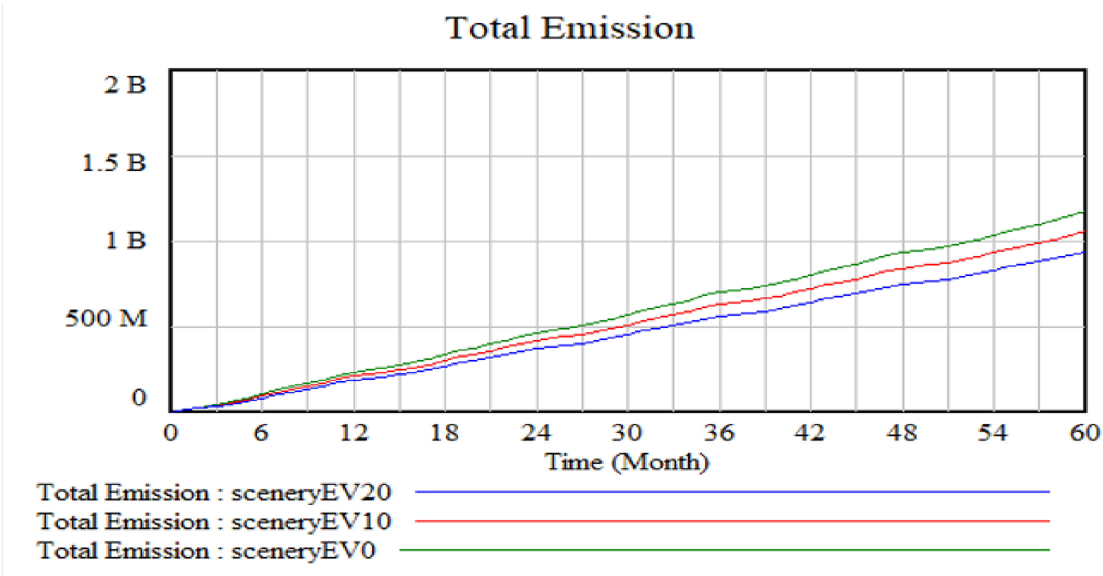

Figure 5: Simulation of emissions in capitals.
Source: Survey results (2022).

Based on the data provided, it shows that the current scenario (EV0) does not present good results for environmental protection policies, which corroborates the conclusions of Stokes and Breetz (2018), who state that governments should encourage the use of electric cars to decrease CO2 emissions - a fact proven in this study since the scenarios that analyze the insertion of electric cars obtained more positive results for the environment.

In sixty months, the EV0 scenario will emit about 130 million tons of CO2, a significant and worrisome figure. If the buying behavior of electric cars increases by ten percent, the accumulation of CO2 in sixty months will decrease by about 20 million tons. This difference is equivalent to generating approximately 41,898 GW in a natural gas power plant. According to the SEEG (2021), a natural gas plant that generates 1GW emits approximately 477.34 tons of CO2. An oil-fired plant, on the other hand, could generate approximately 29,985 GW. For the SEEG (2021), an oil-fired plant emits about 623 tons of CO2 to generate 1GW. A coal-fired plant emitting 667.36 tons per GW would generate around 27,000 GW.

If the increase in electric cars were 20%, the difference in CO2 emissions would be even greater. In sixty months, the EV20 scenario would probably emit 42 million less CO2 compared to the current scenario. This reduction is equivalent to the generation of 83,857 GW in a natural gas-fired power plant, and in an oil-fired power plant, the electricity generation would be around 64,205 GW, whereas in a coal-fired power plant the figure could reach around 59,972 GW.

The electrification of the world fleet is therefore an important factor in reducing global warming, since a large part of greenhouse gas emissions and air pollution are generated by the combustion of fossil fuels in conventional vehicle engines (Ercan, Onat & Tatari, 2016; Jiao. et al., 2017.; Goldemberg & Lucon, 2012; IEA, 2017).

The second environmental analysis refers to non-capital cities; however, they are considered large cities by IBGE (2022). Concerning this analysis, it was verified the emission by category, since previously it did not conduct this analysis for not having accuracy in the collected data. Figure 6 shows the simulation of all categories.

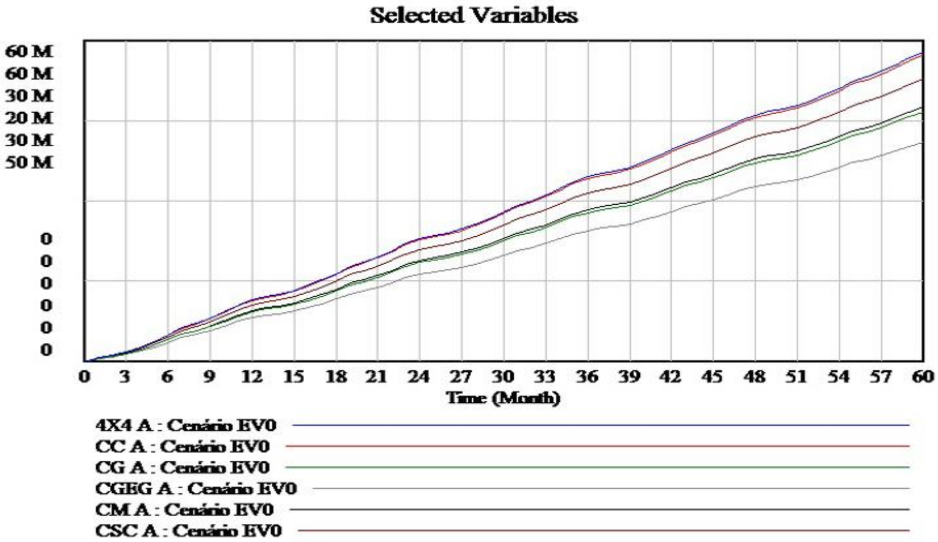

Figure 6:CO2 Emission Category.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

It is worth remembering that the analysis was done proportionally to the number of cars in each category, so the category with the highest emission is not related to the number of cars. Under this bias, the 4x4 category is the largest emitter in the study, since most cars in this category are powered by diesel. Sharma et al. (2020) described that reducing the fossil fuels such as diesel will bring less harmful impacts to the environment. The compact cars emitted similar CO2 as the 4x4 cars, but because they do not have diesel-powered vehicles, the category emitted fewer gases. Figure 7 shows the CO2 emissions from the simulation run.

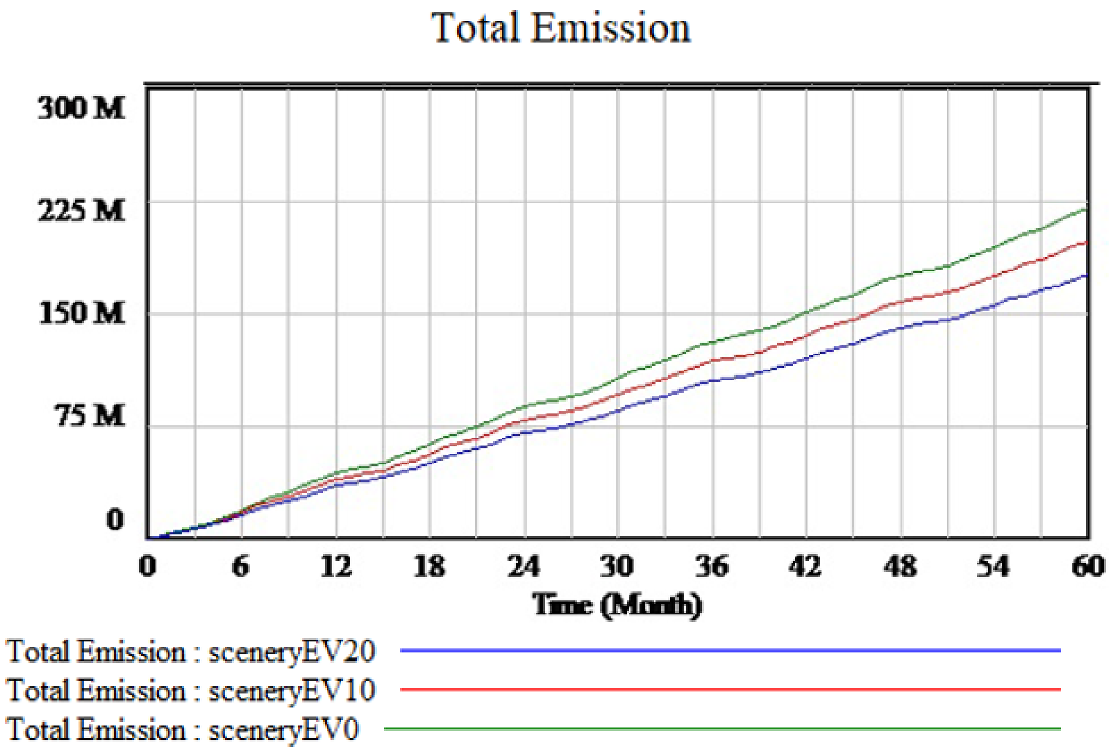

Figure 7:CO2 emissions of EVs from non-capital cities.
Source: Prepared by the authors (2022).
*Developed in VENSIM-PLE software.

The current scenario (EV0) will emit in 60 months about 223 million tons of CO2, and this accumulation of emissions is equivalent to generating 334332 GW in a thermoelectric plant, the energy that could supply different cities in the country. When compared to the scenarios with the insertion of electric cars, the scenario that will insert up to twenty percent of cars in the daily life of the cities will emit 8 million less CO2 per month, while if inserted ten percent the reduced value will be around 38 million less than the EV0 scenarios. For Guller and Yomralioglu (2020), even if it is necessary to emit harmful gases into the environment to generate energy that will fuel electric cars, the electrification of transportation will present lower vehicular emissions.

From the simulation result, it was found that the insertion of electric cars will provide less harmful gases to human health. The result also pointed out a justification for sustainable development and corroborates with Deb et al. (2018), since issues such as low pollutant generation and the use of "clean" energy sources, like the use of electric vehicles a way to assist in current environmental policies. For Guler and Yomralioglu (2022), the incentive for electric car use should be explored more widely and computer simulations justify the application of models that encourage electric mobility. The following section presents the financial impact of the introduction of electric cars.

Although energy costs represent only a small fraction of total transportation costs, high fossil fuel prices and low electricity prices may stimulate the shift to electric buses (Danielis, Giansoldati & Rotaris, 2018). Oil prices are expected to rise in the coming decades owing to the increasing cost of extracting oil in unusual areas (Weis, Zerfass & Helmers, 2019). Moreover, the growing demand for oil in China and India may lead to a steady rise in prices because of supply shortages. Electricity prices are also expected to rise but should be lower than oil prices. Carbon policies will cause additional costs for fossil fuels and the overall impact of price changes will stimulate electrification and the use of more fuel-efficient vehicles (Dijk et al., 2013).

The financial analysis of the study is concerned with the expense for the consumption of the vehicle, comparing the expense with the consumption of electric cars and internal combustion cars. Figure 8 presents the simulation result of the developed model using capitals as a parameter.

Figure 8: Expenditure of capital simulation consumption
Source: Survey results (2022).

The result of the research reinforces the importance of expanding the use of electric vehicles in the country since the scenarios with electric cars obtained a reduction in the cost of monthly consumption. If all vehicles are considered together, fuel costs in a capital city reach about 320 trillion Reais in the 60 simulated months. For Vianna, Garcia, and Szaniecki (2019), most of the population uses private vehicles for their commuting, and with this, a good part of their personal budget is assigned to their vehicle. Thinking in unit values, the average cost with vehicle consumption is around R$ 1,200.00 per month in a capital city.

The EV20 scenario will decrease the cost by around 118 trillion Reais, as twenty percent of electric cars show a reduction of 36.85% when compared to internal combustion cars. Winebrake, Green, and Carr (2017) add to this result that electric cars also reduce the maintenance cost of vehicles used in the population's daily life. In unit values, an electric car could decrease about 432 Reais from the citizen's pocket.

With the insertion of ten percent of electric cars, the median scenario presented a satisfactory result. For Borshiver and Tavares (2018), it is important to encourage actions against environmental pollution, and the electrification of transportation is a viable and necessary action. Hence, the results reinforce a panorama for the insertion of electric vehicles, especially given the monthly savings presented by the scenarios, where there is a solution for reducing the population's day-to-day costs.

Souza and Hiroi (2021) point out that cities that are not considered capitals have more obstacles to the insertion of electric cars, especially concerning the models. In this simulation, the goal is to present the benefits and help people make better decisions. Regarding the consumption cost of non-capital cities.

5. FINAL CONSIDERATIONS

Brazil is a predominantly urban country, with over 80 % of its population living in urban areas, from which one may deduce that most of the vehicular carbon emissions are concentrated in these areas. Several factors influence the participation of each modality in the CO2 emission matrix, among which we may highlight the composition of the matrix of commute modes of the cities, especially relative to the participation of individual motorized transport, which is the most polluting, and the average distance of the motorized trips made by the population. The greater this distance is, the higher the amount of GHGs released into the atmosphere will be.

The main objective of this research was the development, verification, assessment, and experimentation of computational simulation models for assessing scenarios for the insertion of electric cars. Relative to the hypothesis presented in the investigation method, it was confirmed, given that the insertion of electric cars will reduce the amount of CO2 released into the atmosphere.

The method used in this study was that of system dynamics through computational modeling, with the concept and steps developed following Sterman (2000). The modeling process was described in this step. Although there are certain steps through which all modelers go through, modeling is not a standard procedure; each process has its differences, although the same steps always exist. Modeling is a disciplined, scientific, and rigorous process, challenging the modeler and the client in each step to present and test assumptions, collect data, and review their models, both formal and mental.

The model was conceived using data from the Brazilian federal government and free-search platforms, besides data from university research projects. Two cities were used to simulate the model; however, the model is open, enabling the expansion of the study to any Brazilian city. Two scenarios were proposed by the modelers, in addition to one scenario that reflects the current moment.

For developing the computational models, variables such as the number of cars and their average CO2 emissions were used. The results obtained were compatible with reality. With the results generated by the simulation, we emphasize the importance of defining policies for reducing the use of internal combustion-powered cars and encouraging the use of electric vehicles, taking into consideration environmental sustainability in the decision process relative to urban mobility and environmental sustainability.

The main contribution of the model developed to the academic community is the possibility of assessing the environmental impacts of using electric cars. Moreover, for being an open model, it may be altered for application to other locations, rendering possible new pieces of research from this already initiated one.

One of the main limitations of this investigation refers to the fact that the model did not measure the environmental impact of the battery use of electric cars. Another limitation refers to the issue of not having analyzed the possibility of using hybrid electric cars. As future work, we intend to include the mentioned limitations and also increase the time horizon analyzed. Other gases will also be included in the future model.

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