POLITECNICO DI TORINO

Master of Science in Engineering and Management

Forecast Model of Electric Vehicles' Diffusion In Brazil

Supervisor
Prof. Dr. Paolo Claudio Priarone

Candidate
João Guilherme Vidal Moraes Tibau

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ABSTRACT

Sales of electric vehicles are increasing globally and there are at least five main factors driving it: fast changing market, technology evolution, emissions regulations, environmental pressure and decreasing costs. Brazil is experiencing changes in the automotive market, as electric and hybrids reached 1% of total sales for the first time in 2020, rapidly increasing to 1.6% in April, 2021. An adapted Bass Diffusion model with *p* and *q* value estimated via literature comparison was produced and applied considering a maximum market of forecasted 30% fleet share of xEVs in 2050 as the baseline. This standard scenario outputted a tipping point of 2030 and 2032 for optimistic and pessimistic cases, reaching market maturity at 2045 and 2048. Simulating different values of annual and purchase tax rates, the decrease in Total Cost of Ownership caused an increase in the final number of Adopters. Inputting a forecast equation for purchasing price evolution over time caused an extreme expansion of the pool of potential adopters. Government incentives' influence on results was studied by combining annual and purchase tax rate deductions, and increase in electric energy is aligned with existing literature. The model presented limitations mainly due to lack of data, nevertheless it provides a panorama on how fast EV technology will penetrate the Brazilian market and the opportunities and challenges it will bring to public and private sectors.

Keywords: Electric Vehicles. Bass Diffusion. Innovation Forecast.

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ACRONYMS AND ABBREVIATIONS

ABVE	Associação Brasileira do Veículo Elétrico *(Brazilian Association of Electric Vehicle)*
AEVs	All-Electric Vehicles
ANEEL	Brazilian Electricity Regulatory Agency
AR	Adoption Rate
BEVs	Battery Electric Vehicles
DOE	United States' Department of Energy
EV	Electric vehicle
FCEVs	Fuel Cell Electric Vehicles
HEVs	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICMS	Imposto sobre Circulação de Mercadorias e Serviços (*Tax on Circulated Goods and Services*)
IPVA	Imposto sobre a propriedade de veículos automotores (*Tax on motor vehicles' property)*
MEI	Montreal Economic Institute
OAPEC	Organization of Arab Petroleum Exporting Countries
PA	Potential Adopters
PNE	Plano Nacional de Energia (*National Energy Plan)*
PHEVs	Plug-in Hybrid Electric Vehicle
PT	Purchase Taxes
PTR	Purchase Taxes Rate
R&D	Research and Development
ROI	Return on investment
SD	System Dynamics
TCO	Total Cost of Ownership
TRC	Total recharging costs
UE	European Union
WOM	Word-of-mouth
YT	Yearly Taxes
YTR	Yearly Taxes Rate

1. INTRODUCTION

Electric vehicle, or EV, is any vehicle partially or fully powered by electric energy. The United States' Department of Energy (DOE) classifies EVs in the following types:

- All-Electric Vehicles (AEVs): take all of its energy from a battery source and, thus, is charged through plug-in technology.
  - Battery Electric Vehicles (BEVs): do not possess an internal combustion engine, exhaust pipe or fuel tank. They rely on electricity for power and require plug-in charging.
  - Fuel Cell Electric Vehicles (FCEVs): a compressed liquid hydrogen reacts inside a fuel cell stack that powers an electric motor. The recharge is not done by plugging into an electric outlet, but through hydrogen stations, in a shorter time.
- Plug-in Hybrid Electric Vehicle (PHEVs): powered both by fossil fuels and electricity, either independently or combined. PHEVs have internal combustion engines, but also charge an on-board battery through plug-in technology.

It is also important to mention a third type of vehicle, the Hybrid Electric Vehicle (HEVs), in which a small battery only assists the internal combustion engine (ICE). Its charging is derived from energy generated by the ICE and regenerative braking.

Nowadays, they are largely perceived by the general public as a new and innovative technology, ready to clutch on to climate change and increasing CO_2 emission. However, EVs may be considered one of the first vehicle technologies, dating as far back as the early 19th century with technological breakthroughs and production of small-scale electric cars. This past shows that the search for and development of EVs were not a single, isolated event, but a logical next step in motor vehicles' evolution. Hence, this study aims to model how the technology will diffuse throughout the Brazilian market at current rates in order to grasp how fast EVs will become a quotidian reality.

2. OVERVIEW OF ELECTRIC VEHICLES AND INNOVATION DIFFUSION

2.1. Electric Vehicles' History

In 1890, the first EV was released. Even though it was more similar to a wagon than to the modern perception of a car, it created grounds for the rise of a success of such technology, accounting for over a third of all vehicles in the US at the first decade of the 20th century.

One of the reasons for this early success was, for sure, its contrast with the other available technologies. Steam vehicles, despite using well-known and developed mechanics, had a long startup time (up to 45 minutes during winter) and limited range due to water capacity. Gasoline cars were difficult to manage with gear changes and a hand crank start, as well as their smell and noise. EVs didn’t have any of the downsides and their growing share was self-motivating: the more people owned electric vehicles, the easier and more available were charging systems, leading to even more willingness of purchasing EVs.

However, being comparatively good also means that development in competition can stop its ascension. In 1908, Henry Ford announced the Ford T, the first mass-produced vehicle. Gasoline-powered, it made cars affordable, being sold by $650 while electric models were still in the upper range of $1,750. Combined with the invention of the electric starter, it dominated the market and set up grounds for the subsequent widespread of internal combustion engine vehicles (ICEVs) in the following decades at the expense of other technologies [1].

Other factors also came into play for the early fall of EVs. The increasing oil exploration boosted ICEVs sales even more, as well as the development of road systems. Electric vehicles still required bulky and costly batteries that required long charging times and did not provide lengthy ranges. Thus, it can be noticed that the development and diffusion of technologies do not close at themselves: they are also a product of social, economic and governmental contexts, maybe even more important so than their own mechanics. For the next decades, they had little to no development, shadowed by ICEVs rise.

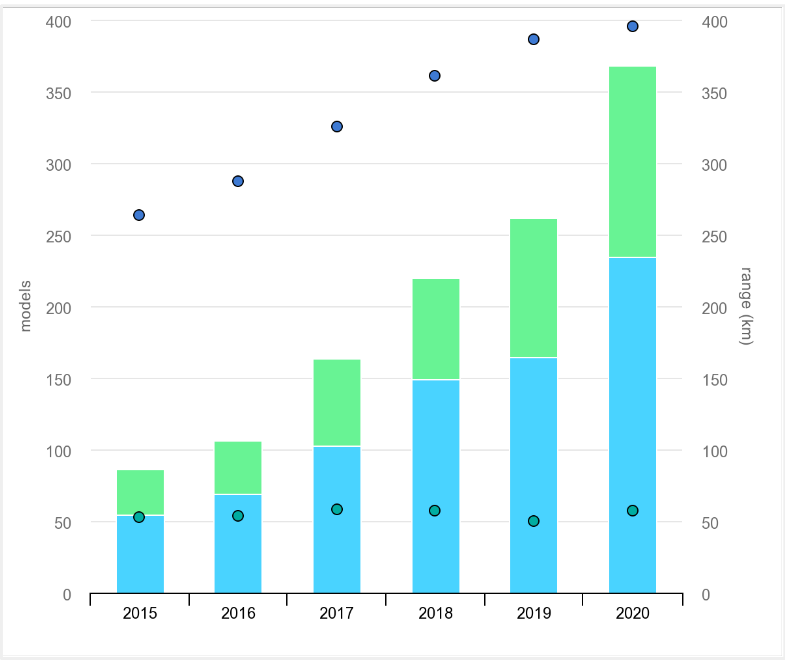
In 1973, the global oil crisis and declared embargo by the Organization of Arab Petroleum Exporting Countries (OAPEC) led to steep oil prices and gasoline shortages across the US. With interests to lower the dependency on the commodity, federal governments started to finance incentives on R&D of alternative technologies. In parallel, automakers also started the search for substitutes, amongst them electric and hybrid vehicles. The final models, however, came short in comparison to existing ICEVs, with limited range and speed.

It was only 20 years later, during the 1990s, that EVs were brought into the spotlight again. The increasing concern with climate change, pushed by United Nations environment conferences such as Rio de Janeiro Earth Summit (1992) and the Kyoto Protocol (1997), prompted federal governments to set targets to limit and reduce greenhouse gasses emission. The EU, for example, targeted a collective reduction of 8% by 2012 in comparison to the base year 1990 [2].

In that decade, many automakers started to modify their popular ICEVs models into electric-powered. The Toyota Prius, released worldwide in 2000, became the first mass-produced hybrid vehicle, reaching over 19,000 worldwide sales in its first year alone [2novo]. Some believe it to be the first milestone in recent EVs history.

Figure 1 - Electric car models available globally and average range, 2015-2020.

Source: International Energy Agency, 2021 [3].



In 2006, Tesla Motors announced an electric car with breakthrough powertrain and battery technologies, reaching up to 320 kilometers per charge. This leap fueled competition and urged other manufacturers to dive deeper into R&D, solidifying even more EVs' presence and future expectations. In fact, the number of electric models increased by 328% in the past 5 years alone, as seen on Figure 1.

Though there are still many disagreements and different point-of-views regarding the spread of electric vehicles, it is agreed that they play an important and bright role in the future of urban and rural mobility, affecting the dynamics between people and their surroundings.

2.2. Status-quo of Electric Vehicles

So far, the diffusion of FCEVs and PHEVs has been more significant than FCEVs (0.31% of total car stock), as seen on Table 1 and Figure 2.

Table 1 - Stock of electric cars.
Data from International Energy Agency, 2021 [4].

Year	**EV Car Stock Worldwide**			
	BEV	FCEV	PHEV	**Total**
2010	16,875	90	403	17,368
2011	55,209	128	9,457	64,794
2012	114,303	158	70,050	184,511
2013	225,336	187	161,756	387,279
2014	407,088	275	296,039	703,402
2015	728,217	936	516,731	1,245,884
2016	1,184,735	3,235	807,700	1,995,670
2017	1,930,245	6.600	1,207,513	3,144,358
2018	3,257,976	12,603	1,835,762	5,106,341
2019	4,760,961	22,853	2,361,863	7,145,677
2020	6,850,327	31,225	3,346,713	10,228,265

Since this study intends to forecast the diffusion of Electric Vehicles until 2050, it will disregard FCEVs and focus on the other two categories of vehicles.

In recent years, the car market has seen both a decline in sales growth and ultimately a decrease in total global sales as shown in Figure 3. Though this may be a natural fluctuation, it is expected that the current Covid-19 pandemic will have a strong impact in the sector. In fact, 2020 had the lowest sales since 2011, with a 15.76% reduction regarding the previous year.

Figure 2 - Electric car stock globally, 2010-2020.
Source: International Energy Agency, 2021 [4].

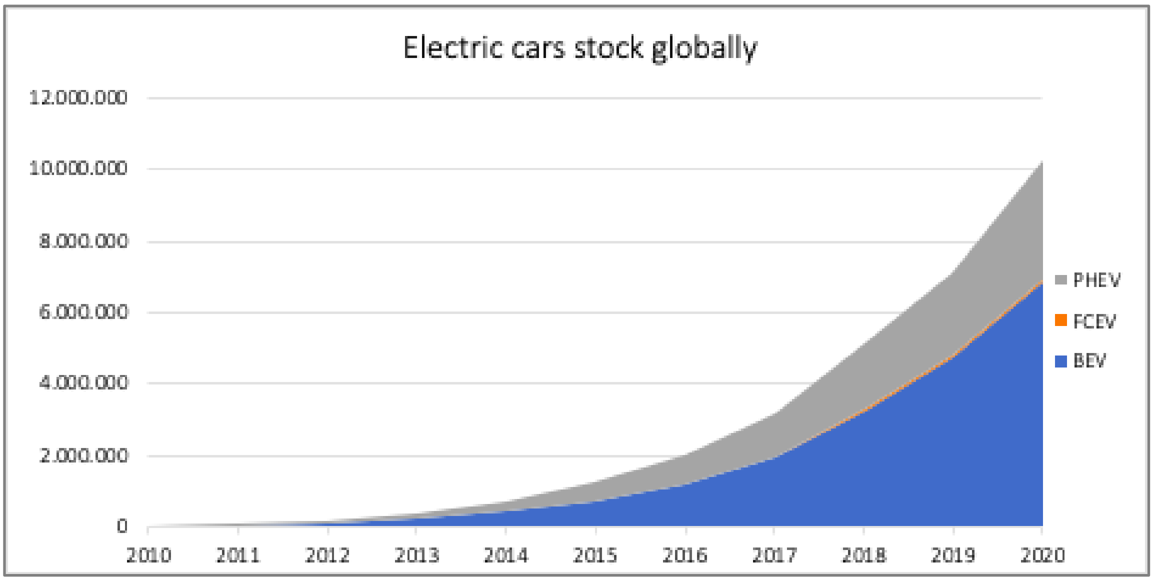
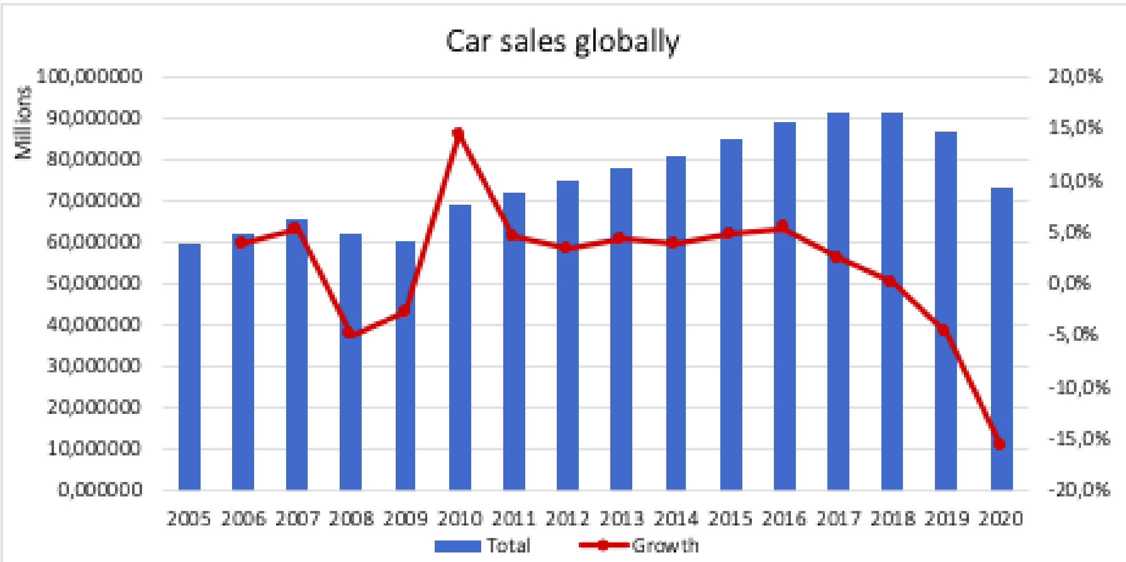
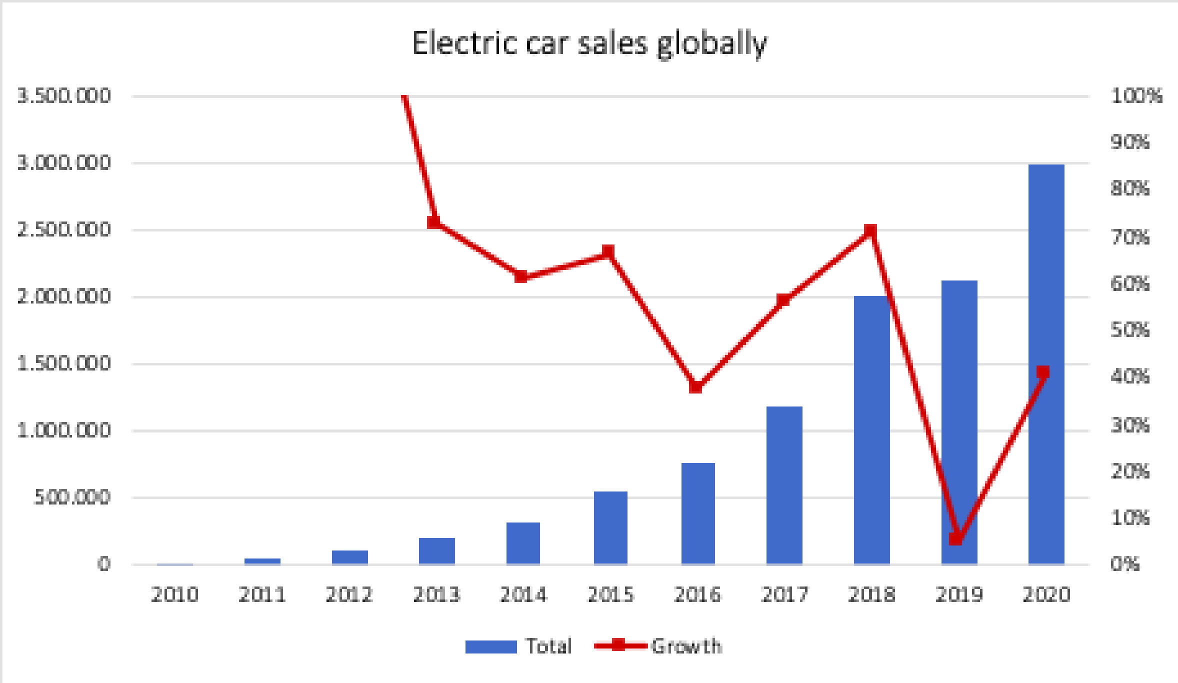


Figure 3 - Car sales globally, 2005-2020.
Source: International Energy Agency, 2021 [4].



The EV cars market, however, has experienced a different situation, as seen on Figure 4.

Figure 4 - Electric car sales globally, 2010-2020. Excludes FCEV.
Source: International Energy Agency, 2021 [4].



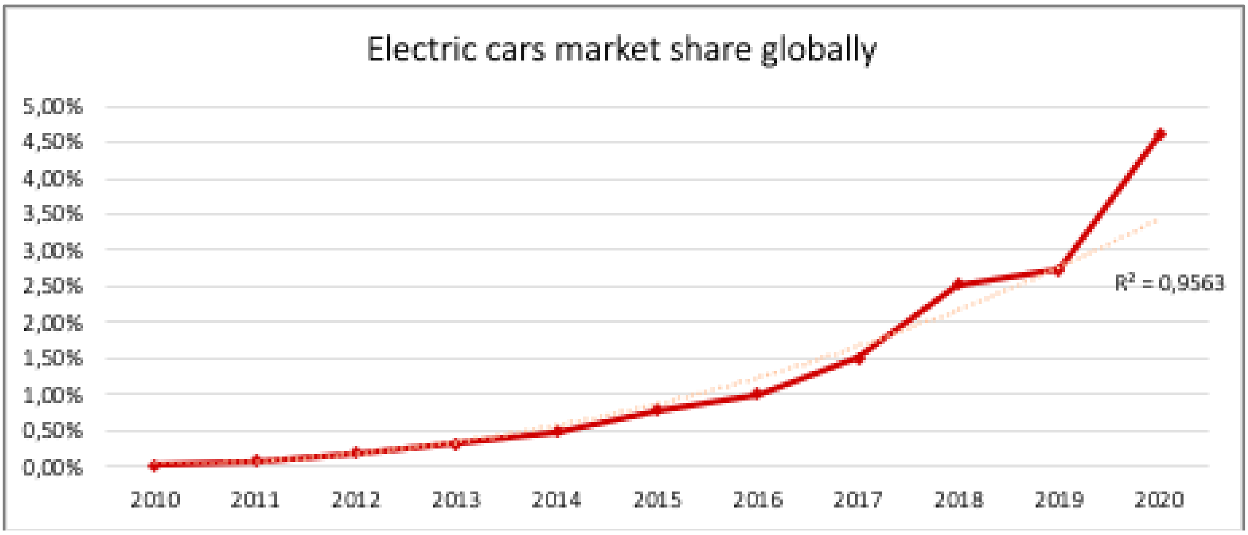
In recent years, EV sales have been consistently increasing despite fluctuations. Annual growth numbers before 2013 were suppressed due to their extremely high values (up to 485%), which difficulted the reading of the graph. It is important to notice that, despite the decrease in overall car sales in 2020, electric cars still had a 40.9% increase globally. This possibly indicates the firmness of the recent EV diffusion trend. In fact, taking a closer look at its market share evolution, one can notice a power trendline growth, with R^2=0.992.

2.2.1. Factors driving the Electric Vehicles market worldwide

Sales of electric vehicles are increasing globally (Figure 5) and there are at least five factors [23] driving it.

A fast-changing market: car companies are evolving everyday to a transition to an electric market, motivated by the competition with Tesla. Technologically, Tesla is ahead, but other brands are bringing a more complete range of models and prices. There are announcements of more than 400 new models of hybrid electric and plug-in by 2025. In addition, battery technology continues to improve continuously, having practically no problems with degradation over time.

Figure 5 - Electric car sales globally, 2010-2020. Excludes FCEV.
Source: International Energy Agency, 2021 [4].



Technology: Currently, the average battery cost for a typical EV works out to about $6,300. Battery pack prices have improved and come down about 89% over the past decade [5].

Emissions regulations: Regulations worldwide to reduce the emissions of CO_2 are becoming more severe and promote the use of electric vehicles. For example, the UE imposes emissions limits for vehicle manufacturers, calculated on the total number of vehicles sold. More and more companies are now considering their engine plants as assets that need to be disposed of urgently, disinvesting at an accelerated pace if emissions targets are to be met. In addition, several countries have brought forward the ban on the sale of petrol and diesel vehicles: in the United Kingdom, news that the target date for the phase-out has been brought forward to 2030 has increased interest in electric vehicles by 500%.

The environment: there is a pressure of clients, partners, investors and society who are suffering from global warming to decarbonization. A study by the Montreal Economic Institute (MEI) in Canada considered that in a decade, electric models emit 30 tons of CO_2 less than fossil fuel vehicles [6].

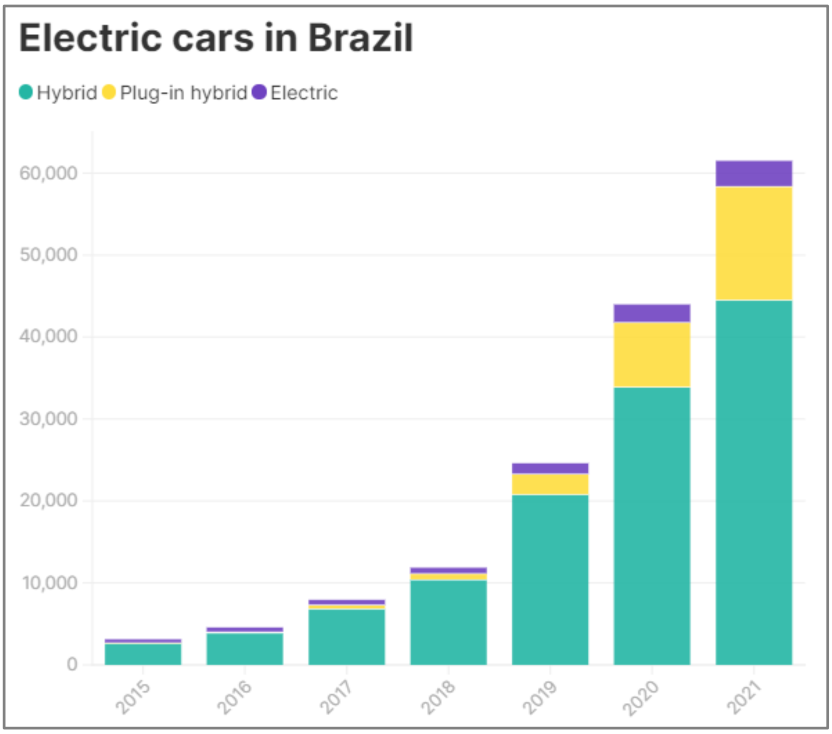
Cost: although the price of electric vehicles is still somewhat higher than that of traditional vehicles, we're getting ever-closer to parity, and there is growing evidence that in terms of total costs, running an electric vehicle is far cheaper, partially due to the price differential between electricity and diesel or gasoline, along with low maintenance.

2.2.2. Brazilian Scenario

Between 2011 and 2016, roughly 4,000 electric or hybrid cars were licensed in the country. According to ABVE, 34.990 xEVs were sold domestically, at the end of 2021, which represents a 77% growth over the segment's total sales in 2020. Electric and hybrids reached 1% of total sales in Brazil for the first time, and in April 2021 they reached 1.6% [7].

The evolution of sales of HEV (majority of sales), PHEV and BEV are shown in Figure 6.

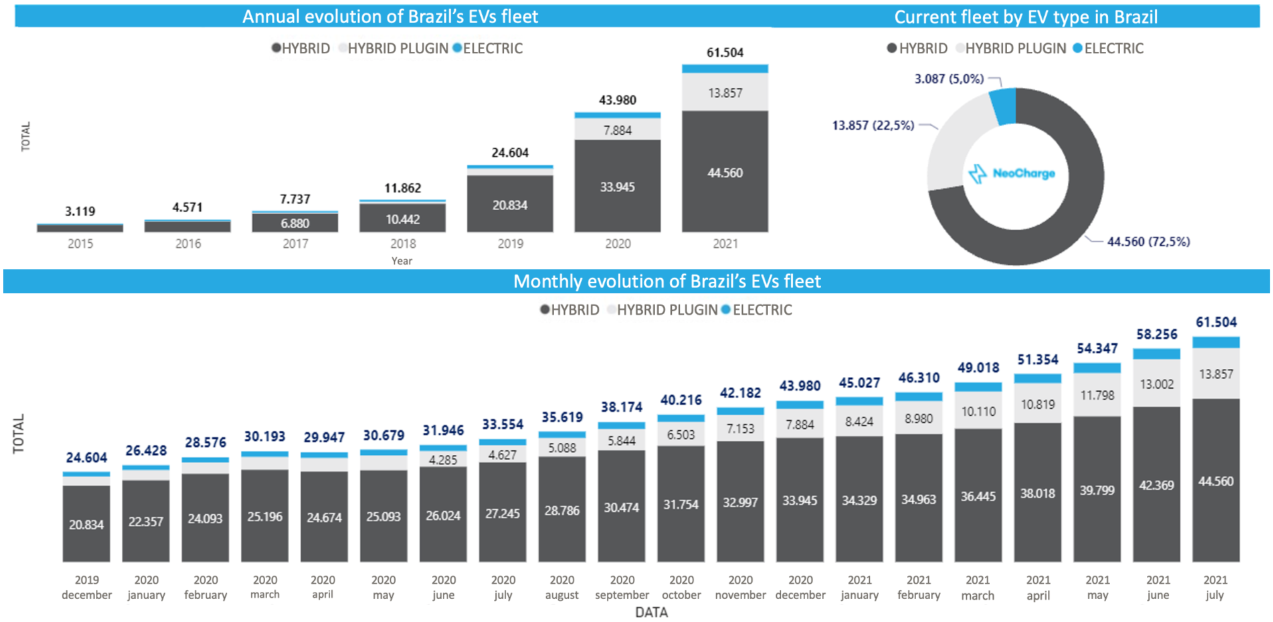
Figure 6 - Evolution of sales of EVs in Brazil.
Source: The Brazilian Report, 2021 [8].



In Figure 7, it is observed that the annual and monthly evolution of Brazil’s EVs fleet presents almost an exponential growth. In 2021, the total EV fleet was 61,504 [9].

Figure 7 - Fleet evolution and representation of EVs in Brazil.

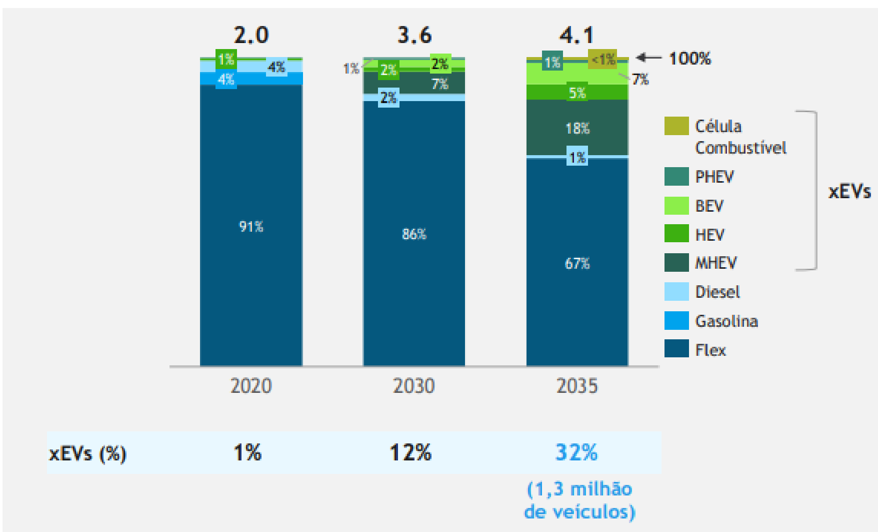
Source: NeoCharge, 2021 [9].



CPFL Energia, one of the largest private groups in the Brazilian electricity sector, estimated that Brazil will need 80,000 public electroshops by 2030 to keep up with the pace of growth of the domestic electric vehicle market [10]. In addition, BCG promoted a study that estimated a need of 150 thousand chargers and investments of R$14 billion until 2035. The study also said that the mix of annual sales of xEV (combustible cell, PHEV, BEV, HEV, MHEV) could reach 32% by 2035 (Figure 8) [11].

Figure 8 - Mix of annual sales of xEV, in millions of vehicles.

Source: BCG, 2021 [11].

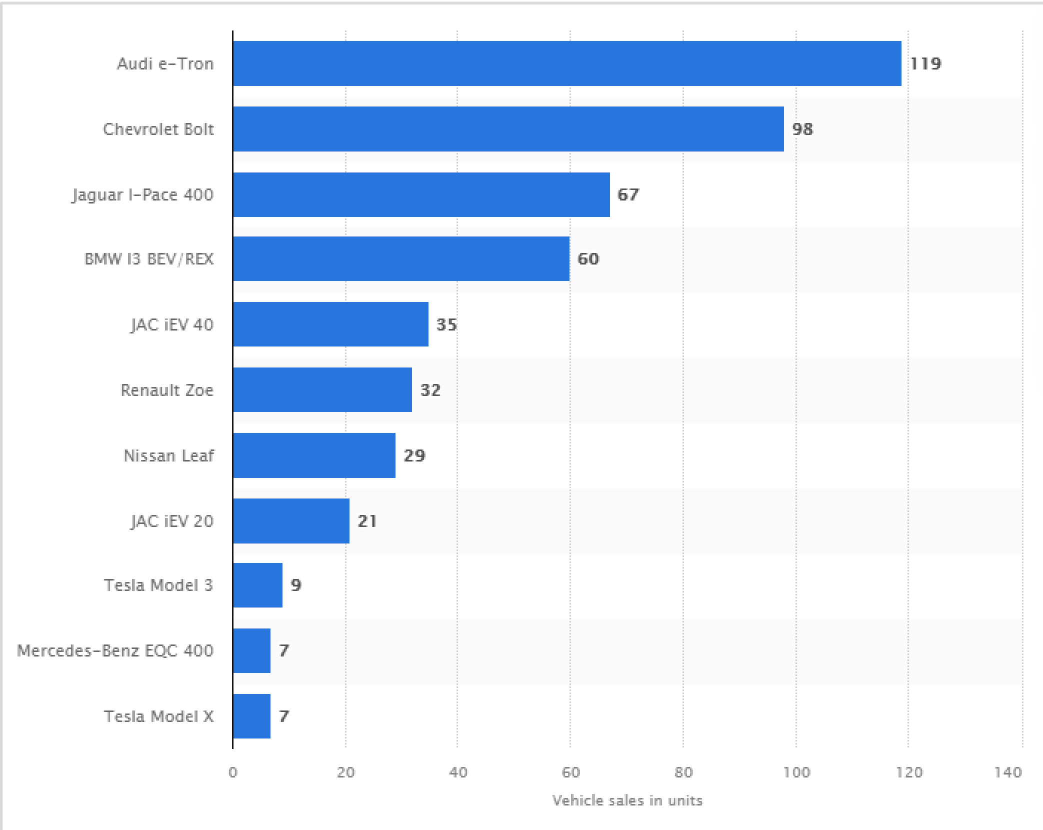


2.2.2.1. Current price of EVs in Brazil

Since automakers in the country do not manufacture passenger cars that utilize this technology, all sales are from imports, which are much more expensive than domestically produced combustion cars. Electric and hybrid vehicles are more expensive than traditional vehicles because of the technology they use, but high taxes lead to even higher final costs.

The Toyota Prius, one of the cheapest sold in the country, costs from R$120,000 [12]. There are around a dozen other models available to the Brazilian consumer, such as seen in Figure 9.

Figure 9 - Leading electric vehicle models in Brazil as of October 2020, by unit sales. Source: Statistica, 2021 [13].



Brazil suffers from a strong inflation and dependence on the fluctuations of the international market, which can make EV prices even higher for the consumer. Thus, purchasing this cleaner vehicle is an even longer-term investment for the average Brazilian. Besides, Brazil has a clean energy mix and a beneficial renewable liquid fuel: ethanol, which makes the idea of buying an EV very distant.

Furthermore Brazilian drivers have to ride long distances for traveling between states, for example, which would call for several stops to recharge the battery along the road (which is not equipped with sufficient recharging stations).

2.2.2.2. Government policies

In Brazil, measures that could stimulate widespread use of electric vehicles by the public and encourage their production include tax reductions, incentives for purchase, exemption from road space rationing, and access to exclusive bus lanes and restricted areas of the city.

In 2015, the government reduced the import tax for electric and hybrid cars from 35% to a maximum rate of 7% . Several states, including Ceará, Rio de Janeiro, Rio Grande do Sul and São Paulo have exempted or reduced motor vehicle taxes on these vehicles, and the city of São Paulo has exempted electric cars from road space rationing rules [14].

Another challenge to conquer is the need for battery-recharging infrastructure, involving the construction of electric vehicle recharging stations in urban centers and on major roads.

Figure 10 - Example of recharging station from the project Ecovagas.
Source: Estadão, 2021 [15].

Public and semi-public charging stations increased from 500 in March, 2021 to 754 in July, 2021; partnerships and new business models should continue to drive the charging infrastructure. For example, the company Enel-X created, in partnership with Estapar, the first semi-public electric vehicle charging network in Brazil. Called Ecovagas, the project launched at the end of 2020 wants to install, initially, an integrated network of 250 stations in about 100 points, in parking lots of Estapar [15].

2.2.2.3. Impacts on the energy grid

Brazilian legislation prohibits charging money to use public recharging stations, as only energy suppliers registered with the Brazilian Electricity Regulatory Agency (ANEEL) are allowed to sell electricity.

CPFL Energia suggested that the mass use of EV would poorly increase energy consumption from the national grid by 0.6% to 1.7% by 2030, when forecasts indicate that there could be between 5 million and 13 million electric vehicles in the country.

According to experts, as well as having a low impact on the grid, battery-powered cars could be used to balance the national electricity system. It is the concept of a smart grid. Although electric vehicles do not produce energy, they have the potential to function as an input at peak times, such as late afternoon. While connected to a charging outlet, they could return unused power to the grid, supplying the system.

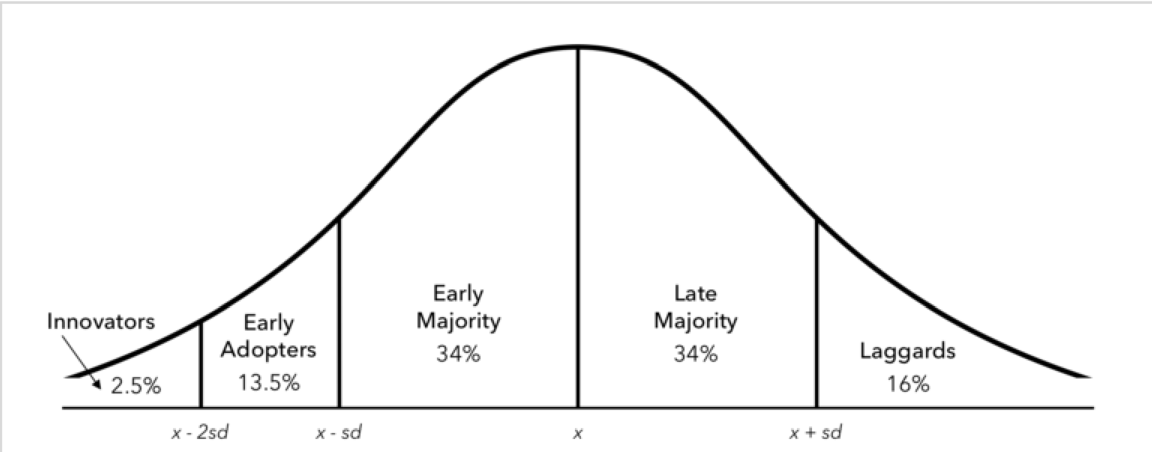
2.3. The adoption of innovations and openness to EV

In 1962, E.M. Rogers developed the Diffusion of Innovation Theory, which models how new products and ideas spread inside a specific population until it reaches saturation. It studies how some consumers are more open to innovation than others, and their behavior is thereby affected [16]. A target population is divided into 5 sequential groups that follow a normal distribution (Figure 11):

1. Innovators: those who wish to be the first to experiment and adopt.
2. Early Adopters: consumers comfortable with change, usually aware of emerging innovations.
3. Early Majority: public that adopts the innovation before the average person, but only after there is enough concrete evidence (and diffusion) to prove the new product’s effectiveness.
4. Late Majority: consumers who are not very open to change but will adopt it after it has been accepted and used by the majority.

5. Laggards: last adopters, extremely conservative and traditional when it comes to innovation.

Figure 11 - Relationship between types of adopters classified by innovativeness and their location on the adoption rate curve. Source: Rogers, 1995 [16].



The adoption is defined not as a binary yes/no, but rather a process that starts at the awareness of the innovation, the decision to adopt (or not), the initial use and, finally, the continued use. This progression will be influenced by five main factors: relative advantage (how much better the new product is in comparison to the current one), compatibility (with the consumer's beliefs, values and demands), complexity (user-friendly), testability (possibility to test before a purchase or commitment to adoption), and observability (traceability of observable results). The importance of each factor varies according to the group in question and with the product itself.

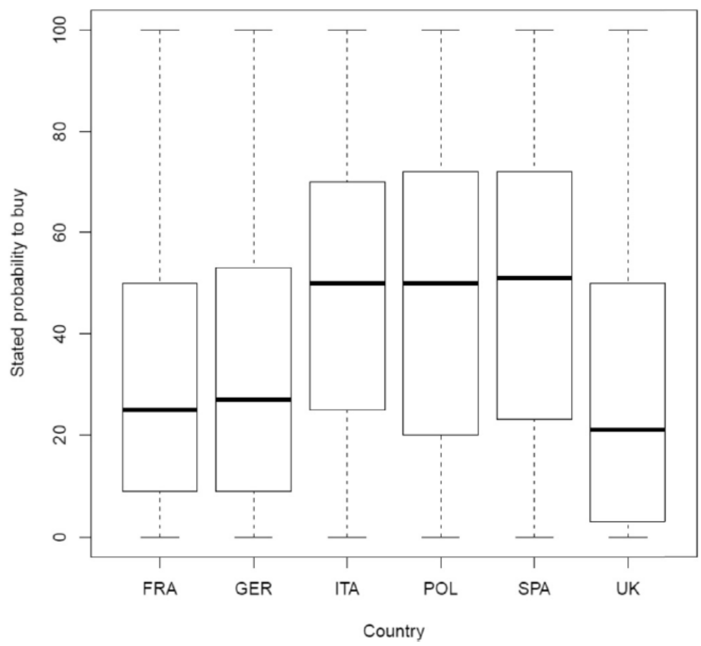
When discussing openness to adopt new goods, it is important to consider not only the technical factors, but also psychological, social, and present time aspects. Specifically with green products, Coad et al. (2009) states that consumer behavior relies both on intrinsic and extrinsic motivations, such as a sense of self-responsibility (the first), and financial incentive and positive social feedback (the latter) [17]. Likewise, Heffner et al. (2007) and Kahn (2007) have shown that consumers with a higher level of environmental awareness or pro-environmental are more probable to buy EVs and/or commute daily via public transport as a representation of their beliefs when compared with their opposing group [18], [19].

In a survey conducted by Cecere et al. (2017), it was found that the average daily driving distance for the collected sample was between 50 km and 60 km for Italy, France, and Germany, and only 40 km for the UK [20]. Moreover, the average parking time overnight was of 16 hours, thus confirming, by both data, that the substitution potential of ICEs is perfectly compatible with the most recent EVs technology, since the values fall inside the current range, battery duration, and necessary charging times (Thiel et al., 2012) [21]. However, it was also seen that only 10% of the interviewees had access to a private garage, imposing the access to charging station as a limiting to the diffusion of EVs.

Regarding the intention to buy, Cecere et al. (2017) shows that, for the analyzed countries (France, Germany, Italy, Poland, Spain and UK), people holding a driver's license and driving an ICE car are 35% likely to purchase an EV when changing their current vehicle. In Italy, this probability is even higher, with an average of around 50% [20]. Figure 12 shows the distribution of the answers.

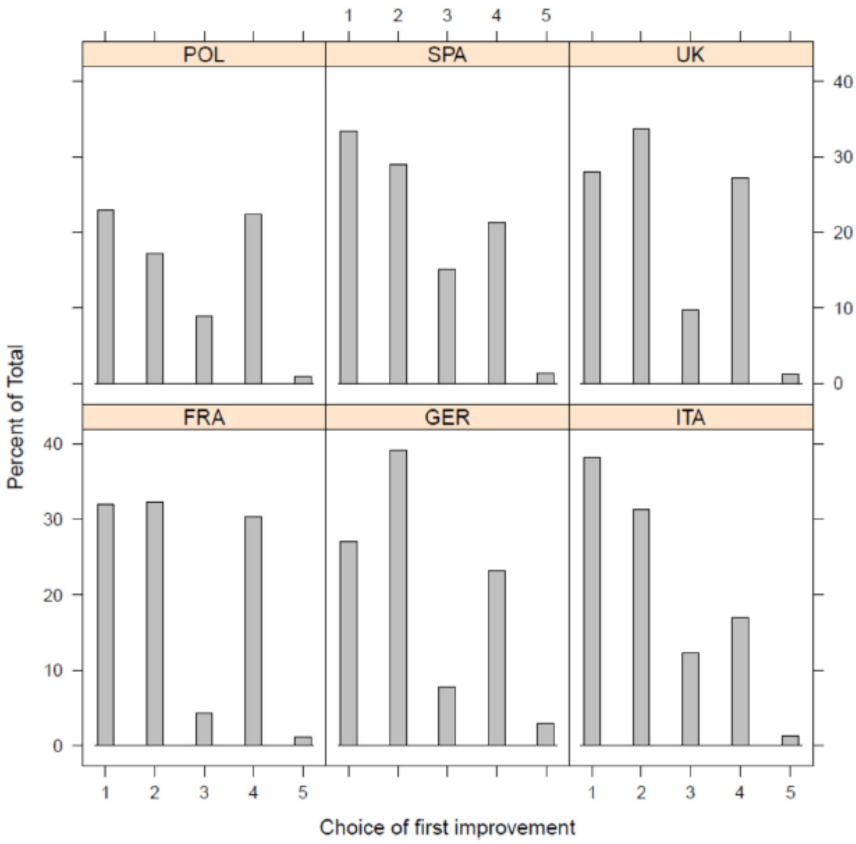
Figure 12 - Boxplot of stated probability to buy an EV before improvements.

Source: Cecere et al, 2017 [20].



The survey questioned how attributes and their improvements can influence the probability of consumers' intention to buy. More specifically, interviewees were asked to choose between price, driving range, recharging time, recharging at home, and maximum speed, and then indicate their likeliness of purchase in the new scenario. Reducing the price of the EV and a longer driving range were the overall top priorities, but price was predominant for Italians. Speed and recharging times were the least selected. Figure 13 details the first choice by country.

Figure 13 - Choice of first improvement by country.
1 = price, 2 = driving range, 3 = recharging time, 4 = recharging at home, 5 = max speed.
Source: Cecere et al, 2017 [20].

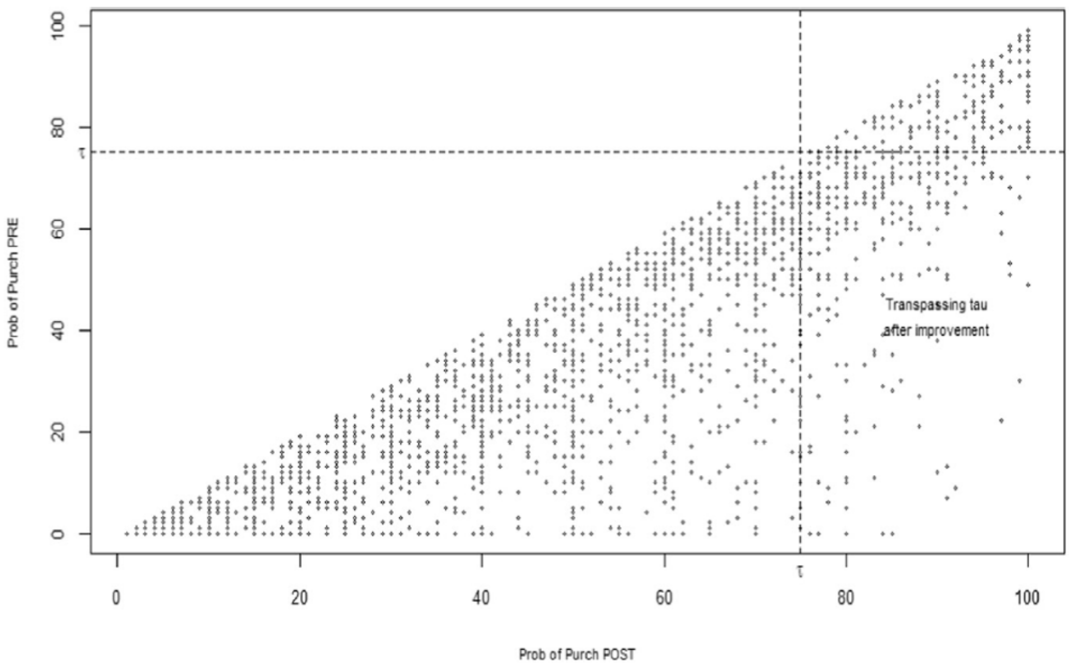


Going more in-depth into the changes in intention to purchase, a graph was plotted considering the probability before the improvements, and in the post-scenario (Figure 14). Tracing a threshold of 0.75, three different areas are defined: those who will not buy, even after modifications (bottom-left quadrant); those who would buy the EV from the initial point (top-right quadrant); and those who would buy the vehicle only after the modifications.

The third group is the most important, as their motivations to switch from non-adoption to adoption should be the focus of EV manufacturers and the drivers of the diffusion and growth of the market.

The results of Cecere et al. (2017) have shown that price reduction is the most important trigger for the transition of consumers from non-intention to intention to buy. In second, the increase in the driving range is valued especially by people with a lower initial probability of purchase, while access to recharging equipment at home assumes that place for those with a higher initial purchasing probability. This indicates that technological development should focus on batteries (to increase range) and cost reduction, aligned with possible government incentives, in order to accelerate the diffusion of EVs. A forecast model needs to take such factors into account as critical curbs for a realistic prediction of the market development.

Figure 14 - Pre and post-improvement scatterplot of probability to buy.
Source: Cecere et al, 2017 [20].



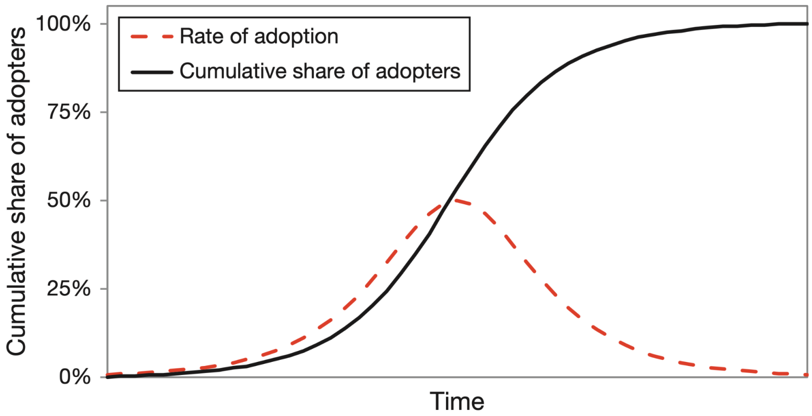
2.4. S-shaped growth curve

When discussing the diffusion of innovations, one usually refers to the decision of agents, or potential adopters, to acquire or use an innovation as 'adoption.' The diffusion of an innovation is the result of many adoption decisions over time and the cumulative share of adopters represents the diffusion curve, which is often S-shaped [22].

S-shapes consist of exponential growth followed by a change in concavity corresponding to a declining rate of adoption as the technology matures and reaches market saturation. From the literature reviewed for this report, it was seen that the diffusion of new vehicle technologies follows S-shaped curves as is shown in Figure 15 [23].

Figure 15 - S-shaped diffusion curve and rate of adoption over time.

Source: Fleiter and Plotz, 2013 [22].



The rate of adoption evolution starts with the technology information spread by a few adopters and reaches an inflexion point when it becomes increasingly unlikely that users are in contact with remaining potential adopters, as their number decreases, and the diffusion process decelerates. Thus, the adoption rate is proportional to the number of adopters and the number of remaining potential adopters [22].

3. METHODOLOGY

3.1. Bass Diffusion Model

The Bass Diffusion Model estimates the adoption rates of a new technology by the maximum market size and two types of public: innovators and imitators. Firstly are those who are not influenced by the purchasing behavior of others and secondly, are those who adopt the technology in response to the purchasing experience of others.

The model requires sales data to estimate the parameters, as seen on equation 1 [24], where:

- *N(t)*: the cumulative number of adopters at time t,
- *M*: the total population or potential adopters at t=0,
- *p*: the coefficient of innovation,
- *q*: the coefficient of imitation.

$$\frac{dN(t)}{dt} = p[M - N(t)] + \frac{q}{M}N(t)[M - N(t)] \tag{1}$$

At the same time, it still takes into account customers' needs and behaviors, word-to-mouth recommendations, availability of information about a product and models through the parameters *q* and *p*.

The EV market is considered a complex and dynamic system and the Bass diffusion model can be adapted to the System Dynamics (SD) field. Therefore, to model the adoption of electric vehicles, it was used here the Vensim PLE software (simulation language created by the company Ventana Systems. Inc, Harvard, MA, USA), based on SD.

The SD Bass diffusion model has two communication paths: adoption through mass media (external influence), and word-of-mouth (internal influence). Its dynamic behavior is represented by the S-shaped growth curve of a cumulative number of adopters over time.

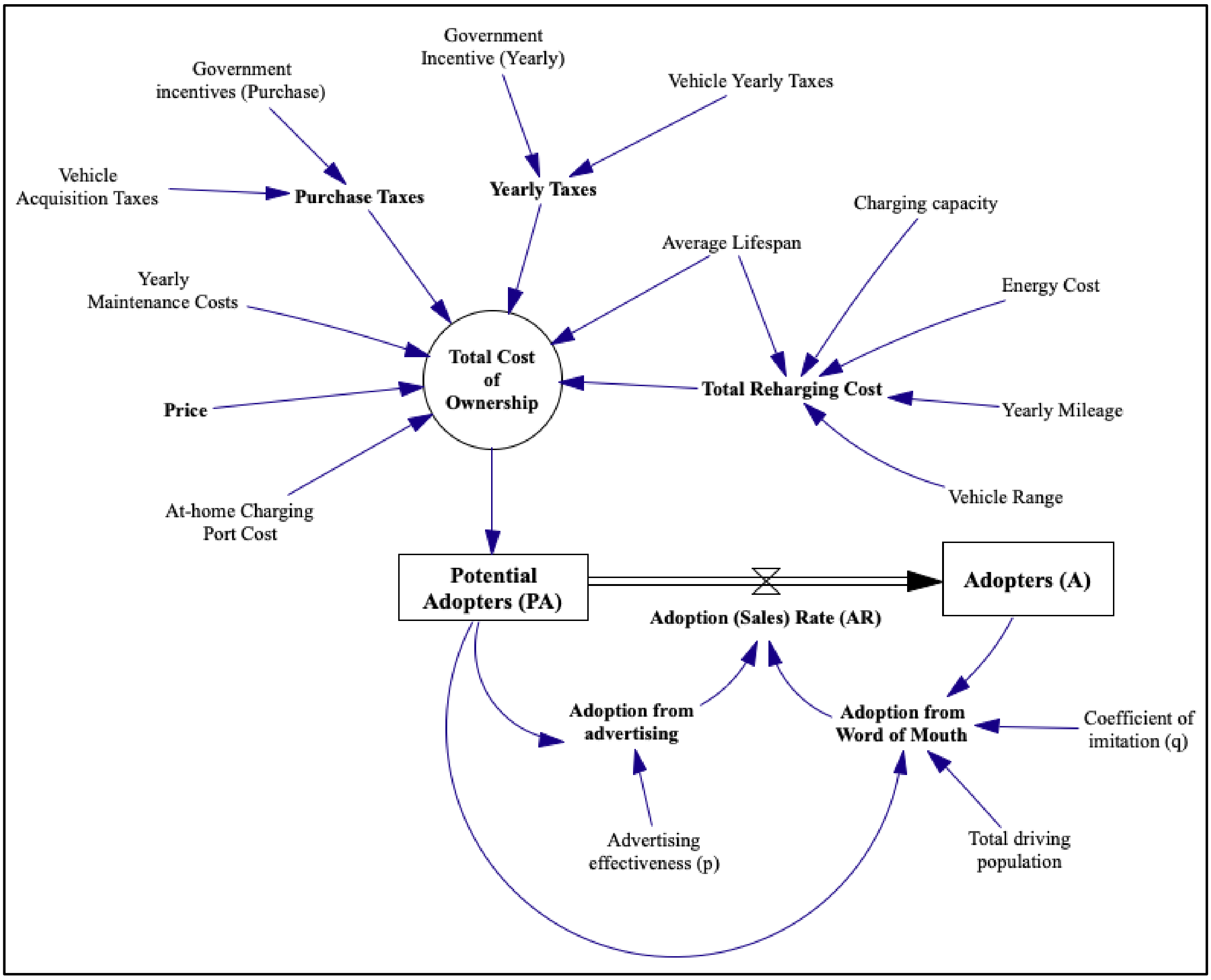
3.2. Vensim Software

Developed by Professor Forrester, Vensim qualitatively and quantitatively studies the interactions between components of dynamic and complex systems [25]. This software allows users to modelize and simulate different types of models and compare them. Its interface is facilitated by logic menus to explore all the structure of the models.

3.3. Simulation Inputs

The constructed model is described in figure 16. Each arrow represents a mathematical relation between the parameters it connects, in which the origin parameter is a variable in the equation that determines the destination parameter. All parameters and their associations are described in this section.

Figure 16 - Model created for baseline and tax-variation simulations.



3.3.1. Potential Adopters

The variable Potential Adopters determines how many people will eventually become users of the studied technology. Its evolution overtime is given by:

$$Potential\ Adopters\ (t)\ =\ M\ - Adopters\ (t)\ =\ M\ -\ \int_0^t Adoption\ rate(t)\ dt \qquad (2)$$

In the present work, the maximum market M will be considered as 39 million in 2050. According to the Ministério de Minas e Energia's Plano Nacional de Energia 2050 of Brazil, the light vehicles fleet is estimated to be 130 millions in the Energy Challenge Scenario, based on a stagnation scenario and Brazil’s energy demand challenge [26]. Besides, it was assumed that Brazil will follow the global tendency of 31% of the light vehicle fleet is xEVs [27], resulting in 39 million of total xEVs. Furthermore, for the total driving population it was considered the population who owns a CNH (Carteira Nacional de Habilitação) in February, 2022, which is 77,122,865 [28].

To try and quantify the variation of Potential Adopters (PA) based on Total Cost of Ownership (TCO), data from a 2012 research conducted by European Commission's Joint Research Centre on the attitude of European drivers towards EVs was collected.

Since TCO is the variable studied in the model, only the willingness to buy of price-driven respondents was considered. Assuming only those who stated a probability of purchasing the technology of over 70% as potential adopters, an increase of 16 percentage points occurred for a cost variation of R$ 46,350 [21]. From these, the following function was estimated:

$$Potential\ Adopters_{t=0}\ (TCO) \ = \ -747.93 * TCO \ + \ 219{,}256{,}196 \tag{3}$$

Nonetheless, a minimum value of 39 million was maintained even in scenarios with TCO variation.

3.3.2. Adoption from Word of Mouth and Advertising

Word-of-mouth (WOM) and Advertising are two main drivers of adoption of the new technology in the present study. As given by the Bass Diffusion model, their calculations are [24]:

$$Adoption\ from\ Advertising_t \ = \ Potential\ Adopters_t \ \times p \tag{4}$$

$$Adoption\ from\ WOM_t \ = \ Potential\ Adopters_t \ \times q \times \frac{Adopters_t}{Total\ driving\ population} \tag{5}$$

3.3.2.1. Coefficients of innovation and imitation

Numerous values for the Bass model were tested to check which one would correspond best to the behavior of the total EV fleet of Brazil (considering existing data from December, 2015 to November, 2021).

It was decided to work with an adaptation of Lamberson (2008) parameters values in the litterature. Lamberson examined the adoption rate of HEVs using the Bass and compared the diffusion of HEV technologies to that of other automotive innovations and extrapolated results to the US fleet. He sets the Innovation coefficient p=6.18x10^{-4} and Imitation coefficient q=8.736x10^{-1} other values are shown in Figure 17.

Figure 17 - Values of the coefficients p and q of the Bass Model on the literature.
Source: Massiani and Gohs, 2005 [23].

Source Technology	Method	Innovation coefficient P	Imitation coefficient q	Market Potential
Becker, Sidhu et al. (2009) Electric cars	Authoritative sources	0.01 0.02 0.025	0.4	Exogenous: 70% or 90% of the light-vehicle market in each year.
Davidson et al. (2013) Electric cars	Authoritative sources, but eventually refers to Becker (2009)	Idem	Idem	Exogenous : Number of Household are "0.03, 0.25, and 0.7 in the low, medium, and high growth scenarios"
Gross (2008)	Authoritative sources	0.01	0.1	
Li (nd) Electric cars	Based on "a statistic model of EVs in US from 1999 to 2008"	0.0000365	0.447	Exogenous: "At most half of the vehicles in market can be EVs, the ultimate market potential is calculated as 2.5 million".
Cordill (2012) Prius Hybrid Civic Hybrid Ford Escape Hybrid	Calibration on US market data 2000-2010	 0.0016 0.00343 0.036	 1.45 0.631 0.432	Estimated 2.87 million 3.68 million 0.36 million
Steffens (2003) - Conventional cars	First car purchase (not specifically AFV) in Australia 1966-1996	0.0076	0.0905	Exogenous: 91% of the population would finally purchase the technology.
Shoemaker (2012)* Passenger vehicles Utility vehicles	Calibration on AFV monthly sales in the US Dec 1995 (oct 2004 for utility AFV) dec 2011 in the US	 0.0912 0.008124	 0.4692 0.4632	Estimated 436 000 2 300 000
Lamberson (2008)* HEV	Calibration on US monthly sales (Feb. 2001 - Oct. 2007)	0.000618	0.8736	Estimated 1.6 million veh.
Park et al (2011) HEV	HEV sales in Japan (1997 - 2006) parameterized to Korea[7]	0.0037	0.3454	10,2 million veh.
Jensen et al. (2014) Electric cars	Norwegian new electric car registration data from (Jan. 2003 - Jun. 2013)	0.002	0.23	Exogenous: Result of a Discrete Choice Model
MacManus (2009) HEV	HEV annual Data in the US. (1999-2008)	0.0026 (0.00124 generalised Bass)	0.709 (0.77922 generalised bass)	Estimated : 1.9 million veh.
Cao (2004) E85 CNG Hybrids	Calibration on annual sales in the US 1993-2002	 0.00441 0.0210 0.000446	 0.491 0.265 0.4788	 E85: 245 971 CNG : 100 000 Hybrid: Exogenous. Based on EIA scenario of 19 million HEV sold until 2025, subsequently varies in function of HEV awareness and (lagged) fuel price

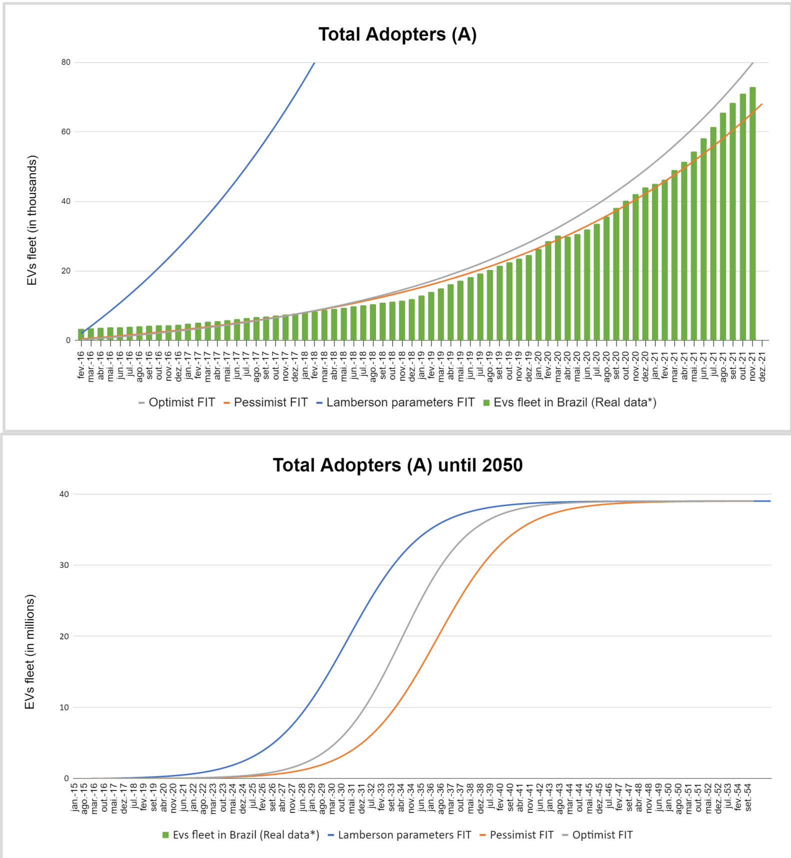
Small changes in values of p and q parameters were performed to find the best fit to the actual Brazilian scenario of electric cars sales. Note that it was considered *q* in function of Purchase Fraction and Contact Rate in Vensim. When working with *p* equal to

Lamberson's p divided by 10, a better curvature was observed in sales history since 2016. Lamberson's q parameter fits satisfactory sales history in Brazil.

Changes in q parameter were done to investigate different possibilities of sales evolution in the Brazilian market. Decreasing and increasing this parameter of one decimal unit allowed the analysis of an optimistic (faster) and a pessimistic (slower) scenarios in the achievement of the mark of 39 millions adopters of electric vehicles in Brazil.

In blue in Figure 18 is the curve with Lamberson's p and q. In orange is the curve of $p/10$ and q equal to Lamberson. The gray curve is the curve of $p/10$ and q equal to Lamberson but shifted by some months.

Figure 18 - Graphic analysis of EV fleet x time (months) according to different values of p and q. Top: from 2016 to 2021; Bottom: from 2016 to 2050.



3.3.3. Total Recharging Costs

The recharging costs were calculated in function of the data in Table 2:

$$TRC = \frac{Average\ Annual\ Mileage}{Average\ EV\ Range} \times Charging\ Capacity\ \times Energy\ Cost\ \times\ Average\ Lifespan \quad (6)$$

Table 2 - Inputs for Total Recharging Costs.

	Baseline Value
Energy Cost* [29]	*0.594 R$/kWh*
Charging Capacity [30]	*17.6 kWh*
Average Annual Mileage [31]	*13,000 km/year*
Average Vehicle Range [30]	*313 km*
Average Lifespan [32]	*3*

*Price for the state of São Paulo.

3.3.4. Total Cost of Ownership

The Total Cost of Ownership (TCO) was calculated with the following formula using the data values in Table 3:

$$TCO = Price + Taxes + Total\ Recharging\ Cost + Charging\ Port\ Cost + Maintenance \quad (7)$$

where:

$$Maintenance = Yearly\ Maintenance \times Average\ Lifespan \quad (8)$$

$$Taxes = Purchase\ Taxes + Yearly\ Taxes \quad (9)$$

and

$$Purchase\ Taxes = Price \times Purchase\ Tax\ Rate \quad (10)$$

$$Yearly\ Taxes = Price \times Yearly\ Tax\ Rate \times Average\ Lifespan \quad (11)$$

Table 3 - Inputs for TCO.

	Baseline Value
Purchase Price	*R$187,895.00*
Yearly Maintenance Costs [33]	*R$1,450/year*
At-home Charging Port [34]	*R$10,000*
Purchase Tax [35]	*14.5%*
Yearly Tax [36]	*1.59%*

3.3.4.1. Tax Rates

For EV Purchase taxes, the ICMS (Imposto sobre Circulação de Mercadorias e Serviços) was reduced to 80.56% of its previous rate since January 2022 for the State of

São Paulo, reaching 14.5%, which will be considered the Purchase Tax Rate in the model [37].

In 2021, São Paulo approved the IPVA (Property Tax on Motor Vehicles) exemption for electric cars and that hybrid cars will pay half the tax [36]. Considering that 95% of the electrified vehicles in Brazil are hybrid [9], it was considered an average reduction of the tax of 47%. According to the 2015 IPVA rules in São Paulo, the tax rate for electric cars is 3% of the market value [14]. This gives a vehicle Yearly Tax Rate of around 1.59%.

To understand public sector an taxes influence on the model, 4 deduction cases were be studied, as described on Table 4. The deductions were chosen based on the most extreme possibility (complete removal of Tax) and a middle-ground (50%) in order to understand how these taxes affect the diffusion of EVs in the market, rather than try to predict how much the taxes will be reduced in the coming years, since the time range of the model is extensive and tax policies are determined mostly by political forces, whose views on EVs can greatly change depending on elections' results.

Table 4 - Scenarios for Tax Rates Variation models.

	Yearly Tax Rate		**Purchase Tax Rate**	
	Deduction	**Value**	**Deduction**	**Value**
Case I	50%	0.795%	0%	14.5%
Case II	100%	0%	0%	14.5%
Case III	0%	1.59%	50%	7.25%
Case IV	0%	1.59%	100%	0%

Furthermore, a combination of multiple values of purchase and tax rates was also inputted in the software. For each Yearly Tax Rate on Table 4, the model was run with all values of Purchase Tax Rate on Table 5, creating 54 scenarios.

Table 5 - Varied values of Yearly Tax Rate.

	Percentage of IPVA					
Yearly Tax Rate	50%	40%	30%	20%	10%	0%

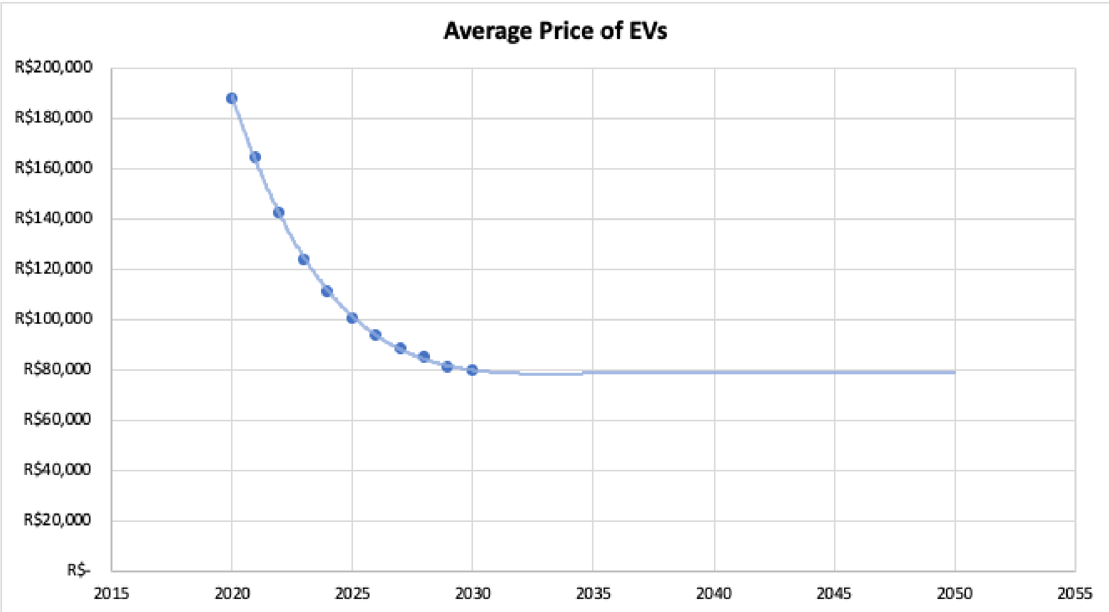
Table 6 - Varied values of Purchase Tax Rate.

	Percentage of 2021 ICMS								
Purchase Tax Rate	80%	70%	60%	50%	40%	30%	20%	10%	0%

3.3.4.2. Price

The value for EV price in the baseline model is R$187,895.00, which is the average in 2020 [12]. To analyze how the expected price decrease with technological advancement will affect diffusion, BloombergNEF's report on forecasted price evolution was used as a base for a polynomial regression, extrapolated until 2056 (final time of model) as seen on Figure 19 [38].

Figure 19 - Forecasted average price of EVs.



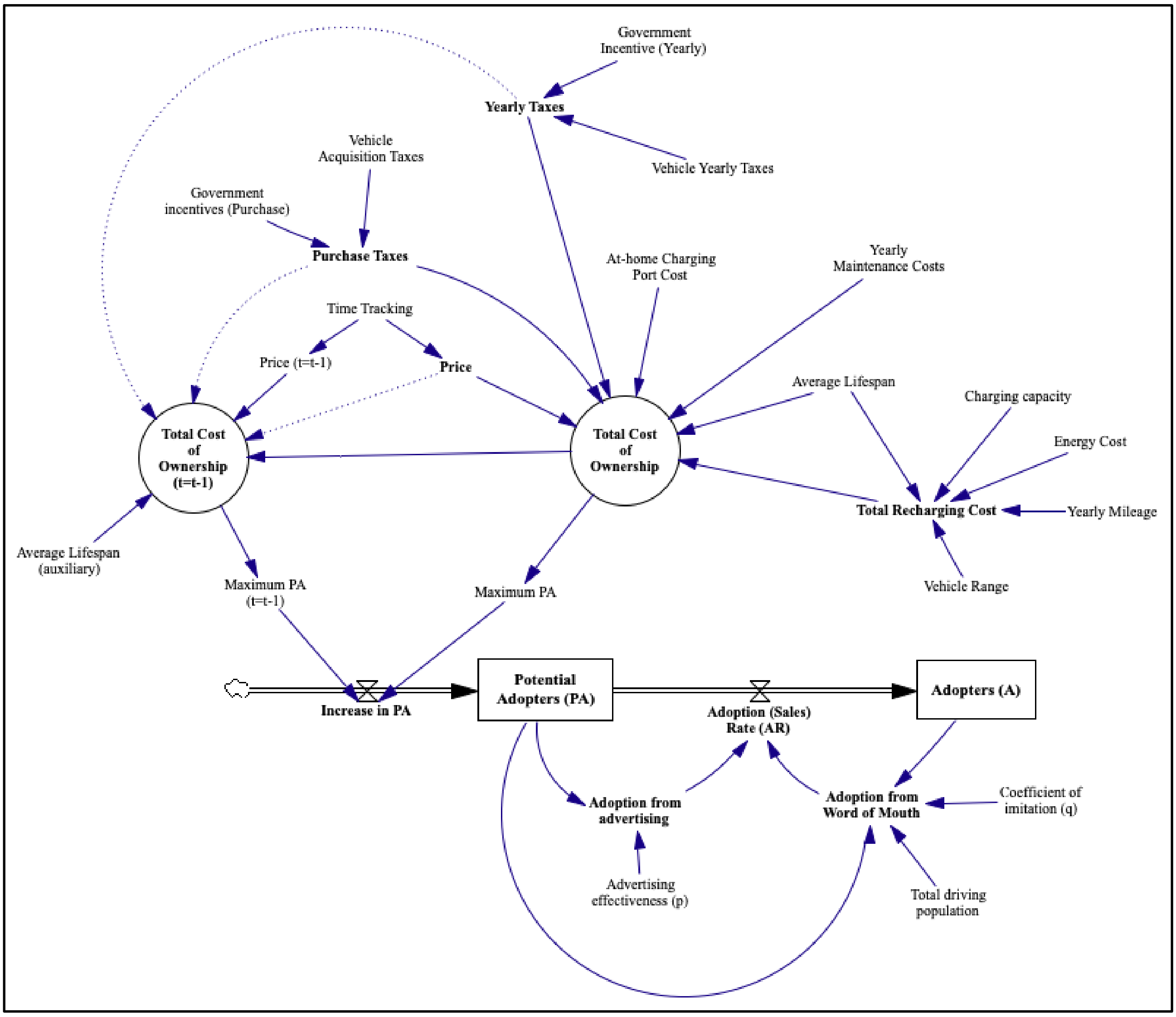
Prices will stabilize at around R$79,000 from 2030. Thus, the following equation is used, with a R^2 of 0.9995:

$$Price(t) = (-1.1E^{-7})\, t^5 + (1.7E^{-4})\, t^4 - 0.1\, t^3 + 33.0\, t^2 + 4{,}887.1\, t + 358{,}285.6 \quad (12)$$

where *t* is the time step (in months).

Since $\frac{dPrice(t)}{dt} \neq 0$, the number of total Potential Adopters (total market share) needs to be recalculated at all time steps, while also accounting for its decrease due to adoption here. To account for this transformation, the model was incremented as seen on Figure 20. Additional variables are described in Table 7.

Figure 20 - Model used for price-varying simulation.



Once again, each arrow represents a mathematical relation between the parameters it connects, in which the origin parameter is a variable in the equation that determines the destination parameter. The dotted arrows are simply a visual mechanism used to indicate that the same parameter used to calculate TCO(t=t) is also being used to calculate TCO(t=t-1). All parameters and their associations were already described in this section or on table 7.

Table 7 - New and/or modified parameters description in model used for price-varying simulations.

Parameter	**Description**
Time tracking	Assumes the value of current time-step *t*.
Price (t=t-1)	Assumes value of price at previous time-step.
Total Cost of Ownership (t=t-1)	Total cost of ownership at previous time-step.
Maximum PA	Maximum market calculated for current TCO(t) with minimum value of 39 million.
Maximum PA (t=t-1)	Maximum PA at previous time-step.
Increase in PA	Growth of maximum market at each time-step, greater or equal to 0.
Potential Adopters	$Potential\ Adopters\ (t) = M + \int_0^t (Increase\ in\ PA - Adoption\ rate\ )dt$

4. RESULTS

4.1. Baseline

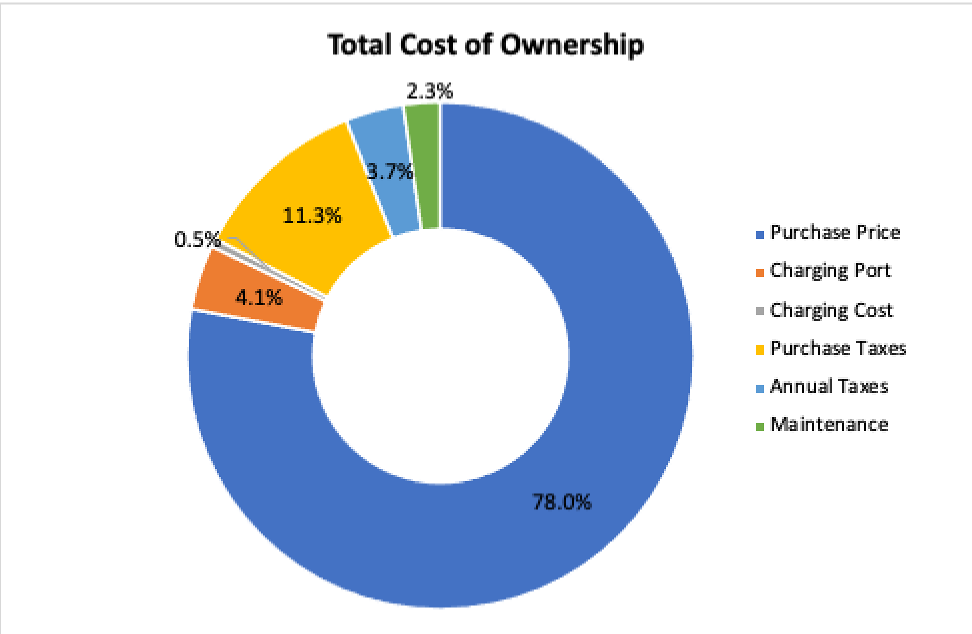
The baseline scenario is the simulation using only parameters found in literature and/or estimated, such as the ones in Table 8. Its main focus is the study of how EV technology diffusion will occur, given that everything stays the same or follows current trends, being also a benchmark to other scenarios applied in this research.

Table 8 - Parameters for baseline model.

	Input value
Potential Adopters	39 million
Yearly Tax Rate	1.59%
Purchase Tax Rate	14.5%
Price	R$ 187,895

In this case, both the Total Recharging Cost and Total Cost of Ownership are constant, assuming values of R$1,302.62 and R$241,006, respectively. Moreover, the TCO is distributed according to Figure 21.

Figure 21 - Total cost of ownership for Baseline, both in optimistic and pessimistic scenarios.



It is clear that the purchase price is the main source of expenditures by an EV owner. This result is aligned with the existing literature on the relationship between customers and Electric Vehicle, in which price remains the main barrier to adoption. The sum of purchase and annual taxes accounts for 15% of TCO, deemed as the second highest spendings. Thus, these three parameters will be further evaluated.

EVs require a high initial investment, as charging port installation costs and purchase price and taxes altogether sum up to 93.4% of total cost of ownership, the subsequent expenses have a much lower disbursement of approximately only R$ 4,800 per year. Indeed, charging costs represent 0.5% of total expenses and shows itself as an increasingly important aspect for consumers with recent trends of escalating fossil fuel prices in Brazil.

4.1.1. Optimistic

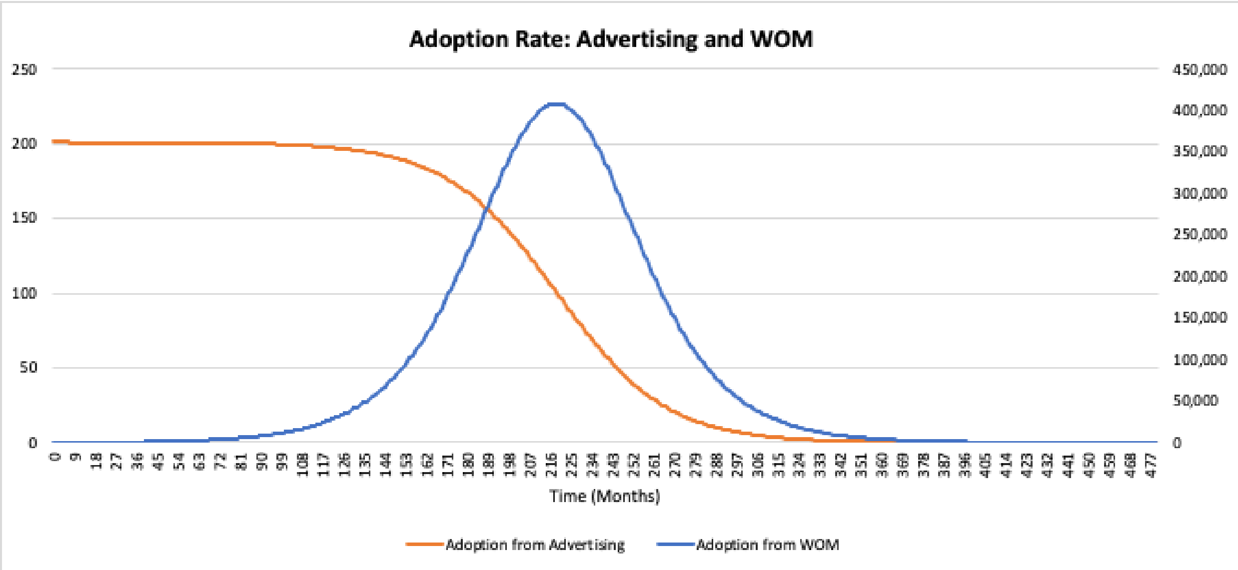
For the optimistic scenario with fixed TCO, the initial number of Potential Adopters and final number of Adopters are 39 million, as determined by the parameters input. However, it will achieve market maturity earlier than the pessimistic scenario.

Using the determined coefficients of innovation (p) and imitation (q), the behavior of adoption rates from advertising and word-of-mouth are described in Figure 22. Adoption from WOM is much higher than Adoption from Advertising, caused mainly due to the magnitude difference between *p* and *q*.

Exploring the Brazilian market, this conduct is expected as there is little to no investment in EVs publicity. The segment is still narrow in comparison to its Internal Combustion counterpart, thus companies are yet to get interested in heavily expanding advertising campaigns for electric models, as it would likely not generate enough ROI[1] levels. Nonetheless, there is a large opportunity for the private sector, as a higher value of p would further accelerate the diffusion of electric vehicles.

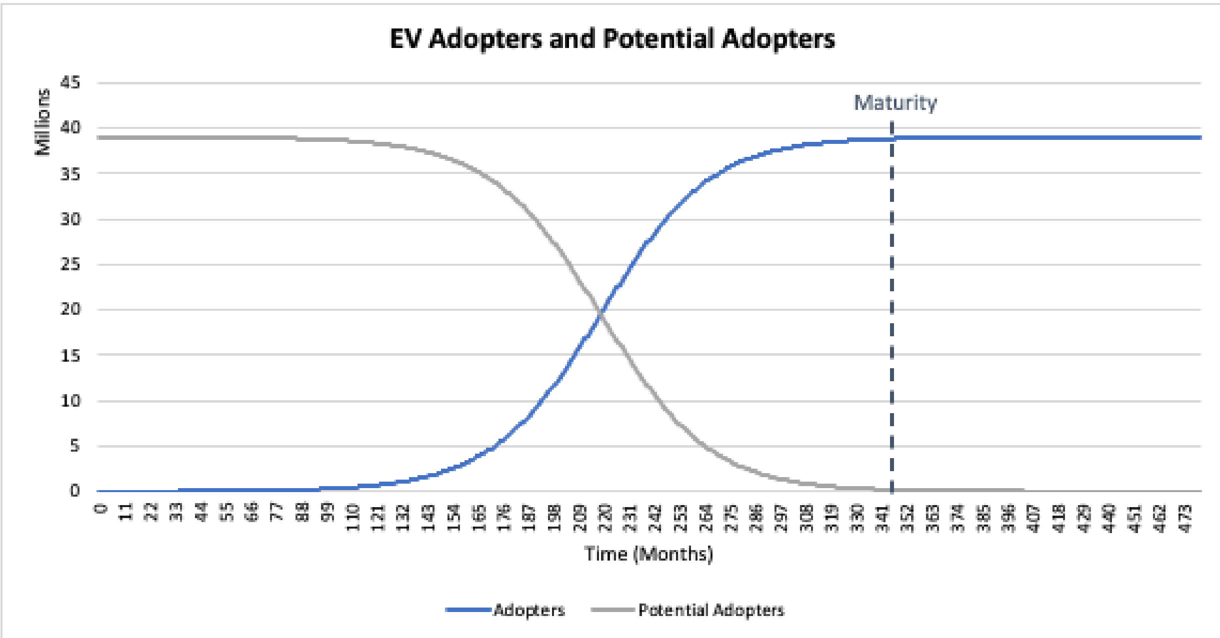
[1] Return on Investment = Net Investment Gain ÷ Cost of Investment

Figure 22 - Evolution of adoption rate for optimistic scenario broken down in advertising and word-of-mouth components.



Analyzing Figure 23, the EV market will reach maturity at t=348, or 2045, already 5 years earlier than forecasted by the Plano Nacional de Energia 2050.

Figure 23 - Evolution of EV Adopters and Potential Adopters in the optimistic scenario.



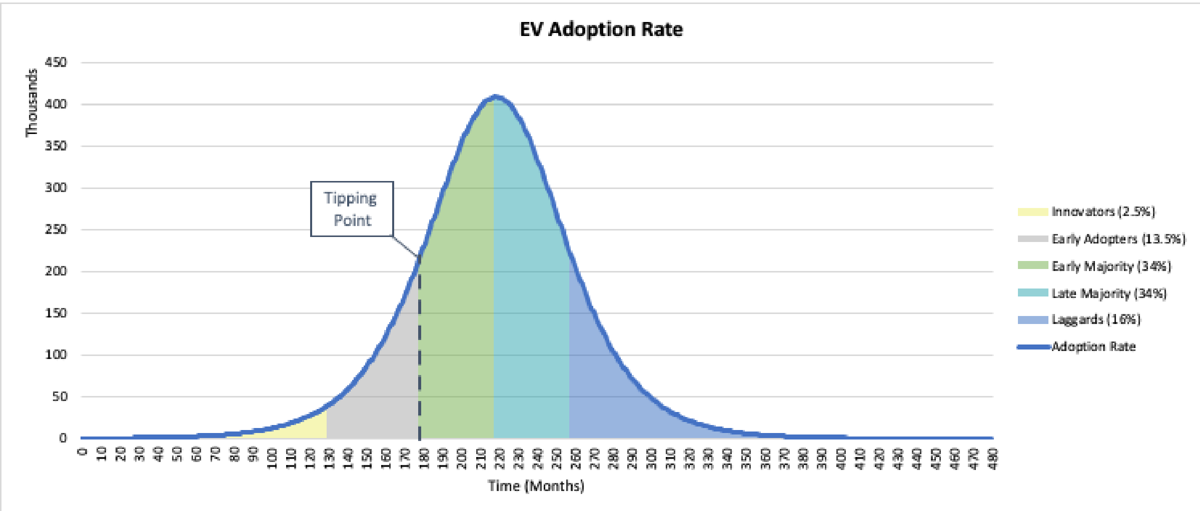
Adoption rate will peak, however, at 2034, as seen on Table 9.

Table 9 - Maximum values for adoption rate and its components.

	Highest Value	Time achieved	Year Achieved
Adoption Rate	408,323	219	2034
Adoption from Advertising	200.85	0	2016
Adoption from WOM	408,223	219	2034

Monitoring the evolution of the adoption, the innovation diffusion curve is produced, as seen on Figure 24.

Figure 24 - Innovation diffusion curve in optimistic scenario.



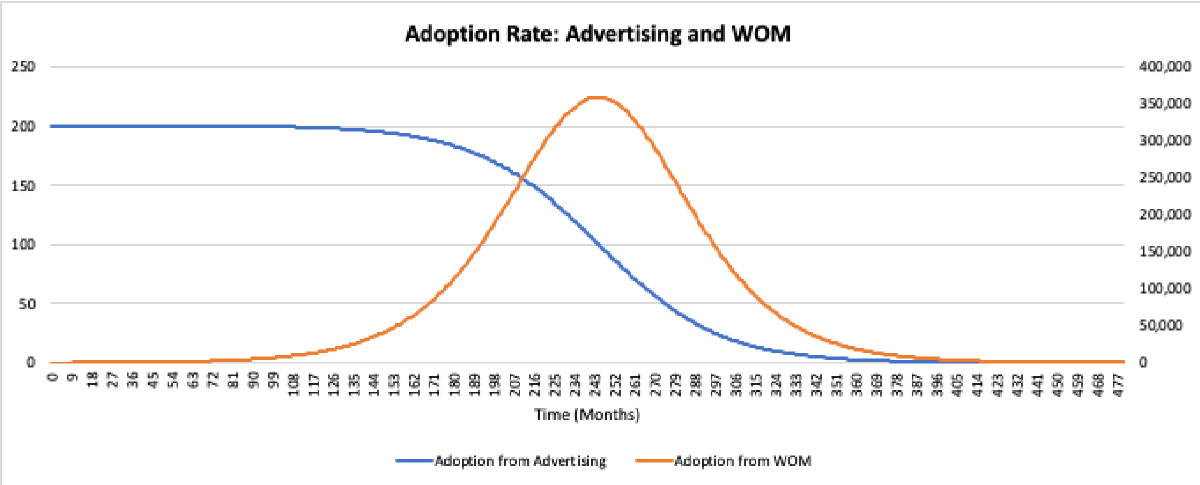
The transition from early adopters to early majority, known as the Tipping Point, happens at t=177 (September, 2030). Therefore, the most crucial moment in the diffusion of EVs will be the next 8 years, in which stakeholders of the segment must assume strategic actions in order to encourage the adoption of the technology by the two groups. After such a period, the sector will likely maintain its growth by withholding the generated momentum.

4.1.2. Pessimistic

In the pessimistic scenario, the initial number of Potential Adopters will also be 39 million. The difference to the optimistic scenario is the 12.1% lower coefficient of imitation.

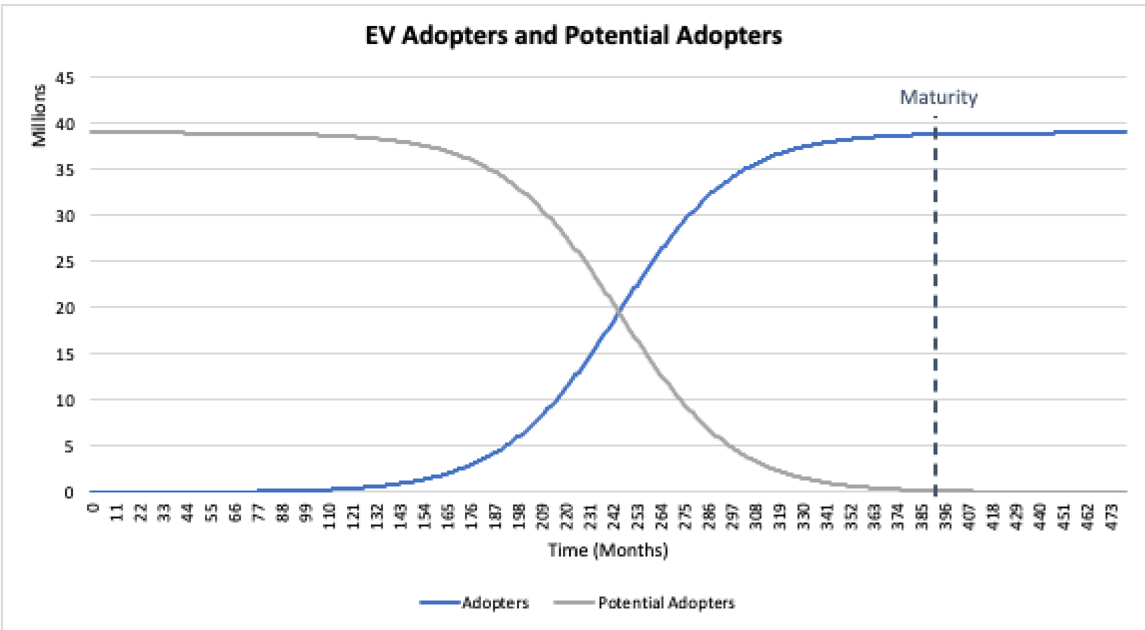
Similarly, adoption from word-of-mouth is even higher than adoption from advertising, as seen on Figure 25.

Figure 25 - Evolution of adoption rate for pessimistic scenario broken down in advertising and word-of-mouth components.



Once again, there is a great opportunity for the private sector to invest further in advertising and accelerate EVs diffusion. Even with such a low p coefficient, an analysis of figure 26 reveals the market will reach maturity at t=392, or 2048, still 2 years in advance than forecasted by the Plano Nacional de Energia 2050.

Figure 26 - Evolution of EV Adopters and Potential Adopters in pessimistic scenario.

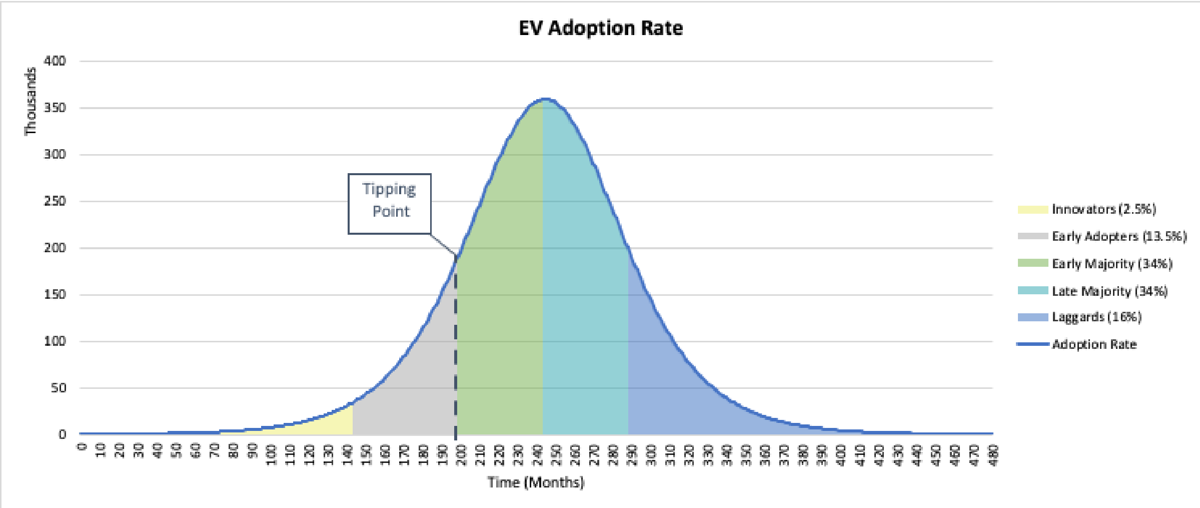


Studying the adoption rate, a peak is achieved at 2036 (t=245), both later and smaller than in the optimistic scenario. The maximum adoption from advertising remained the same, as both *Potential Adopters*$_{t=0}$ and p are unchanged.

Table 10 - Maximum values for adoption rate and its components.

	Highest Value	Time achieved	Year Achieved
Adoption Rate	359,021	245	2036
Adoption from Advertising	200.85	0	2016
Adoption from WOM	358,921	245	2036

Figure 27 - Innovation diffusion curve in pessimistic scenario.



From the innovation diffusion curve (Figure 27), the *Tipping Point* happens in July 2032 (t=199), 22 months after the optimistic scenario. With a slower adoption rate, stakeholders have a 10-years period to engage the EVs segment and create momentum for the new technology to spread amongst potential adopters.

4.2. Varying Cost of Ownership

To further investigate the market behavior, a variation of the Total Cost of Ownership will be applied to the model. Since price and taxes (annual and purchase) represent the highest fraction of the baseline TCO and are also the easiest parameters to be modified by the public and private sector, a study will be carried out on each.

4.2.1. Price

The modified model was inputted with the parameters described on table 11, already previously obtained.

Table 11 - Parameters inputted for price variation model.

	Input value
Potential Adopters	Equation (3)
Yearly Tax Rate	1.59%
Purchase Tax Rate	14.5%
Price	Equation (12)

Total Recharging Cost remained unchanged at R$1,302.62. The price varies at each time-step *t*, which affects purchase and yearly taxes, as well as TCO and its distribution. Figures 28 and 29 describe the behavior of such parameters.

Figure 28 - Absolute evolution of TCO, Price and Taxes in price-varying model.

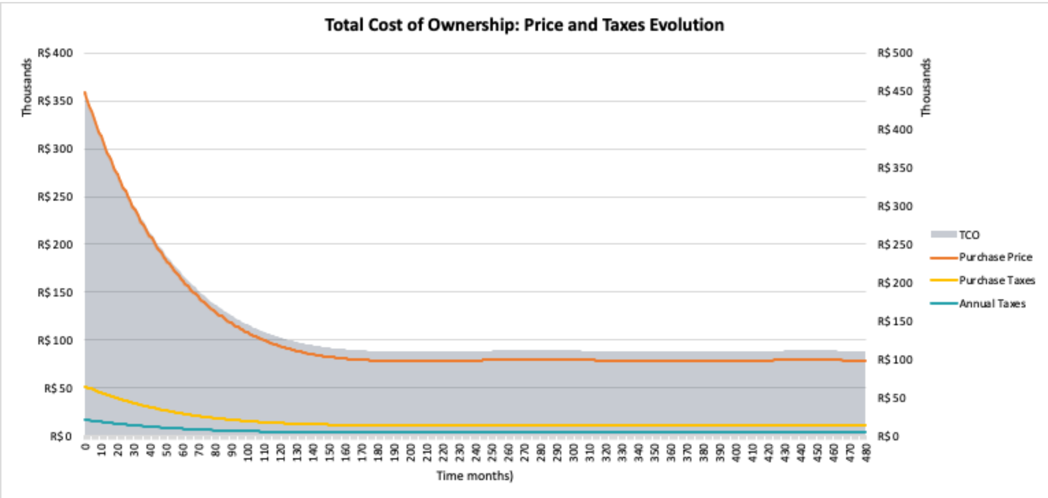
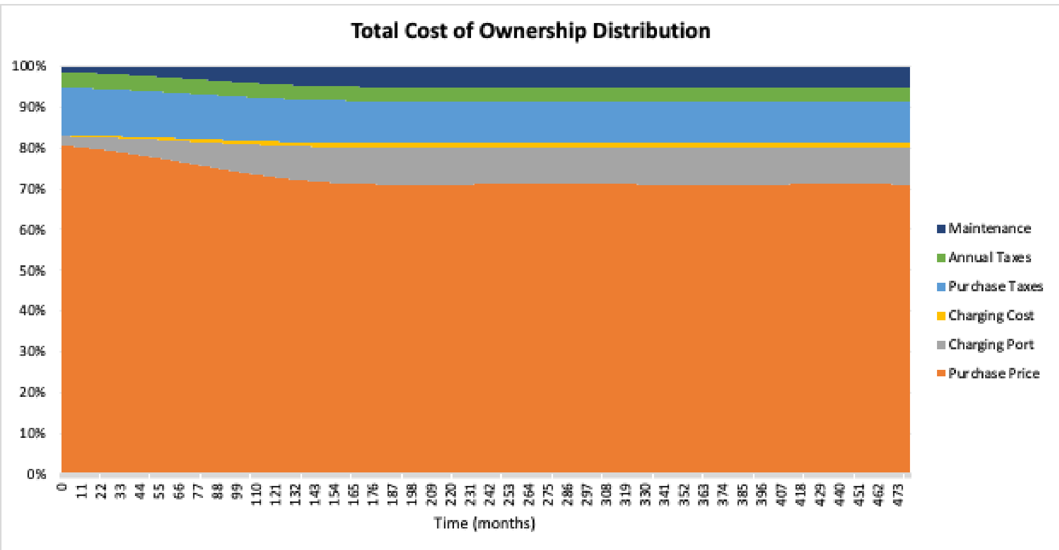
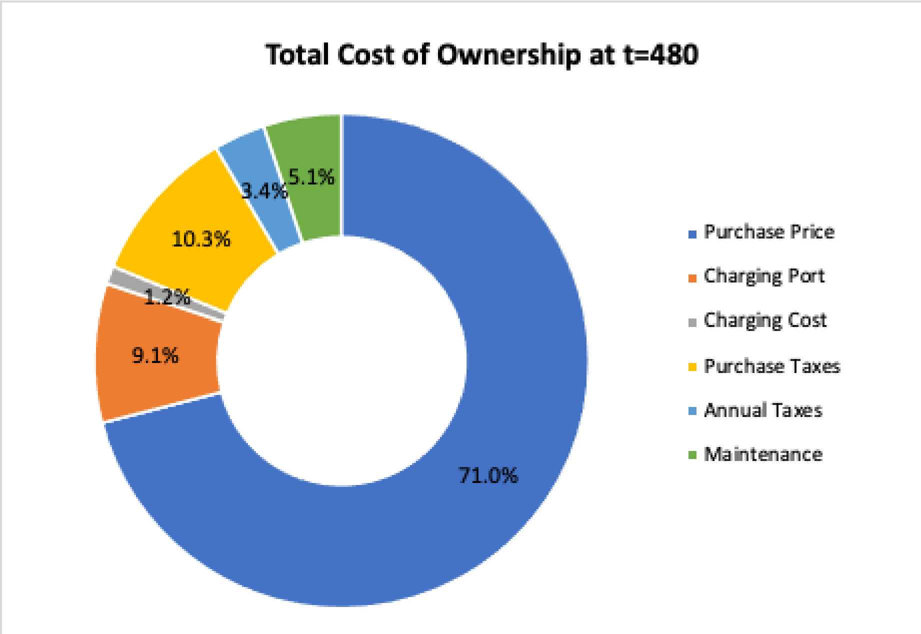


Figure 29 - Relative evolution of TCO distribution in price-varying model.



Price will stabilize near R$79,000 at around t=180. Final distribution of TCO (at t=480) is described in figure 30.

Figure 30 - TCO distribution at last time-step in price-varying model.



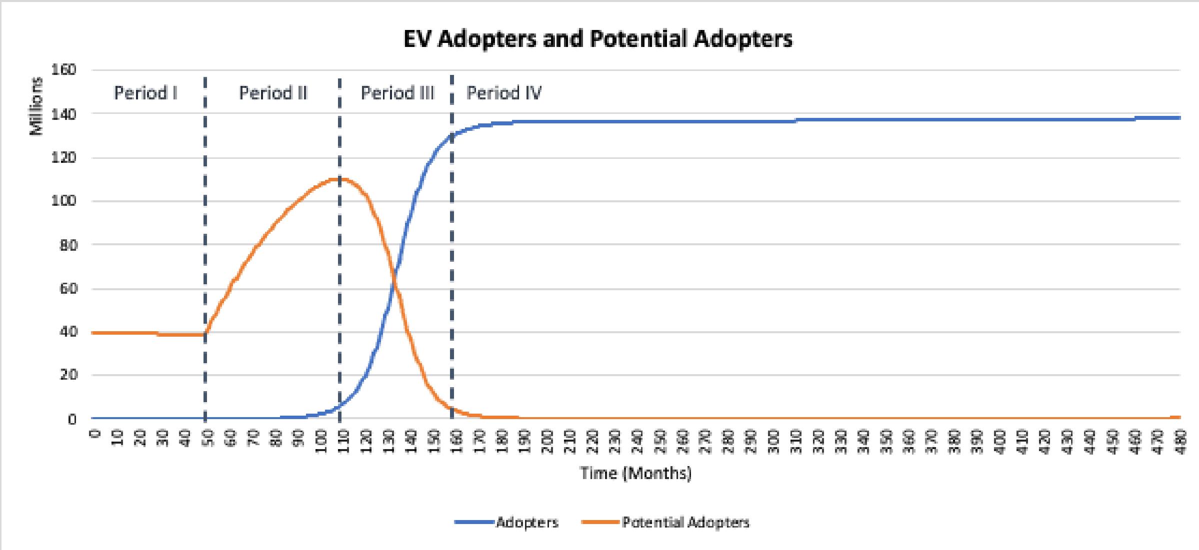
Even though the final Total Cost of Ownership (R$110,000) had a 54.4% decrease in comparison to baseline, price's representation dropped only 7 percentage points. This happened due to the parameter's magnitude: a decrease in price will provoke an almost equal absolute decrease in TCO, thus changing little the relative distribution.

Nonetheless, inputs related to price (purchase and annual taxes) lost share, while unrelated parameters elevated theirs (despite unchanged absolute values).

4.2.1.1. Optimistic

The innovation and advertising coefficients are equal to the baseline, therefore adoption from word-of-mouth remains more significant than adoption from advertising. The main difference in the price-varying scenario will be the behavior of Potential Adopters: since TCO is decreasing, the pool of Potential Adopters is expanding simultaneously to its reduction due to conversion to Adopters.

Figure 31 - Evolution of EV Adopters and Potential Adopters in optimistic price-varying scenario.



Analyzing Figure 31, four distinct periods can be determined based on the model's evolution.

Table 12 - Phases of Potential Adopters' evolution in price-varying model.

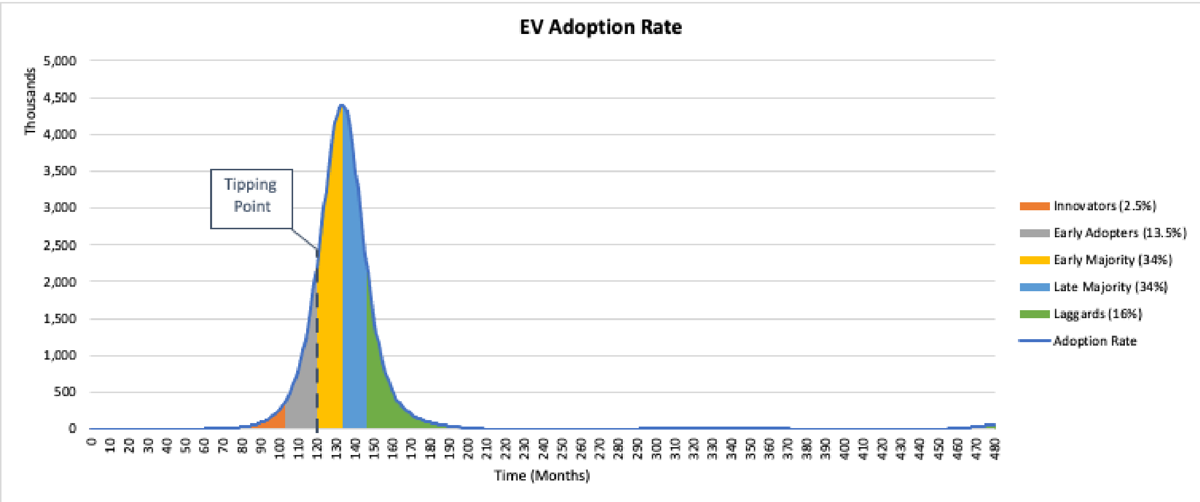
Period	Time Interval	Characteristics
I	t < 49	Pool of potential adopters is unchanged and fixed at 39 million (minimum PA adopted in model). Adoption rate is small and causes an imperceptible decrease in PA(t).
II	49 ≤ t ≤ 109	Pool of potential adopters starts to expand due to TCO decrease. Expansion of the pool is greater than adoption rate, thus causing an increase in PA(t) until peak value (110,155,000).
III	109 < t ≤ 160	Absolute value of expansion is lesser than the adoption rate. PA(t) will start to decrease.
IV	t > 158	Market has reached maturity.

Due to the increase in PA, adoption rate will escalate and diffusion of EVs will be accelerated, as seen on Table 12. Indeed, Figure 31 explicits market maturity at t=158 (2029), much earlier than the baseline, with a value of Total Adopters of around 138 million. Such a number exceeds even the total vehicle fleet forecast for 2050, which can be explained by the sharp decrease in acquisition costs for EVs. This scenario, however, is extremely unlikely, and the model may be overestimating the prices' decrease.

Table 13 - Maximum values for adoption rate and its components.

	Highest Value	Time achieved	Year Achieved
Adoption Rate	4,402,650	134	2027
Adoption from Advertising	567.30	109	2025
Adoption from WOM	4,402,340	134	2027

Figure 32 - Evolution of EV Adopters and Potential Adopters in optimistic price-varying scenario.

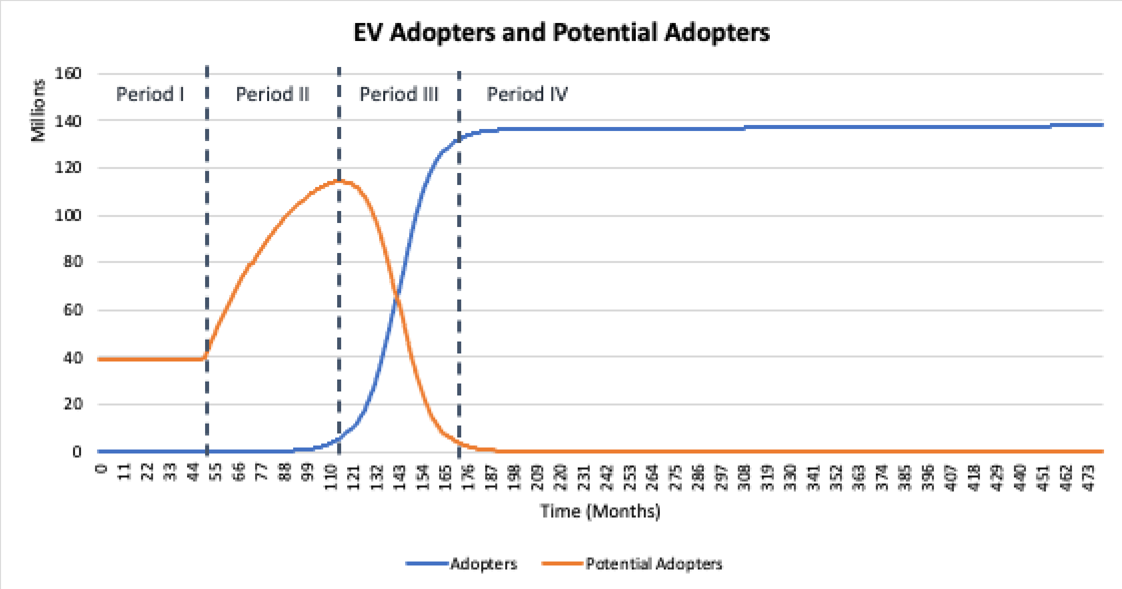


Tracing the innovation diffusion curve (figure 32), the *Tipping Point* for the optimistic price-varying scenario happens at t=121, or October 2026. As adoption rate has a higher peak and the market maturity is reached earlier, the curve is much sharper and narrower than the one obtained at the baseline.

4.2.1.2. Pessimistic

For the pessimistic scenario, it is expected similar numbers of maximum potential adopters at the final time-step of the model, but an achievement of such value at a lower speed. Figure 33 describes the evolution of Potential Adopters.

Figure 33 - Evolution of EV Adopters and Potential Adopters in pessimistic price-varying scenario.



Similarly, the four periods based on the model's behavior are well-defined, and can be seen on Table 14.

Table 14. Phases of Potential Adopters' evolution in price-varying model.

Period	Time Interval	Characteristics
I	t < 49	Pool of potential adopters is unchanged and fixed at 39 million (minimum PA adopted in model). Adoption rate is small and causes an imperceptible decrease in PA(t).
II	49 ≤ t ≤ 115	Pool of potential adopters starts to expand due to TCO decrease. Expansion of the pool is greater than adoption rate, thus causing an increase in PA(t) until peak value (112,248,000).
III	115 < t ≤ 170	Absolute value of expansion is lesser than the adoption rate. PA(t) will start to decrease.
IV	t > 170	Market has reached maturity.

In comparison to the optimistic scenario, Period I has the same length since it depends only on the Maximum PA, equal over time to both cases. Periods II and III are longer as the adoption rate is smaller. The peak value for PA(t), on the other hand, is higher in the pessimistic scenario: since the adoption rate is smaller, the pool expansion is able to counterbalance the conversion and further elevate PA(t).

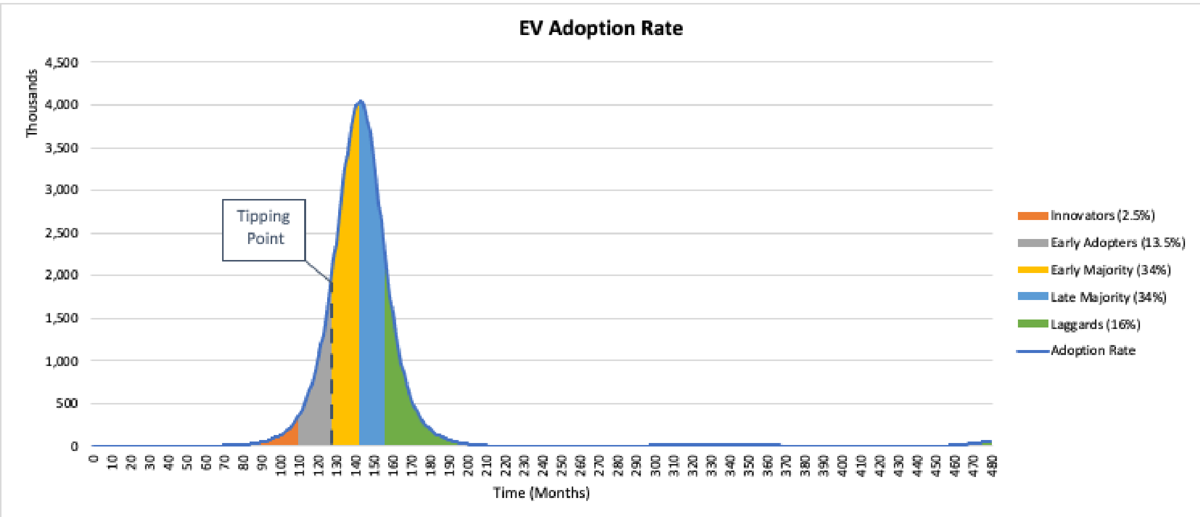
Market maturity is reached at t=170, or 2030, approximately 20 years earlier than the baseline and 1 year after the optimistic scenario. At the last time-step, Total Adopters are 138 million, also greater than the forecasted vehicle fleet of 2020.

Table 15 - Maximum values for adoption rate and its components.

	Highest Value	Time achieved	Year Achieved
Adoption Rate	4,045,590	143	2027
Adoption from Advertising	588.38	115	2025
Adoption from WOM	4,045,260	143	2027

The peak values for adoption rate are achieved in the same year for both scenarios, but a few months delayed in the pessimistic. Tracing the innovation diffusion curve (figure 34), the *Tipping Point* happens at t=127 (July, 2026), 6 months later.

Figure 34 - Evolution of EV Adopters and Potential Adopters in pessimistic price-varying scenario.



4.2.2. Yearly Tax Rate

The modified Yearly Tax Rate (YTR) variation model was inputted with the parameters described on Table 16, either previously obtained or arbitrarily determined.

Table 16 - Parameters inputted for YTR variation model.

	Case I (50% YT)	Case II (0% YT)
Potential Adopters	42,351,200[1]	45,702,900[1]
Yearly Tax Rate	0.795%	0%
Purchase Tax Rate	14.5%	14.5%
Price	R$ 187,895	R$ 187,895

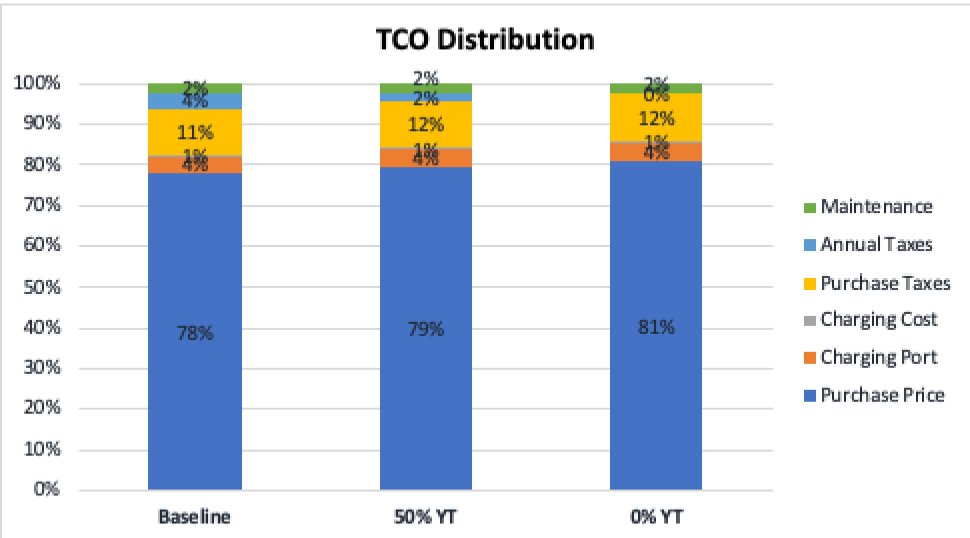
[1]Calculated based on equation (3).

Total Recharging Cost remained unchanged at R$1,302.62. Total Cost of Ownership is constant throughout each case, valued and distributed according to Table 17 and Figure 35.

Table 17 - Absolute TCO for YTR variation model.

	Baseline	50% YT	0% YT
Total Cost of Ownership	R$ 241,006	R$ 236,525	R$ 232,044
Variation	-	-1.9%	-3.7%

Figure 35 - TCO distribution for YTR variation model.

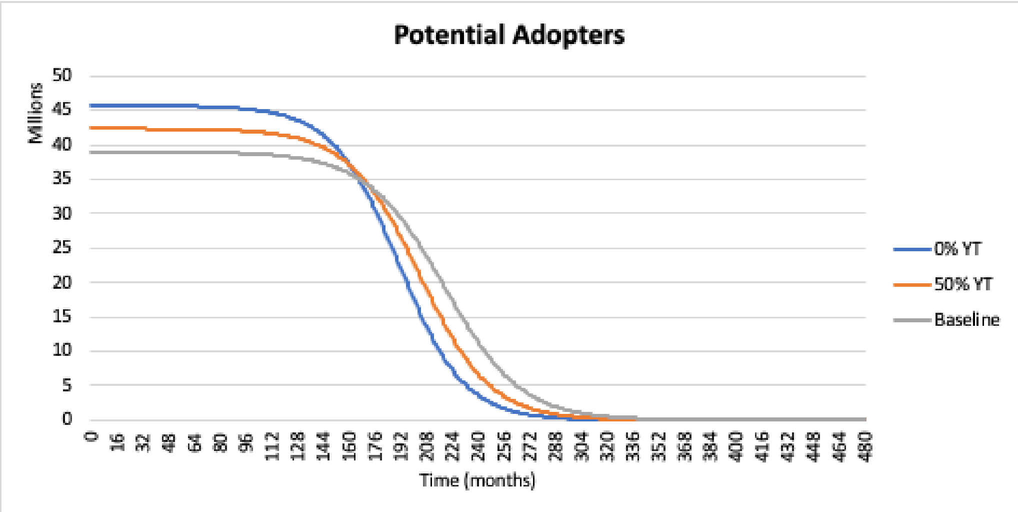


As expected, a decrease in yearly taxes increased the TCO share of all other parameters, more significantly in those with a previously already great representativeness (*e.g.* price, purchase taxes).

4.2.2.1. Optimistic

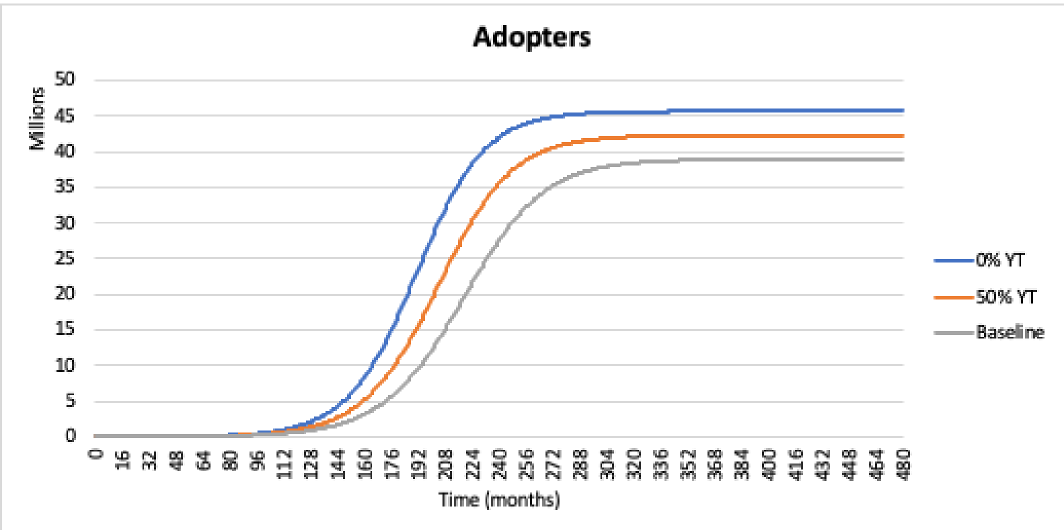
As in the price-varying model, both optimistic and pessimistic scenarios will have a coefficient of imitation (*q*) greater than the coefficient of innovation (*p*), causing adoption from word-of-mouth to prevail. A deduction of Yearly Taxes and consequently of TCO generated an increase in Potential Adopters and an acceleration of EV's diffusion, as noticeable in Figure 36.

Figure 36 - Evolution of Potential Adopters for optimistic YTR variation model.



Analyzing Figure 37, market maturity is reached earlier than in the baseline scenario, at t=280 (2039) and t=265 (2037) for 50% and 0% YT, respectively. Such evolution represents a 6 and 8 years anticipation in comparison to the baseline and an advancement of 32-35% of fleet share as for Plano Nacional de Energia 2050's forecast.

Figure 37 - Evolution of Adopters for optimistic YTR variation model.



Adoption rate curve is sharper with smaller TCOs, peaking at higher values than the baseline, as seen in Figure 38 and Table 18.

Figure 38 - Evolution of Adopters for YTR optimistic variation model.

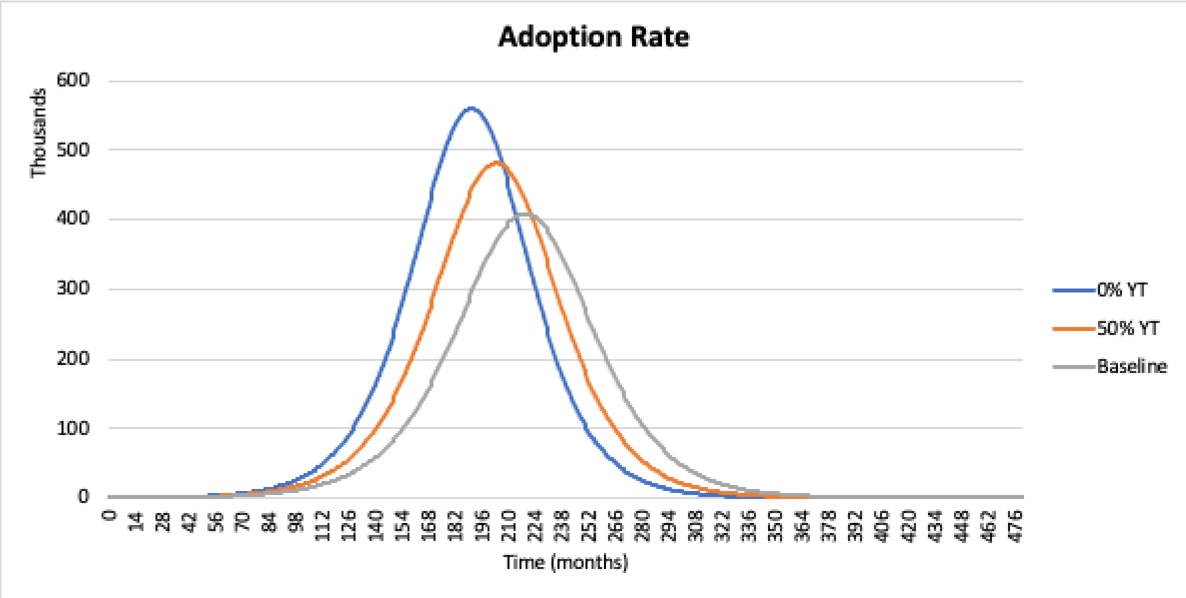


Table 18 - Maximum values for adoption rate and its components in optimistic YTR variation model.

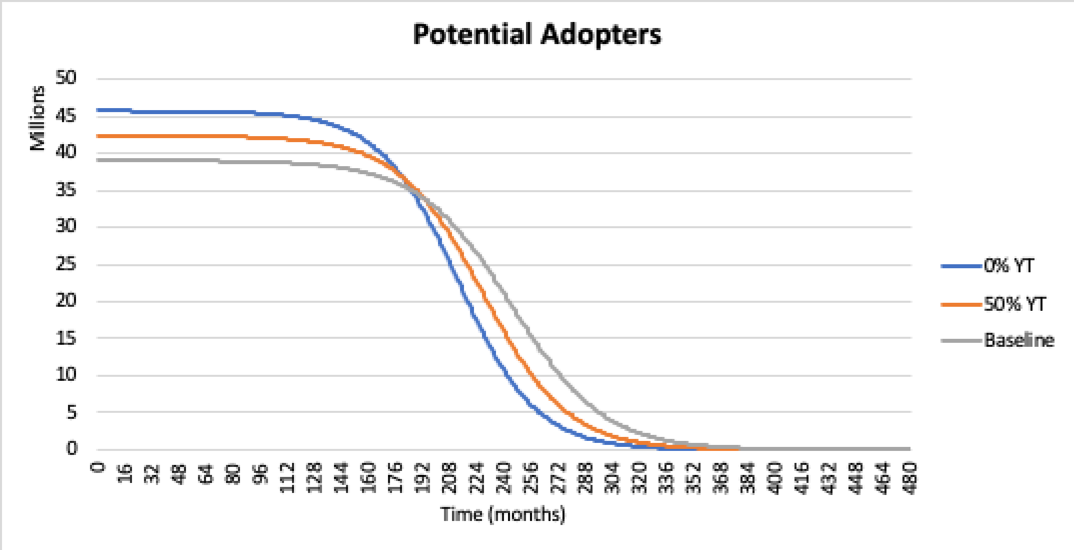
	50% YT			0% YT		
	Highest Value	**Time achieved**	**Year Achieved**	**Highest Value**	**Time achieved**	**Year Achieved**
Adoption Rate	481,489	204	2033	560,683	191	2031
Adoption from Advertising	218	0	2016	235	0	2016
Adoption from WOM	481,381	204	2033	560,566	191	2031

The *Tipping Points* are September, 2029 and November, 2028 for 50% and 0% YT, respectively. This is an anticipation of only 1 and 2 years in regards to the baseline, meaning that a deduction of Yearly Tax Rate in the next few years would not greatly impact EV diffusion in the short-term.

4.2.2.2. Pessimistic

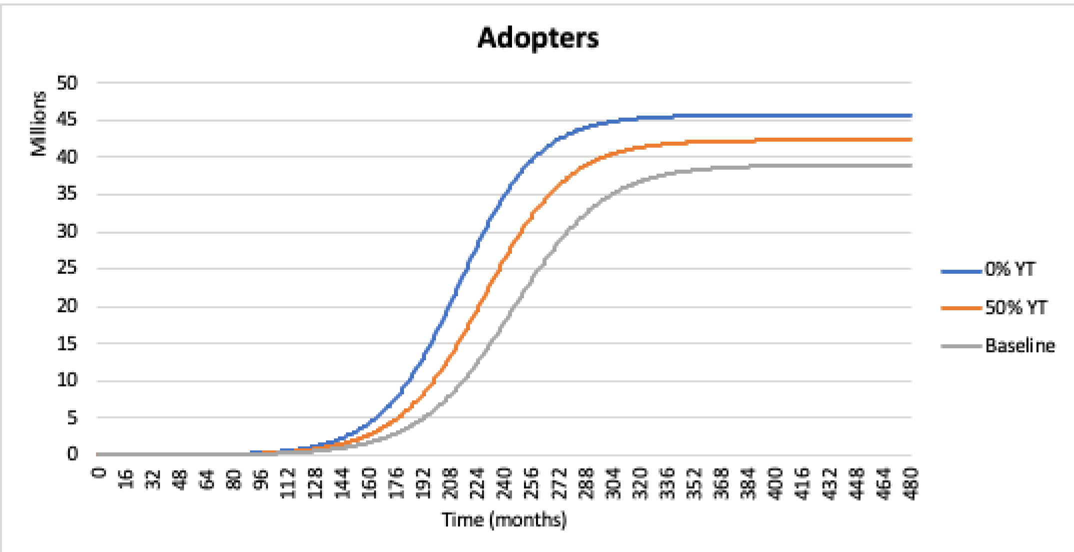
The YTR variation model's pessimistic scenario behaves almost identically to the optimistic one, except slower. However, the differences to the baseline are the same, as the pessimistic baseline scenario also progresses slower than its optimistic counterpart. Figure 39 explicits this difference.

Figure 39 - Evolution of potential adopters for pessimistic YTR variation model.



According to the evolution of adopters (Figure 39), market maturity is reached 6 and 8 years earlier in comparison to the baseline, at t=315 (2042) and t=290 (2040), after which the fleet share of EVs will near 33% and 35% (assuming previously stated total vehicle fleet number forecasted by the PNE 2050).

Figure 39 - Evolution of adopters for pessimistic YTR variation model.



Adoption rate (AR) will be inversely proportional to tax deduction, with 0% YT being the fastest scenario (Figure 40). Table 19 explicits the higher values for its peak AR.

Figure 40 - Evolution of adoption rate for pessimistic YTR variation model.

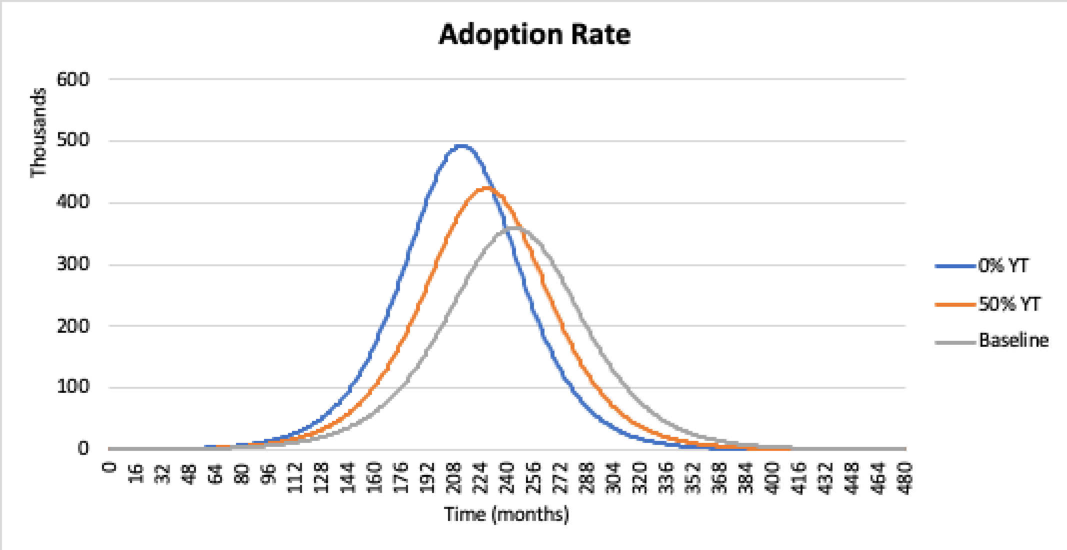


Table 19 - Maximum values for adoption rate and its components in pessimistic YTR variation model.

	50% YT			0% YT		
	Highest Value	**Time achieved**	**Year Achieved**	**Highest Value**	**Time achieved**	**Year Achieved**
Adoption Rate	423,374	228	2035	493,031	213	2033
Adoption from Advertising	218	0	2016	235	0	2016
Adoption from WOM	423,266	228	2035	492,913	213	2033

Tipping Points are May 2031 and 2030 for 50% and 0% YT, respectively, only 2 and 1 years before the baseline. Thus, also in the pessimistic scenario a deduction of Yearly Tax Rate in the next few years would not greatly impact EV diffusion in the short-term.

4.2.3. Purchase Tax Rate

The modified Purchase Tax Rate (PTR) variation model was inputted with the following parameters previously obtained:

Table 20 - Parameters inputted for PTR variation model.

	Case III (50% PT)	Case IV (0% YT)
Potential Adopters	49,188,700[1]	59,377,600[1]
Yearly Tax Rate	1.59%	1.59%
Purchase Tax Rate	7.25%	0%
Price	R$ 187,895	R$ 187,895

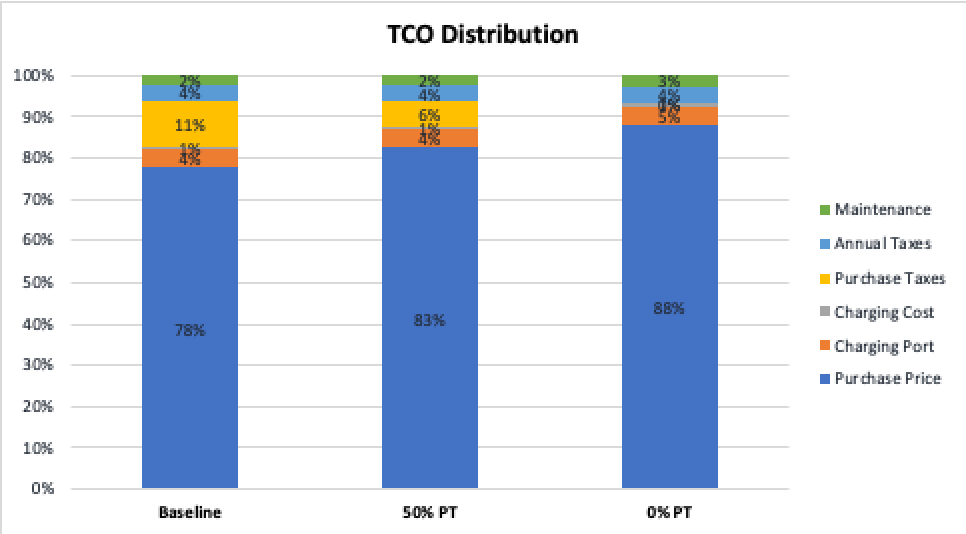
[1]Calculated based on equation (3).

As the varied data affects only a portion of TCO, Total Recharging Cost remained unchanged at R$1,302.62. Total cost of ownership is constant throughout each individual case, valued and distributed according to Table 21 and Figure 41:

Table 21 - Absolute TCO for PTR variation model.

	Baseline	**50% PT**	**0% PT**
Total Cost of Ownership	R$ 241,006	R$ 227,383	R$ 213,760
Variation	-	-5.7%	-11.3%

Figure 41 - TCO distribution for PTR variation model.

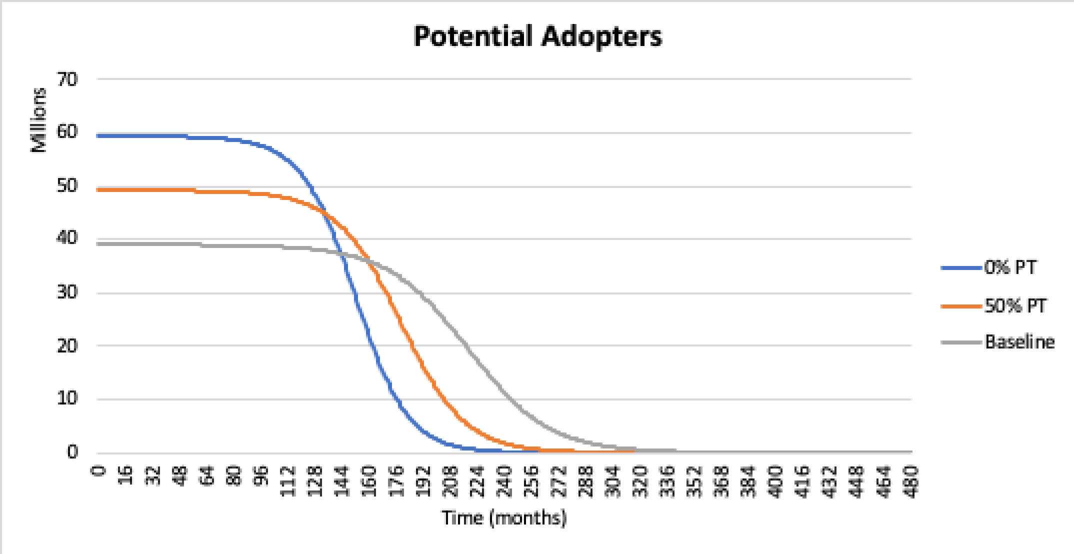


Since purchase taxes represented 11.3% of the baseline TCO against annual taxes' 3.7%, the decrease in value is comparatively greater and causes an escalation of price to almost 90% of ownership expenses at tax elimination (0% PT).

4.2.3.1. Optimistic

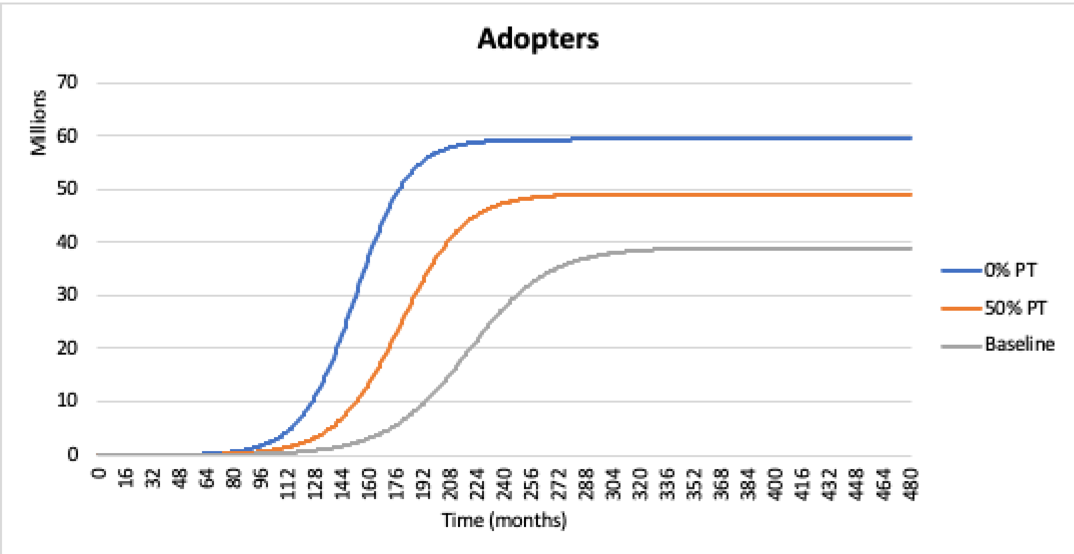
In the Purchase Tax Rate (PTR) variation model, potential adopters are much higher than in the YTR counterpart. Indeed, since purchase taxes have a greater TCO share, the consequent impact of its deduction is an even more noticeable distinction between baseline, 0% PT and 50% PT, as seen on Figure 42.

Figure 42 - Evolution of potential adopters for optimistic PTR variation model.



Analyzing the adopter's evolution curve, EV diffusion reaches maturity in 2037 (50% PT, t=253) and 2033 (0% PT, t=215), a 8 and 12 years difference to baseline forecast. The stabilized fleet share of EVs is around 37.8% and 45.7% for cases III and IV, respectively, over 5 percentage points greater than the YTR optimistic scenarios.

Figure 43 - Evolution of adopters for optimistic PTR variation model.

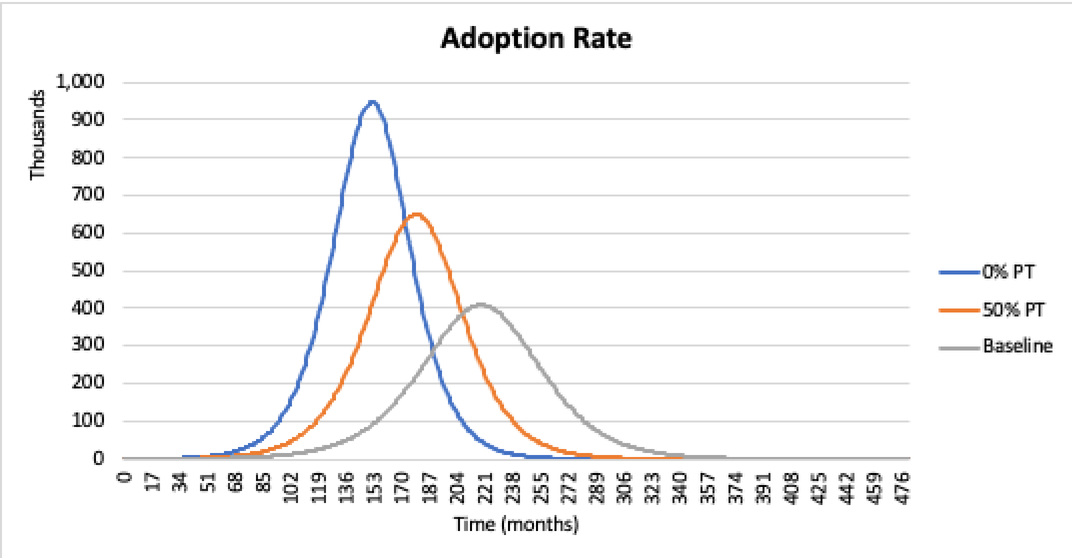


The innovation curve is even sharper due to increased Potential Adopters, TCOs, peaking at over 900 thousand and 600 thousand new adopters/month, as seen on Table 22.

Table 22 - Maximum values for adoption rate and its components in optimistic PTR variation model.

	50% PT			0% YT		
	Highest Value	**Time achieved**	**Year Achieved**	**Highest Value**	**Time achieved**	**Year Achieved**
Adoption Rate	649,510	179	2030	946,431	152	2028
Adoption from Advertising	253	0	2016	306	0	2016
Adoption from WOM	649,384	179	2030	946,279	152	2028

Figure 44 - Evolution of adoption rate for optimistic PTR variation model.

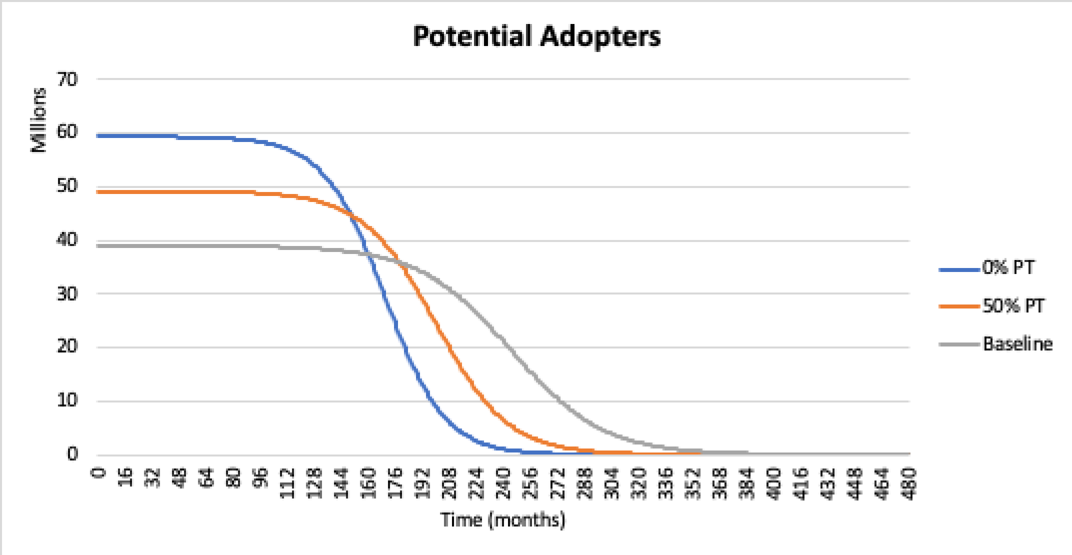


According to Figure 44, the *tipping points* are at t=124 (April, 2026) and t=146 (February, 2028), 4 and 2 years earlier than the baseline for 0% PT and 50% PT, respectively. Therefore, a purchase tax rate has a greater impact in creating momentum for the EVs' market in Brazil, and can be a good strategy to leverage adoption of the technology, specially when taking into account the final EVs' fleet share obtained.

4.2.3.2. Pessimistic

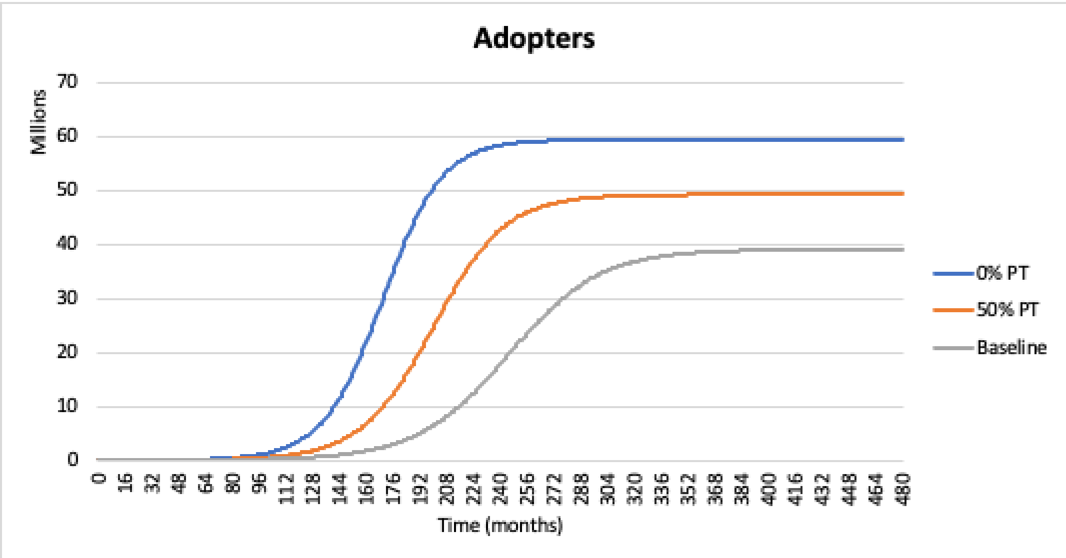
As expected, the pessimistic Purchase Tax Rate (PTR) variation model yields a more accelerated and dramatic behavior in comparison to the YTR variation and baseline models, yet it falls short when set side by side with its optimistic PTR counterpart. Figure 45 describes the resulting Potential Adopters evolution curve.

Figure 45. Evolution of potential adopters for pessimistic PTR variation model.



Initial potential adopters is the same as the optimistic scenario, but the S-curve stretches further in the time axis, as seen also in Figure 45. Market maturity will be reached in 2039 (t=278) and 2036 (t=2036) for 50% and 0% PT respectively, after which the EV fleet share will near 37.8% and 45.7%.

Figure 45 - Evolution of adopters for pessimistic PTR variation model.

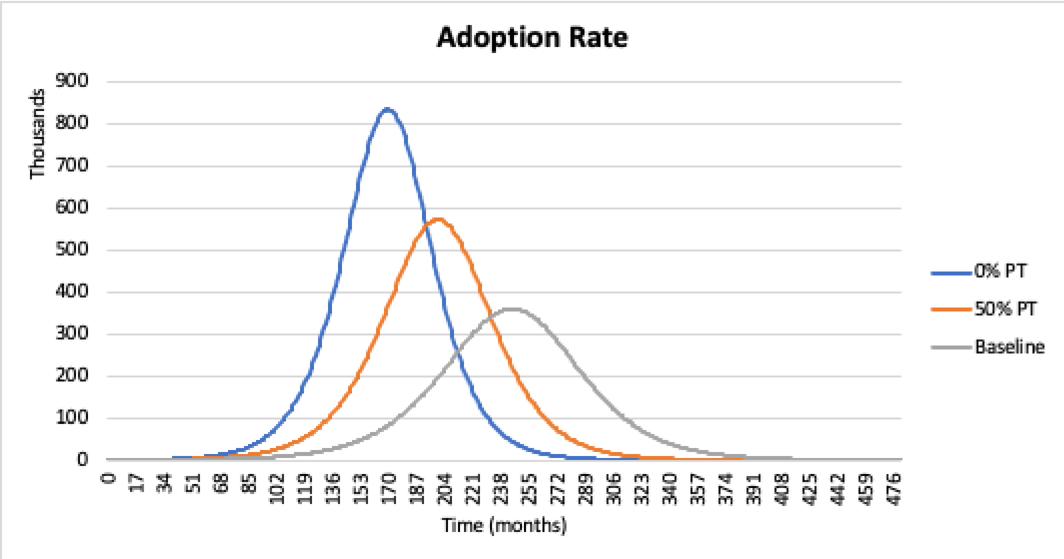


The innovation curve is even sharper than the baseline and YTR variation model, but smaller than the optimistic scenario, peaking at 832 thousand and 571 thousand new adopters/month, as seen on Table 23.

Table 23 - Maximum values for adoption rate and its components in optimistic PTR variation model.

	50% PT			0% YT		
	Highest Value	Time achieved	Year Achieved	Highest Value	Time achieved	Year Achieved
Adoption Rate	571,103	200	2032	832,138	170	2030
Adoption from Advertising	253	0	2016	306	0	2016
Adoption from WOM	570,977	200	2032	831,986	170	2030

Figure 46 - Evolution of adoption rate for pessimistic PTR variation model.



Analyzing the adoption rate curve (Figure 46), the *tipping points* are in June 2029 (t=162) and June 2027 (t=138) for 50% and 0% PT, respectively. Compared to the baseline, it represents a 3 and 5 years anticipation. In such a way, deduction of purchase taxes is a good strategy to boost EV adoption in the short-term even in a pessimistic scenario.

4.2.4. Government Incentives

The influence of TCO reduction on the output of the model has already been studied in the other scenarios. By combining a decrease in both tax rates, the main outcome of the model is a deeper understanding of how much the public sector (both state and federal governments) can boost EV adoption and diffusion with direct, straightforward measures. Table 24 and Figures 47-48 depict the total number of potential adopters and adopter's evolution curve for all combinations in both scenarios.

Table 24 - Potential adopters for different Yearly and Purchase Tax Rates combinations.

Potential Adopters (in thousands)		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	39,521	40,785	42,050	43,315	44,580	45,845
	70%	42,050	43,315	47,109	45,845	47,109	48,374
	60%	44,580	45,845	49,639	48,374	49,639	50,904
	50%	47,109	48,374	52,169	50,904	52,169	53,433
	40%	49,639	50,904	54,698	53,433	54,698	55,963
	30%	52,169	53,433	57,228	55,963	57,228	58,493
	20%	54,698	55,963	59,757	58,493	59,757	61,022
	10%	57,228	58,493	62,287	61,022	62,287	63,552
	0%	59,757	61,022	62,287	63,552	64,817	66,081

Figure 47 - Evolution of adopters for pessimistic scenario.

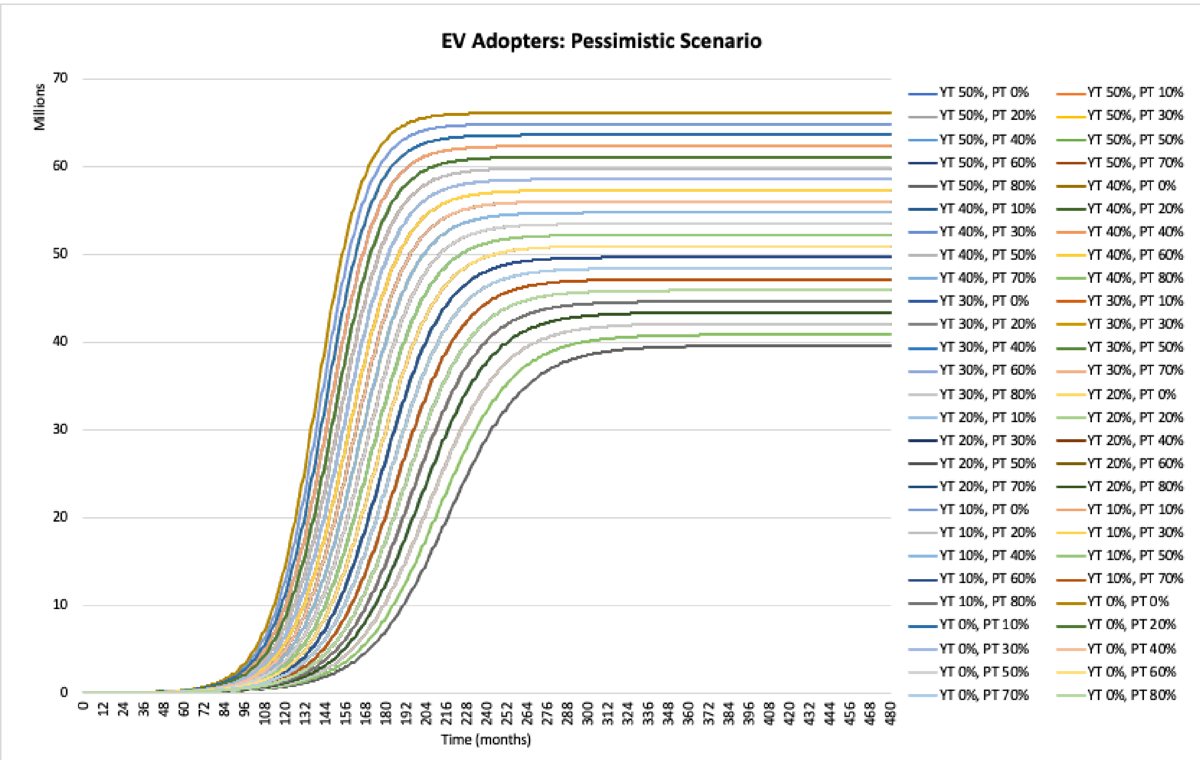
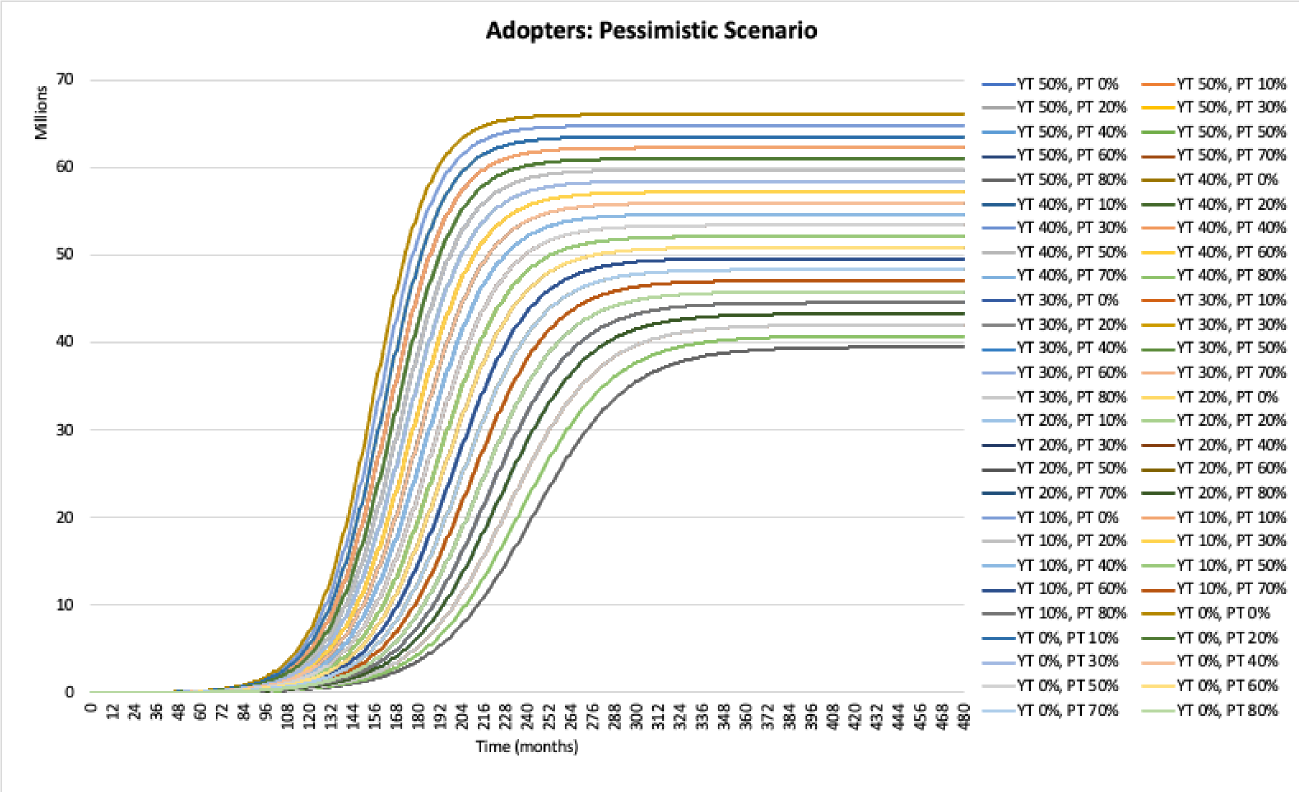


Figure 48 - Evolution of adopters for pessimistic scenario.



Comparing the Adoptor's curves, the pessimistic scenario is slightly delayed. However, since TCO is smaller than the baseline for all combinations, every government incentive in both scenarios surpasses the PNE 2050 forecast of 39 million adopters in 2050, as seen in Tables 25 and 26.

Table 25 - Model output for Yearly and Purchase Tax Rates combinations in optimistic scenario.

Optimistic Scenario							
Year at which Adopters surpasses 39M		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	2042	2039	2037	2036	2035	2034
	70%	2037	2036	2035	2034	2034	2033
	60%	2035	2034	2034	2033	2032	2032
	50%	2034	2033	2032	2032	2031	2031
	40%	2032	2032	2031	2031	2030	2030
	30%	2031	2031	2030	2030	2030	2029
	20%	2030	2030	2030	2029	2029	2029
	10%	2030	2029	2029	2029	2028	2028
	0%	2029	2029	2028	2028	2028	2028

EVs' fleet share in December/2050		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	30.4%	31.4%	32.3%	33.3%	34.3%	35.3%
	70%	32.3%	33.3%	34.3%	35.3%	36.2%	37.2%
	60%	34.3%	35.3%	36.2%	37.2%	38.2%	39.2%
	50%	36.2%	37.2%	38.2%	39.2%	40.1%	41.1%
	40%	38.2%	39.2%	40.1%	41.1%	42.1%	43.0%
	30%	40.1%	41.1%	42.1%	43.0%	44.0%	45.0%
	20%	42.1%	43.0%	44.0%	45.0%	46.0%	46.9%
	10%	44.0%	45.0%	46.0%	46.9%	47.9%	48.9%
	0%	46.0%	46.9%	47.9%	48.9%	49.9%	50.8%

PNE Overshooting		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	1.3%	4.6%	7.8%	11.1%	14.3%	17.5%
	70%	7.8%	11.1%	14.3%	17.5%	20.8%	24.0%
	60%	14.3%	17.5%	20.8%	24.0%	27.3%	30.5%
	50%	20.8%	24.0%	27.3%	30.5%	33.8%	37.0%
	40%	27.3%	30.5%	33.8%	37.0%	40.3%	43.5%
	30%	33.8%	37.0%	40.3%	43.5%	46.7%	50.0%
	20%	40.3%	43.5%	46.7%	50.0%	53.2%	56.5%
	10%	46.7%	50.0%	53.2%	56.5%	59.7%	63.0%
	0%	53.2%	56.5%	59.7%	63.0%	66.2%	69.4%

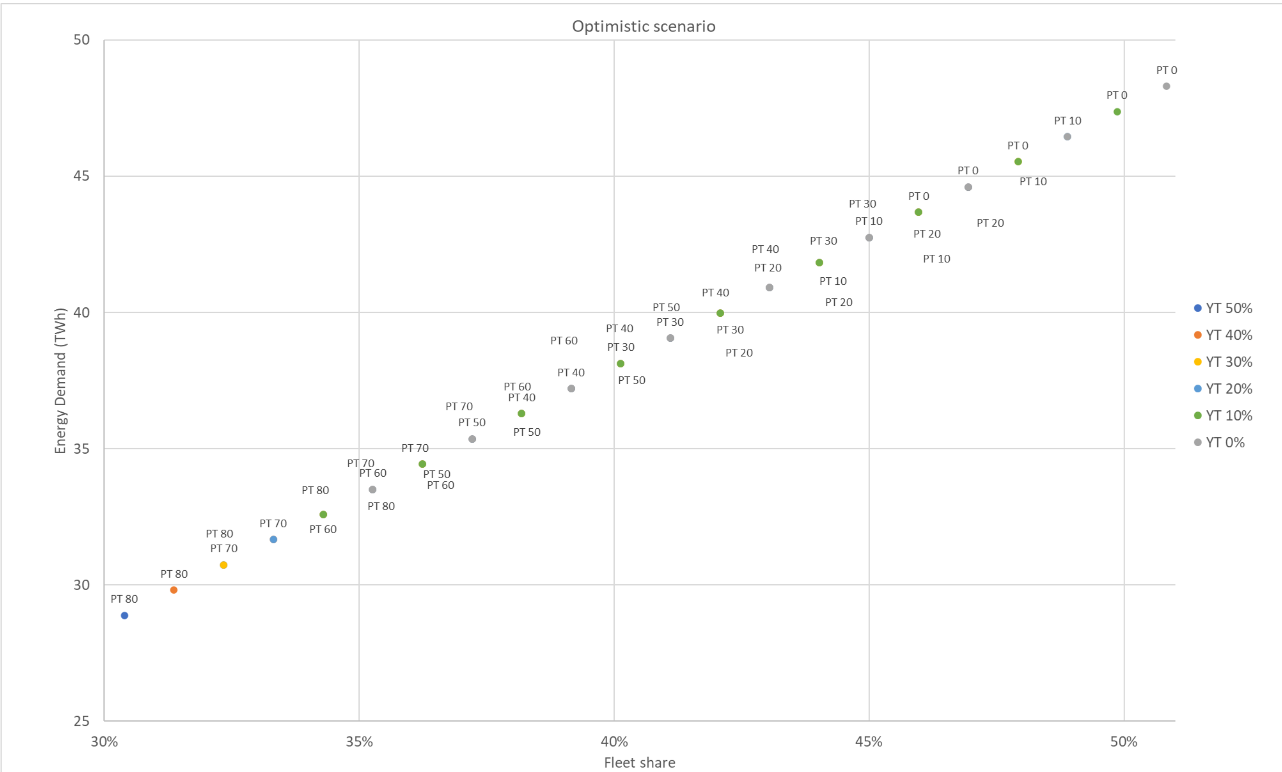
Table 26 - Model output for Yearly and Purchase Tax Rates combinations in pessimistic scenario.

Pessimistic Scenario							
Year at which Adopters surpasses 39M		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	2045	2042	2040	2039	2038	2037
	70%	2040	2039	2036	2037	2036	2035
	60%	2038	2037	2034	2035	2034	2034
	50%	2036	2035	2033	2034	2033	2033
	40%	2034	2034	2032	2033	2032	2032
	30%	2033	2033	2031	2032	2031	2031
	20%	2032	2032	2031	2031	2031	2030
	10%	2031	2031	2030	2030	2030	2030
	0%	2031	2030	2030	2030	2029	2029
EVs' fleet share in December/2050		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	30.4%	31.4%	32.3%	33.3%	34.3%	35.3%
	70%	32.3%	33.3%	36.2%	35.3%	36.2%	37.2%
	60%	34.3%	35.3%	38.2%	37.2%	38.2%	39.2%
	50%	36.2%	37.2%	40.1%	39.2%	40.1%	41.1%
	40%	38.2%	39.2%	42.1%	41.1%	42.1%	43.0%
	30%	40.1%	41.1%	44.0%	43.0%	44.0%	45.0%
	20%	42.1%	43.0%	46.0%	45.0%	46.0%	46.9%
	10%	44.0%	45.0%	47.9%	46.9%	47.9%	48.9%
	0%	46.0%	46.9%	47.9%	48.9%	49.9%	50.8%

PNE Overshooting		Yearly Tax Rate					
		50%	40%	30%	20%	10%	0%
Purchase Tax Rate Incentive	80%	1.2%	4.5%	7.8%	11.0%	14.3%	17.5%
	70%	7.8%	11.0%	20.8%	17.5%	20.8%	24.0%
	60%	14.3%	17.5%	27.3%	24.0%	27.3%	30.5%
	50%	20.8%	24.0%	33.8%	30.5%	33.8%	37.0%
	40%	27.3%	30.5%	40.3%	37.0%	40.3%	43.5%
	30%	33.8%	37.0%	46.7%	43.5%	46.7%	50.0%
	20%	40.3%	43.5%	53.2%	50.0%	53.2%	56.5%
	10%	46.7%	50.0%	59.7%	56.5%	59.7%	63.0%
	0%	53.2%	56.5%	59.7%	63.0%	66.2%	69.4%

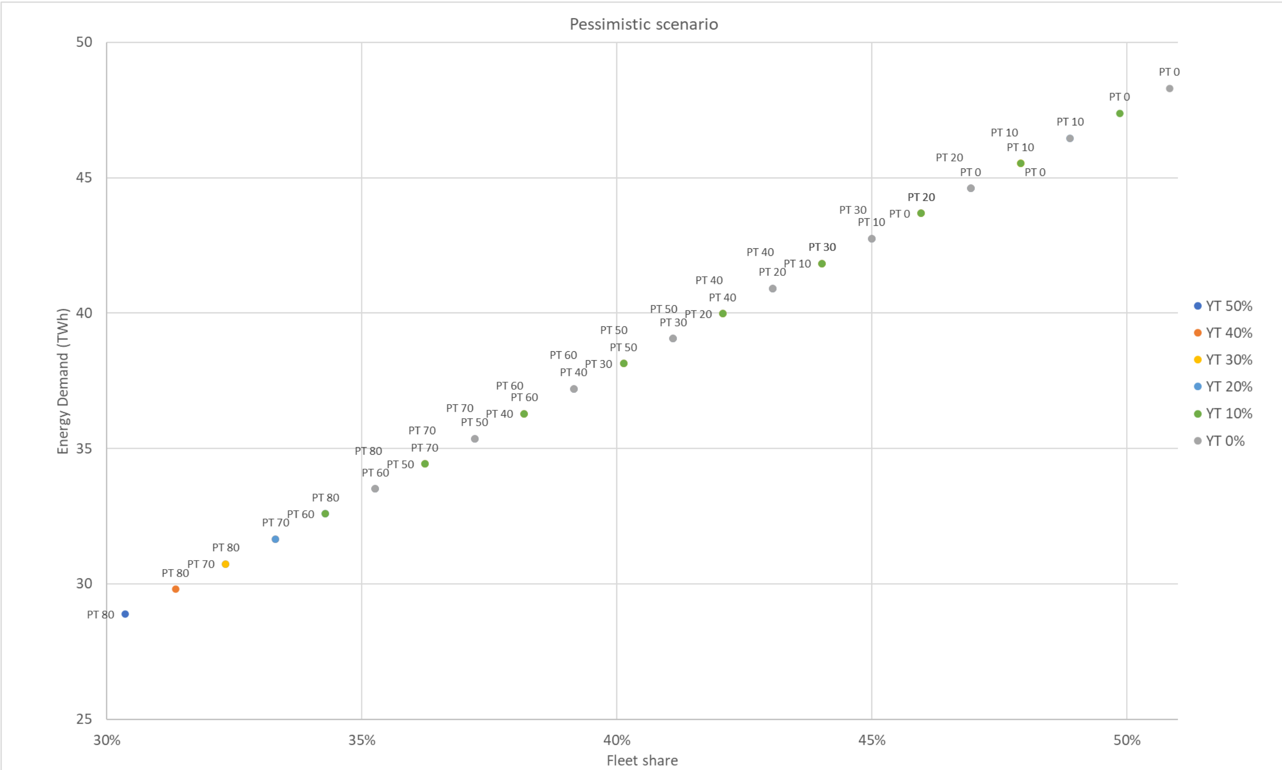
The reported numbers are not simply an opportunity to boost EV adoption as much as possible, especially since it means a surge in electricity demand that current production may not be able to fulfill. Crossing forecasted EVs' fleet share with calculated energy demand derived only from electric vehicles, a few operational points are traced (Figures 49 and 50).

Figure 49 - Energy demand (TWh/ year) and Fleet Share (%) for tax rates-varying optimistic scenarios.



From both graphs, it is noticeable that the fleet share will be between 30% and 51% of the total national fleet of light vehicles, being necessary an Energy Demand of between 29 and 48 TWh. This value corresponds to the government projections for the transportation sector that estimates the overall electricity demand for the EV-fleet share in 2050 to be near 38.8 TWh [39].

Figure 50 - Energy demand (TWh/ year) and Fleet Share (%) for tax rates-varying pessimistic scenarios.



It is clear that the fleet of EV is the lowest when taxes are high, e.g. both purchase taxes at 80% and Yearly Taxes at 50%. There is almost a linear effect, meaning that Brazil could reach 50% Fleet Share of EVs if taxes would be reduced to 0%.

Some points on the graphs overlap, which one may suppose that the government has various options to analyze what are the optimum taxes rates to induce adoption of an EV without collapsing the energy grid.

Furthermore, another way to encourage EV adoption without compromising Annual and Purchase Tax Rates is to provide financial aid or corporate tax breaks to EV Automakers and Assembler Factories that settle in Brazil, helping with price decrease, the scenario with the highest maximum market output according to the model.

4.3. Limitations of the model

The present study is mainly limited due to the lack of data and support about the current and potential EVs fleet in Brazil. Therefore, some inputs were based on estimated regression of data from the United States or Europe, which can result in uncertainties. For instance, *p* and *q* were adapted from the study of the US fleet to fit Brazil's EV scenario, and price evolution was based on an European forecast.

Additionally, some qualitative information cannot be inputted in the method, such as accessibility factors (e.g. number of charging points per km; exclusive parking spots) or non-financial government incentives (e.g. exemption of traffic restrictions in busy areas or of toll), which can potentially persuade adoption and opting out combustion engine for EVs cars.

In addition, it does not consider the impact of future factors (decrease of some components of TCO over time) directly, being necessary to run the model for each change of scenario (e.g. optimist or pessimistic). The model estimates the variation of adopters along the years, but it depends on a fixed value of total driving population and also of an estimated potential market from external studies.

Finally, it is not taken into account huge price variations in the fossil fuels industry, which can lead more people to switch to EVs technology.

5. CONCLUSION

Of the vehicles registered in Brazil, 1% are xEVs. The country suffers from great inflation and economical instability which makes the thought of buying a new technological car distant. Besides, the lack of government incentive, environmental regulations, a stable energy grid and infrastructure all present challenges for the development of the electric vehicles market. Nevertheless, studies point that the EV significance will continue to grow and the necessary structure and management will follow.

The diffusion of EVs depends on various factors such as word-of-mouth, advertising, TCO, taxes and government incentives. Brazil's scenario is currently limited by the high prices of purchase because of the dependency of importation and taxes. To boost the adoption of the future of green mobility, it is of great importance to focus on efficient advertising and government regulations and incentives. Nevertheless, the country should be aware of energy capacity to supply the growth of EV adoption and avoid the energy matrix collapse.

Though the forecast is a 30% fleet share at only 2050, the model indicates the tipping point at around 2030, and even earlier in some scenarios, summarized in Appendix A. This signifies that the automotive industry stakeholders (including the public sector) are highly recommended to have a strategic plan already in the medium-term to effectively provide EVs availability and their infrastructure for the new adopters, generating momentum to transfer for early and late majority groups. This infrastructure should contemplate charging points density, government policy and electric energy consumption.

Regarding the present study, some further investigation and developments can be carried out in order to not only assess other factors' (already in the model) effect on the diffusion of EVs, but also try and create a more complex model, that accounts both for parameters directly related to the electric vehicles market (*e.g.* price, range, maintenance costs) as well as external elements that influence consumers' attitudes (*e.g.* fossil fuel costs, environmental awareness, urban infrastructure changes).

In conclusion, despite the obstacles and still small share of EVs in the Brazilian context, crucial planning should be carried out in the next few years to implement a controlled growth incentive while also managing the already existing diffusion of the technology. In parallel, it is important that further studies of the technology's diffusion behavior be executed to understand and anticipate the market demand and how to effectively fulfill it.

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APPENDIX A – Summary of simulation outputs

Table 27: Maximum market of EVs, Maturity and Tipping points for simulations.

Simulation				Maximum Market	Maturity	Tipping Point
Optimistic	Baseline			39 MM	348	177
	Total Cost of Ownership Variation	Price		138 MM	158	121
		Yearly Tax Rate	Case I	42 MM	280	165
			Case II	46 MM	265	175
		Purchase Tax Rate	Case III	49 MM	253	146
			Case IV	59 MM	215	124
Pessimistic	Baseline			39 MM	392	199
	Total Cost of Ownership Variation	Price		138 MM	170	127
		Yearly Tax Rate	Case I	42 MM	315	185
			Case II	46 MM	290	173
		Purchase Tax Rate	Case III	49 MM	278	162
			Case IV	59 MM	246	138