Model to estimate the impact of future CO_2 emissions due to the increase in the electric vehicle fleet – the case of the Brazilian capital

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Abstract: This article proposes a model that estimates the growth of the individual transport vehicle fleet and the impact of electric vehicles on CO_2 emissions by the year 2050. For this purpose, a case study was carried out in the federal capital of Brazil, Brasília, to characterise real driving cycles, with measurements of speeds, fuel consumption and CO_2 emissions, and thus validate the proposed model. Therefore, the model was applied in scenario simulations, obtaining an 84% reduction in CO_2 emissions with the total change in the fleet from combustion vehicles to electric vehicles by the year 2050. In another perspective, by changing the composition of the current vehicle fleet to 50% ethanol-powered hybrid vehicles and 50% electric vehicles will reduce CO_2 emissions by 92%. The simulated scenarios indicated the potential for decarbonising CO_2 emissions by replacing the fleet of vehicles with ignition engines for hybrid and electric ones.

Keywords: vehicle fleet growth; driving cycle; CO_2 emissions; electric vehicles and Brazilian energy matrix.

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1 Introduction

In recent decades, worldwide, the energy consumption of the fleet of light passenger vehicles has become too dependent on non-renewable fuels, such as gasoline, diesel and natural gas. In Brazil it is no different, in 2021 gasoline fuel was used by 76.4% of light vehicles, while renewable fuel ethanol was used by 23.6% of light vehicles (EPE, 2022).

It is worth mentioning that Brazilian common gasoline is currently a mixture of gasoline with 27% (by volume) of anhydrous ethanol, and this percentage has varied between 18% and 27.5% depending on the annual production of the fuel, the economy and the market. Therefore, in 2021 the total consumption of ethanol represented 44.8% of the fuel consumed by light vehicles.

Unlike European countries, the increase in electric propulsion in Brazil has not been as pronounced as expected, due to the peculiarities of the Brazilian scenario, with a slowdown in economic growth since 2014 and the incentive to use ethanol as a renewable fuel with low emissions. Currently, the electrified fleet in circulation in Brazil is 126,500 cars, including hybrids, plug-in hybrids and fully electric vehicles (ABVE, 2022).

In the coming decades, electric propulsion will increase the energy efficiency of urban mobility and will be the best option for most countries to meet CO_2 emission reduction targets (Alam et al., 2017; Hill et al., 2019). However, the resulting gain in energy efficiency and the reduction in CO_2 emissions will depend on the local electrical matrix, the fuel matrix, the number of electric vehicles and the characteristics of the fleet. With this, electric propulsion technology will be divided between pure battery and hybrid systems, depending on the context of the countries. The local economy will also play an important role in the greater or lesser share of electric vehicles in the fleet.

In Brazil, it is predictable that cities with gross domestic product (GDP) per capita above 10 thousand dollars have the highest number of electric vehicles in their fleet. In this context, one of the Brazilian cities with the greatest prospect of adopting electric vehicles is Brasília, the Brazilian capital and with a per capita GDP of US$ 16,733.84 in 2022, one of the highest in the country (IBGE, 2023).

Therefore, for the coming decades, the scenario of the Brazilian fleet of light vehicles will be defined by the balance between economic variables, vehicle technology, type of fuel and characteristics of the electrical matrix, which currently has a high share of renewable resources. Thus, the model proposed by this study is essential to assess the impacts of electric propulsion of light passenger vehicles on energy consumption and CO_2 emissions.

In this sense, many models described energy consumption and CO_2 emissions separately, leaving a gap on how other parameters can influence energy consumption and CO_2 emissions. Thus, the proposed numerical model aimed to evaluate the energy consumption and CO_2 emissions of the future fleet of light vehicles, considering local characteristics, due to the increase in the fleet of electric and hybrid vehicles, the decrease in energy consumption and of the emission factors due to the improvement of technology, the variation in kilometres travelled annually, the use of ethanol as fuel by the fleet of light vehicles and CO_2 emissions from the life cycle of fuels and the electrical matrix.

To address these issues, the present study modelled CO_2 emissions and energy consumption, considering how the increase in the fleet of electric and mild hybrid vehicles will impact the consumed energy and CO_2 emissions of the Brazilian capital, mainly in the economic factor, vehicle technology, use of ethanol as fuel, fuel life cycle emissions and characteristics of the electrical matrix.

However, for the proper assessment of the potential impacts of the net reduction in energy consumption and CO_2 emissions from EVs, compared to the options of hybrid vehicles powered by ethanol, it is necessary to consider the phases of the life cycle of electric energy and vehicle fuels. Only with the quantification of CO_2 emissions during all stages of the life cycle, both of electric energy and of Brazilian vehicle fuels, will it be possible to compare the emissions of the fleet of combustion vehicles, the emissions of the fleet of electric vehicles and vehicles hybrids.

2 Literature review

To estimate air pollutant emissions from light vehicles, from the end of the 1970s until 2004, MOBILE was the methodology, or model, approved by the Environmental Protection Agency of the USA. MOBILE has been replaced by the motor vehicle emission simulator (MOVES). MOBILE and MOVES calculate emissions from passenger cars, motorcycles and trucks and are used to determine current and future inventories of these emissions (EPA, 2022).

Eggleston et al. (1991) described the European CORINAIR methodology for the vehicle emissions inventory. This methodology developed in 1985 is composed of three parts: hot emissions, cold emissions and evaporative emissions, and resulted in a computer software called COPERT 90 that estimates the emissions of atmospheric pollutants from road traffic in urban, rural and road conditions. The COPERT 4 version was used to assess the annual road emissions of the city of Athens (Fameli and Assimakopoulos, 2015). COPERT was applied to calculate fuel consumption and road emission inventories adapted for other cities and countries outside Europe.

The methodologies for inventories of emissions and energy consumption depend on the fuel consumption and emission factors of vehicles circulating in a well-defined and approved driving cycle. The importance of conduction cycles in inventory results has been addressed by several authors. Barlow et al. (2009) compiled and detailed more than 200 cycles, aiming to standardise all known conduction cycles in a single format. The work by Barlow et al. (2009) allowed new studies to compare driving cycles and adapt the best ones to local characteristics, to test vehicles for inventories of fuel consumption and emissions of air pollutants. There is a high impact of using legislated driving cycles compared to driving cycles under real conditions in calculating the inventory of energy consumption and emissions of light vehicles, consequently, this subject has been addressed in recent publications.

An experimental work in real conditions (André, 2004) collected data from real driving cycles in urban, rural and road conditions, allowing a better calibration of the driving cycles for a more accurate inventory of energy consumption and pollutant emissions of vehicles light. Furthermore, Fontaras et al. (2008) analysed two hybrid vehicles in a comparison of real driving cycles (Artemis) with New European Driving Cycles (NEDC) indicating an observable difference for urban cycles and, similarly, in Brazil, driving in real conditions, measurements of fuel consumption and emissions in cycles differed from NEDC and FTP75 (Cassiano et al., 2016), indicating an impact on the result of inventories when considering, or not, driving cycles in real conditions.

In Brazil, the consolidated methodology (CETESB, 2022) is similar to those applied by COPERT and MOVES, being based on the emission factors of the vehicles tested in the American cycle FTP75. The Brazilian methodology, used for the inventory of fuel consumption and pollutant emissions, has been successfully applied in the cities of São Paulo and Fortaleza (Policarpo et al., 2018). However, this methodology is very reliable in terms of variables such as fleet age, kilometres driven annually and emission factors based on the FTP75 driving cycle. Thus, the application of methodologies such as those mentioned above, in scenarios other than São Paulo, European cities or the USA, needs to be adapted to the appropriate age of the fleet, the kilometres travelled annually, the emission factors by levels and the driving cycles. Therefore, it brings challenges on how to calibrate these variables to obtain more accurate results.

As mentioned above, the methodology used in Brazil for the inventory of fuel consumption and air pollutant emissions from light vehicles is based on the FTP75 driving cycle. Therefore, assessing the future impact of electric propulsion for light vehicles, especially in Brasília, requires a more accurate inventory considering the characteristics of the local fleet and a representative driving cycle. Recent work has analysed the impact of electric propulsion and has included adapting real conditions for a more accurate calculation of energy consumption and emissions (Faria et al., 2013) and (Wu et al., 2015). Considering the particularities, the present study presents an improved methodology applied in the city of Brasília, in order to evaluate the future impact of the electric propulsion of light passenger vehicles.

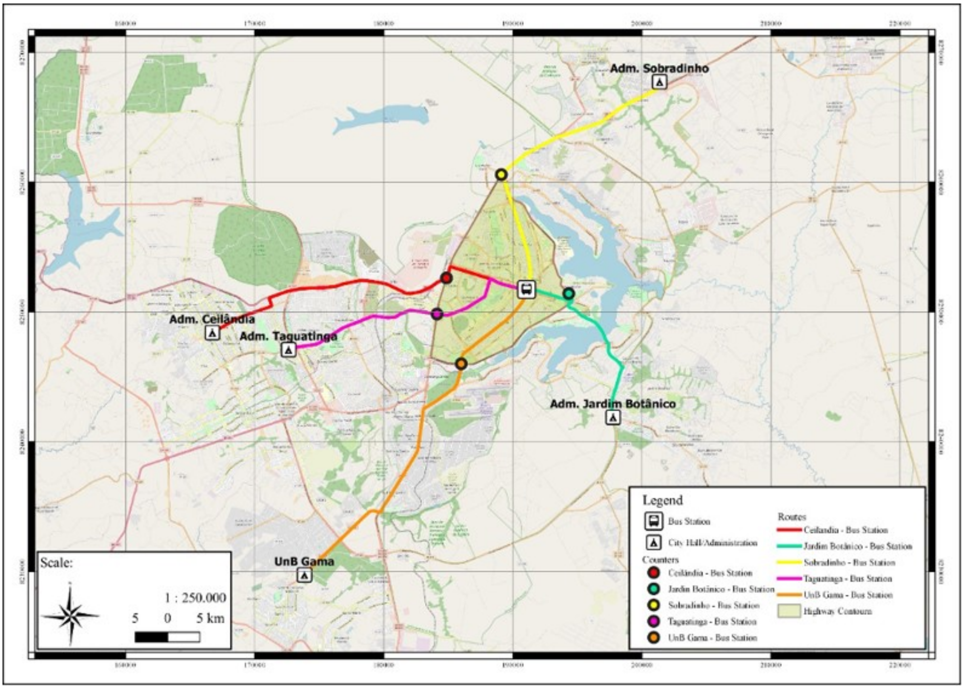
3 Methodology

The first step of the work was to characterise the driving cycles under real conditions in Brasilia, due to the disparity that occurs when using the FTP75 to represent real cycles of fuel consumption and CO_2 emissions. The city is in the central region of Brazil, it was planned, designed from scratch, and founded in 1960. Currently, the metropolitan region of Brasília has about 3 million inhabitants (IBGE, 2023), and its mobility characteristics are the same as many metropolitan regions in the world. That is, the centre of the city is the point of attraction for the peripheral neighbourhoods. In this sense, daily trips for all purposes, such as work, shopping, and leisure, characterise typical commuting in the city.

Brasilia was conceived and organised with a central area and administrative regions, today 33 regions make up the metropolitan area (CODEPLAN, 2023). In addition to the metropolitan region, neighbouring municipalities in other states are part of Brasilia's zone of influence. The population residing in the central area adds up to around 500,000 inhabitants, with inhabitants of the administrative regions accessing the central area through five main routes: one from the north region, one from the south region, one from the east region, and two from the west region. These regions demand the largest number of origin-destination trips in the entire metropolitan area of Brasília.

There are a few other access routes to the city centre, but most transport vehicles use these five routes according to the PDTU (2010) and Metro (2018), as shown in Figure 1. The western region of Brasília has the highest concentration population among administrative regions; therefore, two main roads serve this region.

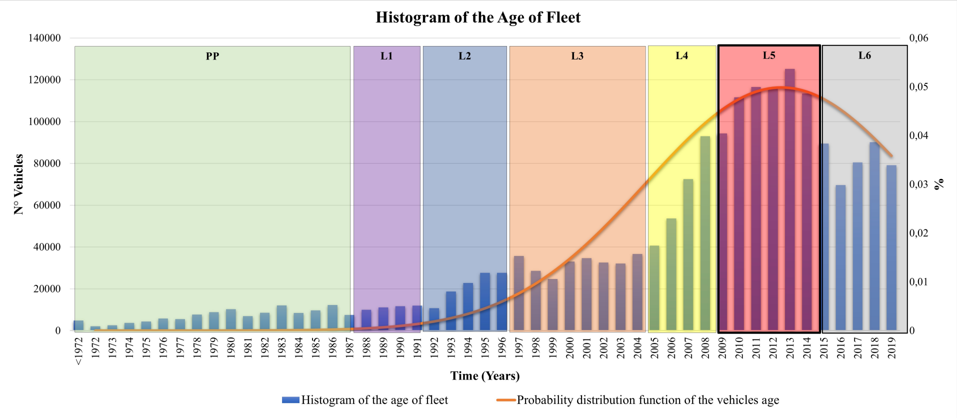
Figure 1 Five chosen routes for evaluation of driving cycles (see online version for colours)



As shown in Figure 1, five routes were chosen for the evaluation of Brasilia's driving cycles. All trips ended at the same point: the Central Bus Station in Brasília. Trips on the south route started at the Bus Rapid Transit station in the Gama administrative region, while on other routes trips started in front of the respective regional administration buildings (equivalent to a city hall).

The trips started around 7:30 a.m. on the routes from the administrative regions toward the central region. After arriving at the Central Bus Station, another return trip was made from the central area to the administrative regions around 9:00 a.m., back to the Central Bus Station at 10:00 a.m. and finally at 5:30 p.m. to characterise the morning peak time, off-peak time and afternoon time of each route. These times were chosen through the analysis of the database regarding the volumetric count of each route, made available by the transit authorities.

Figure 2 Histogram of the age of the fleet with the corresponding tiers and the solid line represents the probability distribution function of the vehicles age (see online version for colours)



The ages of the vehicles that make up the vehicle fleet in Brasília were obtained from data from the Brazilian transit agency (SENATRAN, 2022). In addition, data on emission factors (by level and year) and fuel economy (by level and year) were obtained from the Vehicle Emissions Inventory of the city of São Paulo (CETESB, 2022) and available dynamometer test results (INMETRO, 2022). It is important to note that, as mentioned earlier, these emission factors and fuel economy data in Brazil are based on the FTP75 driving cycle and therefore needed to be adapted for the improved methodology considering actual driving cycles applied in Brasilia, as proposed. by the present study.

Figure 3 Intensity of use – vehicle mileage curve depending on age – vehicle fleet in Brasília-DF (see online version for colours)

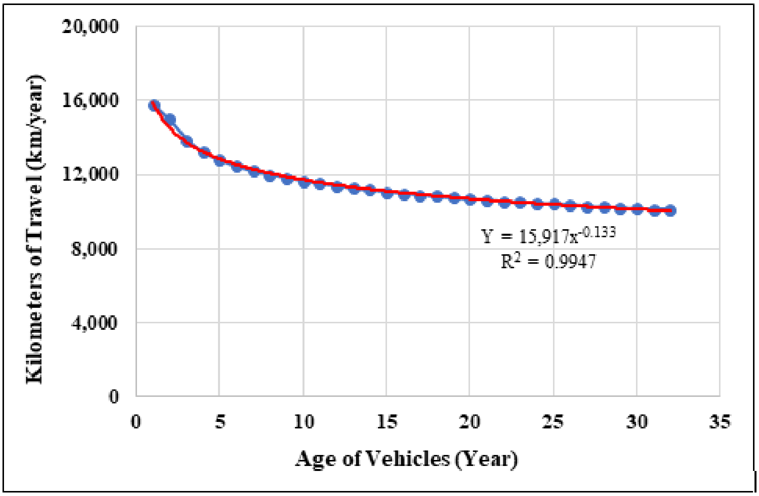
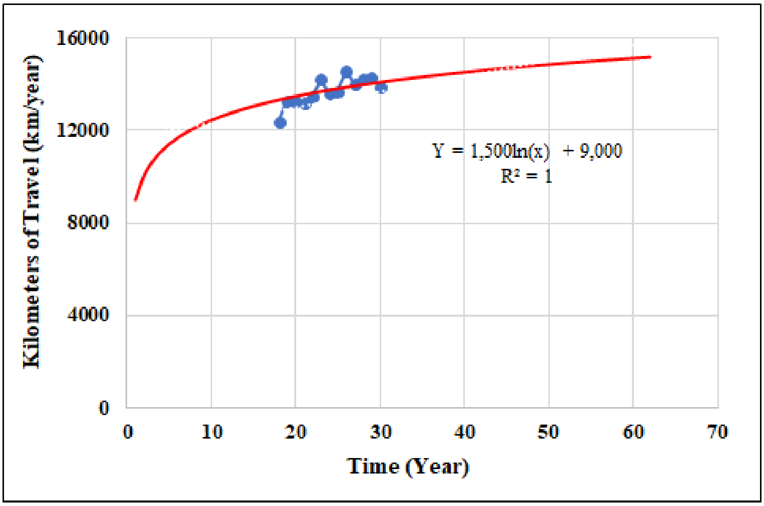


Figure 2 presents a histogram of the age of light passenger cars in the vehicle fleet in Brasília with the corresponding years, together with the probability distribution function for the age of the vehicles represented by the solid line. As a result, the most frequent fleet age is for vehicles manufactured between 2012 and 2013, which corresponds to the transition level established by the air pollution control program for motor vehicles (PROCONVE) from L5 to L6. PROCONVE establishes deadlines, emission limits and technological requirements for national and imported motor vehicles, this program is mirrored in European standards.

The model proposed by this work considered that the annual kilometre travelled by vehicles is a function of the age of the vehicle. This function is also considered by the Vehicle Emissions Inventory (CETESB, 2022), but needed to be evaluated locally. To infer the proposed function for the case of Brasilia, samples of vehicles were collected at local dealerships and websites dedicated to the sale of cars in the region, and then the year of manufacture of the vehicle was correlated with the total number of kilometres recorded on its vehicles. odometers. 1,389 vehicles less than 20 years old were analysed. The intensity of use is shown in Figure 3 by the curve of annual kilometres travelled by vehicles in Brasilia. A best-fit function indicates a maximum value of 16,000 km/year for new vehicles, while for old vehicles this value decreases over the years, with a trend towards a figure of 10,000 km/year for vehicles over 30 years old.

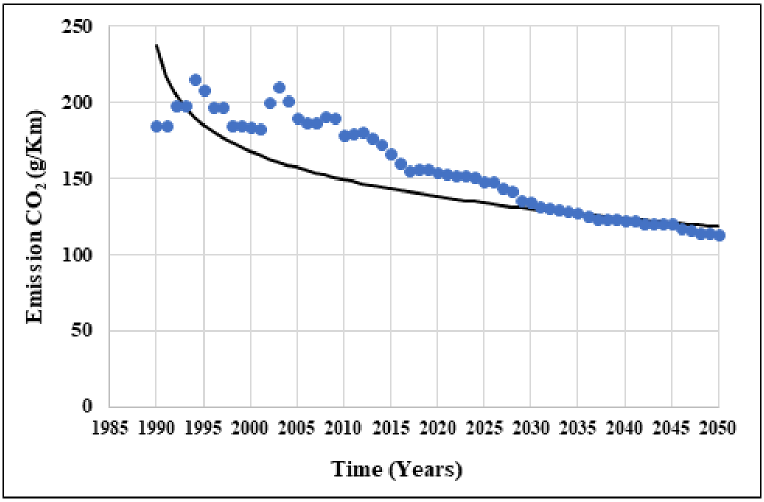
Figure 4 Increase of the average kilometres of travel as a function of the years for BRASÍLIA-DF (see online version for colours)



Additionally, the increase in the average kilometres travelled in the last decade was evaluated based on a 10-year time series, as a result, it is expected that this average will continue to increase due to the expansion of the city and the increase in GDP per capita that promotes the increased use of private passenger cars. In Figure 4, the increase in average kilometres travelled over the years is noticeable, from 2009 to 2019, the symbols are the available data, and the black line is a suitable curve to project the increase in kilometres travelled for the next decades. There is a slight trend towards an average kilometre of travel of 15,000 km/year.

To account for the impact of improved vehicle technology on the carbon dioxide emission factor, the proposed model considered the same dataset (CETESB, 2022) and (INMETRO, 2022). Figure 5 shows the decreasing historical function of the emission factors.

Figure 5 Trend function of the vehicle technology improvement of the CO_2 emission factors (black line) (see online version for colours)



The plotted data indicate a historically decreasing function of the emission factors to determine the trend for the next decades (gray line). The trend function was implemented in the proposed model and can vary allowing the simulation of higher or lower emission factors in the future.

Table 1 Technical files Fox/Prius/Leaf

Features	*Fox 1.6 – flex Gasoline/ethanol*	*Prius hybrid gasoline*	*Leaf ZE electric*
Power (a 5,250 rpm)	101 cv (G)/104 cv (E)	134 cv	149 cv
Torque (a 2,500 rpm)	15.4 kgfm (G)/15.6 kgfm (E)	14.5 kgfm	32.6 kgfm
Weight-power ratio	10.06 kg/cv	10.55 kg/cv	10.62 kg/cv
Fuel tank/battery capacity	50 litres	45 litres	40kWh
Kerb weight	1,046 kg	1,415 kg	1,582
Acceleration 0–100 km/h	10.5 s	10.3 s	7.9 s
Fuel consumption urban	8.6 km/l (G)/6.6 km/l (E)	15.7 km/l (G)	165 Wh/km
Fuel consumption highway	11.1 km/l (G)/8.5 km/l (E)	14.3 km/l (G)	-
Urban autonomy	430 km (G)/330 km (E)	706.5 km	240 km

The actual driving cycles for the case of Brasilia were experimentally characterised by carrying out three trips with the proposed vehicles on the five routes presented. For the experimental study, based on the characteristics of the local vehicle fleet, two vehicles were selected considering the most frequent type of vehicle in the fleet by age and level (Figure 2): a vehicle with a gasoline/ethanol ignition engine (SI), light vehicle, other gasoline hybrid vehicle (HEV). Regarding the vehicle with battery electric technology (BEV) used, according to the diffusion of vehicles with this technology in the country, the most likely to find this type of vehicle in the fleet is with less than one year of use.

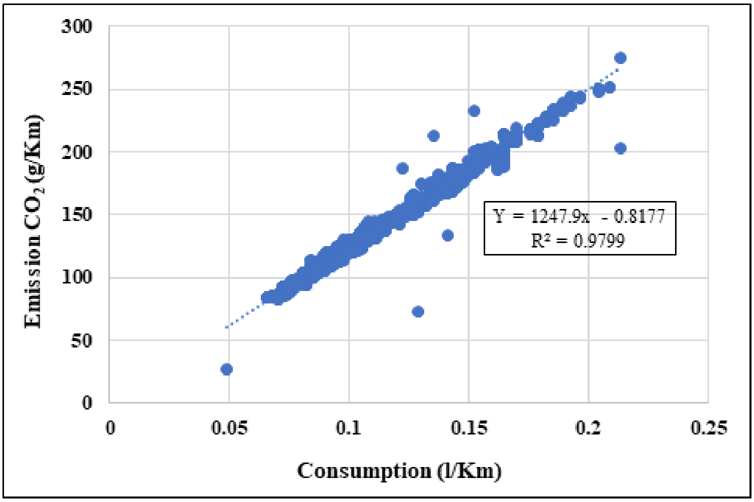
In this context, for the selection of the 3 vehicles used, the maximum specific power was preserved, with about 0.07 kW/kg. The main characteristics of the three vehicles selected for route measurements are shown in Table 1.

As already mentioned, the experimental study was carried out at peak times on the five routes. To record the information, an OBD2 ELM327 was connected to the OBD port of the vehicles, sending data via Bluetooth to an Android 9 device that served as a datalogger with an acquisition rate of 1 Hz. The following values were measured via OBD: vehicle speed (m/s), fuel consumption (litres/s), and CO_2 emissions (g/s). In addition, through the built-in GPS, altimeter, and accelerometer of the Android device, ground speeds (m/s), altitudes (m), accelerations (m/s2), and distances covered in trips (m) were recorded.

For the first phase of the experimental study, the SI-powered vehicle performed the five route measurements to fully characterise driving cycles, fuel consumption, and CO_2 emissions. In the second phase, the hybrid vehicle and the electric vehicle carried out measurements only on the southern route (the route with greater vehicle movement) to assess the impact of electric propulsion on fuel (and energy) consumption and CO_2 emissions.

CO_2 emissions in g/km were obtained from OBD data, but these values were calibrated by the function shown in Figure 6 based on fuel consumption values from INMETRO data.

Figure 6 Calibration curve for the CO_2 emissions in g/km as a function of the fuel economy in l/km (see online version for colours)



This calibration was necessary because the fuel consumption values obtained from the OBD are more reliable than the CO_2 emission values from the OBD, therefore, the CO_2 emission values from the OBD were discarded being two standard deviations from the calibration curve.

Another step taken in this work was to estimate the future fleet of electric vehicles. In this context, worldwide, it is predicted that the BEV fleet will increase in the next three decades (Wang et al., 2022), but the rate of increase and the total amount of BEV in the fleet will depend on the characteristics of each country and city. Therefore, in Brazil, renewable biofuels will continue to play an important role as energy sources for the fleet, so electric propulsion will face competition with hybrid technology combined with ethanol due to the resulting low emissions.

Therefore, to increase the electric vehicle fleet in Brasilia, a fleet growth function was assumed following the work of Dargay et al. (2007), Lu et al. (2017), and Lian et al. (2018). Time series of vehicle ownership, population, and GDP of Brasilia were obtained from IBGE (2022) and CODEPLAN (2022). A forecast for the GDP, population, and car ownership time series was applied to estimate the scenario in 2050. Then, the correlations of vehicle ownership with GDP were determined.

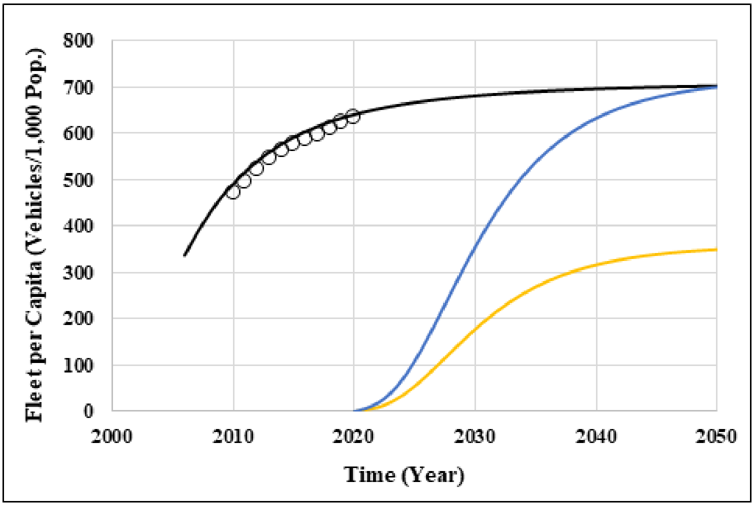
A first correlation analysis of GDP versus vehicle ownership was obtained by applying the Gompertz Function, presented in Equation 1. The application of this function allows for generating a curve that results in vehicle ownership as a function of GDP, about the year.

$$f(t) = ae^{-be^{-ct}} \tag{1}$$

where:

$f(t)$	vehicle ownership as a function of GDP per year (vehicles per 1,000 inhabitants)
a	number of vehicles (vehicles per 1,000 inhabitants)
b e c	curvature parameters
t	growth rate (GDP per year)

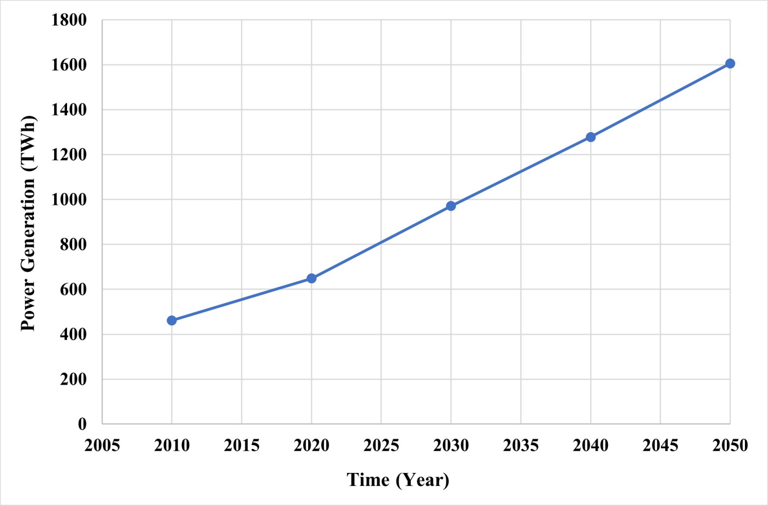
Figure 7 Gompertz functions of the growth of electric vehicles fleet (see online version for colours)



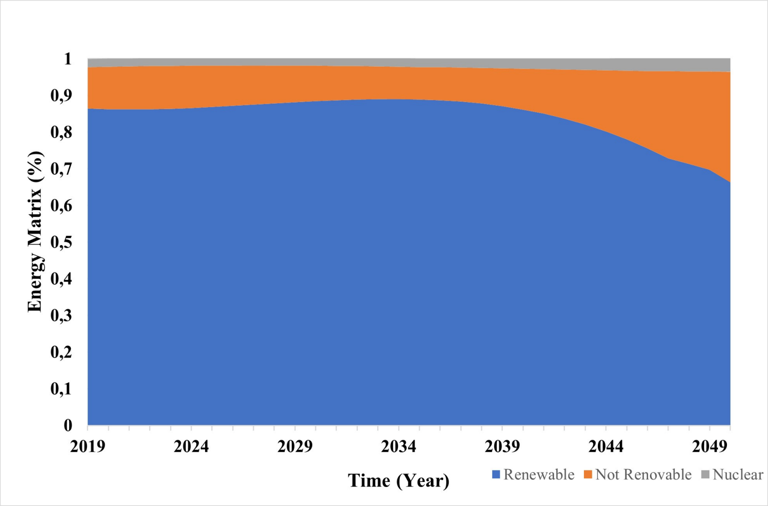
Therefore, this equation was applied to three scenarios, one with low expectations (worst scenario), an optimistic one (optimistic scenario) and an overly optimistic one (overly optimistic scenario). In these scenarios, the Gompertz functions were adjusted based on the original correlation function, with an initial value imposed of zero electric vehicles in

2020 and reaching the final values of 50% and 100% of the total fleet in 2050. Figure 7 shows the results of applying this growth function until 2050 for the proposed scenarios.

Figure 8 (a) Electric energy generation (b) Brazilian electric energy matrix share for 2050 horizon (see online version for colours)



(a)



(b)

In Figure 7, the circle symbols are the actual vehicle ownership data, and the solid black line is the Gompertz Function adjusted for total vehicle ownership. The solid blue and yellow lines represent Gompertz Functions assuming two scenarios for the fleet of electric vehicles in Brasília, with 50% and 100% of the total fleet by 2050. As a result, the adjusted correlation function of vehicle ownership estimated a value of 705 vehicles per 1,000 inhabitants by the year 2050. Consequently, in 2050 the BEV fleet would be respectively 352 or 705 vehicles per 1,000 inhabitants for the proposed scenarios.

The following possibilities were assumed for the scenarios:

a Worse: it has low expectations, with the fleet consisting only of gasoline spark engine vehicles by 2050. The black line in Figure 7 determines the total fleet and represents 100% of gasoline spark engine vehicles for this scenario.

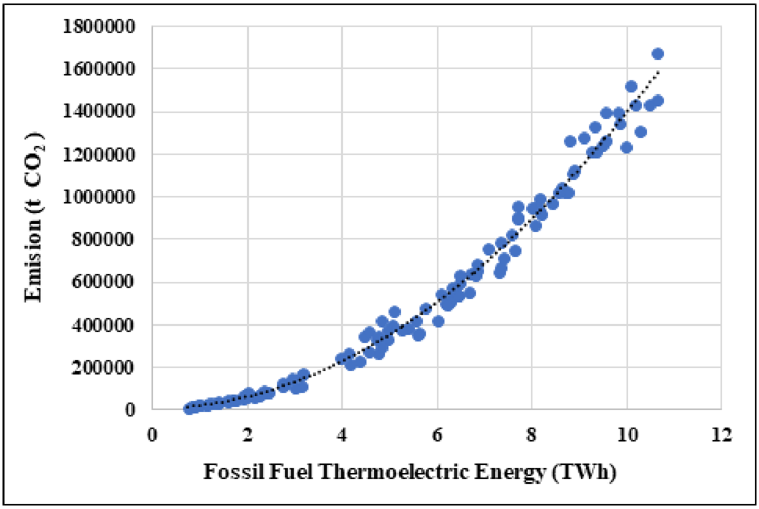
b Optimistic: the fleet of gasoline vehicles with a spark engine would drop to zero by 2050, being partially replaced by 50% by electric vehicles (yellow line in Figure 7), and partly by 50% by hybrid vehicles powered by gasoline or ethanol.

c Overly optimistic: The fleet of vehicles with gasoline engines would drop to zero by 2050, being replaced only by electric vehicles (blue curve in Figure 7), with the BEV fleet reaching 100% in 2050.

Another point to be determined to meet the objectives of this study is to quantify CO_2 emissions in the energy matrix.

For the Brazilian case, Dias de Oliveira et al. (2005) showed that a litre of ethanol represents 0.37 kg of CO_2 considering the cradle-to-tank life cycle, while a litre of gasoline represents 0.49 kg of CO_2 considering the well-to-tank life cycle (Weiss et al., 2000). In addition, the emission factor of the Brazilian electricity matrix is between 108.23 and 59.64 tons of CO_2/GWh (SEEG, 2022). In economic terms, GDP per capita increased from USD 9,234 in 2,000 to USD 14,034 in 2018, while vehicle ownership increased from 196 vehicles per 1,000 inhabitants in 2008 to 297 vehicles per 1,000 inhabitants in 2018.

Figure 9 Emission factor of CO_2 as a function of fossil fuel thermoelectric energy (see online version for colours)



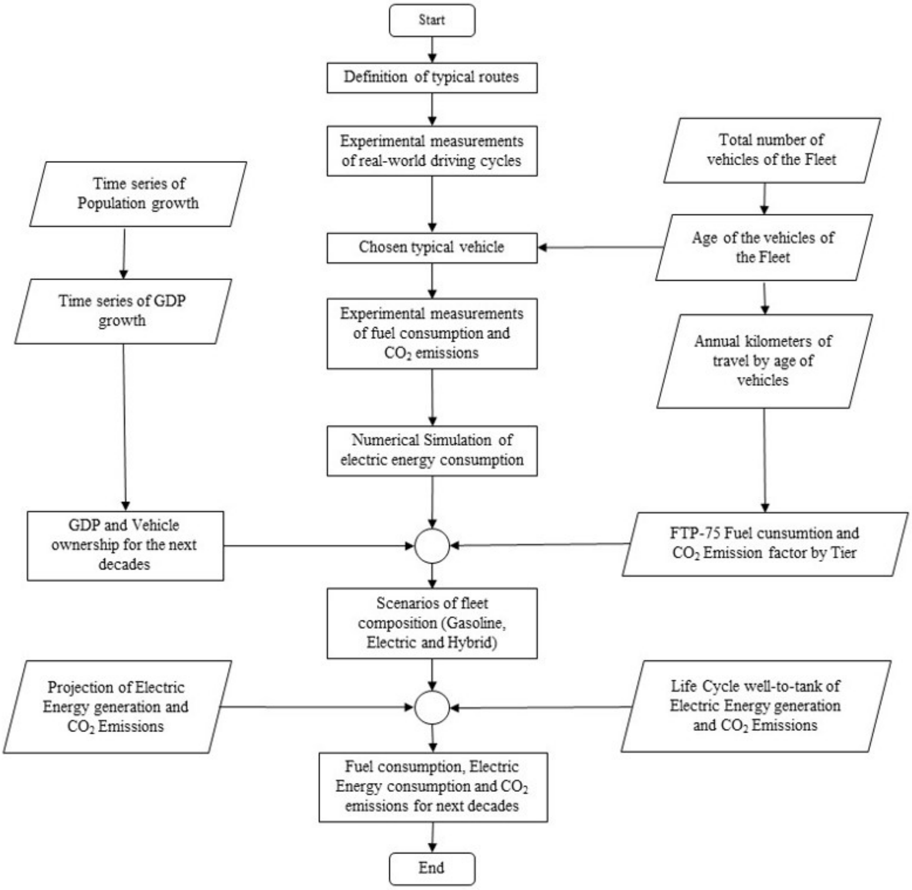
Different vehicle technologies were assumed for future scenarios. Therefore, life cycle values for the production and distribution phase were needed to compare CO_2 emissions between SI, HEV Flex (gasoline/ethanol) and BEV vehicles. Tank-to-wheel CO2 emissions were considered only for the SI gasoline engine, while tank-to-wheel emissions for ethanol and electricity were assumed to be zero. Well-to-tank values of 0.49 $kgCO_2/L$

of gasoline were obtained (Weiss et al., 2000) and 0.37 kgCO_2/litre of ethanol were obtained from Dias de Oliveira et al. (2005).

The estimation of future electricity demand and share of the matrix of non-renewable energy resources was based on two works: the Brazilian Energy Plan Horizonte 2050 (EPE, 2017) and Scenarios of the Electric Matrix 2050 (Kelman, 2015). Based on these studies, Figure 8(a) presents the projection of Brazilian electricity consumption, and Figure 8(b) the projection of the share of the electrical matrix.

Additionally, CO_2 emissions from the Brazilian electricity generation system were evaluated based on the inventory of emission factors published by the Ministry of Science, Technology, and Innovation (Dantas et al., 2019). A correlation function was obtained for CO_2 emissions with fossil fuel thermoelectric generation to be shown in Figure 9, and from Figure 8(a) and Figure 8(b) it was possible to estimate the increase in the CO_2/TWh emission factor of the Brazilian electric energy until 2050, thus allowing to determine the amount of CO_2 that will be emitted with the generation of electric energy that will be consumed by the fleet of BEV vehicles over the years until 2050.

Figure 10 Algorithm of the method to determine fuel and electric energy consumption, and CO_2 emissions for the next decades



At this juncture, after all these explanations, Figure 10 summarises the methodology used to determine the consumption of fuel, electricity, and CO_2 emissions by the Fleet of Vehicles in the city of Brasília for the coming decades.

4 Results

4.1 Measured driving cycles, fuel consumption, and CO_2 emissions of vehicles on route

The results of the experimental study on the five chosen routes allowed estimating the FTP75 usage errors in comparison with the real-world driving cycle for the case of Brasilia. These errors indicate the impact of using FTP75 for CO_2 emissions inventories instead of applying actual driving cycles. To highlight the differences between the actual driving cycles and the FTP75, the instantaneous speeds on the South route are shown in Figure 11(a) and Figure 11(b).

Through Figure 11(a) of Figure 11(b), it is possible to visually see that the velocity profiles of the real driving cycles are more coincident with the FTP75 in the peak hours. In this context, the figures resulting from the overall fuel/energy consumption and CO_2 emission factors of the five routes are summarised in Table 2, with two different situations on the five routes (07:00 a.m. peak time and 10:00 a.m. off-peak time).

During the experimental study, the Gama route (south route) was fully characterised using the three vehicles, it is important to note that the HEV and the BEV operated only on the Gama route (south route) even because it is the route travelled by the largest number of vehicles. vehicles in the city, while the other four journeys were made only by the SI vehicle.

For the SI vehicle during peak hours, the average real-cycle fuel economy error was 4.47% less than the FTP75 using gasoline and 2.29% less than the FTP75 using ethanol, while for the off-peak hours, fuel economy the average error was 10.90% more than FTP75 for gasoline and 6.92% more than FTP75 for ethanol.

Furthermore, fuel economy errors are consistently greater for off-peak conditions when actual cycle measurements are compared to FTP75. For HEV, the average error over FTP75 for fuel economy during rush hour was 21.19%, and 40.79% during rush hour, while the average error for energy savings for BEV was 31.16% for rush hour and 4.04% for an off-rush hour. It is interesting to highlight that the BEV's energy savings are greater during off-peak hours.

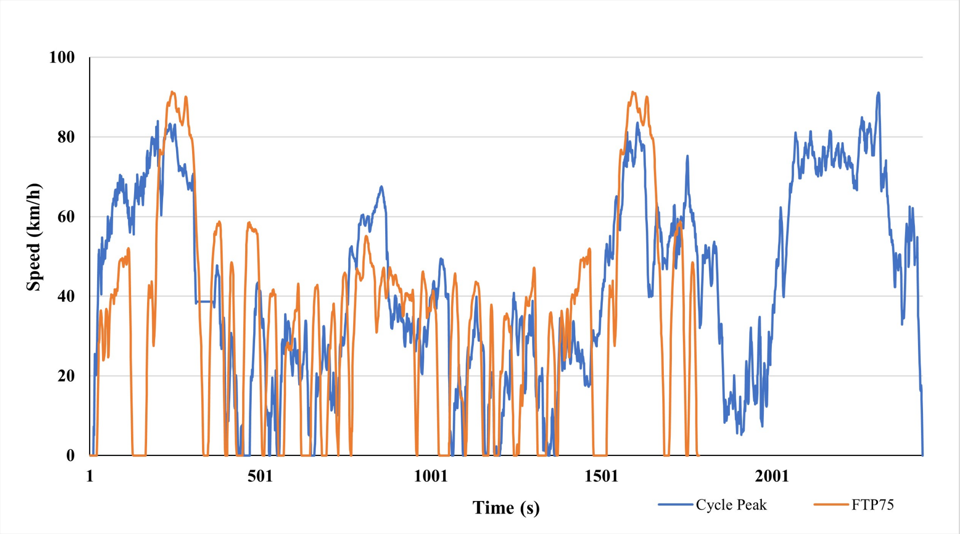
It is also observed that the results of tank-wheel CO_2 emissions in g/km, as expected the errors for CO_2 emissions followed the same pattern of errors for fuel economy, being consistently higher for peak hours.

The energy efficiency of vehicles can be analysed for peak hour conditions, as a comparison, considering the lower calorific value of gasoline and ethanol. The average equivalent energy range of the SI vehicle for the five routes resulted in 1.33 km/kWh for gasoline and 1.64 km/kWh for ethanol, while the equivalent energy range of the HEV resulted in 2.91 km/kWh.

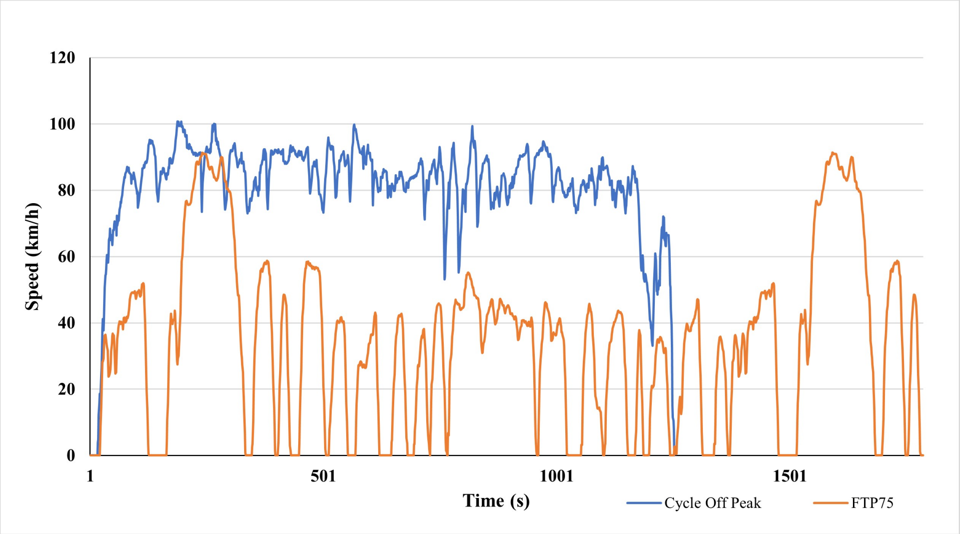
Table 2 Overall average values and errors of the real-world cycle compared to FTP75

Vehicle	*Hour*	*Route*	*OBD*		*FPT 75*		*Energy autonomy (km/kWh)*	*Average error economy*	*Average error CO_2*
			CO_2 (g/km)	*Economy (l/km)*	*CO_2 (g/km)*	*Economy (l/km)*			
SI FOX gasoline	7h00	South/Gama	110.34	0.09	111	0.09	1.37	–4.47%	–3.03%
		West/Ceilândia	118.96	0.10	111	0.09	1.27		
		East/Jd. Botânico	117.39	0.09	111	0.09	1.29		
		North/Sobradinho	106.48	0.09	111	0.09	1.42		
		West/Taguatinga	118.62	0.10	111	0.09	1.27		
	10h00	South/Gama	96.66	0.08	111	0.09	1.56	10.90%	12.13%
		West/Ceilândia	86.96	0.07	111	0.09	1.74		
		East/Jd. Botânico	105.84	0.08	111	0.09	143		
		North/Sobradinho	90.62	0.07	111	0.09	1.67		
		West/Taguatinga	107.58	0.09	111	0.09	1.41		
SI FOX ethanol	7h00	South/Gama	-	0.14	-	0.13	1.57	–2.29%	-
		West/Ceilândia	-	0.14	-	0.13	1.67		
		East/Jd. Botânico	-	0.16	-	0.13	1.38		
		North/Sobradinho	-	0.10	-	0.13	1.81		
		West/Taguatinga	-	0.12	-	0.13	1.77		
	10h00	South/Gama	-	0.10	-	0.13	1.63	6.92%	-
		West/Ceilândia	-	0.11	-	0.13	1.54		
		East/Jd. Botânico	-	0.10	-	0.13	1.65		
		North/Sobradinho	-	0.18	-	0.13	0.96		
		West/Taguatinga	-	0.11	-	0.13	1.58		
HEV PRIUS	7h00	South/Gama	53.03	0.04	71	0.05	2.91	21.19%	25.30%
Gasoline	10h00	South/Gama	39.85	0.03	71	0.05	3.87	40.79%	43.87%
BEV LEAF	7h00	South/Gama	-	0.07	-	0.11	13.80	31.16%	-
Electric	10:00h	South/Gama	-	0.10	-	0.11	9.90	4.04%	-

Figure 11 **(a)** Southern route real-world driving cycles during peak hours (7:00 a.m.) compared to ftp75 (b) Southern route real-world driving cycles during off-peak hours (10:00 a.m.) compared to FTP75 (see online version for colours)



(a)



(b)

These results, when compared to the BEV's autonomy of 13.8 km/kWh, indicate a great gain in energy efficiency for the electric propulsion system. Therefore, for the coming decades, the increase in the hybrid vehicle fleet has the potential to decrease energy consumption during traffic conditions, while battery electric vehicles are the best option to decrease the total energy consumption and decrease the emissions of CO_2. However, it is important to note that tank-to-wheel CO_2 emissions are zero for both electricity and ethanol, so ethanol hybrid vehicles could be a notable transition option for the fleet in the coming decades.

Consequently, considering the results presented, for the case of the Brazilian capital, the use of FTP75 emission factors for the inventory methodology would estimate the CO_2 emissions of the fleet of vehicles with SI engines with an error between –3.03% to 12, 13%. As for the HEV with gasoline fuel, this error would reach 43.87%.

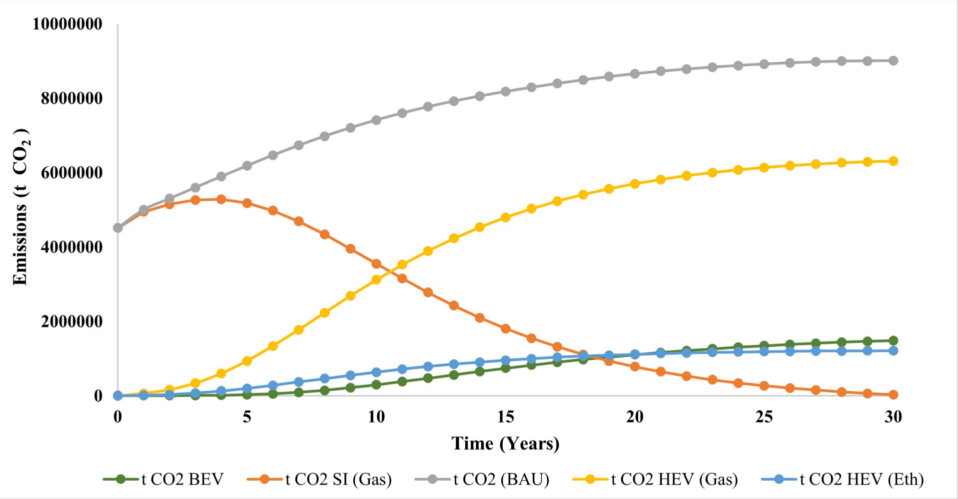
4.2 Fleet CO_2 Emissions Estimates for the Next Decades

As seen in the previous item, the results obtained in the measurements of the real driving cycles for the case of the city of Brasília estimated errors in the use of the FTP75 values for the CO_2 emission factors, when the inventory methodology was applied to determine the total emissions of CO_2 from vehicles.

When applying the model proposed in this study to estimate CO_2 emissions by the year 2050, the worst scenario was assumed with all vehicles in the fleet composed of SI vehicles powered by gasoline, the optimistic scenario with SI vehicles reduced to zero by year 2050 and being replaced by 50% by HEV (gasoline or ethanol) and 50% by BEV and, finally, the excessively optimistic scenario with SI vehicles being completely replaced by BEV.

In Figure 12, the vertical axis is the emission values in tonnes of CO_2 and the horizontal axis is time in years, where zero means the reference year 2020 with consolidated data for 2019.

Figure 12 Total CO_2 emissions of the simulated scenarios (see online version for colours)



The lines and dots represent the model's calculated values in tons of CO_2, and the errors determined in Table 2 are also indicated by the error bars in Figure 12. The gray line represents the worst-case scenario emissions, as if all vehicles in the fleet would be SI gasoline engine vehicles by 2050. The orange line represents emissions from SI gasoline vehicles for the optimistic and overoptimistic scenarios, meaning that SI engine vehicles would be completely replaced by BEV and/or HEV.

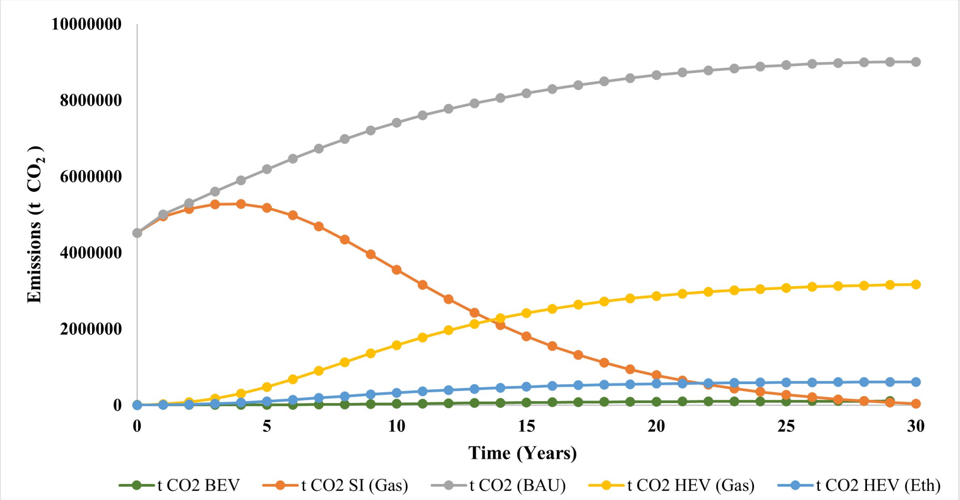
The yellow line represents the emissions from gasoline-powered hybrid vehicles for the optimistic scenario as if SI engine vehicles are being completely replaced by gasoline-powered HEVs by the year 2050. The blue line represents the same optimistic scenario just mentioned, but for HEV running on ethanol. Finally, the green line represents the electricity grid emissions due to BEV consumption for the overly optimistic scenario when vehicles with SI engines would be completely replaced by BEV.

The simulated scenarios indicate the potential impact of reducing CO_2 emissions from passenger cars if the fleet of vehicles with SI engines is replaced by BEVs or HEVs in the next three decades. In the Worst Scenario, gray line in Figure 12, total fleet emissions would be 9 million tons of CO_2 in 2050. However, in the overly optimistic scenario, total emissions would be reduced to 1.4 million tons of CO_2 for BEV fleet. In addition, the optimistic scenario with SI vehicles being replaced by gasoline or ethanol HEVs would be able to achieve a reduction in CO_2 emissions equivalent to the BEV, with values of the same order of magnitude, of around 1.2 million tons of CO_2.

An optional and interesting comparison is shown in Figure 13. The gray line represents the Worst Scenario, the orange line represents the emissions of SI vehicles for the scenarios where these vehicles would be replaced partially by BEV and partially by HEV. The yellow line represents emissions from gasoline-powered hybrid vehicles for the Optimistic Scenario, as if SI-Engined vehicles were replaced partially by 50% by HEV and partially by 50% by BEV by 2050. The blue line represents the same optimistic scenario mentioned only, but for HEV running on ethanol. As before, the green line represents the electricity grid emissions due to BEV consumption for the optimistic scenario, when these vehicles would represent 50% of the fleet.

The results of the simulated scenario shown in Figure 13 are compared as if the SI engine vehicle fleet in the next three decades were reduced to zero and the total fleet was composed of 50% BEV and 50% HEV.

Figure 13 Total CO_2 emissions of the simulated scenarios (see online version for colours)



In the worst scenario, the total emissions would be the same 9 million tons of CO_2 just for a fleet of IS-powered vehicles. However, the 50% gasoline-powered HEV fleet would emit 3.6 million tons of CO_2. Additionally, the fleet with 50% HEV powered by ethanol would result in total emissions of 608 thousand tons of CO_2, while the fleet composed of 50% BEV would represent 108 thousand tons of CO_2.

The simulated scenarios showed the great potential for degreasing CO_2 emissions by replacing the fleet of vehicles with SI engines by BEV and HEV, but it is very important to highlight that although the BEV has shown the greatest reduction in emissions, the HEV running on ethanol it will be an option to reduce emissions in the same order of magnitude as the BEV in the coming decades.

5 Conclusions

The present study proposed a model to estimate CO_2 emissions and energy consumption from the increase in the fleet of electric and light hybrid vehicles, for which a case study was carried out in the city of Brasília, capital of Brazil. The future fleet of vehicles in Brasília was simulated, for the next three decades, applying Gompertz functions to the time series of population growth, GDP growth and vehicle ownership.

In this case study, he evaluated and characterised the errors of using the FTP75 driving cycle to calculate CO_2 emissions instead of real-world driving cycles. The results of the experimental study showed that for the SI vehicle, the average error of CO_2 emissions can reach 12.13% more than the FTP75 for gasoline, in low-speed conditions, while for the HEV, the average error can reach 43.87% during off-peak hours, and the average BEV error can reach 31.16% during peak hours.

The energy efficiency of the vehicles was analysed for the conditions of use at peak hours, resulting in an equivalent energy autonomy of 1.33 km/kWh for gasoline SI vehicles, 1.64 km/kWh for ethanol SI vehicles and 2, 91 km/kWh for gasoline HEV vehicles. These values were compared with the BEV's autonomy of 13.8 km/kWh, confirming the gain in energy efficiency of the electric propulsion system.

The modelled scenarios simulated the total CO_2 emissions up to the year 2050. In the Worst Scenario, the total emission of the fleet in the year 2050 becomes 9 million tons of CO_2. In the Optimistic Scenario, with the fleet composed of 50% BEV and 50% HEV powered by gasoline, the emission becomes 3.6 million tons of CO_2 by 2050, and if the fleet is composed of 50% BEV and 50% HEV powered by ethane, emission is now 1.2 million tons of CO_2. In the Excessively Optimistic Scenario, total emissions would be reduced to 1.4 million tons of CO_2 for a fleet composed of BEV.

The simulated scenarios indicated the potential for decarbonising CO_2 emissions by replacing the fleet of vehicles with SI engines by BEV and HEV. Furthermore, although the BEV fleet had the greatest potential to reduce CO_2 emissions, the ethanol-powered HEV would be an option to reduce emissions by the same order of magnitude as the BEV in the coming decades.

Furthermore, it is important to develop models, such as the one proposed in the present study, which calculate and simulate future scenarios of increasing the fleet with electric propulsion, compared to the options for using Brazilian ethanol in hybrid vehicles, and determine the net reduction in energy consumption and CO_2 emissions in an electrical matrix with a high share of renewable resources. Thus, the proposed model will be able to subsidise decision-making on public policies and energy planning, in order to minimise any impacts on the energy matrix, city mobility, public health and the environment.

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