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ORIGINAL ARTICLE

# Carbon dioxide emissions by tetrafuel technology vehicles (gasoline-ethanol-NGV) with air conditioning on and off

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**Abstract** This research aims to estimate and compare $CO_2$ emissions from fuel consumption by motor vehicles operating with different types of fuel, such as gasoline (E00), gasoline blended with 25% anhydrous ethyl alcohol fuel (E25), hydrous ethanol, and natural gas vehicles (NGV), as well as showing the impacts of the air conditioning of the vehicle on $CO_2$ emissions. The $CO_2$ emissions from the fuel consumption of a vehicle with tetrafuel technology in roller dynamometer that simulates an urban path and road are estimated. The tests were carried out on a climate chamber under controlled conditions, and the results were corrected for a default condition, 101,325 kPa and 20 °C. The study demonstrates that $CO_2$ emissions, by the very burning of liquid and gaseous fuels in an Otto cycle engine, essentially depends on the mechanical characteristics of the propellant, on the specific weight of the fuel, and the conditions of operation of the vehicle and not only of the calorific value of fuel. The results showed that the NGV fuel, to deliver the same torque and power of ethanol to the motor of the vehicle, would be producing 13.5% more of $CO_2$ in urban areas and at least 9.5% on the road with the air conditioning system turned off. With the air conditioning system turned on, the four kinds of fuels in urban route conditions showed similar values of $CO_2$ as in the road; the NGV that presented $CO_2$ emissions is in about 12% more than other fuels, which had equivalent values. For a vehicle to achieve its best performances in combustion and reduce its $CO_2$ emissions, it is necessary to have an individualized propellant, prepared specifically for the type of fuel it might be using.

**Keywords** Greenhouse effect · Vehicular emissions · Fuel consumption · Pollution · Carbon dioxide

## Introduction

Currently, oil is the main source of energy that feeds the developing industrial system and, especially, through the automobile, penetrated deep into the global economic structure. With the increased use of road transport, this greatly increased the demand for fossil fuels (gasoline, NGV, diesel, etc.) and bleach (methanol and ethanol). As each fuel has physico-chemical combustion of such fuels, this produces emission content with a high photochemical activity with unique features that impact on the air quality. The mobility sector consumes approximately 30% of all the energy available in the world and is responsible for half of the oil consumption available (Dargay and Gately 1996, 1999).

About 80% of the energy consumed in the world supplies still comes from oil and gas: non-renewable fuels that, when used, become the main sources of $CO_2$ emissions, which increase the intensification of the greenhouse effect and other problems just like acid rain and lung diseases, strengthening the theory of using

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alternative fuels. Brazil serves as an example for the use of flex fuel vehicles using fuels that can vary between 20 and 100% ethanol. From the oil crisis in the 1970, ethanol stands out as an important biofuel in the world energy scene. In certainty of the scarcity and high price of fossil fuels, alternative fuels just like ethanol, NGV, gasoline, and ethanol blends get featured. In addition to Brazil and Paraguay in the fuel ratio of 20 and 27% by volume of ethanol mixed with gasoline, several countries, such as the USA, China, European Union, Japan, India, South Africa, Philippines, Mozambique, Nigeria, Kenya, and Colombia, among others, use between 10 and 15% of ethanol mixed with gasoline to supply their fleets. Other countries like Canada, Chile, the Sudan, Uruguay, Mexico, Argentina, Australia, and Taiwan, among others, are using up to 5% ethanol mixed with gasoline.

The NGV is a versatile fuel that can replace several petroleum products. Its importance can be explained by various reasons, such as sulfur-free burning, where it does not emit particulate matters (ash, nitrides, anhydrides, etc.) which cause the acid rain, which is harmful but can produce high levels of $CO_2$ and greenhouse. In automobiles, it is a substitute alternative to gasoline and ethanol fuels. It is about a total of burning fuel, which leaves no residues or ashes. Such advantages justify the participation of the NGV in the world energy matrix.

According to the reports submitted by the Intergovernmental Panel on Climate Change cited by Baird (2002), the gaseous pollutants from vehicular source are one of the causes of relevance in the deterioration of air quality, intensifying due to disordered urban growth, coupled with the increase in the number of vehicles, mostly from the public-private transport systems. Faced with the prospect that the increase in $CO_2$ emissions, during this century, it can result in a significant rise of global air temperature with the resulting climate changes; national governments, researchers, and other organizations have debated about how future emissions can be minimized in the Earth's atmosphere, leaving shore, however, so that there might be economic growth.

There is a global concern about the levels of emissions of greenhouse gases, in particular $CO_2$ levels, focused on the burning of fossil fuels or bleached. For being a non-toxic gas $CO_2$, there are no restrictions or sanctions on its issue; however, there is a government incentive through reduced tax rates for those who directly or indirectly contribute to the mitigation of this gas. For auto industries, tax incentives encourage the development of technologies that contribute to the vehicular energy efficiency and developing alternative fuels.

In the last decades, the use of NGV gas, bleached as methanol and ethanol, pure or mixed with gasoline, has grown due to the benefits introduced in world energy matrix, in addition to being less aggressive to the air quality. Consequently, there is a need for studies of the possible impacts of the greenhouse gas, $CO_2$, about the burning of these fuels in internal combustion engines used in motor vehicles. To this end, this study shows the different concentrations of $CO_2$ emitted by a motor vehicle tetrafuel technology when it is subjected to a simulated urban and road route, using different fuels: pure gasoline (E00), gasoline with 25% anhydrous ethyl alcohol fuel (E25), hydrous ethanol and natural gas vehicles (NGV), and with or without air conditioning entered. In summary, this research seeks to answer the following question: in a vehicle technology, which used fuel does tetrafuel will produce as much $CO_2$ in exhaustion with the air conditioning turned off and on?

Following this text is presented a review of relevant studies on $CO_2$ emissions and, then, the methodology used for testing of consumption and $CO_2$ emissions. A result section with proper statistical treatments and discussions on the numbers is presented in the form of bar charts. Finally, are given the conclusions about the comparative study of $CO_2$ emissions, when using different gaseous and liquid fuels, in a vehicle with tetrafuel technology and without air conditioning on, urban routes and road.

## State of art

According to studies submitted by DeCicco and Thomas (1998), emissions of new vehicles, as determined in the laboratory, essentially depends on two key factors: the characteristics of the vehicle and, another factor, the type of fuel used. By different factors, actual emissions of the vehicle in use vary differently from those measured in laboratory. Yet, according to the authors, the vehicular emission reduction is only possible by the using of fuels with low potential polluter, with the use of technologies in the construction of vehicles, motors with greater energy efficiency, and control devices. In addition, the compatibility between the fuel and the engine is crucial for the full exploitation of the benefits, both in improving performance and in mechanical maintenance, as emissions of gases like $CO_2$ by reducing demand for fuel.

According to Ciuffo and Fontaras (2017), vehicles and their technologies are changing rapidly and political regulations must accompany these changes in same speeds. In those terms, European countries have updated the emission test procedure for the type-approval of vehicles, adopting the Worldwide Harmonized vehicle Light duty Test Procedure (WLTP). It was necessary to introduce a new modeling tool for certification of vehicles, along with new software-based instruments, which had to be developed and implemented. A vehicle using a software certification can reduce the chances of manipulations on experimental tests. Improving the type approval of the vehicle in Europe demanded the development of a software CO2MPAS. It is a simulation model to calculate the fuel consumption and $CO_2$ emissions. The CO2MPAS will be used until 2020 in the approval of any light vehicle in Europe.

Fontaras et al. (2016) showed in a study that a European Commission is preparing a new regulatory initiative to monitor $CO_2$ emissions and fuel consumption of heavy-duty vehicles in Europe. The new methodology is based on a combination of tests of components and computer simulation of fuel consumption. Experiments were carried out in two trucks, Euro V and Euro VI. The measurements were carried out on the chassis dynamometer and road. A simulation software was used to simulate the tests. The simulation results coincide with the dynamometer tests, with a detour around ± 2–4% fuel consumption in comparison with the measured value. On the road, the fuel consumption was about ± 3.5% compared to simulation. Given the variability of the actual measurement ($\sigma \geq 2\%$), it was concluded that certification can be based on this approach and have a high representative. The simulation can provide with accuracy differences in fuel consumption and $CO_2$ between different vehicles.

Santos (2008) studied the energy consumed by the use of fossil fuels and greenhouse gas emissions for light vehicles. The methodology recommended by the "Revised 2006 IPCC Guidelines for National Greenhouse Gas Inventories" was used to evaluate the impact of adding ethanol to gasoline in those emissions. The assessment was made by two methods—"top-down" and "bottom-up." The results show that the addition of ethanol substantially reduces the greenhouse gas emissions from light vehicles. According to the author, due to the increase of the percentage of ethanol in gasoline, 20 to 25% in the period between the years of 2001 and 2002, $CO_2$ emissions were avoided through the use of fuel ethanol, from 12100 to 15000 Gg per year, with an increase of 24%.

Baddu et al. (2016) investigated the effect on the emission and propagation of calls to different proportions of the mixture of gasoline and ethanol in a constant volume Chamber. The parameters included different types of injection pressure, flame propagation characteristics, and fuels with different proportions of gasoline and ethanol mixture. As a result, the burning rate increases when the percentage content of ethanol in gasoline has increased. Therefore, the largest area of spread of the flame to 0.2, 0.3, and 0.4 MPa was led by gasoline containing 15% ethanol (E15), followed by gasoline with 10% ethanol (E10), gasoline containing 5% ethanol (E5), and pure gasoline (E00), respectively. According to the authors, the increase in the percentages of ethanol blends with gasoline can raise the $CO_2$ emission due to improvement of combustion process.

Ristovski et al. (2005) conducted a study of the $CO_2$ emissions of a fleet of six passenger cars, Ford Falcon, with dedicated NGV gas engine and five passenger cars, Ford Falcon, fueled with unleaded gasoline. The tests were conducted on a chassis dynamometer at four different speeds 40, 60, 80, and 100 km/h. In general, the NGV was considered a fuel "cleaner," although in most of the results, the differences were not statistically significant due to the large variations between different vehicle emissions. The emission factors of the number of particles ranged from the 1013 to 1011 $km^{-1}$ and were 70% less with the NGV compared to sulfur-free gasoline. The corresponding differences of the emission factor between the two fuels were small and varied the order of 10 μg/km to 40 km/h to about 1000 μg/km to 100 km/h. The $CO_2$ emission factors varied from about 300 to 400 g/km to 40 km/h, falling with increasing speed in about 200 g/km to 100 km/h in all speeds; the values were 10 to 18% larger with sulfur-free gasoline than with NGV.

Zhiliang and collaborators (2014) studied 20 taxis-fuel emissions fed with natural gas vehicles (NGV). The tests were carried out using portable emissions measurement system (PEMS) in real driving conditions in Yichang, China. The results of the tested vehicles showed that the emissions of $CO_2$, CO, HC, and $NO_x$ of cabs using natural gas vehicles tested in urban traffic were 1.6, 4.0, 2.0, and 0.98 times larger than in driving conditions on the road, respectively. Comparing the values of gasoline vehicles indicated in the literature, emissions of $CO_2$ and CO of NGV taxis tested were lower. However, significant increases were observed in the HC and $NO_x$ emissions. Thus, they concluded that more attention should be paid to NGV vehicles emissions. As for the NGV-fueled bi-fuel taxi currently in use, the Environmental Protection Department should strengthen the inspection to reduce emissions of these vehicles.

Canakci et al. (2013) performed an experimental investigation of the effect of mixtures of ethanol-gasoline and methanol-gasoline in the Otto cycle engine performance and combustion characteristics, which used a vehicle with a system of four-cylinder, four-stroke, multipoint injection system. The tests were conducted on a chassis dynamometer with the vehicle in two different speeds (80 and 100 km/h) and four powers of different wheel (5, 10, 15, and 20 kW). The emission values measured with the use of gasoline containing 5% ethanol (E5), gasoline with 10% ethanol (E10), gasoline with 5% methanol (M5), and gasoline with 10% methanol (M10) were compared to those of pure gasoline. The results revealed that in the engine fueled with blends of ethanol-gasoline or methanol-gasoline, emissions of CO and $CO_2$ decreased for all potencies of the wheels at the speed of 80 km/h. However, for speed of 100 km/h, there were more complex trends in emissions, especially to the power of 15 kW wheel. The study verified that the equivalence relation of fuel-air, temperature of the exhaust gases, and fuel consumption increased with the increase of the percentages of ethanol and methanol compared to pure gasoline. All exhaust gas emissions reduced with the use of E10.

Weilenmann et al. (2005) investigated the influence of air-conditioning activity in emissions and fuel consumption of passenger cars. Besides the USA, few US MOBILE6 study data is available about the impact of air conditioning (A/C) on vehicles, which tested six gasoline-powered passenger vehicles in different climatic conditions. A series of tests were carried out separately for the initial cooling and stationary condition to keep the interior of the vehicle cooled. The authors concluded that $CO_2$ emissions and fuel consumption increase with the thermal load. In addition, to cause a considerable increase in carbon monoxide (CO) and hydrocarbons (HCs), the cooling tests highlight significant differences between vehicles but show that the operation of A/C for the initial cooling the passenger compartment overheated flier does not result in additional emissions for the fleet as a whole.

Studies show that changes in vehicle designs, through materials and more efficient mechanisms, reduce the size of vehicles using alternative fuels, reduction of the activities of transport of passengers and cargo by the change of the pattern of land use, transport systems, displacement patterns and lifestyles, and the shift to less intensive transport modes into energy; the transportation sector can reduce $CO_2$ emissions in 2025, up to 40% (Michaelis and Davidson 1996).

Martin et al. (2017) present a methodology to determine the impact of engineering improvements in vehicles, on fuel consumption and $CO_2$ emissions, using the parameters of the vehicle and the Powertrain within a Bayesian framework. The results showed how changes in vehicle design (e.g., weight, engine size, and compression ratio) result in improvements in fuel consumption on average of 5.6 L/100 km in 2014 and 3.0 L/100 km in 2030. The authors concluded that improvements in internal combustion engine result in a reduction in $CO_2$ emissions of $48 \pm 10\%$.

The NGV is a mixture of hydrocarbons in the gaseous state at normal temperature and pressure. It has a lower density than gasoline, and its composition is much simple. He provides about 8% more energy per unit of weight than unleaded gasoline. Although it is expected that the operation of the vehicle with NGV is more efficient than with sulfur-free gasoline in terms of fuel consumption and mileage, in practice, this is not seen unless the engine design is optimized for the NGV fuel (Gamas et al. 1999; Caton et al. 1997). In these cases, the NGV gas engines have parameters of performance and efficiency as good as better than gasoline engines, while showing lower exhaust emissions. The NGV usually produces 15% less $CO_2$ than sulfur-free gasoline, since the equipment's and NGV engines are installed and maintained correctly.

In the absence of additional climate policies, in studies conducted by the Intergovernmental Panel on Climate Change IPCC (2007), around the year 2100, it is envisaged that the air temperature increases 3.2 °C, considering the worst-case scenario emissions of pollutants in the atmosphere. A further increase in temperature would occur after the year 2100, but the IPCC projections do not go beyond this year. In the IPCC, the global average temperature will rise during this century between 1.1 and 6.4 °C above the average of the years 1980 to 1999, depending on the socio-economic scenarios IPCC (2000). This uncertainty ranges of the variable on the amount of greenhouse gases will be issued in the future and the uncertainty about climate sensitivity.

## Instrumentation and methodology

Planning for data collection, the instruments needed the allocation of resources, the vehicle, and the location for the execution of the tests, along with a methodology applied systematically guarantee results with high degree of reliability. In Fig. 1, a flowchart is depicted and instrumentation schema is used. The flowchart shows the path taken to achieve the objectives of this work.

### Experimental apparatus

The tests were carried out on a vehicle model Siena of serial production, cordially provided by Fiat Chrysler Automobiles with internal combustion engine spark ignition, 1.4 liters of four times, tetrafuel technology, moved to pure gasoline E00, E25 gasoline, hydrated ethanol, and NGV, with four cylinders and eight valves. The technical characteristics of the vehicle are listed as Table 1.

### Measuring systems used

The acquisitions were monitored by measuring systems fitted on the vehicle throughout the operation. The

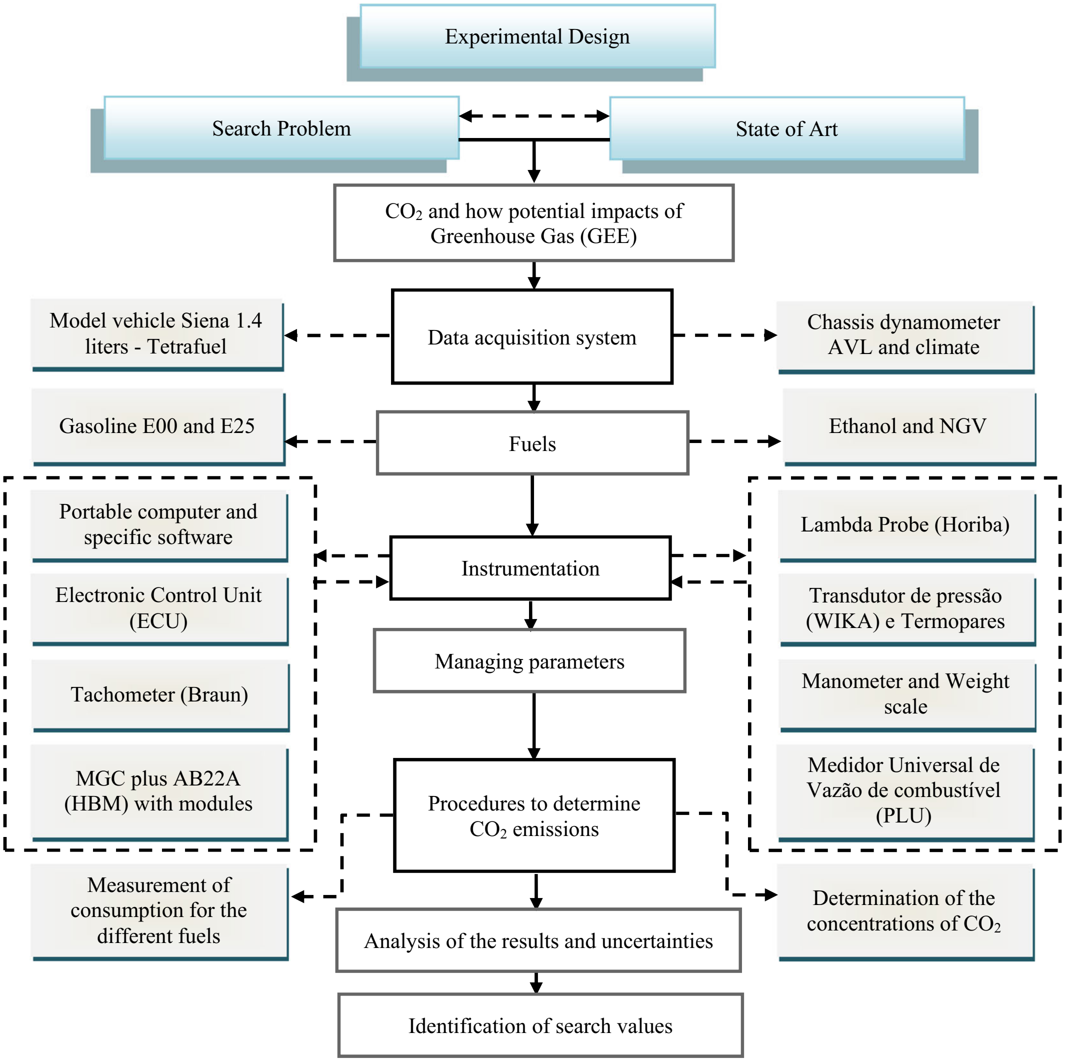


**Fig. 1** Experimental instrumentation flowchart

**Table 1** Technical characteristics of the vehicle Siena tetrafuel

| Vehicle/model | Siena EL tetrafuel |
|---|---|
| Engine | 1.4 liters 8 V tetrafuel |
| Cycle | Otto |
| Fuel | Gasoline (E00) and (E25), ethanol and NGV |
| Number of cylinders | 4 |
| Number of valves | 2 overhead camshafts |
| Compression ratio | 10.35 ± 0.15 |
| Maximum power—gas | 58.9 kW at 576 rad/s |
| Maximum power—ethanol | 59.6 kW at 576 rad/s |
| Maximum power—NGV | 50.0 kW at 576 rad/s |
| Tank capacity | 48 liters |
| Cylinder capacity | $2 \times 6.5$ m$^3$ = 13 m$^3$ to CNTP and pressure 200 bar |
| 4th speed gear | 135 km/h |
| Minimum speed | 89 ± 5.2 rad/s |

Source: manufacturer's datasheet

measurements are performed using a portable computer, an electronic unit that interfaces with the ignition/injection and measuring equipment of the equivalence ratio of the fuel/air mixture (Horiba). The computer receives and records the information provided by the electronic control unit (ECU) of working parameters for she managed. The parameters monitored by the electronic control unit were as follows: engine rpm, butterfly valve, injection time, coolant temperature, air temperature, angle plugs, lambda probe signal injection system, and position of the stepper motor.

For the realization of the following instruments, vehicular tests were used: universal fuel flow meter (PLU) model 116H—factor K43.84; digital display for the universal flow meter; tachometer (Braun GMBH—Model Moviport C118); chassis dynamometer (AVL—Zollner Model Compact 48″—200 km/h—150 kW—10,000 N); climate chamber; pressure transducer (WIKA); MGC plus AB22A (HBM); thermocouple type K—range − 30 to 1200 °C; tire gauge (Excel Pneutronic) range 0 to 70 bar; precision gauge range ± 1.0%; scale instruments (Alfa Model 3104 B); and modules MGC—tension plates of temperature, power, and speed.

The universal fuel flow meter—PLU (model 116H, manufactured by AVL LIST GmbH)—measures continuously and simultaneously the fuel flow with flow rate of 0.3 to 60 L/h. The measurement is performed directly on the power supply line of the injection system/admission. The measurement signals are amplified in a MGC plus measuring system (HBM). The data is continuously recorded in the computer and processed by Catman® measuring Software from HBM for configuration, visualization, and analysis of measurements.

The chassis dynamometer (AVL—Zollner Model Compact 48″—200 km/h—150 kW—10,000 N) is used for the simulation of urban road route to estimate $CO_2$ emissions. Speeds and backlogs are simulated taking into account the rolling resistance imposed on the roller dynamometer. With this equipment installed in a climate chamber, it is possible to simulate the speed of the vehicle in a lab environment with the temperature, humidity, and pressure monitoring during all tests.

The temperature of the lubricating oil and cooling fluid has been monitored by thermocouples. A data acquisition system was used to control the ignition and injection time, plus acquisition of temperature, rotational speed of the engine injection time, and pressure on admission. The electro fan input signals were also monitored.

## Execution of the tests

The standardization of consumer tests for motor vehicles, according to NBR 7024 Brazilian technical standards Association ABNT (2002), prescribes a method for measurement in automotive light road vehicles, through driving cycles developed chassis dynamometer, which simulate the use of the vehicle in urban transit and road, according to NBR ABNT 6601 (2005). This standard adopts the American FTP-75 routine as standard for the testing of emissions in Brazil. However, this FTP-75 cycle does not consider pendency on route. So, for this research, we used a simulation of an urban cycle and on a chassis dynamometer. The urban route represents the central area of the city of Belo Horizonte/Minas Gerais/Brazil (Fig. 2), paved track, and an altitude of 852 m in relation to the level of the sea, whose non-speeds over 60 km/h and the trading of marches occur whenever the rotation hits 314.15 rad/s, as the default for the tests on chassis dynamometer. This change of rotation is given by the vehicle manufacturer as the best performance for the exchange type used in a vehicle.

The road route (Fig. 3), between the towns of Bayou/MG with 786 m high and the town of Carmópolis/MG/

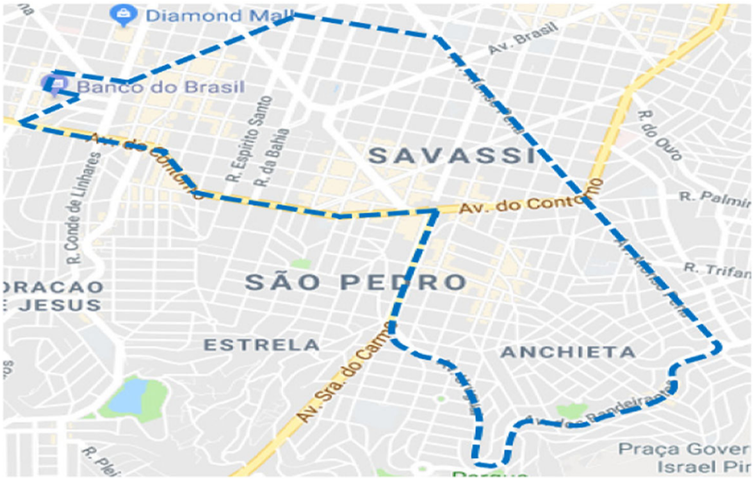


**Fig. 2** Urban route cycle for $CO_2$ emissions. Source: Guide Four Road Wheels (2013)

Brazil with 841 m high relative to sea level, paved track and with maximum permitted speed of 80 km/h. BR 381 is a simulated federal highway between the snippets of 513 and 594 km, totaling an 81-km path covering real situations with flat track ascending and descending backlog. Following the standard recommended by the vehicle manufacturer, the gear changes occurred when the engine speed reaches 314.15 rad/s.

The tests were carried out with the vehicle fueled with gasoline E00, gasoline E25 with ethanol and NGV, under-conditioned temperature climatic chamber. All the results are corrected for a pressure of 101,325 kPa and 25 °C temperature. The speeds in urban pathway are kept below 60 km/h and the road course, maximum speed of 80 km/h, depending on the legislation of local transit.

The acquisitions are carried out with the vehicle in a stable phase, warm, coolant motor between 90 and 93 °C with hood closed as advocating technical standard ABNT NBR 6601 (2005). The vehicle is put on the chassis dynamometer roller with its gear taken by the dynamometer roll, until stabilization and speed; before the start of the measurements, it is put through a period of 300 s for conditioning and then start the acquisitions. The period of preparation is necessary to stabilize the engine and its temperature; ensuring similar tests for all configurations, the study aims to compare $CO_2$ emissions with the vehicle already in circulation and properly heated.

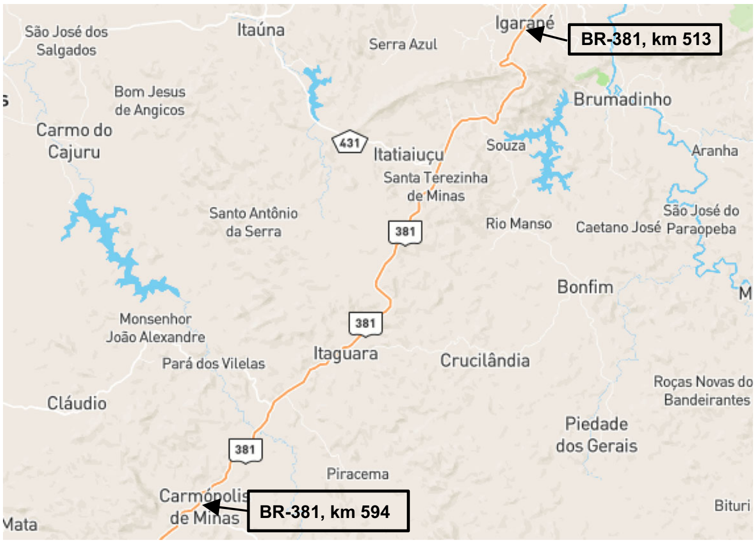


**Fig. 3** Road course cycle for $CO_2$ emissions. Source: Guide Four Road Wheels (2013)

All charts and tables were constructed from the values fixed for three measurements of each condition, considering their combined uncertainty and its truncation errors imposed by numerical methods.

## Calculation of $CO_2$ emissions from fuel consumption

### *Model formulation*

For the combustion reaction, the fuel reacts with oxygen from atmospheric air and, not always, this is a complete combustion reaction that produces only $CO_2$, $H_2O$, and $N_2$. The Eq. (1) represents the most significant products of incomplete combustion of the fuel in the combustion chamber (Heywood 1988; Sodré 2000):

$$C_n.H_m.O_r + \left(n+\frac{m}{4}-\frac{r}{2}\right).\frac{1}{\varnothing}.O_2 + \left(n+\frac{m}{4}-\frac{r}{2}\right).\frac{1}{\varnothing}.N_2 \rightarrow \rightarrow aCO_2 + bH_2O + cN_2 + dH_2 + eHC + fNO_x + gCO + hCH_3CHO + i\mathrm{HCHO} \quad (1)$$

The amount of air varies according to the type of engine and is relevant factor on concentration of the gases regulated in exhaustion, that is because by varying the amount of air in the fuel/air mixture, incomplete combustion may occur with high concentration of exhaust emission. On the other hand, the complete burning of this fuel will actually produce natural carbon dioxide, $CO_2$ (Costa and Valle 2013).

### *Emission of $CO_2$ per liter of fuel for each fuel studied*

Carbon dioxide, although it is not a toxic gas, is a product of complete combustion of fuels that contribute significantly to the greenhouse effect.

Representing the chemical formula of pure gasoline for $C_8H_{18}$ (iso-octane), stoichiometric combustion reaction ($\Phi = 1$) can be written according to Eq. (2). This equation shows the maximum amount of $CO_2$, produced in the burning of fuel, by the internal combustion engine Otto cycle.

$$C_8H_{18} + \frac{1}{\varnothing}\left(8+\frac{18}{4}\right)\left(O_2 + \frac{79}{21}N_2\right) \rightarrow 8CO_2 + 9H_2O + 47.02N_2 \quad (2)$$

Being the iso-octane density equal to 0.75 kg/l (Perry and Chilton 1973), for each liter of iso-octane ($C_8H_{18}$) consumed in the reaction of combustion, there are produced 2315 kg of $CO_2$.

For ethanol ($C_2H_5OH$), the stoichiometric combustion reaction ($\Phi = 1$) is

$$C_2H_5OH + (3)\frac{1}{\varnothing}O_2 + (3)\frac{1}{\varnothing}\left(\frac{79}{21}\right)N_2 \rightarrow 2CO_2 + 3H_2O + 11.28N_2 \quad (3)$$

In this case, with the density of ethanol equal to 0.79 kg/l (Russomano 1987; Costa and Valle 2013), for each liter of ethanol ($C_2H_5OH$) consumed by the reaction of combustion are produced 1512 kg of $CO_2$.

In the state, anhydrous ethanol is miscible in gasoline (iso-octane) and this allows the use in automobiles, alcohol, and gasoline mixture. The amount of ethanol mixed with gasoline has varied over the years between 20 and 27%, in volumetric basis. A car circulating 10000 km per year, with gasoline containing 25% of anhydrous alcohol and maintain an average consumption of 10 km per liter, will issue, in theory, a maximum of the following annual rate of $CO_2$:

$$(0.75 \times 2.315 + 0.25 \times 1.512)\left(\frac{\mathrm{kgCO_2}}{L}\right) \times 10000\frac{km}{\mathrm{year}} \times \frac{1}{10}\frac{\mathrm{liter}}{km} \times \frac{1}{1000}\frac{L}{\mathrm{liter}} = 2.114\frac{\mathrm{tCO_2}}{\mathrm{year}} \quad (4)$$

This calculation does not consider the portion consumed by the vehicle when you stopped idling.

The NGV is a mixture of light hydrocarbons and to a lesser concentration with inert gases and oxygen, whose compositions feature with limit values: the methane ($CH_4$) 86%, ethane ($C_2H_6$) 10%, propane ($C_3H_8$) 3%, butane ($C_4H_{10}$) 1.5%, oxygen ($O_2$) and the inert ($N_2$ and $CO_2$), with a value of 4% in volume, as in the Brazil (2002). However, this value may vary depending on several factors, especially the geological and those relating to the extraction process and obtaining. Soon, the complete combustion of NGV, used in motor vehicles, can be represented by Eq. (5).

$$0.905CH_4 + 0.086C_2H_6 + 0.009C_3H_8 + 1.052O_2 + 1.052(3.76)N_2 \rightarrow 1.104CO_2 + 2.104H_2O + 1.052(3.76)N_2 \quad (5)$$

From this equation, whereas NGV-specific mass equal to $7.77 \times 10^{-4}$ kg/l, on each liter of NGV-burning, production is $2162 \times 10^{-3}$ kg of $CO_2$.

### Physico-chemical properties of fuels

The tetrafuel technology offers the opportunity to use different fuels, gasoline room E00, E25 gasoline, ethanol, and NGV, for a same Otto-cycle engine. St. fuels with physico-chemical characteristics (calorific value, specific weight, stoichiometric ratio, etc.) are well influenced directly in the vehicle performance and $CO_2$ emissions. The calorific value is the amount of heat that the fuel can generate when it is burned. As a general rule, lower calorific value fuels generate less heat and, consequently, are consumed faster; on the other hand, the less specific weight fuels also have smaller combustion efficiency. Some of the main physical-chemical characteristics of the fuels used in this work are presented in Table 2.

## Results

The results of emissions of carbon dioxide, $CO_2$, were estimated from the demand consumed of each fuel in simulation of the urban routes and road and chassis dynamometer. Simulations were considered with the air conditioning turned off and with the air conditioner on. $CO_2$ emissions were also estimated for the vehicle idling and operating in conditions of constant speeds to 60, 90, and 120 km/h.

The $CO_2$ emissions were determined considering the uncertainty sources combined, for an occurrence of the measured values corresponding to the 95% confidence interval. As the carrier tests are quite sensitive to the vehicle's driving condition, statistical studies were carried out to determine the uncertainties of the measurements of the tests performed, using the methodology of Kline and McClintock (1953). In the case random of variables, for the results of the measurements of $CO_2$ emissions with different fuels, the maximum uncertainty was determined according to the *t*-distribution "Student" Pedro (1977). To increase the reliability, it was based on measurements carried out with the same vehicle and pilot.

### $CO_2$ emissions

The results of $CO_2$ emissions by burning of different fuels in internal combustion engine vehicle tetrafuel technology applied are presented in Figs. 4, 5, 6, 7, and 8, exploring the different operating conditions of the vehicle. These results consider the complete combustion of fuel in the combustion chamber.

In Fig. 4, it is represented the $CO_2$ emissions for the vehicle to operate with different fuels without air conditioning on, in simulated urban routes and road.

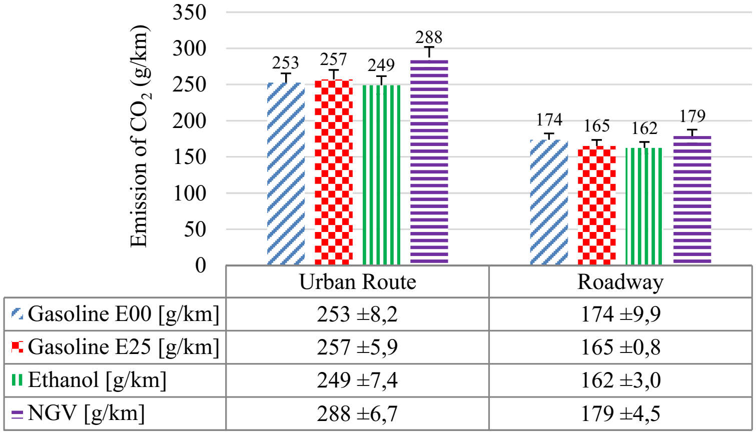
The NGV gaseous fuel produced greater quantities of $CO_2$, in both the urban and road route, followed by gasoline E25. Ethanol is the fuel that produced smaller amounts of $CO_2$, around 13.5% in simulated urban pathway, and 9.5% in simulated road route, with air conditioning turned off, when compared to the results of the NGV. The results of liquid fuels E00, E25, and ethanol are statistically equivalent, with a trend of gasoline E00 and E25 produce greater quantities of $CO_2$ than ethanol. Figure 5 shows the results of $CO_2$ emissions with the vehicle's air conditioner on.

Along the way, although the four fuels differ very closely, E25 gasoline followed by gasoline E00 showed tendency to produce greater quantities of $CO_2$ emissions. Ethanol fuels and NGV in urban route did not show difference between them. Already in route road, gasoline fuel, gasoline E25, and E00 ethanol present values statistically equivalent and NGV gaseous fuel, which emits around 10.5% more $CO_2$ than these fuels.

**Table 2** Physico-chemical characteristics of the fuels 0.101 MPa and 20 °C

| Properties | Gasoline (E00) | Gasoline (E25) | Hydrous ethanol | NGV |
|---|---|---|---|---|
| Specific mass (kg/m$^3$) | 750 | 770 | 790 | 0.777 |
| Calorific value (MJ/kg) | 43.92 at 46.50 | 40.54 at 42.76 | 27.19 at 29.82 | 42.98 at 52.19 |
| Flash point (K) | 233.15 | 230.15 | 286.15 | 85.35 |

**Fig. 4** $CO_2$ emissions, with the vehicle without air conditioning in urban and road course



| | Urban Route | Roadway |
|---|---|---|
| ▨ Gasoline E00 [g/km] | 253 ±8,2 | 174 ±9,9 |
| ▦ Gasoline E25 [g/km] | 257 ±5,9 | 165 ±0,8 |
| ▥ Ethanol [g/km] | 249 ±7,4 | 162 ±3,0 |
| ▤ NGV [g/km] | 288 ±6,7 | 179 ±4,5 |

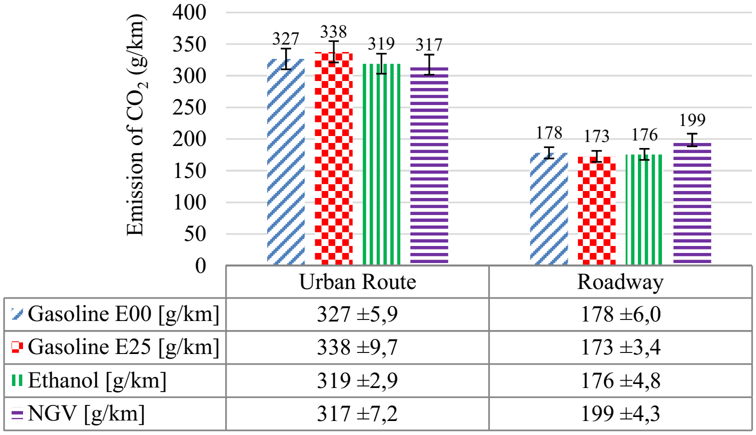
Tests for estimates of $CO_2$ concentrations, whereas the test vehicle is with constant speeds of 60, 90, and 120 km/h, are presented in Figs. 6 and 7, without air conditioning and with air conditioning on, respectively.

With the speeds to 60, 90, and 120 km/h and the air conditioning off, the NGV gaseous fuel produced higher concentrations of $CO_2$, around 15.5% at a speed of 60 km/h and 17.7% at 90 and 120 km/h, compared to ethanol. When compared with gasoline E00, the NGV issued an average of 9.0% more $CO_2$ in three speeds and in relation to the percentage increase in E25 gasoline as it increases speed, 11.0% being the 60 km/h, 15.1% to 90 km/h, and 30.2% to 120 km/h. The results between ethanol and gasoline E25 are very close, but with slight tendency to E25 gasoline, at 60 and 90 km/h. At the speed of 120 km/h, the ethanol yields, around, 15.1% more $CO_2$ than gasoline E25. The four fuels emit, on average, 42,0% more $CO_2$ at the speed of 120 km/h when compared with the emissions at the speed of 60 km/h. The results with the air conditioning turned on are presented in Fig. 7.

The results in operating speeds with air conditioning on confirm the highest $CO_2$ emissions by NGV fuel. In steady speed to 60 km/h, the NGV emits 23.0% more $CO_2$, at speed 90 km/h around 15.3% and, in steady speed, 120 km/h, 22.2% more that the E00, E25, and ethanol fuels. The fuels, gasoline E00, E25, and ethanol, showed values statistically equivalent in the $CO_2$ emissions. Tests on the vehicle operating on minimum rotation (89 rad/s) were also carried out (Fig. 8).

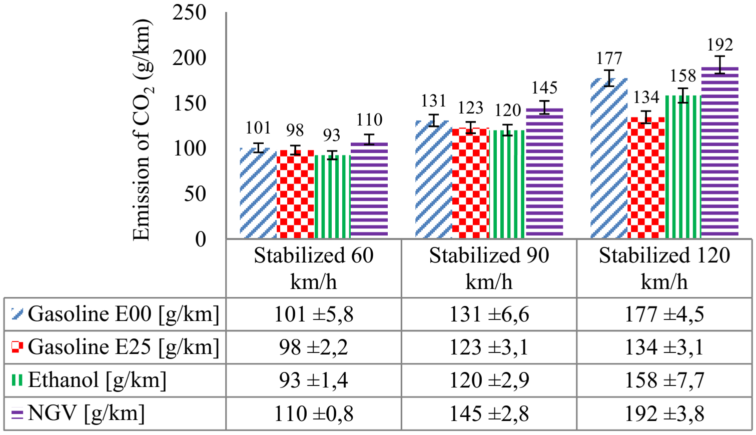
The trend for more $CO_2$ emissions by NGV also follows to the vehicle in minimum rotation. In this mode of operation, the NGV fuel, issued 55.4% more $CO_2$ when compared with gasoline E00, 53.1% compared to E25 gasoline and 57.4% compared to ethanol, with air conditioning turned off. With the air conditioner on, these percentages were 39.9 to 40.3% to E25 and E00 and 40.9% for ethanol. Among the operating liquid fuels

**Fig. 5** $CO_2$ emissions with the vehicle with air conditioning in urban and road course



| | Urban Route | Roadway |
|---|---|---|
| ▨ Gasoline E00 [g/km] | 327 ±5,9 | 178 ±6,0 |
| ▦ Gasoline E25 [g/km] | 338 ±9,7 | 173 ±3,4 |
| ▥ Ethanol [g/km] | 319 ±2,9 | 176 ±4,8 |
| ▤ NGV [g/km] | 317 ±7,2 | 199 ±4,3 |

**Fig. 6** $CO_2$ emission at 60, 90, and 120 km/h without air conditioning



| | Stabilized 60 km/h | Stabilized 90 km/h | Stabilized 120 km/h |
|---|---|---|---|
| ▨ Gasoline E00 [g/km] | 101 ±5,8 | 131 ±6,6 | 177 ±4,5 |
| ▦ Gasoline E25 [g/km] | 98 ±2,2 | 123 ±3,1 | 134 ±3,1 |
| ▥ Ethanol [g/km] | 93 ±1,4 | 120 ±2,9 | 158 ±7,7 |
| ▤ NGV [g/km] | 110 ±0,8 | 145 ±2,8 | 192 ±3,8 |

with air conditioning turned off, ethanol emits on average 10.0% less $CO_2$ when compared to E25 gasoline and 4.5% less than gasoline E25. With the air conditioning turned on, there is no statistical difference in $CO_2$ emissions between the three liquid fuels.

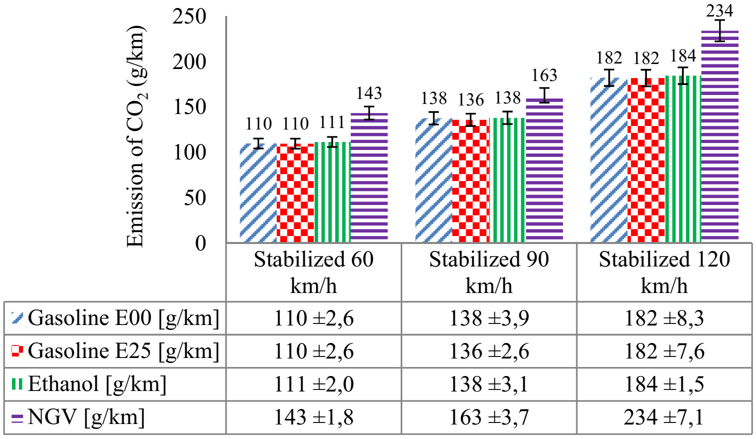
The results show that the liquid fuels have a higher sensitivity with inlet and outlet air conditioning, that is, operating with liquid fuels; $CO_2$ emissions with air conditioning on can increase of 32.7 to 28.9% to E25 and E00, 34.6% for ethanol, and, in more modest amount with the NGV, 9.4% increase in $CO_2$ emissions, when the air is inserted.

## Conclusions

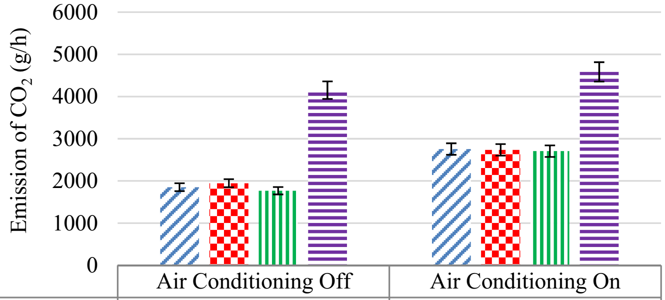
The tetrafuel engines are based on the Otto cycle, with a motor calibration that tends to fit the type of fuel injected into the combustion chamber. The stoichiometric ratio of each fuel is as follows: gasoline E00 equals to 14.7:1, E25 gasoline equals to 13.2:1, ethanol equals to 9:1 and to the NGV the proportion is 15.4 parts of air for each part of gas, more than three liquid fuels were used. Although ethanol, a stoichiometric ratio less than gasoline, presented indexes of $CO_2$ emissions well similar to those made by gasoline E00 and E25, it explained the low calorific value and, consequently, burns in greater quantities to deliver the same torque and power of gasoline E00 and E25. The NGV fuel too, even with a higher calorific value to other fuels, but with a density of up to 1000 times lower than the liquid fuels, produces quantities of $CO_2$ up to 13.5% more than gasoline fuels E00, E25 gasoline, and ethanol to deliver the same torque and power that these fuels deliver.

Due to the ideal engine calibration setting for best performance, to work with different fuels, the results show a balance of $CO_2$ emissions when comparing gasoline E00 with gasoline E25. Usually, this leads to

**Fig. 7** $CO_2$ emission at speeds of 60, 90, and 120 km/h, with air conditioner



| | Stabilized 60 km/h | Stabilized 90 km/h | Stabilized 120 km/h |
|---|---|---|---|
| ▨ Gasoline E00 [g/km] | 110 ±2,6 | 138 ±3,9 | 182 ±8,3 |
| ▦ Gasoline E25 [g/km] | 110 ±2,6 | 136 ±2,6 | 182 ±7,6 |
| ▥ Ethanol [g/km] | 111 ±2,0 | 138 ±3,1 | 184 ±1,5 |
| ▤ NGV [g/km] | 143 ±1,8 | 163 ±3,7 | 234 ±7,1 |



| | Air Conditioning Off | Air Conditioning On |
|---|---|---|
| ▨ Gasoline E00 (g/h) | 1852 ±264 | 2755 ±288 |
| ▦ Gasoline E25 (g/h) | 1946 ±243 | 2737 ±323 |
| ▥ Ethanol (g/h) | 1769 ±344 | 2706 ±135 |
| ▤ NGV (g/h) | 4151 ±194 | 4583 ±381 |

**Fig. 8** $CO_2$ emissions with and without air conditioning in minimal rotation, 89 rad/s (idling)

tetrafuel engines that deliver power and torque less than when you are operating at NGV, in relation to their peers and ethanol gasoline. So, the conclusion is based on the physico-chemical characteristics of fuel, in the form of motor systems, work cycle, and the settling of calibration of the propellant, that is, the NGV gaseous fuel even with a high calorific value, but with low density of 1 kg/m$^3$, will produce large amounts of $CO_2$ when operating in a prepared to operate also with liquid fuels such as gasoline and ethanol. On the other hand, a propeller operating with ethanol, a fuel that generates less heat compared with the gasoline pair, a larger amount is required to provide power and torque that are delivered by gasoline; therefore, it can generate higher concentrations of $CO_2$ than gasoline E00 and E25.

Tetrafuel technology uses the same propellant and mechanicals for the four different fuels; a difference between the gaseous fuel NGV and liquid fuels lies in the need of greater quantity by weight of NGV to generate results of torque and power similar to those generated by liquid fuels. Even though, in the NGV, higher calorific value requires a greater injection of fuel into the combustion chamber, due to its specific mass being set below, in the order of 1000 times compared to liquid fuels.

The use of intermediate parameters for that same Otto cycle engine is used for liquid and gas fuel burning with physical characteristics; peculiar chemical is a limiting factor for achieving the optimum performance of each fuel. Geometrical characteristics, compression ratio, and number of CC's are only a few parameters that should be specific to each type of fuel used. An evolution of this business would be the performance of the tests using Otto cycle engines with specific parameters for each fuel type.

Ethanol fuels and NGV can be an effective alternative to the reduction of $CO_2$ emissions since the vehicle uses an engine with specific features for burning of these types of fuel. The tetrafuel technology must evolve scientifically so it might absorb the peak performance of each fuel.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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