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# On-board monitoring and simulation of flex fuel vehicles in Brazil

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## Abstract

On-road measurement of vehicle tailpipe emissions, analyzing the data and developing a model, is very important to identify and recommend improved design and management approaches for the transport sector. A light-duty vehicle, the flex-fuel Nissan Versa equipped with a 1.6 liter engine and manual transmission was monitored in real operation. The on-board monitoring equipment consisted of a five-gas analyzer for CO, HC($CH_4$), $NO_x$, $CO_2$ and $SO_2$ in addition to dry systems, with sample lines directly connected to the tailpipe, and an on-board diagnostics (OBD II) connector, GPS, including other additional parameters monitoring (i.e. data logger with embedded microcontrollers). The operating parameters registered in this vehicle were: vehicle speed, engine speed, fuel consumption, angle position of the throttle valve, cooling water, oil and exhaust gas temperatures. The measurements were performed using gasoline with 27%, and 100% ethanol blends (E27 and E100 respectively, where E27 is used in emission certification). The vehicle-experiment (driving pattern) was realized in an urban route in the Fortaleza City, Brazil, under typical traffic conditions. The analysis indicates that the average emission rates (kg/h) for CO are more than a factor of 10 higher to NO idling emissions. AVL CRUISE integrated with AVL BOOST software were used to model the vehicle and the flex-fuel engine engine in both certification driving cycles and real operation ones. Real operation data is used to validate the model.

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*Keywords:* on-board monitoring; flex-fuel vehicles; simulation; optimization

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## 1. Introduction

### *1.1. Background*

In the last ten years, Brazil has shifted its focus towards diversifying its energy matrix, seeking other renewable resources such as wind power, small hydro, and biomass. National electricity in 2012 (ANEEL – Agência Nacional de Energia Elétrica, 2014), was, besides coal, gas and nuclear, 77% hydroelectric and 6% biomass and waste.The transport sectors will continue to rank first in energy consumption, accounting more 67 percent of the overall demand. In this situation, energy efficiency in transport can substantially contribute to reduce emissions, as well as the use of biofuels (Colvile et al., 2001; Souza et al., 2013). A program supporting the use of ethanol made effective 30 years ago, helped Brazil to replace half of its gasoline consumption with ethanol today (Tolmasquim, 2012). Actually, increased the ethanol blend in gasoline has been from 25% to 27%, and the consumers can also use 100% ethanol (E100) to fill up their Flex Fuel Vehicles (FFVs) (Popp et al., 2014). The flex fuelled vehicles fleet represent more than 90 percent of new cars sold today in Brazil, and due to consumer demand these vehicles now make up about half of the country's entire light vehicle fleet (Popp et al., 2014)(GAIN, 2014). Ethanol supply chain in Brazil is significantly integrated with the sugar production sector, since both are produced from sugar-cane. Around 27.5 billion liters (7.3 billion gallons) of ethanol (Glaucia Mendes Souza, Reynaldo L. Victoria, 2015) have been produced. Ethanol production for vehicles in Brazil is roughly 400 thousand barrels per day (GAIN, 2014)(Vilar et al., 2003). To support the introduction of biofuels in Europe it was established that 10% of fuels must come from renewable sources until 2020 ((EMEP – EEA, 2009)(Suarez-Bertoa et al., 2015)). Similarly, the United States Environmental Protection Agency (EPA-US environment Protection Agency, 2010) expects that 136 million liters of biofuels will be mixed in the gasoline, like Brazil (Unger et al., 2010).

Mobility in Brazil is characterized by having a fleet with around 33 million vehicles (data for 2011), with a motorization index of 288 vehicles/1000 inhabitants and a primary energy consumption of 10 million TEP (accountable for 61% of total pollution) (Urban LEDS, 2015). Passenger transportation is made 30.9% by individual transportation, 28.8% by collective transportation and the remaining by soft modes (walking and biking). Typical travelling distance by individual transportation is 8 km/trip (ANTP – Associação Nacional de Transportes Públicos, 2008). Located in the Brazil's northeast in the state of Ceará, the Fortaleza city had a fleet composed by 971,466 vehicles in February of 2015 (DENATRAN-DEPARTAMENTO NACIONAL DE TRÂNSITO, 2015) as shown in Fig. 3.

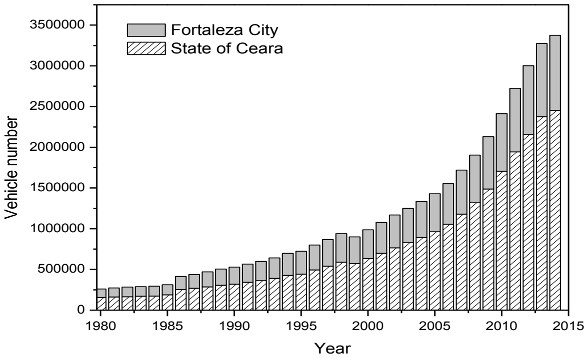

Fig. 1. Evolution vehicle number of state of Ceará and Fortaleza city.

Fortaleza mobility challenge is related to the high growth of its private fleet, which doubled in the last decade, with 11% per year growth rate, Fig. 1 (Loureiro, C. F. G., Paula, F. S. M., Souza, D. D. DE M. R., Maia, 2004) (ANTP – Associação Nacional de Transportes Públicos, 2008) (DENATRAN-DEPARTAMENTO NACIONAL DE TRÂNSITO, 2015); (Maia, 2013).

According to (Loureiro, C. F. G., Paula, F. S. M., Souza, D. D. DE M. R., Maia, 2004), an operational analysis has indicated that 1/3 of Fortaleza's arterial system resultant in average travel speeds during peak hours around 20 km/h. In this scenario is very important an whole approach to flex fuel vehicles as sustainable mobility planning in this city. Fig. 4 presents the volume of traffic on route realized in this work. From this time, for vehicle emissions analysis it is often the higher level quantifications are of most interest. The conditions under which vehicles tend to emit high levels of emissions are of interest because of the potential to impact atmospheric concentrations of key pollutants (Carslaw et al., 2013); (Maia, 2013).

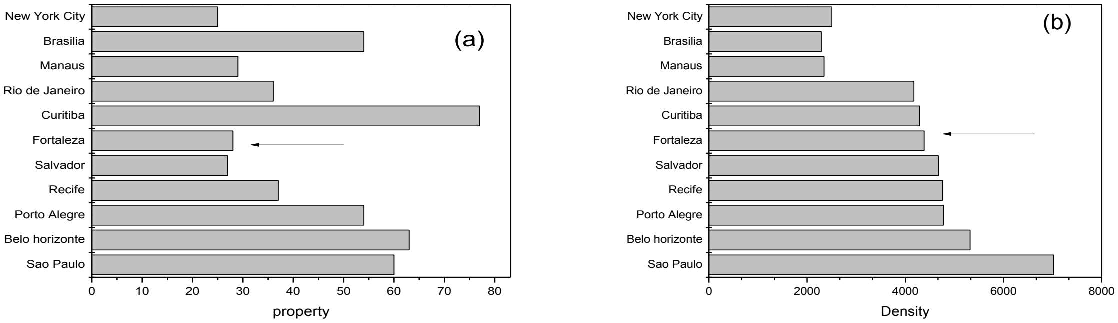

Fig. 2. property vehicle/100 hab (a) and density vehicle/km$^2$ (b).

In this paper a novel approach will be followed. A real flex vehicle will be experimentally measured on the road and results are used to calibrate its vehicle/powertrain model in AVL-BOOST integration with AVL-CRUISE. Afterwards the hybridization will take place with the calibrated model in computer environment.

**Nomenclature**

| | |
|---|---|
| $A_f$ | Frontal area |
| ABDC | After Bottom Dead Centre |
| ATDC | After Top Dead Centre |
| B | Bore |
| BBDC | Before Bottom Dead Centre |
| BTDC | Before Top Dead Centre |
| CADC | Common Artemis Driving Cycle |
| CAT | Catalyst |
| CL | Air Cleaner |
| EV | Electric vehicle |
| E# | Ethanol blend in #mass percentage |
| fd | Final drive |
| FTP | Federal Test Procedure |
| ICE | Internal combustion engine |
| J | Junction |
| MP | Measuring Point |
| NEDC | New European Driving Cycle |
| PL | Plenum |
| R | Restriction |
| RC | Compression ratio |
| S | Stroke |
| SB | System Boundary |
| TEP | Ton of equivalent petrol |
| WOT | Wide Open Throttle |

## 2. Literature review

In (Hsieh et al., 2002) the engine performance and pollutant emissions of a commercial SI engine using ethanol – gasoline blended fuels between 0% and 30% was investigated in an experimental engine test-bed. WOT and part load engine tests were conducted. At WOT the torque increases with ethanol content increase. HC and CO emissions decrease and $NO_x$ emissions present a variable behaviour. Moreover (Shidore et al., 2011) compares fuel consumption and emissions for two ethanol blends with gasoline (E50 and E85) for conventional (nonhybrid), and series-type plug-in hybrid vehicles (PHEV). Engine and catalyst experimental data was used to simulate vehicle behaviour in UDDS by using the Autonomie software. A $NO_x$ increase is observed with the increase in ethanol content in the blend. Total HC and CO decreases.

In this context, (Dardiotis et al., 2015) tested two flex vehicles (Euro IV and V) under the New European Driving Cycle (NEDC) and the Common Artemis Driving Cycle (CADC) at two temperatures (22 °C & -7 °C). It measured fuel consumption and tailpipe emissions of HC, CO and $NO_x$ for E5 and E85. For the 22ºC, CO emissions decreased when the high ethanol fuel blend was used. Total HC emissions were practically unaffected. $NO_x$ emissions decreased for both vehicles (NEDC), while over the CADC the vehicles exhibited different $NO_x$ behavior. At -7 °C both CO and total HC emissions increased with the use of the high ethanol. $CO_2$ decreases by a factor of 3-6% and fuel consumption in l/100 km increases by a factor of 30%.

A flex-fuel vehicle with hydrous and anhydrous ethanol containing fuel blends of 23% and 7%, was tested in laboratory by (Suarez-Bertoa et al., 2015) over the World harmonized Light-duty vehicle Test Cycle (WLTC) and the New European Driving Cycle (NEDC). The use of E85 and E75 blends lowered $NO_x$ emissions by 30–55% but increased the emissions of carbon monoxide, methane, carbonyls and ethanol compared to E5, E10 and E15 blends. WHTC results in higher emissions than NEDC. Other study, (Masum et al., 2013) focuses on the issue of $NO_x$ emissions related to use of ethanol in gasoline engine, and reviews several studies finding different trends of vehicle performance with the ethanol content increase. Besides the inconsistencies among the studies it highlights that the higher flame speed of ethanol helps in achieving complete combustion for rich mixtures attained during higher engine loads as well as higher engine speeds. This results in higher $NO_x$ emission for ethanol–gasoline blends than that of gasoline. No significant change or a little decrease in $NO_x$ emission is observed at low engine load for ethanol.

According to (Colvile et al., 2001) and (EPA-US environment Protection Agency, 2010), atmospheric pollution in urban areas, mostly from the use of passenger and cargo road transportation, has been a great negative contributor to health of the local population. In order to minimize these impacts, Brazil was the first country in South America to implement legislation focused on reducing air pollutants emissions from engine vehicles (Guimarães and Lee, 2010). In the field studies on-road measurement of vehicle tailpipe emissions, analyzing the data and developing a model, is very important to identify and recommend improved design and management approaches for the transport sector. From the literature review, we understand that few papers study on-road measurements together with simulation models for flex engine vehicles. This paper seeks to contribute to fill this gap.

## 3. Methodology

Both experimental measurements and simulation with respective validation were first approached. After the model tuning, the hybridization of the vehicle may take place and scenarios for Fortaleza forecasted.

### *3.1. Characteristics of ethanol-gasoline blends and Brazil Emission Standards*

The properties on fuel ethanol-gasoline blends show that a gallon of ethanol contains less energy than a gallon of gasoline. The amount of energy difference varies depending on the blend. Ethanol has approximately two thirds of the energy content of gasoline, and therefore more ethanol is required to drive the same number of kilometres. It does, however, have a higher octane value which partially offsets this decrease in energy content. Different ethanol blend (E5, E27, E75, E85) properties are taken into consideration, in terms of unburned hydrocarbon density, fuel density, and fuel consumption carbon balance formula ((Vilar et al., 2003) (Carslaw et al., 2013). The *Program to Control Air Pollution from Motor Vehicles* (PROCONVE) by the Brazilian National Council of the Environment (known as CONAMA) have been established air pollutant emission limits for motor vehicles with Diesel cycle engines (i.e. light-commercial and heavy-duty vehicles) and Otto cycle engines (i.e. light-duty vehicles). The program followed a pattern of gradual implementation phases, so that the automobile industry and fuel suppliers could gradually adapt and the emissions of conventional air pollutants could be reduced over time. Table 1 show emission standards Brazil for Passenger Vehicles (FTP-75; Durability: 80,000 km/5 years).

Table 1. Emission limits established by PROCONVE (DieselNet, 2014).

| Tier | Date | Idle CO | CO | THC | NMHC | $NO_x$ | HCO | PM |
|---|---|---|---|---|---|---|---|---|
| | | *% vol* | | | | *g/km* | | |
| L-4 | 1.1.2007$^{1,2}$ | 0.50 | 2.0 | 0.30 | 0.16 | 0.25$^{3}$/0.60$^{4}$ | 0.03 | 0.05 |
| L-5 | 1.1.2009$^{5}$ | 0.50 | 2.0 | 0.30 | 0.05 | 0.12$^{3}$/0.25$^{4}$ | 0.02 | 0.05 |
| L-6 | 1.1.2013$^{6}$ | 0.20 | 1.3 | 0.30 | 0.05 | 0.08 | 0.02 | 0.025 |

Idle CO limits apply to Otto cycle engines only

THC limits apply to natural gas vehicles only

Aldehydes (HCO) limits apply to Otto cycle engines only; Natural gas vehicles exempted

PM limits apply to Diesel cycle engines only

(1) 1.1.2005: at least 40% of annual production (passenger vehicles + light commercial vehicles); (2) 1.1.2006: at least 70% of annual production (passenger vehicles + light commercial vehicles); (3) Otto cycle engines; (4) Diesel cycle engines; (5) Never enforced for diesel vehicles due to lack of low sulfur fuel; (6) For all diesel vehicles. Otto cycle 1.1.2014/1.1.2015 for new models/all registrations, respectively.

### *3.2. On-board experimental setting*

The on-board system used data is composed to vehicle dynamics analysis with instant emissions. Overall, the results show the importance of performing sampling in real traffic condition, since the emission standards set by approved driving cycles do not often depict local/regional reality.

Three differing fuels were used in this study. The reference fuel (today E27) was a blend of gasoline and 27% v/v ethanol, the second fuel blend (E85) had an ethanol content of 85% v/v and the third fuel (E100) an pure ethanol content of 100% v/v. The passenger car used was a versa Nissan, SV 1.6 L/ 2014 powered by an engine flex-fuel.

The real urban circuit (proximally 8.0 km) chosen is part of the main street of the Fortaleza city –Brazil. All tests were carried out in a real-world traffic flow, and the driving cycle data were gathered through a robust real-time data acquisition system (i.e. data logger an embedded microcontrollers compatible OBD-II). Thus, data measured parameters by on-board system vehicle used were: instantaneous speed,% load, internal pressure, air flow/temperature. For emission measurements were realized by portable gas analyzer (greenline Ecil®, Non--Dispersive Infrared – NDIR). Finally, all data were monitored/integrated and treated using a portable computer. These devices were allocated inside the car and in the tailpipe, as shown in Fig. 3. On-board emissions measurement is widely recognized as a desirable approach for quantifying emissions from vehicles since data are collected under real-world conditions at any location travelled by the vehicle (Achour et al., 2011; Aguiar S. O., Araújo R.S. Cavalcante F. S. Á., Bertoncini B. V., Lima R.K.C., 2015; EPA-US environment Protection Agency, 2010; Prati et al., 2014). In this context, Fig. 7 show a general view of the real-world driving cycle obtained for the studied urban circuit in the study (typical urban driving conditions in Fortaleza city). The average and instantaneous speed (km/h), instantaneous acceleration and deceleration (m/s$^2$), RPM (r/min), time (s), $CO_2$ (%), HC ($CH_4$), $SO_2$, CO and $NO_x$ (ppm) were some of the parameters monitored. Two urban circuits (using E27 and E100) were measured and used to teste the vehicles.

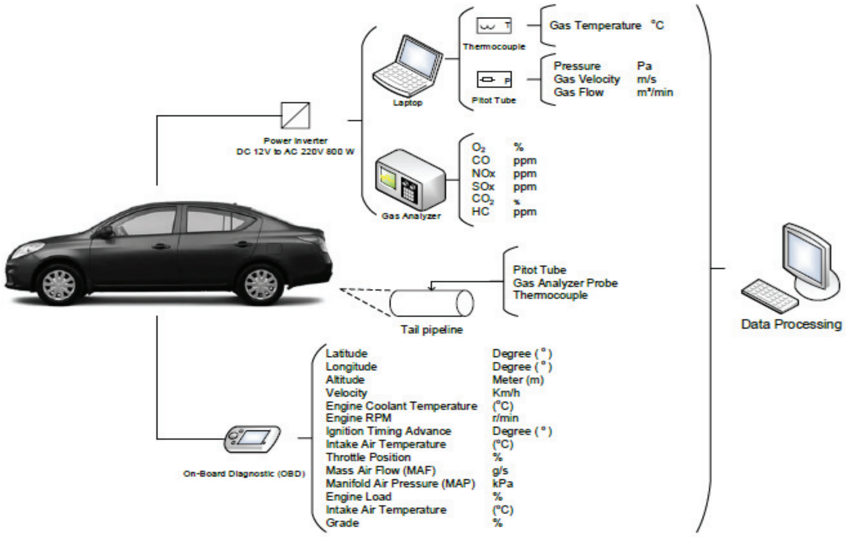

Fig. 3. Design of the on-board system.

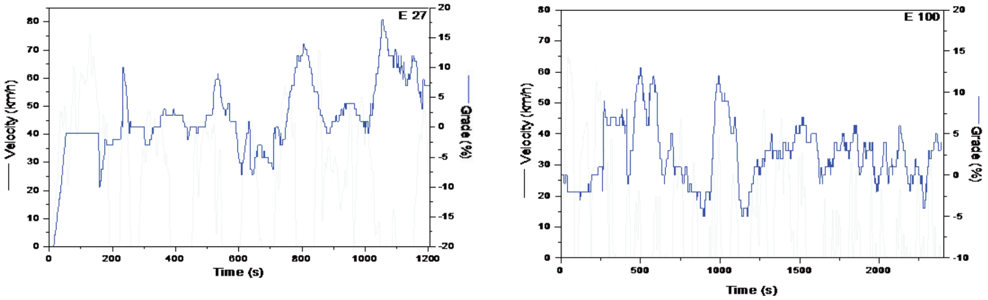

Fig. 4. Real-world driving cycle for E27 (Fortaleza#1) and E100 (Fortaleza#21).

### 3.3. AVL-BOOST engine simulation

The 1-D engine simulation model embedded in AVL-BOOST software was used to simulate the behavior of the engine running on E27, E85 and E100. The Nissan Versa flex engine input data is in Table 2 and vehicle layout in Fig. 5. Wide-open throttle performance (defined as R3 in Fig. 5), specific fuel consumption and emissions are depicted for the several blends. Part load results are obtained by considering the following correspondence between flow coefficients in R3: full load 0.85, 75% load 0.089, 50% load 0.058 and 25% load 0.036.

The Wibe 2-zone function has the disadvantage of needing detailed combustion experimental data for each fuel and operating condition. Even fractal model needs tunning with experimental data for each engine speed and load (de Melo, T., Machado, G., and Matias, 2014). In most studies regarding vehicle simulation the engine maps are not know a priori. Therefore, without having experimental combustion data to build engine maps, BOOST software was used to generate E27 map which after connected with AVL-Cruise software made available the urban-FTP data. This data was compared against real NBR 7024 legislation for tunning the models. Then E100 data was obtained by rescaling the E27 map according to the urban driving results of NBR 7024 legislation (ABNT – Associação

Brasileira de Normas Técnicas, 2010). These maps were added to AVL-CRUISE database and further used to simulate the Nissan Versa vehicle on real driving conditions.

Table 2. Flex engine and vehicle input data for simulations. BTDC=Before top death centre, ABDC=after top death centre, BBDC=before bottom death centre, ATDC=after top death centre.

| **Engine** | | **Vehicle** | |
|---|---|---|---|
| # valves | 16 | Curb weight (kg) | 1080 |
| # cylinders | 4 | Frontal area (Af) | 2.17 m$^2$ |
| Compression ratio (RC) | 10.7:1 | Aerodynamic drag coefficient (CD) | 0.318 |
| Stroke (S) | 86.6 mm | Rolling resistance coefficient (Cr) | 0.011 |
| Bore (B) | 78 mm | Dynamic radius (m) | 0.19 |
| Displacement | 1.6 L (1,598 cm³) | Transmission | Manual, 5 speed |
| Connection rod length (mm) | 143.5 | Gear ratios and Final drive (fd) | 1st 3.727; 2nd 2.047; 3rd 1.029; 4th 1.029; 5th 0.82 fd = 4.07 |
| Intake valve open (deg) | 20 BTDC | Fuel tank | 41 L |
| Intake valve open (deg) | 70 ABDC | Ethanol consumption (km/l) | Urban 7.8 |
| | | NBR 7024 | Extra-urban 9.3 |
| Exhaust valve open (deg) | 50 BBDC | Gasoline consumption (km/l) | Urban 11.7 |
| | | NBR 7024 | Extra-urban 13.9 |
| Exhaust valve close (deg) | 30 ATDC | Emission certification | Proconve (L-6), see Table 12 |
| Piston surface area (mm$^2$) | 5809 | | |
| Cylinder head surface area (mm$^2$) | 7550 | | |
| Heat transfer model | Woschni 1978 | | |
| Species option | General | | |
| Combustion model | Vibe 2-zone, single zone chemistry | | |
| Ambient temperature (ºC) | 25 | | |

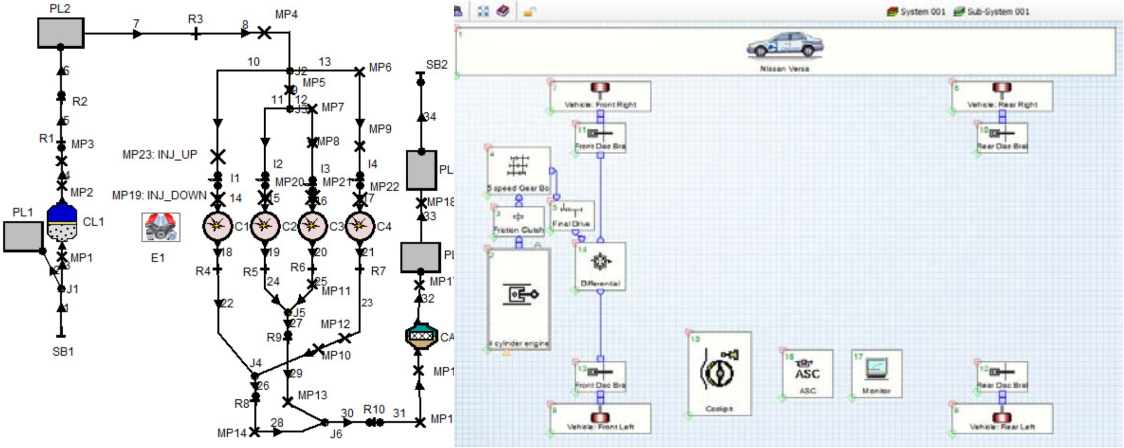

Fig. 5. Layout of engine model on AVL-BOOST (based on AVL-BOOST E85 file) input for Nissan Versa Model in AVL-CRUISE.

### *3.4. AVL-CRUISE vehicle simulation*

Vehicle specifications were the main input in AVL-CRUISE (Table 2). Real idle data was used (see Table 3).

## 4. Results

### *4.1. Emissions performance of real-world driving cycle*

Table 3 presents the parameters of idle on-board measured in this study as well as real driving data. The analysis indicates that the average emission rates (kg/h) for CO are more than a factor of 10 higher than NO idling emission for E27. While that idle $NO_x$ emission factor for E27 is 100 higher than for E100.

Real driving tailpipe emissions are well below the standard PROCONVE limits (see Table 1). On the other side fuel consumption in urban conditions show an increase of 2% for E27 and 17% for E100 in comparison with standard data (INMETRO, 2014).

Table 3. On-board measured values.

| **Parameters** | **E27 Idle (kg/h)** | **E27 Fortaleza#1 g/km** | **E100 Idle (kg/h)** | **E100 Fortaleza#2 g/km** |
|---|---|---|---|---|
| FC | 0.2968 | 8.69 (l/100 km) | 0.6447 | 14.95 (l/100 km) |
| HC | $< 10^{-10}$ | 0.0011 | $6.95 \times 10^{-8}$ | 0.0000 |
| CO | $9.29 \times 10^{-5}$ | 0.0067 | $8.42 \times 10^{-5}$ | 0.0000 |
| $NO_x$ | $1.86 \times 10^{-6}$ | 0.0004 | $3.46 \times 10^{-8}$ | 0.0001 |

The reproducibility of the driving cycles with variable ethanol blend is not conclusive due to traffic variabilities. We can only observe deviations between standard and real driving. Idle measurements reveal similar CO levels and much lower NO for higher ethanol content. Additional tests will take place that will help bypassing the traffic effect: cold idle vs hot idle for 2 minutes; hot 20 km/h, 30 km/h, 50 km/h constant speed events for 5 minutes;and, to account the traffic effect: Morning peak 6:30–8 h; Lunch 11:30–13:00; Afternoon peak 17:00–19:00.

### *4.2. Flex-fuel vehicle simulations*

After all inputs characterizing the vehicle and powertrain, the Standard NEDC, FTP, HWEFT and real measured Fortaleza #1 and Fortaleza #2 (Fig. 4) were simulated. A Three-Way catalyst was considered to be working at its maximum conversion efficiency for hot starts (98% conversion efficiency for all pollutants).

Tailpipe emissions are well below the standard PROCONVE limits (see Table 1). On the other hand the simulated fuel consumption shows an increase of 40–90% on real Fortaleza driving cycles. The simulated fuel consumption is higher than observed experimental values which indicate that further validations and the traffic effect on the driving cycles are significant issues and are mandatory prior to any optimization or hybridization of the vehicles. When using ethanol rich blends, or even pure ethanol to fuel the vehicle, one of the advantages is clearly the lower cost of this fuel relatively to the gasoline. Nevertheless, the fuel consumption may increase up to around 50% (Fig. 6). Since the ethanol blends have lower heat content than gasoline rich blends, the break specific fuel consumption is usually higher for ethanol rich fuels.

Nevertheless, the use of an ethanol rich fuel may decrease the tailpipe emissions, namely HC and CO up to 50% also. The $NO_x$ emissions tendency is not so conclusive.

The availability of extra oxygen molecule in the fuel makes the combustion process to be enhanced and therefore the CO emissions and HC emissions are reduced. However, the $NO_x$ may increase in certain operating conditions, namely due to the increase of the peak temperature in combustion of ethanol rich blends.

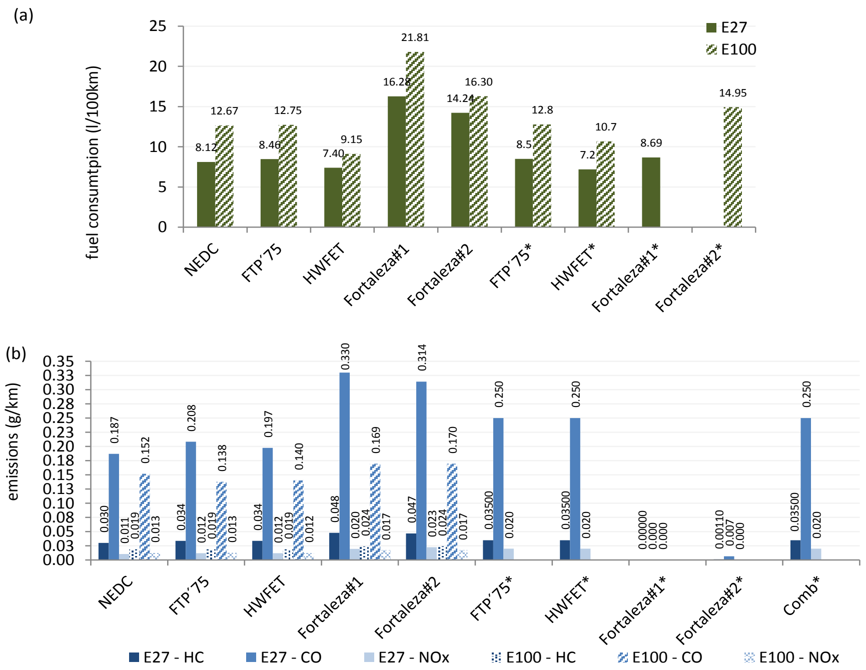

Fig. 6. Fuel consumption (a) and emissions (b) results of the simulated and real driving cycles for E27 and E100 fueled vehicles.
*Real measured driving cycles (INMETRO, 2014), where Comb is the combined cycle from FTP and HWFET.

Additional tests must take place to better calibrate and validate the flex engine/car model. It is expected that fuel consumption be within 10% of experimental data, emissions will be harder to validate but at least 20% deviation is common (Silva et al., 2006).

## 4. Conclusions

It is difficult to compare the effect of ethanol blends in real on-road situation due to traffic variability. Only comparisons with standards are possible. After calibrating the simulation model, the analysis of the effect of the ethanol content was possible. Tailpipe emissions are well below the standard PROCONVE limits for both real measurements and simulated data. Fuel consumption in Fortaleza driving cycles show a 2–17% increase in face of published data. Simulation results on other driving cycles show consistency in E100 increasing fuel consumption in comparison with E27. Regarding emissions trends, the CO and HC tend to decrease with the increase of the ethanol content in then fuel blend, although the $NO_x$ do not show a conclusive trend.

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