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Assessing light flex-fuel vehicle emissions with ethanol/gasoline blends along an urban corridor: A case of Fortaleza/Brazil

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ABSTRACT

Brazil is the 9th largest producer of vehicles in the world, with 62.7% of the global fleet of Flex-Fuel Vehicles (FFVs). These vehicles used in Brazil operate with E27 (anhydrous ethanol used for gasohol blending) or E100 hydrous ethanol or any blend between these two. In recent years, Fortaleza city/Brazil has implemented Bus Rapid Transit (BRT) systems in two of the city's most important avenues. Fortaleza BRT has two-way busways on the central verge of the roadway separated by two lanes from mixed traffic used by passenger cars, light commercial trucks, motorcycles, and heavy-duty vehicles. These systems have been regarded as a potential solution to improve some traffic factors, for only Buses, such as the average driving speed, thus benefiting both transportation and the environment. Thus, this research proposes a comprehensive impact evaluation of an FFV when traveling on BRT corridors, specifically on lanes from mixed traffic, and evaluate the emission factors, specifically on lanes from mixed traffic, composed of a wide variety of vehicle types. All tests in this study were performed at lanes from mixed traffic. Carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC_t) emissions were experimentally measured using a Portable Emission Measurement System (PEMS) under real-world traffic conditions in Fortaleza. FFV tailpipe emissions from E27, E85, and E100 fuels were highly sensitive to the power demand and traffic flow. Additionally, the VSP (Vehicle Specific Power) methodology was applied to characterize the driving modes. Overall, results showed the following: CO_2 was, by far, the most highly emitted gas; the highest CO release occurred with E85 blend; NO_x emission factors were similar for both E27 and E85, but much greater for E100; and HC_t did not show a pattern, presenting both the highest and lowest emission levels with E100.

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1. Introduction

According to the International Organization of Automobile Manufacturers (IOAM, 2017), Brazil is the 9th largest producer of vehicles in the world, owning a large internal market in flex-fuel vehicles (FFVs) capable of running on gasoline and ethanol in any proportion. The commercialization of FFVs in Brazil began in 2003, with these vehicles rapidly gaining consumer preference and stimulating the production of this type of engine by automakers. The existing fleet of FFVs grew from 10.8% in 2006 to 62.7% in 2017 (SINDIPEÇAS, 2018), when it was observed that 88.6% of licensed light commercial vehicles were FFVs, against 3.2% of gasoline vehicles and 8.2% of diesel ones (ANFAVEA, 2018).

The Brazilian national fleet accounts for 65.8 million vehicles, with 62.65% light vehicles, 23.01% motorcycles, 10.67% light commercial vehicles, 3.09% trucks, and 0.57% buses (BIPT, 2018). Of this total, the State of Ceará has about 1.83 million vehicles, occupying the 9th position regarding the overall number of vehicles in Brazil, and the 3rd position in relation to the Northeast region. With a dense fleet concentrated in a small space, the problem of urban mobility claims for attention, emphasizing the need for efficient solutions for population displacement. In developing countries, the Bus Rapid System (BRS) has emerged as an upgrade of the common road bus system, allowing greater control, and planning of vehicle displacement, with predefined stop points and exclusive lanes, thus improving transit efficiency. Bus Rapid Transit (BRT) – Express Road Corridor can be considered a BRS evolution, presenting the same characteristics, with the added advantage of physical separation between its rolling ranges and the rest of the traffic. In addition, there is the presence of high-loading and unloading stations, integration with other modes of transport, and GPS (Global Positioning System) vehicle tracking, providing more comfort and safety for users (Oliveira, 2009).

More than 1,800 km of BRT systems are operational in Latin America, with more than 20,000,00 passengers per day led by Brazil, Mexico, Colombia, and Chile (Global BRT Data, 2021). In Brazil, several systems were deployed during the 2016 Olympic and Paralympic Games (GMTR, 2017). Before 1990, BRT operated only in eighteen cities, while, nowadays, it is active in 173 cities and serves 34,026,459 daily passengers (Salvatore et al., 2020). In Fortaleza city (Ceará/Brazil), the fast bus (BRT) infrastructure includes two BRT systems in operation with more than 150 km of BRT lines, 21 stations, 2,000 buses of the urban fleet, transports over 184,777 passengers per day, and the average daily traffic is more than 10,000 vehicles specifically in these city-regions (Sousa, 2015; Gidicsin et al., 2021). Thus, there is an impact on conventional vehicles traffic, which is forced to relinquish part of the avenue space, altering these vehicles' flow dynamics, and consequently changing emission concentrations around this road type. Regarding vehicular emissions, factors such as complex wear in internal combustion engines and fuel quality can lead to an incomplete combustion process, resulting in several pollutants emissions. The most notable of these pollutants are carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), sulfur oxides (SO_x), aldehydes (CHO), and particulate matter (PM), as well as greenhouse gases (GHG) and carbon dioxide (CO_2), which are not considered pollutants (Dagosto, 2015).

Brazilian emissions standards for motor vehicles and engines are developed and adopted by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the Brazilian National Environment Council (CONAMA) – two agencies within the Ministry of the Environment (MMA). However, the Air Pollution Control Program for Vehicles (PROCONVE) establishes emission standards for light-duty vehicles, defining standard limits and testing requirements that are much less restrictive compared to those of other regulatory bureaus, such as the European (EU) and the American (US) agencies (IBAMA, 2011).

In Brazil, fuel 100% gasoline (CG) not usually commercialized and most of vehicles cannot use gasoline with less than 27% of ethanol because of engine project technical features like high compression ratio. The Flex Fuel Vehicles (FFV) used in Brazil operate with E27 (anhydrous ethanol use for gasohol blending) or E100 hydrous ethanol or any blend between these two. These are the standard fuel available at gas stations in Brazil. The E85 blend was obtained by hydrated ethanol mixing E27 with E100 until obtaining an 85/15 fraction of ethanol and gasoline, respectively (Cassiano et al., 2016; De Melo et al., 2011; Policarpo et al., 2018a, USDA, 2020). This highlight the increase in the use of ethanol worldwide and its relevance, because vehicle technologies for ethanol are already proven along with the compatible fuel systems globally.

To determine the emission factors, fuel consumption, and to approve new vehicles models and engines, each country adopts a standard driving cycle that tries to simulate real-world use in a controlled environment, usually in a chassis dynamometer. In Brazil, an American cycle (Federal Test Procedure 75) adaptation (NBR 6601) is used. Although tests are standardized, reproducible, and allow the comparison of emissions between vehicles, obtained results are often distant from reality. EU is changing the New European Driving Cycle (NEDC) to Worldwide Harmonized Light Vehicles Test Procedure (WLTP), to minimize the difference between driving cycle and real-world driving results (Unger et al., 2010).

In this context, the on-board test appears to be the best choice. It obtains the most realistic and accurate data for each region using PEMS (Portable Emissions Measurement System) technology for data gathering. PEMS consists of portable gas analyzers, GPS, flow meters/controllers, and an On-Board Diagnostic (OBD) system for data collection of emission levels from vehicles used in tests (Dimaratos et al., 2016; Gonçalves and Farias, 2015; Kousoulidou et al., 2013). The use of biofuels blended with fossil fuels (e.g. ethanol in gasoline) has been a key factor in determining the need to evaluate the effect such mixtures have on vehicular emissions. This paper attempts to obtain the emission factors of an Sport Utility Vehicles (SUV) – FFV using gasoline and pure hydrated ethanol blends. Experiments were realized out on a BRT road, which has two-way busways on the central verge of the roadway separated of two lanes from mixed traffic used by passenger cars, light commercial trucks, motorcycles, and heavy-duty vehicles. The tests in this study were performed at lanes from mixed traffic, considering an urban displacement situation, typical of a large city in northeastern Brazil, also VSP (Vehicle Specific Power) methodology was applied.

2. Literature review

The search for experiments that faithfully portray reality has led researchers to carry out tests and procedures in real conditions of use. In this sense, the study of vehicular emissions and fuel consumption has increasingly left the laboratory environment and proceeding to test under real conditions, in which the on-board and on-road methodology stand out, including to validate mathematical models of estimates of emissions and dynamometric tests.

Suarez-Bertoa et al. (2014) compared the regulated and unregulated emissions of a EURO5 flex vehicle in the WLTC (World 38 harmonized Light-duty vehicle Test Cycle) and NEDC (New European Driving Cycle) driving cycles using different blends of gasoline and hydrated and anhydrous ethanol. The experimental results show differences in emissions when using hydrated and anhydrous ethanol for the same blend. The use of E85 and E75 blends resulted in a reduction of 30% to 55% of NOx, but there was an increase in the emission of carbon monoxide, total hydrocarbons, and ethanol, compared to E5, E10, and E15 blends. The increase in the emission of acetaldehyde and ethanol (120% and 350%, respectively), especially in cold starts (more than 400% and 390%, at −7 °C), is a concern for the increase in the potential for ozone formation tropospheric.

Liu and Frey (2015) studied the variability trend of emission factors measured directly in the exhaust of various vehicles to validate the emission factors used in the MOVES® software developed by the EPA (Environmental Protection Agency), using VSP (Vehicle Specific Power) modes correlated to emission factors. Light vehicles, light commercial vehicles, and hybrid vehicles were tested. Compared to the situation of lower average speed, simulating congestion cycles, emission rates can be lower by 50% for CO_2, 70% for NO_x, 40% for CO, and 50% for HC_t.

Cassiano et al. (2016) carried out on-road tests with a flex vehicle under real conditions in traffic in Fortaleza, with E27 and E100 blends, monitoring the CO, $NO_{x,}$ and HC_t emission rates, and used the data to estimate the factors of real emissions and standardized cycles. Given the variability of traffic under real driving conditions, it is difficult to compare emissions between E27 and E100. However, all emission factors were below the limit stipulated by PROCONVE L6.

Delavarrafiee and Frey (2017) verified the difference between consumption and emission rates between flex vehicles operating with gasoline (E0) and blend E85. Based on dynamometric test data, the E85 blend should emit −23% NO_x and −30% CO, however, studies comparing emissions between E85 and gasoline (E0) using the PEMS methodology have been inconsistent, as the variability linked to the driving cycle and power demand may reach the conclusion of contradictory results. Khan and Frey (2018) compared emission factors obtained through standardized cycles, such as FTP, US06, and SC03, with those obtained through PEMS under real conditions of use. The conclusion is that standardized cycles underestimate actual emissions, and therefore emissions inventories, which use standardized test emission factors, are potentially underestimated.

Kuppili et al. (2021) analyzed in real-world driving conditions and developed emission factors for passenger cars using an on-board emission measurement technique while driving on different routes in Delhi. Typically, their authors showed that speed and acceleration significantly impact emission rates increasing during all routes. Kummer et al. (2021) also reported the impact of delivery companies and other commercial sectors on urban road traffic in Vienna. The results show that passenger cars account for 86.5% of urban road traffic.

Adamidis et al. (2020) estimated the impact on traffic flow and CO_2 emissions of different driving profiles extracted by real-world data. Three distinct scenarios were studied as many traffic states as possible. The results of their study confirmed that an increase in the number of vehicles on the road results in higher emissions per vehicle because they must perform more accelerations and decelerations in comparison to vehicles on an empty street.

Abbasi et al. (2020) evaluated the BRT system for the Tehran city case as a high-quality bus-based transit system that delivers high-speed and efficient services, and have been some solutions to such traffic issues. In this study was realized an economic and air pollution analysis. In terms of vehicle emissions and fuel consumption, some scenarios have been the most impact on vehicle emissions and fuel consumption. The results of their study presented that by converting shared lines to exclusive lines, commute times could reduce by 2.95%, CO emissions by 9%, PM emissions by 1.13%, NO_x emissions by 3.45%, and fuel consumption by 5.3% per kilometer. But, in the case of cars, have observed an increasing car's travel time by up to 5% also has presented severely adverse environmental impacts with the increase in pollutant emissions.

Although research on emissions and consumption on public roads under real conditions of use have their results difficult to compare, it is important to have a basis for comparison with the standardized cycles to bring the results closer to what the common user will face. BRT is an expanding global trend as a simple and effective solution to the problem of urban mobility, and studies on the impact of this modal on the dynamics of the road and light vehicle emissions are still scarce. Therefore, it is important to study the impact of a BRT road corridor on the emission factors for light vehicles in real-world traffic conditions.

3. Methodology

The BRT system in this study have two-way busways in the central verge of the roadway separated of two lanes from mixed traffic used by passenger cars, light commercial trucks, motorcycles and heavy-duty vehicles. The tests in this study were performed at lanes from mixed traffic. The Express Road Corridor selected for the present work is the Bezerra de Menezes Avenue. It is about 8.0 km long and is located in the Northern region of Fortaleza city (see Fig. 1).

This length is similar to a typical daily displacement traveled by the inhabitants of the State of Ceará, which was about 8.0 km/day (Rubino et al., 2007). Bezerra de Menezes Avenue BRT system (see Fig. 2) was implemented in 2012; this avenue is one of the most important in the city, due to local commerce, shopping centers, and university in the neighboring area. The flow on this avenue is approximately 22 thousand vehicles per day (NCI, 2012). The tests were performed at the lanes from mixed traffic, especificaly, with focus on light-duty vehicles.

In the present study, a flex-fuel passenger car, a typical SUV (Sport Utility Vehicle) – Renault Duster 2.0 4WD (2013, was used. Such a car was typically licensed as a flex-fuel vehicle in Brazil in 2015 (MAT, 2018). It is important to mention that the same driver drove the vehicle during all the experiments to avoid the influence of distinct driver behavior and to evaluate the variability of intravehicular characteristics, conform also suggested in the literature (Putradamazman et al., 2021). All tests were carried out in a real-world traffic flow during weekdays and driving cycle data were georeferenced. Parameters measured by this on-board system: (i) instantaneous speed (km/h), (ii) engine load (%), (iii) throttle position (°), (iv) engine speed (RPM) and (v) intake manifold internal pressure (kPa). For emission measurements were realized by portable gas analyzer (Seitron-Chemist 900, Ecil®), as specification of NOx (Electrochemical sensor, 0–1000 ppm of range; 1 ppm of resolution and ±5% measured); HCt (NDIR sensor, 0–5% of range, 1 ppm of resolution and ±2% measured); CO (NDIR sensor, 0–15.0% range vol, 1 ppm resolution and ±2% measured) and CO_2 (NDIR sensor, 0–20.0 %vol range, 0.01%vol resolution and ±5% measured).

Finally, on-board system used data is composed to vehicle dynamics analysis with instant emissions. Data acquisition was continuously monitored and treated by a portable computer. All described devices were placed inside the car, and device probes were inserted perpendicularly into the tailpipe, as shown in Fig. 3.

Properties of pure ethanol (E100), ethanol-gasoline blend (E85), and regular gasoline (E27) used can be seen in Table 1. The amount of energy difference varies according to the blend. Ethanol has approximately two-thirds of the energy content of petrol, and thus more ethanol is required to drive the same number of kilometers.

Different ethanol blend (E27) properties are considered in terms of unburned hydrocarbon density, fuel density, and fuel consumption carbon balance formula (ANFAVEA, 2015).

Fig. 1. BRT system: Express Road Corridor - Bezerra de Menezes.

Fig. 2. BRT path in Fortaleza city.

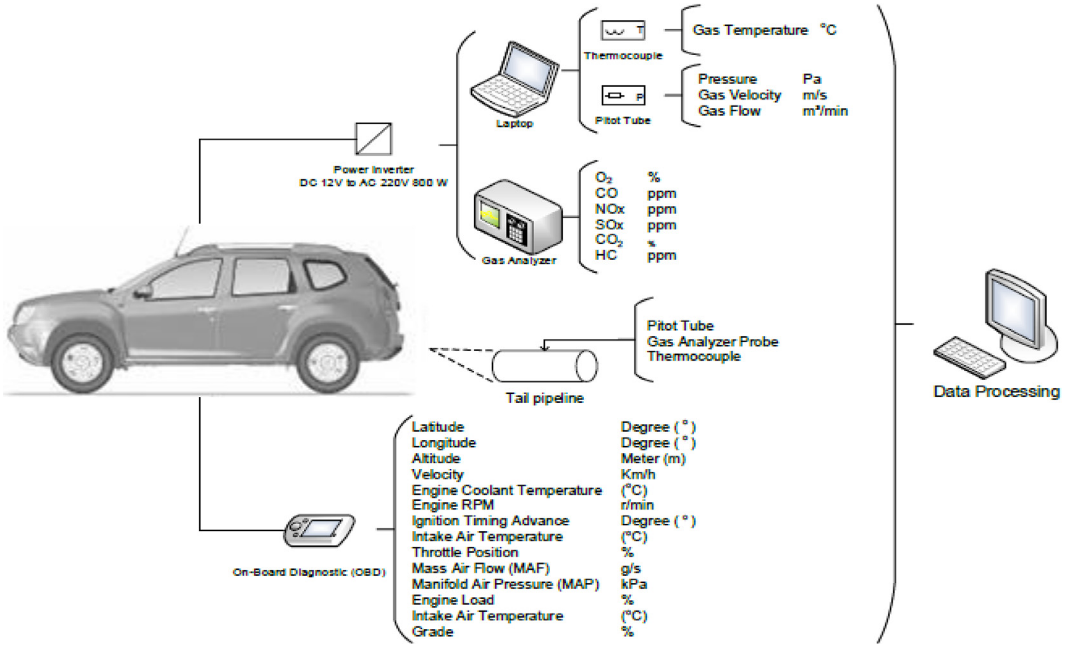

Fig. 3. Schematic of data acquisition from light-duty vehicle in this study (Adapted by Cassiano et al., 2016).

Table 1
Physical-chemical properties of fuels.

Parameter	Method	Unit	E27	E85	E100
RON	ISO 5164	–	92.7	94.8	93.8
MON	ISO 5163	–	82.2	91.8	95.3
Density @ 20 °C	NBR 14065	kg/m^3	734.19	793.82	811.61
Distillation @ 77 °C	NBR 9619	vol%	80.5	90.0	5.0
Ethanol content	NBR 13992	vol%	27.5	87.5	94.1

VSP is a methodology developed by Jiménez-Palacios (Carslaw et al., 2013) to estimate the power demand through an equation that relates vehicle dynamic factors to the road slope, as shown in Equation (1).

$$VSP = v \cdot (1.1 \cdot \alpha + g \cdot inclination + Coef_{resistance}) + Coef_{aerodynamic} \cdot v^3 \tag{1}$$

where VSP is Vehicle Specific Power (W/kg), v is the velocity (m/s), α is acceleration (m/s^2), g is gravity acceleration (m/s^2), $inclination$ represents the vehicle vertical elevation divided by the horizontal distance (%),$Coef_{resistance}$ is rolling resistance coefficient, and $Coef_{aerodynamic}$ is the coefficient of aerodynamic resistance.

According to Jiménez-Palacios (1999), Equation (1) can be approximated to a typical light vehicle by using Equation (2).

$$VSP = v\hat{A} \cdot (1.1\hat{A} \cdot a + g\hat{A} \cdot inclination + 0.132) + 3.02\hat{A} \cdot 10 - 4\hat{A} \cdot v^3 \tag{2}$$

The combination of vehicle dynamic parameters with road slope makes VSP an overall energy measure that can synthesize vehicle driving profile on track. For group energy-requiring points together, according to similar mass units, VSP can be categorized according to the maneuverability modes, in which deceleration is VSP < 0, neutral is VSP = 0, and acceleration is VSP > 0.

4. Results and discussions

Studies performing Real-World Driving Tests have become more frequent. They elucidate local characteristics from where tests are performed. The tests bring a large amount of data in each study case, showing real region information on dynamics and emissions.

4.1. Dynamic data

Real-world driving was performed on a BRT avenue approximately 7 km long with flat topography. Tests varied according to time--rush time (RT) and out of rush time (ORT), with regular gasoline (E27), ethanol-gasoline blend (E85), and pure

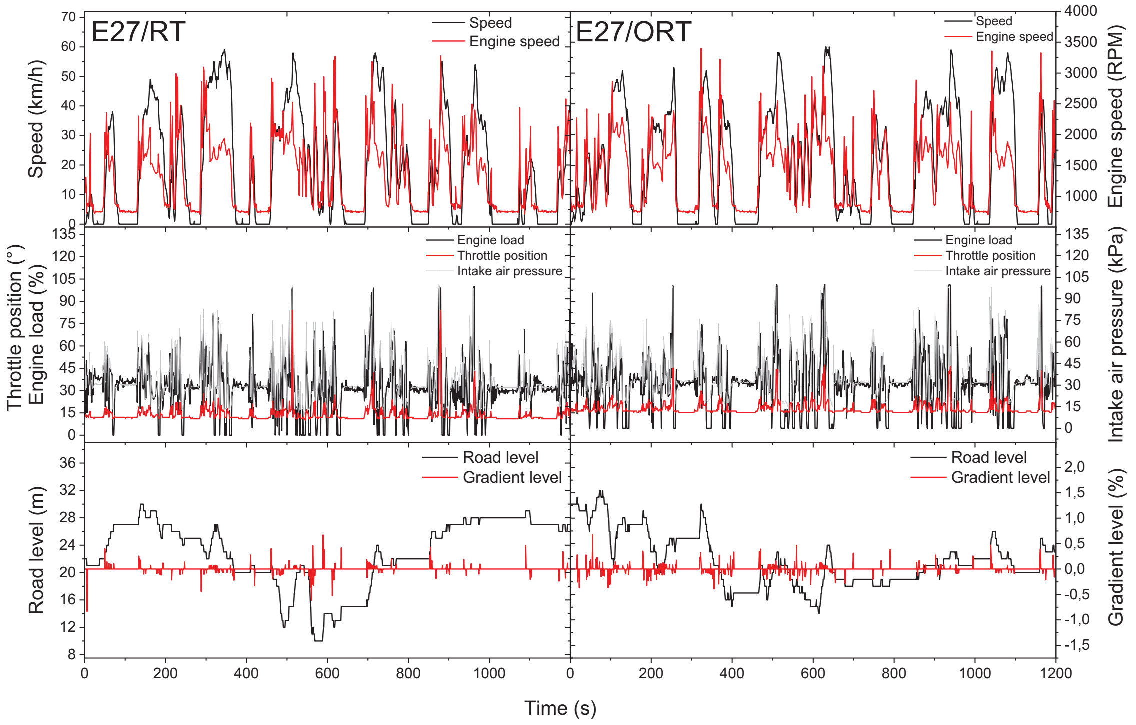

Fig. 4. Speed, engine speed, engine load, throttle position, intake air pressure, road level, and gradient level at Rush Time (RT) and Out of Rush Time (ORT), with regular gasoline (E27).

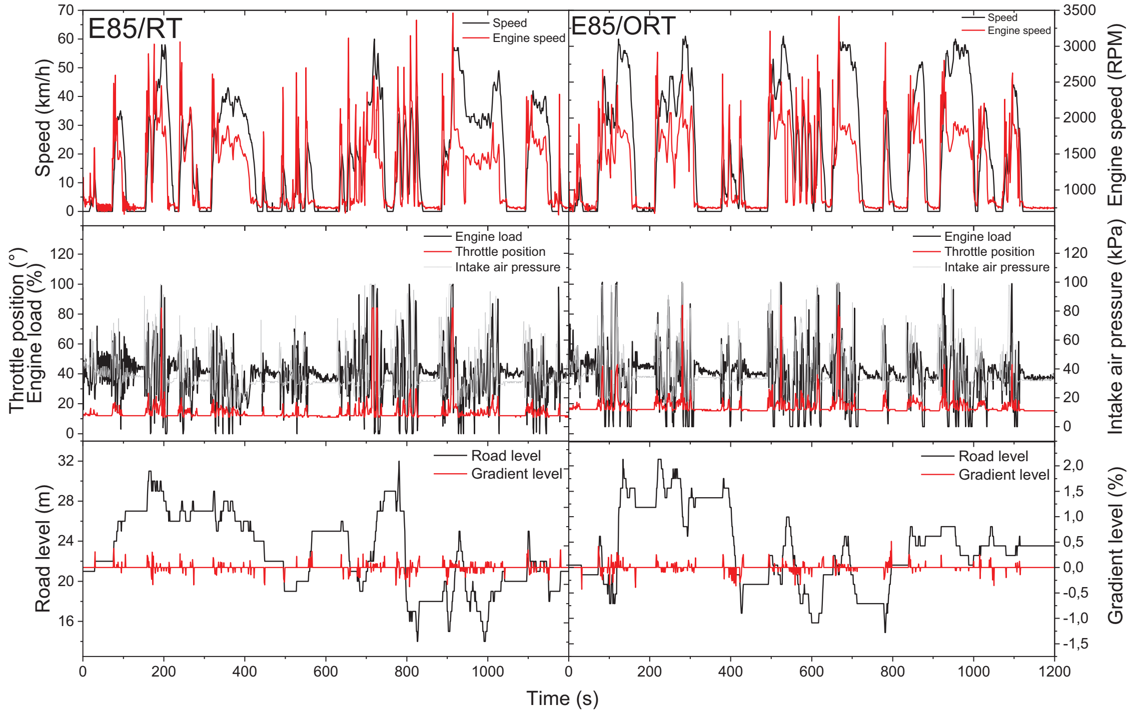

Fig. 5. Speed, engine speed, engine load, throttle position, intake air pressure, road level, and gradient level at Rush Time (RT) and Out of Rush Time (ORT), with ethanol-gasoline blend (E85).

hydrated ethanol (E100). Results of dynamic data, speed, engine speed, engine load, throttle position, intake air pressure, road level, and gradient level, for each experimental test, can be observed in Figs. 4–6, respectively, E27, E85 and E100.

As the constant peaks show, traffic was quite heavy, especially at the rush time, when traffic flow is very slow, and the vehicles are almost always in "stop and go" mode. RPM values ranged from 750 rpm (idle speed) to about 3500 rpm – typical results for Otto-cycle engine operation, which has a working idle speed range up to 6000 rpm. The engine load variation, open throttle, and intake manifold pressure rates correlate to each other. These factors vary abruptly, according to the vehicle momentary energy demand. The course altitude ranged from 10 to 35 meters within the routes with a low slope (less than 1%) and slight variations in ground level.

All urban areas in Fortaleza city have a speed limit of 50 km/h, similar to other major cities around the world. Comparing driving cycles, the average speed obtained in ORT is similar for the new WLTP phase Low 3, which simulates urban traffic, as shown in Table 2.

The maximum speed limit in urban areas is 60 km/h, but the average value obtained during tests was between 20.5 km/h (ORT) and 11.6 km/h (RT). The time required to run the same distance varies 78%, because of concentrated flow during the RT. Idle time varied 230%, showing that traffic congestion during RT can be extreme, with cars at a complete standstill in the streets with engines still running, producing pollutants. The test performed with E100 at RT was the worst one in terms of

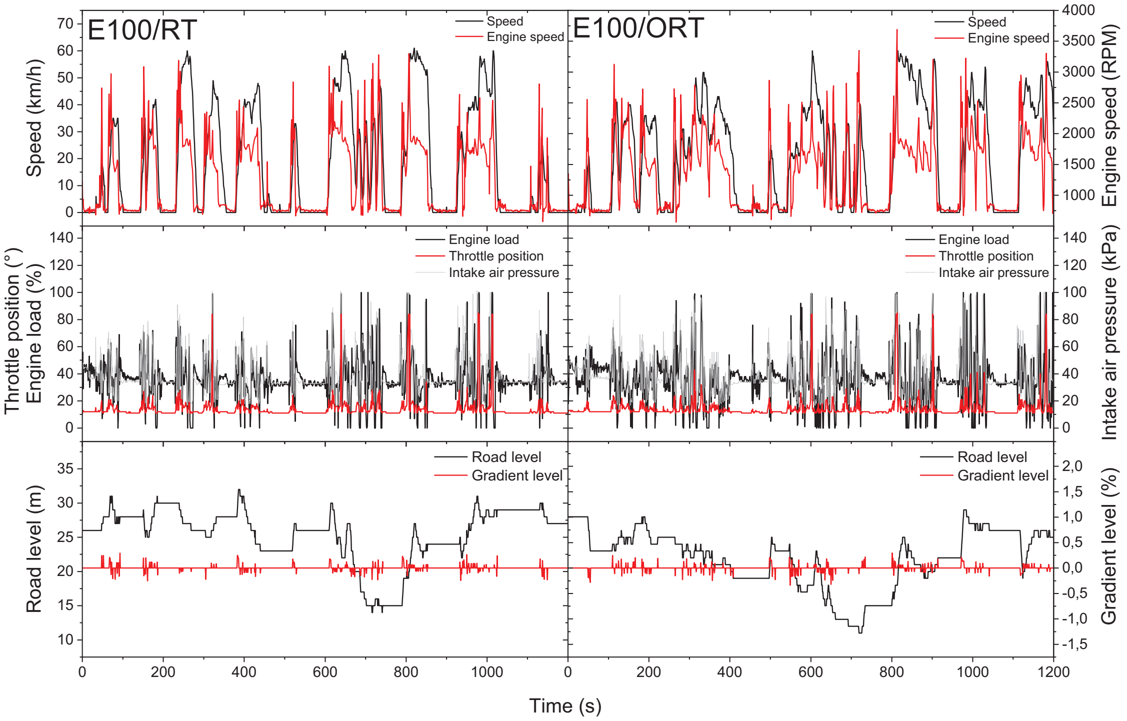

Fig. 6. Speed, engine speed, engine load, throttle position, intake air pressure, road level, and gradient level at Rush Time (RT) and Out of Rush Time (ORT), with pure hydrated ethanol (E100).

Table 2
Dynamics parameters on BRT street and driving cycles.

	Average Speed (km/h)	**Maximum Speed (km/h)**	**Duration (s)**	**Distance (m)**	**Stopped Time (s)**	**Acceleration Time (s)**	**Deceleration Time (s)**	**Exhaust Gas Temperature (°C)**	**Autonomy (km/L)**
E27/RT	13.52	59.00	1859	7253.99	779	425	477	87.62	0.50938
E27/ORT	20.48	60.00	1226	7189.01	330	354	376	101.69	0.80793
E85/RT	16.08	60.00	1569	7240.75	566	359	445	85.60	0.56782
E85/ORT	20.01	60.00	1262	7242.83	445	318	369	98.63	0.76051
E100/RT	11.57	60.00	2183	7326.08	1093	395	504	85.05	0.29357
E100/ORT	19.04	60.00	1336	7276.81	441	327	409	93.67	0.59396
FTP-75	34.20	91,25	1874	17786.59	241	683	574	–	–
NEDC	33.60	120.00	1180	11016.63	241	278	204	–	–
WLTP	18.90	131,30	589	3095.00	156	–	–	–	–
Low3	13.52	56,50	1859	7253.99	779	425	477	87.62	0.50938

poor traffic, presenting the lowest average speed, the highest congestion duration, the highest standstill time, and the worst fuel autonomy.

In contrast, the test performed with E27 at ORT presented the best parameters, with the highest average speed, the lowest duration and idle time, and the best fuel autonomy. In comparison with driving cycles, parameters obtained for BRT avenue show that driving cycles underestimate big-city traffic congestion, with a lower standstill time. Only WLTP Low3, which consists of an urban phase of WLTP, has a similar average speed to data acquired during ORT tests, thus underestimating the heavy traffic flow during rush time.

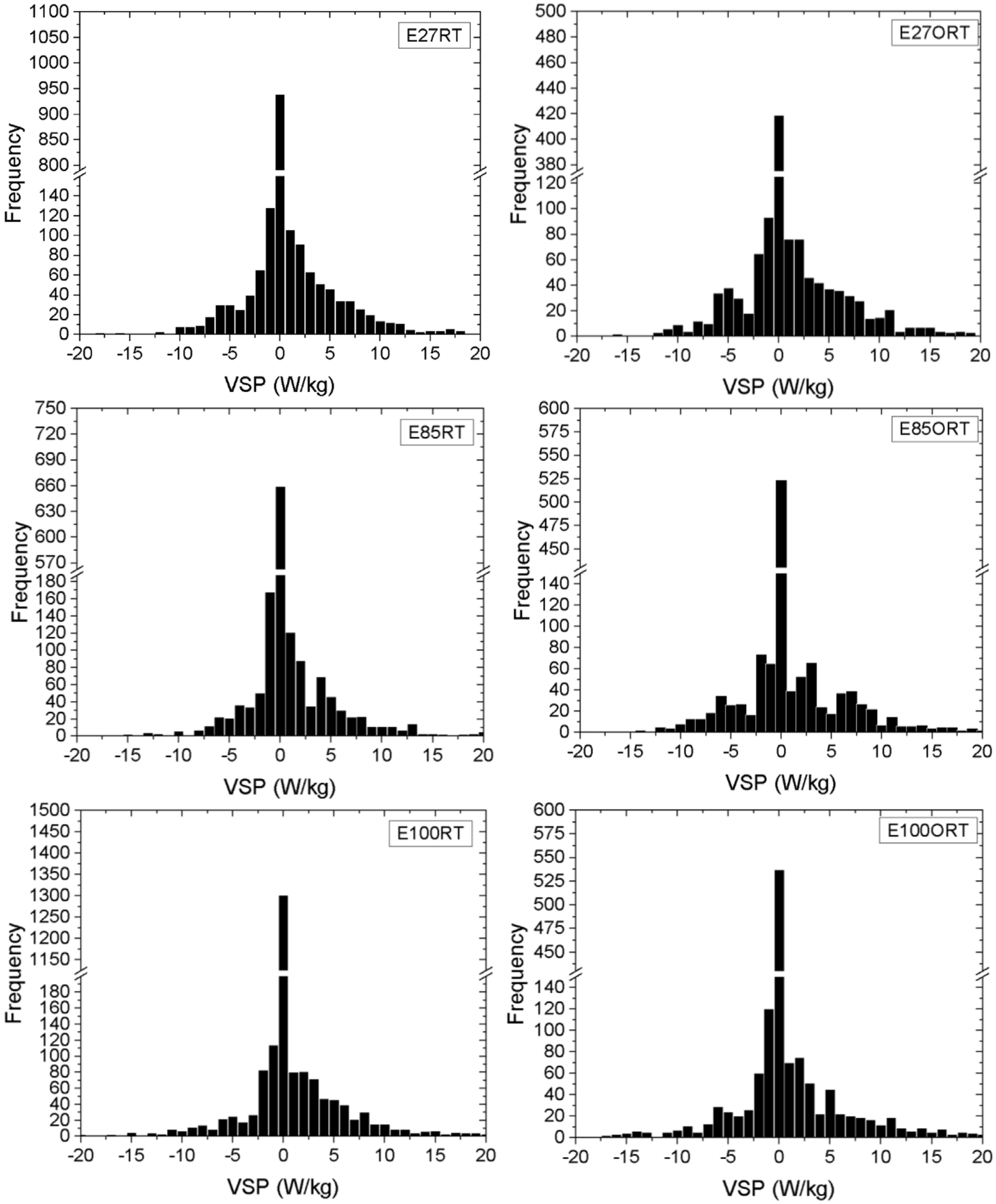

Fig. 7. VSP frequency distribution at Rush Time (RT) and Out of Rush Time (ORT) with regular gasoline (E27), ethanol-gasoline blend (E85), and pure hydrated ethanol (E100).

4.2. VSP frequency distribution

As mentioned previously, VSP is a measure of vehicular power demand as a function of driving mode. Fig. 7 shows VSP obtained for all tests performed. Similar behavior can be noted in all situations, that is, peaks are concentrated at zero power demand (the larger frequencies) and also at negative and positive values around zero. Such behavior indicates intense traffic flow of vehicles at low speed, decelerating to immobility (negative values close to zero), stationary (VSP = 0 W/kg), and accelerating from immobility (positive values close to zero), respectively.

The lower peaks in E27/ORT distribution show less-intense traffic. Consequently, frequencies reached peaks above 10 W/kg, showing that vehicle speed and acceleration were higher, as evidenced by the faster average speed (Table 2). Additionally, high negative values, above −10 W/kg, mean decelerations from higher speeds. In comparison, the other tests presented very high peaks at 0 W/kg (>450 %) and concentrated peaks around zero.

4.3. Emission factors

Emission factors were measured at a frequency of 1 Hz and then converted to the average emission factor of the test in g/km. Fig. 8 and Table 3 show emission factors and standard deviations for CO_2 (a), CO (b), NO_x (c), and HC_t (d) in the BRT-avenue, with different fuels (E27, E85, and E100), at both RT and ORT.

The emission factor for the greenhouse gas CO_2 is much higher than for other gases since it is a natural by-product of combustion. In addition, the catalytic converter present in the vehicles oxidizes CO to CO_2, reducing its conversion efficiency with increasing power demand. Blends with higher amounts of ethanol emit less CO_2 (Jiménez-Palacios, 1999). However, results show that carbon dioxide emission was similar for all fuels and between RT and ORT, with a tendency to reach higher values when the ethanol content of the fuel is increased, as previously observed (Cassiano et al., 2016).

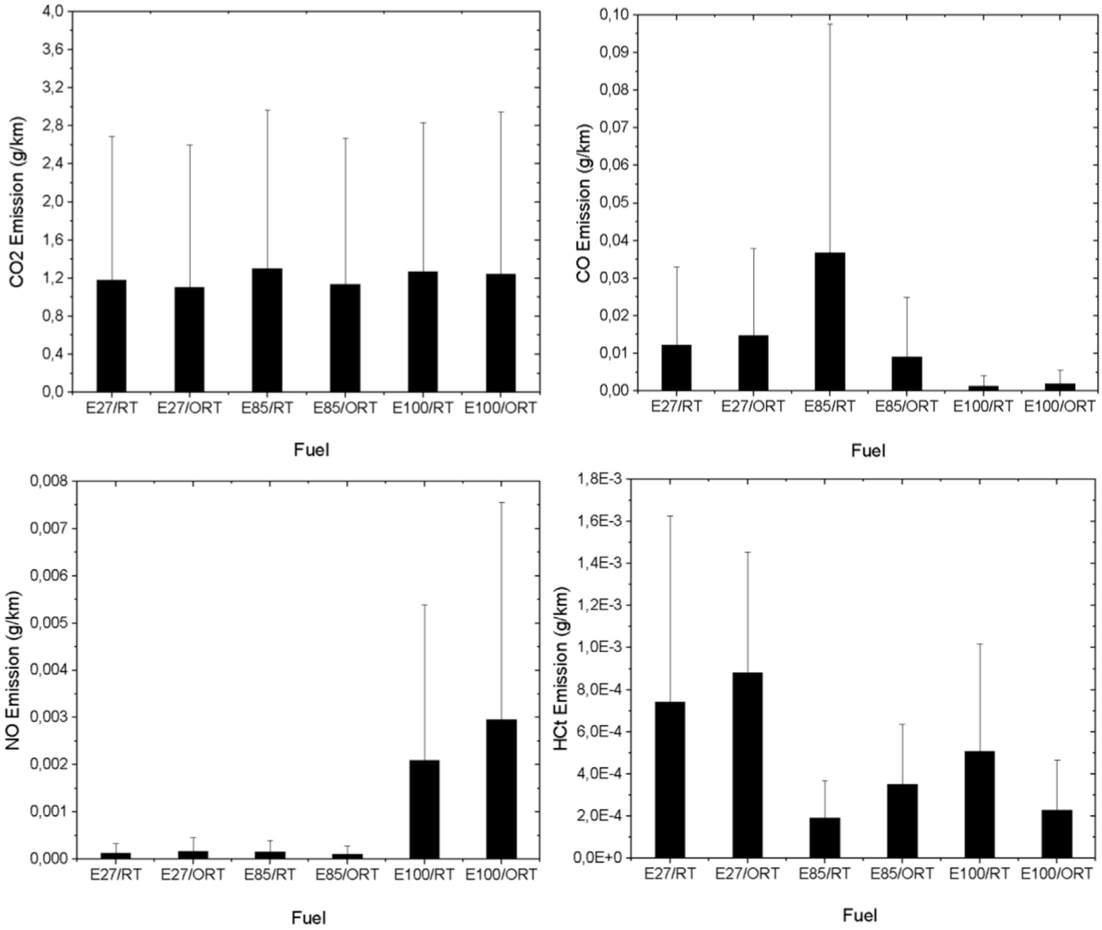

Fig. 8. Emission factors of CO_2 (A), CO (B), NO_x (C), and HC_t (D) with different fuels at the rush time (RT) and out of rush time (ORT) with regular gasoline (E27), ethanol-gasoline blend (E85) and pure hydrated ethanol (E100).

Table 3
Comparison of emission factors obtained from results and values found in literature. Emission factors are in g/km. AVE = Average. SD = Standard Deviation. E27 = regular gasoline; E85 = ethanol-gasoline blend; E100 = pure hydrated ethanol; RT = rush time; ORT = out of rush time; AHE15 = Anhydrous Ethanol 15%; HE85 = Hydrous Ethanol 85%.

	BRT STREET						Suarez-Bertoa et al. (2015)		**Delavarrafiee and Frey (2017)**		Dardiotis et al. (2015)	
	WEEK DAY						**WLTC**		**PEMS**		**NEDC**	
	E27/RT	E27/ORT	E85/RT	E85/ORT	E100/RT	E100/ORT	AHE 15	HE85	E0	E85	E5	E85
	CO_2 (g/km)						CO_2 (g/km)		CO_2 (g/km)		CO_2 (g/km)	
AVE	1.19	1.11	1.30	1.14	1.27	1.25	155.00	146.00	80.77	105.60	191.5	180.5
SD	1.50	1.49	1.66	1.53	1.56	1.70	–	–	–	–	1.6	1.6
	CO (g/km)						CO (g/km)		CO (g/km)		CO (g/km)	
AVE	$1.23\cdot10^{-2}$	$1.49\cdot10^{-2}$	$3.69\cdot10^{-2}$	$9.25\cdot10^{-3}$	$1.48\cdot10^{-3}$	$2.07\cdot10^{-3}$	$4.00\cdot10^{-1}$	$6.06\cdot10^{-1}$	$4.97\cdot10^{-2}$	$9.32\cdot10^{-2}$	$4.71\cdot10^{-1}$	$2.68\cdot10^{-1}$
SD	$2.07\cdot10^{-2}$	$2.29\cdot10^{-2}$	$6.07\cdot10^{-2}$	$1.57\cdot10^{-2}$	$2.72\cdot10^{-3}$	$3.56\cdot10^{-3}$	–	–	–	–	$1.81\cdot10^{-1}$	$8.34\cdot10^{-2}$
	NO_x (g/km)						NO_x (g/km)		NO_x (g/km)		NO_x (g/km)	
AVE	$1.39\cdot10^{-4}$	$1.82\cdot10^{-4}$	$1.69\cdot10^{-4}$	$1.19\cdot10^{-4}$	$2.11\cdot10^{-3}$	$2.97\cdot10^{-3}$	$5.10\cdot10^{-2}$	$2.30\cdot10^{-2}$	$1.12\cdot10^{-1}$	$2.24\cdot10^{-1}$	$2.65\cdot10^{-2}$	$1.09\cdot10^{-2}$
SD	$1.98\cdot10^{-4}$	$2.76\cdot10^{-4}$	$2.28\cdot10^{-4}$	$1.57\cdot10^{-4}$	$3.29\cdot10^{-3}$	$4.58\cdot10^{-3}$	–	–	–	–	$4.50\cdot10^{-3}$	$3.00\cdot10^{-4}$
	HC_t (g/km)						HC_t (g/km)		HC_t (g/km)		HC_t (g/km)	
AVE	$2.77\cdot10^{-4}$	$8.42\cdot10^{-4}$	$1.45\cdot10^{-3}$	$1.05\cdot10^{-4}$	$1.12\cdot10^{-3}$	$1.73\cdot10^{-3}$	$7.00\cdot10^{-3}$	$2.40\cdot10^{-2}$	$8.70\cdot10^{-2}$	$1.43\cdot10^{-1}$	$4.87\cdot10^{-2}$	$5.67\cdot10^{-2}$
SD	$4.18\cdot10^{-4}$	$1.27\cdot10^{-3}$	$1.96\cdot10^{-3}$	$1.55\cdot10^{-4}$	$1.33\cdot10^{-3}$	$2.36\cdot10^{-3}$	–	–	–	–	$8.40\cdot10^{-3}$	$7.50\cdot10^{-3}$

Considering CO, there was no standard behavior between RT and ORT. The lowest emission rates were registered for E100 tests; these results support one of the objectives of adding ethanol to gasoline, to produce lower carbon monoxide emissions (Suarez-Bertoa et al., 2015). For E27 and E85 blends, emission rates were higher, especially with E85. As Anderson (2015) has reported, current flex engines are gasoline engines adapted to run a high-ethanol-content fuel; thus, the compression ratio is not the best for any such fuel, rendering combustion far from ideal. Furthermore, Otto engines work with a rich fuel/air ratio when in high power demand, reducing the efficiency of CO to CO_2 oxidation by the catalytic converter, resulting in a higher carbon monoxide emission (Anderson, 2015).

Concerning NO_x, similar emission factors were observed for E27 and E85 fuels, which were much lower than those for E100. NO_x formation model is potentiated by the increase in temperature that occurs during accelerations (Anderson, 2015), a fact that occurred more frequently in tests with E100 fuel, as can be seen for high VSP values in the frequency distribution of Fig. 5. Previous studies have shown inconsistent NO_x emission results related to the variation of ethanol proportion in gasoline; some studies show an increase in emission (Dardiotis et al., 2015), while others found no significant variation or even reduced emissions (Durbin et al., 2007). However, Delavarrafiee and Frey (Knoll et al., 2009) found the same increased NO_x tendency with high-ethanol-content blends; others found increased values.

No standard behavior for HC_t emission was observed, and there was a large variation in emission factors, even when including the same fuel in different tests, as seen with E85HP and E85FP. The highest and the lowest emission factors for hydrocarbons occurred with E100 fuel. Characteristically found in unconsumed fuel, HC_t is usually emitted during the cold phase of engine operation. The literature contains contradictory case results for HC_t emissions, showing both increased and decreased emission rates with higher-ethanol-content gasoline (Durbin et al., 2007; Knoll et al., 2009; Delavarrafiee and Frey, 2018).

Furthermore, catalytic converters may help to reduce global warming in a small way, as catalytic converters remove carbon monoxide and oxides of nitrogen whose emissions would otherwise lead to a build-up of tropospheric ozone. Other important fact is that temperature of the exhaust gas in a warmed-up spark-ignition engine can vary from 300 to 400 °C during idle, to about 1000 °C in full load operation. However, during a cold engine start up, the temperature of the catalytic converter is very low and the converter is not activated. Till the moment that the activation (light-off) temperature of the converter is attained (200–300 °C), the HC and CO produced by the engine are not converted and contribute to a high pollution of the atmospheric air (Ashrafur Rahman et al., 2021; Kritsanaviparkporn et al., 2021; AECC, 2022).

5. Conclusions

This paper is yet another more case with much data to report regarding emission factors obtained by real-world driving tests, including the use of pure hydrated ethanol, which is a commercialized fuel exclusive to Brazil. Experiments were realized out on a BRT road at the lanes from mixed traffic, especificaly, with focus on FFV. Dynamics data vary approximately 78% for the test duration and 230% for standstill time (speed equal to zero) during the experiments. Many researchers demonstrated that difficult to compare the effect of ethanol blends in real on-road situation due to traffic variability. Regarding emissions trends in this study, as CO and HC_t emissions, revealed the necessity for improving FFV technology, with a commitment toward developing better blends for gasoline and ethanol combustion. The extremely high standard deviations in some cases can be explained by peak emission (for all compounds) during engine start-up. This BRT system and exclusive lanes for mass-transportation vehicles (buses) allow better traffic organization. Nevertheless, this did not yield better emissions test results for case lanes from mixed traffic. In comparison with the literature data, in which a similar experiment was performed in the same city, dynamics results were seen to be worse. At this moment, the engine is not at the ideal temperature, and the catalytic converter has low efficiency until it reaches 300 °C. After this point, emission rates reach and remain at a much lower level for the entire test duration. Also, it is important to highlight the significantly increased NOx observed when flex engines are operated with pure ethanol. However, the present study shows that it is not possible to claim the same results for light vehicles. In this way, was observed an impact significantly this express road corridor on emission factors when a flex fuel-vehicle (passenger car) monitoring.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Felipe S. Frutuoso: Software, Methodology. **Camila M.A.C. Alves:** Visualization, Investigation. **Saul L. Araújo:** Methodology. **Daniel S. Serra:** Software, Validation. **Ana Luiza B.P. Barros:** Writing – review & editing. **Francisco S.Á. Cavalcante:** Methodology, Writing – review & editing. **Rinaldo S. Araújo:** Methodology, Writing – review & editing. **Nara A. Policarpo:** Writing – review & editing. **Mona Lisa M. Oliveira:** Software, Writing – review & editing.

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