Steady state emissions of two light duty engines operating with ethanol-gasoline (E20) blend

J. Tibaquirá [a], J.Huertas [b], S. Ospina [c] and F. Quirama [d]

[a] *Universidad Tecnológica de Pereira - UTP, Pereira, Colombia, juantiba@utp.edu.co*
[b] *Instituto Tecnológico de Estudios Superiores de Monterrey - ITESM, Toluca, México, jhuertas@itesm.mx*
[c] *Universidad Tecnológica de Pereira – UTP, Pereira, Colombia, sebaospina@utp.edu.co*
[d] *Universidad Tecnológica de Pereira - UTP, Pereira, Colombia. luisfelipequirama@utp.edu.co*

Abstract
This document contains information about the behavior of the emissions and performance of an internal combustion engine and a light duty vehicle operated with only gasoline and ethanol-gasoline blend E20 in fifteen operational steady states selected from four angular speeds and four load conditions which in turn were measured using the signal of the Throttle Position Sensor (TPS). The steady state emissions reported herein were measured from the tailpipes of a GMZ16SE engine located in Toluca Mexico and a light duty Chevrolet Sail 1400 cm^3 located in Pereira Colombia. These cities have two different atmospheric conditions. This study provides emission indices for five gases (CO, CO_2, HC, NO_X, O_2) produced by both the vehicle and the spark ignition engine. The emission rates were calculated in [g/km] and [g/kWh] from the measurements obtained in lab. Rather than giving a non-discriminated weighted total index of emissions, this work delivers results for each one of the fifteen testing modes. The contribution of this proposal is report specific emission indexes for each steady state mode based on an integrated approach that combines static and steady-state tests.

Keywords
Emissions, Ethanol, Gasoline, Emission indexes, Internal combustion engines.

1. Introduction

In the world, exist a necessity of use alternative and renewable fuels to replace the fossil fuels that have been used during the oil age. Given the regenerative and biodegradable characteristics of ethanol, it is widely used as an alternative fuel at the present time. The use of gasoline containing 3–10 vol% bioethanol is being promoted in many parts around the world for last few years [1].

The potential of ethanol fuel for improving the performance of internal combustion engines has been extensively investigated [2], Park et al. and Huang et al. found that adding ethanol fuel to gasoline could improve the mixture burnt rate and combustion efficiency due to its high combustion velocity [3] [4].

Ethanol also called ethyl alcohol is a substance with molecular formula C_2H_5OH, which can be used as fuel in internal combustion engines with spark ignition (Otto cycle) in two ways, ethanol-gasoline blends using anhydrous ethanol, and pure ethanol usually hydrated. A comparative study on E10 blend and gasoline found that the mixture requires 16.5% more heat to vaporize fully, which poses a problem for cold start. However when the engine is operating at normal running conditions, an increase in the engine thermal efficiency is expected, between 1% and 2% with respect to gasoline without the oxygenate additive due to the higher heat of vaporization of E10 blend [5]. The use of low concentrations (<10%) of ethanol in the biofuel blend could generate a slight effect on fuel consumption; but higher concentrations such as 25% of ethanol generate an increase in fuel consumption between 3% to 5%, compared with gasoline.

Combustion of ethanol-gasoline blends and pure ethanol compared to gasoline without the oxygenate additive produce lower emissions of carbon monoxide (CO), sulfur oxides (SOx), unburned hydrocarbons (HC) and other pollutants compounds as a result of more complete combustion. Conversely, aldehydes (R-CHO type compounds) and nitrogen oxides (NOx) increase depending on the characteristics of the engine [6, 7, 8].

The known results about the emissions behavior have been obtained based on three kind of methods: static tests, dynamic test using driving cycles and steady-state cycles. Static procedures deliver results as volume percent concentration or part per million (ppm). On the other hand, dynamic and steady-state tests deliver results as emission indexes, which are factors that determine the amount of mass in grams generated of a particular emission when an engine produces an energy unit in kWh or in km when a vehicle travels a certain distance. Both methods also report weighted averages after completing the cycle.

Steady-state cycles appeared as an alternative to the dynamic emission tests, Because the effects of transition periods between steady operation modes are minimized to prevent unclear and changing trends from affecting the results, thus giving more relevance to the measures obtained from the steady operation points. Moreover these periods can be prolonged to keep constant speeds and loads. Currently the steady state cycles are worldwide recognized and suggested for the analysis of diesel engines and classified by the quantity of operation modes of each cycle. However both dynamic and steady-state cycles have the communality of weighting all measured data to report only one result at the end.

The first steady-states cycle tests to be used were the Japanese 6-Mode Cycle and 13-Mode Cycle. In 1987, ECE R49 with 13 modes was adopted by the United Nations Economic Commission for Europe (UNECE), which was replaced in 2000 with the European Steady State Cycle (ESC) being the most updated nowadays [9]. ESC is a set of 13 consecutive steady modes of operation for a predetermined time using a weighting factor for each mode. Results obtained for the emissions are reported in [g/km].

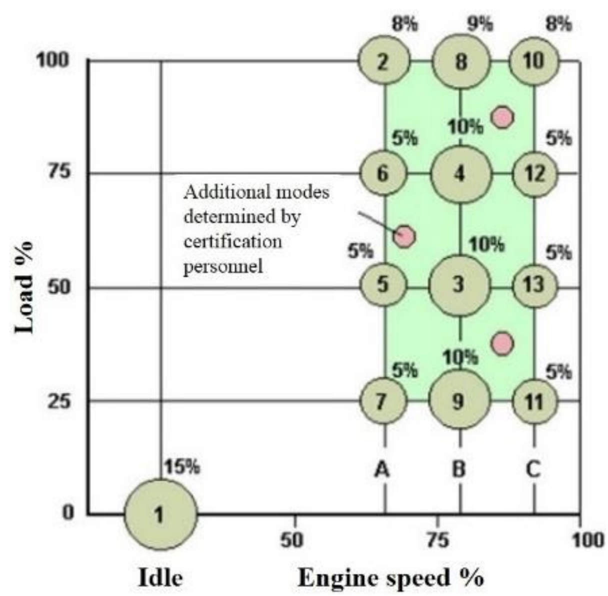

Fig 1. European Steady-state Cycle ESC.[9]

In this work, a new array of test points was established to cover different speeds and loads that represent several conditions of the work map of the engine. This method allows to obtain results in terms of the performance and emissions of the vehicle in each steady states mode of operation tested.

2. Methodology

This paper presents the results of the research project "Determination of steady-state emissions generated by a light duty vehicle operating with ethanol and gasoline, E20 blend" developed jointly by the Research Group on Energy Management (Genergetica) at UTP (Universidad Tecnológica de Pereira, Colombia) and CIMA (Research in Automotive Mechatronics) at ITESM (Instituto Tecnológico de Estudios Superiores de Monterrey, Campus Toluca, México).

2.1. Theoretical simulations

Due to the existence of two scenarios, a preliminary theoretical comparison was necessary. It was developed in three parts:

- Data collection based on previous experiences with only gasoline and E20.
- Processing of the aforementioned data using a combustion simulation model generated by CIMA to calculate emission concentration values and the mechanical, energetic and environmental performance of engines.
- From the already processed information, emissions indexes were calculated in [g/km] and [g/kWh] using a methodology elaborated by Genergetica research group.

The information collected from the previous experiences consists of:

- Intake air pressure for each steady-state mode.
- Combustion chamber dimensions.
- Compression ratio of each engine.
- Environmental conditions (pressure and temperature).
- Low heating value of each fuels tested.
- Air/fuel relationship (AFR) for each fuel tested.
- Air excess (λ) for each steady state tested.

In order to choose the most reliable combustion simulation model, a preliminary test were run. It consisted in comparing Otto cycle and CIMA model results to experimental data. The experimental part of this preliminary test involved the measurement of both internal pressure of the chamber and crankshaft position angle, from the operation of an internal combustion engine equipped with a Kistler spark plug pressure sensor and a crankshaft position sensor (CKP). The maximum pressure points of the combustion cycles depicted in Figure 4 allow to see how CIMA model approaches better to the experimental data. For this reason, CIMA model was chosen over Otto cycle as the combustion simulation model for this work.

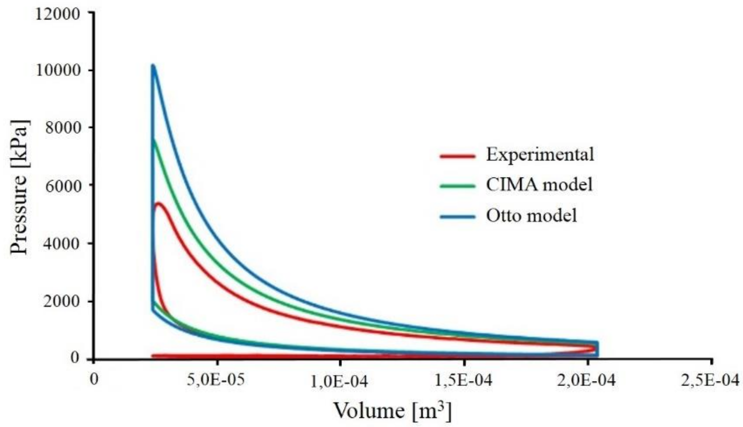

Fig 2. P-V diagram theorical Otto's Cycle and CIMA´s model.

The theoretical calculations of the engine performance variables such as fuel mass flow and power were done using Engineering Equation Solver (EES) V9.710 software, whereas the combustion temperature (T3) at maximum pressure point and the volume concentration of the combustion gases were obtained using GASEQ 0.79 software. For calculate theoretical emission volume fractions, the software was fed with: molar fractions of the combustion reactants, initial conditions for T3, environmental conditions for the output of combustion products. Leading to the theoretical data of the concentration of CO, CO_2, O_2, NO for nitrogen oxides case and CH_4 representing the unburnt hydrocarbons (HC). With a mass balance tool designed by Genergetica research group using EES V9.710, emission indexes were obtained based on the above results from GASEQ and EES softwares.

2.2. Experimental tests

The objective was to determine steady-state emissions resulting from the operation of an engine GM Z16SE and a light duty vehicle Chevrolet Sail 1400 cm^3 operating with a 20% ethanol-80% gasoline blend (E20). Table 1 reports technical specifications for each engine. Fifteen operation modes were tested at steady states for each engine taking place under two different atmospheric conditions: for GMZ16SE at 2660 m above sea level in Toluca (México) and for the Chevrolet Sail at 1410 m above sea level in Pereira (Colombia). The altitude of Pereira represents the operating conditions of vehicles in towns located at altitudes between 1000 and 2000 m above sea level, like most cities in Colombia and Mexico. The tests were performed in Toluca at the CIMA lab and in Pereira at the LPDA (Laboratory of Automotive Dynamic Tests) from UTP. Figures 2 and 3 present the different experimental setups and equipment used in the two locations.

Characteristics	Chevrolet Sail / LPDA Pereira	Chevy / CIMA Toluca
Powertrain	1,4 Liters DOHC	GM Z16SE
Displacement [cm^3]	1 398	1 597
Orientation	Transversal	Longitudinal
Compretion ratio	10,2	9,4
Cilinder diameter/ Stroke	79,8 mm / 81,8 mm	-
Distribution	4 valves per cilinder / 2 camshafts	2 valves per cilinder/ 1 camshaft
Fuel System	Indirect fuel injection	Sequential multipoint fuel injection
Horsepower / RPM	76 kW / 6000 RPM	74,5 kW / 5600 RPM
Torque / RPM	130 Nm / 4200 RPM	135,6 Nm / 3200 RPM

Table 1. Technical specification of engines.

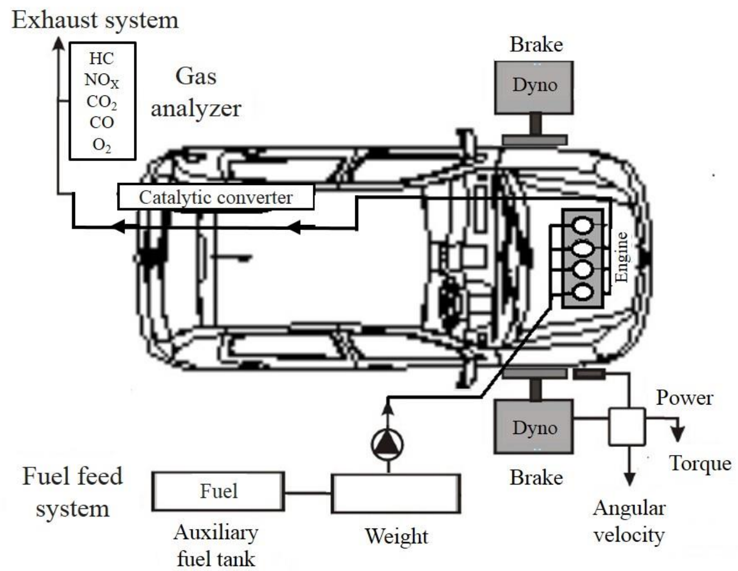

Figure 3. Experimental setup at LPDA (UTP, Pereira) for Chevrolet Sail.

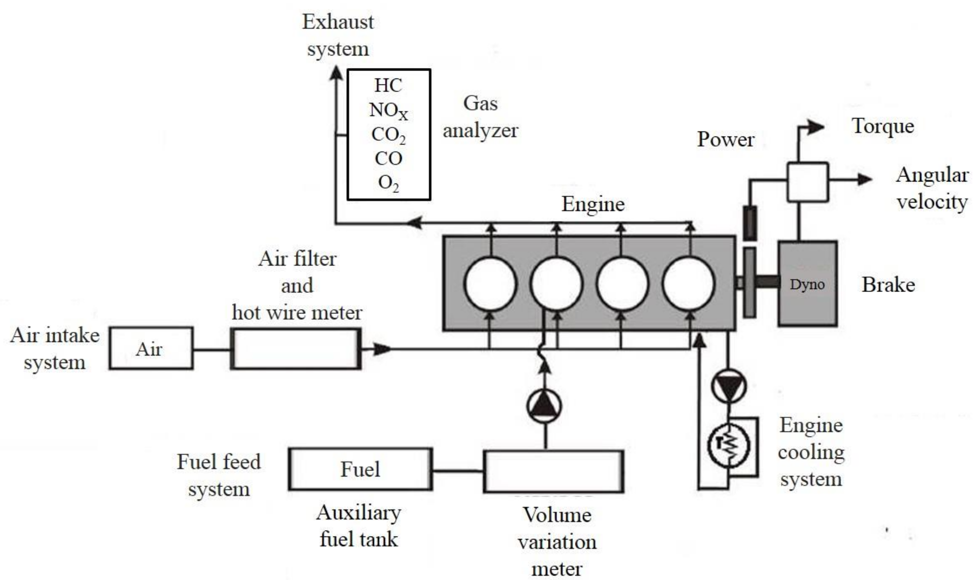

Fig 4. Experimental setup at CIMA (ITESM, Toluca) for GM Z16SE.

With the purpose of covering different points in the operating range of the internal combustion engines, the steady states tested were selected at four engine revolutions and four load points which were controlled with the assistance of the Throttle Position Sensor (TPS) signal. To monitor the four selected engine revolutions and to measure the power, the following equipments were used: Dynapack 2WD-2 dynamometer and Vgate OBD scan in Pereira and SuperFlow SF902 dynamometer and ELM327 OBD scan in Toluca. Table 2 shows the steady-state modes selected to evaluate both systems (engine/vehicle).

Fuel mass flows were obtained with a gravimetric technique in Pereira using a Summit Racing Fuel Tank SUM-290122, a 6 kg Fenix Lexus Electronic Scale with assistance of an interface designed with LabView software. Similarly in Toluca, the volumetric measurements for fuel mass flow were performed using a combustible consumption measuring system designed by CIMA equipped with an auxiliary fuel tank, a calibrated tube and a Camera DVT Legend Vision.

For both locations, the measurements of combustion emissions resorted to gas analyzer devices (Galio Smart 2000X in Pereira and Infrared FGA-4000XD in Toluca) taking samples before gases enter the catalytic converter in order to keep samples from being affected by the oxidation process occurring in the catalytic converter.

TPS	**RPM**			
	1500	2500	3500	4500
25%	X	X	X	-----
50%	X	X	X	X
75%	X	X	X	X
100%	X	X	X	X

Table 2. Matrix with steady-state regimes evaluated

Six iterations of the fifteen regimes were carried out for each engine. Three iterations corresponded to only gasoline operations and the remaining three to E20. Unlike the theoretical calculations, their experimental counterparts used averages of emission data, fuel mass flow and engine performance variables, measured directly with equipment monitoring the running engines. The averages, in turn, were calculated based on the three iterations formerly explained. Owing to the reduced sample size, the validation of the averages resorted to a Student's T distribution with a confidence interval of 95%. Finally, the EES mass balance tool developed by Genergetica was fed with the validated averages to calculate the experimental emission indixes.

3. Experimental results

3.1 - Toluca test results

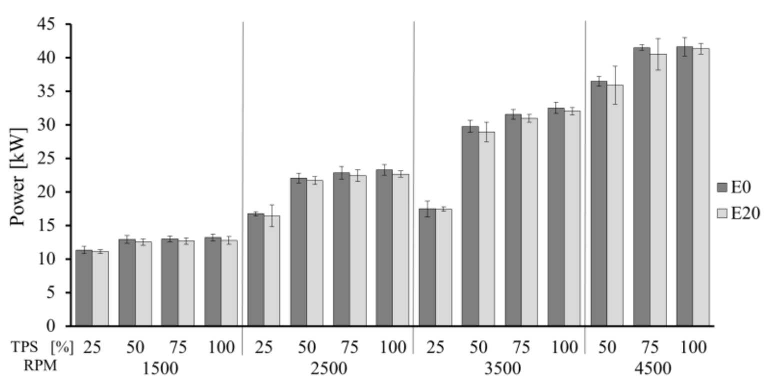

Fig 5. Power CIMA ITESM tests.

As expected, Figure 5 shows that power increase at higher speeds for both E20 and E0. Having said that, power with E20 is on average 1,9% less than the power with E0. None of the steady states reverted this trend of behavior of the variables. And the largest difference in power (3.17%) between E20 and E0 can be seen at 1500 rpm with a load of 100%.

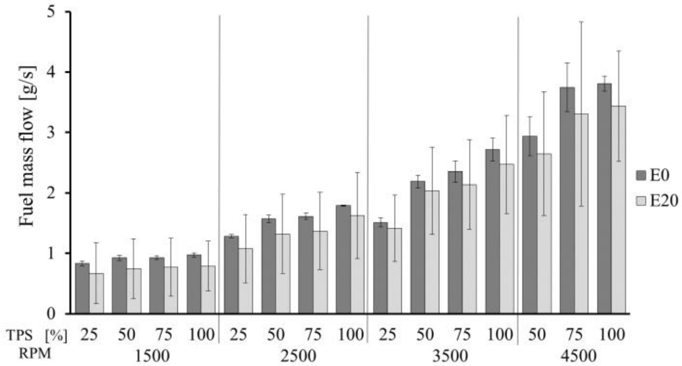

Fig 6. Fuel mass flow CIMA ITESM tests.

Figure 6 reveals that fuel mass flow with E20 is on average 12,89% less than that with E0. None of the steady states reverted this trend of behavior of the variables. And the largest difference in fuel mass flow (19,63%) between E20 and E0 can be seen at 1500 rpm with a load of 25%.

Figure 7a-b shows results for CO_2 and following is their respective analysis. According to the Figure 7a, the [g/kWh] emission indexes with E20 are on average 18.38% less than those with E0. And Figure 7b reports that the [g/km] emission indexes with E20 are on average 20.05% less than those with E0. At 1500 RPM with a load of 50%, were reported the largest differences in emissions indexes: 38% for indexes expressed in [g/kWh] and 40 % for indexes expressed in [g/kWh]. However three steady states reverted the behavior of the indexes, namely: at 1500 RPM with a load of 75%, at 3500 RPM with a load of 100% and at 4500 RPM with a load of 100%.

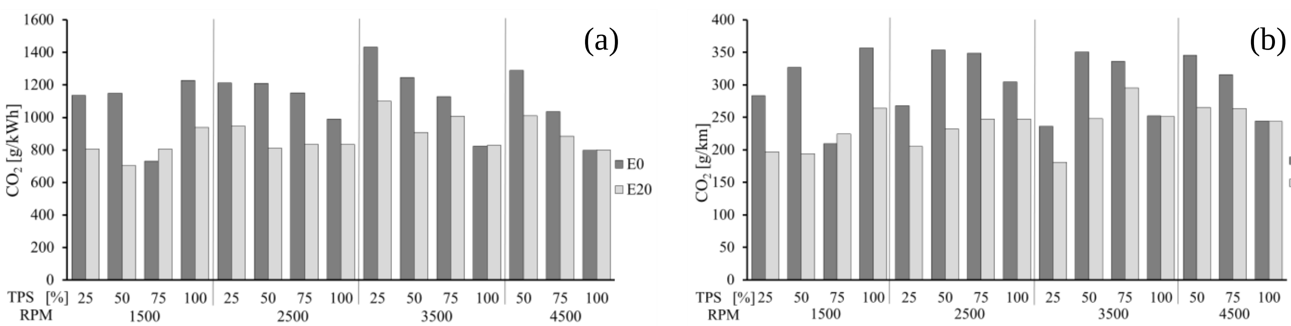

Fig 7. CO_2 CIMA – ITESM tests, (a) [g/kWh], (b) [g/km]

Figure 8a-b shows results for CO and following is their respective analysis. According to the Figure 8a, the [g/kWh] emission indexes with E20 are on average 15.69% less than those with E0. And Figure 7b reports that the [g/km] emission indexes with E20 are on average 17.33% less than those with E0. At 1500 RPM with a load of 100%, were reported the largest differences in emissions indexes: 56,53% for indexes expressed in [g/kWh] and 57,92 % for indexes expressed in [g/kWh]. Finally, CO readings reported reversion on behavior of the indexes for the same three steady states that reverted for CO_2.

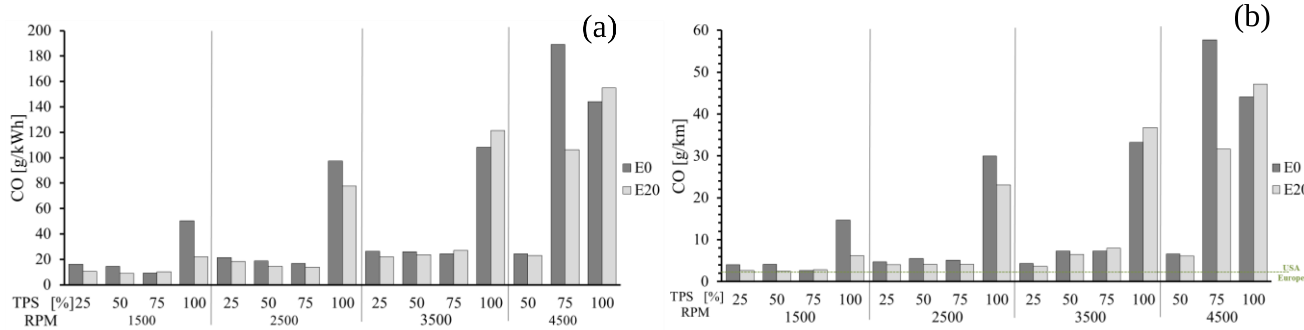

Fig 8. CO CIMA –ITESM tests, (a) [g/kWh], (b) [g/km]

Figure 9a-b shows results for HC, and following is their respective analysis. According to the Figure 9a, the [g/kWh] emission indexes with E20 are on average 9,27% less than those with E0. And Figure 9b reports that the [g/km] emission indexes with E20 are on average 11.07% less than those with E0. In spite of showing a decreasing trend of E20 with respect to E0, the largest differences in emissions indexes were presented at a point that reverted the behavior of the variables: 30,77% for indexes expressed in [g/kWh] and 27,5% for indexes expressed in [g/kWh], at 1500 RPM with a load of 100%. Additionally, other two points reverted the trend: at 3500 RPM with a load of 25% and at 45000 RPM with a load of 100%.

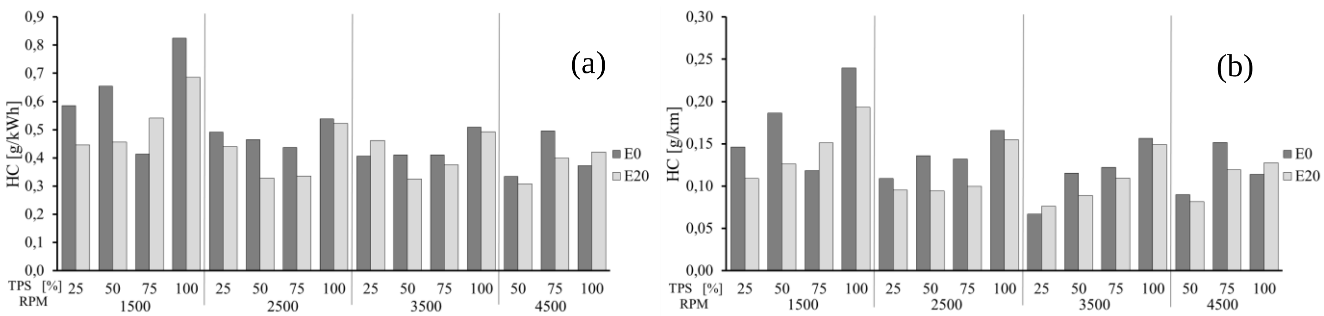

Fig 9. HC CIMA – ITESM tests, (a) [g/kWh], (b) [g/km]

3.2 - Pereira test results

Since each engine operated its own fuel injection program, the resulting discrepancies regarding the air/fuel ratio affect the readings for power, fuel mass flow and CO_2.

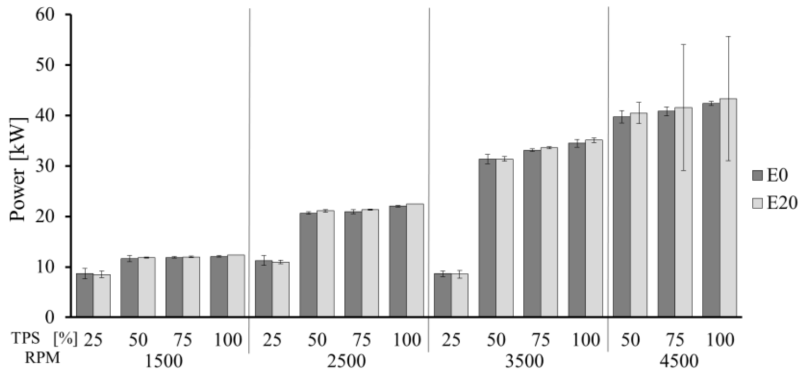

Fig 10. Power LPDA UTP tests.

Figure 10 shows the expected power increase at higher speeds for both E20 and E0. Unlike the trend seen in the experimental results from Toluca, the behavior of the power variables from the test in Pereira reports that power with E20 is on average 0,9% greater than the power with E0 and the largest difference in power (2.24%) between E20 and E0 can be seen at 4500 rpm with a load of 100%. Three steady states slightly reverted the behavior of variables: at 1500, at 2500 and 3500 RPM, all of them combined with a load of 25%.

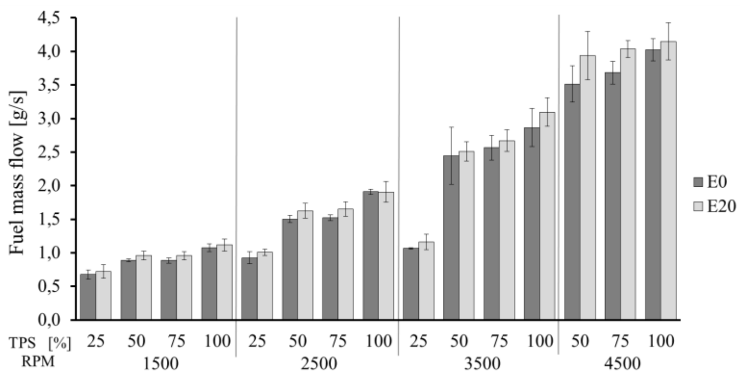

Fig 11. Fuel mass flow LPDA UTP tests.

Figure 11 reveals that fuel mass flow with E20 is on average 6,74% greater than that with E0, which implies an opposite trend of behavior in comparison to results from Toluca. The largest difference in fuel mass flow (12%) between E20 and E0 can be seen at 4500 rpm with a load of 50%. Only one steady state reverted the behavior of variables: at 2500 RPM with a load of 100%

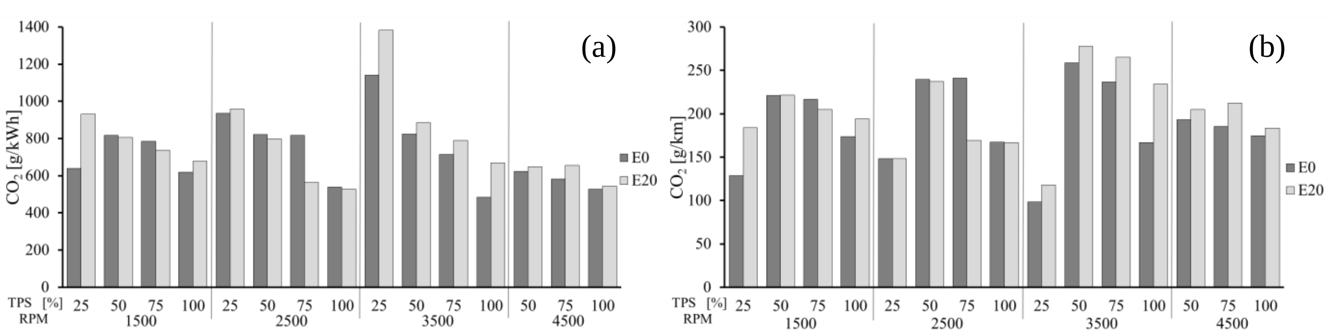

Fig 12. CO_2 LPDA UTP test results, (a) [g/kWh], (b) [g/km]

Figure 12a-b shows results for CO_2 and following is their respective analysis. According to the Figure 12a, the [g/kWh] emission indexes with E20 are on average 7.3% greater than those with E0. And Figure 12b reports that the [g/km] emission indexes with E20 are on average 8.25% greater than those with E0. Due to all of the above, results from Pereira concerning emission indexes are regarded to exhibit an opposite trend to that of the results from Toluca. At 1500 RPM with a load of 25%, were reported the largest differences in emissions indexes: 45,52% for indexes expressed in [g/kWh] and 42,7 % for indexes expressed in [g/km]. The following six steady states reverted the behavior of the indexes: for both emissions reversion coincided at 1500 RPM with a load of 75%, and also with regimes at 2500 RPM with loads of 50%, 75% and 100%; additionally reversion didn't coincided for two emissions: at 1500 with a load of 50% exclusively for the case of [g/kWh] emission, and at 2500 RPM with a load of 25% exclusively for the [g/km] emissions.

Figure 13a-b shows results for *CO* and following is their respective analysis. According to the Figure 13a, the [g/kWh] emission indexes with E20 are on average 12,76% less than those with E0. And Figure 13b reports that the [g/km] emission indexes with E20 are on average 12,1% less than those with E0. At 3500 RPM with a load of 50%, were reported the largest differences in emissions indexes: 56.97% for indexes expressed in [g/kWh] and 56.9 % for indexes expressed in [g/km]. Six steady states reverted the behavior of the indexes for both emissions: at 1500 RPM with loads of 25% and 50%, at 3500 RPM with loads of 25% and 100%, and finally at 4500 RPM with loads of 50% and 75%.

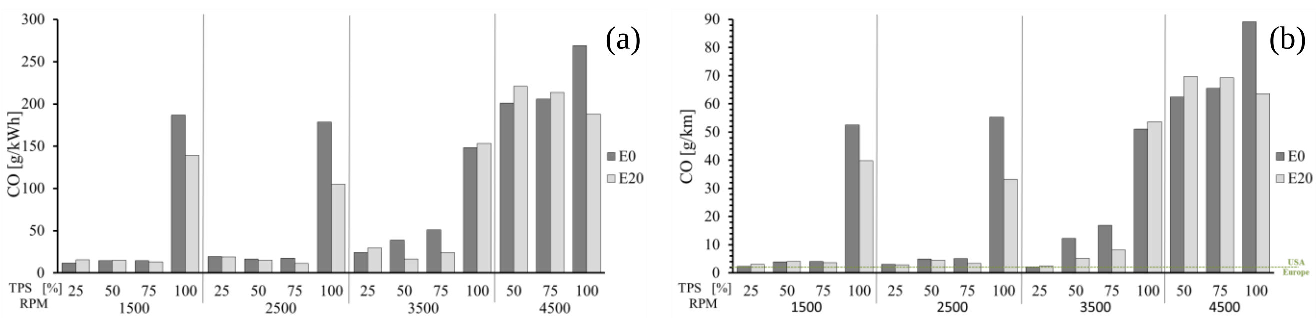

Fig 13. CO LPDA UTP test results, (a) [g/kWh], (b) [g/km]

Figure 14a-b shows results for HC and following is their respective analysis. According to the Figure 14a, the [g/kWh] emission indexes with E20 are on average 2% less than those with E0. And Figure 14b reports that the [g/km] emission indexes with E20 are on average 1.1% less than those with E0. At 2500 RPM with a load of 75%, were reported the largest differences in emissions indexes: 35,76% for indexes expressed in [g/kWh] and 34,52 % for indexes expressed in [g/km]. Five steady states reverted the behavior of the indexes for both emissions: at 1500 RPM with a load of 25%, at 3500 RPM with loads of 25% and 100%, and at 4500 RPM with loads of 50% and 75%.

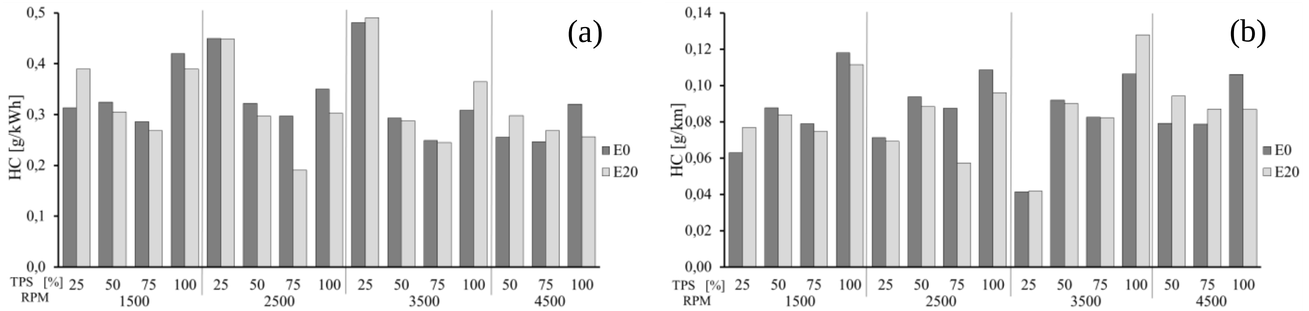

Fig 14. HC LPDA UTP test results, (a) [g/kWh], (b) [g/km]

4. Conclusions and recommendations

- The methodology proposed to perform discrete measurements for each steady state is introduced as a useful tool for programming and optimization operational of engines because allows to determine the behavior of variables to be analyzed for their subsequent adjustments and hence improving the combustion efficiency.
- The identification of specific trend-reverting points shown in this paper would not have been possible with conventional test that only provide weighted averages.
- The emission indexes expressed distinctly in [g/kWh] and [g/km] enable the direct association of emissions with performance variables of engines in order to analyze the impact of different fuels in the same motor.
- With a view to expand the scope of this study, it is advisable to replicate these tests with the same engine at different atmospheric conditions and thus obtaining a more complete analysis of behavior of combustibles.
- The reverted steady states against average trends for any variables are points to take into consideration when reprograming fuel injection systems to adapt engines for new biofuels.

5. Acknowledgments

This research was possible thanks to the financial support that the Vice-Chancellor Office for Research and Innovation from UTP granted to the project identified with a code 8-13-1. We also like to express our gratitude to Asocaña (Association of Sugarcane Growers and Mills of Colombia) and Fedebiocombustibles (Colombian National Biofuels Federation) to promote and encourage these kind of initiatives. And last but not least, we like to thank the staff members of CIMA and LPDA.

6. References

[1] S. M. Yunoki S, «A simple method to determine bioethanol content in gasoline using two-step extraction and liquid scintillation counting,» Bioresource Technology, vol. 23, p. 100, 2009.

[2] G. H. Yuan Zhuang, «Primary investigation to leveraging effect of using ethanol fuel on reducing gasoline fuel consumption,» Fuel, vol. 105, pp. 425-431, 2013.

[3] C. Y. K. C. O. S. L. G. M. Y. Park C, «Performance and exhaust emission characteristics of a spark ignition engine using ethanol and ethanolreformed gas,» Fuel, vol. 89, pp. 2118-25, 2010.

[4] D. R. L. H. X. H. S. S. Tian GH, «Laminar burning velocities of 2,5- dimethylfuran compared with ethanol and gasoline,» Energy Fuels, nº 24, pp. 3898-905, 2010.

[5] A. P. I. -. API, «Alcohol and ethers, a technical assessment of their application as fuel and fuel components,» Washington, 1998.

[6] T. J. G. L. Q. L. O. S. Rios L.C, «Protocolo E20,» Universidad Tecnológica de Pereira, Grupo de investigación en gestión energética - GENERGETICA, Pereira, 2012.

[7] C. y. BNDES, Bioetanol de caña de azúcar - Energía para el desarrollo sostenible, Rio de janeiro, 2008.

[8] M. y. Goldemberg, «The Brasilian Alcohol Program - An overview,» Energy for Sustainable Development, vol. 1, nº 1, 1994.

[9] Dieselnet, «Dieselnet,» 2013. [En línea]. Available: https://www.dieselnet.com/standards/cycles/#us-ld. [Último acceso: 2013].