COMPARISON OF ENERGETIC EFFICIENCY OF MOTORCYCLES WITH ELECTRIC AND INTERNAL COMBUSTION ENGINES

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Abstract. This paper presents a comparison between the energetic efficiency of motorcycles driven by electricity and by different combustion engines. Tests were carried out according to the European standards for motorcycles exhaust emissions (Directive 97/24/EC). Such standard has been adopted by CONAMA for homologation and certification of motorcycles in Brazil. Chassis dynamometer tests simulated road load conditions in cycles with variable speed in normalized time. Work performed during the each test was computed and the fuel energy expenditure along the cycle was measured. The energy efficiency was thus calculated by the ratio between the two. Results show that electric driven motorcycles are three times more efficient than motorcycles than internal combustion engines (ICE). Regulated emissions carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NOx) and carbon dioxide (CO$_2$) were measured in the exhaust gases of the combustion engines.

Keywords: energy efficiency, vehicular emissions, motorcycles

1. INTRODUCTION

Electric motorcycles are gaining widespread acceptance nowadays due to their environmental advantages compared to gasoline-powered motorcycles and are considered as a possible way of improving the transportation system sustainability. In Europe, 2012, the transportation sector was responsible for 33% of the final energy consumption, with the road transportation sector presenting an 82% share of that energy consumption (Magno *et al*, 2015). In the USA, 2014, 28% of total energy was consumed by the same sector (EIA, 2016). In Brazil, 2012, numbers are similar to those of Europe and the USA and the transportation sector was responsible for 31% of total energy use (EPE, 2014). Furthermore, the transportation sector is a source of local pollution which results in health problems.

Electrification is widely considered as a viable strategy for reducing the oil dependency and environmental impacts of road transportation. In pursuit of this strategy, most attention has been paid to electric cars. However, substantial, yet untapped, potentials could be realized in urban areas through the large-scale introduction of electric two-wheelers (Martin *et al*, 2015).

In China and India, the market share for electric two-wheelers (E2Ws), including e-bikes and e-motorcycles, improves rapidly. By 2006, annual sales of E2Ws equaled those of gasoline two-wheelers (G2W). It is likely that E2Ws will continue to substitute bicycles as incomes rise in China (Weinert *et al*., 2008). A study carried out in Taiwan regarding green products examined the antecedents of purchase intention and the relation between purchase intention and image, risk and value in the electric motorcycle market. The authors propose an integrative approach to understand green marketing and innovation models due to its importance on Taiwanese Market where E2Ws are considered as green products (Jih *et al*., 2015). Studies have been conducted in Vietnam regarding the use of sustainable transportation two-wheelers vehicles since the country is experiencing rapid growth in the ownership of personal gasoline powered motorcycles and a shift away from relatively low-emitting modes of transportation such as electric two-wheelers have the potential for significant air pollution reductions (Jones *et al*., 2013).

Energy use and GHG emissions of electric two-wheelers critically depend on the system boundary of the analysis, i.e., whether tank-to-wheel, well-to-wheel, or the entire life cycle of the vehicle is considered. The tank-to-wheel electricity consumption of electric two-wheelers ranges from 7.0 ± 3.0 kW h 100 km^{-1} for e-motorcycles making mid-size electric two-wheelers the most energy efficient powered vehicles for individual road transportation. If electric two-wheelers replace conventionally-powered two-wheelers, tank-to-wheel energy savings of 50–90% can be achieved as electric motors are more efficient than internal combustion engines. The efficiency benefits of electric two-wheelers decrease, however, when the well-to-wheel energy chain of resource extraction, conversion, and energy transport is considered (Martin *et al*, 2015).

Weinert *et al*. (2008) report for China a well-to-wheel energy use of small electric two-wheelers (7 ± 1 kW h 100 km^{-1}) that is substantially lower than that of conventionally-powered two-wheelers (29 kW h 100 km^{-1}).

Magno *et al.*(2015) reported that tests conducted in Lisbon show that tank-to-wheel (TTW) energy consumption for motorcycles was reduced by 61% when shifting to electric mobility, while a 30% well-to-wheel (WTW) reduction is obtained. For the electric bicycles, an additional energy use is quantified due to the battery electricity consumption.

However, some articles report some disadvantages of E2Ws vehicles. Conventional scooters and motorcycles possess five times the range of electric equivalents and twice the top speed, and are therefore considerably more flexible in terms of day-to-day use (Walker *et al.*, 2015).

Electric motorcycles have emerged as a reliable way to improve the transportation sustainability in Brazil as well. The Brazilian transport energy matrix differs from other countries due to the impressive presence of ethanol fuel and, consequently, the large use of flexfuel vehicles throughout the country. This paper presents tests results of five motorcycles. Tests were focused on energetic efficiency and tailpipe emissions. Four motorcycles are powered by combustion engines (ICE) and one is E2Ws type. One motorcycle is a flexfuel type and was fueled with different gasoline/ethanol blends: E22 (22% anhydrous ethanol and 78% gasoline), E61 (50% E22 and 50% hydrous ethanol) and E100 (100% hydrous ethanol).

2. METHODOLOGY

The motorcycles were tested according to the European Regulation - 97/24/EC (EC, 1997) over an AVL chassis dynamometer with 648 mm of diameter. Regulated tailpipe emissions (CO, HC, NO_x and CO_2) were measured with Constant Volume Sampler (CVS) and 7000 series Horiba benches. A minimum of three tests were performed for each analyzed situation.

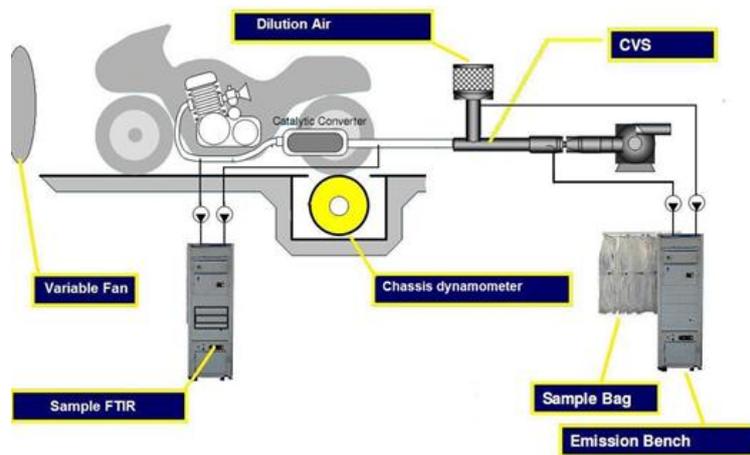Figure 1 presents the test procedure lay-out.

Figure 1. Test procedure layout

For motorcycles equipped with engines smaller than 150cc the dynamometer driving cycle consists of just of a single phase The emission test cycle simulates an urban path, composed of six elementary cycles lasting 195s each, with periods of idling, acceleration and speed levels of 15, 32, 50 and 35 km.h^{-1}, totaling 1170s. The test comprises approximately 6.0 km. Figure 2 shows the driving speed versus time developed on the dynamometer during the emissions test.

The tests were conducted according to EURO standards. The resistive power was defined based on motorcycle inertia, added to 75 kg (representing the driver's mass). Based on these information coefficients are calculated and applied to the chassis dynamometer. The coefficients vary according to the vehicle inertia class and are defined as A (N) and C (N km^{-1} (h^2)$^{-1}$). The force applied to the motorcycle is calculated according to the following equation 1:

$$F = A + C \times v^2 + i \times \frac{dv}{dt}$$
(1)

Where F is the force (N), *A* is the static friction coefficient (N), *C* is the aerodynamic friction coefficient (N km^{-1} (h^2)$^{-1}$), *v* is the vehicle speed (km h^{-1}), *i* is the inertia (kg) and *dv/dt* is the vehicle acceleration.

The work (energy) produced during the test was calculated based on the instant forces (N) applied to the motorcycle, speed and instant accelerations measured along the test. The transmission losses, energy transformation, heat, friction and others losses involved in the operation of motorcycles were not considered.
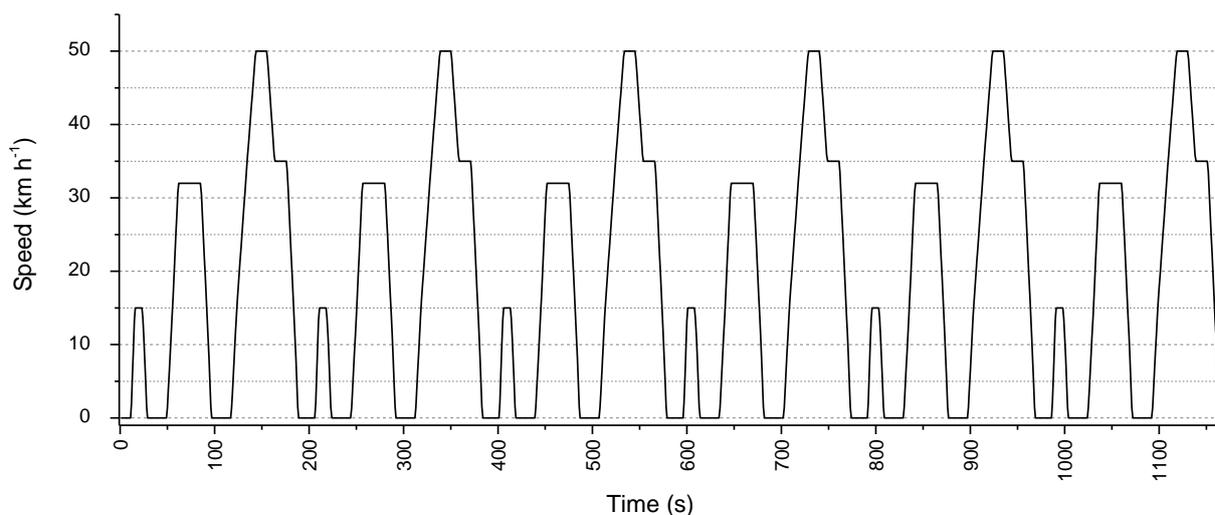
Figure 2. Test cycle

For internal combustion engines, the energy was calculated by using the carbon balance method and the fuel consumption data according to NBR 7024 (ABNT, 2010), which uses THC, CO and CO_2 emissions values, in addition to the characteristics of the fuel.

The superior calorific value of the fuel was determined with bomb calorimetry technique according to ASTM D240-14. The inferior calorific value was determined by applying the Dulond equation. The energy was determined based on the fuel volume spent during the test and its inferior calorific value.

For electric motorcycle the energy was measured with one B class energy meter, with accuracy of 1%, according to the NBR 14519 (ABNT, 2011). For every test the motorcycle batteries were fully charged. The energy spend during the whole test was measured. At the end of the each test the batteries were fully loaded again. The energy required to recharge the batteries was measured between the electrical grid and the motorcycle boot, in order to include its efficiency in the system.

The sample efficiency was measured by the equation 2.

$$\eta = \frac{Q_{out}}{Q_{in}} \times 100 \tag{2}$$

In equation 2, η is the sample efficiency (%), Q_{out} is the energy produced during the chassis dinamometer test (kJ), and Q_{in} is the primary energy provided by the fuel/battery used in the test (kJ).

2.1 Motorcycles characteristics

Table 1 shows the main characteristics of motorcycles used in the experiments, as well as its inertia class and the resistive power imposed by the dynamometer to a speed of 50 km h^{-1}.

Table 1. Characteristics of motorcycles used in tests

Sample	Production year	Emission regulation	Engine	Injection fuel system	Inertia class (Kg)	Resistive power at 50 km h^{-1}
Mc1	2003	Euro I	ICE/125cc	Carburetor	190	1.03 kW
Mc2	2008	Euro II	ICE/100cc	Carburetor	170	0.99 kW
Mc3	2009	Euro III	ICE/125cc	EFI	180	1.01 kW
Mc4	2011	Euro III	ICE/ 150cc	EFI/ flex fuel	200	1.04 kW
Me1	2011	N.A.	Electric/2 kW	N.A.	210	1.06 kW

The electrical system of the test motorcycle was composed of four batteries 12 V lead acid totaling 48 V and 35 Ah. The engine power is 2 kW, specified autonomy of 50 km and a maximum speed of 60 km h^{-1}. In order to verify if the battery pack had a linear behavior of discharge, sets of one, two and three consecutive tests were performed. In this procedure it was observed a linear behavior of the battery load.

2.2 Fuel Specification

The motorcycles were fueled with the reference standard fuel for emissions, gasoline blended with 22% anhydrous ethanol (E22) by volume. The flex fuel motorcycle was tested with different gasoline/ethanol blends: E22 (22% anhydrous ethanol and 78% gasoline), E61 (50% E22 and 50% hydrous ethanol) and E100 (100% hydrous ethanol). The fuels were certified according to the Brazilian standard NBR 8989 (ABNT, 2012)

2.3 Statistical analysis

The results presented for each motorcycle were obtained from the average of three tests. For data analysis we used the analysis of variance (ANOVA). Fischer / LSD test was used to identify statistical differences.

3. RESULTS AND DISCUSSION

Regarding the electric motorcycle, a series of tests were performed to check the linearity of the batteries discharge. In order to measure the energy for batteries recharge, firstly the batteries were recharged after one emission test. Secondly, the batteries were recharged after two emission tests. And thirdly, after three tests. Figure 3 illustrates the relation between the distance and energy needed to recharge the batteries. This data were obtained as a result of 14 tests.

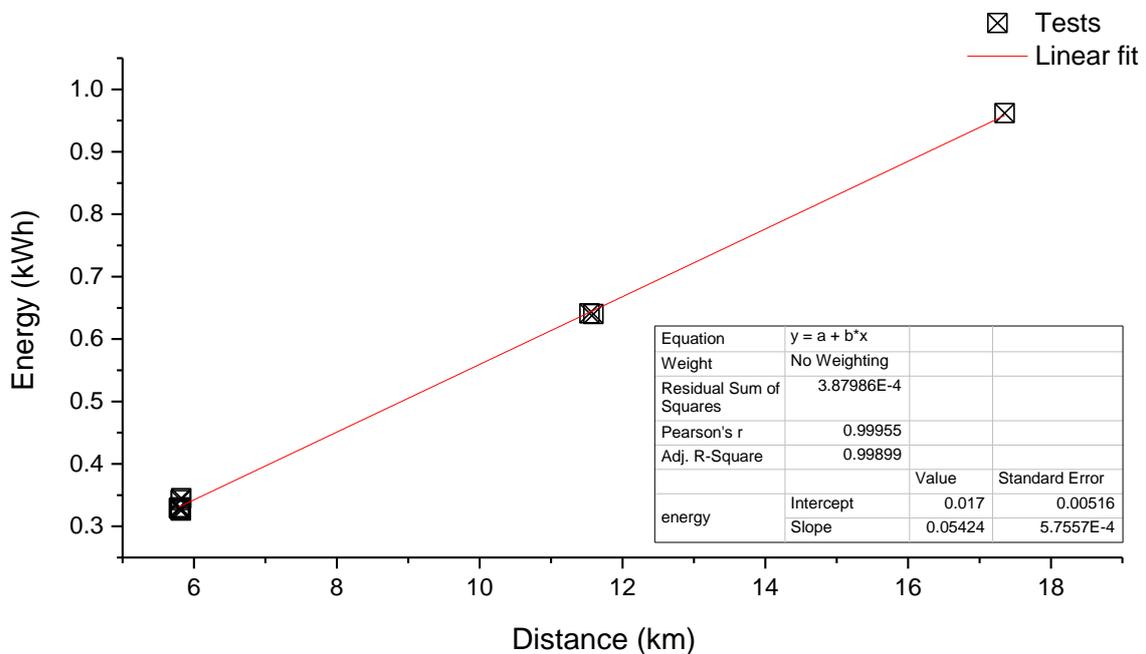| Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.87986E-4		
Pearson's r	0.99955		
Adj. R-Square	0.99899		
		Value	Standard Error
energy	Intercept	0.017	0.00516
	Slope	0.05424	5.7557E-4

Figure 3. Test distance and energy needed to recharge the batteries

According to the technical specification, the maximum speed for the electric motorcycle is of 60 km h-1. However, during the tests it was observed that even at maximum acceleration level the vehicle did not reach 50 km h- 1, which is the higher speed required for the emission test.

In the case of two or three consecutive tests, one after the other, without battery recharge, there was a drop in the maximum speed according to the increase in the number of tests. Figure 4 illustrates the sequence of three consecutive tests and the decrease on the motorcycle maximum speed on the first 195s of test.

The results of the energy efficiency are shown in Figure 5, recalling that the flexfuel (Mc4) was fueled with three different levels of ethanol. Regarding the efficiency results, it was observed that ICE sample models with electronic fuel injection (Mc3 and Mc4) presented higher efficiency compared to the carbureted ones (Mc1 and Mc2).
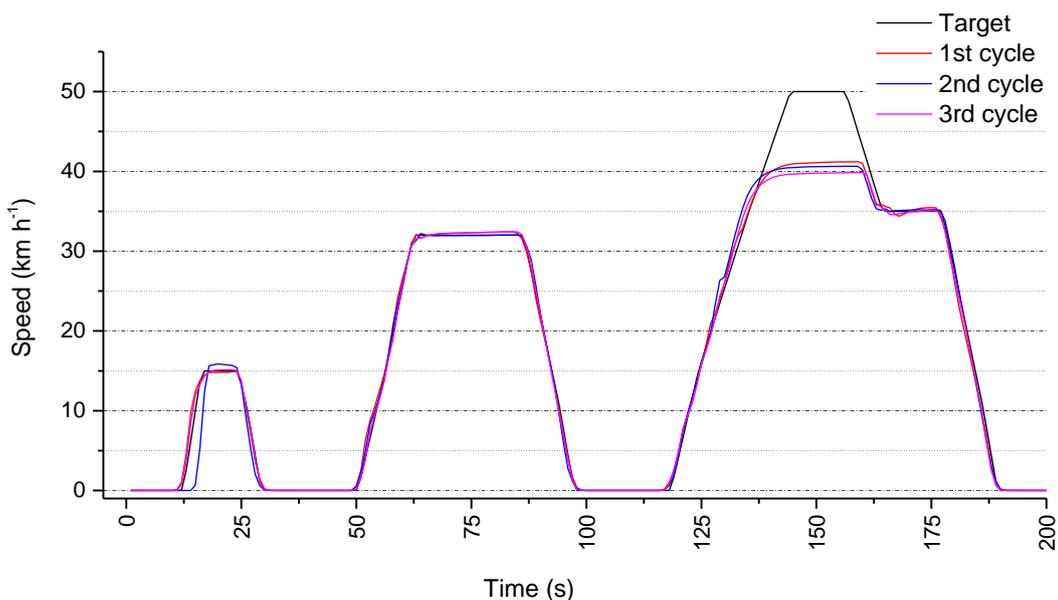
Figure 4. Motorcycle maximum speed on the first 195s of the emission test

The flexfuel engine was calibrated to operate with different levels of ethanol (Mc4) and had lower efficiency compared to the model dedicated exclusively to gasoline and equipped with an electronic injection (Mc3). The error bars refer to standard deviation between tests.
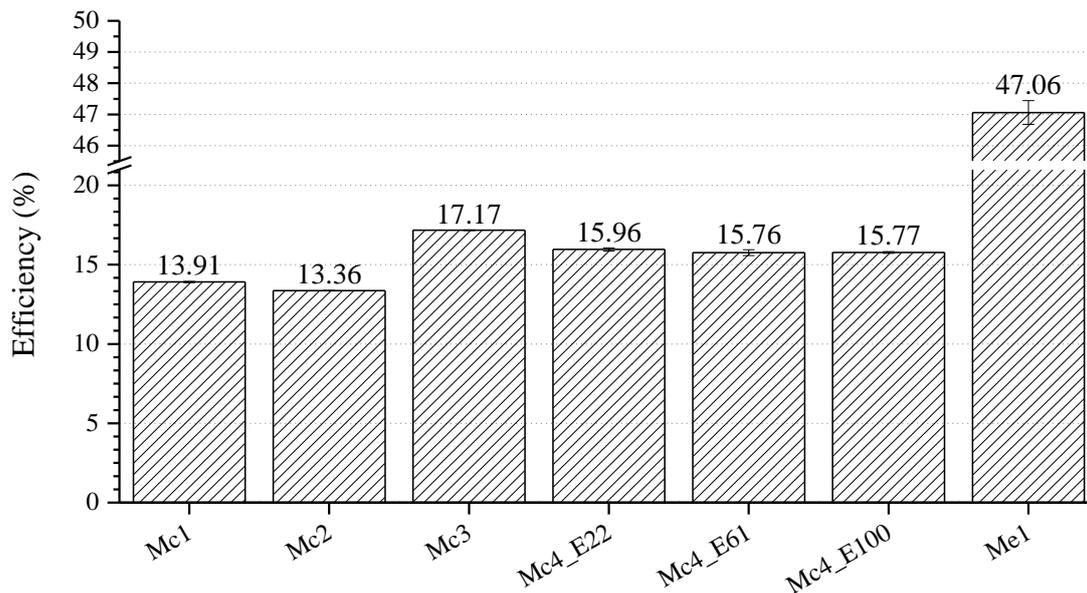

Figure 5. Motorcycles energy efficiency Euro testing cycle

The statistical analysis (ANOVA, Fischer/LSD) indicated that the test results considering all the motorcycles were statistically different. However, the results related exclusively to flexfuel motorcycle using different levels of ethanol were considered without statistically significant differences. Regarding efficiency the statistical power was 1,00, demonstrating the adequacy of sample size, deviations and effects under examination (Hair, 2006).

CO, THC, NOx and CO_2 emissions in ICE motorcycles are presented in Figure 6. It is observed a significant reduction in CO and THC emissions with emission limits Euro I and II (Mc1 and Mc2) compared to EURO III motorcycles equipped with electronic fuel injection and catalyst.
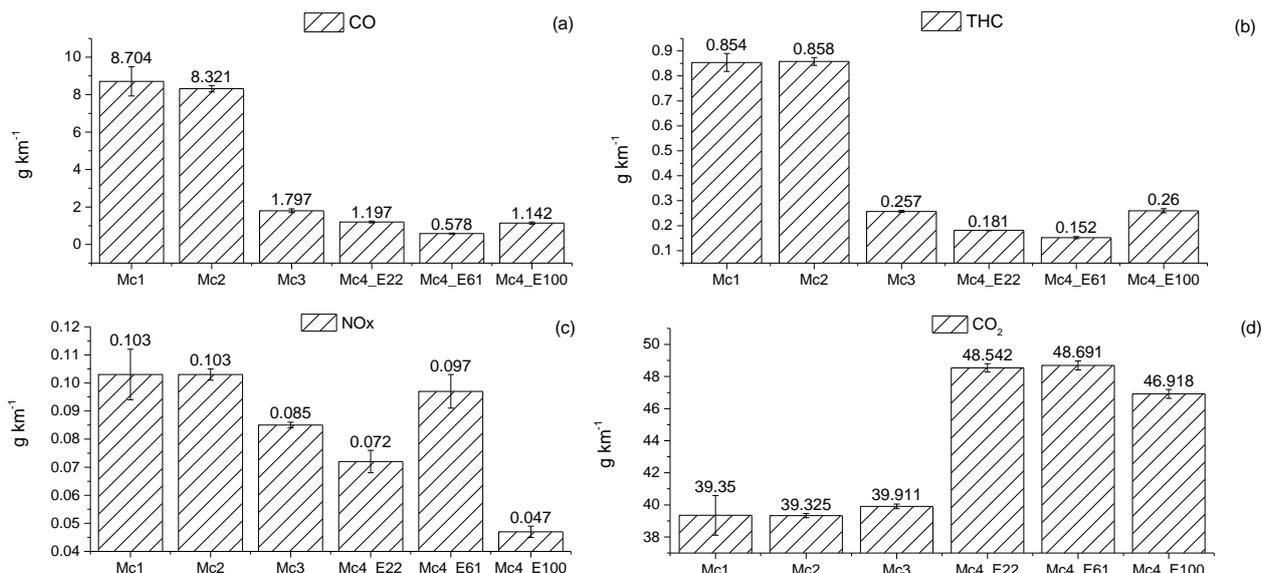
Figure 6. Legislated emissions and CO_2 for ICE motorcycles

The statistical analysis indicates the same level of emissions for CO for Mc1 and Mc2 motorcycles. MC4 motorcycle emissions were considered statistically different if E61 and E22 results are compared. THC emissions have no statistical difference if Mc1 and Mc2 results are compared as well as Mc3 and Mc4 when fueled with E100. Regarding NOx the emissions were considered with no differences for Mc1, Mc2 and MC4 fueled with E61. CO_2 emissions did not present significant statistical differences for Mc1, Mc2 and Mc3 and the same occurred between for MC4 when fueled with E22 and E61. For all comparisons the statistical power was 1.00.

4. CONCLUSION

The energy efficiency of the electrical motorcycle is about three times higher if compared to ICEs. Similar results were found by other authors as cited in the Introduction of this paper. The electrical motorcycle is still more efficient when one considers the primary conversion in a power plant. Power plants with contemporary technology of combined cycle (Brayton and Rankine) can reach nearly 60% of efficiency.

Regarding the flexfuel motorcycle it was observed that the energy efficiency did not vary significantly with the ethanol level in the fuel. These results may be due to an adequate engine calibration.

Euro I and II motorcycles are less efficient in energy, compared to Euro III. This may be due to the engine calibration and the use of electronic fuel injection device. Regarding CO and THC emissions, the same trend was observed probably because of the presence of electronic fuel injection together with the catalyst. CO_2 results are higher for Euro III probably due to the conversion of CO to CO_2 inside the catalyst converter.

Electric motorcycles are an economical option with less environmental impact with respect to air emissions compared to ICEs, but require improvements in their performance and autonomy to better market acceptance

5. ACKNOWLEDGEMENTS

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