PERFORMANCE ANALYSIS OF AN CNG-FUELLED FLEX ENGINE TO DIFFERENT COMPRESSION RATIOS

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Abstract. *Nowadays, the utilization of CNG is a reality due to its low fuel consumption, low cost and available technology. The engine, originally fuelled by gasoline or alcohol, can be also fuelled by CNG including some modifications, turning it into a multi-fuel engine. However, commonly, the gasoline compression ratio is not changed, causing losses to the performance when it is running with CNG. The CNG has a higher resistance to ignite by compression, what means that it can work in higher compression ratios. In this work, the 1.3-L 8v FIRE FLEX engine performance curves are obtained and analyzed for different compression ratio. A BRC 5th generation CNG multi-point fuel injection system is used for 11:1, 12,5:1 and 15:1 compression ratios. To perform the system electronic management, it was used an development engine control unit and its calibration software. The performance curves for the different compression ratio are compared in order to indicate significant torque, power and specific fuel consumption improvement.*

Keywords*: flex engine, performance, compression ratio, compressed natural gas*

1. Introduction

The demand for alternative fuelled engines has increased steeply in the last 05 years. It is caused by the instability of the dollar in Brazil and the petroleum prices around the world. In order to respond to this demand Brazilian automotive industry has released multi-fuelled engines using normally gasoline and alcohol.

Gasoline is the most common fuel for passenger cars in Brazil followed by alcohol. Brazilian gasoline, also known as E25, is added with 25% anhydrous ethanol. Heavy duty vehicles are mainly fuelled by diesel oil. However, recently, there have been a growing demand for CNG-fuelled engines (compressed natural gas), although these engines are not sold by car manufacturers. There are not any models originally fuelled by CNG in the market.

The most common alternative fuels in Brazil are alcohol and CNG. The alcohol used in Brazil, also known as E94 or hydrated ethanol, is extracted from the sugar cane and it is a mixture of 94% ethanol and 6% water. Alcohol was firstly introduced by Brazilian government through the PROALCOOL (Alcohol National Program) after the international oil crisis in the 1970's when the cost of oil barrel rose suddenly. After some years, around 90% of the cars produced in Brazil were fuelled by alcohol. However, this market share decreased to less than 5% in the late 1990's.

In the middle of 1980's, aiming to find an alternative fuel to replace diesel in heavy duty vehicles, Brazilian Government released the PLANGÁS (Natural Gas National Plan). In spite of this initial intention, it became popular with passenger cars mainly among taxicabs due to its low price.

The use of this fuel requires an adaptation in the gasoline or alcohol fuelled engine, installing what is called "Kit gás" (CNG kit). Although it shows lower level of pollutant emissions, it also shows a significant reduction in the engine efficiency since the engine does not work with the ideal compression ratio for CNG.

When FIAT AUTO faced a period of crisis in 1980, its engineers developed a project with the proposal of improve the production stages. The result was an innovative concept of compact engines named FIRE (Fully Integrated Robotize Engine). The main characteristics of this engine are a high specific power, high torque in low speeds and high thermal and volumetric efficiencies. There was also an enhancement of the constructive characteristics since the numbers of parts were significantly reduced and its assembly process was undoubtedly revolutionary. In 2000, this engine in its first generation, 1.3 16V, was released in Brazilian market. In 2003, a multi-fuelled FIRE engine was launched. The aim of this work is to implement this engine with a methane gas multipoint fuel injection system. However, it works with only one compression ratio, what causes losses to its efficiency due to a low compression ratio. A variable compression ratio is ideal for engines fuelled by gas and gasoline or alcohol. Despite being technically possible, a mechanism with this purpose would be economically unfeasible due to the high cost of production.

This work aimed to show the differences between the original compression ratio of the engine and different compression ratio for CNG. A comparison of these three configurations was made after optimizing the system, aiming to achieve the best performances for all compression ratios.

2. Objectives

The objectives of this project were to reconfigure the engine to be fuelled by methane gas, optimize the calibration to achieve the best performance, analyze the results and compare performance and volumetric efficiency curves of a CNG-fuelled FIRE FLEX 1.3 8V engine for 11:1, 12.5 and 15:1 compression ratios. These curves were also compared to the E25 curves from the engine with the original ECU and from the MoTeC ECU (electronic control unit) set with a calibration based on the original ECU results. A pollutant emission analysis will be done in a further work and compared with the obtained results.

3. Methodology

This work was developed to compare the efficiency curves of an engine fuelled by CNG with three different compression ratios: the original engine 11:1, and 12.5 and 15:1. To analyze and validate this comparison, they were also compared to gasoline curves that were obtained from this engine using a MoTeC ECU configuration.

In order to develop this work, some partner companies provided a significant contribution, supplying a great part of the needed systems and components such as engine, linear lambda sensors, flowmeter, fuel and sets of pistons for the compression ratio of 12.5:1 and 15:1. The other essential items like a CNG multipoint system and the MoTeC electronic control unit were bought.

3.1. Preliminary stage

Before performing the dynamometer tests, some preliminary stages were necessary. These stages have already been described previously by Baêta (2004a).

After these preliminary stages the MoTeC was chosen as the best option for this work since it allows setting the system to operate with any kind of fuel and combustion engine. Specific technical information about MoTeC M4 ECU could be found at MoTeC Internet site. All the procedures, including programming and adjusting can be done using this ECU.

3.2. Test stages

The first part of this work was to obtain the performance curves of the engine fuelled by E25 (gasoline). The engine was set with the original configurations, using an IAW 4AF.FF ECU. The acquisition process of the whole performance curves in this work is in conformance with NBR ISO 1585 standard. The engine was installed in a hydraulic bench dynamometer (Fig. 1) with the original system (ECU, body computer and other components). It was also interlinked with EDI software, instrumented with a linear lambda sensor, thermocouples along the admission and exhaust systems, barometric sensor, humidity sensor and room temperature sensor. In sequence, the break in process was performed in order to prepare the engine to the tests. Afterwards, the engine performance curves (torque, power, lambda value, fuel consumption and specific fuel consumption) were acquired for E25. The measurement of the fuel consumption was made timing the consumption of a measured mass of E25.

In the second part of this work, the original control system was retired and replaced by the MoTeC ECU and its harness. Also, the CNG multipoint injection system and its components except its ECU were installed and adapted to be controlled by the MoTeC system. The CNG multipoint injection components installed were:

- CNG filter;
- CNG pressure regulator;
- CNG injectors;
- Tubes and other accessories;

In order to measure the methane consumption, after the pressure regulator a flow meter (Fig. 2) was coupled to the whole system. The consumption calculation was made through an approximation of the CNG with the ideal gas model.

CNG composition necessary to calculate the relative molar mass, with the percentage of its components, was provided by GASMIG. All the needed CNG for the project and a trailer with a set of 6 cylinders were supplied by IGÁS.

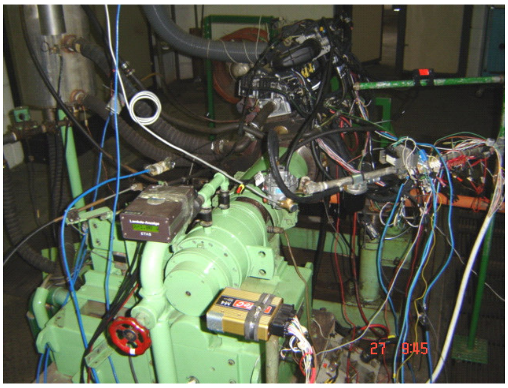


Figure 1. engine on the bench dynamometer

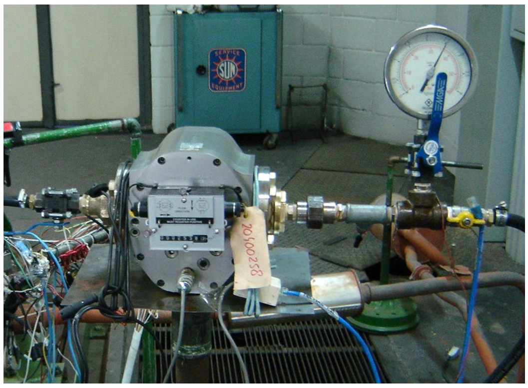


Figure 2. CNG Flowmeter coupled to system

Then, the MoTeC software was initially configured for this stage. The first part of this configuration is setting the characteristics of the engine, injectors and sensors. The calibration process includes dwell adjustment, injection timing adjustment, injection pulse width and ignition advance. The followed mapping procedure in this work for E25 and CNG was described by Baêta (2004b).

However, there were some different steps from those described by Baêta (2004b) that were adapted to CNG:

- There is not, in this work, any stage which includes a turbo compressor.
- The efficiency and load (EFF and LOAD) calculation were no longer a function of MAP (manifold air pressure) and BAP (barometric air pressure) values. These variables were set as throttle position, simplifying the calibration maps and further, the calibration.
- The “injection timing table” calibration was no longer made by calculating the specific fuel consumption point by point for each engine speed, but observing the variations in lambda value. According to this method, the richer the lambda value is, the better is fuel delivery.
- The entire fuel map was set to reach lambda value equals 1.00 independently the engine speed and engine load. Since there is no effective reduction on exhaust temperature and no significant increase on torque for rich mixture in a CNG-fuelled engine, there is no reason for setting richer lambda values. So, the lambda sensor was set up in closed loop in order to improve the lambda value, and consequently, the performance curve. It was done due to little deviations in lambda values for the same injection pulse width because the CNG pressure in the cylinders varied from 200MPa to 10MPa causing change in the CNG specific volume.

In some cases, when there is an alteration in the engine compression ratio it is necessary to change the valve diagram because volumetric efficiency might be influenced by this new configuration. To prove that in this case it did not occur, a global volumetric efficiency test was made following the FIAT standard for this test. The Equation 1 was used to calculate the global volumetric efficiency:

$$\eta = \frac{1000 \cdot F \cdot (A/F)_{STOICHIOMETRIC} \cdot \lambda}{V/2 \cdot [1{,}2928(P/1{,}0133) \cdot (273/(273+T))] \cdot n \cdot 60} \tag{1}$$

where: F = fuel consumption (kg/h)
(A/F)STOICHIOMETRIC = Stoichiometric air-fuel ratio
λ = lambda (kg_{air} actual/ kg_{air} stoich)
V = Displacement (dm^3)
P = atmospheric pressure (bar)
T = manifold air temperature (°C)
1,2928 = air density: 0°C and 1,0133 bar
n = engine speed (rpm)

After, for E25 and for CNG running each compression ratio, all the stages described below were executed:

- Calibration and adjustment of the EMS (engine management system);
- Performance curve data acquisition at WOT (wide open throttle), including torque, power, fuel consumption, specific fuel consumption and lambda values;
- Volumetric efficiency data acquisition at WOT (only for CNG).
- Replacement of the set of four pistons (if it was necessary)

To change the engine compression ratio, it was used three different pistons that are shown in Fig. 5, Fig. 6 and Fig.7 below. The method to increase compression ratio was to add material on the top of piston head, reducing the clearance volume.

Fig. 3. 11:1 compression ratio piston

Fig. 4. 12.5:1 compression ratio piston

Fig. 5. 15:1 compression ratio piston

4. Results

The first result data obtained in this work were both ignition advance maps and fuel maps. These maps are from the calibration of the engine fuelled by CNG with MoTeC ECU. Other maps such as dwell time and injection timing were also obtained for this initial configuration but they are not so relevant as fuel and the ignition maps.

The fuel maps that are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9 are presented in percentage of IJPU (% IJPU). IJPU is the maximum time of the injector pulse width. The value in the map represents a percentage of this maximum time. Then although the range of percentage values in the maps are near among them, they do not represent the same value because each fuel has an IJPU value. The IJPU time for each fuel is demonstrated in Tab. 1:

Table 1. Injection time table according to each fuel

FUEL	IJPU (ms)
Gasoline E25	15
CNG	10

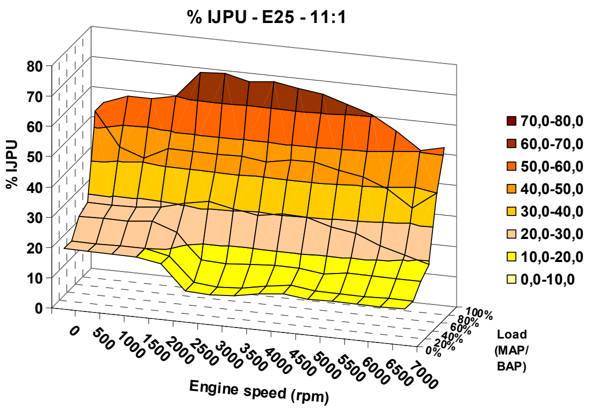


Figure 6. E25-fuelled engine fuel map for compression ratio of 11:1

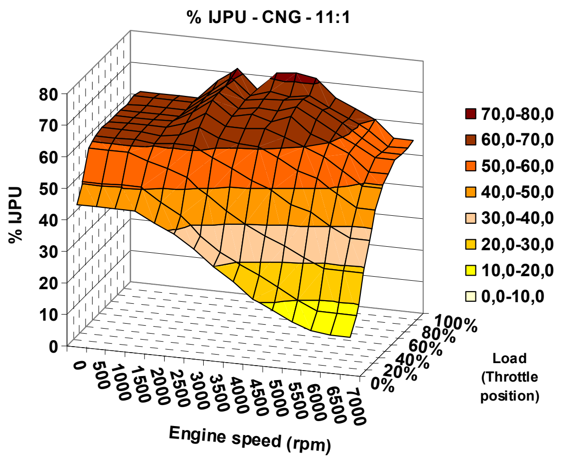


Figure 7. CNG-fuelled engine fuel map for compression ratio of 11:1

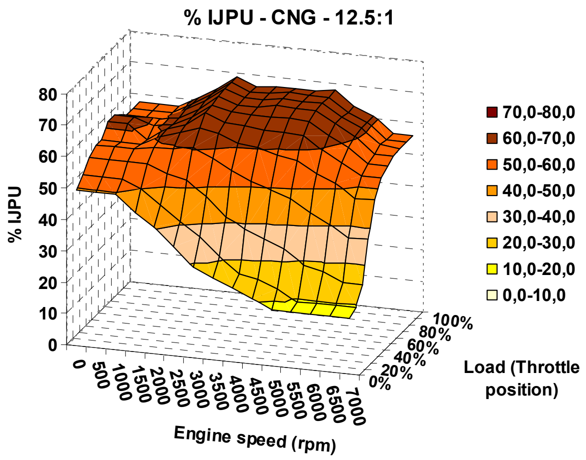


Figure 8. CNG-fuelled engine fuel map for compression ratio of 12.5:1

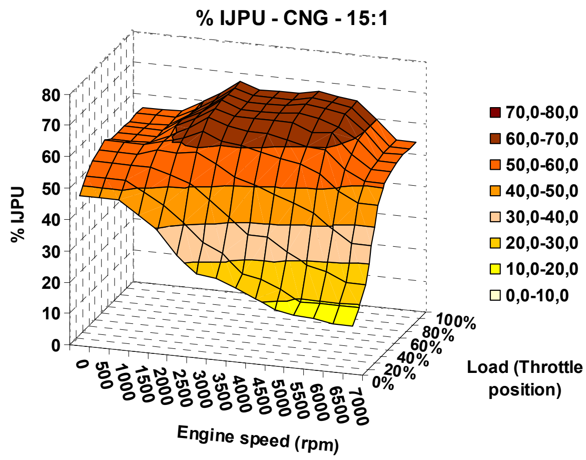


Figure 9. CNG-fuelled engine fuel map for compression ratio of 15:1

Regarding to Fig. 6, Fig. 7, Fig. 8 and Fig. 9, the fuel maps show the difference among E25 and the three engine configurations for CNG. This differences in the amount of fuel delivered of E25 and CNG is due to the higher stoichiometric air/fuel ratio of CNG.

The calibration of the ignition advance map was obtained trying to reach either LKL (lower knock limit) or MBT (maximum break torque). These maps are shown in Fig. 10, Fig 11, Fig. 12 and Fig. 13. The engine ran three different compression ratios. According to these maps, E25 accepts less ignition advance than CNG. It is easy to verify that, for CNG, the higher the compression ratio the lower the ignition advance. During the calibration of CNG 11:1 compression ratio, there was not found any knocking, so the entire calibration was made with MBT. Otherwise, in the calibration of 12.5:1 compression ratio, in lower revs and higher loads, some knocking was found decreasing a little ignition advance in these points. Moreover, the presence of knocking rose in 15:1 compression ratio calibration what reduced even more the ignition advance.

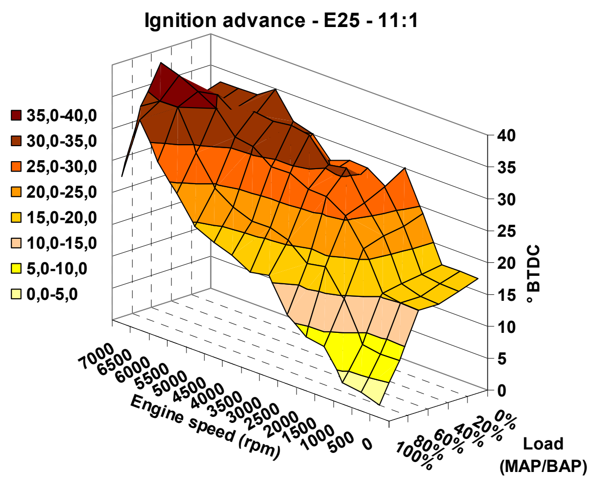


Figure 10. E25 -fuelled engine ignition advance map for compression ratio of 11:1

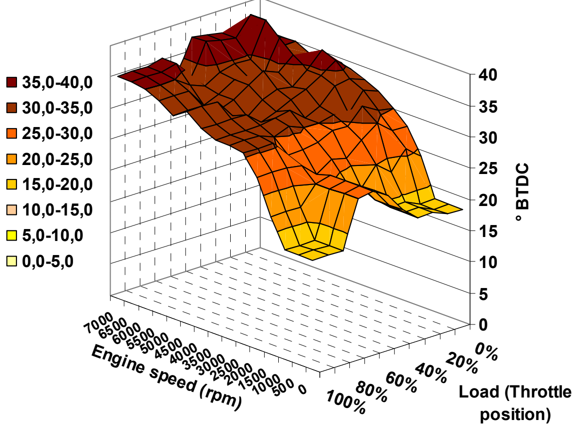


Figure 11. CNG-fuelled engine ignition advance map for compression ratio of 11:1

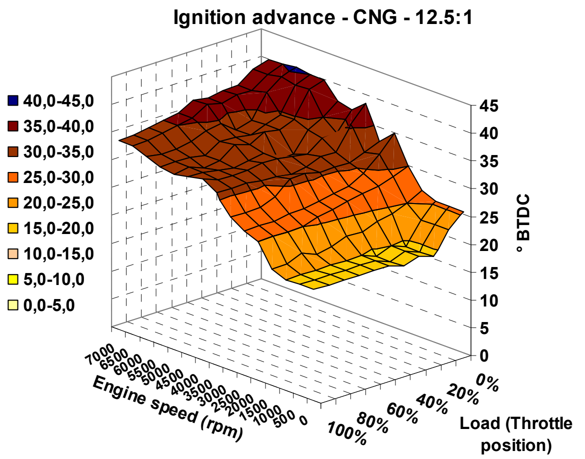


Figure 12. CNG-fuelled engine ignition advance map for compression ratio of 12.5:1

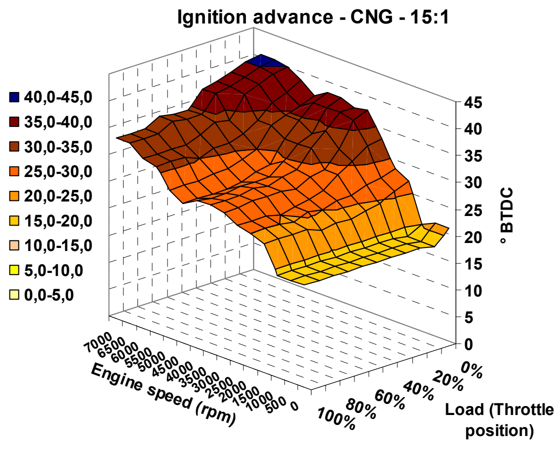


Figure 13. CNG-fuelled engine ignition advance map for compression ratio of 15:1

Fig. 14, Fig. 15, Fig. 16 and Fig. 17 present the corrected torque, corrected power, fuel consumption and SFC curves that were obtained from the tests. Figure 18 show the global volumetric efficiency graph that was obtained using CNG for the three compression ratios. Figure 19, Figure 20 and Figure 21 show the gain that were obtained from the compression ratio increase. All gain graphs compare 12.5:1 and 15:1 compression ratios to 11:1 compression ratio only for CNG. Analyzing the CNG performance graphs the compression ratio of 11:1 shows the lowest performance data compared to other compression ratios, being a low compression ratio to extract the maximum performance from this gaseous fuel. Then observing the performance, fuel consumption and SFC gain graphs in Fig. 18, Fig. 19 and Fig. 20 and comparing the results for the compression ratios of 12.5:1 and 15:1, and according to the obtained results of fuel consumption, SFC, corrected power and torque, there is no significant difference between both, but the figures show a very small gain for the compression ratio of 12.5:1. However the expected results should have demonstrated that the compression ratio of 15:1 was better for CNG. The modification in the combustion chamber geometry caused by 15:1 piston geometry influenced badly in the combustion behavior, mainly the combustion velocity. It will be explained in details in further works. Another problem was the high temperature reached on the top of the pistons due to the great quantity of mass on this region, obligating the use of lower ignition advance angle causing loss in performance data for the compression ratio of 15:1.

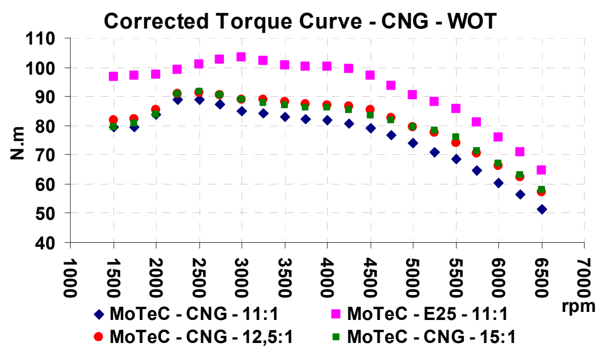


Figure 14: Corrected Torque Curve for CNG and E25 at WOT.

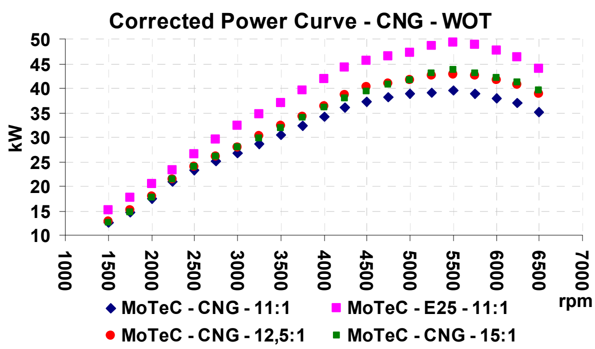
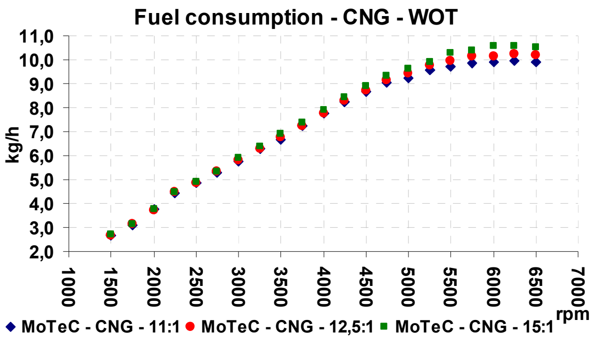


Figure 15: Corrected Power Curve for CNG and E25 at WOT.



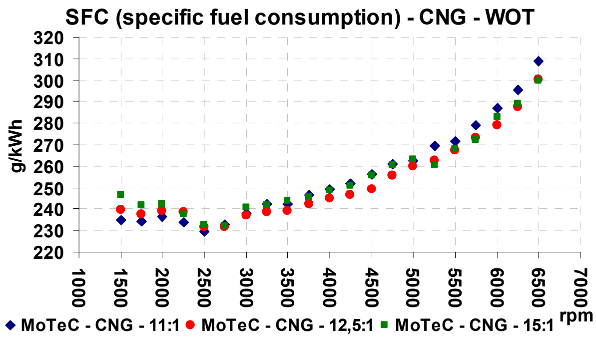
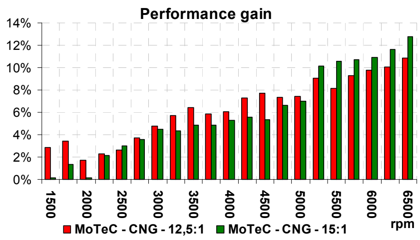
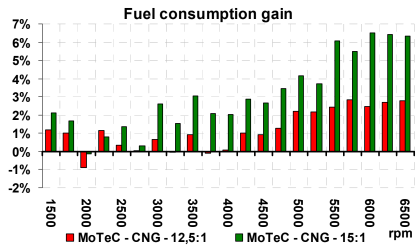


Figure 16. Fuel consumption Curve for CNG and E25 at WOT.

Figure 17. SFC Curve for CNG and E25 at WOT.





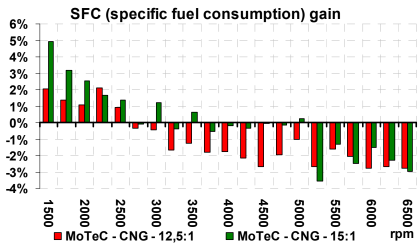


Figure 18. CNG Performance gain

Figure 19. CNG Fuel consumption gain.

Figure 20. CNG SFC gain

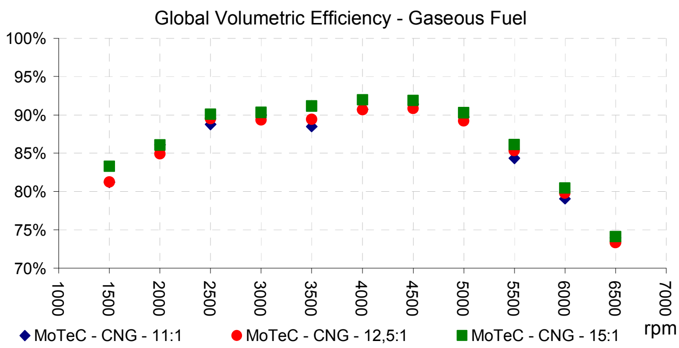


Figure 21. Global volumetric efficiency curve for CNG

The volumetric efficiency curves are shown in Figure 18 and revealed that the use of CNG generates accurate data to evaluate Global volumetric efficiency tests during engine development in different configurations. Since there was no significant change in global volumetric efficiency for all compression ratios, it was not necessary to chance the valve diagram. Lastly, Table 2 shows the uncertainties measured in this work.

Table 2. Uncertainty table

Uncertainty	
Engine speed	± 40 rpm
Corrected Torque	± 1.1 N.m
Corrected Power	± 1 kW
Fuel consumption	± 0.4 kg/h
SFC	± 13 g/kW
Performance gain	± 1 %
Fuel consumption gain	± 1 %
Volumetric efficiency	± 2 %

5. Conclusions

The purpose of this work was to analyze and compare the performance of different fuels in a multi fuel engine with the same configuration. A pollutant emission analysis will be done in a further work and compared with the results obtained from this project. Each fuel is calibrated separately due to the fact that they have different properties which influence on dwell time, injection timing, fuel and ignition map.

The behavior of CNG is different for each compression ratio, changing the maps and the performance data. The best performance results should have been attained by the highest compression ratio, but there has been much influence by the combustion chamber geometry. It is easy to verify that the 12.5:1 and 15:1 performance is better than 11:1, but there is no significant difference between them. However the fuel 15:1 fuel consumption is higher, what makes its SFC be worse than 12.5:1.

This work has the objective of providing data to develop a multi fuel engine proposed by Baêta (2004a). Comparing and analyzing the results it is possible to see that some fuels like CNG could have better results. However, in this case, they do not present the best performance that can be achieved because of the lower compression ratio which reduces torque and power and increases specific fuel consumption. This permits to develop a new system which can get better results from the CNG fuel such as using a turbo compressor to increase the engine internal pressure in order to attain its peak efficiency as proposed by Baêta (2004a). As alternative fuels such as CNG present lower costs and can offer greater performances when they are better used, they offer various advantages to the final costumer who can profit from a better use of them.

6. Acknowledgements

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