HIGH EFFICIENCY FLEX-FUEL ENGINES, THE ROUTE FOR BRAZILIAN MOBILITY

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ABSTRACT

In order to mitigate the greenhouse gases emission from automobiles and to reduce the dependency on fossil fuels, various alternatives for replacing the internal combustion engine are available. However, the best solution for this dilemma must take into account the geographic and social-economic characteristics of the country, its energy matrix, its emission legislation, and the fuel carbon footprint during its entire lifecycle. Brazil has a strong reputation for its fleet of Flex-Fuel vehicles, long date experience in the use of ethanol fuel and its distribution network. This differentiates it from other global markets and justifies a unique approach for the CO2 emission reduction.
This article describes a project with the main objective of optimizing the efficiency of Flex-Fuel engines running on ethanol, without deteriorating their performance with gasoline. The influence of the geometric compression ratio, the airflow structure and the inlet valve opening/closing strategy was investigated for fuel consumption and engine performance. The analysis of the experimental data confirmed the benefits of the compression ratio optimization on the combustion efficiency. Therefore, the development of efficient Flex-Fuel engines will lead to a sustainable route for mobility in Brazil.

INTRODUCTION

Nowadays, there are many alternatives to replace the vehicles moved by ICE (Internal Combustion Engines) in order to reduce the GHG (greenhouse gases) emission and the dependency on fossil fuels. In order to solve this problem in a balanced way, one must consider the geographic and socio-economic characteristics, the energy matrix, the fuel complete life cycle, and the emission legislation of the country. Brazil is recognized world widely by its large fleet of Flex-Fuel vehicles, vast experience in the use of ethanol fuel, and continental size distribution network. That differentiates it from other countries and by itself justifies a different approach to reduce the CO_2 emission of the national fleet.

This article reports part of an extensive research project, of which the main objective is to optimize the energy conversion efficiency of Flex-Fuel engines running on ethanol without affecting their performance with gasoline. The investigation consisted of verifying the influence of the compression ratio (CR), the flow structure, and the valve opening/closing strategies on the fuel consumption and engine performance. The experimental data analysis, which was supported by numerical simulation, confirmed the benefits of optimizing the volumetric compression ratio on combustion efficiency. Therefore, the development of high efficiency Flex-Fuel engines, in combination with well-planned governmental policies and people consciousness to environmental issues will point to an alternative and sustainable route in Brazil that may set an example to the world.

1. EXPERIMENTAL SETUP AND EQUIPMENTS

1.1. Engine

As part of the work here described, normal production engines with the CR altered to 15:1 and with the characteristics listed in Table 1 were tested on the engine test benches of Robert Bosch Ltda. and of UFMG-CTM.

Table 1. Physical and operating characteristics of the normal production engine.

Number of cylinders	3
Cylinder bore	74.5 mm
Stroke	76.4 mm
Swept volume	999 cm^3
Fuel injection system	Port Fuel Injection system, Flex-Fuel
Air charge system	Natural aspirated
Valves per cylinder	4 (2 intake, 2 exhaust)
Valve control system	DOHC – VVT on Intake System
Engine management system	ME 17.5.24
Maximum speed	6500 rpm
Compression Ratio	11.5:1 (original) 15:1 (modified)

The special design of the new pistons for 15:1 compression ratio took into account the minimum gap between piston and cylinder head in order to avoid flame quenching phenomena. Figure 1 shows details of the CR 15:1 piston specially developed for this project.

Figure 1 – Details of the CR 15:1 piston.

1.2. Non-conventional thermodynamic cycles – Atkinson/Miller

In order to mitigate the knocking phenomena that occurs when the HCR engine uses low-octane gasoline (92 RON) [1], the efficacy of the Miller/Atkinson thermodynamic cycles to change the ECR (effective compression ratio) was investigated. This is possible by the early intake valve closing (EIVC – Miller Cycle) or by the late intake valve closing (LIVC – Atkinson Cycle). Since the original engine is equipped with a VVT system for the intake valves only, it was necessary to know its theoretical operating limits for the two conditions. In figure 2, the angular distance ($\Delta\theta$), between the intersection of the horizontal line with the valve diagram and the vertical line representing the piston at TDC, indicates the maximum theoretical angle that the system can reach in the direction of EIVC to avoid contact between the piston and the valves.

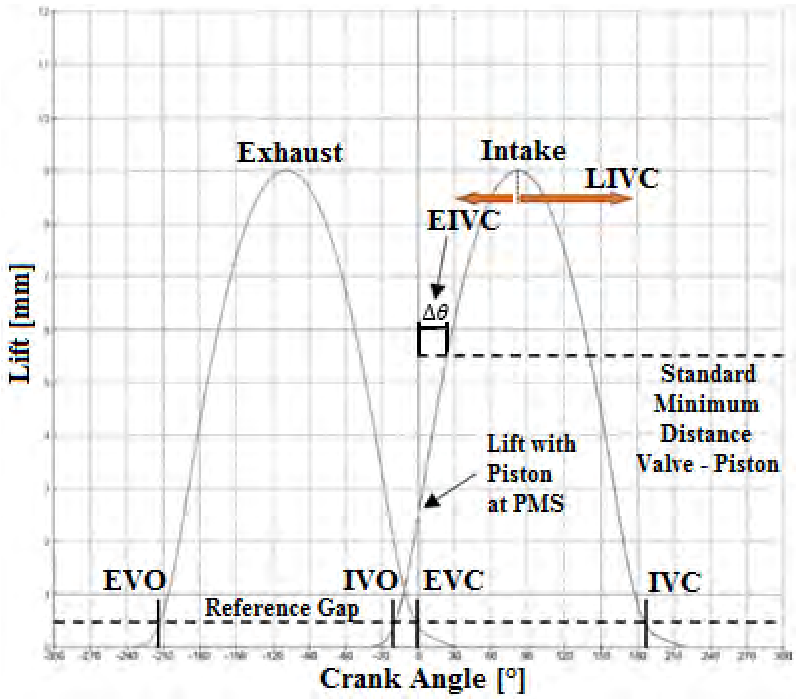

Figure 2 – Analysis of the limits of actuation of the intake VVT.

With this analysis, one concludes that operation with EIVC is not possible with the engine modified to CR 15:1, since the maximum angular variation is only 25 °c.a. Regarding the operation with the Atkinson cycle, established by the late intake valve closing (LIVC), it was possible to run the engine in the full operating range of the original intake VVT system, however with limitations of the ECR needed for mitigation of the knocking phenomena. To amplify the variation of the effective compression ratio, the operating range of the original intake VVT was increased during the engine tests. It is important to mention that the Atkinson and Miller cycles would be more effective if the engine had a VVL (variable valve lift) system for intake and exhaust valves, or a VVT system also for the exhaust valves, or yet cam profiles specially designed for this end.

1.3. Methodology for calculating the compression ratio

The study of the Atkinson/Miller cycles relies on different analysis of the compression ratio. In this sense, it is necessary to clarify the differences between the Geometric Compression Ratio (GCR), Effective Geometric Compression Ratio (EGCR) and the Effective Compression Ratio (ECR).

1.3.1. *Geometric Compression Ratio - GCR*

The geometric compression ratio of an engine is the ratio of the cylinder volume when the piston is at the bottom dead centre (V_{bdc}) to the cylinder volume when the piston is at the top dead centre (V_{tdc}).

$$GCR = \frac{V_{bdc}}{V_{tdc}} \tag{1}$$

However, the real compression starts effectively by the time the intake valve closes, what in most cases does not occur exactly when the piston is at the bottom dead centre (BDC). Thus, it is necessary to define the effective geometric compression ratio (EGCR).

1.3.2. *Effective Geometric Compression Ratio - EGCR*

The effective geometric compression ratio is defined as the ratio of the cylinder volume at the intake valve close (V_{ivc}) to the cylinder volume at TDC (V_{tdc}). This definition is independent if the intake valve close occurs late or early, with ample application.

$$EGCR = \frac{V_{ivc}}{V_{tdc}} \tag{2}$$

However, the EGCR does not explain the compression induced by the movement of the piston and of the gas during the intake phase, each of which contributes to the total compression process. The definition of the effective compression ratio (ECR) expresses these phenomena.

1.3.3. *Effective Compression Ratio - ECR*

The effective compression ratio is determined by analysing the in-cylinder pressure and the pressure in the intake manifold. With the in-cylinder pressure measurements, it is possible to draw a LogP-LogV diagram. In this diagram, a horizontal line corresponds to the mean intake manifold pressure in relation to intake stroke. The effective volume at the start of compression ($V_{ivc_{\mathrm{eff}}}$) is the volume at the intersection of the line of mean intake manifold pressure with the in-cylinder pressure line.

Thus, the definition of the effective compression ratio is:

$$ECR = \frac{V_{ivc_{\mathrm{eff}}}}{V_{tdc}} \tag{3}$$

Figure 3 illustrates a diagram LogP-LogV typical of an engine operating with EIVC, in which it is possible to apply the methodology for calculating the compression ratios. In the diagram is shown the event of intake valve close (IVC), which allows the determination of the volume at that time (V_{ivc}). The intersection of the mean intake-port pressure curve and the in-cylinder pressure curve allows the determination of the effective volume in the beginning of compression ($V_{ivc_{\mathrm{eff}}}$). These volumes extracted from the diagram, in conjunction with the cylinder volume at BDC (V_{bdc}) and at TDC (V_{tdc}), allow the calculation of the geometric compression ratio (GCR), the effective geometric compression ratio (EGCR) and the effective compression ratio (ECR).

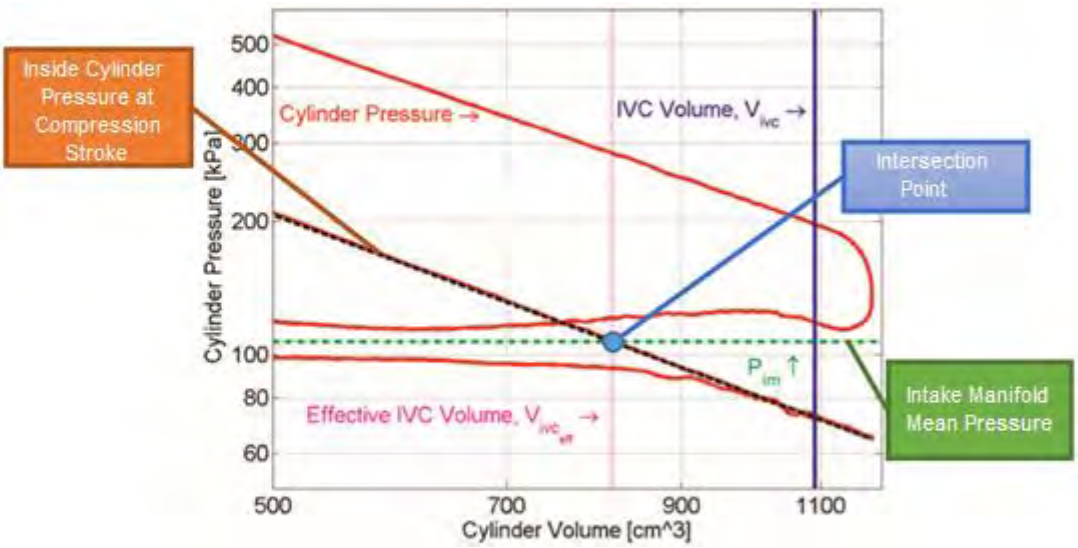

Figure 3 – Diagram LogP-LogV needed for applying the methodology to calculate the compression ratios

In this way, it is possible to calculate the effective compression ratio following the methodology above described, as long as the in-cylinder and the intake-port pressure measurements are available. It is worthy to remember that the strategy of varying the effective compression ratio, by varying the intake valve close time, can deteriorate the volumetric efficiency and affect the engine performance at WOT [2; 3; 4].

With the objective of cooling the combustion chamber and reducing the knocking tendency in the complete operating range of the HCR (high compression ratio) engine, fuelled with low-octane gasoline, and not affect the engine performance, different technologies (ex. water injection, iEGR, etc.) will be investigated and the results will be published in the near future.

2. RESULTS

2.1. Influence of the geometric compression ratio

The graphic of figure 4 illustrates the relation between the geometric compression ratio and the Otto cycle thermodynamic efficiency, calculated according to equation 4, where r_c is the geometric compression ratio and γ the polytropic coefficient [5].

$$\eta_{t,\text{ideal}} = 1 - \frac{1}{{r_c}^{\gamma-1}} \tag{4}$$

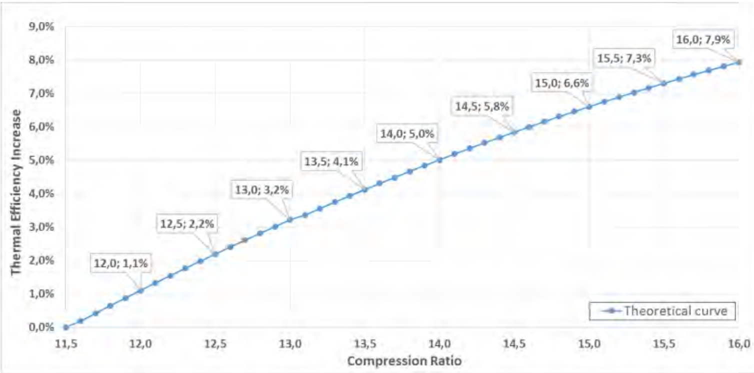

Figure 4 – Influence of compression ratio on theoretical thermodynamic efficiency

In order to verify the influence of varying the geometric compression ratio on the specific fuel consumption, measurements were made in a wide engine operating range using E100 and Podium gasoline, and CRs of 11.5 and 15:1.

Figure 5 shows that due to the ethanol anti-knocking properties the increase of the geometric compression ratio from 11.5 to 15:1 results in significant reductions of the specific fuel consumption. That indicates that the original engine compression ratio is not the ideal for the biofuel. In average, there was a reduction of 6% in the specific fuel consumption of ethanol, mainly in the speed range of 3000 and 4000 rpm. On some engine operating conditions, the specific fuel consumption reduction reached 8%.

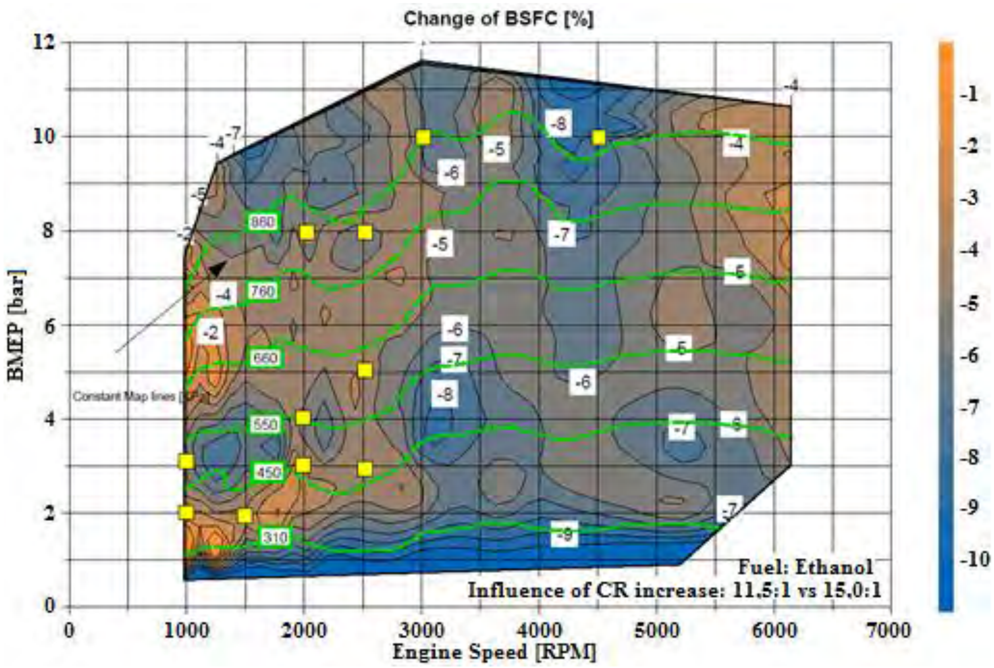

Figure 5 – Comparison of specific fuel consumption for CR 11.5 and 15:1.

The engine was also tested in the full operating range using Podium gasoline, with high octane (RON 102) [6], to compare the effects of compression ratio on the specific fuel consumption. Figure 6 shows BMEP versus engine speed at the points where the engine was tested with CR 11.5 and 15:1.

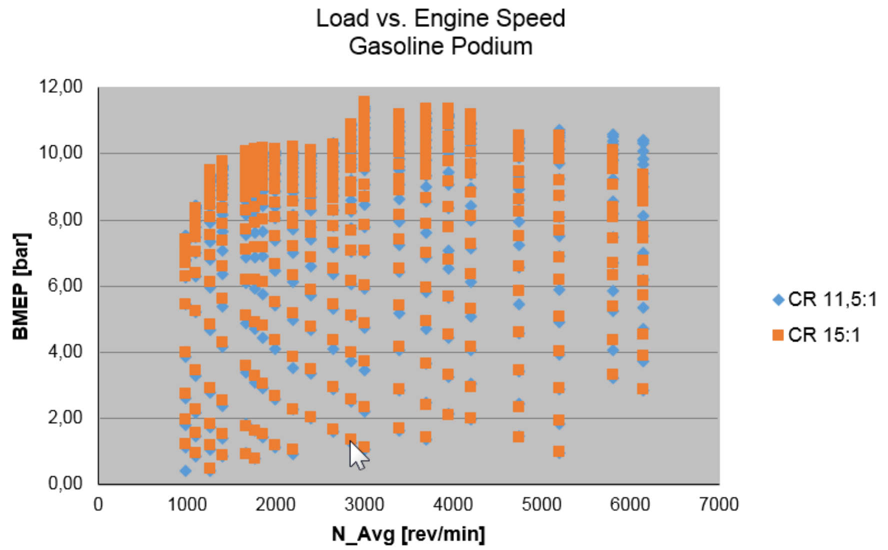

Figure 6 – Engine operating points: Influence of CR on specific fuel consumption using Podium gasoline.

As illustrated in figure 7, the tests with Podium gasoline show similar results to those found with ethanol, but less specific fuel consumption reduction, on average 2.15%. The reason is that at high load, CR 15:1, it was necessary to retard the spark ignition, thus affecting combustion efficiency and fuel consumption.

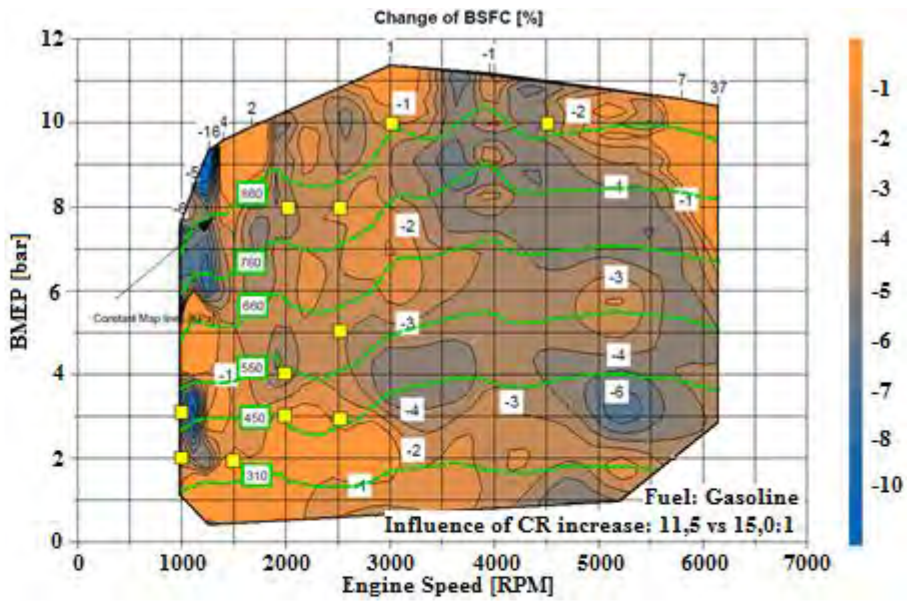

Figure 7 – Specific fuel consumption reduction resulting after the CR increase from11.5 to 15:1

As reported previously in the reports of the SCRE measurements [7, 8], the benefit of increasing the compression ratio is limited if the engine is fueled with low-octane gasoline (92 RON) [1] due to knocking phenomena.

2.2. Operation with LIVC – Atkinson Cycle

Aiming at evaluating the variation of the intake valve close position and its efficacy on mitigating the knocking phenomena, the intake VVT operating range, which originally is 40 °c.a., was amplified in this work to 85° c.a. The designation VVT0 corresponds to the earliest intake valve close, whilst VVT85 to the latest IVC

2.2.1. *Full Load*

In this section, it is possible to analyse the main results of the HCR (15:1) engine measurements, for evaluating the influence of LIVC operation on engine performance and knocking mitigation using Podium gasoline.

Figure 8 shows the results of the effective compression ratio and the effective geometric compression ratio calculated at WOT and 1400 rpm. At this operating condition, the difference between the ECR and the EGCR increases with the delay of the IVC. The ECR decreases in about 19% from the earliest IVC position to the latest position, while the EGCR drops 44%. This is the typical behaviour of the ECR and EGCR in LIVC operation.

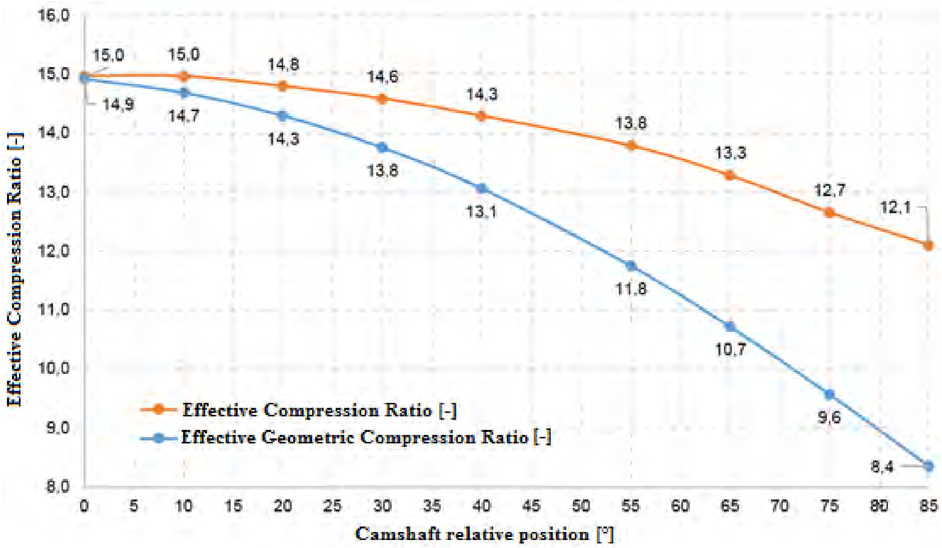

Figure 8 – Calculation of the ECR and EGCR as function of the intake valve close position in full load at 1400 rpm.

However, one should pay attention that for higher engine speeds, the efficacy of the effective compression ratio variation falls because of fluid dynamic effects. At high engine speeds, the volumetric efficiency is also greatly affected. The analysis of figure 9, referring to the full load operation at 6000 rpm, reveals that the delay of the intake valve close has minor influence on the reduction of the effective compression ratio, however, one sees that the later the intake valve closes, the greater is the syringe effect and the pumping losses. The volumetric efficiency also falls due to reduced cylinder charging, which causes additional performance losses. The syringe effect occurs in other operating conditions, mainly because of the LIVC associated to the small duration of the intake cam profile.

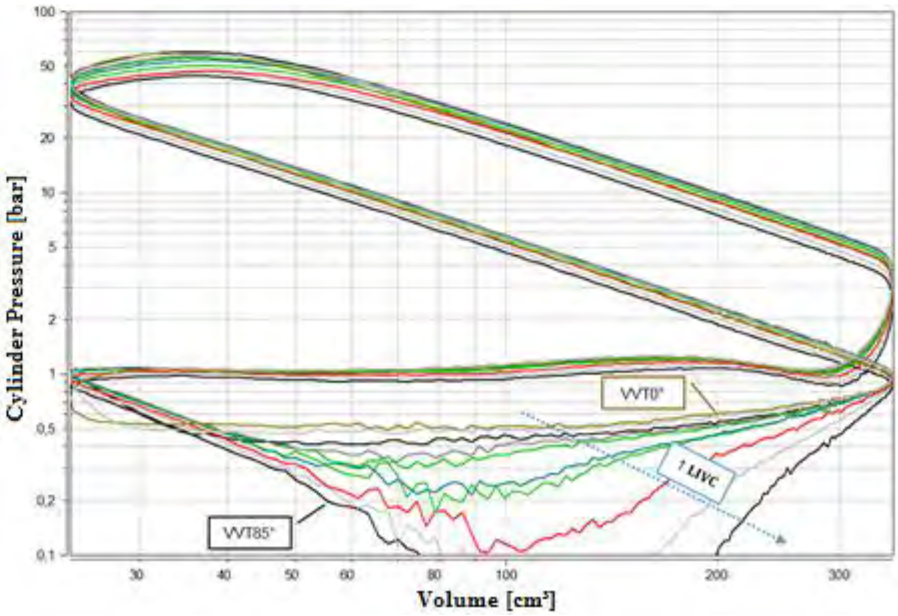

Figure 9 – Diagram logP x logV for different IVC positions at WOT and 6000 rpm.

The variations of the IVC position cause torque and power variations that directly affect the ISFC and BSFC. In this respect, the specific fuel consumption variations depend on the engine load fluctuations, and not only on the relative effects of the compression ratio adjustment and combustion efficiency changes allowed by the knocking mitigation. By analyzing the graphic, it is possible to see that there is great influence of the load variation on the ISFC, simply by the change of the engine operating condition.

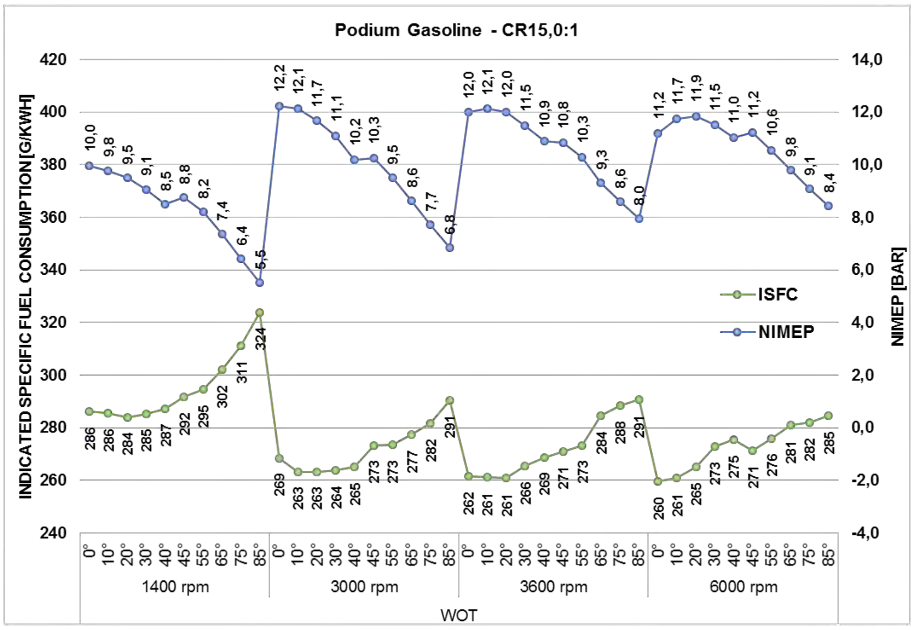

Figure 10 – NIMEP and Specific Fuel Consumption as function of engine operating condition and relative position of the intake valve camshaft.

2.2.2. *Mitigation of knocking by Late Intake Valve Close operation (Atkinson Cycle)*

The determination of the range of knock mitigation by the intake valve close timing is possible by evaluating the KBL (knock borderline) in the full range of engine operation. A spark ignition sweep affects the engine torque, which varies in a parabolic way in relation to the spark advance. When knocking occurs before reaching the maximum torque, it indicates that the engine is limited by the KBL (Knock Borderline). On the other hand, if the maximum torque is reached, it is a MBT (Maximum Brake Torque) operation. Figure 11 shows the operating regions for KBL and MBT achieved at different IVC positions. The region delimited by MBT-VVT0° indicates the area in which it is possible to operate the engine without knocking and the earliest intake valve close position. By retarding the IVC to the latest position (VVT85°), the region for operation at MBT expanded in respect to the VVT0° and VVT40° operating conditions. This limited area is marked on the graph and designated as MBT-VVT85°. Above the MBT-VVT combinations, there is knocking and the spark advance is limited by the KBL; on top, the map is limited by the WOT line. The analyses reveals that the technology of mitigating knocking by varying the intake valve close timing is viable, but restricted to a narrow range of the full engine operating range.

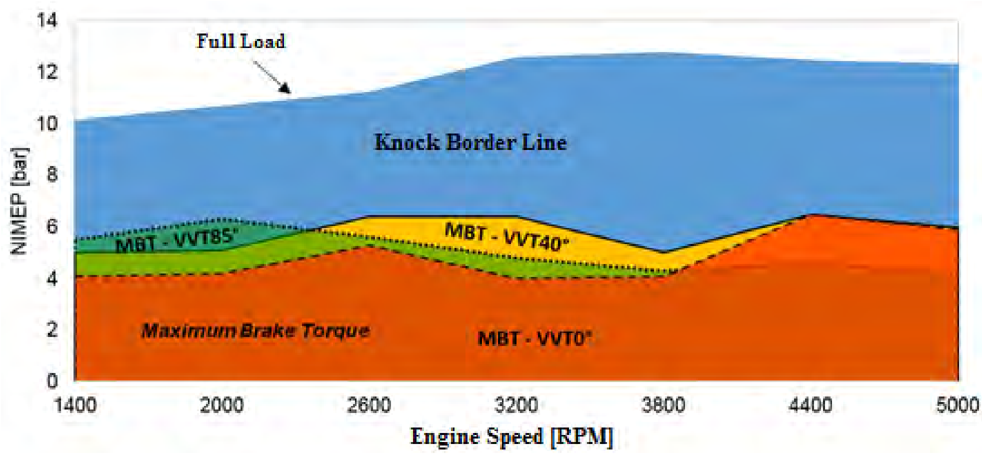

Figure 11 – Engine operating area delimited by MBT and KBL for different intake VVT positions.

CONCLUSIONS

The emissions of CO_2 from ICE vehicles running on ethanol are comparable to the expected emissions of electric vehicles in 2030, if one considers the actual European energy matrix and the WTW emissions [9]. Considering the CO_2 emissions in a WTW basis, a reduction of 66% in the CO_{2eq} emissions (g/MJ) is possible by replacing gasoline by ethanol in the vehicle propulsion [9]. This fact in itself justifies the effort in promoting the use of ethanol, a renewable fuel, in replacement of the fossil fuels. With that in mind, the benefits of different technologies tested in a normal production engine are summarized below.

High Compression Ratio

The original CR of a normal production Flex-Fuel engine was increased to 15:1 by assembling specially designed pistons. The high compression ratio resulted in specific fuel consumption reductions for ethanol and Podium gasoline in a wide engine operating range, with the best reductions for the biofuel.

The use of low-octane gasoline in engines with CR optimized for ethanol (HCR) may compromise its durability and increase fuel consumption due to heavy knocking. In order to mitigate this problem the use of non-conventional cycles (Atkinson/Miller) was investigated.

The use of even higher compression ratios (above 15:1) could bring additional gains of fuel conversion efficiency, but would require relevant modifications in the engine design. Aspects related to the engine structure, combustion quality, and losses due to higher compression loads are some issues to be further investigated. The costs associated to the additional investments must be evaluated against the benefits acquired by the reduction of fuel consumption and of GHG emissions.

Non-conventional cycles – Atkinson/Miller

The analysis of the intake valve diagram revealed the impossibility to run the CR 15:1 engine with the Miller cycle (EIVC) due to the risk of contact between the inlet valves and the piston.

The original intake VVT system was adequate to reduce the effective compression ratio with the Atkinson cycle by LIVC operation. However, the LIVC operation has some limitations because it affects the engine performance by increasing the pumping losses and decreasing the volumetric efficiency. The increase of the pumping losses was associated to the syringe effect during the intake stroke. On the other hand, the decrease of the volumetric efficiency related to the return of the air-fuel mixture to the inlet port, during the compression stroke resulting deterioration of the engine torque and power.

The mitigation of knocking by late intake valve close is viable but restricted to a narrow engine operating range. However, this range can be enlarged, as function of the compression ratio variation, by altering the spark-plug thermal grade, new piston designs (eliminating hot spots) and re-work of inlet camshaft (Ex. greater intake valve open duration).

The ECR variation as determined by the intake valve close time depends also on the engine operating conditions due to fluid dynamic effects as analysed in the numerical simulation work conducted by UFMG-CTM.

The technologies presented in this article aim at the reduction of ethanol consumption of Flex-Fuel vehicles without affecting the engine performance when fuelled with gasoline. By applying them, it is expected to improve the autonomy ratio between E100 and E27 (km/l), and indirectly promote the use of the national biofuel, bringing Brazil to a highlighted position in the international scenery by offering sustainable alternatives for the generation of clean and renewable energy. This is part of a suggested route being constructed for a better mobility in Brazil and the world.

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DEFINITIONS/ABBREVIATIONS

BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CR	Compression Ratio
CO_2	Carbon dioxide
ECR	Effective Compression Ratio
ECU	Electronic Control Unit
EGCR	Effective Geometric Compression Ratio

EIVC	Early Intake Valve Close
E100	Ethanol
GCR	Geometric Compression Ratio
GHG	Greenhouse Gases
HCR	High Compression Ratio
ICE	Internal Combustion Engines
ISFC	Indicated Specific Fuel Consumption
KBL	Knock Border Line
KC	Knock Control
LIVC	Late Intake Valve Close
MBF50	Crank angle position corresponding to 50% of the mass burned fraction
MBT	Minimum advance for Maximum Brake Torque
NIMEP	Net Indicated Mean Effective Pressure
RON	Research Octane Number
SCRE	Single Cylinder Research Engine (UFMG-CTM)
UFMG	Universidade Federal de Minas Gerais
V_{bdc}	Cylinder volume when piston is at bottom dead center
V_{ivc}	Cylinder volume at intake valve closure
$V_{ivc_{\mathrm{eff}}}$	Cylinder volume at the start of compression
V_{tdc}	Cylinder volume when piston is at top dead center
VVT	Variable Valve Timing
VVT_0	Position of VVT corresponding to the earliest intake valve closure
VVT_{85}	Position of VVT corresponding to the latest intake valve closure
WOT	Wide Open Throttle
WTW	Well to Wheel
$\eta_{t,\mathrm{ideal}}$	Ideal Thermodynamic Efficiency
γ	Polytropic coefficient