REDUCING EMISSIONS THROUGH LOW FRICTION RING PACK IN PASSENGER CAR DIESEL ENGINE[1]

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Abstract

In order to meet the increasingly restrictive environmental regulations, the automotive industry has been driven by the challenge of reducing exhaust emissions, as well as fuel consumption. In terms of piston rings the main efforts on keep the new developments within the said regulations rely on reducing associated friction losses. The present work comprises the presentation of a low friction ring pack for passenger car diesel engines, rather focusing in showing their improved performance on exhaust emissions compared to the baseline version. The low friction ring pack presented around 30% of potential friction reduction. This ring pack in an engine leaded to a CO_2 emission reduction between 1.6% and 2.0% in the dynamometer emission tests.

Key words: CO_2; Piston ring; Fuel consumption; Internal combustion engine.

REDUZINDO EMISSÕES ATRAVÉS DE PACOTE DE ANÉIS DE BAIXO ATRITO EM MOTORES A DIESEL DE CARRO DE PASSAGEIROS

Resumo

Com o intuito de atender às crescentes restrições das legislações ambientais, a indústria automotiva tem sido guiada pelo desafio de reduzir as emissões dos gases de exaustão, assim como consumo de combustível. Em termos de anéis de pistão, os esforços em colocar os novos desenvolvimentos dentro das mencionadas legislações focam na redução associada das perdas por atrito. O presente trabalho compreende a apresentação de um pacote de anéis de baixo atrito para motores a Diesel para carros de passageiros, direcionado para o foco de mostrar a melhoria de desempenho para a emissão de gases de exaustão comparado com a versão referência. O pacote de anéis de baixo atrito apresentou cerca de 30% de potencial redução de atrito. Esse pacote aplicado em um motor levou a redução de CO_2 entre 1.6% e 2.0% em testes de emissões no dinamômetro.

Palavras-chave: CO_2; Anel de pistão; Consumo de combustível; Motores de combustão interna.

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1 INTRODUCTION

Global environmental concerns are driving internal combustion engine designs. New legislations are setting up milestones to reach vehicle emission goals and limit CO_2 emission levels to achieve more environment friendly engines. All these focus are related to engine fuel consumption. Engine components contribute to fuel consumption from their inherent friction power losses. In a Diesel engine, the contribution of piston rings can reach 25% of mechanical losses, which is related up to 10% of the engine power output.(1) Figure 1 shows that 20% of friction reduction in a Diesel engine can reach around 8% of fuel consumption reduction.(2)

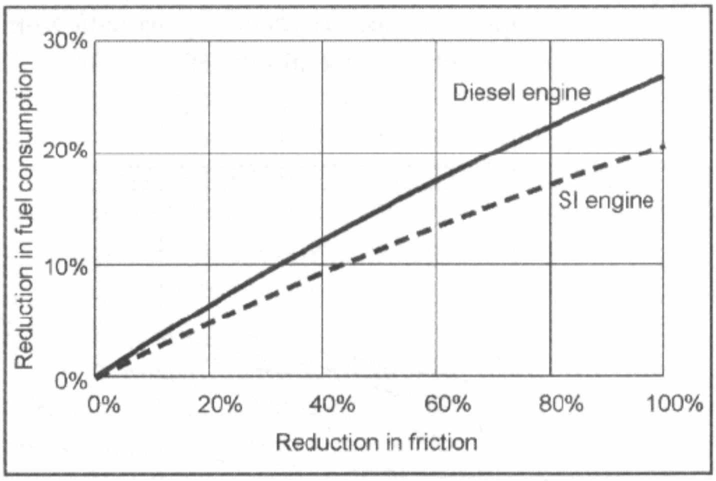
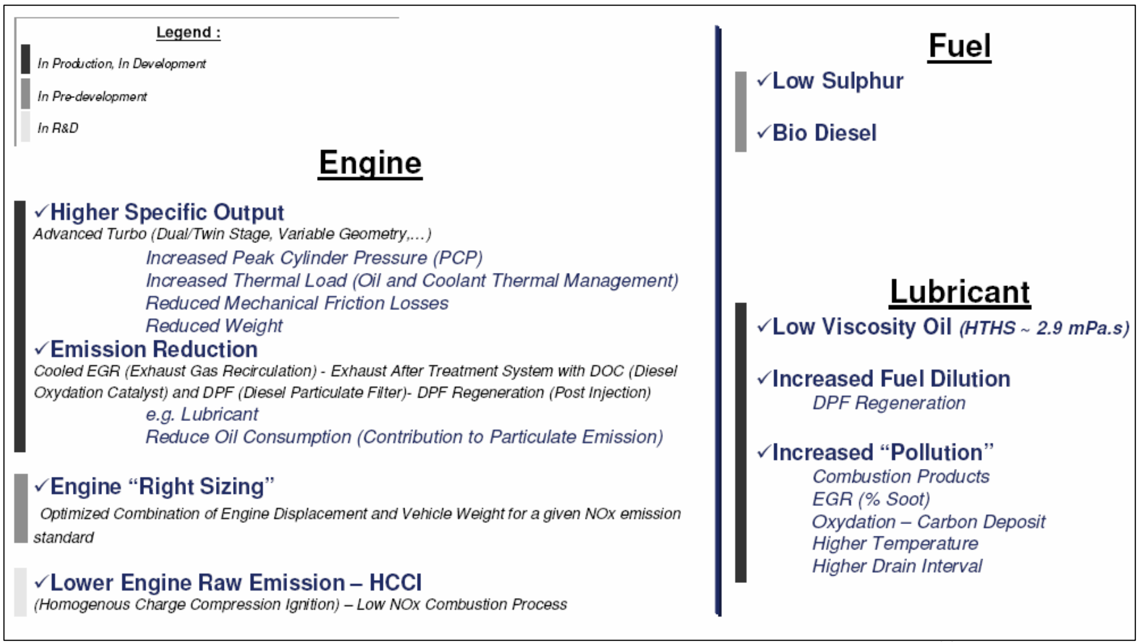


Figure 1: Relation of friction reduction and reduction of fuel consumption.(2)

The tribology environment of piston rings can be summarized by the interaction of ring-cylinder and ring-piston. The main responsible for ring friction is the interaction of ring-cylinder, which will be the focus of this paper. Inside this tribosystem, the technology trends indicate that the ring must perform at increasingly more demanding operating conditions as shown in Figure 2.

The new trends of surface cylinder finishing also influence the ring pack performance. The trends indicated in Uehara(3) and Jocsak et al.(4) show a constant decrease in cylinder roughness. The smoother honing by different honing techniques impacts the lube oil film between ring and cylinder. Figure 3 presents a comparison of the impact of different honing characteristics on oil film behavior.

Notice in Figure 3 that the smoother the honing, the smaller the contact area (A_C/A_0) for the same lube film thickness. However the reverse areas show reduced lube film thickness for smother honing. In spite of this reduced lube film thickness, the area of contact is still reduced compared to rough finishes and higher volume of oil is presented on the contact (V_{oil}/A_0). Even with lower wear potential, the smooth finishes can have the film easily broken, which leads to a concern of scuffing risks. It needs to be considered during ring and cylinder material selection.



Legend :
- ■ *In Production, In Development*
- ▨ *In Pre-development*
- □ *In R&D*

Engine

✓**Higher Specific Output**
Advanced Turbo (Dual/Twin Stage, Variable Geometry,...)
Increased Peak Cylinder Pressure (PCP)
Increased Thermal Load (Oil and Coolant Thermal Management)
Reduced Mechanical Friction Losses
Reduced Weight

✓**Emission Reduction**
Cooled EGR (Exhaust Gas Recirculation) - Exhaust After Treatment System with DOC (Diesel Oxydation Catalyst) and DPF (Diesel Particulate Filter)- DPF Regeneration (Post Injection)
e.g. Lubricant
Reduce Oil Consumption (Contribution to Particulate Emission)

✓**Engine "Right Sizing"**
Optimized Combination of Engine Displacement and Vehicle Weight for a given NOx emission standard

✓**Lower Engine Raw Emission – HCCI**
(Homogenous Charge Compression Ignition) – Low NOx Combustion Process

Fuel

✓**Low Sulphur**

✓**Bio Diesel**

Lubricant

✓**Low Viscosity Oil** ***(HTHS ~ 2.9 mPa.s)***

✓**Increased Fuel Dilution**
DPF Regeneration

✓**Increased "Pollution"**
Combustion Products
EGR (% Soot)
Oxydation – Carbon Deposit
Higher Temperature
Higher Drain Interval

Figure 2: Tribosystem impacts for piston rings in Diesel engines.(5)

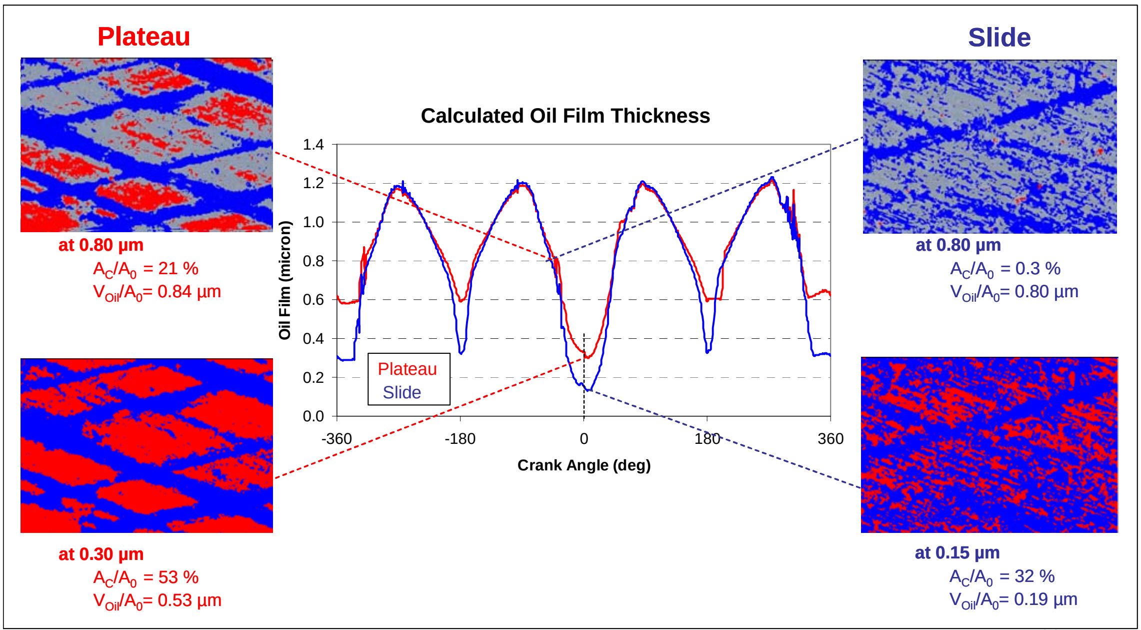


Figure 3: Lube film thickness between ring and cylinder in different cylinder finishes(4)

Several works have been presented about friction reduction on rings in Gasoline(6) and Diesel(5) engines. However the results are always presented in terms of friction and not in terms of fuel consumption or CO_2 emission. This paper intends to cover this gap.

In part 2, it is presented the main paths to achieve reduced friction in piston ring pack. The methodology of emission measurement is showed in part 3, as well as the test cell characteristics. Then the results are shown and discussed in part 4 with the focus on CO_2 emissions and fuel consumption, but also including the results of other gases emissions. Finally, the conclusions are presented in part 5.

2 LOW FRICTION RING PACK

The reduction of ring pack friction can be assessed by 3 main routes:

- Reduction of ring pack load
- Reduction of ring pack width (lower combustion gas pressure influence)
- Use of coatings with low friction coefficient

The effect of each route depends on the ring lubrication which is very dependent on the piston position along the engine stroke. An example is presented in Figure 4 from the use of numerical simulation of piston ring dynamics.

Notice that boundary lubrication is important in the total lubrication mode of piston rings, around 65%. For this reason, the use of coatings or materials on piston rings with reduced friction coefficient can reach good reduction in friction without significant difference on engine performance. Figure 5 presents the main coatings usually applied on piston rings and their friction coefficient.

The baseline ring pack applied to passenger car Diesel engines uses Cr Ceramic coating. As it will be presented ahead, the low friction pack will use PVD (CrN).

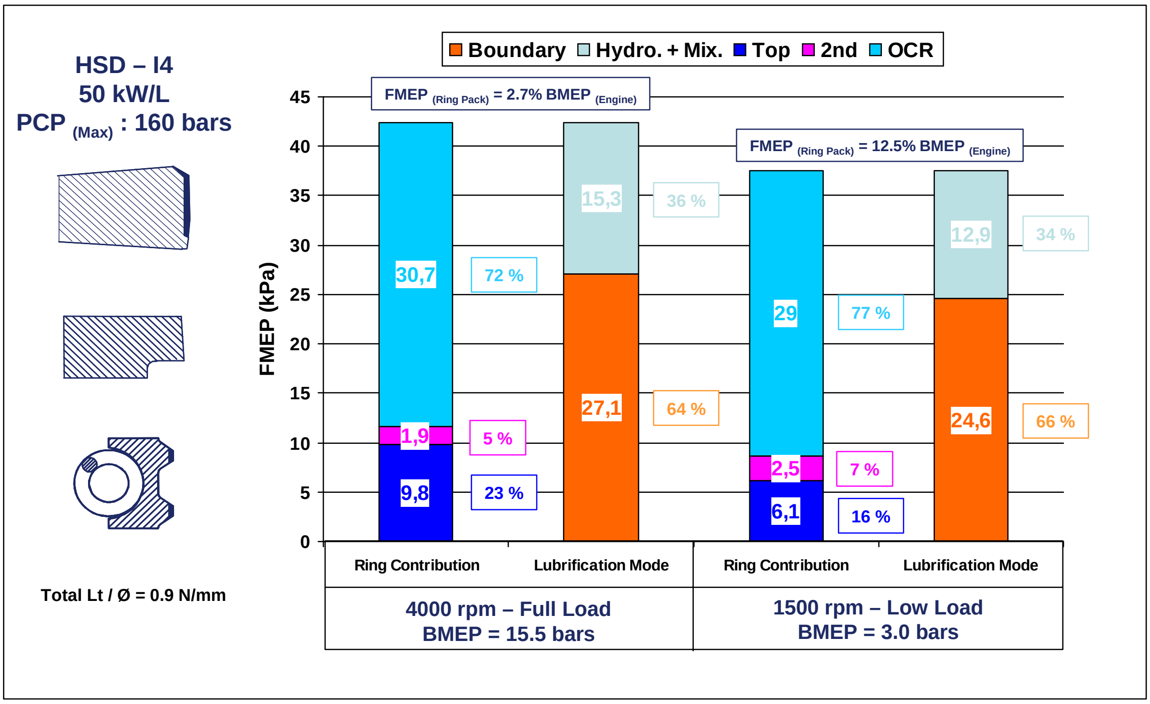


Figure 4: Numerical simulation of ring friction in a Diesel ring pack in different operational conditions.

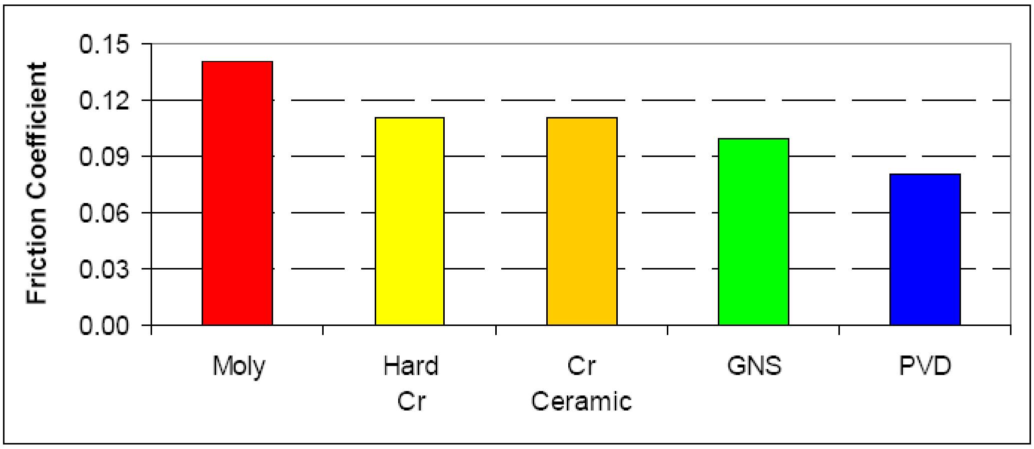


Figure 5: Dry friction coefficient of coatings applied to rings - block on ring test.

In Figure 4, it is noticed that the total load of piston ring pack (from one engine cylinder) divided by the bore diameter is 0.9 N/mm, which became a guideline for Euro 4 and 5 references. For Euro 6 legislation, there is a trend of reducing ring pack load to almost 50% of this value.(5) Such characteristics were respected in the tests presented in this paper. Table 1 summarizes the tested ring packs.

Table 1: Tested ring design summary

	Baseline	**Low Friction**
Top Ring	3.0 mm Ceramic Cr Symmetric Barrel Profile Keystone Cross Section Load = 19.0 N	2.0 mm CrN PVD Symmetric Barrel Profile Half Keystone Cross Section Load = 8.5 N
2nd Ring	1.95 mm Alloyed Cast Iron Napier Scraper Profile Rectangular Cross Section Load = 14.2 N	1.5 mm Alloyed Cast Iron Napier Scraper Profile Rectangular Cross Section Load = 8.8 N
Oil Control Ring	2.5 mm Hard Chromium 2-piece Oil Ring Design unitary pressure = 1.75 MPa Load = 37.5 N	1.5 mm Steel + CrN PVD 2-piece Oil Ring Design unitary pressure = 1.75 MPa Load = 13.0 N
Total Load / Bore Diameter (N/mm)	0.94	0.40

The proposed pack of Table 1 can lead to a ring friction reduction of 30%.(1,6) Once the ring friction corresponds to 25% of total friction [1 and 6], it is expected a 7.5% reductioin in total friction. Using the graph if Figure, it would possible to expect around 2% of fuel consumption reduction.

The challenge of piston ring pack design is how to reduce load, while maintaining its performance in terms of sealing and scrapping for lube oil and blow by control. This was accomplished with innovative MAHLE designs presented in Lopez and Rabute.(5) This paper will focus on the emission results and not in the engine performance data.

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3 EXHAUST EMISSIONS TEST

In the field of exhaust emissions tests, two variants of test are mainly applied: chassis and engine test bed dynamometers. Chassis dyno tests are usually destined for light vehicle evaluations. In this test type the vehicle follows a preset cycle on dynamometer, while the exhaust gases are collected. The results of each gas are presented in g/km.
On the other hand, commonly used for diesel engines and commercial vehicles, the engine test bed dynamometer allows the access of more details on the behavior of the engine and its components due to a higher level of instrumentation possibility. Due to this enhanced test response, the engine test bed dynamometer was selected for the assessment of CO_2 emission reduction through mechanical friction losses approach.

3.1 Test Bed Characteristics

The test bench for emissions and particulate determinations is composed of a central gas analyzer AVL AMAI60 with the possibility of determination of pre-and-post-catalyst gases: Hydrocarbons, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Methane and Oxygen. This set is also possible to determine the particulate matter by gravimetric sampling equipment called AVL Smart Sampler. Other more common engine data like torque, speed etc is also possible with this test cell. The results are presented in g/kWh.
For this study, the tests were performed based on the procedures of the Euro 4 standard, because the engine platform used for the study was homologated for this phase of legislation.
The test cycles were conducted in accordance to European rules being used in continuous cycle (ESC) and transient (ETC) cycle. These cycles in conjunction with the ELR (particulate analysis) have been used for certification of diesel engines in several countries.(7)

European Steady Cycle – ESC:
The test consists of a sequence of 13 points with different speed, load and duration as presented in Figure 6. These sequences simulate the conditions of higher utilization of the engine in normal use. At the end of the test, values obtained in each point are subjected to a predetermined weighting(7) that results in a single final value, which is regarded as the test result, expressed in g / kWh.

European Transient Cycle – ETC:
The ETC cycle (also referred to as FIGE transient cycle), was developed by the FIGE Institute, Aachen, Germany, based on an real measurement in one heavy duty engine. Different driving conditions are represented by three parts of the cycle including: urban, interurban and highway tracks (Figure 7). The total cycle time is 1800s, divided in 600s duration parts as follows:

- The first part represented by an urban cycle with a maximum speed of 50 km/h with frequent stops and points of IDLE
- The second part is a rural track with accelerated conditions, and the average speed of 72 km/h.
- The third part is on the motorway with an average speed of 88 km/h.

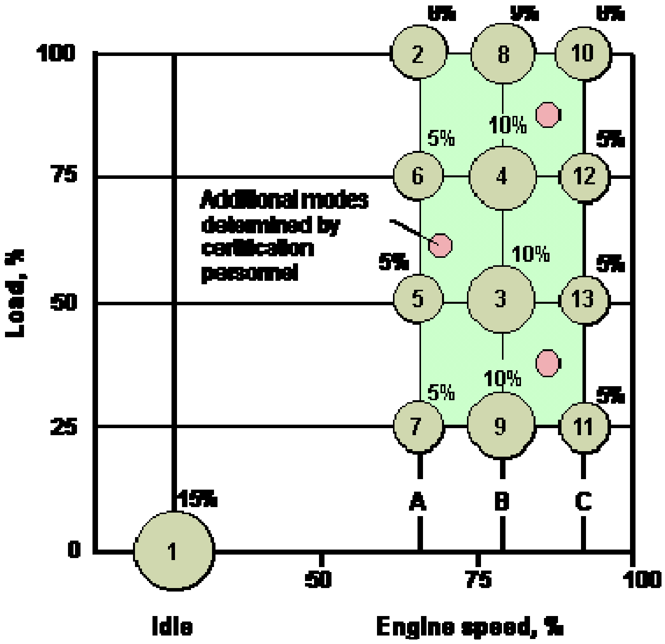

Figure 6: Overview of ESC Cycle.(7)

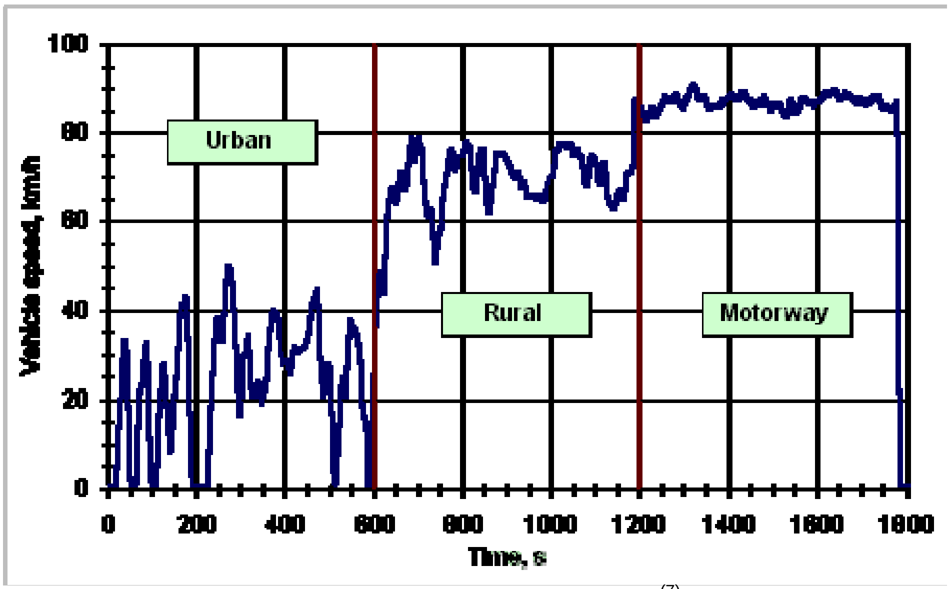

Figure 7: Overview of ETC Cycle.(7)

Methodology:

The methodology used for the study in this paper was done through comparative analysis between the proposed version and the baseline one. The major changes implemented in the ring pack were designed to reduce friction and therefore providing reduced fuel consumption, with more noticeable reduction of CO_2 emissions.

As the results are comparative, knowing the variances of measurement and its uncertainty is crucial to determine the real contribution of the ring pack in the result. The comparison was taken by the replication of baseline tests in the end of the procedure. So the test sequence was:

1. Baseline ring and pistons
2. Low friction ring pack and modified pistons
3. Replication of baseline parts

For all these steps it was applied running-in procedure to guarantee the proper condition to enable comparisons. The mentioned modified pistons were using similar design of baseline pistons, , the differences being only the geometry of the piston ring grooves to accommodate the lower widths of the low friction pack.

For all test assemblies (1, 2 and 3), ESC and ETC cycles were performed with 3 repetitions each one in order to monitor precision. In both conditions CO_2 and Fuel Consumption were measured. Other emission gases were also measured but they are not the main scope of this paper.

4 RESULTS

The results in terms of CO_2 Emissions and Fuel Consumption are discussed for the overall result of each tested Cycle (ESC and ETC). However, in order to explore more information from the acquired data, steady state cycle received “deeper” evaluation for each speed/load point evaluated along the test. Although were not the focus of this work, additional gases (NO_X, CO, THC, PM) were evaluated and same way presented.

All test figures were constructed according to Concawe,(8) which indicates that the improvements are presented only in cases where there is significant statistical confidence (higher than 85%).

4.1 Summary of CO_2 and Fuel Consumption Weighted Results

Weighted results of Steady State (ESC) and Transient (ETC) are presented below in Figures 8 and 9.

As main considerations, over both ESC and ETC evaluations, the results of CO_2 emissions and fuel consumption presented strong correlation as indicated by Pearson correlation coefficient of +1.0.

Related to this trend between CO_2 emissions and Fuel Consumption, it is clearly showed by the plots (Figures 8 and 9) that the consistency of results for steady-state tests is higher than for transient evaluations which can be self explained for the regime applied on each test.

The results also point lower specific values for transient evaluation over steady-state test. Although in general lines transient conditions might be understood as less efficient when compared to steady regimes, the higher consumption for the ESC test is related to their strength field of engine map data acquisition, with points of evaluation very far from engine efficiency curve.

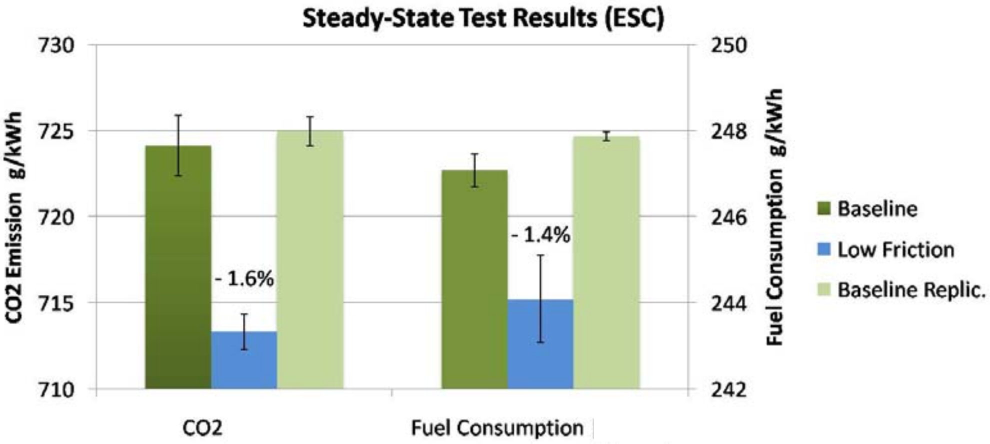

Figure 8: Steady-State Test Results for CO_2 and Fuel Consumption.

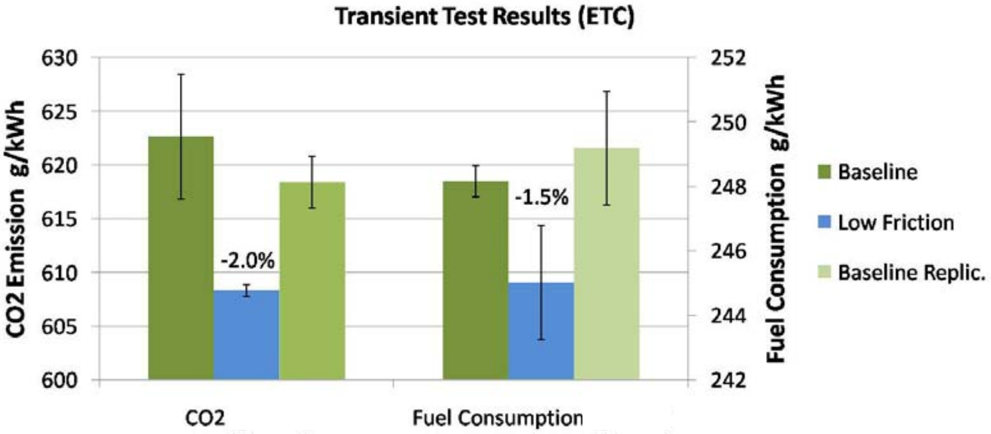

Figure 9: Transient Test Results for CO_2 and Fuel Consumption.

4.2 Detailed Results from ESC Load and Speed Conditions

Closer look of ESC results were applied for each point of the evaluated test in order to enhance test response and also to evaluate if the usual predictions in terms of piston ring common expertise of friction have been reproduced on CO_2 emissions tests. The following Figures 10 to 12 covers the performance points of ESC test (without IDLE evaluation) according to the Figure 6.

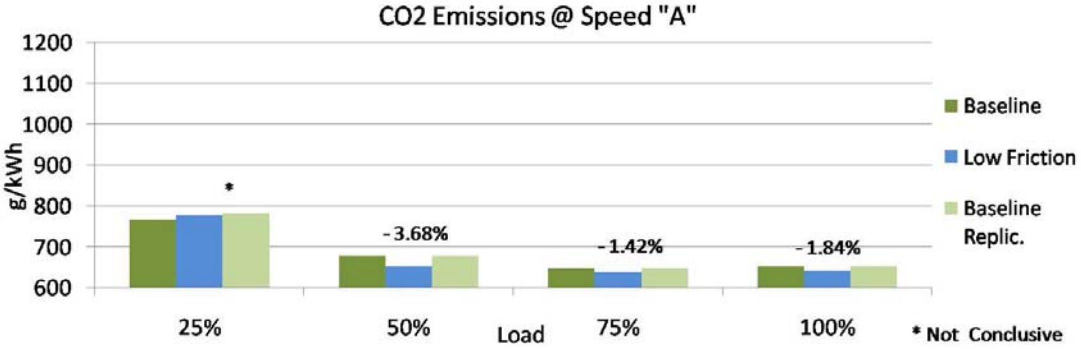

Figure 10: ESC CO_2 emission results for Speed “A” – 60% of engine max speed.

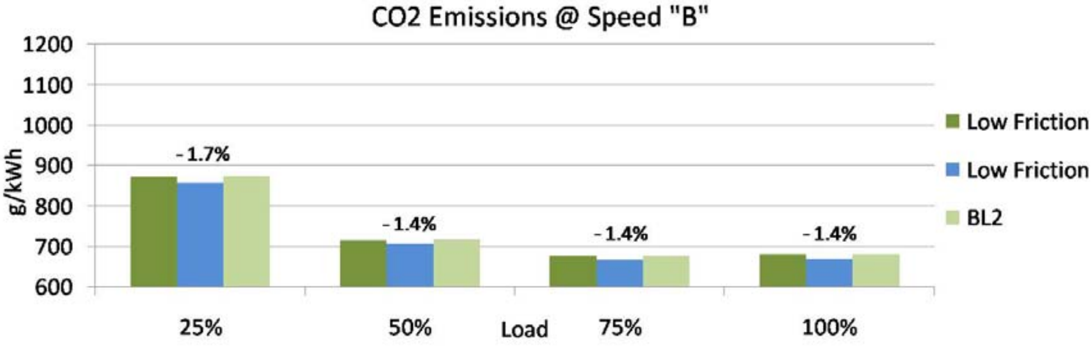

Figure 11: ESC CO_2 emission results for Speed “B” – 80% of engine max speed.

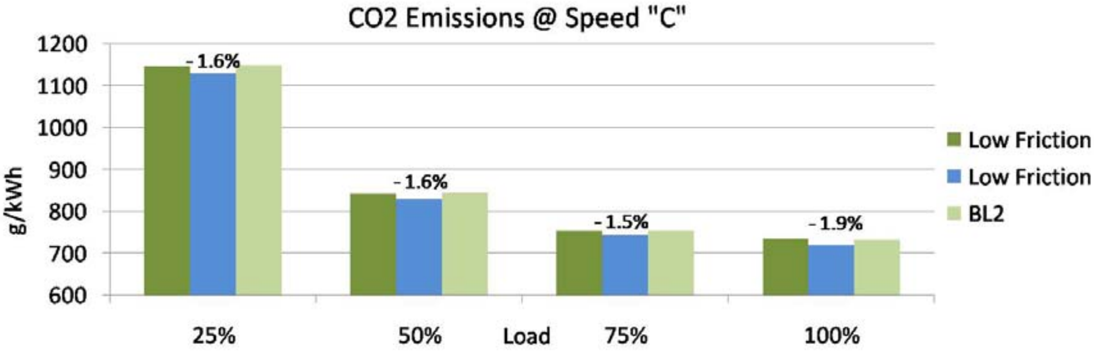

Figure 12: ESC CO_2 emission results for Speed “C” – 90% of engine max speed.

As already presented Item 2, from the numerical simulation results,(4) the higher contribution in terms of friction losses, rely on oil control ring contribution, reaching up to 70% of the total friction losses potential of ring pack, acting in all over engine load conditions. It may probably has been represented on the plots from Figures 10 to 12, by the consistency of the trendy of CO_2 emissions reduction verified over almost all engine data acquisition (except by one measurement that returned not conclusive response due data dispersion).

Additional remark over the detailed ESC results evaluation is that the higher level of specific emissions reduction is related to a low speed, partial load condition. At this condition, the ratio FMEP/BMEP is usually higher, hence being more sensitive to the impact of the association of low friction technologies applied in the study.

4.3 Additional Exhausted Gases Emissions Evaluation

Even though the focus of this work was the CO_2 emissions, other exhaust gases emissions were evaluated: NOx, CO, THC and PM at ESC and ETC. See Figure 13. It seems to be lower influenced by the low friction technologies applied over the experiments. The mechanisms in reduce these gases are more related to combustion efficiency improvement. An additional comment over these evaluations lay down on THC results that might be associated to the lubricant oil consumption, always treated as a critical subject to deal with when the time of implementation of low friction ring packs designs, especially when applying oil control ring load reduction.(5) As presented on the results below, the limits of THC were kept within baseline values, or even reduced when compared to the baseline results.

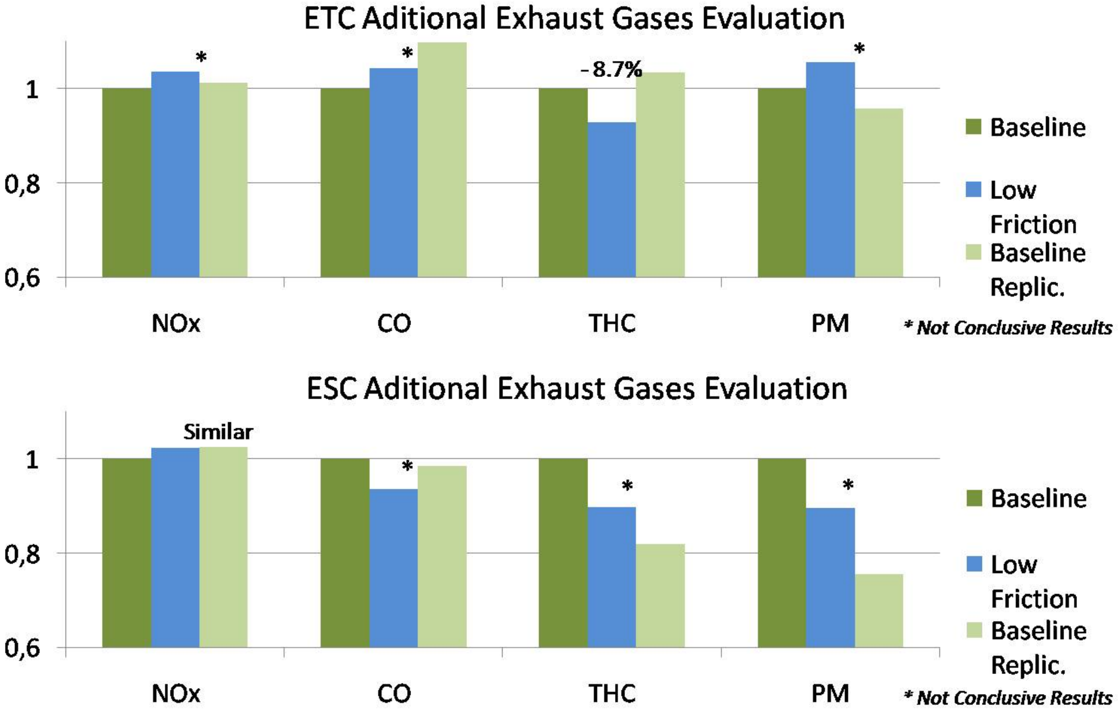

Figure 13: ESC and ETC additional exhaust gases emissions results.

5 CONCLUSIONS

On the field of friction reduction, the alternative of using emission evaluations for asses the influence of low friction components alternatives goes to the direction of have a closer eye on costumer usual language.

The low friction ring pack presented CO_2 emissions reductions of 1.6% on ESC evaluation and of 2.0 % on ETC evaluation. On specific points of ESC, higher reductions were observed, reaching levels up to 3.6%.

CO2 Emissions Evaluation shows to be a suitable approach for evaluate performance of Low friction ring packs. The confidence in this type of evaluation relies on the results and to their good correlation between CO2 emission results and fuel consumption as presented on item 4.

As next steps in terms of ring pack contribution for friction losses reduction developments, further investigations will be carried out on Otto cycle engines like impact of fuel (Flex Fueled engines), Ring, Low Friction Cylinder coatings influence and also extreme low friction concepts.

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