Influence of Oil Control Ring on Real-Time lube Oil Consumption and Particulate Emission

Bruno Fineto
Felipe Mazuco
Fernando Simas
Guilherme Buzzi
MAHLE Metal Leve S.A.

ABSTRACT

The global scenario is increasingly rigorous in controlling emissions of particulate materials, which are suspended in the atmosphere, being harmful to health and the environment. An important source of particulates is the combustion reaction of vehicular engines. In Europe, the engines already have post-treatment systems installed to meet the levels of Euro 6 legislation. However, in national flex fuel vehicles (ethanol and gasoline) this post-treatment system is not applied.

The objective of this work is to evaluate the impact of the oil control ring profile on the levels of particulate emission and oil consumption with the use of low environmental impact fuel (ethanol) and absence of any exhaust gas post-treatment system.

Two variants of oil control ring profile were evaluated in a turbocharged, direct injection and flex fuel engine that meets the Brazilian legislation PROCONVE L7. The evaluation was performed in dynamometer tests using a particle counter and a system with mass spectrometer to measure oil consumption in real time. The results show a direct influence of the oil control ring profile on the level of transient cycle particulate emissions and oil consumption under full load conditions.

RESUMO

O cenário global está cada vez mais rigoroso no controle de emissões de materiais particulados, que ficam suspensos na atmosfera, sendo nocivos à saúde e ao meio ambiente. Uma fonte importante de particulados é a reação de combustão de motores veiculares. Na Europa, os motores já possuem sistemas de pós-tratamento instalados para atender aos níveis da legislação Euro 6. Entretanto, nos veículos bicombustíveis nacionais (etanol e gasolina) esse sistema de pós-tratamento não é aplicado.

O objetivo desse trabalho é avaliar o impacto do perfil de anel de controle de óleo nos níveis de emissão de particulado e consumo de óleo com a utilização de combustível de menor impacto ambiental (etanol) e sem utilização de sistemas de pós-tratamento dos gases de escape.

Duas variantes de perfil de anel de controle de óleo foram avaliadas em um motor com turbocompressor, injeção direta e bicombustível que atende a legislação brasileira PROCONVE L7. A avaliação foi realizada a partir de testes em dinamômetro de bancada utilizando um contador de partículas e um sistema com espectrômetro de massa para medição de consumo de óleo em tempo real. Os resultados mostram uma influência direta do perfil de anel de óleo no nível de emissões de particulados em ciclo transiente e consumo de óleo em plena carga.

INTRODUCTION

Europe has been at the forefront of implementing stringent vehicle emissions legislation to tackle the growing concerns over air pollution and climate change. The European Union (EU) has introduced various measures to reduce vehicle emissions and promote cleaner transportation. One of the key regulations is the Euro emission standards, which sets limits on the amount of pollutants vehicles can emit, including nitrogen oxides (NOx) and particulate matter.

Real Driving Emissions were introduced to complement laboratory testing. RDE measures pollutants emitted by vehicles in real-world driving conditions, addressing the issue of discrepancies between laboratory tests and actual on-road emissions. This change ensures that vehicles meet emission limits not only in controlled lab environments but also during real-world driving. Portable Emissions Measurement Systems (PEMS) were used during on-road testing. PEMS devices are installed directly on vehicles and measure pollutant emissions during real-world driving. This method allows for accurate and continuous monitoring of vehicle emissions, providing more reliable data for regulatory purposes.

Brazil has recognized the urgent need to address vehicle emissions and improve air quality. The country has implemented its own set of regulations to regulate vehicle emissions. The Inovar-Auto program, introduced in 2012, and ROTA 2030, introduced in 2021, aimed to promote innovation and improve energy efficiency in the automotive industry. Under these programs, automakers were required to meet certain fuel efficiency targets, reduce greenhouse gas emissions, and invest in local production and research and development. Brazil has also adopted the PROCONVE (Program for the Control of Air Pollution from Motor Vehicles) standards, which set emission limits for vehicles, including limits for carbon monoxide, hydrocarbons, and nitrogen oxides. The PROCONVE L7 defined by the CONAMA resolution 492 [1] is valid since 2022 and its requirements meets similar Euro 6 limits and improvements in emissions measurement.

One important emission that must be considered on the vehicle development are the particulate emissions (PM) since it has various adverse effects on human health. The size and composition of the particles determine their potential health impacts. Particulate emissions can act as carriers for allergens, such as pollen or mold spores, exacerbating allergies and respiratory sensitivities. Additionally, particulate matter can cause eye, nose, and throat irritation, leading to discomfort and respiratory distress [2].

There is already available technology to decrease the vehicles emissions, for example optimized combustion engine power cell unit (PCU) [3] and post-treatment systems. Moreover, the automotive industry challenge is to enhance even more the components durability generating lower emissions. The use of ethanol has shown lower PN emissions only optimizing the PCU [4].

Inside the PCU, the piston chamber design and its temperature have important contribution on the chemical combustion process. However, the piston rings are the responsible to seal the combustion pressure, to transfer heat from the piston to the bore and, mainly, to control the lubricant oil consumption of the engine [5]. Specifically, to control the oil consumption there is a ring called oil control ring (OCR) positioned at third piston groove, which has some characteristics that influence directly on lubricant oil consumption and particulate emission.

OIL CONTROL RING

The oil control rings have two main types: the two pieces oil ring and the three pieces oil ring [6 and 7]. For both designs, there are an expander element to provide the load and two ring contact faces touching the cylinder. This work is based on three pieces oil control ring design (Figure 1), which one is mostly used in spark ignition engines, and it is the combination of two rails and one expander.

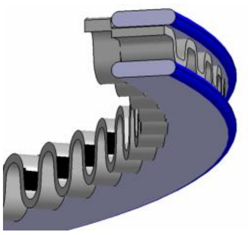


Figure 1 – Three pieces oil control ring design.

The main features that influence the lube oil consumption [7, 8 and 9] are the unitary pressure, conformability and running contact face profile. The OCR studied in this work is the state of the art (Figure 2). This ring comprises low unitary pressure, high conformability, and PVD coating on the rail contact face leading to the best compromise of oil scraping, friction, and wear.

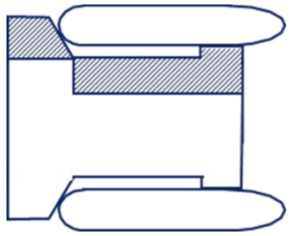


Figure 2 – MAHLE High Tech OCR design.

Nevertheless, the new turbocharged, direct injection and flex fuel engines are demanding components' fine tuning, and it is known the relation of oil scrapping and contact face profile. For this reason, with the best technology available to OCR its available different rail profiles (Figure 3).

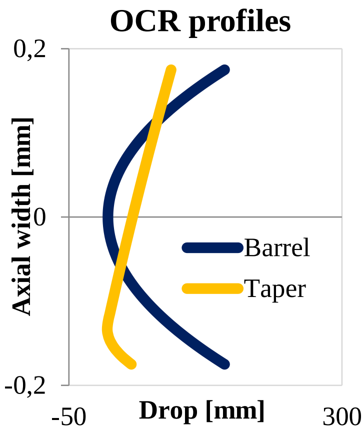


Figure 3 – Oil control ring contact face profile.

The focus of this work is to evaluate the influence of two different rail profiles on lube oil consumption for full-load and no-load conditions using drain and weigh method, and on particulate number (PN) emission and oil emission (OE) during a transient cycle known as WLTC (Worldwide Harmonized Light Vehicles Test Cycle) using a particle counter and a system with mass spectrometer to measure oil consumption in real time.

MATERIAL AND METHOD

A) Lubricant oil consumption by Drain and Weigh (D&W) method

In this method, as the name suggests, it is necessary to drain and weigh the engine oil mass before and after the test. The oil consumption can be determined by subtracting the measurements and dividing by the test duration. To improve the results replicability and reproducibility, strict procedures are adopted, such as standardized heating and conditioning engine protocol before draining, the drainage duration and procedures.

B) Lubricant oil consumption by real-time method

The LUBRISENSE 320 system is used for real-time measurement of the oil emissions in the exhaust gas from combustion engines [10]. It works by means of a heated probe, the measuring device continuously extracts a small quantity of exhaust gas from the exhaust pipe at a selected point, and a part of the removed gas sample is transferred into the ion source via the inlet. Then, using an electron impact ionization (EI), the molecules are ionized and then fed through a hexapole and a lens system to the mass filters (Figure 4).

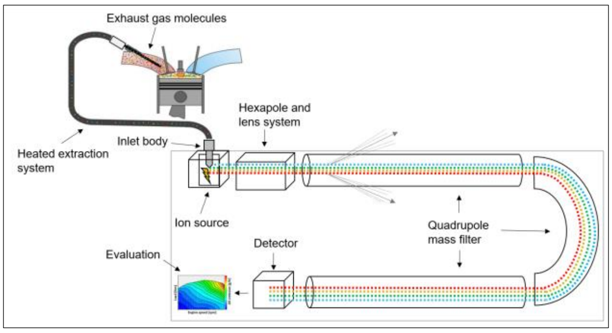


Figure 4 – Diagram of the analytical path.

The measuring method is based on the separation of different exhaust gas components based on their molecular mass. The very volatile compounds from the combustion process and the incoming air, and the non-burned hydrocarbons from the fuel are separated from the higher molecular lubrification oil components by the quadrupole mass filter [10].

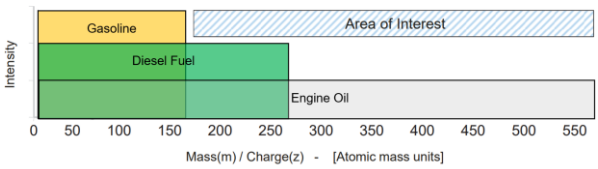


Figure 5 – Range of hydrocarbons and area of interest.

This method scans all ions from low volatile components simultaneously utilizing a high-pass filter. The detected ions from the oil molecules define the concentration of lubrication oil in the removed exhaust gas and applying this method it is possible to achieve very low detection limits at a very high time resolution [10].

C) Particle number (PN) measurement

The measurement principle for light vehicles consists of sample the exhaust gas from a full dilution tunnel with constant volume sampling (CVS) to a system called Volatile Particle Remover, which is responsible for diluted the exhaust gas in a subsystem named Particle Number Diluter, after the dilution the flow is conducted through the Evaporation Tube, where the diluted gas is heated to a temperature that causes the volatile emission components to vaporize, maintaining only the solid particles. After that, the exhaust gas can be diluted again (optional) using another Particle Number Diluter and fed into the Particle Number Counter (PNC). In the PNC, butanol is condensed on to the exhaust gas particles to enlarge them, making them visually detectable and countable based on the scattered light pulses generated when the particles pass through the laser beam, so determining the particle number per volume unit (Figure 6) [11 e 12].

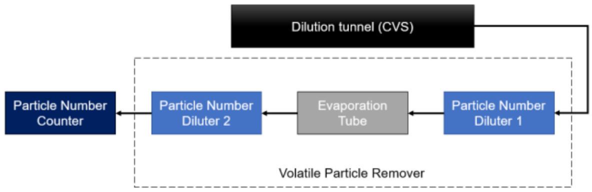


Figure 6 – Diagram of particle counter.

According to relevant legislation, the PNC measures the concentration of particles greater than 23 nm, which allows the measurement of the primary soot (23 nm), excluding the smaller and low volatility hydrocarbons. The counting efficiency is (50 ± 12) % at 23 nm and greater than 90% at 41 nm [12].

For this work, the equipment employed was the AVL Particle Counter 489, using exhaust raw sampling mode, which is a method commonly used in research and development activities, that substitutes the use of a dilution tunnel while maintaining similar results to the legislated procedure [12].

MEASUREMENT PROTOCOL

The experimental study of this work was performed at MAHLE Jundiai facilities. The engine selected is representative of a turbocharged, direct injection and flex fuel engine that meets the Brazilian legislation PROCONVE L7. The Table 1 presents the engine characteristics.

Table 1 - Engine characteristics.

Engine Type	Turbocharged
Fuel	E100 - Ethanol
Lubricant Oil	0w30
Bore diameter	70.00 mm
Stroke	86.50 mm
Number of cylinders	4
Max. Specific Power	102 kW/l @ 5750 rpm
Max. Specific Torque	203 Nm/l @1750 rpm
Engine Block	Aluminum

The engine test protocol consists, basically, in two phases:

1. Steady state phase

This phase evaluates the oil consumption by the drain and weigh method. The first LOC protocol was performed at full load condition, i.e., the engine throttle was kept fully open (wide open throttle - WOT), and the engine speed maintained at 5175 rpm. The second was performed at a condition named No-Load, which is a high engine speed rotation (5175 rpm) with quite low load (around 12 Nm of torque). Each protocol is four hours long, requiring at least 3 repetitions to ensure results replicability.

2. Transient phase:

This phase evaluates the oil consumption by the drain and weigh method during two different transient protocols: Start-Idle and WLTC. Additionally, for the WLTC protocol the particle number and oil emission were also measured.

After the steady state protocols, the dynamic cycle called Start-Idle of 12 hours duration is the next step to measure the LOC and guarantee the components' run-in. This protocol consists of accelerate the engine from low idle condition to a middle engine speed (3325 rpm) and middle load (50% of maximum torque) condition, then return to low idle several times, with some steps of full load condition at the same speed (3325 rpm) between the cycles.

The WLTC is required to test the whole vehicle in a chassis dynamometer to control the PN emissions. For this work, it was adapted to run only the engine in an engine dynamometer (Figure 7).

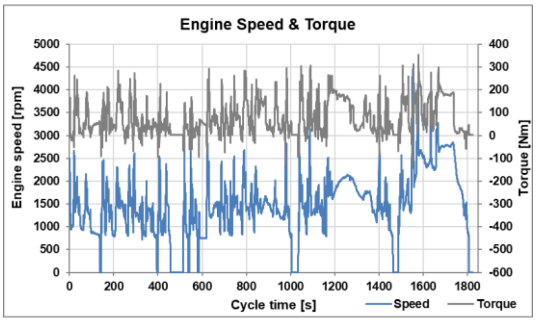


Figure 7 – WLTC: Engine Speed and Torque profile.

As this protocol is based on a street circuit, the Figure 8 shows the residence time of each condition evaluated during the cycle ran.

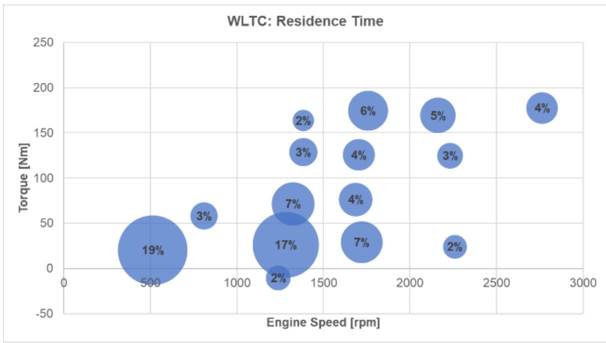


Figure 8 – Residence time for WLTC: most relevant residence conditions (>2%) plotted, resulting in 90% of the total cycle.

The WLTC cycle is 30 min long, it was repeated 40 times with an intermediate pause to determine the lube oil consumption using the D&W method.

For this test, performance and blow-by curves were performed to check the engine behavior at the start and end of each assembly tested, to ensure that the engine ran in an acceptable condition. Performance and blow-by curves are quite similar, both intend to cover all the engine operating speed at full throttle condition and. The difference is regarding the blow-by. Blow-by is a gas flow generated by the air-fuel mixture or exhaust gas leakage through the piston rings and cylinder wall to the oil sump. This flow can cause a high pressure in oil sump and must be recirculated or expelled to the atmosphere. According to relevant legislation, blow-by must be recirculated, because it can carry fuel, oil and causes undesirable pollutant emissions.

RESULTS

It was done a virtual simulation using the MIT-Code TPOCR [13] to evaluate qualitatively the expectative of rail profile influence on lube oil consumption. All the OCR features were measured and inputted on the software to achieve better accuracy. The Figure 9 shows the main ring characteristics.

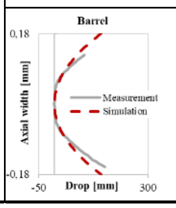
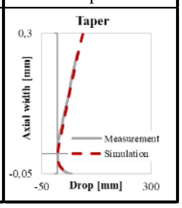
Tangential Load	20.5 N	21.5 N
Gap	0.43 mm	0.41 mm
	Barrel	Taper
Profile		

Figure 9 – Main ring characteristics.

The Figure 10 shows, the main output, the minimum oil film thickness (MOFT) for the full-load condition at 5175 rpm.

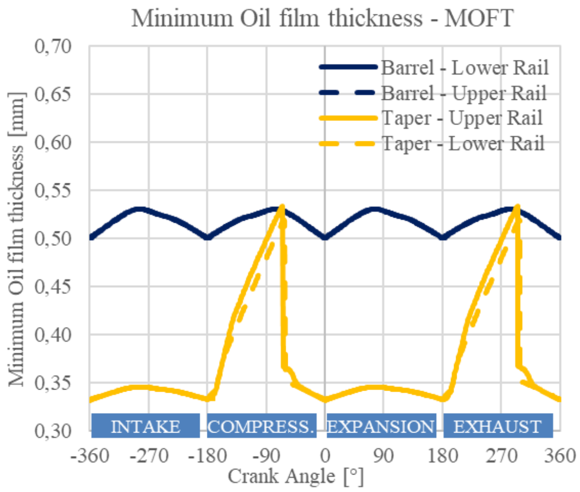


Figure 10 – Minimum Oil Film Thickness (MOFT).

The MOFT curve shows during the downstrokes (intake and expansion) lower oil film thickness to taper profile when compared to barrel profile. As consequence, qualitatively, for this condition is expected lower oil consumption.

The reason of different oil film thickness is the dynamics behavior of the rails with each contact face profile. The Figure 11 illustrates the rails twist and its lift, and the main difference occurs during the end of downstrokes allowing more effectiveness on oil scrapping.

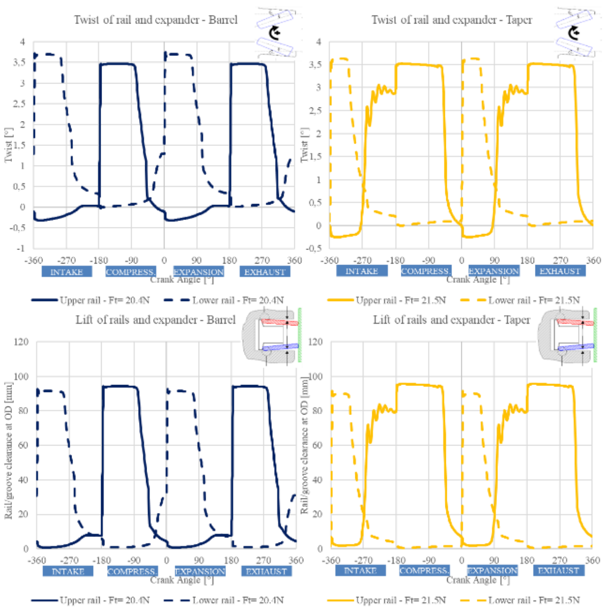


Figure 11 – OCR dynamic behavior (Twist and Lift).

On the experimental side, by the drain and weigh method the lube oil consumption was measured on full-load condition and no-load condition, both at 5175 rpm. For the transient condition the Start-Idle cycle was measure by the drain and weigh method. The Figure 12 shows the comparison between rail profiles. It is noticed that the Taper profile has better performance on full-load condition decreasing 10% of lube oil consumption and similar performance to transient condition. In another engine with higher specific power (112kW/l) the taper profile reached up to 30% less oil consumption on full-load condition.

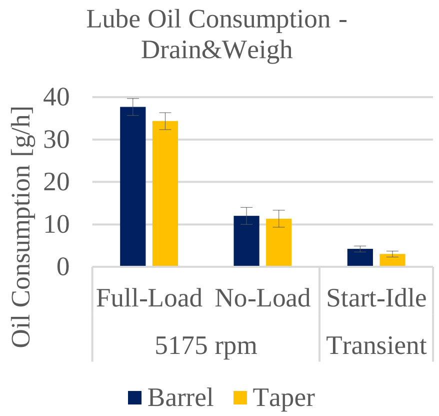


Figure 12 – LOC by drain and weigh method.

Additionally, by the real-time measurement using a particle counter and a system with mass spectrometer the transient cycle WLTC was evaluated. The Figure 13 and Figure 14 shows the rail profile influence on PN emission. The high PN emissions occurred at high acceleration after a period in low loads and low speeds.

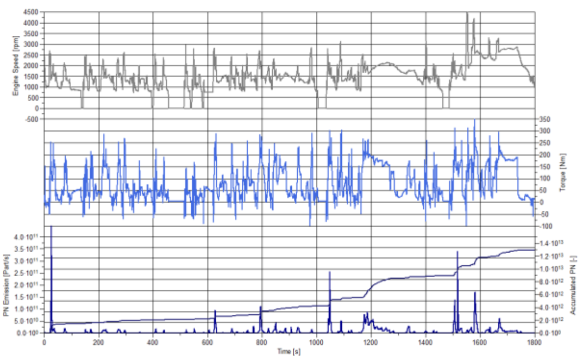


Figure 13 – WLTC for Barrel profile.

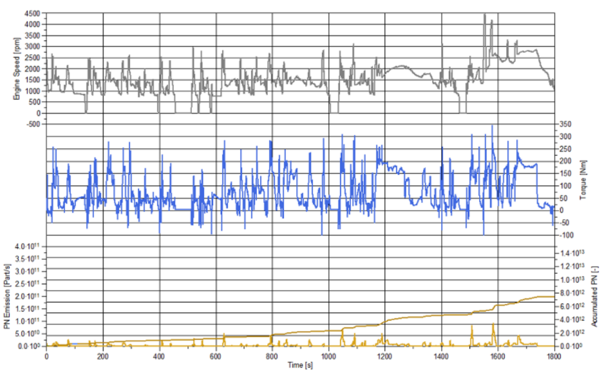


Figure 14 – WLTC for Taper profile.

The emission throughout WLTC clarifies that for the same transient cycle, after the same quantity of hours to guarantee equivalent run-in, the contact rail profile has high influence on the PN peaks and, consequently, on the accumulated particle number emission. The Figure 15 compares the average of PN emission during WLTC cycles and the taper profile has the best performance decreasing 33% of the accumulated particles.

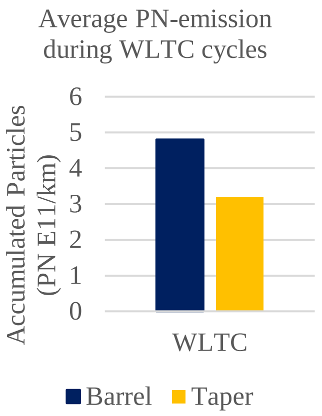


Figure 15 – Average of PN emission during WLTC cycles.

For the transient cycle was also measured the oil emission in real-time. The Figure 16 and 17 presents the oil emission during the WLTC it is possible to notice similar behavior of the emission, consequently, the accumulated OE is similar for both rail profiles.

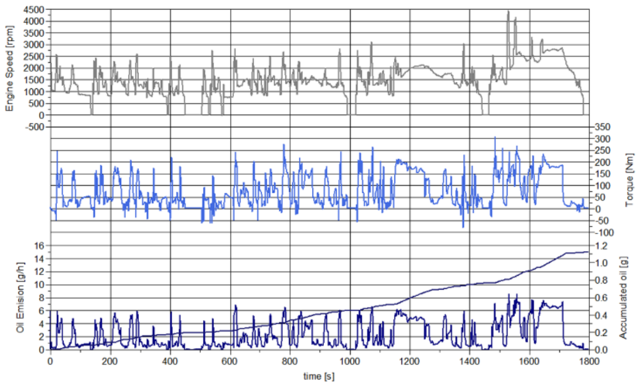


Figure 16 – Oil emission for Barrel profile.

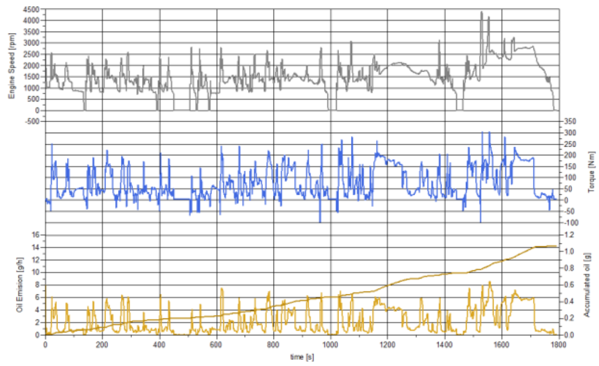


Figure 17 – Oil emission for Taper profile.

The Figure 18 shows the average of the OE measurements for all WLTC cycles, and it is evident the similar performance for both rail profiles.

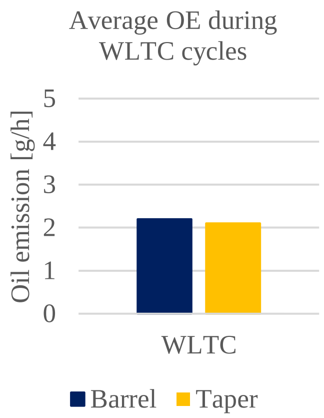


Figure 18 – Average of oil emission during WLTC cycles.

To increase the confidence of this work it was measured the lube oil consumption by the drain and weigh method after the transient cycle WLTC. As already explained, this method is the more robust one due to quantify the total consumed oil after a specific cycle. On the other hand, the real-time oil consumption method measures the unburned oil, which represents part of the total consumed oil. The Figure 19 shows the total oil consumption measured by drain and weigh and the unburned oil and it confirms the similar behavior for both rail profiles clarifying the low influence of the rail profile on LOC for transient cycles.

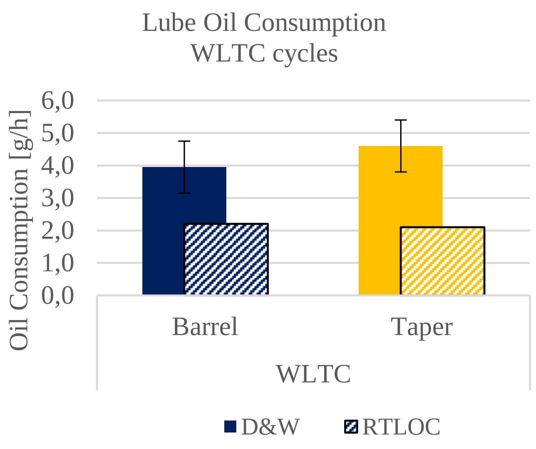


Figure 19 – Lube oil consumption during WLTC cycles.

CONCLUSIONS

For the simulated results the rail profile influences on the oil film thickness. Consequently, as the experimental results endorsed the simulation showing the lowest oil consumption with the taper profile at full-load condition and 5175 rpm.

An important reduction in the PN emission was seen for the taper profile, which means that the dynamics of the rail were effective to control the oil film available to be burned at high acceleration (most important for PN emission). Despite of the lower PN emission, the total oil consumed and the oil emission (RTLOC) during transient cycle were not affected. This is an indication that the short periods where the PN is high have minor effect on total oil consumption.

As conclusion, the results show a direct influence of the oil control ring profile on the level of transient cycle particulate emissions and oil consumption under full-load conditions.

REFERENCES

[1] “Resolução CONAMA nº 492, de 20 de dezembro de 2018. Estabelece as Fases PROCONVE L7 e PROCONVE L8 de exigências do Programa de Controle da Poluição do Ar por Veículos Automotores – PROCONVE para veículos automotores leves novos de uso rodoviário.” 2018.

[2] CETESB. “Qualidade do ar no Estado de São Paulo”. 2022.

[3] Ferreira, M.; Bruno, R.; Fineto, B.; Chaves, H.; "Efficient light vehicle pcu to meet rota 2030 targets", p. 546-561. In: XXVII Simpósio Internacional de Engenharia Automotiva. São Paulo: Blucher, 2019.

[4] Fineto, B.; Bruno, A. R.; “Pacote de anéis Euro 6 de baixa emissão de particulado com etanol e sem filtro”. AEA, 2020.

[5] Tomanik, E.; “Piston Ring Conformability in a Distorted Bore”, SAE Brasil; SAE-960356; São Paulo, Brazil, 1996.

[6] Tomanik, E.; Ferrarese, A. “Low Friction Ring Pack For Gasoline Engines” – paper ASME ICEF2006-1566 (2006).

[7] Tomanik, E. and Ferrarese, A.; “Use of a Micro-contact model to Optimized SI Engine’s 3-piece oil ring profiles regarding Wear and Lubrication”; ASME-Internal Combustion Engine – Fall Technical Conference; ICEF 2002-526, vol. 39; New Orleans, USA, 2002.

[8] Ferrarese, A.; Rovai, F.; “Oil Ring Design Influence on Lube Oil Consumption of SI Engines”, ASME paper ICEF2004-868.

[9] Pereira, M; Bruno, R. A.; “Low Width Oil Control Rings for SI Engines” SAE paper 2007-01-2830 (2007).

[10] Airsense Automotive: Lubrisense User Manual. 2012.

[11] AVL Particle Counter – Product Guide, AT2858E, Rev. 05, January 2010.

[12] AVL Particle Counter 489 – Application Guide, AU4576E, Rev. 00, November 2019.

[13] Tian, T., Rabute, R., Wong, V. W., and Heywood, J. B. Effects of Piston-Ring Dynamics on Ring/Groove Wear and Oil Consumption. Submitted to the 1997 SAE International Congress and Exposition in Detroit, Michigan, February 24-27, 1997.