Effect of using a metal conditioner in performance, fuel consumption, and powertrain wear of new small-capacity motorcycles

Oriana Palma Calabokis

Yamid Nuñez de la Rosa

Paulo César Borges

Tiago Cousseau

Universidade Tecnológica Federal do Paraná.

ABSTRACT

Metal conditioners (MC) are firmly inserted into the Brazilian market as friction, wear, and heat-reducing agents between the metal components in motion, mainly in engines and transmission boxes. The effect of adding a MC on the performance of two new motorcycles (160 cc) under actual conditions was studied. The viscosity, dispersancy, TAN, and TBN values of the used engine oil with and without MC were similar. FTIR results showed that specific components in the MC formulation do not allow direct comparison between oils and their mixtures with MC. The MC provided aluminum and iron metal parts protection in the first 7000 km of engine break-in, but wear of copper-containing parts although at levels below the warning limits. The dimensions of the cylinder, piston, and transmission system pieces changed of less than 0.05%, except for gear #5. There was a wear reduction of the transmission kit (chain, crown, pinion) and gear #5 lubricated with the MC. Fuel consumption was statistically equal (ANOVA, 95%). However, the motorcycle that drove with MC kept higher average fuel economy improvements (+1 km/l), representing a 2.5% gain compared to the other motorcycle.

Keywords: Powertrain, motorcycles, metal conditioner, additives, engine break-in.

INTODUCTION

Metal conditioners (MC) are firmly inserted into the Brazilian and worldwide market, as friction, wear, and heat reducers between the metal pieces in tribological contacts [1-4]. Some MC's companies states that it increases the life of motors and transmissions systems, and also reduce polluting emissions and fuel consumption [5-8]. In Brazil, they are mainly added by consumers into the crankcase engine lubricant oil despite the MCs have no product registration at ANP (*Agência Nacional Do Petróleo, Gás Natural E Biocombustíveis*). Nowadays, they are not registered as additives neither as lubricating oils. Therefore, they are also not approved by large vehicle manufacturers and have a small market share compared to commercial engine oils. This situation causes that metal conditioners had low systematic research. In fact, most of the publications on MC are from informal sources (blogs, videos, social media), while reliable, and scientific references are scarce. The works development by Alves, D. (2014) [9], Nunes, E. (2014) [10], Santos de Oliveira, F., (2015) [11], and Coppini, et al. (2017) [12] demonstrated that the prior conditioning of cutting tools (enlargement, threading, and drilling) with MC, improved the performance and tool life, while reduced the overall costs, compared to those unconditioned tools. Unexpectedly, to the best of the authors' knowledge, it was not found any peer-reviewed reference about MC performance in powertrains, yet is its main application. In order to cover this gap, experimental work was put forward to evaluate a commercial MC response in a new motorcycle (160 cc).

MATERIALS AND METHODS

Two new motorcycles (0 km) Honda model Titan 2019 (160 cm³) were purchased specifically for this study. Their performance, in typical urban driving conditions, was monitored in the first 15000 km regarding lubricant conditioning, engine parts dimension measurements (wear), and fuel consumption. The drivers did not know which motorcycle was lubricated with metal conditioner. Figure 1 summarized the field study. More detailed information can be found in the work of Calabokis, et al.[13].

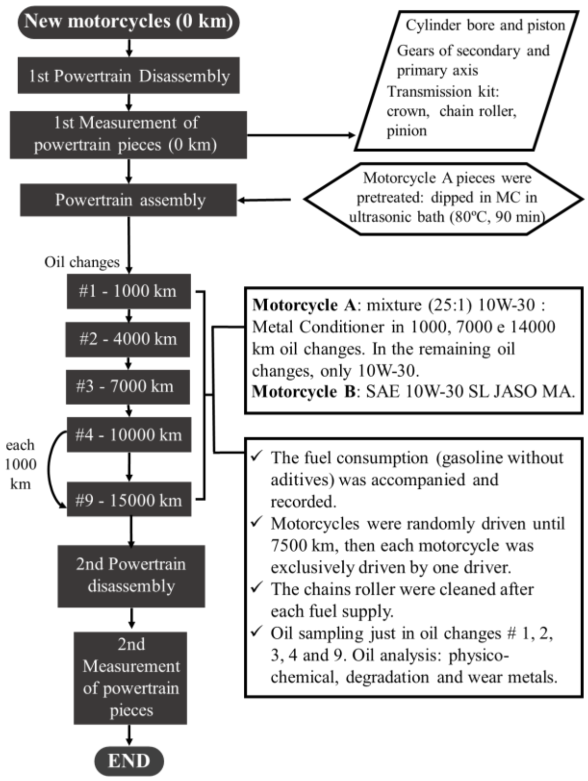

Figure 1. Flowchart.

OIL ANALYSIS – The lubricants analysis were performed by an external company following the American Society of Testing Materials (ASTM) procedures listed in Table 1. The protocol followed for sampling was: (i) The engine was started for 5 min to ensure the recirculation of the engine oil. (ii) A disposable hose was inserted up half of the tank, via the inlet hole of the oil level verification rod. (iii) The oil was extracted with an oil sampling pump. (iv) Two sampling bottles were filled. (v) The remaining oil (~ 600 mL) was allowed to drain until the total emptying of the crankcase.

The automaker suggests different oil change intervals: the first one with 1000 km, the second with 6000 km, and then every 6000 km. This suggestion was not followed because most motorcycle users (dealers, delivery) do not follow this recommendation.

WEAR ANALYSIS IN THE MAIN ENGINE PARTS – The engines were disassembled twice because their components were measured at the beginning (0 km) and at the end of the field study (15000 km). An experienced external company measured the parts:

- The cylinder diameter was measured using a dial bore gauge (0.1 µm) at the top, center, and base.
- The piston skirt diameter was measured using a digital micrometer (1 µm) at the standard 10mm height.
- The chain roller was evaluated in terms of the pitch distance and roller diameter.
- The remaining pieces were measured with standardized gear procedures using two rollers and measuring the resulting diameter with a caliper (5 µm). The remaining pieces are: Primary axis (axis and gears #1 to #4), secondary axis (gears #1 to #5), crown, and pinion.

After the second engine disassembly, some pieces were observed in the stereoscopic microscope to detail the wear mechanisms and severity.

Table 1. Lubricants Analysis Techniques.

Physico-chemical and degradation
ASTM D445 [14]: Kinematic viscosity 40°C and 100°C [cSt]
ASTM D2270 [15]: Viscosity Index (VI) C [Dimensionless]
ASTM D7899 [16]: Merit of Dispersancy, Contamination Index, Weighted Demerit [Dimensionless]
ASTM D91 [17]: Precipitation Number [Dimensionless]
ASTM D4739 [18]: Total base number (TBN) [mg KOH/g]
ASTM D974 [19]: Total acid number (TAN) [mg KOH/g]
ASTM D7889 [20]: IR Spectroscopy (FTIR) [abs/cm]
Wear metal particles
ASTM D5185 [21]: Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) [ppm]
ASTM D7684 [22]: Microscopic Characterization [Dimensionless] Soot/oxidation products, Silicon dioxide, Iron alloy particles >5µm<15µm

ANALYSIS OF FUEL ECONOMY – Fuel consumption was recorded during the 15000 km. The fuel economy results (km/l) were statistically evaluated (95% confidence) using the MATLAB® Software Analysis Tool: Two-Way Analysis of Variance (ANOVA) for unbalanced design. This analysis tested the null hypothesis of whether the averages between motorcycles are equal. Also, the ANOVA analysis revealed the effects, on fuel consumption, of different factors or variables and its levels. In other words, the "motorcycle" factor has two levels: "Motorcycle A" and "Motorcycle B". The "regime" factor has 3 levels: "0k to 1k", "1k to 10k" and "10k to 15k". While the "driver" factor has 2 levels: "random" and "unique".

RESULTS AND DISCUSSION

PHYSICO-CHEMICAL AND DEGRADATION OIL ANALYSIS – Figure 2 shows the evolution of TAN, TBN, and dispersancy as a function of mileage. The dispersancy of the used oils was adequate: always higher than 85% (0.85). It is important to point out that TAN and TBN values of the fresh 10W-30 oil and its mixture with metal conditioner (Fresh + MC) are clearly different. It is evident from Figure 2, that motorcycle A, in which metal conditioner was added, always presented higher TAN and smaller TBN values from the first oil change (>1000 km). However, all TAN and TBN values presented in Figure 2 are within the acceptable operating range, according to the “warning limits” defined by several researchers and summarized by Booser (1993) [23]. Though, it is important to mention there are no universally accepted warning limits. Macián et al. (2021) [24] stated that TBN should always be higher than TAN at the time of the oil drain interval, so the oil formulation ensure a sufficient mileage window. The TAN/TBN ratio is particular for each engine oil formulation and therefore, the evolution of Figure 2 suggests that both oil formulations (oil and its mixture) had an adequate performance all along the field study.

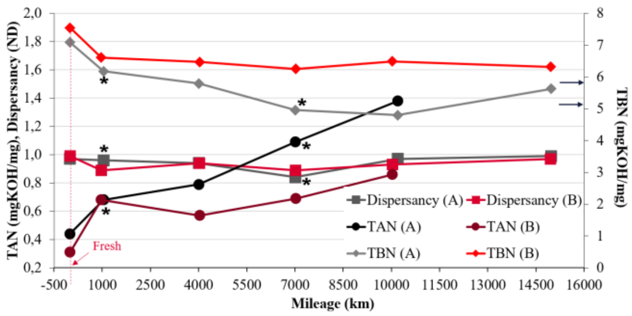

Figure 2. Evolution of Total Acid Number (TAN), Total Base Number (TBN) and Merit of dispersancy values based on mileage and motorcycle. TAN values were not determined in the last samples (15000 km). * Indicates the oil changes in which the engine A received the mixture of oil + MC.

Fourier transform infrared spectrometry (FTIR) is a simple technique used to measure oil degradation. It identifies the presence of organic compounds derived from oil degradation reactions as oxidation, nitration, and sulfation. Figure 3 shows the absorbance values (abs.cm^{-1}) of the characteristic’s degradation bands according to ASTM D7889 [20] for the fresh SAE 10W-30 SL JASO MA and its mixture with MC. It stands out that the fresh mixture has higher nitration, oxidation, and sulfation values compared to fresh 10W-30 oil. Those higher values (Figure 3 - Fresh Mixture) do not indicate that it is degraded. Instead, it advises that the metal conditioner contains organic compounds with infrared absorbance in the oxidation (1800 to 1670 cm^{-1}) and sulfation (1180 to 1120 cm^{-1}) regions. In particular, chemical compounds containing the carbonyl group (C = O), such as esters, ketones, aldehydes, and carboxylic acids strongly absorb in the oxidation region [26]. The standard ASTM E2412 [25] emphasized that it may be the case of several additives of the formulation package, such as detergents, dispersants, antioxidants. Therefore, the evaluation of FTIR spectra of those sulfur-containing and oxygen-containing used oil can generate precipitated conclusions causes by its spectral interference.

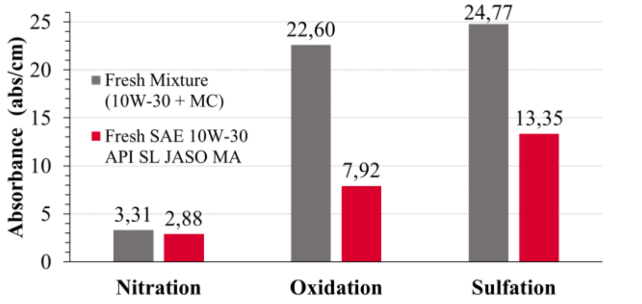

Figure 3. Fresh oil and mixture properties estimated using IR Spectroscopy (ASTM D7889).

Table 2 show the percentage variation of the nitration, oxidation, and sulfation of the used oils in comparison to the corresponding fresh ones, respectively. In the case of motorcycle A, the percentage variation at 4k and 10k oil changes were calculated based on the fresh mixture; in the remaining ones, the fresh oil values were considered. Table 2 revealed that the oxidation and sulfation percentage change for the used oil from motorcycle A was very unstable. Perhaps, in some oil drains the MC molecules might not be completely adsorbed on the metal surfaces, remaining in the crankcase oil as a reserve for being progressively consumed. This hypothesis would explain why in 4k oil change, the oxidation and sulfation percentage change were negative: all-metal conditioner had been consumed in that 3000 km of operation.

Table 2. Evolution of nitration, oxidation and sulfation of oil based on mileage and motorcycle, results are presented by the percentage change based on fresh condition. * Indicates the oil changes in which the engine A received the mixture of oil + MC.

Mileage	Moto	Nitration (%)	Oxidation (%)	Sulfation (%)
1k	A*	27.9	23.51	15.28
	B	28.2	12.15	4.45
4k	A	58	− 23.6	− 17.4
	B	60.3	36.1	16.2
7k	A*	54.5	218.4	141.0
	B	70.3	43.8	20.3
10k	A	78.3	28.9	21.54
	B	109.7	67.46	29.89
15k	A	22.8	28.82	21.05
	B	19	14.7	5.88

Finally, the physico-chemical and degradation oil properties of used oils of both motorcycles remained within the acceptable limits. FTIR results (Figure 3, Table 2), revealed that the addition of the MC in the fully formulated oil has generated absorbance interferences in the oxidation and sulfation region, because the presence of certain additives (containing C=O). According to the manufacturers of metal conditioners [5-8], the product does not propose to improve the physico-chemical properties of engine oil.

WEAR METALS ANALYSIS IN USED OIL – The motorcycles use a single lubrication system for the engine and the transmission system, so the oil poured in the crankcase lubricates all the parts involved and the wear metals presents in oil, might come from all the powertrain components. Table 3 presents the contents of wear metals (ppm) along the 15000 km estimated through ICP-AES spectrometry. This technique failed to quantify particles > 5 µm, and therefore only evaluated particles associated to mild wear and corrosion. The chromium and nickel contents were found at the equipment's lower detection limit (0.1 ppm). The motorcycles did not have the same mileage (km, service time) at each oil change, so Table 3 presented the standardized values (ppm/km).

Table 3. Wear metals (ppm and ppm/km) in used oil analysis.

Element (ppm/km)	Moto	1k *	4k	7k *	10k	15k***
Al	A	0.0468	0.0191	0.013	0.019	0.0126
	B	0.0581	0.0255	0.021	0.0226	0.0122
Cu	A	0.021	0.0058	0.0091	0.0065	0.0001
	B	0.0192	0.0042	0.0026	0.0029	0.0001
Fe**	A	0.0652	0.0254	0.0156	0.0259	0.0228
	B	0.0867	0.0288	0.0194	0.0215	0.0172

* Indicates the oil changes in which the engine A received the mixture of oil + MC.
** The iron content of the fresh oil or fresh mixture was subtracted from the values of each used oil.
***Between 10000-15000 km, oil change intervals were at every 1000 km, only the last oil change was analyzed.

The contents of copper and iron were always below the warning limits established in the literature for both motorcycles (<100 ppm and <40 ppm respectively). However, the content of aluminum was always above (>30 ppm) in both motorcycles, being up to 2.6 times higher than the warning limits for motorcycle B. The aluminum levels were not expected considering that the oil was changed at intervals smaller than those recommended (<6000 km).

The results of Table 3 indicates that in motorcycle A, the application of metal conditioner during the engine assembly decreased the amount of aluminum and iron wear in the first 7000 km of engine break-in. The last used oil analysis (15000 km, Table 3) suggests that the addition of MC for a short oil interval (~1000 km) did not bring significant gains in the content of wear metal, because they remained below the warning limits.

WEAR ANALYSIS IN THE MAIN ENGINE PARTS – The dimensional differences in the powertrain components after 15000 km were calculated in percentage based on the measurements of the new part (0 km). Table 4 contains the results of the dimension differences higher than |0.05%|. Thus, the piston, cylinder, and most of the transmission system pieces changed their dimensions hardly representative (<|0.05%|). It is important to emphasize that the dimensional variations (Table 4) are not directly related to the formation of wear debris (Table 3) because part of it is related to deformation without material removal.

Nevertheless, motorcycle B's transmission kit showed significant dimensional changes on all its elements in comparison to the other. Actually, the chain of motorcycle B broke with 14961 km. The useful life of the chain of motorcycle A was beyond 15000 km without any issue. All the components of the transmission kit of motorcycle B will be replaced to guarantee its operation.

Table 4. Relative change (%). Differences greater than ± 0.05% were considered less representative and not presented.

	Motorcycle A	Motorcycle B
Chain Roller Ø	-0,826%	-1,004%
Chain pitch distance	0,912%	1,484%
Crown Ø	-0,0482% to -0,0429%	-0,0643% to -0,0589%
Pinion Ø	-0,331% to -0,302%	-0,374% to -0,359%
Gear #2 - Primary axis Ø	-0,0733% to -0,0367%	-0,0184%
Gear #5 - Secundary axis Ø	-0,031% to -0,015%	-0,170% to -0,015%

The relative changes (Table 4) are direct measures of the macroscopic wear and/or deformation of those pieces but it will not prevent the proper engine operation of both motorcycles. Just the transmission kit and gear #5 of the secondary axis, both of motorcycle B, need to be replaced (its chain broke with 14961 km). The crown and the gear #5 of both motorcycles were observed through stereoscopic microscopy in order to understand the dimensional significant differences (Table 4). The images are shown in Figure 4 to Figure 5.

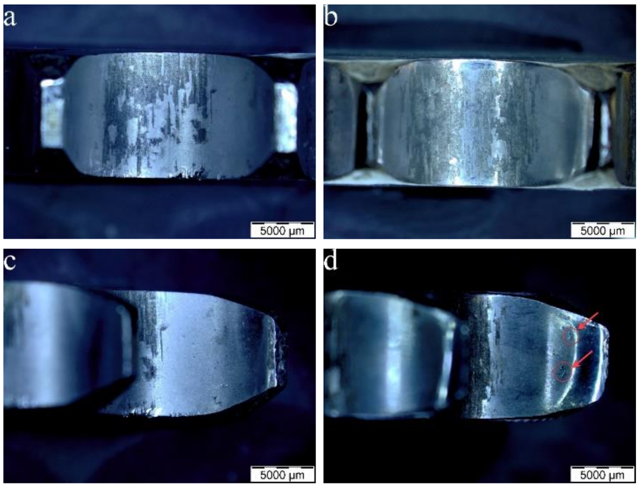

Figure 4. Optical macrograph of the crown of the motorcycle A (a, c) and motorcycle B (b, d).

The crowns of motorcycle A and B are showed in Figure 4a,c and Figure 4b,d respectively. A larger worn area where the primary contact with the roller's chain occurs in the crown of motorcycle B (Figure 4b) is observed. This result is consistent with the smaller diameters of both the crown and the chain rollers of motorcycle B (Table 4). Also, the crown B (Figure 4b) showed a more intense abrasive wear compare to crown A (Figure 4a). The red arrows in Figure 4d indicate the micropitting sites on the face of the tooth which contacts the chain of motorcycle B. Micropitting was not detected in the crown's teeth face of motorcycle A (Figure 4c).

The gears #5 were the only ones with visible wear to the naked eye in both motorcycles as observed in Figure 5. The gear A (Figure 5a,c) showed less severe wear on all teeth compared to gear B (Figure 5b,d). Also, both gears #5 exhibited micropitting in the addendum region and frosting wear in the dedendum region as shown in Figure 5. Both gears exhibited destructive pitting but the gear from motorcycle B it was more severe with in-depth material removal (spalling wear).

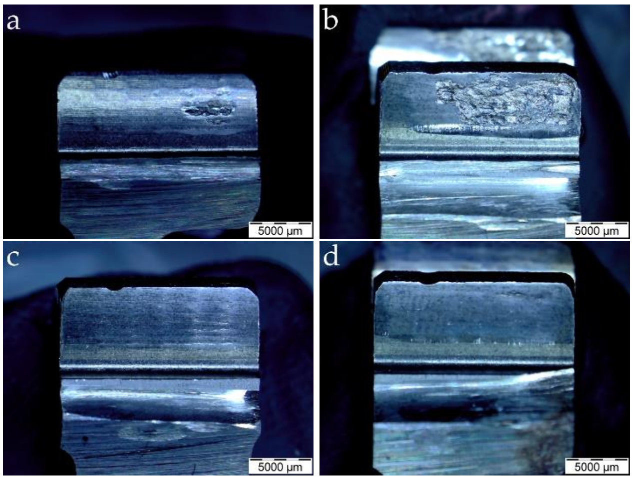

Figure 5. Optical macrograph of the Gear # 5 of the motorcycle A (a, c) and motorcycle B (b, d). Teeth with moderate to destructive wear (a, b) and teeth with light wear (c, d).

In short, the dimensional changes of some powertrain pieces (Table 4) and their macrograph (Figure 5 and Figure 6) revealed different macroscopic wear levels between the motorcycles. Those results may suggest that the metal wear particles were larger than those detected through ICP-AES. However, the particle analysis following the ASTM D7684 did not revealed ferrous particles larger than 5 µm. Even so, the results pointed out that the periodic lubrication of the transmission kit with MC ensured light wear and longer service time. In addition, under the gear tribological conditions (high contact pressures and cyclic loads), the mixture of 10W-30 + MC significantly increased wear resistance, as seen in gear #5 (Figure 5a, 5c).

ANALYSIS OF FUEL ECONOMY – Fuel economy (FE) was statistically evaluated through the analysis of variance (ANOVA). All the interactions between the factors ('Motorcycle', 'Driver' and 'Regime') obtained a p-value > 0.05, representing no differences in FE. In other words, neither the application of metal conditioner, the driver's changes, nor an oil drain interval did not produce differences in fuel economy that are statistically significant. However, tha bar graph presented in Figure 6 shows some interesting trends: (i) The powertrain break-in period (first 1000 km). had the lowest FE in both motorcycles; (ii) When the driver was randomly changed (<7500 km), both motorcycles showed a tendency to higher FE compared to the single driver (>7500 km). Figure 6 showed that although the driver changes and engine break-in period had a certain effect on fuel efficiency, the trend of higher FE for the motorcycle with metal conditioner (A) remained.

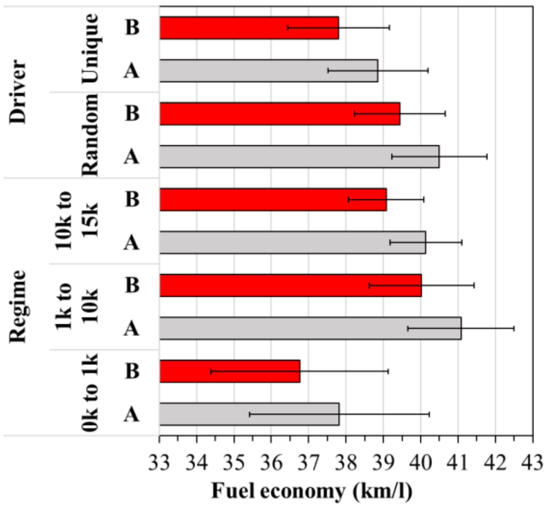

Figure 6. Fuel economy as function of the different factors: 'Motorcycle', 'Driver' and 'Regime'. Confidence intervals given by ANOVA.

Moreover, Figure 6 showed that motorcycle A maintained higher average FE values, approximately one km/l higher, compared to motorcycle B. It represents an average extra 16 km autonomy under the real city conditions, considering the 16.1-liter fuel tank. The addition of the metal conditioner to the engine oil, brought around a 2.5% gain of fuel economy improvements (FEI%).

According to [29], the requirement for better fuel efficiency has led to lower viscosity grades containing friction and viscosity modifiers additives. Nowadays, the lubricant's ability to meet new specifications and be compatible with older specifications is essential. Therefore, the idea that there is a product that reduces friction and wear while achieves fuel economy, and is also compatible with any powertrain and lubricant, as assured by the MC's manufacturers, is highly promising. In fact, the present field study verified there are effectively certain benefits in terms of wear and fuel consumption with the addition of a metal conditioner.

CONCLUSIONS

The field study suggested that the addition of a MC in the engine oil crankcase (mixture 25:1), along with the conditioning of powertrain pieces prior to engine assembly, brought advantages in terms of wear protection of aluminum and iron components (contents up to 38% and 25% inferior respectively) in the first 7000 km break-in period. This results are relevant because aluminum content was found above the warning limits (>30 ppm). Although it increased the copper wear content, it was always below the warning limits (<40 ppm).

FTIR oil degradation analysis (ASTM D7889) demonstrated that certain additives of the metal conditioner generates spectral interferences, hindering direct comparison between lubricants and their mixtures.

The lubrication of the transmission kit (crown, pinion, and roller chain) with the metal conditioner guaranteed light wear and a longer service life. Also, it significantly reduced the wear in gear #5.

Fuel consumption was statistically equal (ANOVA, 95% confidence) considering the effect of the drivers, oil change intervals and the application of metal conditioner. However, the motorcycle driven with metal conditioner maintained higher FE (+1 km/l), representing a relevant gain of ~ 2.5% fuel economy.

REFERENCES

[1] NORIA CORPORATION. Are Aftermarket Oil Additives Beneficial?. Disponível em: <https://www.machinerylubrication.com/Read/29610/aftermarket-oil-additives>. Acesso em: 11 mai. 2021.

[2] STEWART, C. L. Non-halogenated metal conditioner and extreme pressure lubricant. Estados Unidos: United States Patents, 2004. 12-17-p.

[3] ROBERTS, J. Synthetic anti-friction & extreme pressure metal conditioner composition and method of preparation. Estados Unidos: u, 2016. 1–14p.

[4] KUSCH, K. Halogenated extreme pressure lubricant and metal conditioner. Estados Unidos: United States Patents, 2000. 1–6p.

[5] MIRALUB. Benefícios. Disponível em: https://www.miralub.com.br/beneficios.php. Acesso em: 11 mar. 2022.

[6] MILITEC BRASIL IMPORTAÇÃO E COMÉRCIO LTDA. Perguntas Frequentes – FAQ – Militec Brasil – Condicionador de Metais. Disponível em: <https://militecbrasil.com.br/perguntas-frequentes/>. Acesso em: 11 mar. 2022.

[7] MOTORKOTE BRASIL. Motorkote Brasil. Disponível em: <https://motorkote.com.br/>. Acesso em: 11 mar. 2022.

[8] NANO CONDICIONADOR DE METAL. Perguntas Frequentes – FAQ . Disponível em: <https://www.nanocondicionador.com.br/faq/>, Acesso em: 11 mar. 2022.

[9] ALVES, D. J. ANÁLISE DA VIABILIDADE TÉCNICA E ECONÔMICA DA APLICAÇÃO DE CONDICIONADOR METÁLICO EM PROCESSO DE ALARGAMENTO. 2014. 1–70f. Universidade Nove de Julho, 2014.

[10] NUNES DA SILVA, E. Viabilidade econômica em processos de rosqueamento utilizando machos de roscar com condicionador metálico. 2014. 101f. Universidade Nove de Jhulo, 2014.

[11] SANTOS DE OLIVEIRA, F. Avaliação do desempenho de machos tratados com um condicionador metálico no processo de rosqueamento interno. 2015. 1–127f. Universidade Nove de Julho, 2015

[12] CALABOKIS, O.P.; NUÑEZ DE LA ROSA, Y.; BORGES, P.C.; COUSSEAU, T. Effect of an Aftermarket Additive in Powertrain Wear and Fuel Consumption of Small-Capacity Motorcycles: A Lab and Field Study. Lubricants 2022, 10, 143. https://doi.org/10.3390/lubricants10070143

[13] COPPINI, N. L. et al. Drilling analysis of cemented carbide drills after chemical treatment under low heating. Journal of the Brazilian Society of Mechanical Sciences and Engineering, v. 39, n. 9, p. 3581–3589, 2017.

[14] ASTM STANDARDS. ASTM D445-19a Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity). ASTM International, 2020.

[15] ASTM STANDARDS. ASTM D2270-10 Standard Practice for Calculating Viscosity Index from Kinematic Viscosity at 40 °C and 100 °C. ASTM International, 2016.

[16] ASTM STANDARDS. ASTM D7899: Standard Test Method for Measuring the Merit of Dispersancy of In-Service Engine Oils with Blotter Spot Method. ASTM International 2019. 1–7p.

[17] ASTM STANDARDS. ASTM D91-02 Standard Test Method for Precipitation Number of Lubricating Oils. ASTM International, 2019.

[18] ASTM STANDARDS. ASTM D4739-17 Standard Test Method for Efficient Basicity Determination by Potentiometric Hydrochloric Acid Tritation. ASTM International, 2017. 1–6p.

[19] ASTM STANDARDS. ASTM D974-14 Standard Test Method for Acid and Base Number by Color-Indicator Titration 1. ASTM International, 2010. 1–7p.

[20] ASTM STANDARDS. ASTM D7889-13 Standard Test Method for Field Determination of In-Service Fluid Properties Using IR. ASTM International, 2013. 1–8p.

[21] ASTM STANDARDS. ASTM D5185 Standard Test Method for Multielement Determination of Used and Unused Lubricating Oils and Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). ASTM International, 2018. 1–9p.

[22] ASTM STANDARDS. ASTM D7684-11 Standard Guide for Microscopic Characterization of Particles from In-Service. ASTM International, 2016.

[23] BOOSER, E.R., 1993. CRC Handbook of Lubrication and Tribology, Volume III: Monitoring, materials, synthetic lubricants, and applications (Vol. 3). CRC Press.

[24] MACIÁN, V., TORMOS, B., GARCÍA-BARBERÁ, A., TSOLAKIS, A., Applying chemometric procedures for correlation the FTIR spectroscopy with the new thermometric evaluation of Total Acid Number and Total Basic Number in engine oils, Chemometrics and Intelligent Laboratory Systems, Volume 208, 2021, 104215, https://doi.org/10.1016/j.chemolab.2020.104215.

[25] ASTM STANDARDS. ASTM E2412-10 Standard Practice for Condition Monitoring of In-Service Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry. ASTM International, 2018. 1–24p.

[26] MACIÁN, V., TORMOS, B., GÓMEZ, Y. A., SALAVERT, J. M., Proposal of an FTIR methodology to monitor oxidation level in used engine oils: effects of thermal degradation and fuel dilution, TRIBOLOGY TRANSACTIONS, 2012, 55:6, 872-882, DOI: 10.1080/10402004.2012.721921

[27] TESTOIL 2020, *Monitoring & Alarming Wear Metals*, accessed 20 April 2022, <https://testoil.com/knowledge-center/reference-guides/attachment/monitoring-and-alarming-wear-metals_page_1-copy/>

[28] TAYLOR, R. I., MAINWARING, R., MORTIER, R. M., Engine Lubricant Trends Since 1990, Proceedings of the Institution of Mechanical Engineers, Part J: Journal