Performance and Emission Evaluation of Heavy-Duty Engines Using FAME and HVO blends.

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ABSTRACT

Energy transition and reduction of Green House Gases emissions in the transportation segment has been an increased concern over the years, promoting a more sustainable segment.

In this paper a EURO VI/PROCONVE P8 heavy-duty engine and aftertreatment system was used with multiple blends of diesel fuel with biodiesel and HVO to evaluate engine and emission performance at Test Cell.

The engine provided regulation compliance with all blends tested, showing an improvement in both NOx and engine outlet soot when using pure HVO, as published in similar papers. Increasing the HVO percentage into the blend also increased the overall fuel consumption of the engine, due to its lower density, compared to the tested diesel fuel.

This work concludes that HVO can be used as a drop in fuel in diesel engines, in blends, or as a pure fuel source that can contribute to a life cycle GHG emission reduction. Additionally, an important potential to further develop engine settings and calibration was seen to maximize the results.

INTRODUCTION

Heavy-duty vehicles, such as trucks and buses, make an important contribution to the total emission from road transport, being responsible for more than 25% of the GHG worldwide emissions. Different initiatives and regulations coming into force aim to promote a more sustainable segment. Considering the current global demand to reduce the CO_2 emissions for all industrial sectors, the automotive industry has many opportunities to reduce the CO_2 footprints even in the production line or in their life-time products. One of these opportunities is to promote the use of renewable fuels in the combustion engines, such as Fatty Acid Methyl Ester (FAME), known as biodiesel and in more recent years, the usage of Hydrotreated Vegetable Oil (HVO).

HVO is a renewable source fuel alternative composed of straight carbon chains and iso-paraffins, containing no oxygen or aromatics and almost no sulfur, obtained through the hydrotreatment of vegetable oil. In this process, the triglyceride chain from the vegetable oil is successively hydrogenated and, in the final stage, the intermediates are converted into alkanes (n-alkanes and iso-alkanes). This catalysis provides a fuel with a similar chemical structure to the mineral fuel, but with a higher cetane number and LHV, although HVO density is lower compared to fossil fuel and lubricity is worse. Compared to FAME, HVO can be considered as a robust alternative as a renewable source, since it can improve some of the undesirable effects of the usage of FAME on the fuels, such as the reduction on the Heat Release Ratio (HRR), due to its lower cetane number, leading to a longer ignition delay. The cleaner chemical structure of HVO also contributes to the reduction of the potential deposit formation on the fuel injection system of the engine [10-22].

HVO can be used as drop-in fuel on diesel engines, as reported in many studies, leading to a reduction in PM up to 60%, without any re-adjustment or proper calibration of the engine. This is an advantage to improve other emission and performance parameters, based on the PM-NOx trade-off on emissions [10-22].

Considering the Brazilian market and context, HVO can be blended into mineral fuel, similarly to the conventional FAME, currently added at 14% in volume, according to the executive order from March 2023. This rate may increase to 15% before December of 2025. Another possibility is to incorporate HVO into diesel fuel via the co-processing method. This approach consists of processing the blend of vegetable oils and mineral diesel oil in a conventional hydrotreatment unit under appropriate temperature and pressure conditions. Petrobras has developed its co-processed fuel called "Diesel R" and the patent technology HBIO [1-9].

Since 2023, the PROCONVE regulation P8 was introduced in the Brazilian Market, establishing new emission limits for heavy-duty vehicles in specific Test Cell Cycles, similar to the EURO VI (UN ECE Regulation R49.06) regulation. Additionally, there is also a need to perform Real Drive Emissions (RDE) tests, reporting emissions performance within limits.

In this work, a fuel matrix with a 10-ppm sulfur limit (S10) was prepared by blending different contents of FAME and HVO (obtained either by co-processing or blended with pure HVO) with mineral diesel fuel. A Volvo heavy-duty engine was used to measure engine and emission performance.

EXPERIMENTAL METHOD

ENGINE AND TEST CELL SPECIFICATION – For all tests a Volvo Euro VI engine, an exhaust aftertreatment system (EATS) containing a Diesel Oxidation Catalyst (DOC), Diesel Particle Filter (DPF), Selective Catalyst Reduction (SCR) and an Ammonia Selective Catalyst (ASC) were used. The test campaign was carried out using the Powertrain Engineering Laboratory at Volvo, equipped with state-of-the-art measurement equipment, to measure performance and emissions of the engine. The figure 1shows the engine installed at the test cell:

Figure 1 - Volvo EURO VI engine rigged at the test cell.

FUEL SPECIFICATIONS - In total, five experimental fuels were used during the work, four Brazilian S10 diesel, with different contents of biodiesel, plus one pure HVO (Hydrotreated Vegetable Oil), all complying with ANP regulations RANP 968/2024 and RANP 842/2021. One of the S10 formulations (B14R5) was prepared with a coprocessed diesel with 5% renewable content from the refinery from a different batch compared to the other base S10 diesel used for the other formulations (B14R0, B14R10, B0R15). The fuel names and renewable contents are described in Table 1:

Table 1 - Renewable content on each fuel.

Fuel	Biodiesel (%v/v)	HVO (%v/v)	Coprocessed (%v/v)
B14R0 (reference)	14	0	0
B14R5	14	0	5
B14R10	14	10	0
B0R15	0	15	0
R100	0	100	0

For each fuel, a volume of 3000 L was provided by Petrobras, using the B14R0 formulation as reference, which corresponds to the Brazilian commercial diesel, in accordance with the CNPE resolution and the executive order from March 2023. All blends were tested and characterized at the Petrobras R&D and Innovation Center (Cenpes). Table 2 summarizes the main fuel properties with the limits set according to the RANP 968/2024 regulation. For HVO, the fuel is in accordance with the limits of the RANP 842/2021. B14R5 and B14R10 showed similar characteristics to B14R0, indicating that HVO blend maintained the fuel quality besides increasing renewable content and reducing CO_2 emissions in the life cycle assessment Analysis (LCA). Formulations with HVO and co-processed diesel fuel (B14R5, B14R10 and HVO) showed higher cetane number compared to the reference fuel B14R0.

Table 2 - Experimental fuels main properties

Property	Test method	Limits*	B14R0	B14R5	B14R10	B0R15	B0R100
FAME content, %v/v	NBR15568	14 max	14,1	14,0	13,9	N/A	N/A
Density at 20°C, kg/m3	ASTM D4052	819.9 - 857**	846,0	829,1	838,8	831,3	777,7
Kin. viscosity at 40ºC, mm^2/s	ASTM D 445	2.0 - 4.5	3,389	2,498	3,338	3,310	3,127
Flash point, ºC	ASTM D93	38 min	69,5	65,0	64,3	73,9	89,5
IBP, °C	ASTM D86	N/A	164,7	155,0	176,4	178,1	211,4
10 % vol recovered, °C	ASTM D86	N/A	227,4	199,5	230,7	228,3	268,5
50 % vol recovered, °C	ASTM D86	N/A	290,3	268,4	288,5	279,4	283,3
85 % vol recovered, °C	ASTM D86	N/A	335,6	320,1	331,5	324,6	292,1
90 % vol recovered, °C	ASTM D86	N/A	344,0	327,2	340,4	339,8	294,3
95 % vol recovered, °C	ASTM D86	370 max	360,8	331,5	348,8	353,6	299,0
FBP, °C	ASTM D86	N/A	368,2	343,2	366,1	374,8	307,0
C, %m/m	ASTM D5291	N/A	85,9	77,8	86,3	87,7	83,5
Sulfur, mg/kg	ASTM D5453	10	7,1	1,5	7,9	7,9	7,9
Oxidation stability at 110°C, h	EN 15751	N/A	19,0	20,3	24,8	19,4	> 48
LHV/ MJ/kg	ASTM D240	N/A	41,9	42,7	42,1	42,8	44,0
LHV/ MJ/L	ASTM D240	N/A	35,5	35,4	35,3	35,6	34,2
Cetane number	ASTM D613	48 min	53,9	56,2	55,0	56,2	62,1

N/A: not applicable
IBP: initial boiling point
FBP: final boiling point
*Considering RANP 968/2024
*Considering RANP 842/2021

PERFORMANCE AND EMISSIONS TESTS - As the main goal of the analysis was to evaluate the impact of the different fuel blends on the performance and emissions, an extensive test campaign with each fuel was performed. The focus of this paper was on the performance at full load (UN ECE Regulation 85) and at the standard emission cycles for heavy-duty EURO VI (UN ECE Regulation R49.06) / Proconve P8.

For each fuel, the following sequence was performed:

1) Three Full Load Performance Cycles (FL) were conducted, during which the engine operated at maximum load across different speeds. This process enabled the mapping of maximum load performance characteristics for each fuel.
2) Engine performance sweep test for the denormalization of the emission test cycles setpoints. A Torque Curve Map was performed, to establish the speed and torque setpoints for the emissions cycles.
3) Three WHSC tests, with pre-conditioning at Step 9 of the cycle for 600 s followed by 10 min soak, with the engine turned off, according to the R49.06 regulation.
4) Three WHTC tests starting with a warm engine to analyze the engine performance in the transient conditions.
5) Engine soaked to condition and cooled down prior to the cold start WHTC, until the system temperatures reached the range of 20-30°C.
6) A WHTC campaign according to the regulation, starting with a cycle in cold start, followed by a 10 min soak and the cycle at warm start.

After each campaign, a fuel sample was taken from the fuel measurement equipment into an appropriate bottle and thus a fuel change procedure was performed. This procedure was carried out by first emptying the test cell fuel lines and fuel meter tank, then the system was purged by supplying the engine with the next fuel. The previous fuel purge was performed by maintaining the engine at rated power speed, until the fuel consumption of the engine reached a higher value than the volume of the fuel supply system. In parallel, the fuel density corrected to the temperature was measured by the flow meter system and compared to the previous fuel analysis, to ensure a complete fuel switch.

DATA ANALYSIS AND MEASUREMENTS - Based on the data collected, cycle-specific values were calculated, according to the EURO VI regulation focusing on the performance and the emissions of the engine. The gaseous emissions were taken upstream EATS (Engine Out) and downstream EATS (Tailpipe). The particle matter emissions and particle counter were evaluated as well but only at Tailpipe (downstream of the aftertreatment system). Since only three samples of data for each fuel/cycle were obtained, a boxplot of each data was plotted for each fuel blend and compared to the regulation limits at tailpipe, for NOx, PM (Particle Matter) and PN (Particle Number). For engine outlet parameters, a normalized percentage graph was also plotted, calculating the difference between the average results of each fuel/cycle and the reference fuel.

An additional statistical analysis was performed to determine the significance of difference among all the results, using the combination of ANOVA and Tukey post hoc test at a 95% confidence level.

RESULTS AND DISCUSSIONS

STATISTICAL ANALYSIS RESULTS – Based on the ANOVA and Tukey post hoc test, there were statistical differences among the fuels in most of the parameters analyzed in the tests, as seen in table 3 :

Table 3 - ANOVA and Tukey post hoc test results

	Engine Power [kW]	Cycle Energy [kWh]	BSFC [g/kWh]	Tailpipe NOx [mg/kWh]	Engine Out Soot [mg/kWh]	Engine Out HC [g/kWh]
WHSC	N/A	Yes	Yes	No	Yes	Yes
WHTC Warm	N/A	Yes	Yes	No	Yes	Yes
WHTC CW	N/A	Yes	No	No	No	Yes
FL	Yes	N/A	N/A	N/A	N/A	N/A

The pairwise comparison between B14R5, B14R10, B0R15, R100 and the reference fuel (B14R0), considering each parameter in each test, showed that the differences were observed in 75% of the parameters for B14R5, 8% for B14R10, 67% for B0R15, and 83% for B0R100. The differences will be clarified in the following sections**.**

FULL LOAD PERFORMANCE TESTS - As described in the previous chapter, during the full load performance curve, the engine is operated at maximum load at different engine speeds. The results presented in this chapter will be focused on the engine rated power speed. The main parameters analyzed in this test were engine torque, fuel consumption and engine outlet NOx formation. Unfortunately, soot measurements were not available at all tests for the full load performance, so they will not be present in this section. [1-9]

In terms of engine torque, it was possible to see a very close performance for the B14R10, B0R15 and R100 with a relative difference ranging from -0.85 up to 0.75%, fitting well within the engine performance requirements described in the Reg85 (UN ECE Regulation 85), which states a limit of ± 5% between the declared values for that engine. The only outlier observed was for the B14R5 formulation, in which a torque reduction of 2.29% was observed compared to the reference. This was mainly attributed to the different fuel batch delivered, that showed significantly lower density compared to similar blends, such as the B14R0 and B14R10, as Figure 2 summarizes:

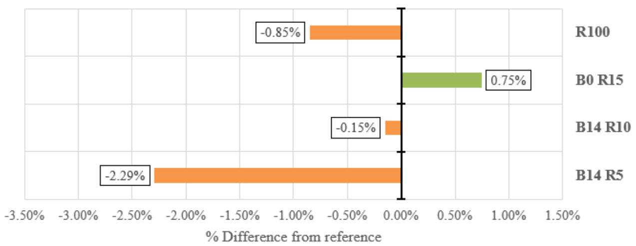

Figure 2 - Engine Torque Difference at Full Load Curve

The BSFC (Brake Specific Fuel Consumption) measured in g/kWh showed an improvement for all fuel formulations tested, with the highest improvement observed for the formulations using only HVO as a source of renewable content, as observed by Aatola et. al (2003). This can be mainly explained by the higher cetane number (CN) observed for the R100 compared to the B14R0 reference, which leads to reduced ignition delay of the fuel, promoting a longer combustion duration. Although the Heat Release Ratio (HRR) was not calculated in this work, it was proved by Dimitriadis et. al (2020) that fuels with lower HVO concentrations have a longer ignition delay due to a lower CN and an overmixing of the fuel from the pilot with the main injection, causing peaks of HRR, especially at lower torque and speeds. Another contribution was that HVO presented the highest LHV per kg among the fuels [10-22]. To account for the fuel densities, a plot with BSFC in L/kWh was also presented, which will be considered for fuel consumption in real-life applications. Since HVO has a significantly lower density compared to mineral fuel, the measured fuel consumption in L/kWh is higher than the blends with mineral fuel. The figures show the results of BSFC in g/kWh and L/kWh.

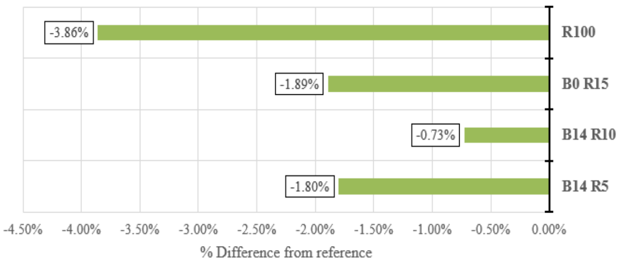

Figure 3 - Fuel Consumption in g/kWh at Full Load Curve.

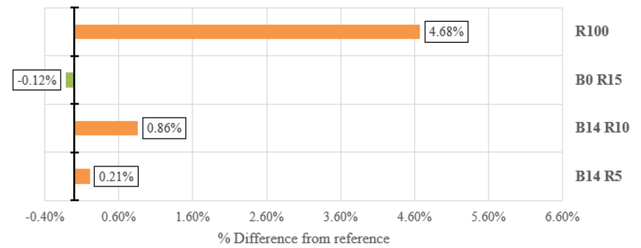

Figure 4 - Fuel Consumption in L/kWh at Full Load Curve.

A clear improvement was observed for NOx engine out emissions with a reduction of the FAME content and an increase of the HVO percentage on the blend. There was almost a 5% NOx reduction when R100 was used. Formulations with FAME exhibited little to no improvement in NOx emissions; some reasons that can be used to explain this behavior involve the density, oxygen content, and presence of double bonds on the chemical chain of FAME [10-22].

Notably, the B14R5 fuel demonstrated significantly higher NOx engine out emission compared to other fuel blends. This increase was primarily due to the engine ECU's internal strategy, which altered the combustion mode to meet the required torque demand. However, as shown in Figure 2, the desired torque was not achieved, leading to higher NOx emissions [10-22]. Figure 5 illustrates the NOx emissions for the tested fuel formulations.

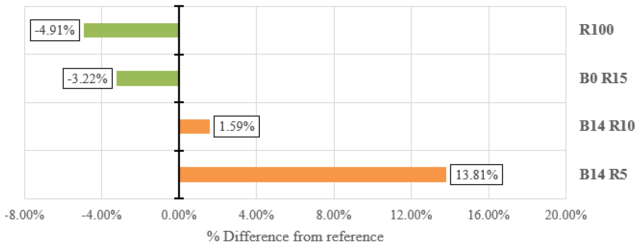

Figure 5 - Engine Out NOx emissions at Full Load Curve.

WHSC RESULTS - The focus of the analysis of these cycles was the evaluation of emission compliance with all fuel blends and the impact of increasing the HVO percentage on the emissions performance, correlating the engine emissions results with each fuel blend properties. The focus was specifically for NOx, PM and PN, which exhibited very good performance results and fitted with margin the regulation limits. Other regulated gaseous emissions such as THC and CO were also found within the regulation limits, but with very low values, very close to zero in all conditions tested.

To further investigate the effects of the fuel properties, a few analyses were made based on the engine outlet data. As seen in the previous chapter, a BSFC (in g/kWh) reduction was seen for the HVO blends, being more significant for the B0R15 and the R100 fuels. When accounting for each fuel density and calculating the fuel consumption in L/kWh, the same behavior from the full load curve was observed. Figures 6 and 7 summarize the BSFC results in g/kWh and L/kWh.

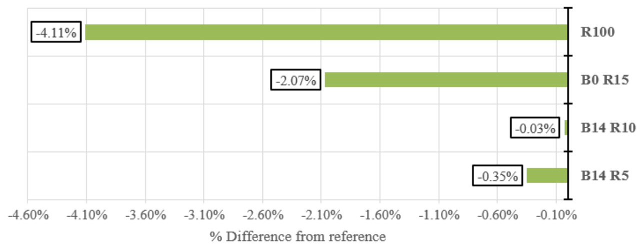

Figure 6 - BSFC on the WHSC in g/kWh difference compared with the reference.

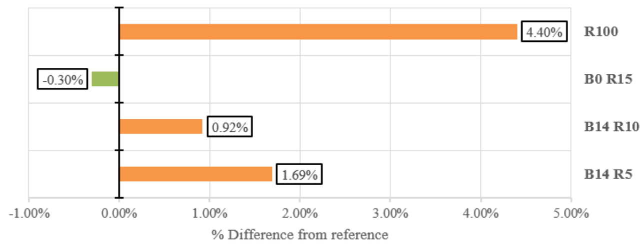

Figure 7 - BSFC on the WHSC in L/kWh difference compared with the reference.

A relevant result was found for the B0R15, when looking at the BSFC in L/kWh, with a slight improvement in fuel consumption was seen. Reductions on CO_2 and NOx on engine outlet were also observed for the blends containing HVO. For NOx, specifically, the blends containing FAME and HVO showed a small increase in emissions, compared to the reference. This increase can be attributed to the FAME content, that can lead to an increase in NOx emissions, due to some mechanisms and FAME characteristics, such as its lower cetane number, higher oxygen content, as also observed by McCaffery et al (2022), and the presence of double bonds on the organic chain. The fuels with HVO as the only renewable have a more paraffinic character and lower aromatic content which contributes for lower temperatures, thus lower generation of NOx. Then, the fuels could be separated into two groups: the ones containing FAME, including the reference B14R0, that showed higher NOx emissions, and the fuels without FAME, and lower NOx emissions [10-22]. The specific CO_2 and NOx results in g/kWh compared to the reference are shown in the figures 8 and 9 :

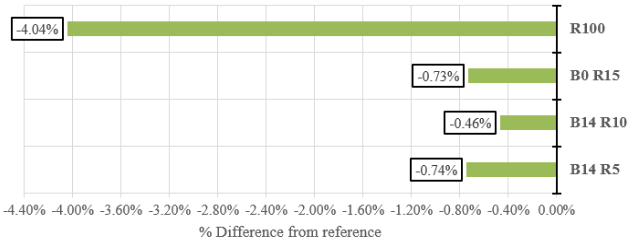

Figure 8 - Engine outlet specific CO_2 Emissions on the WHSC compared with the reference.

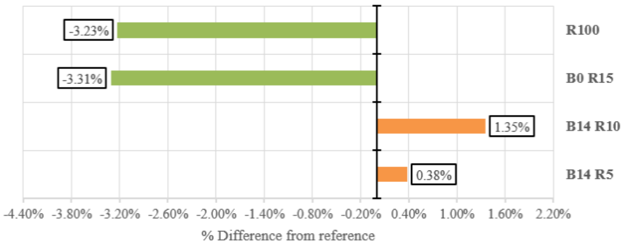

Figure 9 - Engine outlet specific NOx Emissions on the WHSC compared with the reference.

As seen from the WHSC results, using HVO instead of FAME in mineral fuel blends at similar proportions resulted in improvements in CO_2, NOx, and even BSFC. This can be seen as an important alternative to increase the incorporation of renewables in fossil diesel blends. In addition to the improvement in emissions and overall performance, an improvement in the useful life of fuel filters on vehicles might be expected, since there is no glycerin on the HVO [10-22].

WHTC RESULTS – Consistent with the WHSC results, this section will focus on analyzing the emissions performance for all fuels compared to the regulation in both warm start conditions, considering the three-test campaign and the cold start cycles. Analog to the static cycle, the transient cycle also showed results within regulation limits for all fuels tested, with a good margin, on both warm start only and combined cold and warm cycle. Figures 10, 11, and 12 illustrate the combined cold and warm results for tailpipe NOx, PM, and PN for each fuel concerning the regulation limits.

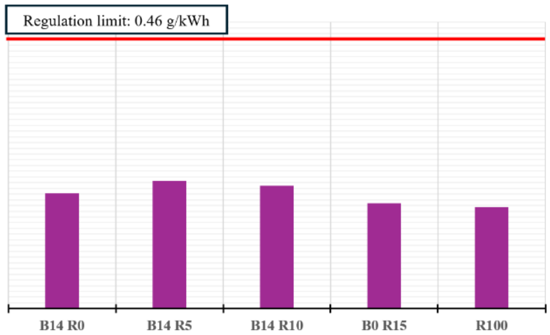

Figure 10 - System outlet specific NOx Emissions on the WHTC CW compared to the regulation limit.

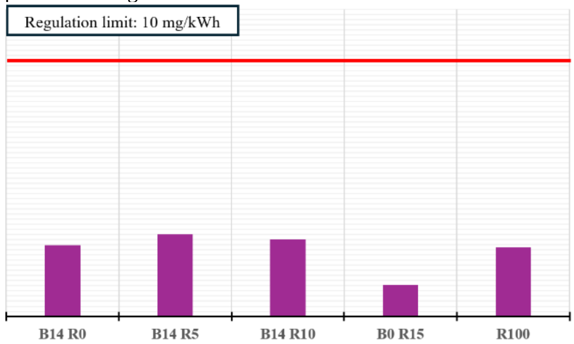

Figure 11 - System outlet specific PM Emissions on the WHTC CW compared to the regulation limit.

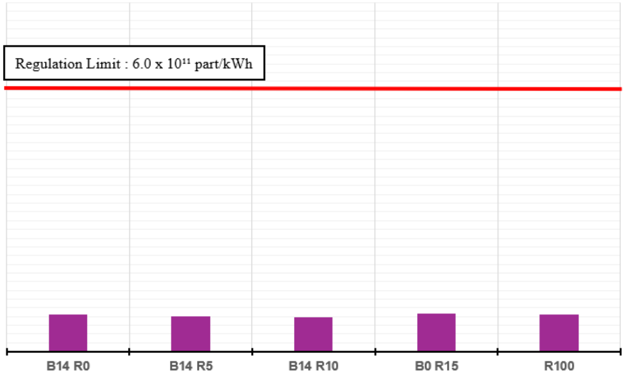

Figure 12 - System outlet specific PN Emissions on the WHTC CW compared to the regulation limit.

An analog investigation from the WHSC was conducted on the engine outlet emissions, focusing specifically on the hot start WHTC since a higher amount of data was collected during the campaign. As per the findings of the WHSC, a decrease in NOx emissions was observed for the blends containing only HVO. CO_2 emissions were reduced for all blends, and the same fuel consumption behavior (in L/kWh) was observed for the B0R15 fuel, according to figures 11, 12, and 13 :

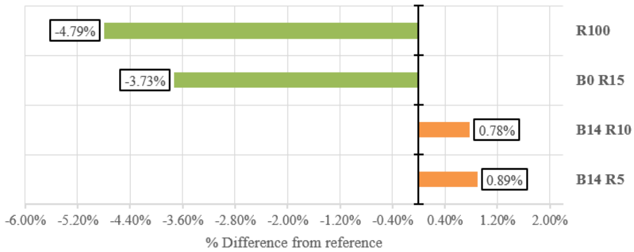

Figure 13 - Engine outlet specific NOx Emissions on the WHTC compared with the reference.

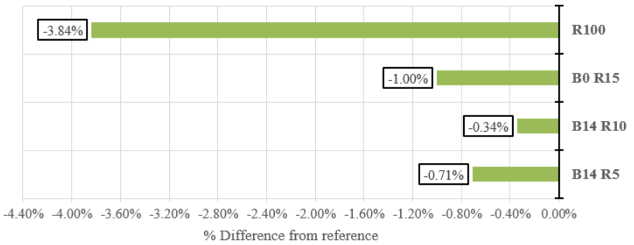

Figure 14 - Engine outlet specific CO_2 emissions on the WHTC compared with the reference.

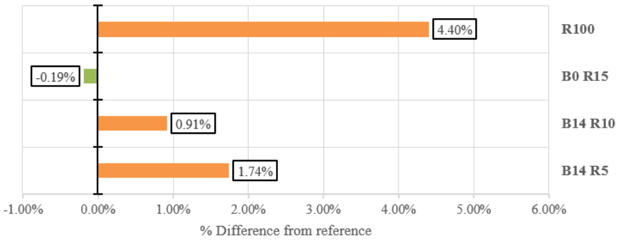

Figure 15 - BSFC on the WHTC in L/kWh difference compared with the reference.

The behavioral similarity between both transient and static cycles confirms how the fuel blends can influence the emissions and the overall performance of the engine, reiterating the benefit of using HVO as a renewable source blended into mineral fuel, avoiding some of the adverse effects of the biodiesel that are widely known in the industry and confirmed by all results presented [10-22].

FINAL CONSIDERATIONS

With all the results being considered, the main conclusions that can be drawn from the results are as follows:

- Due to HVO characteristics, the emissions performance on both NOx and engine out soot was improved in all cycles tests when using the R100 fuel.
- The fuel quality evaluation during the road tests shows that the fuels maintained their properties, meaning no fuel degradation.
- Formulations containing HVO showed a good balance between emissions and BSFC, considering the same renewable source percentage into the mineral fuel as the blends with FAME, confirming the HVO as drop-in renewable [10-22].
- A fuel consumption penalty was observed when using the R100 compared to the reference fuel throughout all conditions tested mainly due to the lower density of HVO. There is ground for further development in engine control strategies to reduce this gap between HVO and mineral fuel, taking advantage of its lower emissions [10-22].
- The higher BSFC for the R100 observed in the cycles can be further diminished on Euro VI systems on real applications. The reduction in PM formation inside the DPF prevents frequent active regeneration, that increases the fuel consumption during the normal operation of heavy-duty vehicles. This hypothesis was only based on the PM emissions and was not possible to be confirmed on the scope of this work [10-22].
- The B0R15 blend showed a good compromise between fuel consumption and emission performance on the system tested, showing the benefit of the HVO as a renewable source compared to the conventional biodiesel, exhibiting a commercially viability for the Brazilian Market Another potential benefit is the lifetime increase of engine components, such as fuel filters that can be jeopardized due to the presence of other chemical components such as glycerin that are common in methyl-ester fuels [10-22].

As observed from the results presented in this paper, the HVO offers an alternative for renewable energy sources which can be used as a drop-in fuel, having a similar and in some conditions an even better performance result when compared to a blend containing FAME in the same proportion. This blend alternative can be viable in both technical and commercial approaches on the Brazilian context, contributing and motivating a renewable fuel transition.

REFERENCES

[1] **DIÁRIO OFICIAL DA UNIÃO**. *Publicado em: 29/03/2023 Edição: 61 Seção: 1 Página: 2. Órgão: Presidência da República. Ministério de Minas e Energia. Resolução nº 3, de 20 de março de 2023, do Conselho Nacional de Política Energética - CNPE.*

[2] **DIÁRIO OFICIAL DA UNIÃO**. *Publicado em: 29/03/2023 Edição: 61 Seção: 1 Página: 2. Órgão: Presidência da República. Ministério de Minas e Energia. Resolução nº 8, de 19 de dezembro de 2023, do Conselho Nacional de Política Energética - CNPE.* ResoluoCNPE8Publicada.pdf

[3] **Brazil, Conselho Nacional do Meio Ambiente (Brazilian National Council for the Environment) – CONAMA.** *Resolution # 490 de 16 novembro de.2018.*

[4]. **United Nations Economic Commission for Europe (UNECE)**, *Regulation No. 49, Revision 6 – Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines and positive ignition engines for use in vehicles*, UNECE, Geneva, Switzerland, 2013. [Online]. Available: https://unece.org

[5] **Agência Nacional do Petróleo Gás Natural e Biocombustíveis**. *RESOLUÇÃO ANP No 50, DE 23.DE DEZEMBRO.2013*. Imprensa Nac 2013;1:1-12.

[6] **Agência Nacional do Petróleo Gás Natural e Biocombustíveis**. *RESOLUÇÃO ANP No 842, DE 14 DE MAIO DE 2021*. Imprensa Nac 2021;1:65.

[7] **Agência Nacional do Petróleo Gás Natural e Biocombustíveis**. *RESOLUÇÃO ANP No 758, DE 23 DE NOVEMBRO DE 2018*. Imprensa Nac 2018;1:54.

[9] **European Committee for Standardization (CEN),** *EN 590:2013+A1:2017 – Automotive fuels – Diesel – Requirements and test methods*, CEN, Brussels, Belgium, 2017.

[10] **United Nations Economic Commission for Europe (UNECE),** *Regulation No. 85 – Uniform provisions concerning the approval of internal combustion engines or electric drive trains intended for the propulsion of motor vehicles with regard to the measurement of the net power and the maximum 30 minutes power of electric drive trains*, UNECE, Geneva, Switzerland, 2012

[11] **Bohl, T., Smallbone, A., Tian, G., & Roskilly, A. P. (2018).** Particulate number and NO_x trade-off comparisons between HVO and mineral diesel in HD applications. *Fuel*, *215*, 90–101. https://doi.org/10.1016/j.fuel.2017.11.023

[12] **Murtonen, T., Aakko-Saksa, P., Kuronen, M., Mikkonen, S., & Lehtoranta, K. (2009).** Emissions with heavy-duty diesel engines and vehicles using FAME, HVO and GTL fuels with and without DOC+POC aftertreatment. *SAE International Journal of Fuels and Lubricants*, *2*(2), 147–166. https://doi.org/10.4271/2009-01-2693

[13] **Aatola, H., Larmi, M., Sarjovaara, T., & Mikkonen, S. (2009).** Hydrotreated vegetable oil (HVO) as a renewable diesel fuel: Trade-off between NO_x, particulate emission, and fuel consumption of a heavy-duty engine. SAE International Journal of Engines, 1(1), 1251–1262. https://doi.org/10.4271/2008-01-2500

[14] **Pechout, M., Kotek, M., Jindra, P., Macoun, D., Hart, J., & Vojtisek-Lom, M. (2019).** Comparison of hydrogenated vegetable oil and biodiesel effects on combustion, unregulated and regulated gaseous pollutants and DPF regeneration procedure in a Euro6 car. *Science of The Total Environment*, *696*, 133748. https://doi.org/10.1016/j.scitotenv.2019.133748

[15] **Rimkus, A., Žaglinskis, J., Rapalis, P., & Skačkauskas, P. (2015)**. Research on the combustion, energy and emission parameters of diesel fuel and a biomass-to-liquid (BTL) fuel blend in a compression-ignition engine. *Energy Conversion and Management*, *106*, 1109–1117. https://doi.org/10.1016/j.enconman.2015.10.047

[16**] Lehto, K., Elonheimo, A., Hakkinen, K., Sarjovaara, T., & Larmi, M. (2012).** Emission reduction using hydrotreated vegetable oil (HVO) with Miller timing and EGR in diesel combustion. *SAE International Journal of Fuels and Lubricants*, *5*(1), 218–224. https://doi.org/10.4271/2011-01-1955

[17] **Graboski, M. S., & McCormick, R. L. (1998).** Combustion of fat and vegetable oil derived fuels in diesel engines. *Progress in Energy and Combustion Science*, *24*(2), 125–164. https://doi.org/10.1016/S0360-1285(97)00034-8

[18] **Huang, Y., Wang, S., & Zhou, L. (2008).** Effects of Fischer-Tropsch diesel fuel on combustion and emissions of direct injection diesel engine. *Frontiers of Energy and Power Engineering in China*, *2*(3), 261–267. https://doi.org/10.1007/s11708-008-0062-x

[19] **Arul Mozhi Selvan, V., & Venkatesan, S. P. (2020).** Improving PM-NOx trade-off with paraffinic fuels: A study towards diesel engine optimization with HVO. *Fuel*, *265*, 116921. https://doi.org/10.1016/j.fuel.2019.116921

[20] **Lapuerta, M., Villajos, M., & Agudelo, J. R. (2011).** Key properties and blending strategies of hydrotreated vegetable oil as biofuel for diesel engines. *Fuel Processing Technology*, *92*(12), 2406–2411. https://doi.org/10.1016/j.fuproc.2011.09.003

[21] **Kuronen, M., Mikkonen, S., Aakko, P., & Murtonen, T. (2007).** Hydrotreated vegetable oil as fuel for heavy duty diesel engines. *SAE Technical Paper Series*, 2007-01-4031. https://doi.org/10.4271/2007-01-4031

[22**] Kim, D., Kim, S., Oh, S., & No, S.-Y. (2014).** Engine performance and emission characteristics of hydrotreated vegetable oil in light duty diesel engines. *Fuel*, *125*, 36–43. https://doi.org/10.1016/j.fuel.2014.01.089

[23] **Happonen, M. (2012).** *Particle and NO_x emissions from an HVO-fueled diesel engine*. Tampere University of Technology. ISBN 978-952-15-2935-1. Disponível em: http://urn.fi/URN:ISBN:978-952-15-2935-1