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Characterization of Hydrotreated Vegetable Oil (HVO) in a Euro 6 Diesel Engine as a Drop-In Fuel and With a Dedicated Calibration

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Abstract. Renewable fuels can play an important role in achieving future goals of energy sustainability and CO_2 reduction. In particular, hydrotreated vegetable oil (HVO) represents one of the most promising alternatives to petroleum-derived diesel fuels. Several studies have shown that conventional diesel engines can run on 100% HVO without significant modifications to the hardware and control strategies. The current activity has experimentally evaluated the potential of HVO as a "drop-in" fuel, i.e., without changes to the original baseline calibration, comparing it to conventional diesel fuel on a 2.3-litre Euro 6 compression ignition engine.
Tests revealed that HVO can significantly reduce engine-out soot (by more than 60%), HC and CO emissions (by about 40%), compared to diesel, while NO_x levels and fuel conversion efficiency remain relatively unchanged under steady-state warmed-up conditions. The advantages of HVO proved to be further enhanced when the engine has not yet warmed up.
Using statistical techniques of design of experiments (DoE) at three warmed-up steady-state operating points, the main engine control parameters were recalibrated to demonstrate that engine-out emissions can be further optimized with a dedicated calibration.

1. Introduction

In the road transportation sector, the internal combustion engine fuelled by fossil fuels remains the most prevalent power source [1]. Urban air pollution and greenhouse gas (GHG) emissions are therefore an urgent issue requiring immediate technological and political solutions [2]. Compression ignition engines powered by petroleum-derived diesel fuel are widespread both for passenger cars, especially in Europe, and for commercial vehicles, all over the world [3]. Due to a higher thermal efficiency, diesel vehicles can reduce CO_2 emissions by about 10-40% compared to their gasoline counterparts [4]. However, diesel vehicles struggle to meet pollutant emission targets, most notably for nitrogen oxides (NO_x) and particulate matter (PM), despite increasingly advanced in-cylinder control strategies [5] and ever-more complex aftertreatment devices [6].

Biomass-derived fuels can be a promising solution for addressing pollutant emissions problems and reducing GHG [7]. The most widespread alternative to diesel oil, obtained from crops such as soy or rapeseed through a process called transesterification, are fatty acid methyl esters (FAME), simply known as biodiesel. FAME certainly provides benefits for the reduction of CO, unburned hydrocarbons (HC) and PM emissions [8]. Unfortunately, it exhibits a lower stability to oxidation, lower suitability to cold temperatures, and a corrosive and ageing effect on polymeric fuel system components [9]. For this reason, in Europe, the maximum allowed concentration of biodiesel in blends with conventional diesel is 7% by volume [10].

HVO (hydrotreated vegetable oil), obtained through the hydrotreating process, is an interesting alternative to FAME. The hydrotreating process uses hydrogen to remove oxygen from the biomass source (triglyceride vegetable oil) to produce straight-chain paraffinic hydrocarbons that are similar to existing diesel fuel components, but free of aromatics, oxygen, and sulphur. As a result, HVO is predominantly made up of paraffins containing between 15 and 18 carbon atoms, whereas conventional diesel is characterized by a number of carbon atoms ranging between 9 and 30 [11]. Hydrotreating has a number of benefits over transesterification, including lower production costs and a much greater compatibility with standard diesel engines [12]: in fact, HVO can be blended with diesel in any proportion, up to 100% (pure HVO), with only minor or even no required modifications to the existing CI engines [13]. Previous research works [14,15] have highlighted the potential advantages of HVO with respect to FAME.

This article compares the effects of HVO and conventional diesel oil on engine performance and emissions by first testing HVO as a “drop-in” fuel (i.e., without any adjustment to the baseline calibration parameters stored in the engine ECU), under warmed-up and cold engine conditions, in a 2.3-liter diesel engine for light-duty commercial vehicles applications. Then, ECU parameters were optimized for HVO operation by means of statistical techniques of design of experiments (DoE), under warmed-up steady-state conditions.

2. Experimental Setup and Fuels

On the dynamic test bench of the ICE Advanced Laboratory at Politecnico di Torino, experimental tests were conducted on a 2.3-liter prototype diesel engine for light-duty commercial vehicles. Table 1 lists the main technical specifications of the engine under consideration.

Table 1. Main engine technical specifications.

Total displacement	2.3 l
Compression ratio	~16:1
Number of cylinders	4
Valves per cylinder	4
Fuel injection system	Solenoidal common-rail
Turbocharger	Single-stage VGT
EGR circuit type	Dual-loop, water-cooled

The engine is equipped with a common-rail injection system with solenoid injectors, a variable geometry turbine (VGT), an intake throttle valve, an exhaust flap, and a dual-loop EGR system, which is made up of a high-pressure (HP) and a low-pressure (LP) circuit.

Multiple pressure and temperature sensors were installed in the air, EGR, and exhaust lines to provide a comprehensive overview of the engine working conditions. In addition, high-frequency piezoelectric transducers (Kistler 6058A) were installed on each cylinder of the engine in order to measure the in-cylinder pressure development (every 0.1 °CA). The intake manifold was fitted with a piezoresistive transducer (Kistler 4007C) to provide the absolute reference for the in-cylinder signals. Specific measurement devices for fuel consumption and intake air flowrate acquisitions were also available. Gaseous engine-out emissions of NO_x, HC, CO, CO_2, and O_2 were measured upstream of the aftertreatment system (using an AVL AMAi60) and the CO_2 concentration in the intake manifold was also measured to determine the EGR rate. Table 2 reports the concentrations and the uncertainties of the gases used to calibrate the pollutant analysers. The expanded uncertainties of brake specific emissions were thoroughly calculated in [16] and fall within a 2–4% range. These values were evaluated considering the accuracy of the fuel flow rate system (0.1% of the measured value) and the maximum errors on engine speed (1.50 rpm at full scale) and torque (0.30 Nm at full scale). For particulate emissions, engine-out soot emissions were measured using an AVL 415S smokemeter. The test bench was controlled by AVL PUMA Open 2 software. The indicating analysis and data postprocessing were performed by AVL IndiCom and AVL CONCERTO, respectively.

Table 2. Composition of the gas calibration cylinders and extended uncertainty (95% confidence interval).

Composition of the Gas Calibration Cylinder and Extended Uncertainty	
NO (lower range) [ppm]	89.7 ± 1.7
NO (higher range) [ppm]	919 ± 18
CO (lower range) [ppm]	4030 ± 79
CO (higher range) [%]	8.370 ± 0.097
CO_2 (lower range) [ppm]	4.980 ± 0.067
CO_2 (higher range) [%]	16.78 ± 0.15
C_3H_8 (lower range) [ppm]	88.8 ± 1.8
C_3H_8 (higher range) [ppm]	1820 ± 36

For the experimental tests, conventional diesel B7 (with up to 7% FAME biodiesel, complying with EN 590 regulation) and HVO were utilized. Table 3 lists the main characteristics of both fuels.

Table 3. Diesel vs. HVO main properties.

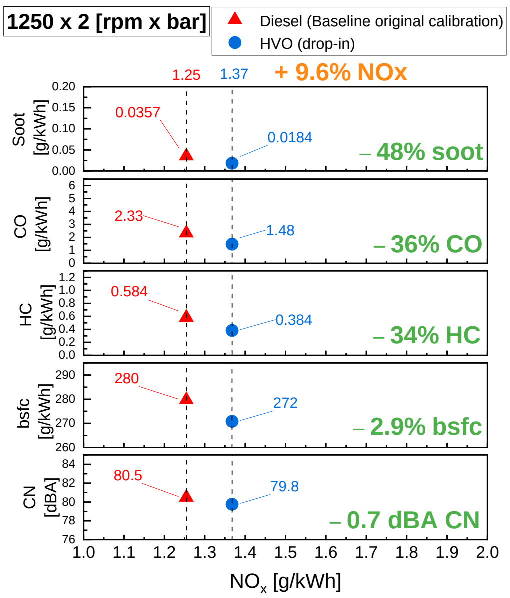
Parameter	Unit	EN590 Diesel	HVO
Density at 15 °C	kg/m^3	830.6	777.8
Kinematic viscosity	mm^2/s	2.969	2.646
Dynamic viscosity	Pa·s	$2.47 \cdot 10^{-3}$	$2.06 \cdot 10^{-3}$
Cetane number	-	54.6	79.6
Monoaromatic	%v/v	20.1	0.50
Polyaromatic	%v/v	3.00	0
Total aromatic	%v/v	23.1	0
Flammability	°C	74.0	60.5
Lower Heating Value	MJ/kg	42.65	44.35
Hydrogen	%m/m	13.72	15.00
Carbon	%m/m	85.67	85.00
Oxygen	%m/m	0.61	0
Sulphur	mg/kg	6.50	0.53
FAME	%v/v	5.00	0.05
Approx. formula	-	$C_{13}H_{24}O_{0.06}$	$C_{13}H_{28}$

The experimental tests were performed at five steady-state engine operating points (expressed as engine speed *n* [rpm] × *bmep* [bar]). Four of these points are representative of the application of the engine to a light-duty commercial vehicle along a Worldwide Harmonized Light-Duty Test Cycle (WLTC): 1250 × 2, 1500 × 9, 1750 × 5, 2000 × 9. The fifth working point, 2250 × 15, was chosen to represent a constant-speed highway use of the vehicle (at approximately 130 km/h). For the sake of brevity, only the results relative to the two engine points 1250 × 2 and 2000 × 9 are discussed below.

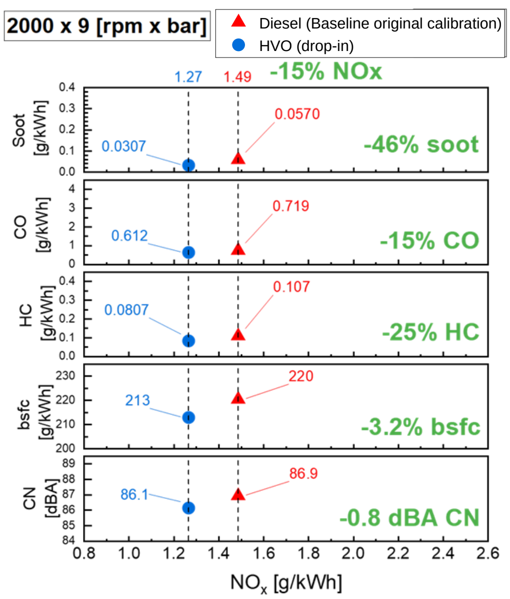
3. HVO as A "Drop-in" fuel in warmed-up conditions

The engine has a preliminary baseline calibration implemented by the engine manufacturer for conventional diesel fuels. This baseline calibration only employs the high-pressure EGR loop. The following preliminary activity compared the two fuels (diesel B7 and HVO) at the aforementioned steady-state working points in order to evaluate the benefits that HVO can bring as a "drop-in" fuel (100% diesel fuel replacement) without modifying the original engine calibration.

Figure 1(a),(b) shows a comparison between the two fuels at the steady-state points 1250 × 2 and 2000 × 9, in terms of engine performance and engine-out emissions. On multiple stacked y-axes, engine-out soot, CO, HC, brake specific fuel consumption (*bsfc*) and combustion noise (CN) are displayed as a function of engine-out NO_x emissions (NO_x values increase as EGR values decline). The results for each of the five tested points are listed in Table 4, showing the percentage variations of the results between the two fuels (value for HVO minus value for diesel, divided by the value for diesel) for emissions and fuel consumption, and the absolute variations (value for HVO minus value for diesel) for brake thermal efficiency (η_u) and CN. Significant reductions are indicated in green, whereas increases are reported in red. Figure 1(c),(d) reports the ensemble in-cylinder pressure signals and the corresponding heat release rate (HRR) for the steady-state points 1250 × 2 and 2000 × 9. The combustion of the engine running on conventional diesel or HVO is similar, in particular when the main injection is considered. When pilot injections are present, the effect of cetane number on the main injection combustion is reduced, because the heat produced by the combustion of pilot injections increases the in-cylinder temperature enhancing the main combustion, thus reducing the differences in heat release and pressure trace between HVO and conventional diesel oil. In fact, the effect of the higher cetane number of HVO is clearly visible only at 1250 × 2 in Figure 1(c) and mostly for the first pilot injection, that shows a reduced ignition delay and a slightly higher peak in the HRR when running on HVO.



(a)



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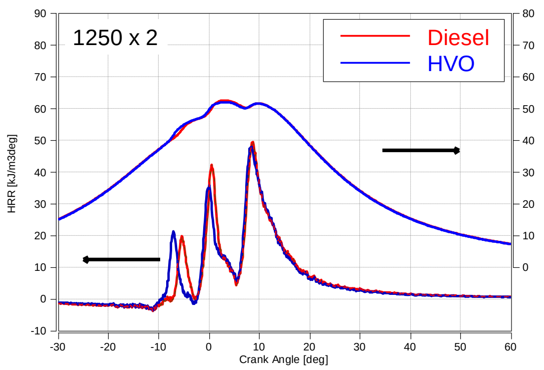
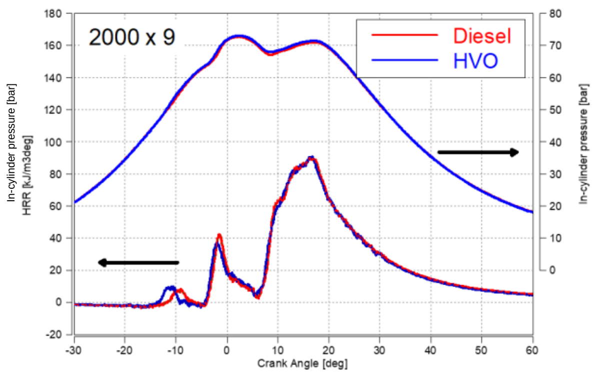


(c)



(d)

Figure 1. Engine-out emissions, fuel consumption and combustion noise for diesel and HVO at 1250 × 2 (a) and 2000 × 9 (b). In-cylinder pressure and heat release rate for diesel and HVO at 1250 × 2 (c) and 2000 × 9 (d). Results with the baseline ECU calibration (performed for diesel fuel).

Table 4. Comparison of HVO and diesel fuel on the five considered steady-state points.

Speed × *bmep* (rpm × bar)	$\Delta_{\%}$*bsfc* [%]	$\Delta_{\%}$HC [%]	$\Delta_{\%}$CO [%]	$\Delta_{\%}NO_x$ [%]	$\Delta_{\%}$Soot [%]	$\Delta_{\%}CO_2$ [%]	$\Delta_{\%}$*vfc* [%]	$\Delta\eta_u$ [%]	ΔCN [dBA]
1250 × 2	-2.9	-34	-36	+9.6	-48	-3.5	+3.7	-1.0	-0.7
1500 × 9	-3.3	-44	-33	-4.8	-67	-4.7	+2.9	-0.2	-1.2
1750 × 5	-3.4	-30	-18	-6.8	-56	-3.1	+3.1	-0.4	-0.9
2000 × 9	-3.2	-25	-15	-15	-46	-4.5	+3.4	-0.7	-0.8
2250 × 15	-2.8	+8.5	+13	-3.3	-15	-3.5	+3.8	-1.0	-0.5

Based on the results in Table 4, NO_x emissions from an HVO-fuelled engine appear to be increasing or decreasing relative to diesel oil (NO_x variations range from -15% at 2000 × 9 to +9.6% at 1250 × 2) with no clear trend, as other researchers have also pointed out. The higher cetane number of HVO (see Table 3) determines a shorter ignition delay (ID) and a prompter combustion development. However, a shorter ID does not always result in a decrease in NO_x [17], and the results are dependent on the particular engine operating point and on the specific ECU calibration. In any case, it appears from Table 4 that NO_x emissions with HVO tend to decrease (in fact the 1250 × 2 point is the only exception).

Considering the other emissions reported in Table 4, soot appreciably decreases with HVO. This is primarily attributable to the specific fuel composition (lacking aromatic hydrocarbons) and other properties such as cetane number, viscosity, and density. A narrow distillation temperature curve (which indicates the evaporation of the fuel as a function of its temperature), such as that of HVO, promotes fuel vaporization and improves mixture homogenization within the air-fuel cloud [18], thereby hindering soot formation. At high load, where soot production is typically high, soot reductions can be more advantageous than at low load, where it is a minor issue.

HC and CO also exhibit a general reduction except for the highest load point. In any case, the percentage increase at this load is not a concern because the absolute values are rather small. In contrast, the high cetane number of HVO results in a faster combustion at low loads, reducing incomplete combustion and, thus, engine-out HC and CO [19].

Brake thermal efficiencies are comparable for the two fuels, with diesel showing slightly higher values than HVO, most likely due to baseline calibration parameters being optimized for diesel fuel. Due to its lower density (slightly higher than 6% compared to diesel), *bsfc* for HVO is approximately 3% lower than diesel. Consequently, if the fuel consumption is measured on a volumetric basis (*vfc*), HVO shows an increase of around 3%. Both *bsfc* and *vfc* can be important to compare: the former can be associated to tank-to-wheel CO_2 emissions, while the latter influences the retail price (€ per litre) and thus the total cost of ownership paid by the vehicle owner.

Additional comparisons of the two fuels through sweeps of single engine parameters at the same steady-state working points are investigated in [20].

4. HVO as A "Drop-in" fuel during engine warm-up

This Section examines the experimental results in terms of combustion, engine-out emissions, and engine performance during engine warm-up, along quasi steady-state operating points. The following test procedure has been considered: the engine was started from ambient temperature (after overnight soaking), and after a few seconds of idling, the engine speed and load were set to the desired values through the testbench controller. The engine was left to warm up while measuring engine-out emissions and fuel consumption in a continuous recorder. Figure 2 depicts the corresponding measured data (several points, one every 5 °C coolant outlet temperature, were extracted from the recorder). More information related to the test procedure is provided in [21].

As shown in Figure 2(a), lower coolant temperatures result in an increase in HC emissions for both fuels. Given that low coolant temperatures convert to correspondingly low cylinder wall temperatures, HC emissions most likely worsen due to an enhancement of over-leaning and flame quenching phenomena, which are the two primary mechanisms affecting HC emissions in diesel engines. Low cylinder wall temperatures may also slow down the oxidation rate of HC both inside the cylinder and at the exhaust. Specifically, at the engine operating point 1250 × 2, HC emissions for diesel are 150 ppm at a coolant outlet temperature of 30 °C and 45 ppm at 85 °C. With HVO, the decrease in HC emissions from low to high coolant temperature is still appreciable, with values ranging from 50 ppm to 30 ppm, but the highest value at 30 °C is three times lower than diesel (50 ppm vs. 150 ppm, respectively). When the engine is warmed up, HVO still emits 60% less HC than diesel. Similar conclusions can be drawn at 2000 × 9 (despite the general reduction in emissions, which is primarily due to the increased engine load). HVO emits half as much HC as diesel when the engine is warmed up (10 ppm vs. 20 ppm) and only a third at low coolant temperatures (15 ppm vs. 45 ppm). In conclusion, regardless of engine operating conditions or coolant temperatures, HVO produces less engine-out HC than diesel, with the difference growing as coolant temperatures are lower.

In terms of CO emissions (shown in Figure 2(b)), HVO outperforms diesel at 1250 × 2, regardless of coolant temperatures. At 85 °C, HVO emits 40% less CO than diesel (150 ppm vs. 250 ppm), whereas at 30 °C, the benefit increases substantially as CO emissions are more than 60% lower for HVO compared to diesel (650 ppm vs. 1700 ppm). It is evident how diesel exhibits a steep fivefold increase in CO emissions from high to low coolant temperatures, while the corresponding increase is more contained for HVO. At 2000 × 9, however, the differences in CO between HVO and diesel tend to be small, as do their absolute values, which are relatively modest because combustion process generates higher in-cylinder temperatures as a result of the increased load.

As shown in Figure 2(c), NO_x emissions tend to rise as coolant temperatures go up. An increase in coolant temperature reduces heat transfer between in-cylinder gases and cylinder walls during both the compression and the combustion phases, resulting in a rise in in-cylinder peak combustion temperatures, which are strongly correlated with NO_x formation mechanisms. The differences in NO_x emissions between HVO and diesel appear to be modest, and there is no clear trend indicating that one fuel emits more NO_x on a consistent basis than the other. This behaviour, which has been already mentioned for the tests in warmed-up condition (cf. Section 3), appears to be confirmed at different coolant temperatures as well. A slightly more significant difference in NO_x emissions between diesel and HVO can be observed at 1250 × 2, at the lowest coolant temperature values. This may be due to the superior combustion quality of HVO compared to diesel.

Figure 2(e) depicts the reduction in *bsfc* between HVO and diesel. The differences are primarily due to the different lower heating values of the two fuels (cf. Table 3). Figure 2(d) shows engine thermal efficiency η_u as a function of the coolant outlet temperature. It is evident from this plot that, for both fuels, η_u is generally higher at high coolant temperatures and lower at low coolant temperatures. However, efficiency drop at low coolant temperatures is less pronounced for HVO than for diesel, especially at low load, due to its better ignitability. At 1250 × 2, η_u of HVO is almost 2% higher at 30 °C, while it appears similar as the coolant temperature rises. Considering all the emission patterns and engine efficiency, it is clear that at 1250 × 2 and low coolant temperature HVO guarantees a better combustion, despite the diesel-oriented calibration of the engine used for the tests. At 2000 × 9, diesel has a marginally higher η_u under all conditions, and its degradation at low coolant temperatures is reduced for both fuels.

Finally, as shown in Figure 2(f), despite the fact that η_u for HVO is lower than that for diesel, engine-out CO_2 emissions are slightly lower for HVO because of the differences in the chemical composition of the two fuels. Nevertheless, this is just related to a tank-to-wheel analysis, while only a well-to-wheel analysis would clearly reveal the true advantage of HVO over diesel in terms of CO_2 emissions.

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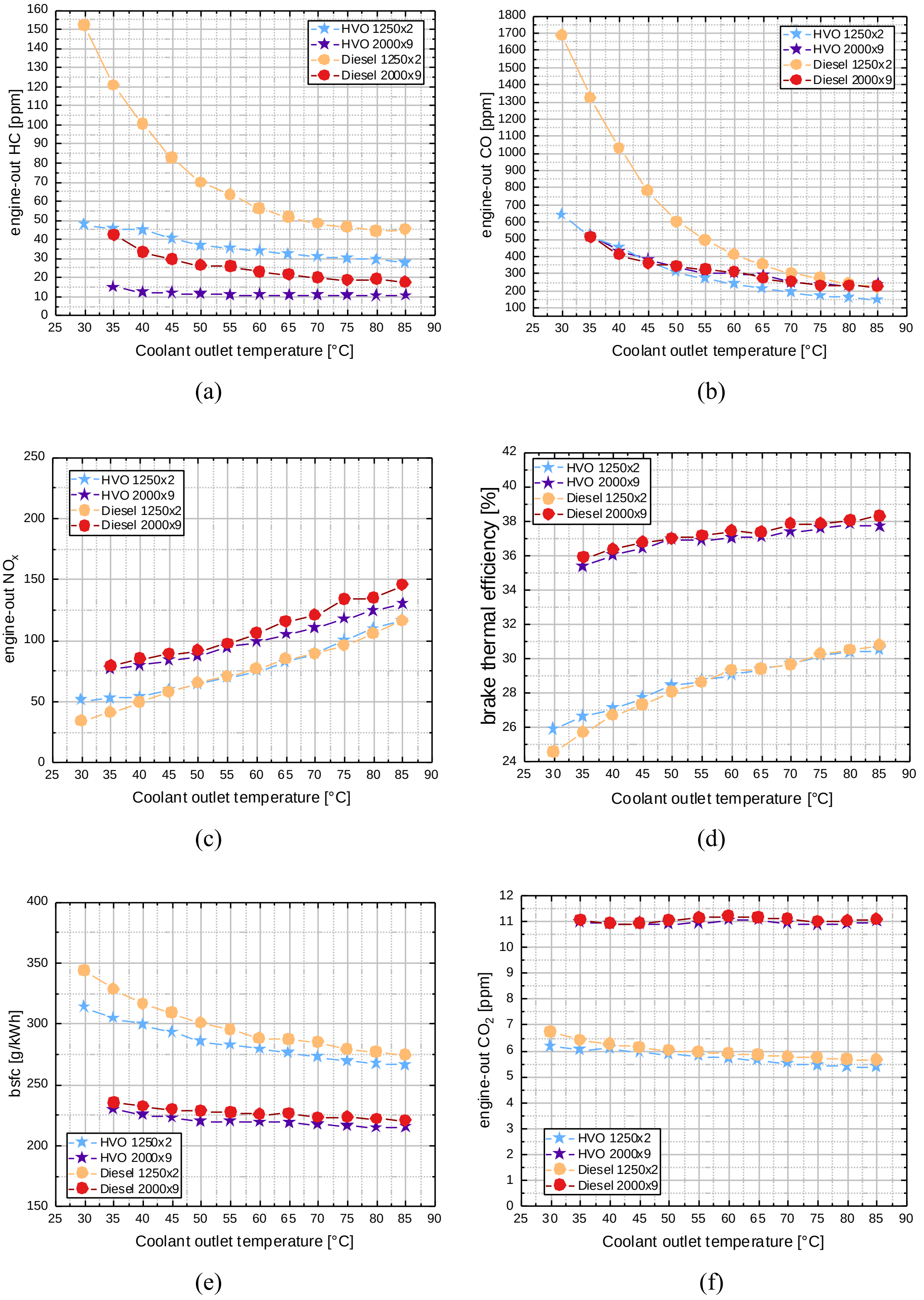

Figure 2: Engine-out emissions, engine thermal efficiency and *bsfc* measured at various coolant temperatures along warm-up tests.

5. Fuel-specific recalibration through DoE

The results obtained thus far can be used to assess the potentialities of HVO as a “drop-in” fuel, i.e., using it as a replacement for conventional EN590 B7 diesel, without modifying the original ECU calibration. The next step is to determine two independent optimal calibrations, one for each fuel, in order to assess the true potential benefits of using pure HVO with a dedicated calibration.

The statistical techniques of design of experiments (DoE) were applied on three of the initial five steady-steady working points, namely 1250 × 2, 2000 × 9, and 2250 × 15. A preliminary experimental analysis revealed that the calibration parameters that have the greatest influence on the engine performance and emissions (regardless of the specific fuel) are: start of injection (SOI) of the main injection, quantity and timing of closer-to-main pilot injection, rail pressure, VGT position, positions of the HP and LP EGR valves. As a result, a 7-dimensional DoE test plan was set up using the “MBC model” Matlab tool. It is useful to recall that the original baseline calibration only employed HP EGR, while the LP EGR valve was kept completely closed (cf. Section 3).

Several levels (i.e., appropriate values) were considered for each of the input calibration parameters. A second-order polynomial model was chosen for all the outputs (NO_x, soot, CO, CO_2, HC, *bsfc*, and CN) as function of the aforementioned inputs. The experimental test plan consisted of about 140 test points extracted from the potential full factorial according to a “V-optimality” criterion, which minimizes the values of the predicted error variance in the test plan. Using the obtained statistical models, the Matlab tool called “CAGE” (CAlibration GEneration) was used to find several optimal engine calibrations for both fuels. For example, one of the optimization criterion was the minimization of a single output variable, NO_x, while imposing some constraints on the other output variables. Other optimizations involving simultaneous minimization of two parameters were also explored (e.g., CO/HC at low load and NO_x/soot at medium/high load), taking into account the most relevant emissions at the different working points

The optimal calibrations generated by “CAGE” were then tested experimentally on the engine. In the following, only the calibration that minimizes NO_x is presented, as other calibrations will be described in more details in next research papers. At each working point, a different calibration was obtained for each fuel. The experimental results obtained for each calibration for diesel and HVO are reported in Table 5 (1250 × 2) and Table 6 (2000 × 9).

It is possible to check that NO_x emissions decrease with both fuels relative to the original calibration (cf. Fig. 1) and this can be attributed not only to the optimization through DoE, but also to the utilization of colder EGR coming from the LP loop. At 1250 × 2 (cf. Table 5) NO_x emissions for HVO decrease drastically (by about 60%). This may also be due to a high EGR value that the engine could tolerate with this fuel (cf. last column of Table 5). HC are appreciably lower, too. At this load, the increase in soot (+15%) is not an issue as the absolute values are rather low. At 2000 × 9 (cf. Table 6), NO_x reduction with HVO is in line with what obtained as a drop-in fuel (see Table 4). The difference in ID between the fuels is in fact mitigated by the much higher in-cylinder temperatures at this load. In contrast, the recalibration with HVO has a really high effect on soot emissions, which are reduced by more than half with HVO (-58%). Reductions in CO and HC are also highlighted, but their significance is marginal as the absolute values are lower compared to light load conditions.

In conclusion, dedicated calibrations for HVO can have a significant impact on the reduction of engine-out NO_x emissions for HVO, ensuring that CO and HC emissions at lower load and soot emissions at higher load remain low.

Table 5. Optimization of HVO and diesel oil at 1250 × 2.

fuel & calibration	***bsfc* [g/kWh]**	**HC [g/kWh]**	**CO [g/kWh]**	**NO_x [g/kWh]**	**Soot [g/kWh]**	**EGR rate [%]**
diesel opt	274.6	0.82	2.72	1.14	0.034	46.0
HVO opt	272.3	0.64	2.6	0.46	0.039	54.6
Δ opt	-0.8%	-22%	-4%	-60%	+15%	+8.6

Table 6. Optimization of HVO and diesel oil at 2000 × 9.

fuel & calibration	*bsfc* [g/kWh]	HC [g/kWh]	CO [g/kWh]	NO_x [g/kWh]	Soot [g/kWh]	EGR rate [%]
diesel opt	218.3	0.15	1.06	0.58	0.091	29.5
HVO opt	217.6	0.10	0.94	0.49	0.038	31.8
Δ opt	-0.3%	-33%	-11%	-16%	-58%	+2.3

6. Conclusions

The present analysis compared HVO and conventional petroleum-derived diesel to assess the potential of HVO as a “drop-in” fuel (i.e., as a replacement of diesel fuel while maintaining the original diesel-oriented calibration) and also explored the potential of HVO vs. diesel oil with a dedicated calibration obtained through design of experiments on a Euro 6 compression ignition engine for light-duty commercial vehicles applications.

The following bullet points summarize the most significant results:

- NO_x emissions generally decrease when HVO is used as a "drop-in" fuel, but they can increase relative to diesel depending on the particular operating point. Relevant reductions in soot (up to 67%), HC and CO (up to 40%) can be obtained at different working points;
- reductions of HC, CO and soot emissions with HVO tend to be further enhanced at low coolant temperatures;
- a dedicated calibration employing dual-loop EGR can provide significant reductions in NO_x for HVO compared to diesel, as well as lower HC and CO at low loads and lower soot at high loads.

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