

Improving Engine Efficiency and Emission Reduction Potential of HVO by Fuel-Specific Engine Calibration in Modern Passenger Car Diesel Applications

Ahmad Omari and Stefan Pischinger
Institute for Combustion Engines, RWTH

Om Parkash Bhardwaj and Bastian Holderbaum
FEV Europe GmbH

Jukka Nuottimäki and Markku Honkanen
Neste

ABSTRACT

The optimization study presented herein is aimed to minimize the fuel consumption and engine-out emissions using commercially available EN15940 compatible HVO (Hydrogenated Vegetable Oil) fuel. The investigations were carried out on FEV's 3rd generation HECS (High Efficiency Combustion System) multi-cylinder engine (1.6L, 4 Cylinder, Euro 6). Using a global DOE approach, the effects of calibration parameters on efficiency and emissions were obtained and analyzed. This was followed by a global optimization procedure to obtain a dedicated calibration for HVO. The study was aiming for efficiency improvement and it was found that at lower loads, higher fractions of low pressure EGR in combination with lower fuel injection pressures were favorable. At higher loads, a combustion center advancement, increase of injection pressure and reduced pilot injection quantities were possible without exceeding the noise and NO_x levels of the baseline Diesel.

In a second stage, WLTP cycle simulations were used to quantify the emissions and fuel consumption benefits with HVO, both for a drop-in scenario as well as for a scenario where HVO was operated with a dedicated calibration. Simulation results revealed that HVO as drop-in fuel shows overall an improved thermodynamic efficiency. An increased volumetric fuel consumption of ~ 2 % was found due to the lower density of paraffinic HVO fuel. NO_x emissions were comparable to baseline Diesel, whereas, a significant reduction in emissions of CO, HC and PM was observed owing to superior ignition behavior, the absence of aromatics or Sulphur and improved evaporation behavior. For the optimized scenario, maintaining NO_x and noise targets similar to baseline Diesel, the engine efficiency with HVO improved by 6.3%, corresponding to a tank-to-wheel CO₂ reduction of 9%. This efficiency improvement was high enough to compensate the low density of HVO, resulting in an overall improvement in volumetric fuel consumption by 1.6% w.r.t. Diesel. Furthermore, the emissions of HC, CO and PM were reduced by more than 50%. The lower PM emissions with HVO contributes to an extended DPF regeneration interval, thereby reducing DPF related drawbacks.

CITATION: Omari, A., Pischinger, S., Bhardwaj, O., Holderbaum, B. et al., "Improving Engine Efficiency and Emission Reduction Potential of HVO by Fuel-Specific Engine Calibration in Modern Passenger Car Diesel Applications," *SAE Int. J. Fuels Lubr.* 10(3):2017, doi:10.4271/2017-01-2295.

INTRODUCTION

Along with EU and US, all the major economic powers of the world have committed to a stricter reduction of climate detrimental greenhouse gases (GHGs). This reduction has a massive impact on the transport sector. The light duty vehicle development faces two major, often opposing challenges simultaneously, the requirement to reduce the CO₂ as well as a compliance with stringent emission standards.

In the EU, an update of the EU6 emissions- level-2 is planned for 2017/18 targeting a significant reduction of the real-world emissions of newly certified vehicles by enhanced testing conditions and real-world measurements [1, 2, 3]. For the North American markets,

from 2017 TIER-3 (resp. LEV-III) the emission thresholds have to be taken into account and rolled out to the whole vehicle fleet successively until 2022 [4]. In emerging markets such as India and China, similar stricter emission and fuel economy legislation has been announced. Figure 1 illustrates a progressive reduction in CO₂ and other crucial regulated emissions (i.e. NO_x and PM) in EU.

In order to fulfill these ambitious targets a significant increase in utilization of the newest and available technologies is required. To enhance the engine efficiency, thereby reducing the CO₂ emissions, a large number of measures are applied (e.g. downsizing, variable compression ratio, electrification, friction reduction, etc.) [5].

However, usually these engine related measures lead to a significant decrease in exhaust gas temperatures, thereby, making the application of exhaust gas aftertreatment (DOC, LNT, SDPF, SCR etc.) more challenging. Furthermore, these two areas of technology can compete with each other with regards to cost effectiveness and complexity [5]. In this regard, alternative fuels could offer a great potential of simultaneous reduction in CO₂ and regulated emissions, to combine with comparatively less complex and more economical engine technologies [6].

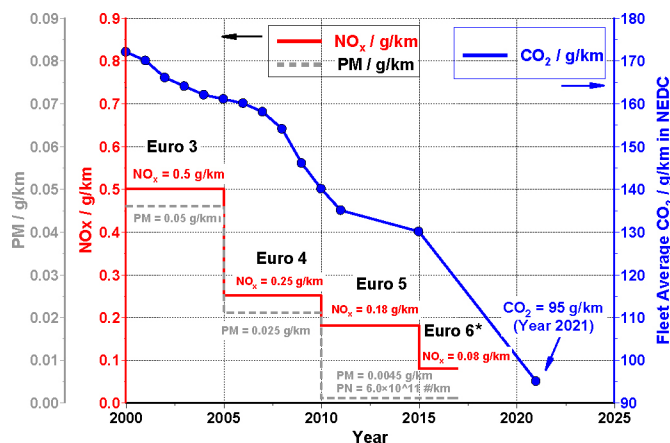


Figure 1. A progressive reduction in the PM emission limit and CO₂ emission targets for passenger cars and light-duty vehicles [1, 2, 3, 4]. As a part of Euro 6d*, the WLTP and RDE test procedures are introduced, starting from 2017.

While some of the alternative fuels such as natural gas and dimethyl ether (DME) clearly require some hardware modification e.g. fueling system [7, 8], the modifications required for biodiesel (FAME) fuel vary depending mainly on the type of engine technology and extent of the blending with diesel [9]. However, there are alternative fuels such as HVO (hydrogenated vegetable oil), biomass to liquid (BtL) or Gas to liquid (GtL) which can be used in the conventional diesel engine with little or no modifications at all [10, 11, 12, 13, 14].

For diesel engine applications, HVO is considered as a premium fuel for several reasons. Except of being almost CO₂ neutral, HVO is also free of aromatics, and thereby, inherently contributes to a particulate emission reduction, which in turn extends DPF regeneration intervals [11, 15, 16]. Also deposits on injectors and EGR paths are reduced, leading to a longer functionality of these components. The high cetane number of HVO is also of major importance, especially when considering the ongoing trend of compression ratio (CR) reduction in Diesel engines to achieve an improved NO_x-Soot trade-off [17]. The application of petroleum-based diesel in low CR engines typically leads to drawbacks in terms of increased HC/CO emissions and combustion noise level, [17, 18] as well as deterioration of cold start behavior. In case of HVO fueling, these issues could be inherently counteracted due to its superior ignition quality. The successful operability of HVO in low compression engines is not only beneficial for Soot-NO_x trade-off but offers additional advantage in specific power output when a given peak cylinder pressure must not be exceeded. Furthermore, the absence of Sulphur content in HVO would eliminate the ageing issues and performance deterioration of sensitive aftertreatment devices such as DOC, LNT, coated DPF and SCR systems [19]. Compatibility with typical elastomers used in

series vehicle is in most cases guaranteed. However, there are some cases known to the authors where the switching from high FAME and aromatic containing diesel (e.g. B20) to aromatic-free HVO have caused some NBR-sealing leakage issues. NBR sealants have a tendency to swell up when exposed to high FAME contents or to high aromatic level fuels. Once the sealant has swollen up, it may shrink when FAME is excluded and aromatic content of the fuel is reduced.

In spite of the improved thermal efficiency with HVO combustion, the volumetric fuel consumption of HVO as a “Drop-in” component is reported similar or slightly higher than petroleum based Diesel [12, 13, 14]. This behavior arises from the lower density of HVO, as a result of its paraffinic molecular structure. In such drop-in scenarios, the engine calibration is not optimum for HVO as it was optimized for petroleum based diesel. Therefore, it might be that the drawback in volumetric fuel consumption as a “drop-in” fuel could be compensated by a fuel specific calibration for paraffinic diesel fuels such as HVO, GtL & BtL [20, 21, 22, 23]. For example, previous studies have found that the injection timings optimized for petroleum diesel operation are not optimum for HVO fueling, which was mainly attributed to ignition delay properties (higher CN) of HVO [13, 14]. Nevertheless, investigations considering all of the calibration parameters of a modern EU6 diesel engine (like: boost pressure, EGR and EGR-split strategy, injection pressure, timing and pilot strategy, etc.) and its interactions are not available in literature yet. Furthermore, investigations covering a complete driving cycle relevant speed-load range are lacking as well. Therefore, there is a need to investigate the potential of HVO by considering all the degrees of freedom for calibration optimization offered by modern EU6 diesel Engines. In a view of future emission legislation, the speed load range of a WLTP cycle needs to be considered.

This paper presents the results of a recent collaborative study conducted by NESTE and FEV Europe GmbH, to assess the potential of HVO Diesel fuel in neat form within modern passenger car diesel applications with a dedicated calibration for HVO.

METHODOLOGY

To provide a complete understanding of the potential to improve efficiency and reduce emissions by dedicating the engine calibration to HVO, this work considers a Global DOE approach [24] on a state-of-the-art multi-cylinder engine. Using the measured data, engine models are created and used for WLTP cycle simulations to obtain emissions and fuel consumption in terms of g/km. Besides the scenario of HVO with a dedicated engine calibration, two drop-in scenarios were considered. In one drop-in scenario, the start-of-injection (SOI) timings for HVO are identical to those of diesel. In the other drop-in scenario the center of combustion (COC) is maintained constant (i.e. 50% mass fraction burned). The latter drop-in scenario was investigated in a view of upcoming engine technologies like fuel sensors or closed loop combustion systems [25]. With the latter technologies, the center of combustion can be maintained almost constant irrespective of the fuel being used. An executive summary of the methodology is given in Figure 2. A detailed description follows below.

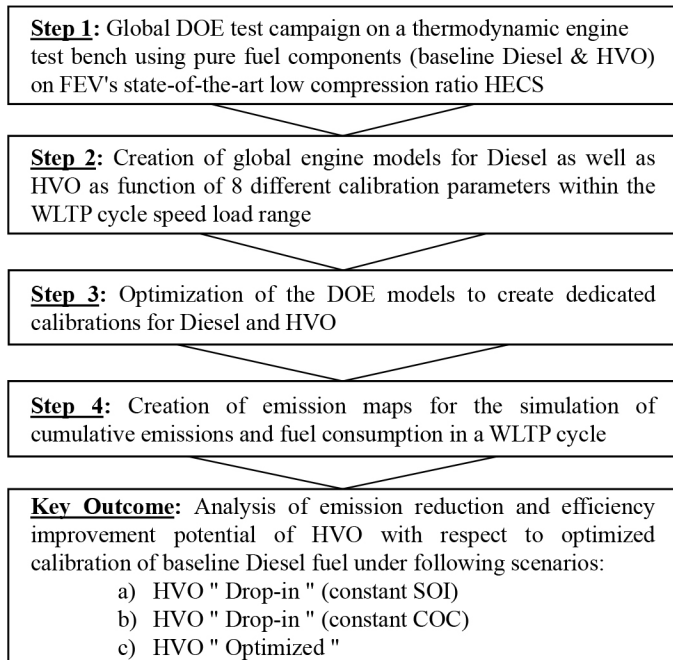


Figure 2. Executive summary of the methodology used in the present work. (Abbreviations: HECS= High Efficiency Combustion System, SOI= Start of Injection, COC= Center of Combustion).

Test Engine and Experimental Set-Up

Considering the high levels of development Diesel engines have gone through in the recent years, it was obvious that the chosen engine has to be equipped with all of the relevant EU6- Diesel engine technologies. For that reason, the 3rd generation of FEV's High Efficiency Combustion System (HECS III) was chosen. Besides hardware design aspects, an important feature of the HECS III engine is its control strategy. This relies on an in house developed model based air-path and torque-path control [26], enabling real-time tracking of many parameters in physical terms, e.g. O₂ concentration in the cylinder. Additionally, the torque path features a closed loop combustion control which allows comparison of fuels for a constant center of combustion (COC). The Model-based ECU algorithm was run on a Micro-Auto-box-II including FPGA unit for online cylinder pressure analysis. More details about the HECS III engine are published elsewhere [25, 26, 27]. The main hardware configurations and features of the HECS III engine are presented in Table 1.

Table 1. HECS III engine specifications.

Engine type	4 cylinder, 4 valves per cylinder
Displacement volume	1.56 liter
Bore x Stroke	75 x 88.3 mm
Peak firing pressure	160 bar
Compression ratio	2-stage, 14 & 17*
Injection system	2500 bar common rail, 9 hole injector
Boosting system	2-stage, HP turbine: Waste gate, LP turbine: VNT.
Charge cooling	water-cooled
EGR paths	cooled LP-EGR, cooled HP-EGR, Internal EGR by exhaust cam phaser*
Variable Valve Train*	Variable exhaust cam phaser Variable intake valve lift (VVL)

* Not used in this work

A simplified schematics of the thermodynamic test bench setup is depicted in Figure 3.

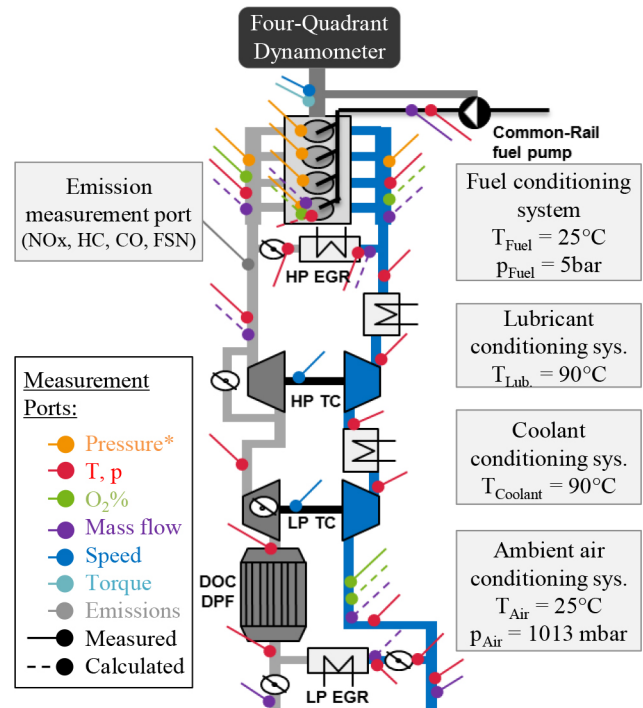


Figure 3. A schematics of the thermodynamic engine test bench set-up used in the current measurements. (*Crank angle resolved pressure measurement using Quartz sensor)

Via an engine exhaust sampling system the regulated and unregulated emissions i.e. CO, CO₂, NO_x and soot were measured as summarized in Table 2. Using the filter smoke number (FSN), determined by the AVL 415s Smoke Meter, the indicated specific particulate emissions (ISPM) are determined. In order to measure the fuel mass flow a Coriolis-type flow meter is used. For the intake air flow an ultrasonic gas meter is used. FEV's "Combustion Analyzing System" is used to record the cylinder pressure as well as the intake and exhaust pressure. Combustion noise level (CNL) was calculated from the cylinder pressure traces using 50 consecutive cycles.

Table 2. Measurement devices used for the analysis of engine-out emissions

Emission	Device	Accuracy (± % of value)
NO _x	Chemiluminescence Detector (CLD): EcoPhysics CLD 700 EL	1 %
THC	Flame Ionization Detector: Rosemount - NGA Platform 2000 Series (as C ₃ H ₈ equivalent)	1 %
CO and CO ₂	Non Dispersive Infrared Absorption Analyzer: Rosemount - NGA Platform 2000	1 %
O ₂	Paramagnetic detector: Rosemount - NGA Platform 2000 Series	1 %
Soot	Filter paper method (AVL 415s)	2 %

Test Fuels

Along with the EN 15940 certified paraffinic HVO fuel, a petroleum-based Diesel fuel was used as reference for baseline tests. In order to ensure a realistic comparison, the EN 590 Diesel available in Germany at fueling stations, containing ~ 5-7% FAME was used as the baseline fuel. A detailed physico-chemical characterization of test fuels is presented in [Table 3](#).

Table 3. Physico-chemical characterization of test fuels

Key Parameters		EN590 Diesel	EN 15940 HVO
Density @ 15 °C	kg/m ³	830	780.3
lower Heating value	MJ/kg	42.8	43.6
	MJ/l	35.52	33.94
Cetane number (CN)	-	53 - 54	80
Carbon content	mass-%	85.8	84.61
Hydrogen content	mass-%	13.49	14.67
Oxygen content	mass-%	0.72	< 0.01
Aromatic content	mass %	< 11%	~ 0 %
Sulfur content	mg/kg	7.1	< 5
Molecular weight	g/mol	186	195
Final Boiling Temperature (T90)	°C	339	291
Eq. Molecular Formula	-	C _{13.3} /H _{24.8} /O _{0.08}	C _{13.7} /H _{28.3}

As it is evident, the CN of HVO is quite high (CN ~ 80) mainly due to its paraffinic nature, which will lead to shorter ignition delay periods and hence a reduced share of the pre-mixed combustion is expected with this fuel. The absence of aromatics in HVO resulted in a higher H/C ratio, which on the one hand attributes to its improved combustion behavior; on the other hand, it lowers the volumetric energy density of HVO due lower density. Furthermore, as a desirable characteristic, HVO has a lower final boiling point as expressed with T90 in [Table 3](#) (temperature at which 90% of the fraction is distilled). The evaporation behavior of the fuel is very relevant especially in low load conditions. More components boiling at higher temperatures increase the risk for oil dilution, soot formation & high CO and HC emission.

Global-DOE Approach

A global design of experiment (DOE) approach [24] was selected for the investigation. The main difference between Global DOE and conventional “Local” DOEs is that in a Global DOE speed and load are taken as variation parameters within the DOE, whereas local DOEs are conducted at a fixed load point. In such a global approach, the DOE models are created over the whole speed-load map. This enables to constrain the calibration optimization processes not only locally (i.e. per load-point), but boundary conditions can also be set over a given driving cycle (e.g. cumulative NOx emissions over WLTP cycle). Furthermore, when optimizing a global DOE, the smoothness of the calibration maps can be controlled ensuring a realistic calibration. The test plan for the 10-Dimensional Global DOE was set up with FEVcal software. A Gaussian approach was selected and hence the test matrix was of random nature with equally distributed variations of the calibration parameters. The 10 varied calibration parameters and their ranges are given in [Table 4](#).

Table 4. Parameters varied in the Global DOE test campaign

Engine Speed	1000 – 2800 [min-1]
Torque	5 – 200 [Nm]
Center of Combustion	5 – 20 [°CA aTDC]*
Rail Pressure	200 – 2000 [bar] *
Pilot Quantity	0.8 - 2.4 [mg]
Pilot Offset	800 – 3000 [μs] rel. to Main Inj.
Boost pressure (high pressure stage)	100 – 300 [kPa]*
Boost pressure (low pressure stage)	100 – 180 [kPa]*
EGR rate	0% – 65% , constrained by $\lambda > 1.1$
EGR Split	100% LP EGR to 100% HP EGR

* Speed-Load dependent

After completion of the measurement campaign on the test bench, the data was analyzed with ETAS ASCMO software, a dedicated tool for the creation of global engine models and optimizing engine calibration. Models were created for all relevant parameters; NOx, CO, HC, Filter Smoke Number (FSN), Combustion Noise Level (CNL), mass flows and Exhaust temperatures. Finally, a total of more than 1000 usable data points were available for creating the models of HVO and Diesel.

Cycle Optimization Process

The optimization was performed using the ETAS ASCMO software as well. To apply driving cycle dependent boundary conditions on the optimization process, the WLTP cycle was reduced to 40 weighted representative points, called mode points, as illustrated in [Figure 4](#). Idle phases were excluded from the determination of the mode points assuming a scenario where the engine is equipped with start-stop technology. The cumulative raw-NOx emissions for the mode points were constrained to 180 mg/km, corresponding to EU6 level (<80 g/km) assuming a nominal aftertreatment system efficiency of 65% in WLTC. Furthermore, local limits were set for the optimizer, such as maximal allowed FSN values (FSN < 3) and combustion noise level.

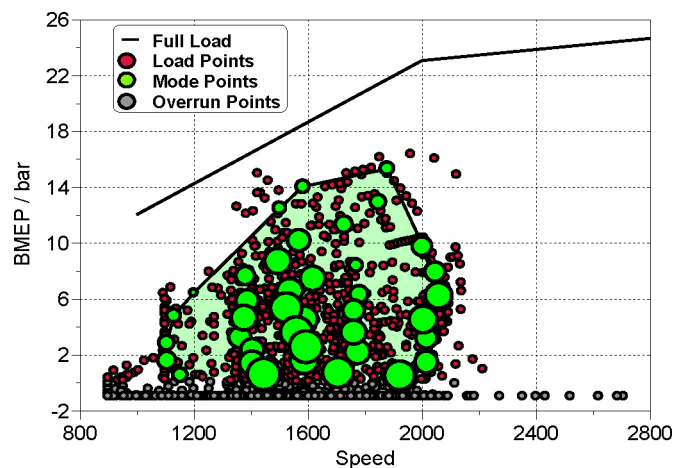


Figure 4. Load points and the corresponding mode points used to optimize a WLTP cycle. (Boundary conditions: Vehicle with a 6 gear manual transmission and start-stop system. Test mass high: 1700 kg)