Hydrotreated vegetable oil blended with waste plastic pyrolysis oil as a renewable alternative to diesel fuel

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Renewable energy sources are gaining traction as efforts intensify to phase out fossil fuels, reduce greenhouse gas (GHG) emissions, and address energy security concerns. Despite the increasing adoption rate of new-energy carriers in the light-duty sector, compression ignition engines running on diesel fuel (DF) remain the prime mover for heavy-duty transport and non-road mobile machinery.

Replacement of DF with hydrotreated vegetable oil (HVO) is a straightforward route to achieve up to 85% well-to-wheel GHG reduction. Regardless of the feedstock, HVO consists of paraffinic hydrocarbons, is free from aromatics and sulphur, exhibits low toxicity, and possesses excellent auto-ignition properties. These characteristics enable clean diffusion combustion with low propensity to create soot, without the storage stability or low-temperature issues associated with FAME-based biodiesels (Millo *et al*, 2025).

While HVO is considered a drop-in fuel, enabling full diesel substitution without engine hardware modifications, concerns regarding its higher reactivity exist. When combusted in a premixed charge mode, the increased reactivity can lead to premature ignition, resulting in higher peak pressures, reduced thermal efficiency, and increased nitrogen oxide (NO_X) emissions (Hunicz *et al*, 2025). Notably, most existing vehicles and machines today are not type-approved for HVO.

Our research addresses this issue by developing a tailored blend of HVO with plastic pyrolysis oil (PPO). Mixing PPO, which has poor auto-ignition properties (Hunicz *et al*, 2024), with highly-reactive HVO can help achieve diesel-like combustion characteristics, while promoting circular economy. This hypothesis is experimentally verified through: (i) fuel ignition delay tests in a heated constant-volume chamber, (ii) a detailed thermodynamic combustion analysis in a state-of-the-art diesel engine, and (iii) exhaust emission characterisation using a Fourier transform infra-red (FTIR) gas analyser and particulate matter (PM) size spectrometry.

Analysing the pressure traces from the constant-volume ignition test (Fig. 1), one can note that HVO ignites earlier than DF (ignition delay 2.07 ms vs. 2.56 ms) while the late stage of combustion is prolonged due to shorter mixing time. The admixture of PPO (obtained from the 50/50 mix of polypropylene and polystyrene) to HVO was experimentally set at 40%. From Fig. 1 it can be further noted, that HVO-PPO fuel blend exhibits the same ignition characteristics as DF.

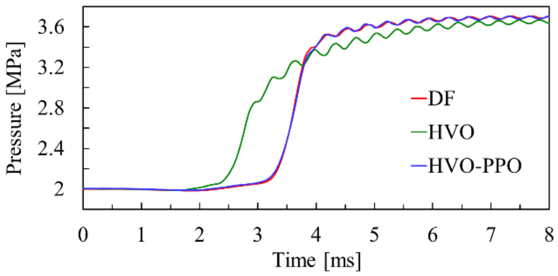

Fig. 1. Pressure curves of the auto-ignition fuel tests in a constant volume chamber at 2 MPa and 923 K.

The engine tests were performed on a single-cylinder AVL 5402 research platform, with a state-of-the-art combustion system, described in detail in previous work (Hunicz *et al*, 2024). It features an 8-hole fuel injector and high-pressure common-rail system, governed by a fully open engine control unit. The research was performed at selected operating points of the World Harmonized Stationary Cycle (WHSC), considering two qualitatively different emission calibrations.

For a representative operating point (1400 RPM, 50% load), Fig. 2a shows fuel-to-fuel differences in heat release rates (HRRs) when the engine was calibrated according to contemporary EPA Tier IV emission standards. Here, the two high-pressure pilot fuel injections preceded the main fuel injection. One can note that high reactivity of HVO does not affect the start of injection of the main fuel because combustion of pilot fuel increases temperature and leaves active radicals which result in immediate ignition of the main fuel, regardless of its reactivity.

However, in Fig. 2a, pilot fuel combustion is substantially advanced and releases more heat for HVO. This builds up in-cylinder pressure during compression while reducing fuel's energy conversion to useful work during the expansion stroke. This manifests in a roughly 1pp worsened thermal efficiency vs. DF in this particular case.

The proposed HVO-PPO mixture exhibits combustion characteristic similar to DF, mitigating the performance derating effects of HVO in split injection mode.

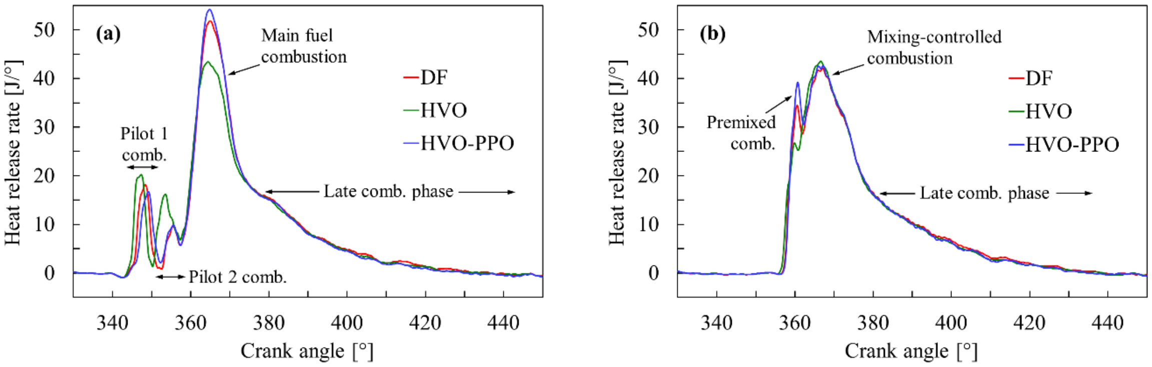

Fig. 2. Comparison of heat release rates for tested fuels at 1400 RPM and 50% load (1.1 MPa brake mean effective pressure – BMEP): a) split injection 80 MPa, b) single injection 45 MPa.

HVO's high reactivity similarly affects a single-injection strategy, typical of legacy low-pressure injection systems (Fig. 2b). Auto-ignition occurs 1° earlier than with DF, reducing mixing time and increasing the fraction of fuel burned in mixing-controlled mode. While these factors have a negligible impact on performance, they can significantly affect emissions. Consistent with the ignitability test results, the HVO-PPO mixture burns similarly to DF, proving its compatibility with the single-injection control strategy.

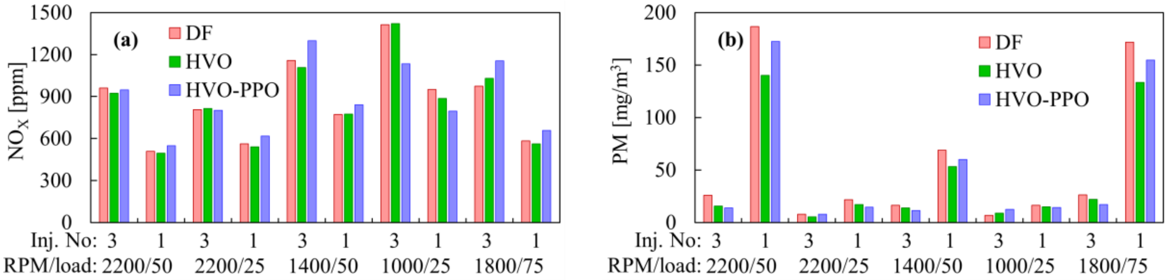

Fig. 3. Concentrations of NO_X (a) and PM (b) for all investigated engine operating points. Load in % related to the full load of 2.2 MPa in BMEP.

Fig. 3 highlights differences between the two emission calibrations. NO_X formation is largely influenced by local combustion temperature, where the slower, diffusion-based combustion of the single-injection strategy proves inhibitory. However, this legacy combustion concept presents an extremely unfavourable trade-off with PM emissions due to constrained fuel atomisation.

Emission responses of different fuels result from a complex interplay of composition, spray properties, and combustion characteristics. While this research enables the decoupling of these influences (even for unlegislated compounds), a detailed discussion is necessarily reserved for the full paper. At this stage, it suffices to say that, on a test-cycle-averaged basis, the proposed HVO-PPO blend offers a better NO_X-PM trade-off than neat HVO while retaining the performance benefits of DF operation. This improvement is observed for both calibrations, with particular efficiency gains in the multi-pulse concept.

References

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