

Investigation on Transient Emissions of a Turbocharged Diesel Engine Fuelled by HVO Blends

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ABSTRACT

Transient emissions of a turbocharged three-litre V6 diesel engine fuelled by hydrogenated vegetable oil (HVO) blends were experimentally investigated and compared with transient emissions of diesel as reference. The transient emissions measurements were made by highly-dynamic emissions instrumentations including Cambustion HFR500, CLD500 and DMS500 particulate analyzer. The HVO blends used in this study were 30% and 60% of HVO in diesel by volume. The transient conditions were simulated by load increases over 5 s, 10 s and 20 s durations at a constant engine speed. The particulate, NO, HC concentrations were measured to investigate the mechanism of emission formation under such transient schedules. The results showed that as the load increased, NO concentrations initially had a small drop before dramatically increasing for all the fuels investigated which can be associated with the turbocharger lag during the load transient. Also, as the load increase period was increased, the peak value of particle numbers and particulate mass declined apparently and the particle sizes became smaller. The HVO blends had lower particulate and HC concentrations under various test conditions compared with diesel, but they had higher NO concentrations. Under the transient load condition, HVO blends had more particulate concentration in nucleation mode while HVO blends produced less and smaller particulate matters in accumulation mode compared to diesel.

CITATION: Tan, C., Xu, H., Shuai, S., Ghafourian, A. et al., "Investigation on Transient Emissions of a Turbocharged Diesel Engine Fuelled by HVO Blends," *SAE Int. J. Engines* 6(2):2013, doi:10.4271/2013-01-1307.

INTRODUCTION

The exhaust emission caused by transient operations, such as cold start, acceleration and deceleration, is a major source of pollution especially in urban transportation and it has attracted the attention of engine researchers and designers in the recent years. Detailed measurement and analysis of engine behaviour under transient operating conditions are required to improve engine calibration. The performance and emissions of turbocharged diesel engines under transient operations are significantly worse than those under steady conditions. Higher particulate matter and HC are produced, because of the difficulties in optimizing the transient response of the intake, injection and combustion systems [1].

Researches on the transient performance and emission of turbocharged engine initially were done by simulation and indirect measurement. Arcoumanis and Jou predicted the

formation of NO based on the cylinder local temperature and the heat release rate which were derived from measured cylinder pressure during transient operation [2]. Conventional slow response analyzers were used to measure transient emission and then recovered by reconstruction techniques to analyze the transient emissions [3]. However, these methods were not convenient and the results were hard to prove.

Detail research on transient engine operation and emission characteristics has been made possible by the application of fast response exhaust gas analyzers. With the highly dynamic gas analyzers, even cycle-by-cycle emissions could be detected to study misfire during cold start [4]. The transient gaseous and particulate emissions of diesel engine were studied during European Drive Cycle for engine transient control [5,6,7]. The impact of engine transient operation on

emissions during acceleration was analyzed due to the significant increase of NO_x and particulate emissions[8].

On the other hand, the alternative diesel fuels are gaining more attention as sustainable energy supplies [9]. In light of the environmental consideration and price risk of the traditional fossil fuel, the European Union has issued a 10 percent minimum target for renewable energy consumption in the transportation sector by 2020. Alternative diesel fuel like HVO and diesel-biodiesel blends have been proved to produce less regulated emissions including CO, HC and particulate matter in steady operation, because these fuels do not have aromatic compounds [10,11,12]. However, few researches have been done on the emission behaviour of these fuels under transient operations especially by discrete fundamental transient schedules.

The transient emissions of a diesel engine fuelled by HVO blends, and diesel fuel were measured by highly-dynamic emissions instrumentations and they are reported and analyzed in the following sections. The experimental setup and fuel properties are presented in the next section followed by result and discussion. Then the drawn conclusions are listed.

FUEL PROPERTIES

HVO is a remarkable alternative diesel fuel, made by a refinery-based process that converts vegetable oils and animal fat into paraffinic hydrocarbons. In this study, the HVO blends are all supplied by Shell Global Solutions UK. The properties of the test fuels are listed in Table 1.

Table 1. Properties of Diesel and two fuel blends

Property	Diesel	HVO30	HVO60
Carbon Content (% wt)	85.9	85.5	85.1
Hydrogen (% wt)	13.6	14	14.4
Cetane Number	56.7	58.8	64.3
Aromatics (% wt)	24.87	17.78	10.37
Lower Heating Value (MJ/kg)	42.72	42.76	43.66
Viscosity (10 ⁻³ Pa·s)	3.6	3.49	3.43
Density (kg/m ³)	832.7	815.5	798.7
Oxidation stability (Hrs)	18.6	40+	40+

The cetane numbers of HVO blends are higher than diesel. This means HVO blends have shorter ignition delay and better cold start performance. This property affects the emission behaviour in both steady state and transient operations.

In addition, since HVO is a mixture of paraffinic hydrocarbons and it is free of aromatics which play an important role in soot formation [13], it has a lower particulate matter emission. Although diesel particulate filters (DPF) are common equipment in modern diesel vehicles, it is an advantage to have low PM emission to face the increasing stringent emission standards.

Compared with traditional biodiesel such as rapeseed methyl ester (RME) or soy methyl ester (SME), HVO has a better oxidation stability and lower viscosity. Oxidation stability is important for vehicle fuel systems. Poor oxidation stability limits the concentration of biodiesel blends and also high viscosity has an adverse influence on injection system [14].

EXPERIMENTAL SETUP

Engine

The engine used in this study was a Jaguar 3.0L Lion V6, parallel sequential twin turbocharged, direct injection diesel engine. The detailed technical data of the engine is supplied in Table 2.

Table 2. Technical data of the test engine

Engine Type	Euro 5 Diesel
Stroke	90 mm
Bore	84 mm
Swept Volume	2993 cc
Max CP	180 bar
Max Power	199 kW @ 4000 rpm
Max Torque	600Nm @ 2000 rpm
Max Speed	5000 rpm @ no Load

Emission Measurement

In this study, emissions including NO, HC, particulate matter, manifold ambient pressure (MAP), mass air flow (MAF), Cylinder pressure and EGR were measured. Some parameters such as fuel injection quantity and injection timing were determined by ECU calibration points and they reflected the changing trends during the transient operations.

Gaseous measurement

To measure the transient gaseous emissions, the ultra-fast response analyzers CLD500 and HFR500 by Cambustion Ltd were installed in the test bench for NO and HC emissions respectively. The Cambustion CLD500 has a time response as low as 2 ms T_{10-90%} [15]. Similarly, HFR500 can measure HC with a short time response of 0.7 ms T_{10-90%} [16]. The tests were conducted at 1500 rpm and these two equipments are fast enough to measure and record the emission data cycle in the tests.

Particulate matter measurement

Particulate emissions were measured using the Cambustion DMS500 which can measure time-resolved particle number (PN) and their spectral weighting in the 5 nm to 1000 nm size range with a time response of 200 ms [17]. Apart from displaying the raw spectrum, DMS500 allows the Nucleation and Accumulation modes to be processed separately, enabling Particle measurement programme (PMP) comparable number concentration measurements without the use of a Volatile Particle Remover (VPR) [18]. Particulate mass (PM) was determined by the calculation of DMS at real-time particle mass concentration. Since the nucleated particulates are sensitive to sampling condition and the proportion of the total PM is small [19], only accumulation mode mass was recorded.

The real-time particle number and particulate mass were measured and recorded to illustrate the effect of load transient on particulate matter. In addition, particle size distributions were averaged from different load transient periods to present the trend of particle size under the transient conditions.

Test Bench

The engine was coupled to an eddy-current type Schenck dynamometer model W230, controlled by CADET test system from the CP Engineering. Required transient schedules were compiled in the CADET. The test rig was equipped with a crankshaft encoder, pressure transducers, thermocouples, air flow metres, a fuel metre and a torque meter. The engine control variables such as injection timing, injection quantity and EGR valve position were monitored and recorded by the INCA software from ETAS. The schematic arrangement of the test bench is shown in Figure 1.

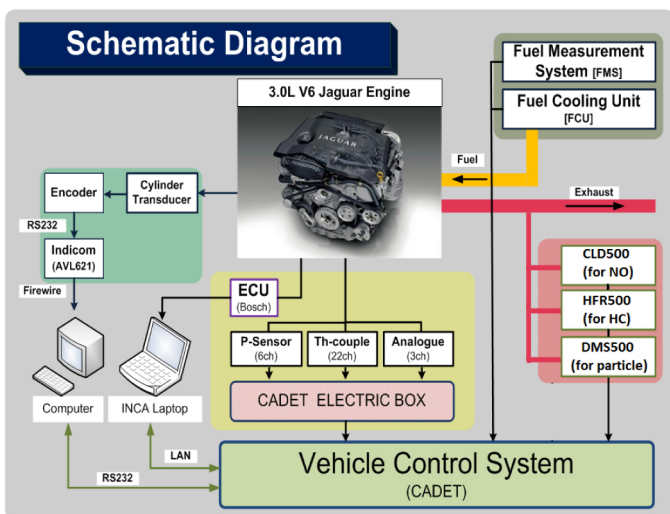


Figure 1. Schematic diagram of the test bench

PROCEDURE

To determine the impact of transient operation on engine performance and emission, several representative transient sequences were selected from the engine calibration chart conditions used by Jaguar. HVO blends and diesel were used as test fuel for the investigation and comparison purposes. The torque and speed settings were kept the same for each fuel tested in each transient sequence. The speed was maintained at 1500 rpm with the transient load profile of 48-143 Nm selected from the engine's calibration chart for the low and high loads. The transient profile of load is presented in Figure 2.

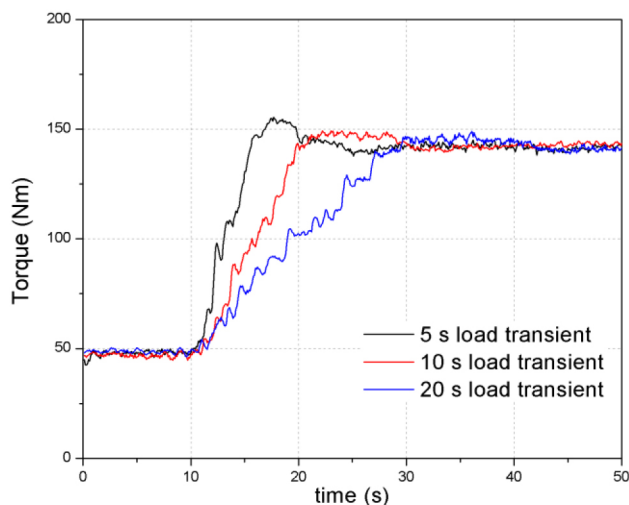


Figure 2. The transient profile of load

Before each data recording, the engine was fully warmed up for at least 20 min to ensure the repeatability and reliability of data. After the change of fuel, the engine was run at least 30 min to eliminate the influence of prior fuel. The sampling time was 50 s in every test. The load transient began at the 10th second of sampling time and 5 s, 10 s and 20 s load increase periods were applied to investigate the impact of load increase rate on emissions.

To illustrate the effect of turbocharger lag on the transient operation, the MAF, boost pressure, nominal air fuel ratio and EGR rate of diesel fuel during the load transient period are presented in Figure 3 as examples. Due to the influence of injection timing, the injection strategy is also shown in Figure 4. Since the engine calibration and turbocharger character were the same for all the test fuels, these figures are illustrative of other fuels as well.

At the start of load transient, the mass flow of intake air remained unchanged about one second because of the turbo inertia, while the fuel injected increased promptly to respond to the increased fuelling demand. The boost pressure measurement validated the air supply delay. Due to the quick response of the injected fuel and delayed air response, the A/F ratio decreased to lower than the required value for the next operation condition especially for the 5-second transient

event. Consequently, the torque response and emissions were deteriorated. It was shown that the EGR rate drop had a delay as well though the EGR valve closed instantly because of the compressibility effect of gases.

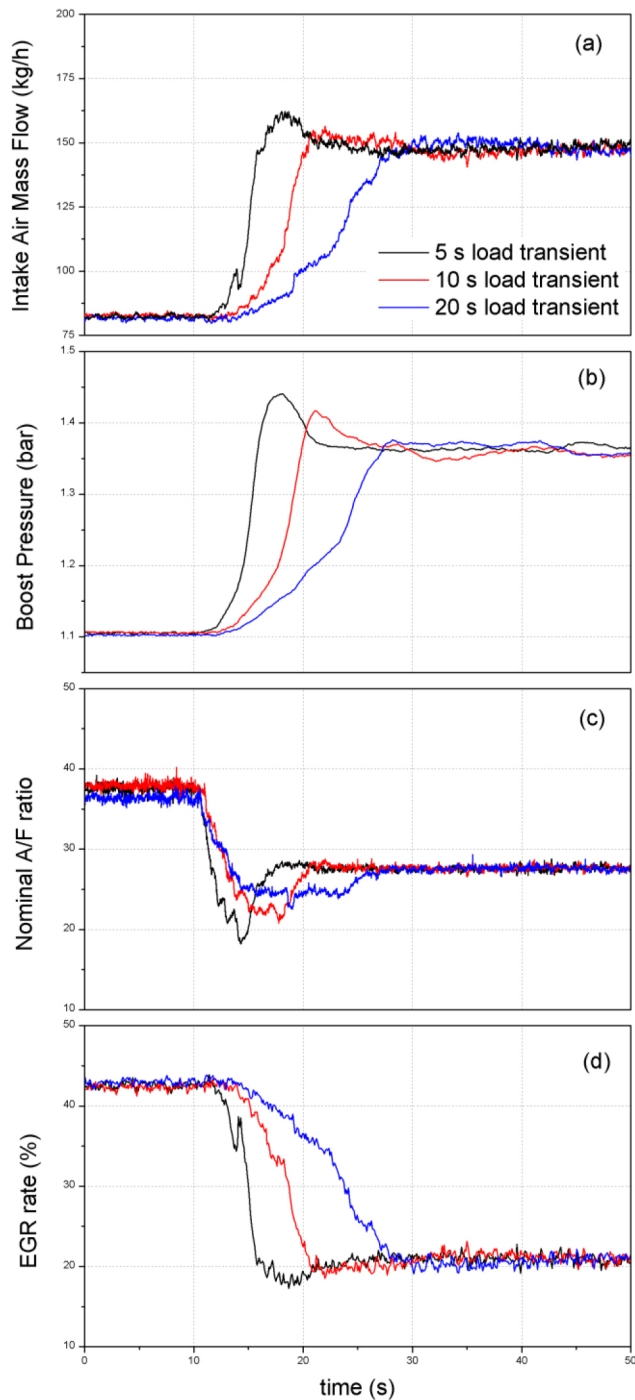


Figure 3. (a) Intake air mass flow, (b) Boost pressure, (c) Nominal air fuel ratio and (d) EGR rate during load transient events

As shown in Figure 4, the injection timing for pilot injections and post injection changed during the transient events. During the load increase, both pilot injections were

advanced with constant injection quantities. At the start of load transient, there was no post injection but it was used when the load increased to the required value.

Figure 3 and 4 will be used in the Result and Discussion section to identify the influencing factors on variation of the NO, HC and particulate emissions.

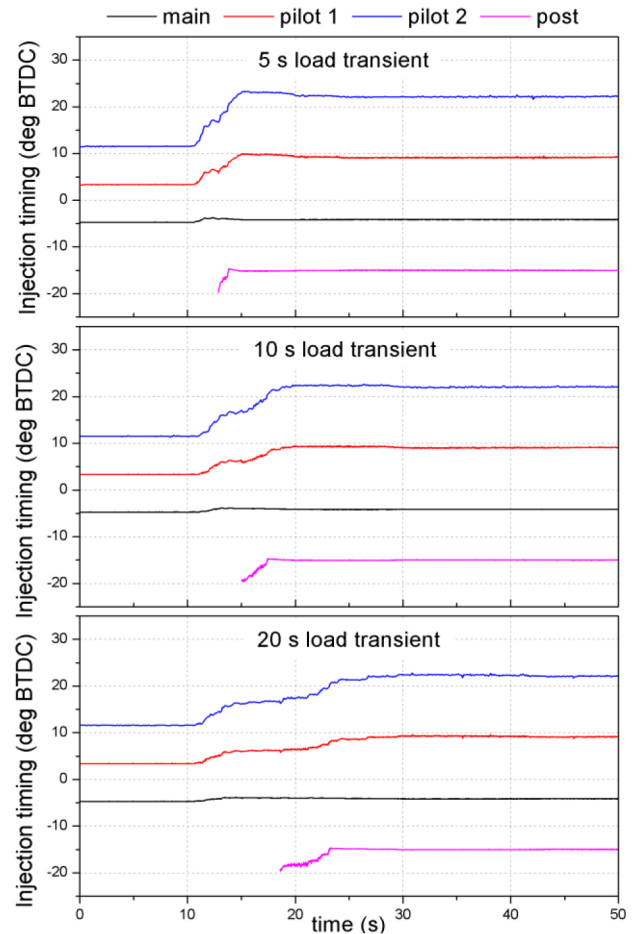


Figure 4. Injection timing during load transient events

DATA PROCESSING

To precisely compare the effect of load increase rate on transient emissions, the data analysed for each test were selected only for the load transient period and the steady operation data were omitted. For example, only data from the 10th to 15th second was used for the 5 s load transient and for the 20 s load transient data from the 10th second to 30th second was used. In this way, only the transient data are compared and the influence of steady operation is cut off.

The fast gas analyzers NO and HC concentration output data are in parts per million (ppm) which were converted to brake specific NO (BSNO) and brake specific HC (BSHC), respectively in g/kWh using following equations [20].