2010-01-1280

# Emission Behavior of a CI Engine Running by Biodiesel under Transient Conditions

**Belachew Tesfa, Rakesh Mishra, Fengshou Gu, Oliver Gilkes**
University of Huddersfield, UK



## 1. ABSTRACT

The emission characteristics of compression ignition (CI) engines running on biodiesel during transient operating conditions, which is the most usual case in urban and extra-urban transportation, have rarely been investigated. In the present study an experimental investigation on emission characteristics of a CI engine has been carried out both under steady state and transient operating conditions. The experimental work has been carried out on CI engine, which is integrated with transient testing facility. This facility is capable of varying the engine speed and load over a given time period. To measure the engine emissions, an emission analyser has been used to measure $CO_2$, CO, THC, and $NO_x$ emissions. The fuels used in the analyses are 25% (25B) and 100% (100B) of biodiesel blend and diesel. The series of the transient events studied are speed changes from 900 to 1200rpm, 1200 to 1500rpm and 1500 to 1800rpm over a time period of 4 seconds each. These tests were performed at a constant load of 105Nm, 210Nm, 315Nm and 420Nm. The transient test results have shown that the emissions of CI engine running on biodiesel were reduced by up to 17%, 52% and 38% for CO, $CO_2$ and THC emissions respectively as compared to diesel fuel. However, the $NO_x$ emission was seen to be 17% higher for engine running on biodiesel than that on diesel during transient conditions.

## 2. INTRODUCTION

The public concern about environmental pollution and the high price of petroleum products have forced the development of alternative fuels for automotive applications. Biodiesel is one of the alternative fuels which is produced from vegetable oils or animal fats. Since biodiesel has properties similar to diesel, it can be substituted for the latter with little or no engine modification. In addition, its use can reduce the emission of gases such as carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen oxides (NOx), and particulate matter (PM) [1,2].

Oxides of nitrogen are chemical compounds formed by the combination of nitrogen and oxygen under the extremely high temperatures that occur during a combustion event in an internal combustion engine [3]. It is reported that using biodiesel as fuel in a diesel engine results in increase in NOx emissions during steady state conditions [4,5]. However, other researchers have found that engines running on biodiesel have similar NOx emission characteristics to those running on normal diesel [6,7,8]. On the other hand some other groups found a decrease in NOx emission when using biodiesel [9,10].

CO is a toxic gas formed due to inadequate oxygen present in combustion chambers. In a diesel engine CO is formed during the intermediate combustion stages. CO discharged from the engine into the exhaust manifold may be oxidized to $CO_2$ if adequate oxygen is present and if the gases remain hot with a sufficient residence time. CO emissions with use of biodiesel have been found to be lower than with use of diesel [1, 6,7, 11].

$CO_2$ is one of the products during the combustion of carbon in the fuel. Ramadhas *et al.* [11] measured the $CO_2$ emission of biodiesel and its blends with respect to the load variation. For all blends of biodiesel, the $CO_2$ emission of the engine increased with an increase in load. Lin C and Lin H [12] experimented with soybean biodiesel (Sample 1 and 2 biodiesel, commercial biodiesel) and ASTM No. 2D. They used a four-cylinder, four strokes, naturally aspirated, direct-injection diesel engine with a displacement volume of 3.856litre. Torque was kept constant and engine speeds varied from 850 to 2000 rpm. The $CO_2$ emission index decreased with increase in engine speed for diesel as well as biodiesel blends. However, biodiesel and its blends had lower $CO_2$ emission indices than diesel.

It is indicated that THC emissions of engines decrease sharply when conventional diesel fuel is substituted with biodiesel fuels. Durbin *et al.* [7] reported that THC emissions were generally lower for biodiesel (20%, 100%) and synthetic diesel as compared with diesel. The 100% biodiesel fuel was found to have lowest THC emissions. Some authors have reported that there is no significant difference in THC emission between diesel and biodiesel [13]. Monyem and Gerpen [14] tested neat biodiesel, 20% blend, and diesel on turbocharged DI diesel engine. The THC emissions for all the biodiesel fuels were less than the base diesel fuel.

As described earlier, many researchers have conducted extensive investigations to establish emission characteristics of engines using biodiesel as a fuel under various steady state operating conditions. The effect of biodiesel blending fraction and the impact of speed and load variation on the engines have also been investigated in detail, but only under steady-state conditions. However, the operation of an automobile in urban settings is mostly transient due to the stop-go nature of traffic. It is reported that the emissions of engines under transient conditions are higher than those under the steady state conditions [15]. Therefore, it is very important to investigate the emission characteristics of the biodiesel blends under such transient conditions. This paper mainly focuses on the transient analysis of emissions of CI engines running on biodiesel.

# 3. MATERIALS and METHODS

## *3.1 Materials*

The biodiesel used in this study was rapeseed oil biodiesel purchased. The biodiesel was produced by transesterfication process from 'virgin' oil using methanol. Normal diesel fuel was obtained from a local fuel supplier. The rapeseed biodiesel was blended with diesel to produce 25% (25B) and 100% (100B) biodiesel by volume. The three types of fuel used in the tests were 25B, 100B, and diesel. The properties of the pure and blended fuels were measured in the *Applied Science* laboratory at the *University of Huddersfield*. These are listed in Table 1.

**Table 1** Physical and Chemical properties of Biodiesel and its blends

| Property | | Diesel | 25B | Biodiesel |
|---|---|---|---|---|
| | C | 87 | 85 | 77 |
| Composition, % | H | 13 | 12.8 | 12 |
| | O | 0 | 2.2 | 11 |
| Density , kg/m$^3$ | | 853 | 865 | 879 |
| LHV*, KJ/Kg | | 42679 | 41843 | 38500 |
| Viscosity , mm$^2$/s | | 3.55 | 4.28 | 5.13 |

LHV*: lower heating value

## *3.2 The CI Engine*

The CI engine test rig in the Advanced Automotive Laboratory of University of Huddersfield was used for this study. It has the transient test unit with 200kW AC Dynamometer, 4 Quadrant Regenerative Drive with Motoring and Absorbing Capability. It is equipped with speed sensors, pressure transducers, thermocouples, air flow metres, fuel flow metres and in-line torque meter. Full engine characteristics of the engine are described in Table 2. The layout of the experimental facilities is shown in figure 2.

**Table 2:** Characteristics of engine

| | |
|---|---|
| Engine type | Turbo charged diesel engine |
| Number of cylinders | 4 |
| Bore | 103mm |
| Stroke | 132mm |
| Compressor inlet diameter | 60mm |
| Compressor outlet diameter | 60mm |
| Compression ratio | 18.3 |
| Number of valves | 16 |
| Injection system | Direct injection |
| Displacement | 4.399 litre |
| Cooling system | Water |
| Recommended speed | 850 rpm |
| Maximum power | 74.2kW @ 2200 rpm |

The engine is also equipped with state of the art performance and emission measurement facilities. It is fully instrumented, and the steady state and transient cycle can be programmed using the *CADET* software accompanying the engine test system. The emission analyser is fitted with the engine to measure $CO_2$, CO, THC and NOx emissions. To supply the blended biodiesel from the fuel tank an air pump was used as indicated in figure 1.

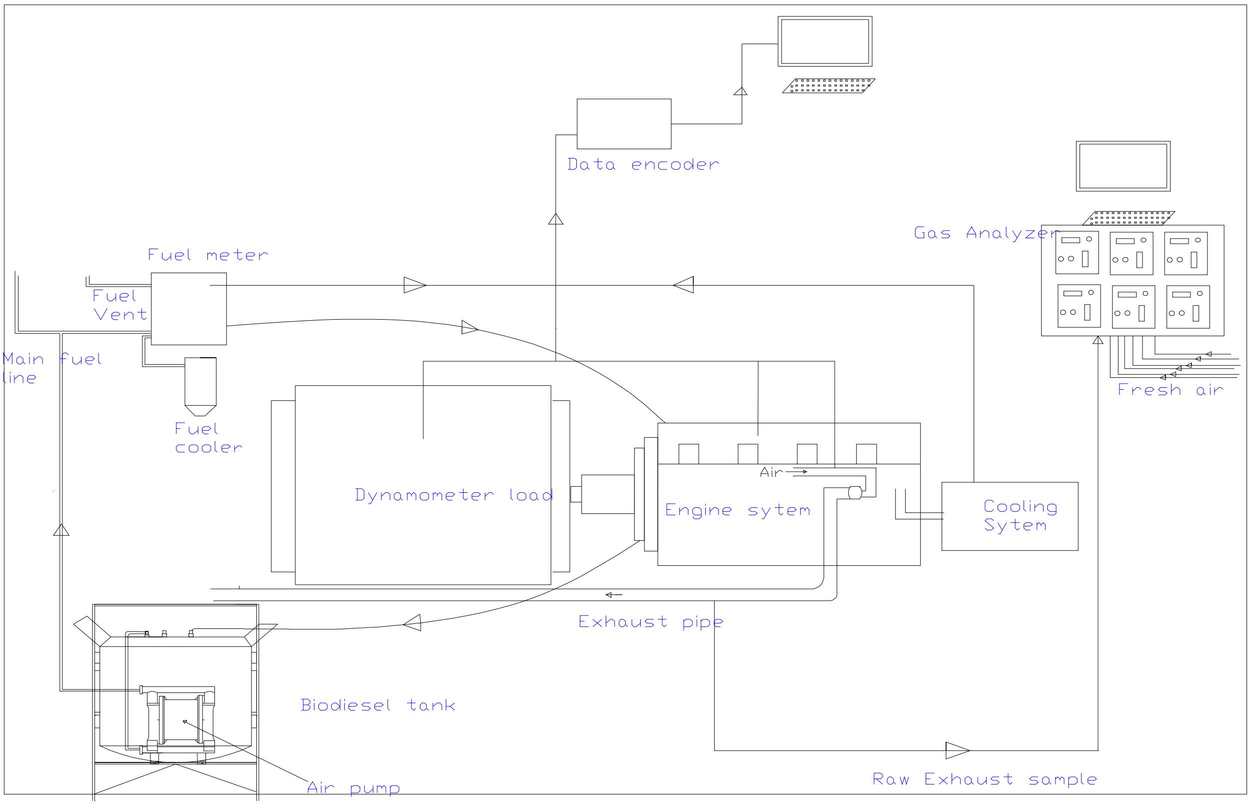


**Figure 1** Experimental setup

## *3.3 Methodology*

The engine speed and the load were the parameters to be controlled in the transient test sequences. The transient processes were programmed using *CADET* program. In this study only the acceleration phase of transient process has been reported. Three sequences of acceleration were considered; these are 900rpm to 1200rpm, 1200rpm to1500rpm and 1500 to 1800rpm. For each of these test sequences the engine load was set at 105Nm, 210Nm, 315 Nm and 420Nm. These test profiles were selected to represent the zone in the engine torque-speed map where the engine emission restrictions are most important in the standard European transient emissions cycle. The transient operation was achieved by keeping the torque constant by the rack and controlling the engine speed with the dynamometer.

On the day prior to testing, and in between each type of biodiesel blend test, a preconditioning procedure at high speed and high load was applied. For each test the fuel lines were drained prior to filling them with the next fuel blend. The engine was first run with the new fuel for 10 minutes without taking data. This was done to ensure that all traces of the fuel used in the earlier is removed from the flow meter, fuel filter and fuel pipes. This was done to purge any of the remaining previously tested fuel from the fuel system and to remove any hydrocarbon deposits in the sample line. The frequency of the data acquisition system was 37kHz and the sampling time used was 60 seconds. The capture of data was started 5 seconds prior to the start of the transient sequence.

For measurement of gaseous emissions, a HORIBA EXSA – 1500 gas test bench was used. The types of gas analysers in the EXSA-1500 and their measuring ranges are listed in Table 3. The sample line of the equipment is connected directly to the exhaust pipe and it is heated to maintain a wall temperature of about 191$^{o}$C to avoid condensation of hydrocarbons in the line. The line that extends from the exhaust pipe to the gas test bench is insulated. The emission analysers are response for the new operation after 21seconds. This is due to the delay in the gases travelling in the insulated duct and also the analyser response time.

**Table 3** The emission analyser type and measuring range

| Emission type | Emission analyser type | Measuring range |
|---|---|---|
| CO | non-dispersive infrared (NDIR) | 0 – 2000ppm |
| $CO_2$ | non-dispersive infrared (NDIR) | 0 – 20% |
| NOx | heated chemiluminescent detector (HCLD) | 0 – 5000ppm |
| THC | heated flame ionisation detector (HFID) | 0 – 100ppm |
| $O_2$ | paramagnetic detector | 0 – 25% |

## 4. RESULTS and DISCUSSION

The emission tests were performed in the dynamic engine test facilities described in section 2. The tests were run using three types of fuels (25% and 100% rapeseed oil biodiesel and diesel), for 105Nm, 210Nm, 315Nm and 420Nm load conditions and a transient speed profile of 900-1200rpm, 1200-1500rpm and 1500-1800rpm as shown in figure 2. The results of the CI engine emissions under various conditions are presented and discussed below.

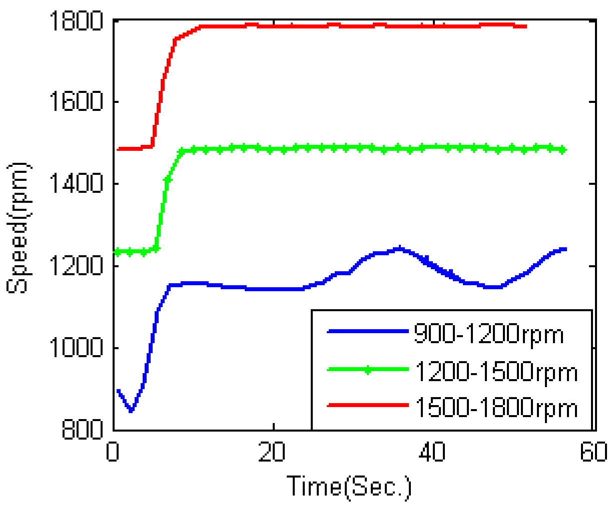


Figure 2 Speed transients' profile

Figure 3 shows the peak value of in-cylinder pressures during the engine runs using diesel, 25B and 100B fuels, at various loads and acceleration corresponding to speed change of 1200 to 1500rpm. At loads of 105Nm and 210Nm maximum in-cylinder pressure is observed at the start of the transient sequences for diesel as well as the biodiesel blends. However, at loads of 315Nm and 420Nm a steep increase of in-cylinder pressure is seen during the transient sequences before attaining steady state for different biodiesel blends. The engine shows different characteristics when running on diesel at a load of 315Nm. The engine achieves its peak in-cylinder pressure followed by a steep decrease during transient conditions before attaining steady state. In all load conditions, the engine running on biodiesel is seen to have a higher in-cylinder peak pressure.

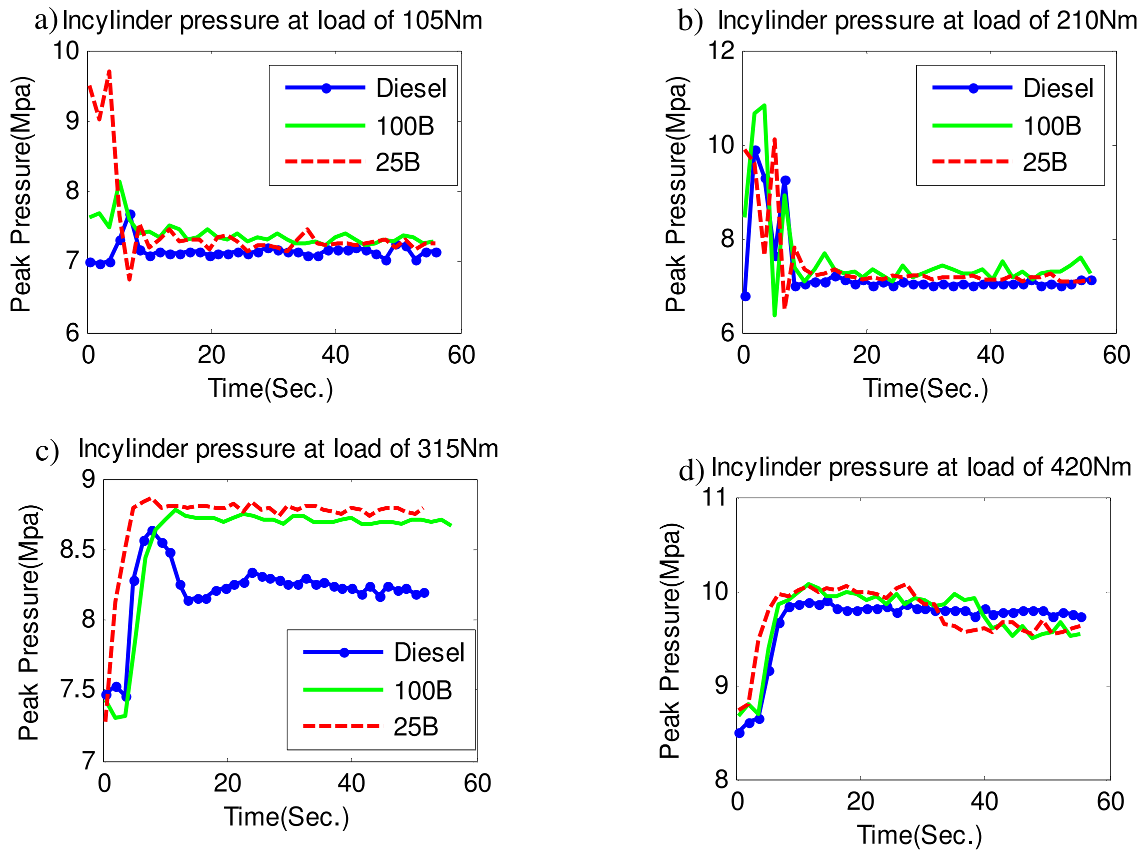


**Figure 3** In-cylinder pressure comparison of diesel and biodiesel for load of a)105Nm, b)210Nm, c)315Nm and d)420Nm and transient process of 1200 to1500rpm.

The main reason for higher peak in-cylinder pressure in a CI engine running by biodiesel is the advanced combustion process initiated by higher fluidity of biodiesel derived from the physical properties of biodiesel in Table 1. Moreover, due to the presence of oxygen in biodiesel, the hydrocarbons undergo complete combustion [16].

Figure 4 shows the carbon dioxide ($CO_2$), nitrogen oxides (NOx), carbon monoxide (CO), oxygen ($O_2$) and total hydro carbon (THC), and emissions from the CI engine running on 100B for a transient condition of operation during which speed is changed from 1500rpm to 1800rpm within 4 seconds at a load of 315Nm. The speed transients used for these tests are described in figure 4(a). These transients had three speed changes (900 to 1200rpm, 1200 to 1500rpm and 1500 to 1800rpm). Figure 4(b) shows the $CO_2$ emission at a load of 315Nm.

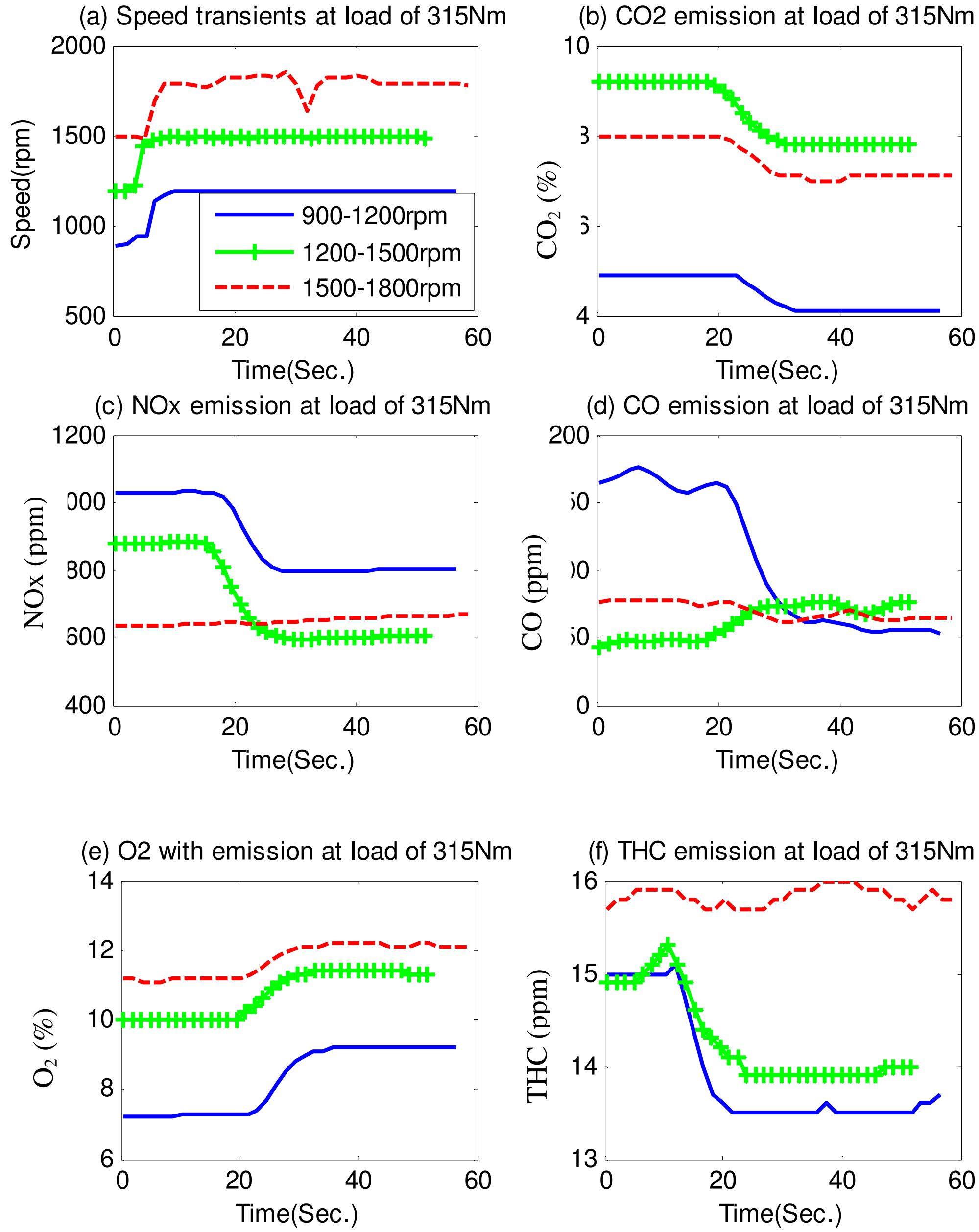


**Figure 4** Carbon dioxide ($CO_2$), nitrogen oxides (NOx), carbon monoxide (CO), Oxygen ($O_2$), total hydro carbon (THC) emissions of the CI engine running on 100B for transient speeds 900 - 1200rpm, 1200 – 1500rpm and 1500 – 1800rpm at load of 315Nm.

It can be seen that in both the steady-state and transient conditions the $CO_2$ emission during the transient process of 1200 to 1500rpm is higher than that observed for other transient conditions. This is because at a higher engine load, the fuel/air equivalence ratio entering the cylinder increases. To provide for the higher torque demand, the fuel must burn completely in the cylinder, resulting in higher $CO_2$ emission.

The NOx emission at a load of 315Nm and various transient speed changes is shown in figure 4(c). These NOx emissions were found to decrease with the increase in engine speed. This is due to the higher volumetric efficiency and gas flow rate within the engine cylinder observed at higher engine speeds. This leads to faster mixing of air and fuel and minimises the ignition delay, which facilitates the NOx emissions [1]. Figure 4(d) shows the CO emissions at a load of 315Nm for transient speed changes. It can be seen that the CO emissions show highest value during a lower speed change (900rpm to 1200rpm). The acceleration between 1200 to 1500rpm corresponds to the lowest observed CO emissions. This is because at lower engine speeds, the gas temperature in the cylinder is lower, which prevents the CO component to be effectively converted to $CO_2$. The CO and $CO_2$ emission values show opposing trends as shown in figure 4(b) and 4(d). At higher engine speeds the air/fuel equivalence ratio increases which results in an increase in the in-cylinder gas temperature. This leads to an increase in the kinetic reaction rate from CO to $CO_2$. This lowers the CO emission at higher engine speeds.

Figure 4(e) shows the CI engine release of $O_2$ gas in the exhaust at a load of 315Nm corresponding to three engine speed profiles. It is found that when the engine speed increases the $O_2$ gas levels also increase in the exhaust line. The THC emissions corresponding to 100B at a load of 315Nm for various transient profiles is shown in figure 4(f). It can be seen that the THC emission increases with increase in the engine speed. This is because when the engine speed increases the fuel demand by the engine also increases. As a result the fuel/air ratio becomes higher, resulting in more unburnt carbon and hydrogen molecules being emitted.

Figure 5 shows the comparison of various emissions for CI engine running on diesel, 25B and 100B fuels at a load of 315Nm and an engine transient corresponding to a speed change from 1200 to 1500rpm. Figure 5(a) shows the engine speed change profiles. It can be seen that the engine speeds for the three fuel tests show variations within an acceptable range. The carbon dioxide ($CO_2$) emission for diesel, 25B and 100B as test fuels under constant torque and a speed change from 1200 - 1500rpm in 4sec are shown in figure 5(b). Under such transient conditions the 25B and 100B fuels show lower $CO_2$ emission value than diesel fuel by 43% and 52% respectively. This is because biodiesel has lower number of carbon molecules than diesel fuel (i.e. biodiesel: 77% and diesel: 87% as described in Table 1). Hence the combustion of biodiesel results in lower $CO_2$ emission than diesel.

Figure 5(c) shows the nitrogen oxides (NOx) emissions at 315Nm load for a speed change from 1200 to 1500rpm. It is seen that NOx emission when running on 25B and 100B fuels is higher than that when runnig on diesel by 13% and 17% respectively. The main reason for higher emission of NOx in case of biodiesel is the advanced combustion process initiated because of the physical properties of biodiesel (viscosity, density, compressibility, sound velocity) [16]. When biodiesel is injected the increase in pressure produced by the pump is quicker as a consequence of its lower compressibility (higher bulk modulus), and thus propagates quicker towards the injectors. In effect, the gases in the cylinder are rich in fuel at the peak temperature which speeds up the formation NOx.

Figure 5(d) shows carbon monoxide emissions (CO) at a torque of 315Nm for speed change from 1200 to 1500rpm in 4 seconds. At lower engine speeds the engine running on biodiesel blends shows higher CO emissions. However at higher engine speeds, when running on 25B and 100B it shows lower CO emissions than normal diesel by 13% and 18% respectively. This may be due to lower carbon content of biodiesel and the early initiation of the combustion due to the additional oxygen molecule in the biodiesel molecular structure. Figure 5(e) shows the release of $O_2$ gas in the exhaust of a CI engine at a load of 315Nm. It can be seen that biodiesel releases a higher level of oxygen than diesel fuel. Figure 5(f) shows the total hydrocarbon (THC) emission at a torque of 315Nm for speed change from 1200 to 1500rpm. When running on 25B and 100B fuels the engine emits lower amount of THC than when running on diesel fuel by 22% and 38% respectively. This may be because of biodiesel having 11% oxygen in its chemical composition. The presence of oxygen a) reduces the number of carbon and hydrogen molecules that enter the cylinder and, b) ensures the complete combustion of hydrogen and carbon. In addition, biodiesel has higher cetane number that reduces the combustion delay.

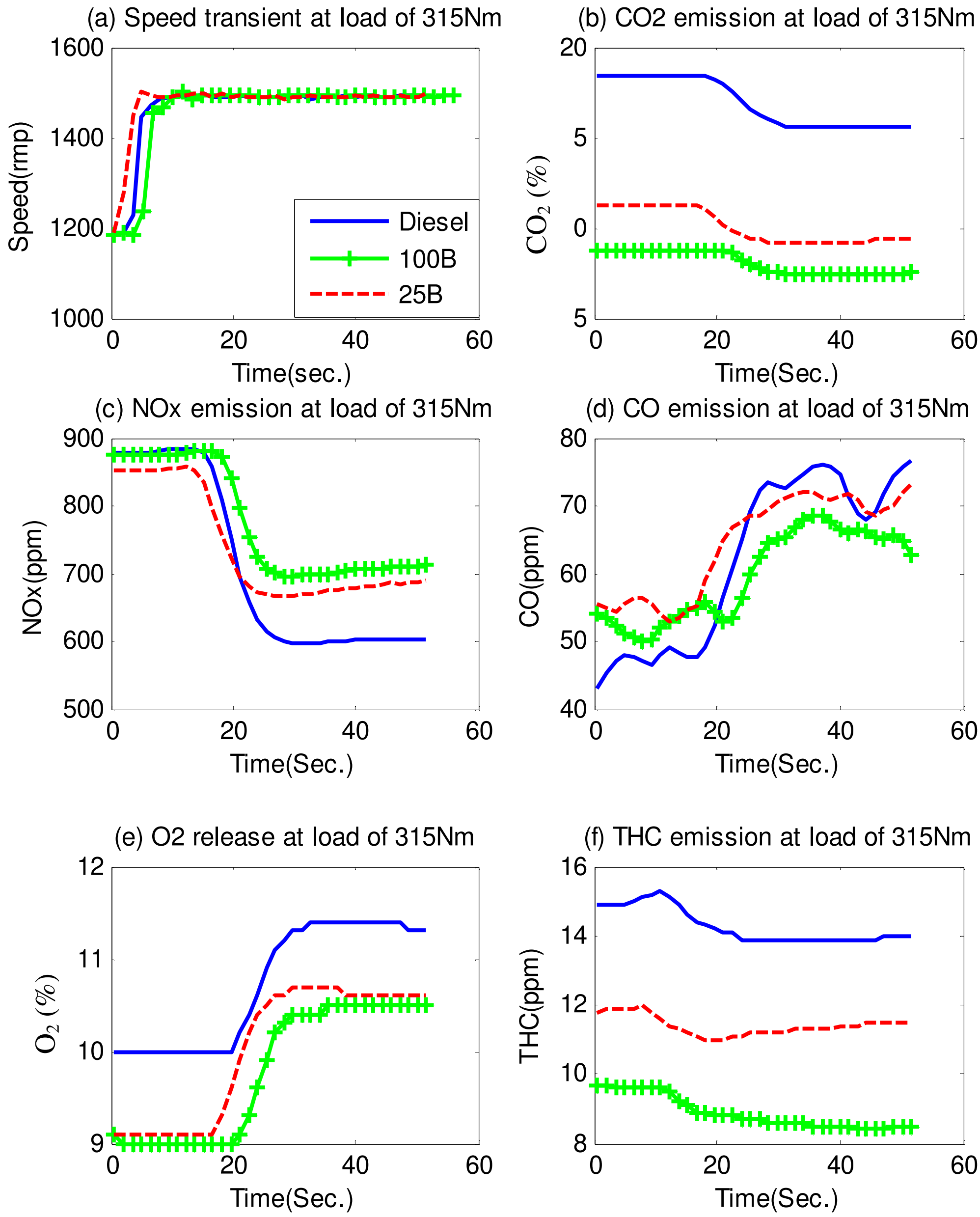


**Figure 5** Carbon dioxide ($CO_2$), nitrogen oxides (NOx), carbon monoxide (CO), Oxygen ($O_2$), total hydro carbon (THC) emissions of the CI engine running on 100B, 25B and diesel for transient speeds 1200 - 1500rpm at load of 315Nm.

# 5. CONCLUSION

In the present study experimental investigation has been carried out on compression ignition (CI) engine using blends of biodiesel and diesel fuels under steady state and transient operating conditions at constant engine load. The experimental results of this study can be summarised as follows.

1. An increase in engine speed causes increase in $CO_2$, NOx and THC emissions and reduction in CO emission for both biodiesel and diesel.
2. In all load conditions, the engine running on biodiesel blends have higher in-cylinder peak pressure.
3. The transient test results show lower emissions from the CI engine running on biodiesel. For CO this reduction was up to 17%, for $CO_2$ the reduction was up to 52% and for THC it was up to 38% as compared to diesel fuel.
4. However the $NO_x$ emission results show up to 17% higher emission for engine running on biodiesels as compared to that running on diesel during transient conditions.

# References


[1] Lin Cherng-Yuan Lin Hsiu, "Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process" Fuel 85, pp. 298–305, 2006.

[2] Magı´n Lapuerta , Octavio Armas, Jose´ M. Herreros, "Effect of biodiesel fuels on diesel engine emissions" Progress in Energy and Cumbstion Science 34(2008), pp. 198-223, 2008.

[3] Mondt, J.R., "Cleaner cars : the history and technology of emission control since the 1960s", Warrendale, Pa. : Society of Automotive Engineers

[4] Graboski, M.S. & McCormick, R.L., "Combustion of fat and vegetable oil derived fuels in diesel engines", Progress in Energy and Combustion Science, 24(2), 125-164, 1998.

[5] Marshall W, Schumacher LG, Howell S "Engine exhaust emissions evaluation of a Cummins L10E when fuelled with a biodiesel blend", SAE paper 952363, 1995.

[6]. Wang, W., Lyons, D., Clark, N., & Gautam, M., "Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification", Environmental Science & Technology, 34(6), 933-939, 2000.

[7] Durbin, T., Collings, J., Norbeck, J., & Smith M., " Effects of Biodiesel, Biodiesel Blends, and a Synthetic Diesel on Emissions from Light Heavy-Duty Diesel Vehicles", Environmental Science & Technology, 34(3), 349-355, 2000.

[8] Lapuerta, M., Armas, O., Ballesteros, R., & Fernandez,J., "Diesel emissions from biofuels derived from Spanish potential vegetable oils", Fuel, 84(6), 773-780, 2005..

[9] Nabi, M.N., Akhter, M.S. & Zaglul Shahadat, M.M., "Improvement of engine emissions with conventional diesel fuel and diesel-biodiesel blends", Bioresource Technology, 97(3), 372-378, 2006..

[10] Dorado, M., Ballesteros, E., Arnal, J., Gómez ,J., & López, F., "Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil", Fuel, 82(11), 1311-1315, 2003

[11] Ramadhas, A., Muraleedharan, C. & Jayaraj, S., "Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil", Renewable Energy, 30(12), 1789-1800, 2005.

[12] Lin Cherng-Yuan Lin Hsiu, Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. Fuel 85, pp. 298–305, 2006.

[13] Turrio-Baldassarri, L., Battistelli C., Conti, L., Crebelli, R., Berardis, B., Iamiceli, A., Gambino M., & Iannaccone, S., " Emission comparison of urban bus engine fueled with diesel oil and biodiesel' blend", Science of the Total Environment, 327(1-3), 147-162, 2004.

[14] Monyem, A. & H. Van Gerpen, J., "The effect of biodiesel oxidation on engine performance and emissions", Biomass and Bioenergy, 20(4), 317-325, 2001.

[15] Armas, O., Hernández, J.J. & Cárdenas, M.D., "Reduction of diesel smoke opacity from vegetable oil methyl esters during transient operation", Fuel, 85(17-18), 2427-2438, 2006.

[16] Lapuerta, M., Armas, O. & Rodríguez-Fernández, J., "Effect of biodiesel fuels on diesel engine emissions", Progress in Energy and Combustion Science, 34(2), 198-223, 2008.

## CONTACT INFORMATION

Belachew C Tesfa
Email: b.c.tesfa@hud.ac.uk, belachewmu@yahoo.com
Telephone: +44(0)1484471193, Fax: +44(0)1484421106
Computing and Engineering
University of Huddersfield
Queensgate, Huddersfield, HD1 3DH, UK