An Analysis of Biodiesel Combustion on Diesel Technologies

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ABSTRACT

The 2 set of engine experiments have been conducted to verify the effect of biodiesel blended fuel on diesel combustion for the low pressure diesel direct injection and common-rail direct injection. For low pressure (300 – 500 bar.G), the presence of biodiesel affect to the improvement of fuel ignition quality. While, the common-rail DI, the fuel conversion efficiency and ignition quality could help improving the engine combustion only at low speed high load condition. This result, at least, broaden our understanding that only 6 number higher in cetane quality will not discriminate the engine performance especially at steady-state condition.

INTRODUCTION

Biodiesel is widely used as a diesel component worldwide as well as in Thailand. Even there are so many research papers studied about biodiesel combustion, performance and emission, the various sources of biodiesel and engine technologies makes it more and more complicated to conclude that how biodiesel combustion react to the engine response especially for transient application. Some of biodiesel user always claims that the presence of biodiesel component in diesel fuel influence on poor engine drive-ability even only 5% v/v. While, there is a few publications comment on the low sensitivity of diesel fuel ignition delay when running with advance common-rail DI engine.

The objective of this study is to determine the effect of biodiesel blended fuel on the combustion quality in terms of performance and drive-ability.

For the 1st experiment, the purpose was to compare the results of CI engine combustion when the testing biodiesel fuel and the fuel injection pressure were varied from “B0” to “B50” and 300 to 500 bar respectively. The test was run in the steady-state mode, and the following parameters were determined.

- Brake Mean Effective Pressure (BMEP)
- Brake Specific Fuel Consumption (BSFC)
- Indicated Mean Effective Pressure (IMEP)
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- The maximum rate of pressure rise (Rmax)
- Ignition delay (IGN_DELAY)

For the 2nd experiment, the purpose was to compare the results of CI engine combustion while the engine was operating in the transient mode. In the test, the normal diesel and “B100” biodiesel were used as fuel to compare the results. The following parameters were determined.

- The response characteristics (SPEED and TIME) of the engine during the transient mode
- Indicated Mean Effective Pressure (IMEP) that was generated inside the combustion chamber
- The maximum rate of pressure rise (Rmax)

EXPERIMENTS

All experiments are base on reference standard fuel properties in Thailand [Euro III], whereas the diesel engine technology [Common-rail DI].

TEST FUELS

Base diesel fuel quality is comparable to Euro III diesel fuel, while the biodiesel blend produced from Palm Oil. All test fuels properties are reported in table A1.

THE 1st EXPERIMENT

In the 1st experiment, the RICADO HYDRA engine was operated in steady-state mode. 5 different types of diesel fuel were tested in this experiment “B0”, “B5”, “B10”, “B20”, and “B50”. The table below summarizes the test conditions according to speed, injection pressure, start of injection, and injection duration.

SPEED (RPM)	IINJECTION PRESSURE (BAR)	START OF INJECTION (DEG)	INJECTION DURATION (DEG)
1200	300	-7.0	9.0
	400	-8.0	7.7
	500	-10.0	6.5
1500	300	-10.0	12.0
	400	-11.0	10.1

	500	-12.0	8.5
1800	300	-14.0	15.5
	400	-15.0	12.8
	500	-16.0	11.0
2000	300	-16.0	18.7
	400	-13.0	15.3
	500	-11.0	12.7
2500	300	-20.0	24.5
	400	-18.0	19.6
	500	-16.0	16.0

There were 5 different speeds, which varied from 1200-2500 rpm, being tested. At each speed, the fuel was injected, following the start of injection and the duration in the table, with the injection pressure of 300-500 bar. Before taking measurement, some parameters were controlled. The fuel temperature was set at 40°C statically during the test, whereas the set point of engine coolant temperature was about 85°C. As everything was readily prepared, all considered parameters were recorded by averaging values in 30 seconds. All parameters indicated in the table above were optimized to the best condition at all engine speeds and common-rail pressures.

THE 2nd EXPERIMENT

In the 2nd experiment, the TOYOTA 2KD-FTV engine was operated in constant speed and load as well as the 1st experiment. This experiment aims to compare the combustion parameter from various contents of biodiesel blend with the recent common-rail DI engine technology [Euro III].

THE 3rd EXPERIMENT

In the 3rd experiment, the TOYOTA 2KD-FTV engine was operated in transient mode. The normal diesel and “B100” biodiesel were used as 2 different types of fuel to compare the results of combustion. In this experiment, the test was categorized into 3 patterns to simulate the real driving situations.

The first pattern

This pattern represented the car acceleration. The engine was programmed to operate from the speed of 1200 rpm with 20% of the throttle position. Then, both of them linearly increased until the speed reached 1800 rpm with fully-pressed 100% of throttle position within 5 seconds. And the speed continued linearly increasing with the same throttle position in the next 10 seconds. In this 15 seconds period, all considered parameters were recorded.

The second pattern

This pattern controlled the engine speed to remain constant while the engine load was increasing. The test was operated at 3 different speeds such as 1800 rpm, 2700 rpm, and 3600 rpm. The throttle was set from 20% to 100% linearly in 15 seconds for the engine speed of 1800 rpm. The considered parameters were recorded. For the engine speed of 2700 rpm and 3600 rpm, the initial throttle position was 30% and 40% respectively.

The third pattern

It represented deceleration situation of the car. Initially, the engine was running at constant speed of 3000 rpm with wide open throttle (WOT) position. Then, the engine speed and the throttle position started linearly decreasing. Within 5 seconds, the engine speed reached 2400 rpm, whereas the throttle position remained 20%. In the next 10 seconds, the engine speed continued decreasing to 1200 rpm with 20% throttle position. In this 15 seconds period, all considered parameters were recorded.

During the experiment, the fuel temperature and the engine coolant temperature were controlled. The fuel temperature was set at 40°c statically during the test, whereas the set point of coolant temperature was about 85°c. As everything was readily prepared, all considered parameters were able to be recorded.

RESULT AND DISCUSSIONS

FUEL PROPERTIES

Referring to Appendix A, the present of biodiesel fuel component is an effective cetane improver for diesel fuel, i.e. B50 cetane number is about 6 number higher than B5. However, the adverse effects of biodiesel fuel are 7% lower in heating value for B50, easily to absorb moisture and higher acidity value which may cause the fuel oxidized faster. Obviously, the higher biodiesel blended fuel has higher Total Acidity Number, higher product of oxidation and higher water content especially in the form of dissolved water. All those factors would be affected to engine component durability, which are not the major topic of discussion by this study. Thus, only a few factors that would have impact on fuel combustion and drive-ability are cetane number and heating value. In general, higher cetane number or higher content of biodiesel blend result in the shorter ignition delayed. The trade-off between ignition delay and heating value must be concerned.

LOW PRESSURE FUEL SYSTEM [300–500 barG]

Effect of fuel injection pressure vs ignition delay

At low engine speed i.e.1,200 – 1,800 rpm, variation of fuel injection pressure from 300 – 500 bar was taken no advantage from the shorter ignition delay (there is no difference ignition delay for a wide range of cetane number fuels), whilst the higher fuel injection pressure caused higher combustion noise. It was noticeable by the higher maximum rate of pressure rise data. At medium to high engine speed 2,000 – 2,500 rpm, the engine combustion behaved in different way. The higher fuel injection pressure affects on the shorter ignition delay when running with the same fuel. Furthermore, the maximum rate of pressure rise has also been improved or decreased by increasing fuel injection pressure. In conclusion, higher fuel injection pressure can reduce combustion noise when running at medium to high engine speed as a result of shorter ignition delay.

<u>Effect of biodiesel content on ignition delay</u>

When focusing on medium to high engine speed (2,000 rpm – 2,400 rpm), the higher biodiesel blended fuel or the higher cetane number fuel help improving combustion noise and ignition delay especially when running at the higher fuel injection pressure. Influence of biodiesel blended fuel will help reducing ignition delay when engine operating at medium to high engine speed while the fuel was injected at higher injection pressure.

HIGH PRESSURE COMMONRAIL-DI [EURO III]

<u>Effect of Biodiesel Blend on steady-state</u>

From engine characteristic, the flat torque region of 2KD-FTV engine is range from 2,000 rpm to 3,200 rpm. The engine responses on biodiesel blended fuels in proportional way i.e. higher biodiesel blend result in the lower output torque as well as BMEP and BSFC. By the way, the engine noise or maximum rate of pressure rise for common-rail DI has been controlled at low level by the engine whether running with up to 50% biodiesel blended fuel. For steady-state condition running at full load, the common-rail DI engine performed excellent output especially during flat torque region and also minimizing the difference fuel properties such as ignition delay, output torque and burn duration. While, running the engine at the outer flat torque region can discriminate the physical fuel properties more easily such as ignition delay at low engine speed. For the part load - low speed condition the shorter ignition delay of B50 has greatly benefit on engine output as compared by IMEP. See appendix C.

<u>Effect of Biodiesel Blend on Transient state:</u>

Acceleration – speed and load variation:

This section considers the combustion quality in terms of performance and drivability during the car acceleration in 15 seconds. The engine speed increased from 1200 rpm to 3000 rpm with the change of the throttle position from 20% to 100%. The graphs below displays the considered parameters – Response Speed and Time, IMEP, Rmax, Start of Injection, Start of Combustion, Ignition Delay, and Fuel Mass Burned Fractions.

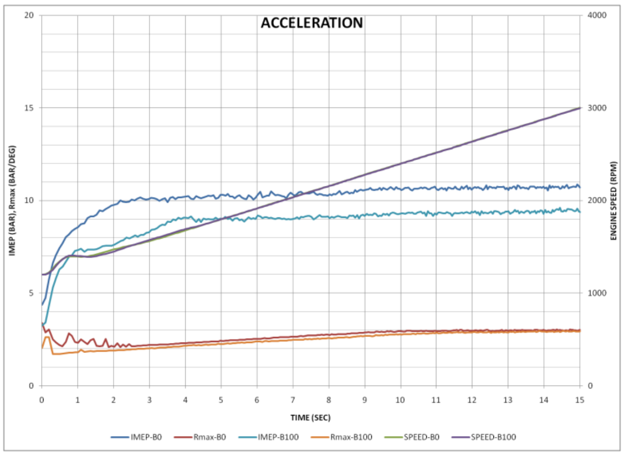

Figure 1: Transient Acceleration Test IMEP, Rmax Vs Time

The results show that the engine using “B0” fuel required approximately 2.2 seconds providing the new steady maximum IMEP, whereas “B100” biodiesel required more response time about 3.8 seconds. When IMEP reached the maximum, it shows that “B100” biodiesel provided less IMEP than “B0” about 12%. The rate of pressure rise shows that “B100” biodiesel combustion was slightly less severe than “B0” about 7%.

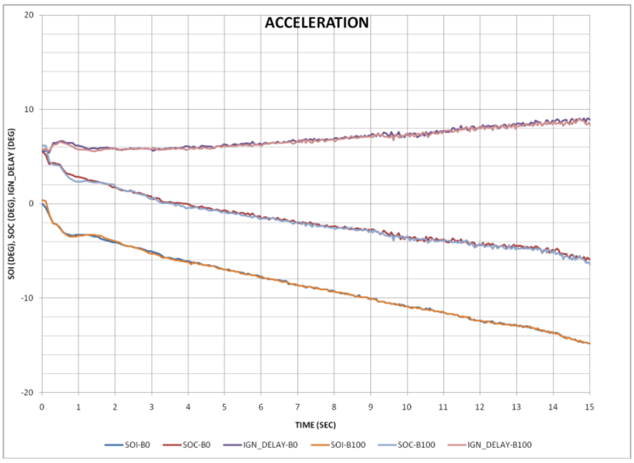

Figure 2: Transient Acceleration Test SOI, SOC, IGN_DELAY Vs Time

For the ignition delay, there was no difference between “B0” and “B100” combustions since both the start of injection and the start of combustion demonstrated the same characteristics.

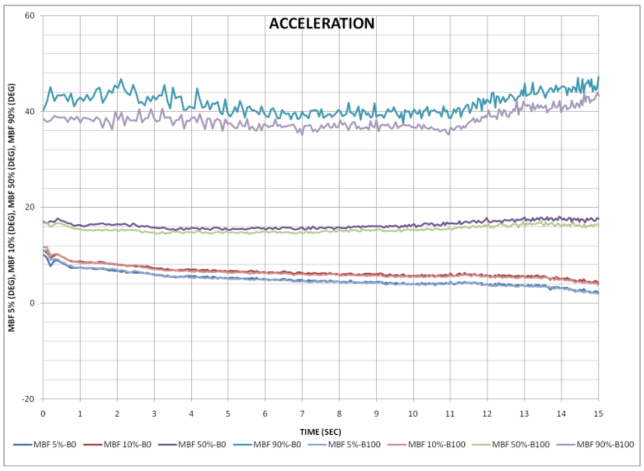

Figure 3: Transient Acceleration Test MBF 5%, 10%, 50%, 90% Vs Time

For the fuel mass burned fraction, “B0” and “B100” biodiesel were burned at 5% and 10% in the same manner. The deviation, however, started to be noticed at 50% burned fraction, and obviously seen at 90%. The 50% and 90% amount of “B100” biodiesel was combusted faster than “B0” about 0.8 °CA and 2.9 °CA respectively.

Constant speed – Increase Load:

This section considers the combustion quality in terms of performance and drivability during the car remains the constant speed. The throttle position increased from 20%, 30%, and 40% to 100% at the speed of 1800 rpm, 2700 rpm, and 3600 rpm respectively in 15 seconds. The graphs below displays the considered parameters – Response Speed and Time, IMEP, Rmax, Start of Injection, Start of Combustion, Ignition Delay, and Fuel Mass Burned Fractions.

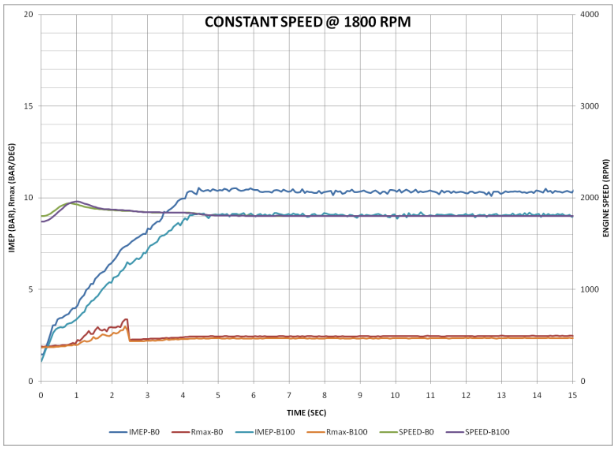

Figure 4: Constant Speed @ 1,800 rpm Test IMEP, Rmax Vs Time

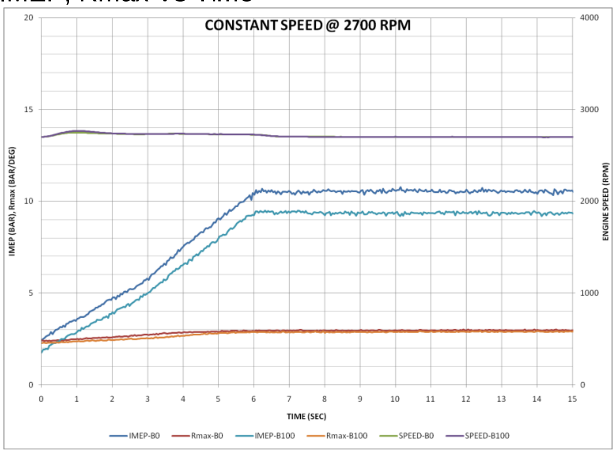

Figure 5: Constant Speed @ 2,700 rpm Test IMEP, Rmax Vs Time

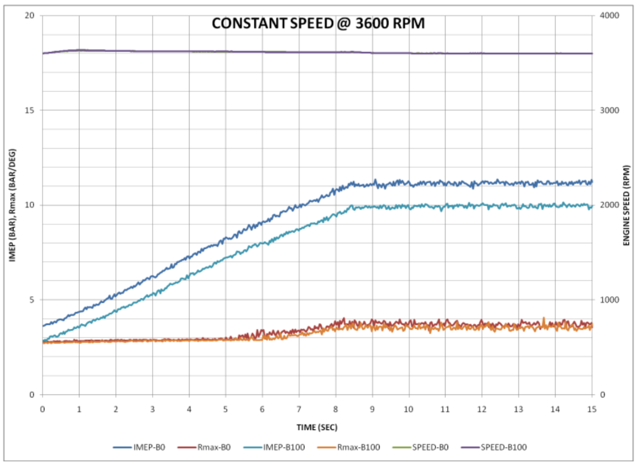

Figure 6: Constant Speed @ 3,600 rpm Test IMEP, Rmax Vs Time

The results show that the engine using “B100” biodiesel required the same response time to provide the new steady maximum IMEP as “B0”. When IMEP reached the maximum, it shows that “B100” biodiesel provided less IMEP than “B0” about 10-13%. The rate of pressure rise shows that “B100” biodiesel combustion was slightly less severe than “B0” about 3-9%.

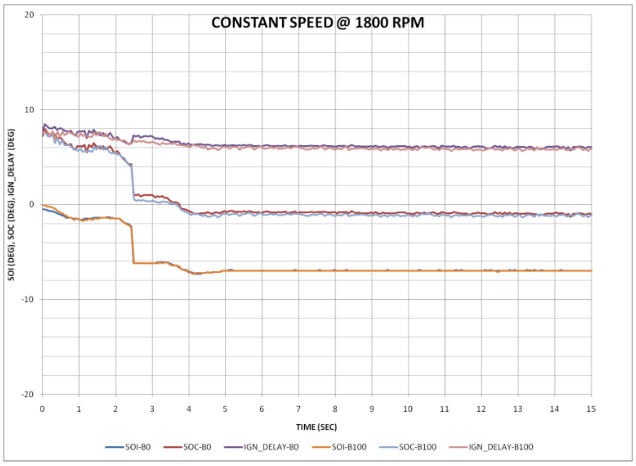

Figure 7: Constant Speed @ 1,800 rpm Test SOI, SOC, IGN_DELAY Vs Time

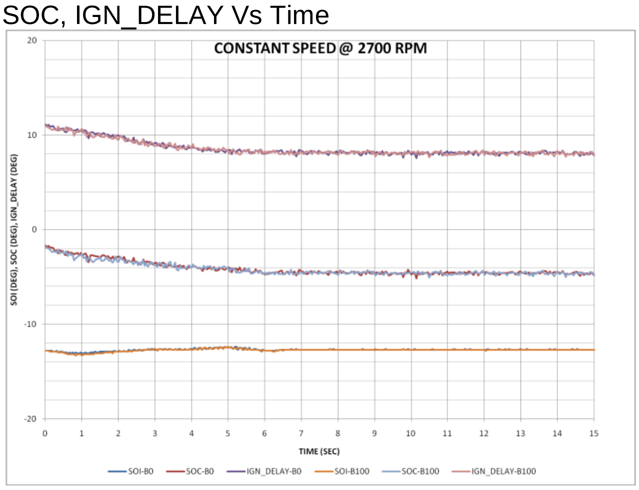

Figure 8: Constant Speed @ 2,700 rpm Test SOI, SOC, IGN_DELAY Vs Time

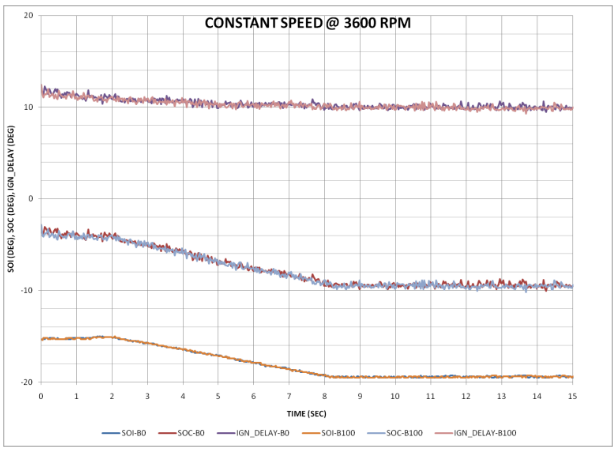

Figure 9: Constant Speed @ 3,600 rpm Test SOI, SOC, IGN_DELAY Vs Time

For the ignition delay, there was no difference between “B0” and “B100” combustions at the engine speeds of 2700rpm and 3600 rpm since both the start of injection and the start of combustion demonstrated the same characteristics. But at 1800 rpm, the auto ignition of “B100” biodiesel started prior than “B0” fuel about 3%.

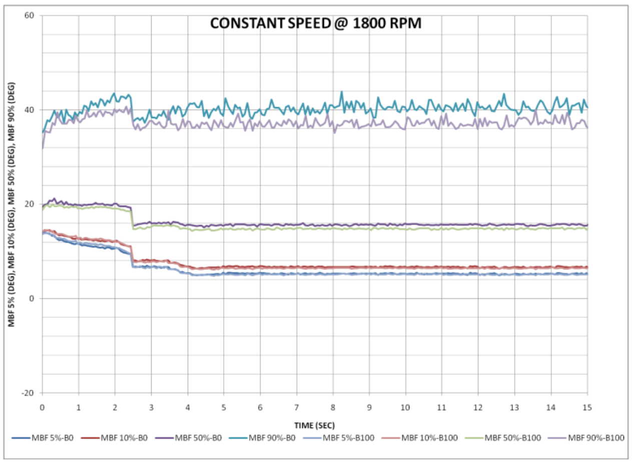

Figure 10: Constant Speed @ 1,800 Test MBF 5%, 10%, 50%, 90% Vs Time

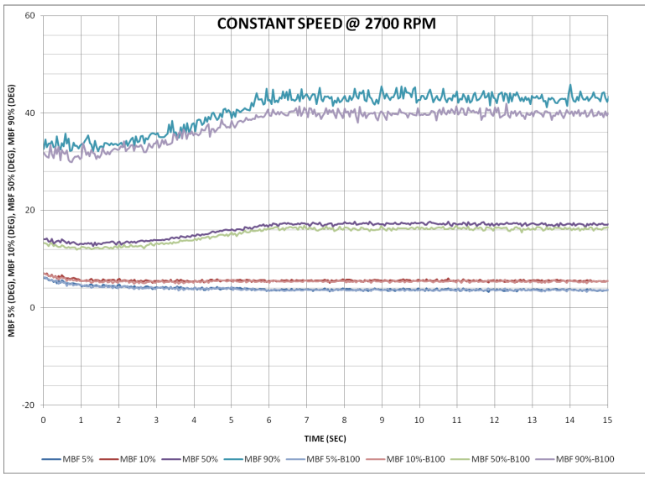

Figure 11: Constant Speed @ 2,700 Test MBF 5%, 10%, 50%, 90% Vs Time

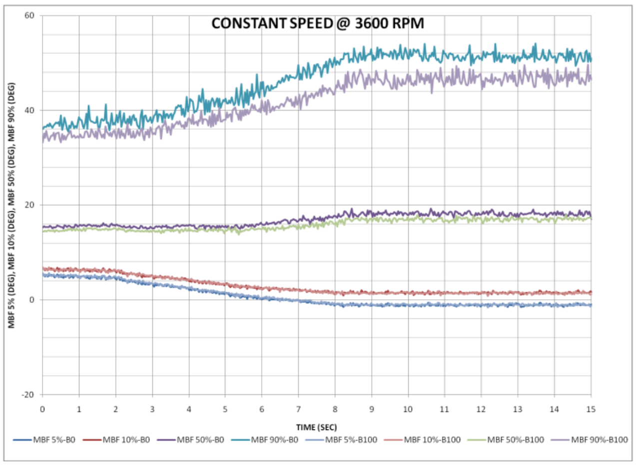

Figure 12: Constant Speed @ 3,600 Test MBF 5%, 10%, 50%, 90% Vs Time

And for the fuel mass burned fraction, “B0” and “B100” biodiesel were burned at 5% and 10% in the same manner. The deviation, however, started to be noticed at 50% burned fraction, and obviously seen at 90%. The 50% and 90% amount of “B100” biodiesel was combusted faster than “B0” about 0.8-1.7 °CA and 3.0-6.2 °CA respectively.

Deceleration – speed and load variation:

This section considers the combustion quality in terms of performance and drivability during the car deceleration in 15 seconds. The engine speed decreased from 3000 rpm to 1200 rpm with the change of the throttle position from 100% to 20%. The graphs below displays the considered parameters – Response Speed and Time, IMEP, Rmax, Start of Injection, Start of Combustion, Ignition Delay, and Fuel Mass Burned Fractions.

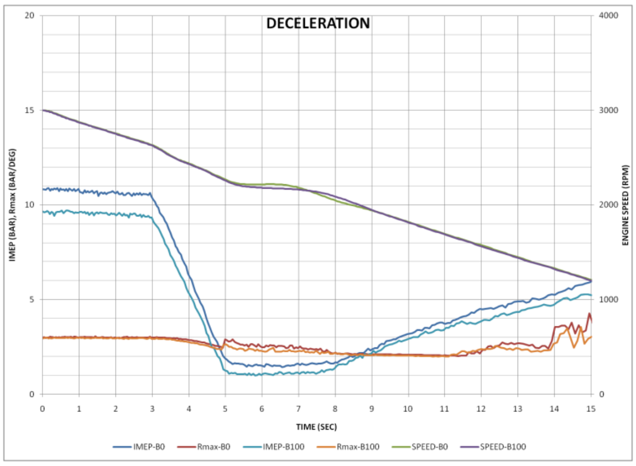

Figure 13: Transient Deceleration Test IMEP, Rmax Vs Time

The results show that “B100” biodiesel provided less IMEP than “B0” about 11%. And “B100” biodiesel combustion was slightly less severe than “B0” about 2% according to the rate of pressure rise.

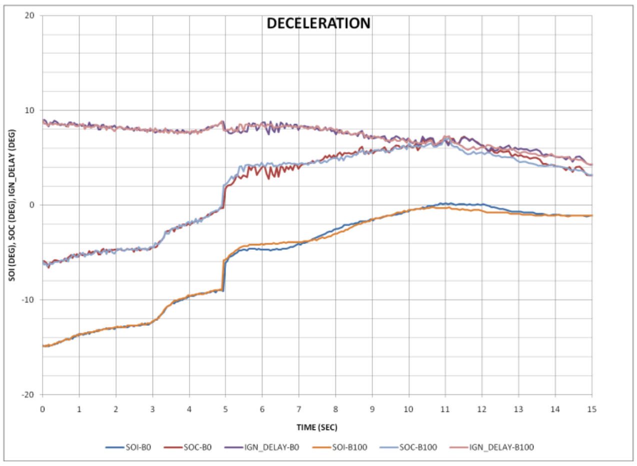

Figure 14: Transient Deceleration Test SOI, SOC, IGN_DELAY Vs Time

For the ignition delay, there was no difference between "B0" and "B100" combustions even though both the start of injection and the start of combustion of each test fuels were not obviously demonstrated in the same characteristics.

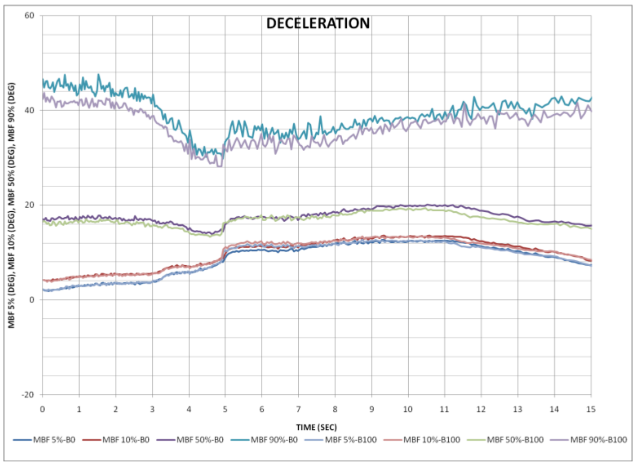

Figure 14: Transient Deceleration Test MBF 5%, 10%, 50%, 90% Vs Time

And for the fuel mass burned fraction, "B0" and "B100" biodiesel were burned at 5% and 10% in the same manner. The deviation, however, started to be noticed at 50% burned fraction, and obviously seen at 90%. The 50% and 90% amount of "B100" biodiesel was combusted faster than "B0" about 1.3 °CA and 3.5 °CA respectively.

CONCLUSION

Biodiesel fuel has high cetane number, but lower heating value comparing to diesel fuel. For conventional DI engine, higher fuel injection pressure can reduce combustion noise when running at medium to high engine speed as a result of shorter ignition. In modern HSDI engine or common-rail DI engine, running the engine within the flat torque region help compensating fuel cetane quality differentiation, while the outer region show more differentiation in fuel quality. In the later experiment, the transient combustion factor were evaluated B0 and B100, The only difference detected from acceleration mode is the 11% lower IMEP of B100 compared to base diesel tended to reduce the acceleration rate from idling to maximum IMEP.

Since the fuels cetane number difference are range from 64 to 70, then the degree of ignition delay will not explicitly difference. In addition, the recent commonrail-DI technology has already compensated the severe premixed combustion by promoting the pilot injection under low speed and low load. While the higher speed condition, the engine injected fuel with extremely high pressure.

From appendix D, the cylinder pressure profile pointed out that at low speed high load the higher fuel cetane (B50) quality help improving fuel conversion efficiency and also output IMEP. Then, the low speed high load is a specific operating regime that mainly influenced by fuel cetane quality.

The future research interest shall be focusing on how to quantify the fuel cetane quality effect onto engine response in some specific operating regime especially when running in transient mode.

REFERENCES

1. S. Jaroonjitsathian, N. Akarapanjavit, S. Siangsanorh, R. In-ochanon, A.Wuttimongkolchai, C. Tipdecho, K. Tsuchihashi, H. Shirakawa, "Evaluation of 5 to 20% Biodiesel Blend on Heavy-duty Common-rail Diesel Engine", SAE 2009-01-1894
2. R.G. Williams, P.J. Zemroch, D.M. Wall and B. Meredith, "The Effect of Fuel Cetane Quality on Light-duty Diesel Performance", Shell Global Solutions – CRC Project No. AVFL-11
3. T. Kamimoto and H. Kobayashi, "Combustion Processes in Diesel Engines", Prog. Energy Combust. Sci. 1991 Vol. 17 pp. 163 – 189.
4. K. Yamane, A. Ueta and Y. Shimamoto, "Influence of Physical and Chemical Properties of Biodiesel Fuel on Injection, Combustion and Exhaust Emission Characteristics in a DI-CI Engine", the 5th International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engine July 1-4, 2001.
5. T. Fang and C. F. Lee, "Bio-diesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies", Proc. of Comb. Inst. 32 (2009) 2785 – 2792.
6. C. Yang, Y. Kidoguchi, R. Kato and K. Miwa, "Effects of Fuel Properties on Combustion and Emissions of a Direct-Injection Diesel Engine", Bulletin of the M.E.S.J., Vol. 28, No. 2.
7. J.B. Heywood, "Internal Combustion Engine Fundamentals", McGraw-Hill Book Company, 1988.
8. J. R. Serrano, F. J. Arnau, V. Dolz and P. Piqqueras, "Methodology for characterization and simulation of turbocharged diesel

engines combustion during transient operation. Part 1: Data acquisition and post-processing. Applied Thermal Engineering 29 (2009) 142 - 149
9. T. Yonekawa, A. Okada, M. Ehara, T. Ogasawara, “Analysis of Driveability on Diesel Vehicles” SAE 840257
10. Y. Icingur, D. Altiparmak, “Experimental Analysis of the Effects of Fuel Injection Pressure and Fuel Cetane Number on direct Injection Diesel Engine Emissions” Turkish J. Eng. Env. Sci. 27 (2003), 291 – 297
11. J. P. Szybist, A. L. Boehman, “Behavior of a Diesel Injection System with Biodiesel Fuel” SAE 2003-01-1039

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APPENDIX

APPENDIX A: BIODIESEL BLENDED FUEL PROPERTIES

Table A1: Test Fuels Properties

PROPERTIES	B0	B5	B15	B20	*B50*
Specific gravity at 15.6/15.6°C	0.8271	0.8295	0.8338	0.8367	0.8514
Density at 40°C	0.8094	0.8117	0.8159	0.8187	0.8331
Cetane number	63.5	64.2	65.9	66.4	69.9
Viscosity at 40°C (cSt)	3.222	3.264	3.353	3.416	3.784
Pour point (°C)	-3	-3	-3	-3	6
Sulfur content (%wt)	0.0049	0.0048	0.0043	0.0040	0.0028
Copper strip corrosion (number)	1a	1a	1a	1a	1a
Carbon residue (%wt)	0.000	0.000	0.000	0.006	0.006
Water and sediment (%wt)	<0.025	<0.025	<0.025	<0.025	<0.025
Ash (%wt)	<0.005	<0.005	<0.005	<0.005	<0.005
Flash point (°C)	65.0	66.0	68.5	70.0	79.5
Distillation 90% recovery (°C)	350.7	349.3	348.4	345.1	340.2
Lubricity by HFRR (micron)	445	216	237	227	197
Gross heating value (J/g)	46,178	45,888	45,347	44,095	42,919
Oxidation stability (g/m^3)	2.3	3.1	4.9	5.7	8.0
Methyl ester for fatty acid, (%vol)	0.0	5.4	15.8	22.0	53.0
Total acid number (mgKOH/g)	0.02	0.02	0.04	0.06	0.13
TAN growth (mgKOH/g)	0.260	0.000	0.005	0.010	0.070
Water content (%wt)	0.007	0.009	0.012	0.014	0.020
Aromatic content (%wt)	15.9	15.0	13.6	12.4	7.79
% C	85.99	85.39	84.79	83.59	80.00
% H	14.01	13.91	13.81	13.61	13.01
% O	0.00	0.65	1.30	2.60	6.50

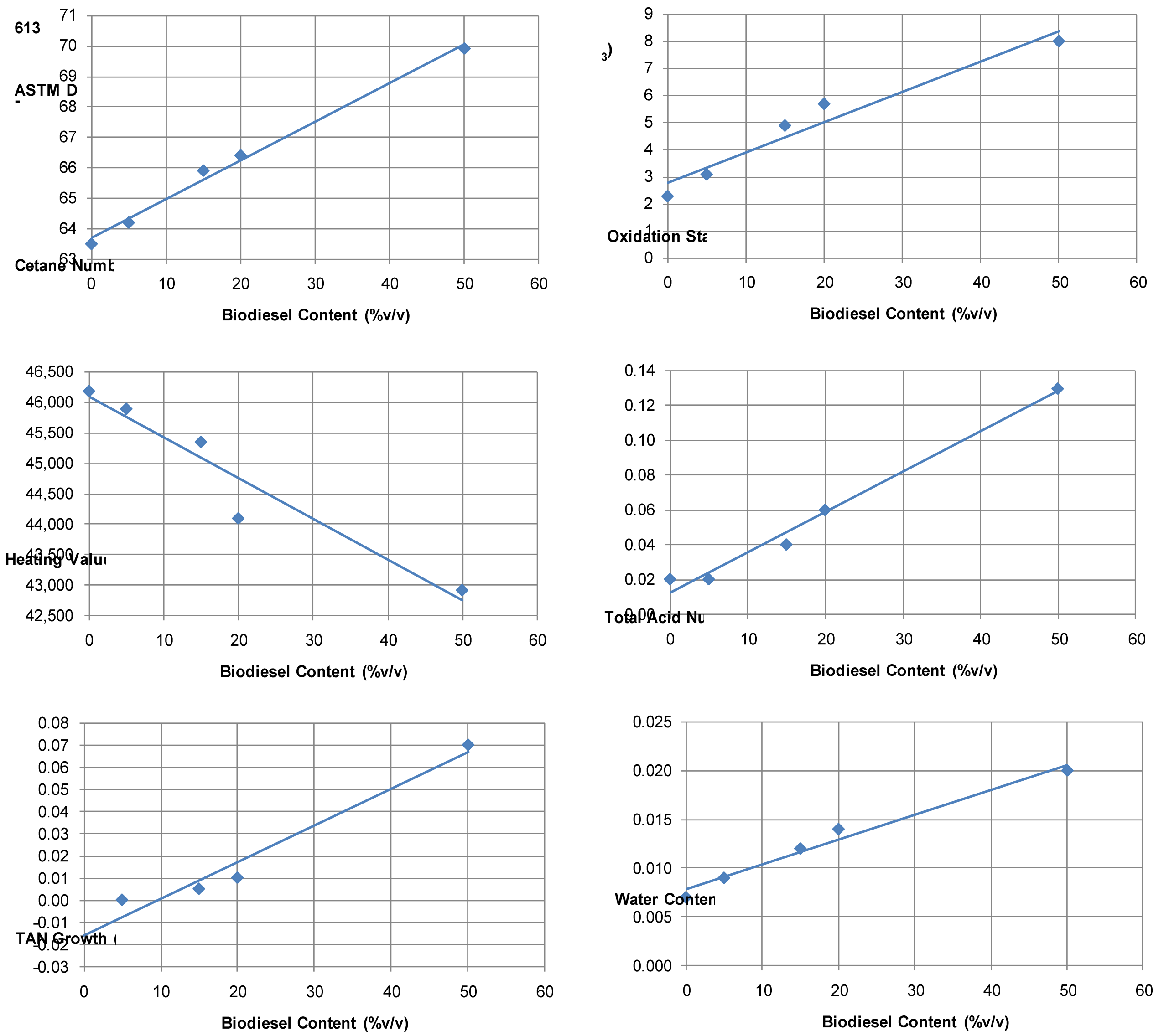
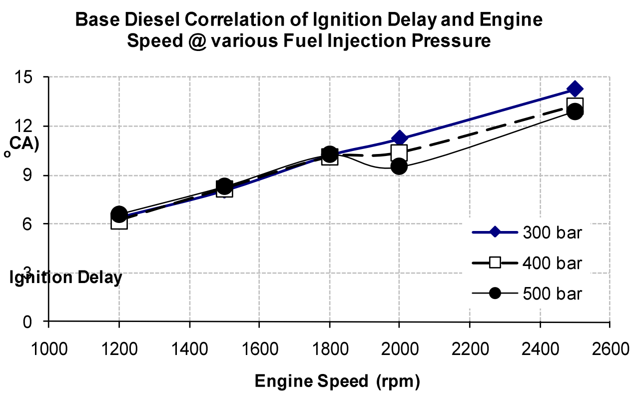


Figure A1: Biodiesel Blended Fuel Properties

APPENDIX B: FUEL INJECTION PRESSURE VS BIODIESEL CONTENT



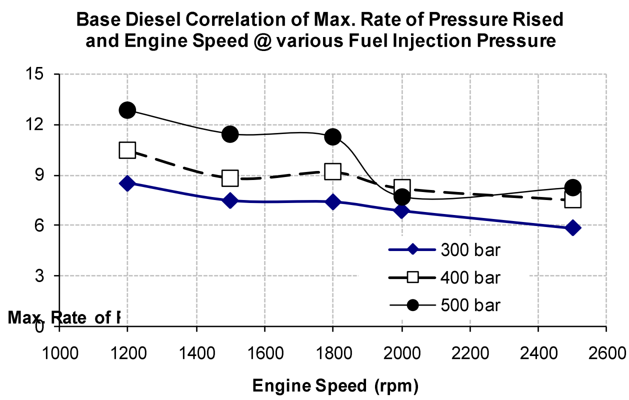


Figure B1: Ignition Delay vs Inj. Pressure **Figure B2:** Max. Rate of P Rise vs Inj. Pressure

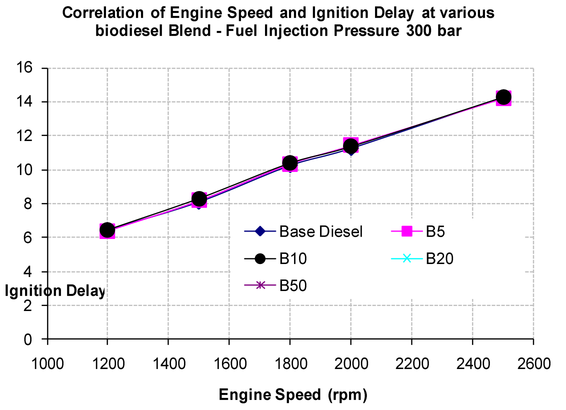


Figure B3: Ignition Delay vs %Biodiesel (300 bar)

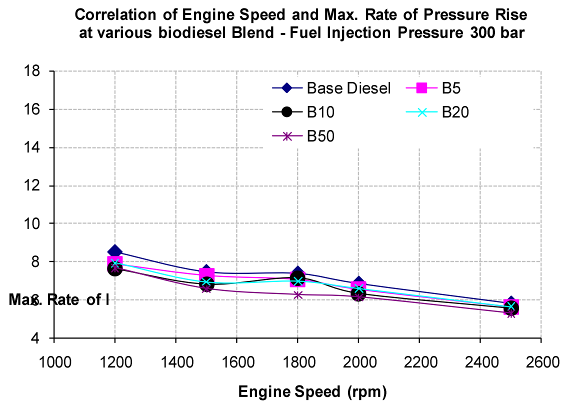


Figure B4: Max. ROPR vs % Biodiesel (300 bar)

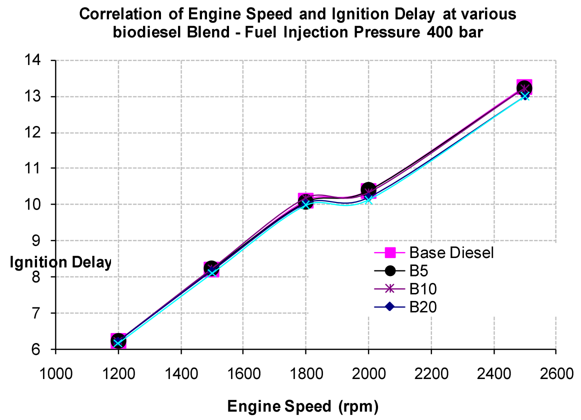


Figure B5: Ignition Delay vs %Biodiesel (400 bar)

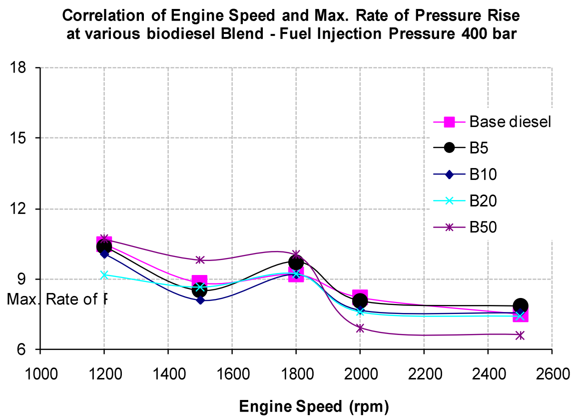


Figure B6: Max. ROPR vs Biodiesel (400 bar)

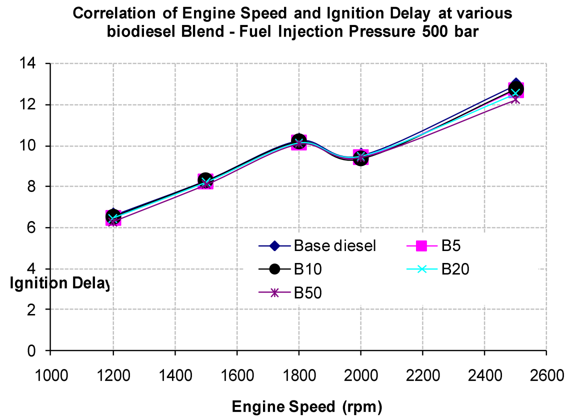


Figure B7: Ignition Delay vs %Biodiesel (500 bar)

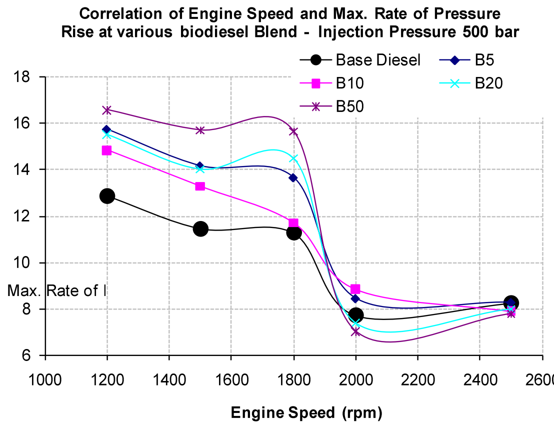
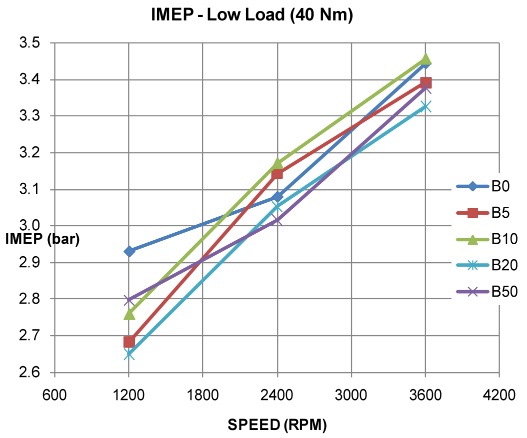
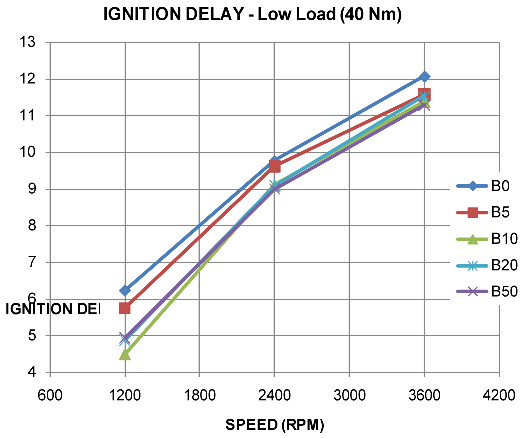
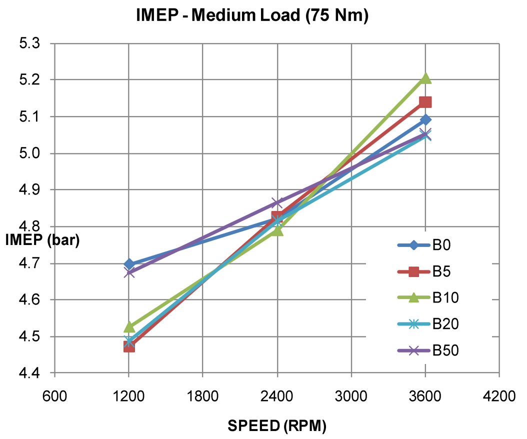


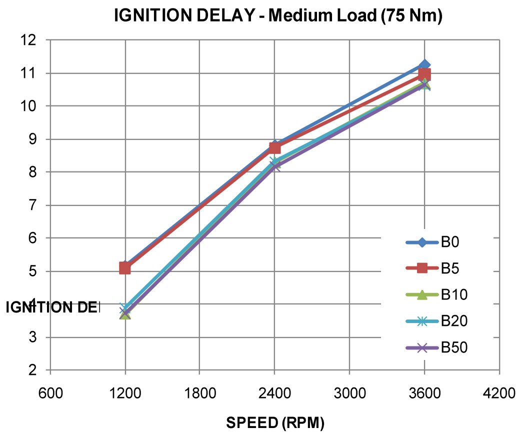
Figure B8: Max. ROPR vs % Biodiesel (500 bar)

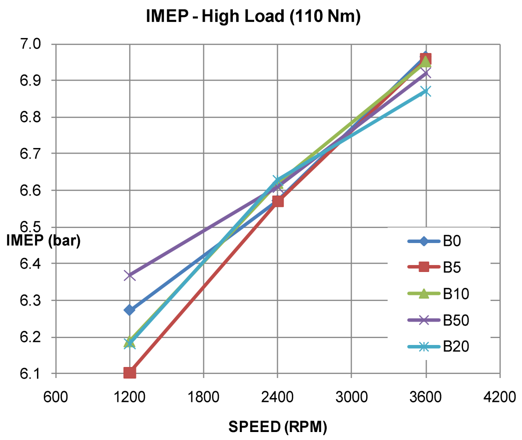
APPENDIX C: IGNITION DELAY VS BIODIESEL CONTENT (COMMONRAIL DI)

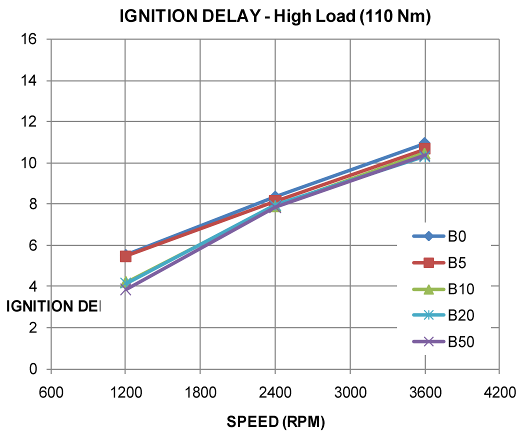


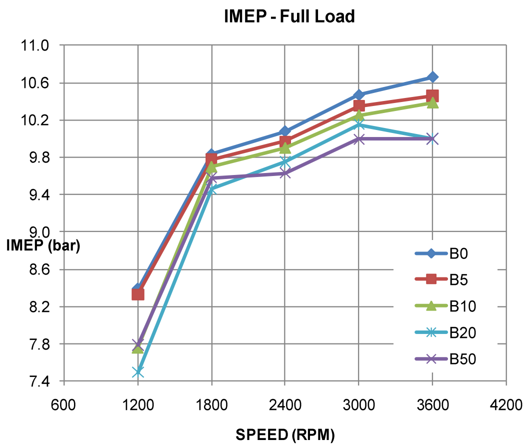












APPENDIX D: AVG. CYLINDER PRESSURE VS DEGREE CR (COMMONRAIL DI)