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CHARACTERISATION OF TRANSIENT DIESEL COMBUSTION WITH ADVANCED DIESEL FUELS

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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Field of Study	Mechanical Engineering
Thesis Advisor	Assistant Professor Dr. Nuksit Noomwongs
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สมนึก จรูญจิตเสถียร : การบ่งชี้คุณลักษณะการเผาไหม้ในช่วงทรานเซียนด้วยน้ำมันดีเซลคุณภาพสูง (CHARACTERISATION OF TRANSIENT DIESEL COMBUSTION WITH ADVANCED DIESEL FUELS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. นักสิทธ์ นุ่มวงษ์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ. ดร. ก่อเกียรติ บุญชูกุศล, 72 หน้า.

การศึกษานี้ได้ออกแบบวิธีการทดสอบทางด้านเครื่องยนต์ และการทดสอบด้วยรถยนต์บนวัฏจักรการขับขี่ NEDC - New European Driving Cycle เพื่อค้นหาวิธีการที่สามารถบ่งบอกพฤติกรรมการเผาไหม้ของเครื่องยนต์ดีเซลในช่วงทรานเซียน ในขณะเดียวกันต้องการใช้วิธีการดังกล่าวไปแยกแยะผลของคุณภาพน้ำมันเชื้อเพลิงกลุ่มดีเซลที่มีต่อเครื่องยนต์ดีเซลในช่วงการเผาไหม้แบบทรานเซียน สิ่งที่ได้จากการศึกษาครั้งนี้คือ พบว่าวิธีการทดสอบทางเครื่องยนต์ที่สามารถแยกแยะคุณภาพของน้ำมันเชื้อเพลิงได้ในช่วงทรานเซียนคือการทดสอบแบบอัตราเร็วรอบคงที่และเพิ่มภาระให้กับเครื่องยนต์ โดยดูจากค่า IMEP-Indicated Mean Effective Pressure, combustion phase ที่ 50% (CA50) และ combustion noise ในขณะที่การทดสอบด้วยรถยนต์บนวัฏจักรมาตรฐาน NEDC วิธีการที่เหมาะสม คือการวิเคราะห์การเผาไหม้ในช่วงวัฏจักรแรกของ ECE ที่มีอัตราเร่งไม่รุนแรง และไม่มีการเปลี่ยนเกียร์ โดยวิเคราะห์จากค่า IMEP, CA50 และ Injection duration เป็นหลัก และผลจากการศึกษานี้ทำให้เห็นว่าพฤติกรรมการเผาไหม้ช่วงทรานเซียนมีอิทธิพลมาจาก diffusion combustion เป็นหลัก ขณะที่การเผาไหม้แบบ steady-state มีอิทธิพลมาจาก premixed และ diffusion combustion ประกอบกัน

ภาควิชา	วิศวกรรมเครื่องกล	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมเครื่องกล	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
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KEYWORDS: DIESEL COMBUSTION / TRANSIENT COMBUSTION / DIFFUSION COMBUSTION / ENGINE EXEPERIMENT / COMBUSTION INDICATION / ADVANCE DIESEL FUEL

SOMNUEK JAROONJITSATHIAN: CHARACTERISATION OF TRANSIENT DIESEL COMBUSTION WITH ADVANCED DIESEL FUELS. ADVISOR: ASST. PROF. DR. NUKSIT NOOMWONGS, CO-ADVISOR: ASST. PROF. DR. KAUKEART BOONCHUKOSOL, 72 pp.

The design of engine experiments and vehicle running on chassis dynamometer by NEDC - New European Driving Cycle have been conducted for characterising diesel transient combustion behaviour, while the methods were intended to use for discriminating the effect of fuel quality difference on diesel fuels. The thesis deliverables are the proposed engine experiment method and vehicle running on NEDC for differentiating the fuel qualities. For the engine experiment, the suitable method of fuel characterising is load acceleration with constant engine speed by comparing the IMEP-Indicated Mean Effective Pressure, Combustion phase at 50% (CA50) and combustion noise. While, the vehicle running on NEDC could be investigated the combustion during the first loop of ECE, which there is no gear-shift. The detected parameters shall be IMEP, CA50 and injection duration. The information obtained from this study is that for transient diesel combustion, the diffusion phase of combustion is the major key of engine performance instead of both premixed combustion and diffusion combustion in the steady-state running.

Department:	Mechanical Engineering	Student's Signature	....
Field of Study:	Mechanical Engineering	Advisor's Signature	....
Academic Year:	2014	Co-Advisor's Signature	....

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The major success of the research comes mainly from my experience at workplace, PTT Research and Technology Institute, where I can acquire the precious knowledge whether from my supervisor Mr. Somchai Siangsanorh, my supporting staffs and colleagues. Many thanks for all of your contribution either direct or indirect support, especially for testing and collecting all research data for me. I am deeply appreciate to my advisor at work, Mr. Nirod Akarapanjavit PTT Vice President who has determined the R&D direction of PTT's engine laboratory for many years.

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CHAPTER 1: REVIEW OF LITERATURES

Recently, the research topics on the effect of biofuel on diesel engine combustion becomes one of the major alternative fuel interests. However, diesel engine technology is more advanced than the previous decade especially, when the high pressure common-rail direct injection was introduced since 1999. Effect of biofuel quality on engine, are range from the source of biofuel such as rapeseed, soy bean, palm oil and jatropha oil. While, the fuel conversion process like straight vegetable oil, refined vegetable oil or FAME – Fatty Acid Methyl Ester (biodiesel) are also one of the key parameter impacted on engine combustion. Engine Technology itself also range from mechanically driven fuel injection pump, electronic fuel injection pump, common-rail with solenoid injector, electronic unit injector and common-rail with piezo-injector. If one of those factors change, it could not be able to compare the result at all.

1.1 Effect of fuel quality on diesel combustion [history]

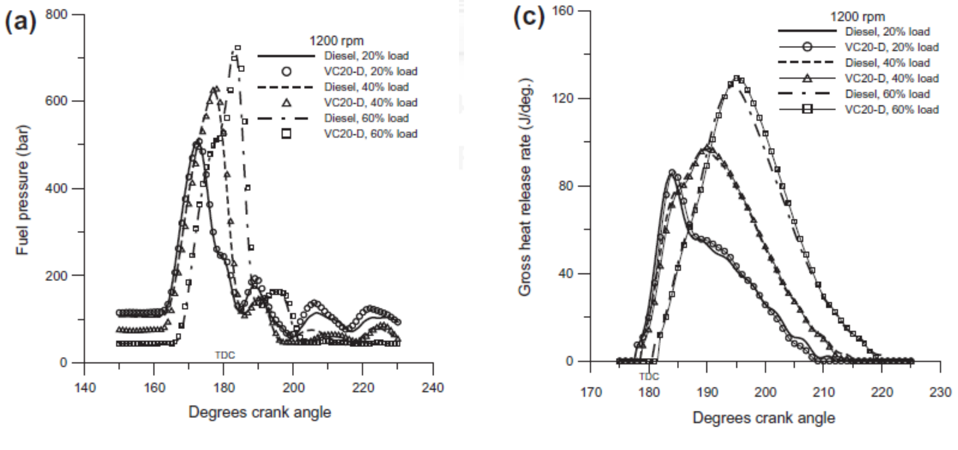


Figure 1: fuel pressure profile and gross heat release rate of mechanical fuel pump

(Rakopoulos 2012) study the effect cotton seed oil and sunflower oil blended with diesel fuel in turbocharged heavy-duty diesel vehicle on engine combustion and emission. He concludes that the blended fuel has insignificant ignition delay, while the maximum cylinder pressure is slightly lower. It does mean that even the fuel quality is much difference in cetane number (52 – 58), there is less impact onto engine combustion – especially at steady-state condition.

The diesel fuel ignition quality can be improved by using of cetane improver additive like (Lu Xing-cai, Yang Jian-guang et al. 2004) works with 15% ethanol diesel blended fuel which has ultimately low cetane or ignition quality. They finally improved the fuel cetane number by adding 0.4% additive and the fuel can combust almost comparable to diesel fuel.

(B. Higgins, D. Siebers et al. 1998) from Sandia Combustion Research Facility studied the effect of diesel additive – 2, Ethyl-Hexyl Nitrate which is a cetane improver. They found that the additive help accelerate the pre-ignition radical pool formation, thus shortening the auto-ignition period. This effect, however, is not uniform. It is the strongest at the lowest gas temperature–density conditions and weakest at the highest temperature–density conditions.

1.2 Cetane quality vs diesel performance

Formerly, the conventional diesel technology use the mechanically drive fuel injection pump to generate high pressure fuel and injected into the combustion chamber, the fuel droplet then vaporized, mixing and start combustion when some of fuel and air mixture are reaching the appropriate pressure, temperature and mixing ratio. The period from start of fuel injection to start of combustion (premixed combustion), in general, term as ignition delay which related to cetane number of diesel fuel. Basically, the fuel with higher cetane quality will also result in the less violent in combustion and lowering emission. Since 1999, when the high pressure diesel common-rail technology has been introduced, the fuel sensitivity due to ignition quality is not yet clarified. This is because of the availability of the pilot fuel injection, therefore the severity of premixed combustion has been alleviated.

(R.G. Williams, P.J.Zemroch et al. 2004) try to link the correlation of fuel cetane quality on the modern light-duty diesel engine performance by varying the fuel cetane number from 41 to 58. They concluded that the modern diesel technology result in the less sensitive to fuel cetane quality.

Diesel engine combustion measuring instrument, compose mainly of piezo-electric pressure transducer combining with the intake & exhaust manifold mostly piezo-resistive typed transducers to correct the ambient pressure level from the cylinder pressure signal. While, the high resolution crank angle encoder must also be installed for determining the time in the horizontal axis. Most engineer study the engine combustion at specific steady-state condition, while some are believe that at transient-state condition. Since, the engine combustion is believed to react differently from the steady-state.

(D. N. Assanis, Z. S. Filipi et al. 2003) tried to correlate the engine test result with the Arrhenius equation, the equation can achieve good correlation during the steady-state. While, it could not represent well when running transient-state, therefore he introduced the new ignition delay correlation which can represent good result at both steady-state and transient state.

Equation 1: Arrhenius Equation

$$\tau_{id} = Ap^{-n} exp\left(\frac{E_a}{R_u T}\right)$$

Equation 2: New Ignition Delay Correlation

$$\tau_{id} = 2.4\,\varphi^{-0.2}\bar{P}^{-1.02} exp\left(\frac{E_a}{R_u T}\right)$$

The equations define the rate coefficient of combustion reaction by input the A = constant, p = pressure, E_a = Activation Energy, R_u = Universal Gas Constant, T = Temperature, ϕ= Equivalence Ratio

(Breuer 2002) verified the Vibe calculation model for diesel combustion. He concluded that the boiling characteristic and the fuel viscosity determine a great extent to the division of the fuel amount into the two combustion phases. The course of the premixed phase can be exactly described by the combustion duration and the shape parameter, while it is also influenced decisively by the cetane number. As expected, it was observed that the remaining amount of fuel from the first phase has an indirect influence on the parameters of the second Vibe-phase, the so-called diffusion combustion. Simultaneously, the boiling curve is directly appointing the combustion duration. The fuel viscosity becomes less important towards the combustion end.

(Ezio Mancaruso and Vaglieco 2011) studied the effect of different fuels on engine combustion. They concluded some interesting discovered for both engine speeds and for all fuels. It can be noted that the ROHR traces show a development of combustion mainly in premixed mode and a small tail indicating the slow diffusive mode. This is due to the combination of both the moderate compression ratio and the high percentage of the EGR employed at the two working points as shown in figure 2.

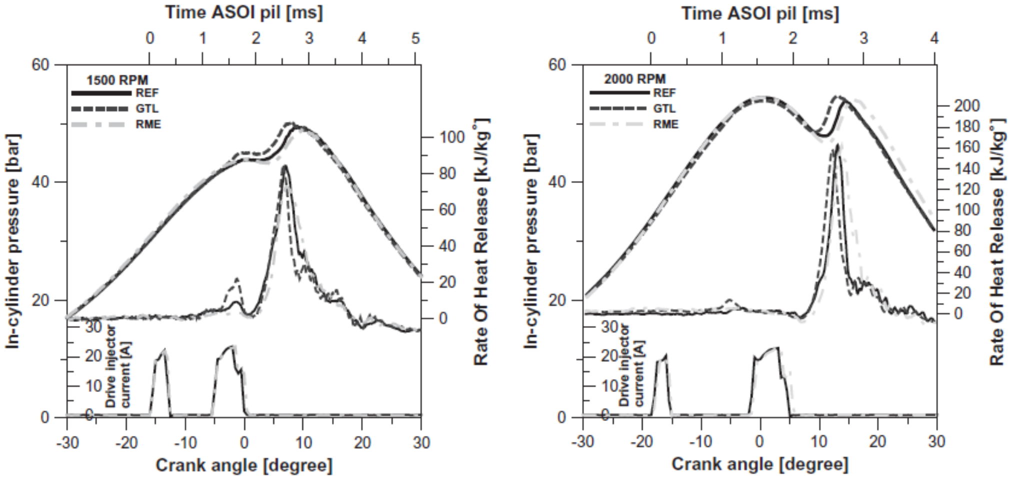


Figure 2: ROHR shape of 2 engine speeds with various fuels

(D. N. Assanis, Z. S. Filipi et al. 2000) study the new methodology to calculate heat release at transient condition by running the direct injected diesel engine equipped with unit injector. His studied focus on the effect of turbocharger lag which will promote the longer ignition delays and more pronounced on premixed burning phase.

1.3 Recent R&D works on fuel quality assessment

Recently, the diesel combustion analysis instrument and technology become more intelligent. While, people rate his/her vehicle drive-ability on fuel related quality by feeling and listening to the combustion noise. Therefore, the combustion analysis during transient-state, become more and more challenging topic for automotive engineer.

According to the progress on CRC – Coordinating Research Councils program on “Fuel for Advance Combustion Engine [FACE]”(Mikhail Alnajjar, Bill Cannella et al. 2010), instead of focusing on the fuel cetane quality, they concern more fuel properties such as Aromatics and distillation curve as shown in the DOE below. By varying the parameters, the FACE program determines the 9 test fuels for evaluating its physical and chemical properties. However, they do not proof their response on advance diesel combustion up to now.

(Koji Yamane, A Ueta et al. 2001) expressed the relation of the effect of conventional fuel injection system with biodiesel fuel properties. They explained that biodiesel has higher bulk modulus of elasticity, thus the fuel system always govern the biodiesel fuel with advance injection timing comparing to diesel fuel or gas oil as shown in figure 3.

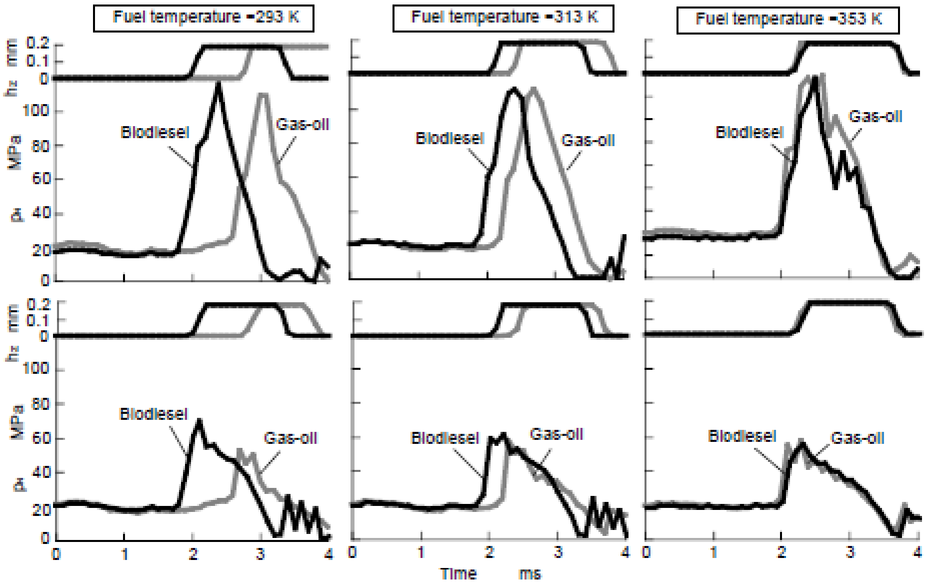
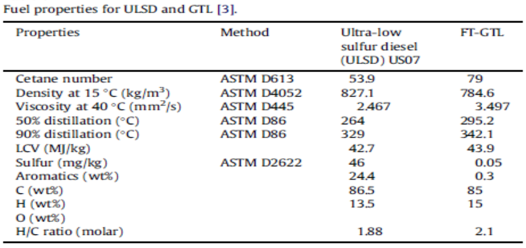


Figure 3: Calculated of injection pressure and nozzle needle-lift for gas-oil and biodiesel at different fuel temperature

R&D works on the effect of fuel properties on diesel engine combustion appointed that cetane number is the major factor that effect onto fuel combustion like R&D works on Gas-to-Liquid (GTL) fuel properties (S. S. Gill, A. Tsolakis et al. 2011) with has substantial high cetane number (80) comparing to diesel fuel (54) as seen in figure 4.



Fuel properties for ULSD and GTL [3].

Properties	Method	Ultra-low sulfur diesel (ULSD) US07	FT-GTL
Cetane number	ASTM D613	53.9	79
Density at 15 °C (kg/m^3)	ASTM D4052	827.1	784.6
Viscosity at 40 °C (mm^2/s)	ASTM D445	2.467	3.497
50% distillation (°C)	ASTM D86	264	295.2
90% distillation (°C)	ASTM D86	329	342.1
LCV (MJ/kg)		42.7	43.9
Sulfur (mg/kg)	ASTM D2622	46	0.05
Aromatics (wt%)		24.4	0.3
C (wt%)		86.5	85
H (wt%)		13.5	15
O (wt%)			
H/C ratio (molar)		1.88	2.1

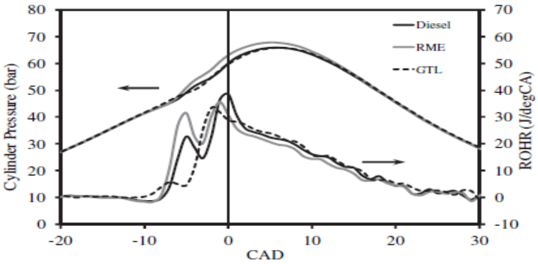


Figure 4: GTL fuel properties and its combustion characteristics with diesel fuel

By the way, most of R&D works on the effect of alternative fuels or fuel additives on diesel combustion when running at steady-state especially for cetane improver. For conventional diesel engine which the premixed combustion and diffusion combustion phases are explicitly separate, the cetane quality is a key factor that determine the start of combustion with no doubt. By the way, diesel engine technology is recently breakthrough and become more advance than the past decade. The pilot injection feature helps compensating the lower fuel cetane quality. Moreover, the new key performance evaluation for advance diesel vehicle has also been introduced as "***Drive-ability Performance***".

1.4 Fundamental of diesel combustion analysis

From fundamental knowledge on engine combustion as explained in many Internal Combustion Engine Series like the most popular one (Heywood 1988)

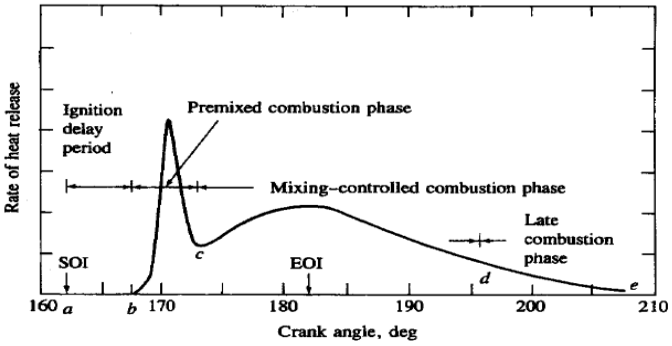


Figure 5: Diesel combustion rate of heat release per 1 cycle

Ignition Delay Period (a-b) – The period from the start of fuel injected or penetrated into the combustion chamber to the start of combustion which can be detected from the change in slope of the p-θ diagram, or from a heat-release analysis of the p(θ) data or from a luminosity detector.

Premixed or rapid combustion phase (b-c). In this phase, combustion of the fuel droplet which has premixed with air until reaching the flammability limits so-called the ignition delay period which will occurs rapidly in a few crank angle degrees. When this burning mixture is added to the fuel which becomes ready for burning and burns during this phase, the high heat-release rates characteristic of this phase then perform.

Mixing-controlled combustion phase (cd). Once the fuel and air which premixed during the ignition delay have been consumed, the burning rate (or heat-release rate) is controlled by the rate at which mixture becomes available for burning. While several processes are involved – liquid fuel atomization, vaporization, mixing of fuel vapor with air, pre-flame chemical reactions – the rate of burning is controlled in this phase primarily by the fuel vapor-air mixing process. The heat-release rate may or may not reach a second (usually lower) peak in this phase; it decreases as this phase progresses.

Late combustion phase (de). Heat release continues at a lower rate well into the expansion stroke. There are several reasons for this. A small fraction of the fuel may not yet have been burnt. A fraction of the fuel energy is present in soot and fuel-rich combustion products and can still be released. The cylinder charge is non-uniform and mixing during this period promotes more complete combustion and less-dissociated product gases. The kinetics of the final burnout processes become slower as the temperature of the cylinder gases fall during expansion.

Equation 3: The first law of Thermodynamics

$$\frac{d(m_c.u)}{d\propto} = -p_c\frac{dV}{d\propto} + \frac{dQ_F}{d\propto} - \sum\frac{dQ_w}{d\propto} - h_{BB}\frac{dm_{BB}}{d\propto} + \sum\frac{dm_i}{d\propto}.h_i - \sum\frac{dm_e}{d\propto}.h - q_{ev}.f.\frac{dm_{ev}}{dt}$$

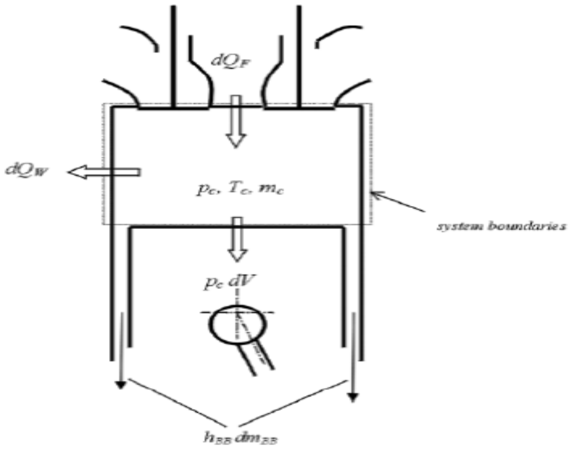


Figure 6: Simplified combustion chamber for modelling as a constant pressure control volume when the intake and exhaust valves are considerably closed.

Equation 4: The conservation of Mass:

$$\frac{dm_c}{d\propto}=\sum\frac{dm_i}{d\propto}-\sum\frac{dm_e}{d\propto}-\sum\frac{dm_{BB}}{d\propto}+\sum\frac{dm_{ev}}{dt}$$

Equation 5: Simplified Cylinder Pressure – Heat Release Determination:

$$\frac{dQ_n}{dt}=\frac{dQ_{ch}}{dt}-\frac{dQ_{ht}}{dt}=p\frac{dV}{dt}+\frac{dU_s}{dt}$$

The apparent net heat-release rate, $\frac{dQ_n}{dt}$, which is the difference between the apparent gross heat-release rate $\frac{dQ_{ch}}{dt}$ and the heat-transfer rate to the wall $\frac{dQ_{ht}}{dt}$, equals the rate at which work is done on the piston plus the rate of change of sensible internal energy of the cylinder contents. If we assume that the contents of the cylinder can be modeled as an ideal gas then

Equation 6: Estimation of simplified cylinder pressure

$$\frac{dQ_n}{dt}=p\frac{dV}{dt}+mC_v\frac{dT}{dt}$$

From the ideal gas law, pV = mRT, with R assumed constant, it follows that

$$\frac{dp}{p}+\frac{dV}{V}=\frac{dT}{T}$$

Substitute into equation 6:

$$\frac{dQ_n}{dt}=\left(1+\frac{C_v}{R}\right)p\frac{dV}{dt}+\frac{C_v}{R}V\frac{dp}{dt}$$

Equation 7: Simplified form of heat release calculation

$$\frac{dQ_n}{dt}=\frac{\gamma}{\gamma-1}p\frac{dV}{dt}+\frac{1}{\gamma-1}V\frac{dp}{dt}$$

Where as: γ is the ratio of specific heats, C_p/C_v. An appropriate range for γ for diesel heat-release analysis is 1.3 to 1.35.

$\frac{d(m_c.u)}{d\propto}$ Change of internal energy in the cylinder

$-p_c\frac{dV}{d\propto}$ Piston work

$\frac{dQ_F}{d\propto}$ Fuel heat input

$\sum\frac{dQ_w}{d\propto}$ Wall heat loss

$h_{BB}\frac{dm_{BB}}{d\propto}$ *Enthalpy flow due to Blow-by*

dm_i Mass element flowing into the cylinder

dm_e Mass element flowing out of the cylinder

dm_{ev} Evaporating fuel

In general, diesel combustion phasing is determined by CA50 or crank angle position at 50% accumulated heat release. (Usman Asad and Zheng 2008) commented on the weakness of using CAP_{max}, CA $(dP/d\theta)_{max}$ and CA50 as the combustion phase . While, they also proposed the alternative apparent heat release model such as Rassweiler-Withrow model and the new diesel departure pressure ratio model which can estimate more acurate combustion phase over a wide range of engine operating conditions on cycle-by-cycle basis. The model shown below;

<u>Equation 8:</u> *the new diesel departure pressure ratio*

$$PDR(\theta) = \frac{P(\theta) + FPC}{P_{mot}(\theta) + MPC} - 1$$

Where as $P(\theta)$ = Fire Cylinder Pressure Curve, FPC = Fired Pressure Characterization Coefficient, $P_{mot}(\theta)$ = Motored Cylinder Pressure Curve, MPC = Motored Pressure Characterization Coefficient

The advance diesel technology need to control the combustion phase by refering the feedback value from CA50. The CA50, in general, need to equip with the in-cylinder pressure measurement which is highly sensitive and high cost. Therefore, some of researcher tried to estimate the CA50 or MBF50 from the combustion model from the fuel injection parameter like (F. Ponti, V. Ravaglioli et al. 2010).

The engine test and experiment is extremely cost consume, thus the instrumental set-up should be conducting carefully. (Usman Asad, Raj Kumar et al. 2011) have concluded the smart way to measure the test parameter and the important sub-system control for excellent result. Which are shown in the figure no. 7 and 8 below;

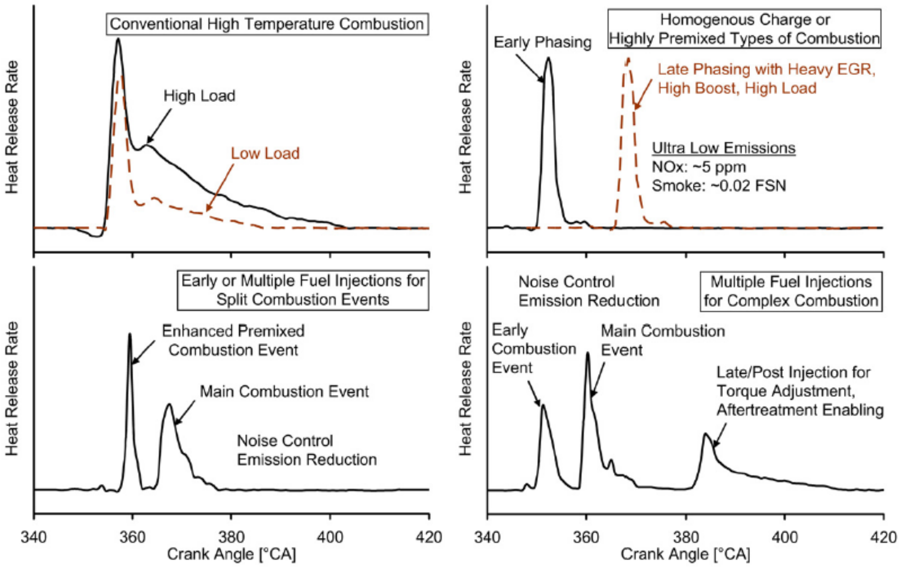


Figure 7: ROHR of different diesel combustion types

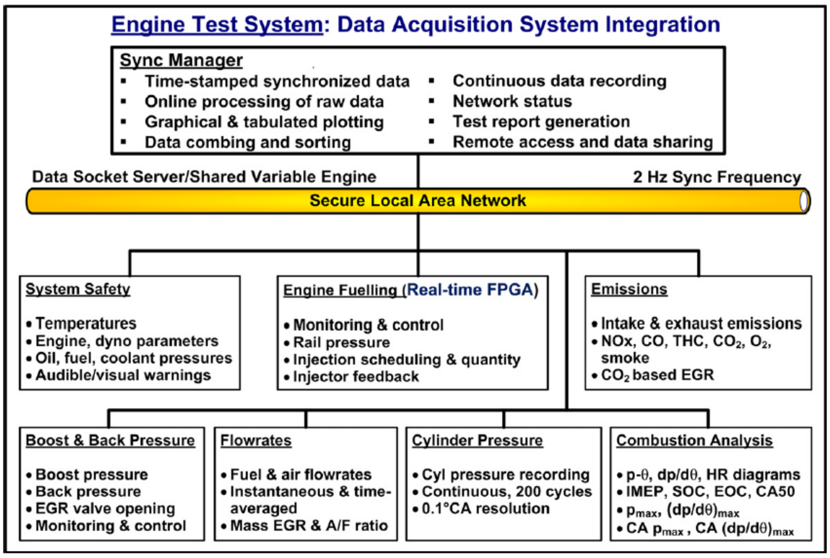


Figure 8: Smart engine test parameter need to be recorded designed by U. Asad

In practical, diesel engine always emit noise during operation, due to the severe turbulent combustion. The noise or ***combustion noise*** is an output of combustion quality or ***combustion roughness***. (Hsu 2002) defined the combustion roughness or noise as the pressure wave generated by the certain portion of gas mixture which form the chemical reaction during kinetic combustion phase. Then, the pressure wave propagates across the cylinder and reflect inside. The high sensitivity transducer can detect the pressure trace and the superimposed of certain frequency pressure wave regarding to the sonic velocity as a function of the gas temperature and cylinder dimension.

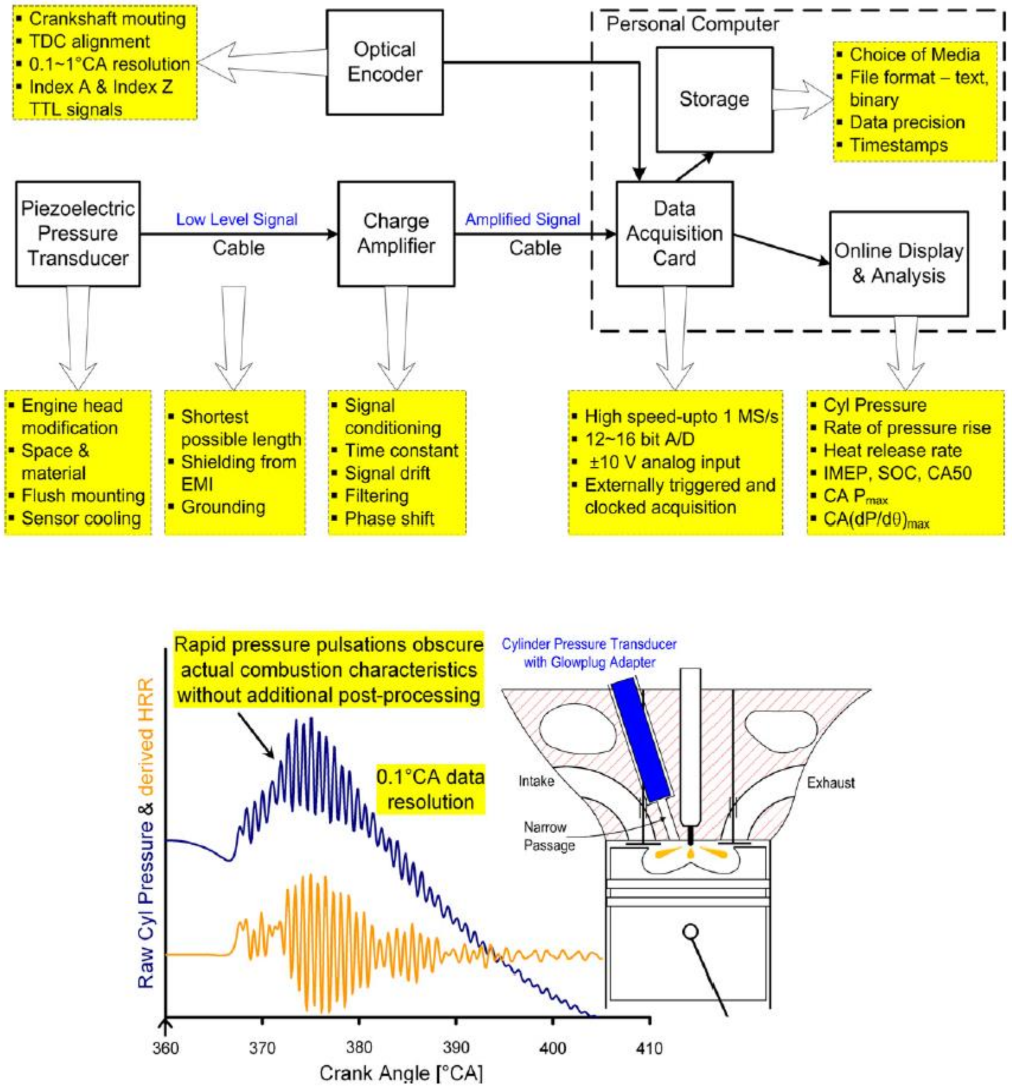


Figure 9: System design for cylinder pressure analysis

Formerly, combustion roughness was defined by the maximum rate of pressure rised, which is no longer valid due to the split injection feature in the high pressure diesel common-rail. B.D. Hsu propose the best way to quantify the combustion roughness is to measure the energy that excites the combustion pressure wave at the characteristic frequency. By performing a Harmonic analysis of the time –based cylinder pressure history, we can distinguish the combustion roughness in the form of a ***power spectrum density (PSD)***.

1.5 Transient diesel combustion analysis

Recently, the new approach on transient diesel combustion has introduced in the R&D on engine control disciplines. Most of them are focusing on the control algorithm and phenomena inside combustion chamber with reference diesel fuel. The most interesting published works on this area are (C. D. Rakopoulos and Giakoumis 2006) and (Constantine D. Rakopoulos and Giakoumis 2009).

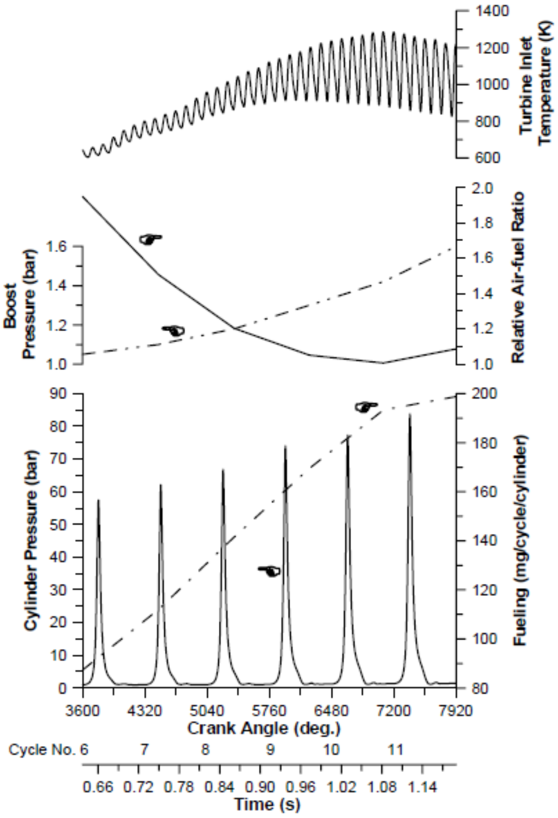


Figure 10: Transient diesel combustion characteristics

The primary difference in combustion characteristics between steady-state and transient-state combustion are

a) The dynamic response characteristics of the fuel injection system,

b) The different quantity and pressure of air-supply owing to the previously discussed turbocharger lag, which affects directly fuel–air ratio, heat release rate and exhaust emissions.

c) The lower cylinder wall temperature compared with the respective steady-state operation as discussed in the previous section

Combustion analysis on transient operation, therefore, differs from steady-state operation. Apart from the ignition delay, start of combustion, burn duration and rate of pressure rise. We have to evaluate the development of cycle-to-cycle such as during acceleration with speed or load increase with constant speed. For example, the fuel injection characteristic comparison from steady-state and transient state can be seen from the figure 1.10 below.

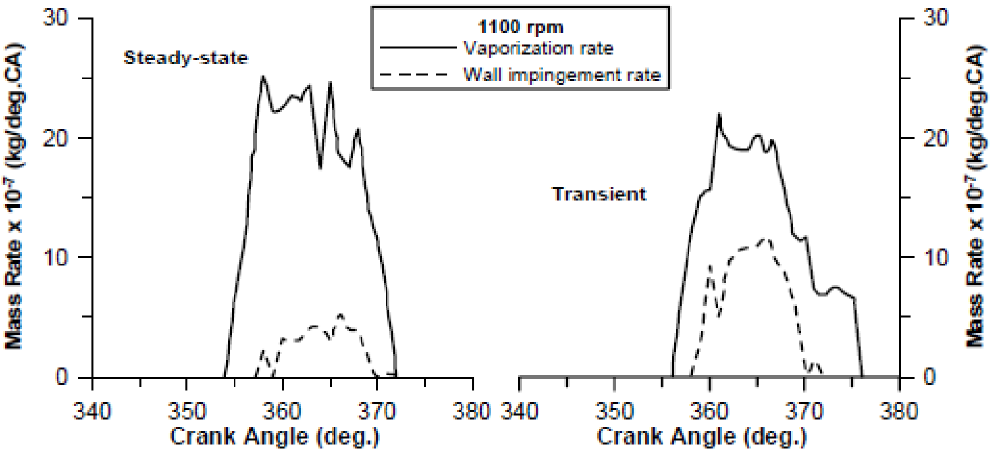


Figure 11: Comparison of the behavior of a spray jet during steady-state and transient conditions at the 1,100 rpm operating point

From figure 11, the lower vaporization rate was detected in transient operation while the higher wall impingement rate was occurred as a general consideration. Thus, the higher vaporization rate fuel shall be accelerated faster.

The physical and chemical ignition delay has also been investigated and found the different response as shown.

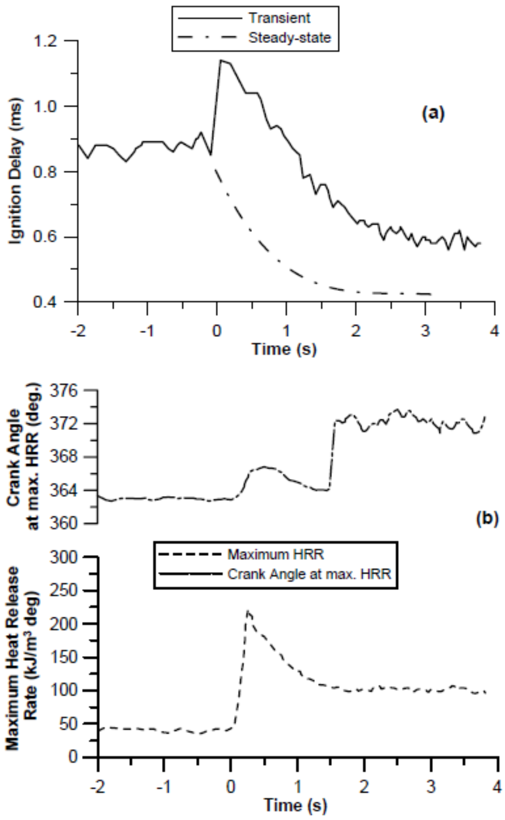


Figure 12: Engine behavior comparing between steady-state and transient-state operation

The cause of different in transient-state and steady-state engine behavior can be concluded as the transient-state combustion result in the longer ignition delay

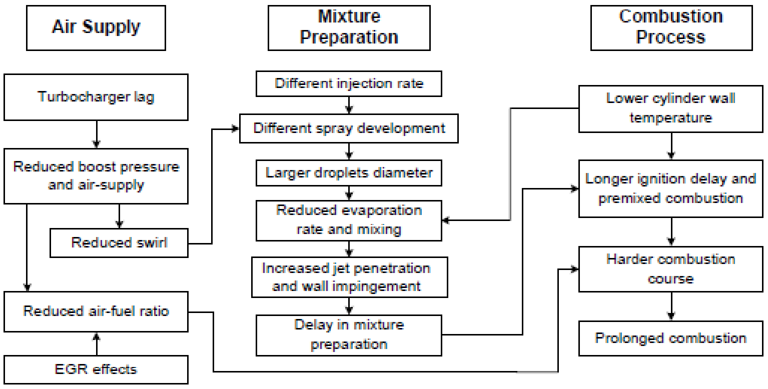


Figure 13: Root-cause analysis of how transient-state combustion react to the engine combustion

(Octavio Armas, Rosario Ballesteros et al. 2011) tried to investigate the effect of diesel and biodiesel fuel on load transient Euro III common-rail engine. They concluded that biodiesel fuel combustion characteristics can comparable to diesel fuel. The limitation of this work is that all fuels have almost the same cetane property.

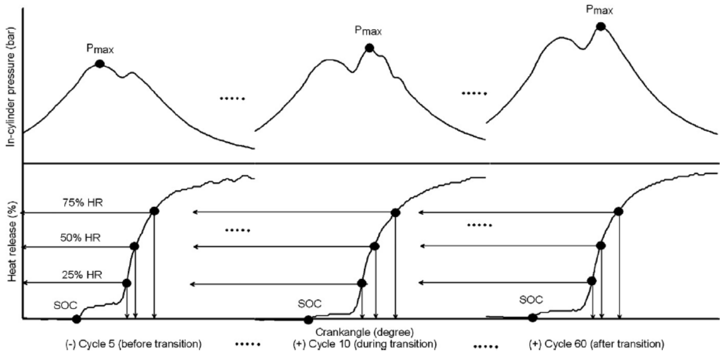
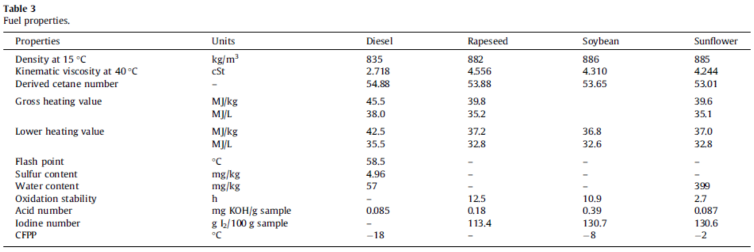


Fig. 3. Scheme of the parameters selected for the representation derived from the thermodynamic diagnosis during transitions.

Table 3
Fuel properties.



Properties	Units	Diesel	Rapeseed	Soybean	Sunflower
Density at 15 °C	kg/m^3	835	882	886	885
Kinematic viscosity at 40 °C	cSt	2.718	4.556	4.310	4.244
Derived cetane number	–	54.88	53.88	53.65	53.01
Gross heating value	MJ/kg	45.5	39.8		39.6
	MJ/L	38.0	35.2		35.1
Lower heating value	MJ/kg	42.5	37.2	36.8	37.0
	MJ/L	35.5	32.8	32.6	32.8
Flash point	°C	58.5	–	–	–
Sulfur content	mg/kg	4.96	–	–	–
Water content	mg/kg	57	–	–	399
Oxidation stability	h	–	12.5	10.9	2.7
Acid number	mg KOH/g sample	0.085	0.18	0.39	0.087
Iodine number	g I_2/100 g sample	–	113.4	130.7	130.6
CFPP	°C	−18	–	−8	−2

Figure 14: Criteria to analyze the combustion phase development in transient-state

(J. R. Serrano, F. J. Arnau et al. 2008) proposed the post processing model for transient combustion detection so-called Calmex parameter in which all the measurement and post processing were inclusive. This control parameter is defined as the ratio between the maximum value of the heat release law and the energy contained in the injected fuel mass. They also verified the Calmex parameter in their subsequent paper (J. R. Serrano, H. Climent et al. 2008) which is very helpful for applying this parameter to transient diesel combustion.

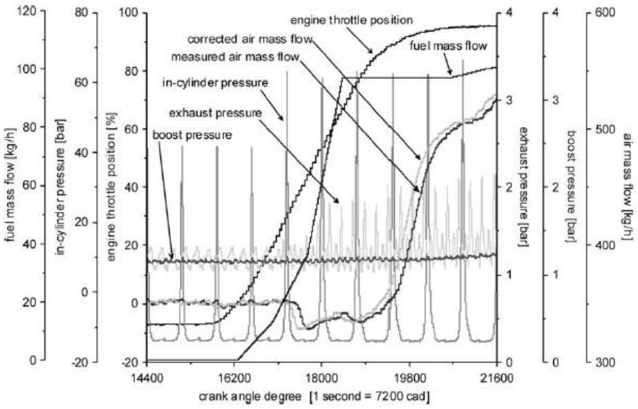


Figure 15: Transient behavior of engine parameter during ramp up

While, the transient diesel combustion analysis has been interested, some of researchers also configure the combustion roughness or noise during transient operation like (Gequn Shu and Wei 2007) They tried to quantify the differentiation of noise generated during steady-state and transient-state operation as shown in the figure below;

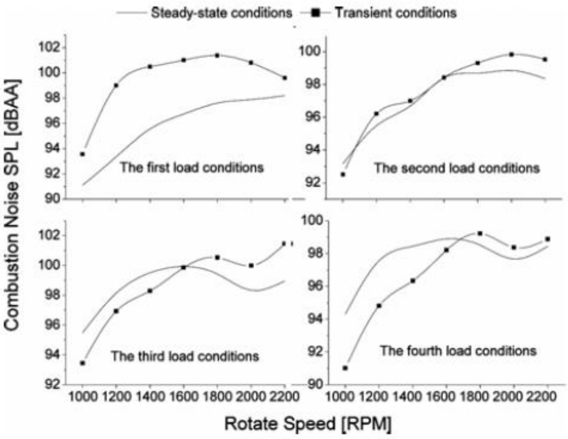


Figure 16: Combustion noise signal comparing from steady-state vs transient-state

Engine noise, in general, can be initiated from combustion noise and also mechanical noise such as noise from piston slab. Thus, the separation of noise from combustion and mechanical source is essential for evaluating the fuel effect on combustion noise or combustion quality.

CHAPTER 2: DISSERTATION PROPOSAL

From previous experiences, the using the different source of diesel fuels in advance diesel vehicle may give the driver feeling difference. When driving the vehicle, especially, in more aggressive behavior like fast acceleration, climbing the hill with heavy load or even deceleration, the driver randomly found that his/her engine response to those fuels in different manner. The new term of fuel quality evaluation mode as “engine drive-ability” is becoming the major factor for consumer who decide where to fuel his/her vehicle. The dissertation will propose the new methodology to justify the fuels quality differentiation in transient mode of diesel engine operation.

2.1 Objectives

2.1.1) To characterize the transient diesel combustion and propose the method of characterizing the transient diesel combustion in term of ignition delay, combustion phasing, burn duration and combustion roughness.

2.1.2) To investigate the transient combustion behavior of advance diesel fuels including new potential component as Hydrogenated Vegetable Oil (BHD) or biodiesel and the cetane improver additive like 2-EthylHexylNitrate or etc.

2.2 Theory

Recently, Engine Development Research, especially for advance diesel engine technology, successfully develops such a high efficiency engine so called “High pressure diesel common-rail Technology” breakthrough the former diesel technology. This technology can achieve extremely high injection pressure as 200 MPa instead of 40 Mpa. Furthermore, the mechanically driven fuel injection has been replaced with the electronically controlled like solenoid or piezo-injector which allow the injection event up to 7 pulses combining of 3 pilot injection, 1 main injection and 3 post injection in only one combustion stroke. This capability helps compensating the effect of premixed combustion which originally depends on fuel ignition quality or cetane number by featuring the pilot fuel injection before the incoming main injection.

Engine Developer / Simulation Engineer always neglecting fuel ignition quality variation in their work. By the ways, people who drive their own vehicles may sensitive to the engine response when fuelling fuel from different oil suppliers. What should be the factors that drive the fuel quality differences? Mostly, people will sense to their engine response when drive in transient mode such as accelerating, decelerating including the combustion noise.

2.3 Experimental Set-up

The fully automated control engine test bed with high accuracy of data acquisition, measuring parameter such as engine output torque and power measurement with 0.5% accuracy including with the high precision speed control dynamometer, fuel consumption measurement with 0.5% accuracy and temperature control ± 2 °C, engine water and coolant conditioning unit with ± 5 °C, Intake air flow measurement and controlled at 25 ± 5 °C, Exhaust Back Pressure controllable, high accuracy optical angle encoder with 0.1 degree resolution and high precision piezo-electric cylinder pressure measurement combining with intake and exhaust port piezo-resistive pressure measurements.

All equipment and instrument can be set an automated test pattern which can repeat with very accurate torque, fuel delivery position (throttle or pedal) and speed maps. The superior post processing equipment so called IndiCom Software can compare up to 200 consecutive cycles in both average and cyclic variation. Therefore, the premixed combustion phase and mixture controlled diffusion phase can be analyzed in more sophisticated direction.

Figure 17: Automated engine test system for engine combustion analysis

2.4 Design of Experiments

By focusing on the specific light-duty diesel common-rail engine which is the certified euro III technology. The engine was selected by the most common model in Thai market (year 2011).

Table 1: Test Engine Specification

Manufacturer	Toyota
Engine Model	2KD-FTV
Displacement	2,494 cc
Bore x Stroke	92 mm x 93.8 mm
Compression Ratio	18.5 : 1
Fuel Injection System	Common-rail with Solenoid Injectors
Fuel Injection Pressure	Up to 1,600 bar
Inlet air system	Turbocharged with intercooler
Speed at Maximum Power / Power	3,400 rpm / 88 kw
Speed at Maximum Torque / Torque	1,600 – 3,600 rpm / 325 Nm

Advance Diesel Fuels:

a) Base Diesel form the specific refinery
b) Hydrogenated Vegetable Oil – BHD (paraffinic diesel)
c) Biodiesel from Palm Oil
d) Cetane Improver Additive

The blending of some fuel or additive or component are mainly intended for differentiate transient diesel combustion characteristic. The correlation between fuel properties such as cetane number, distillation (T90), aromatic content and the transient combustion characteristic is the major interest of this study.

Transient Test Condition:

1) Speed and Load Acceleration Tests: by determining the free acceleration from idling to full load. The engine idling condition at 750 rpm, there is a pilot injection to help reducing noise and ignition delay when the engine is cool.

During the acceleration, the pilot injection will disappear after pass the 2,000 rpm. The final speed was set at 3,600 rpm instead of 4,400 rpm which is the maximum limit, due to the highest output of the engine and for safety concern. The detail of this pattern will be determined during study such as acceleration time and acceleration of pedal actuator.

2) Load Acceleration Tests: to simulate the driving condition as climbing the hill, the engine speed must be controlled constantly while the load must be increased to lift the vehicle up to the hill. The conditions may select the speed range as low, medium and high speed such as 1,000 – 1,400 rpm for low speed (speed under the flat torque region), 2,000 – 3,000 rpm as medium speed and up to 4,000 rpm for high speed. All conditions will also derive when study.

Transient diesel Combustion Analysis:

Combustion analysis are based from the steady-state condition by focusing on

1) Start of Injection and Start of Combustion – Ignition Delay (Premixed combustion phase)
2) Combustion phasing : CA10 / CA50 and CA90
3) Burn duration : CA90 – CA10
4) Maximum rate of pressure rise
5) Combustion roughness or combustion noise – Power Spectrum Density (PSD)

Some modification for transient application proposed by many literatures

1) Transient Ignition Delay Model
2) Diesel Departure Pressure Ration Model
3) The Calmex parameter
4) Etc.

All those proposed models base upon the engine simulation on transient application, while this study, tried to correlate the models with the actual fuel sensitivity or properties on the real engine. If those model result in more accurate prediction during transient test, they shall predict more sensitive fuel response to the transient application too.

2.5 Program Schedule 24 months

Table 2: Research Planning and Scheduling

STEP	TASK / DESCRIPTION	Duration
1	Determine the appropriate transient test cycles for evaluation	3 months (1st – 3rd)
2	Characterizing the transient diesel combustion	5 months (3rd – 7th)
3	Develop the combustion analysis pattern for transient application	5 months (6th – 10th)
4	Test with reference fuel quality product (Good/Bad Fuel)	3 months (11th – 13th)
5	Correct & Improve the test methodology & analysis	5 months (14th – 18th)
6	Benchmarking various diesel fuels quality such as diesel / premium diesel / biodiesel etc.	3 months (19th – 21st)
7	Research Conclusion	14 months (11th – 24th)

CHAPTER 3: PRELIMINARY STUDY

The previous research (Somnuek Jaroonjitsathian, Noomwong et al. 2011) focused on the biodiesel combustion in comparison with base diesel. The most potential biodiesel production in Thailand is derived from Palm Oil. The benefits of Palm Oil Methyl Ester (POME) or biodiesel produced from Palm Oil are good ignition quality and better oxidation stability comparing with rapeseed methyl ester or soy bean methyl ester. By quantifying the biodiesel or FAME fuel qualities, we, therefore, will understand the reason why FAME blended fuel react to the engine combustion in those ways. The table 3 below show the FAME blended fuels qualities directly from the laboratory as

3.1 Test Fuel Properties

Table 3: Biodiesel Blended Fuel Properties

PROPERTIES	B0	B5	B16	B22	B53
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
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
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
Mass % of Carbon	85.99	85.39	84.79	83.59	80.00
Mass % of Hydrogen	14.01	13.91	13.81	13.61	13.01
Mass % of Oxygen	0.00	0.65	1.30	2.60	6.50

3.2 Engine Combustion Experiments

The designed test patterns are separate into 3 main patterns which are

1) Steady-state condition in Ricardo Hydra – the single cylinder research engine to study the effect of the fuel injection pressure on engine combustion behavior such as ignition delay, maximum rate of pressure rise, indicated mean effective pressure and combustion phasing.

Table 4: Test conditions for Ricardo Hydra Single Cylinder Engine

SPEED (RPM)	INJECTION PRESSURE	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

The results can be shown and discussed below.

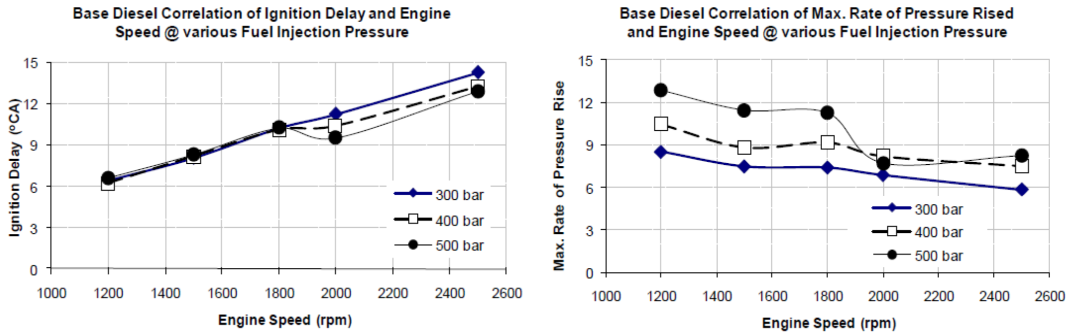


Figure 18: Ignition delay and max. rate of Pressure rise vs fuel injection pressure

From figure 18, at low engine speed i.e.1,200 – 1,800 rpm, variation of fuel injection pressure from 300 – 500 bar had no advantage from the shorter ignition delay (no difference ignition delay for a specific 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 has an effect 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.

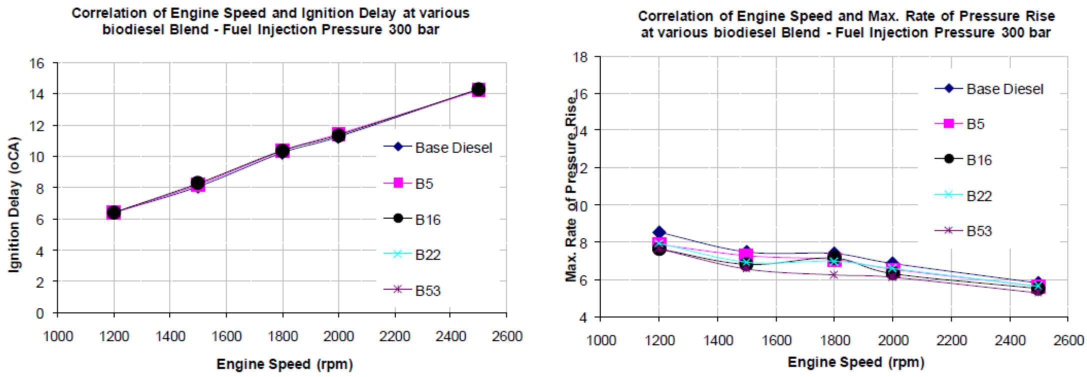


Figure 19: Ignition delay and max. rate of Pressure rise vs biodiesel blended fuels

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. The 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.

2) Steady-state condition in commercial light-duty pickup engine

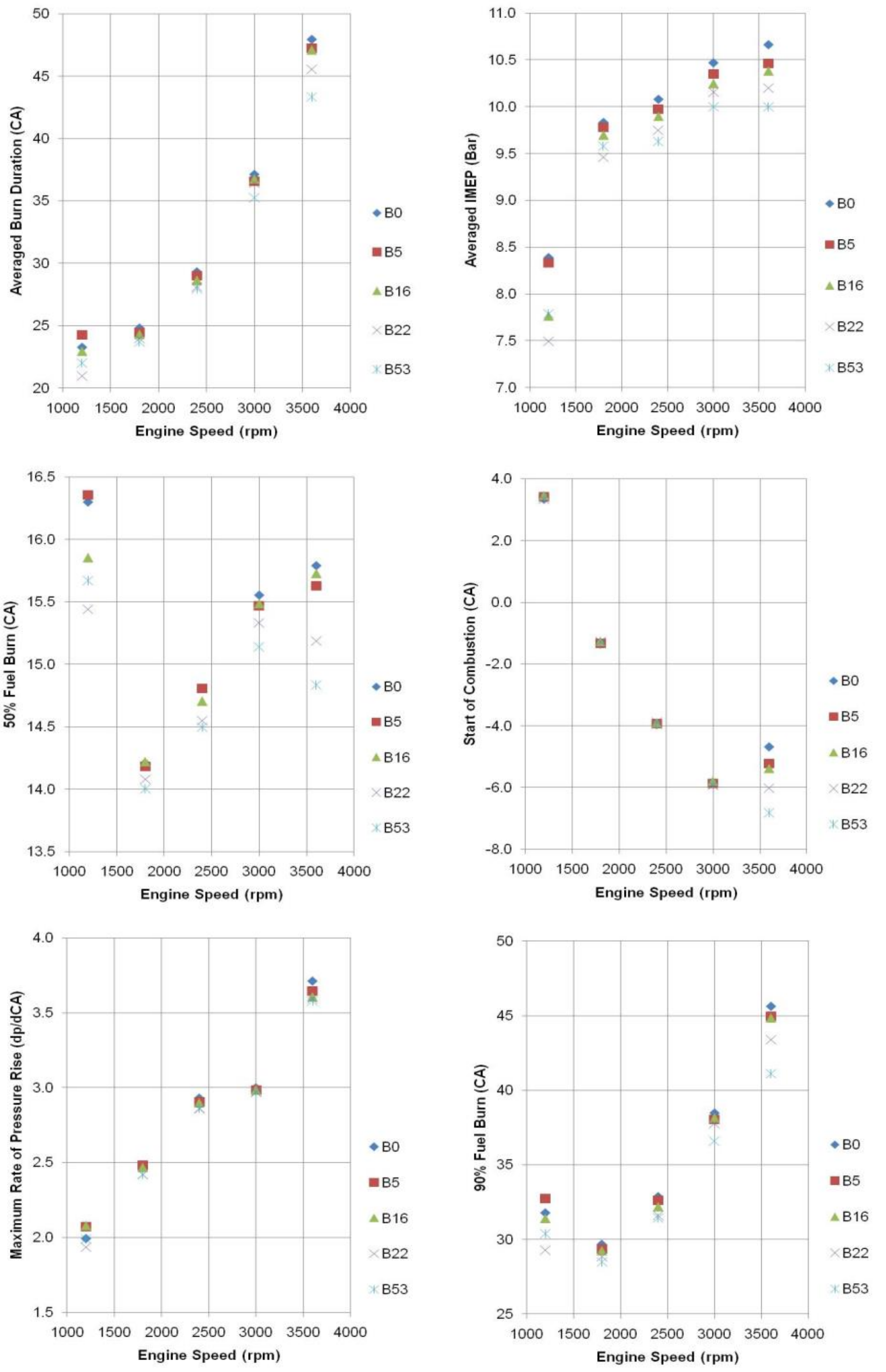


Figure 20: Full load steady-state combustion analysis in single cylinder

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]. Test conditions had been conducted in 4 different ways i.e. the first condition was running the engine at various speed by WOT or full load power. The second pattern was controlling the engine torque at 40 Nm for 1200, 2400 and 3,600 rpm. The 3rd pattern was controlling the engine torque at 75 Nm for 1200, 2400 and 3600 rpm or (Medium Load condition). The fourth pattern was running by controlling the engine torque at 110 Nm at 1200, 2400 and 3600 rpm or (High Load condition)

AT FULL LOAD – Base diesel always gave maximum output IMEP, as a result of higher heating value. The 50% mass burn fraction represents the position of fuel burning better than Start of Combustion, which B50 or the highest cetane number sample contributed to the fastest burning period as well as the shortest burn duration especially at higher engine speed. No sign of combustion noise difference for variation of biodiesel content.

3) Transient-state conditions in commercial light-duty pickup engine

To prove the assumption “In transient-state condition, engine response to fuels differently as a result of physic-chemical property of the fuel and additive”. Therefore, the 3 test patterns had been designed for transient-state application as below:

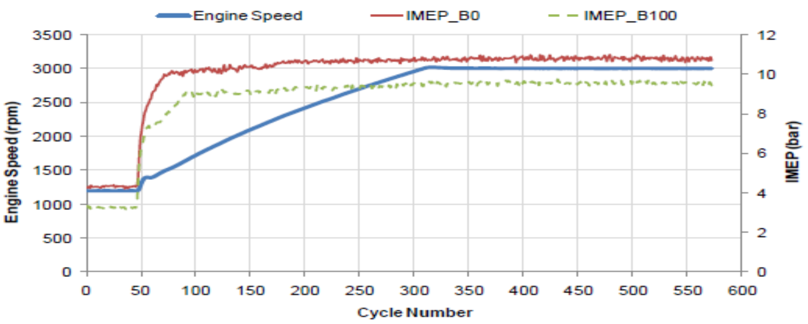


Figure 21: Free acceleration test pattern

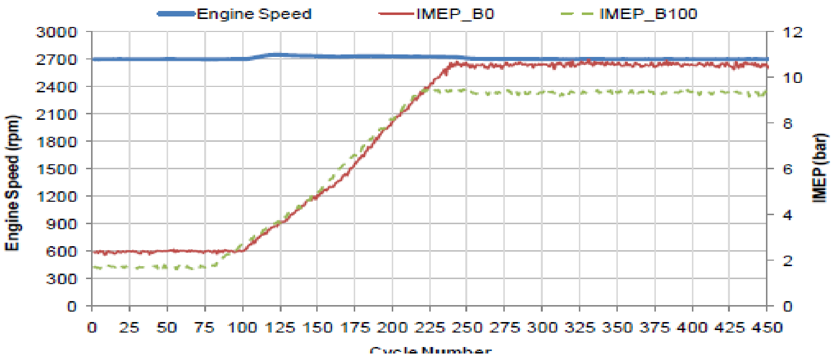


Figure 22: Load Increase @ constant speed pattern

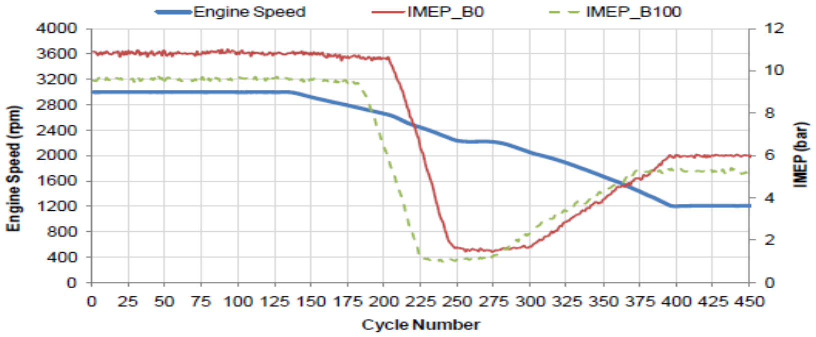


Figure 23: Deceleration test pattern

The transient combustion had been investigated which B100 performed poor engine drive-ability especially at low speed and low load condition. Since the extremely lower in B100 heating value comparing with base diesel, the small amount of pilot injection could not improve the heat release process before the incoming main injection.

Currently, we did not notice any difference in combustion between B0 and B100 from the previous experiments according to the 3 main assumptions below:

- B100 & B0 have cetane number almost the same range (70 & 64)
- Lack of combustion analysis experience
- Need to modify some combustion parameter during transient-state such as combustion phasing, maximum rate of pressure rise.

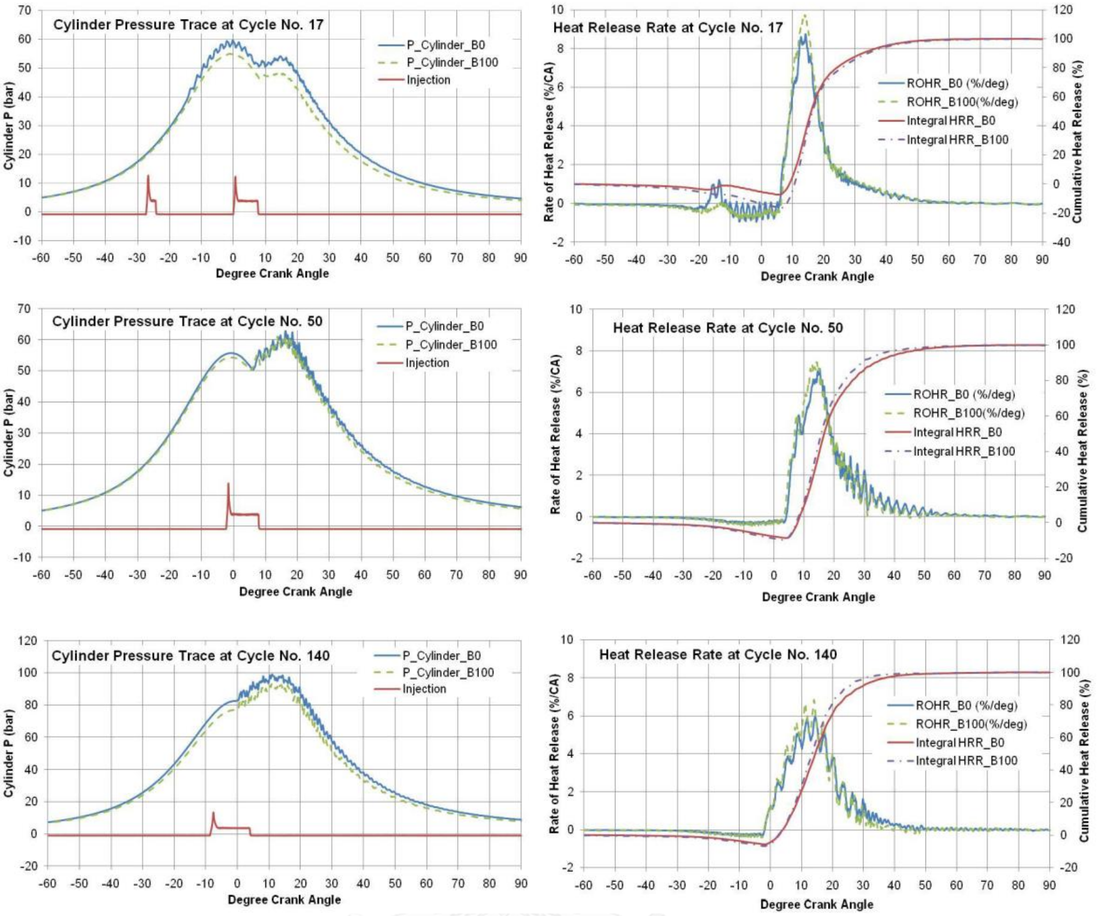


Figure 24: Investigation on transient combustion by free acceleration

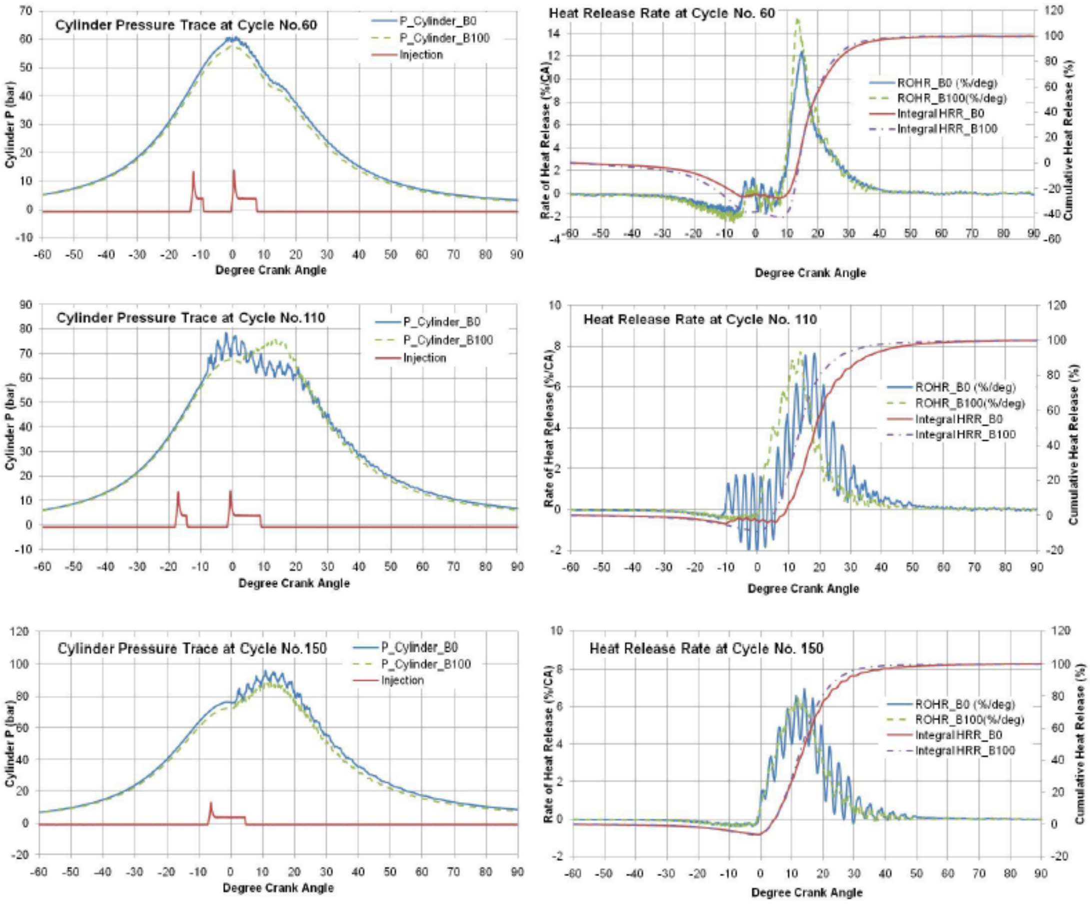


Figure 25: Investigation on transient combustion by load increasing @ 1,800 rpm

3.3 Conclusion

1) At low engine speed, too high fuel injection pressure introduced the higher combustion noise, why there was no benefit from ignition delay improvement either.
2) For the low fuel injection pressure condition, the effect of biodiesel blended fuel was not explicitly gain for ignition delay improvement, but it benefit would be slightly suppression of the combustion noise.
3) For full load and steady-state combustion, B100 has shortest burn duration as can be observed from CA 50.

4) The transient combustion have been introduced in this chapter, but there is no analysis method for evaluation. The result concluded that there is no significance difference between diesel and B100.

CHAPTER 4: DIESEL COMBUSTION MEASUREMENT AND ITS APPLICATION

The most critical parameter for engine combustion measurement is cylinder pressure versus the piston position in degree crank angle, in addition, the exact position of Top Dead Center (TDC) is the most important reference to determine the combustion phasing.

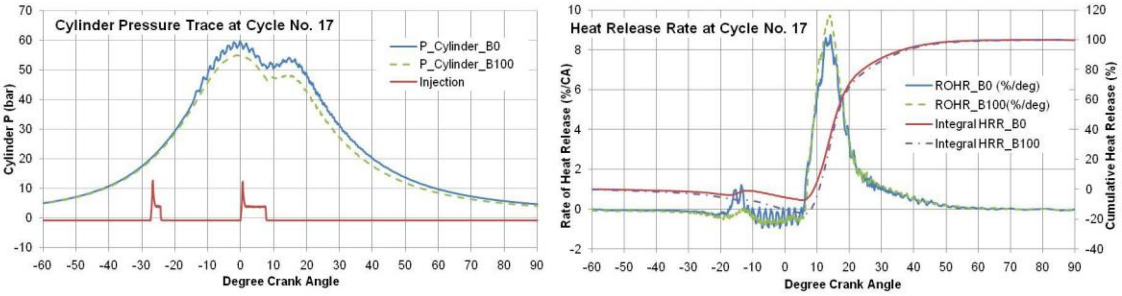


Figure 26: demonstration of diesel combustion in-cylinder measurement

The cylinder pressure is measured by piezoelectric pressure sensor which is made from quartz and has highly response to the pressure change, while the piston position is measured by mounting the optical encoder directly to the front-end of crankshaft. The TDC position can be determined by the neglecting of gear tooth or referencing by motor pressure curve or estimate by thermodynamic principal.

Common-rail fuel injection strategies: the modern common-rail DI diesel engine has more flexibility to control the multiple fuel injection events instead of the single pulse fuel injection, see figure no. 26. There is a pilot injection before the main injection, which can help improving ignition delay and also combustion noise. By the way, the pilot injection will disappear whenever the engine load and speed increase to the condition where there is no requirement for warming up the cylinder wall.

Ignition delay: the duration between start of the main fuel injection and start of fuel combustion which mostly determine by the position when 5% of the total fuel burnt.

Combustion phase: the position where the proportion of the fuel has been burnt or percentage of heat release, in general, define as CA5, CA10, CA50 and CA90. The CA5 usually known as the start of combustion, while the CA50 is the recommended parameter to use for controlling the diesel combustion. Since its value is quite stable even when the engine running in transient state.

Burn duration: the period from CA 5 to CA90 is usually the recommended parameter so called burn "duration".

Heat Release: the heat release model can be calculated by using the first law of thermodynamics for an open system. By applying the ideal gas law as a single zone, the heat release during combustion on a degree crank angle means the gross heat release rate during the period from intake valve close (IVC) to exhaust valve open (EVO) for the crank angle interval dθ, the governing equation can be shown as

Equation 9: Heat Release Model

$$\frac{dQ_{gr}}{d\theta} = \frac{1}{\gamma - 1}\left[\gamma p \frac{dV}{d\theta} + V\frac{dp}{d\theta} + (u - c_v T)\frac{dm_c}{d\theta}\right] - \sum h_i \frac{dm_i}{d\theta} + \frac{dQ_{ht}}{d\theta}$$

Where

m_c is the mass of the cylinder charge

c_v is the specific heat at constant volume

u is the specific internal energy

T is the mean charge temperature

p is the cylinder pressure

V is the cylinder volume

γ is the ratio of the specific heat

dQ_{ht} is the charge-to-wall heat transfer

$\sum h_i m_i$ is the enthalpy flux across the system boundary

Apparent heat release: is the simplified form of heat release calculation by neglecting the heat transfer, crevice volume, blow-by and the fuel injection effects in the previous heat release equation, the estimated heat release rate so called "the apparent heat release rate" or "the net heat release rate (AHRR)". By substituting $dQ_{app} = dQ_{gr} - dQ_{ht}$ and $dm_c = dm_i = 0$, the equation of AHRR is

Equation 10: Apparent Heat Release Calculation

$$\frac{dQ_{app}}{d\theta} = \frac{dQ_{gr}}{d\theta} - \frac{dQ_{ht}}{d\theta} = \frac{1}{\gamma - 1}\left[\gamma p \frac{dV}{d\theta} + V\frac{dp}{d\theta}\right]$$

Cumulative apparent heat release (Cum. AHR): is obtained by summing the incremental values from above equation over the combustion period.

Combustion noise: is calculated from cylinder pressure signal by referencing at the level 2 x 10^{-10} bar. The normal Fourier transformation is then applied and followed by a conversion to a third-octave spectrum. The spectral line then define as the mean signal level in dB. In addition, the signal is filtered using A-weight to focus only the human detectable limit.

CHAPTER 5: TRANSIENT DIESEL COMBUSTION PART I [B0 vs B100]

Setting up the engine experiment to define the specific parameter for comparing the fuel performance or drive-ability when running in transient modes. The transient mode can be defined as free acceleration, deceleration, or load acceleration at constant engine speed. To get more understanding on the transient behavior of engine combustion, it is needed to quantify the combustion development during transient state as below:

5.1 Engine test and experiments

Table 5: Test Engine Specification

ENGINE MODEL	TOYOTA 2KD
Type:	- 4-cylinder diesel engine
Cylinder volume:	- 2494 cc
Compression ratio:	- 18.5:1
Max torque:	- 200 Nm @ 1400-3400 rpm
Max power:	- 75 kW @ 3600 rpm
Max speed:	- 4000 rpm
Fuel injection system:	- Common rail direct injection
DYNAMOMETER	AVL ALPHA 240 ZG
Type:	- Eddy current dynamometer
Max torque:	- 600 Nm @ 1300-3800 rpm
Max power:	- 240 kW @ 3800-10000 rpm
Max speed:	- 10000 rpm
Torque accuracy:	- ± 0.2%
Speed measurement accuracy:	- ± 1 rpm / ± 1 digit

THROTTLE ACTUATOR	AVL THA 100
Type:	- Linear positioning unit, convection cooled servomotor
Shifting travel:	- 110mm
Shifting speed:	- 0.5 m/sec
Positional repetitive accuracy:	- < ± 0.05 mm
FUEL METERING AND CONDITIONING	AVL 733 S (Metering) + AVL 753 (Conditioning)
Type:	- Gravimetric flow mass balance with fuel cooling and pumping system
Measuring range:	- 0-150 kg/h
Consumption measurement accuracy:	- 0.12%
Max measurement frequency:	- 10 Hz (Measuring time 0.1 sec)
Cooling power:	- 1.6 kW at 10°c spread and 0.5 bar water differential pressure
COOLANT CONDITIONING	AVL 533-350
Type:	- High temperature-control precision
Max cooling capacity:	- 350 kW
Temperature control range:	- 70-125°c
Control accuracy:	- ± 1°c
Max pumped flow:	- 20 m^3/h

5.2 Free acceleration on engine test bench

By setting the engine speed and throttle demand position with the condition below in figure 27, the engine response then perform as in figure 28.

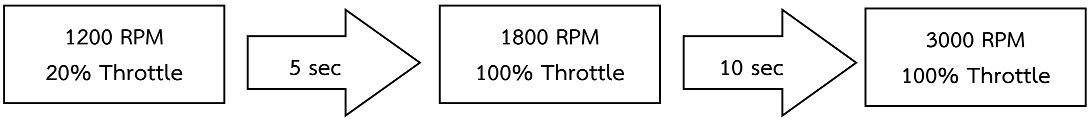


Figure 27: control condition for simulating the free acceleration mode

The free acceleration mode control specific engine accelerated speed, while the full throttle has been demanded via engine ECU which will receive the customer demand and then calculated the maximum allowable fuel quantity for injected at each condition. The engine map for fuel quantity limitation is mainly come from emission regulation and limit.

Figure 28, the pilot fuel injection at early combustion cycle has been detected for help warming up the combustion chamber temperature which will improve the main combustion especially at low speed and light load condition. When, the full throttle activate the period between pilot and main fuel injection become closer until the only main fuel injection is applied. The premixed combustion is detected and influenced the combustion during the early stage of acceleration, while the diffusion combustion is the only major phenomena that influenced the whole combustion cycle.

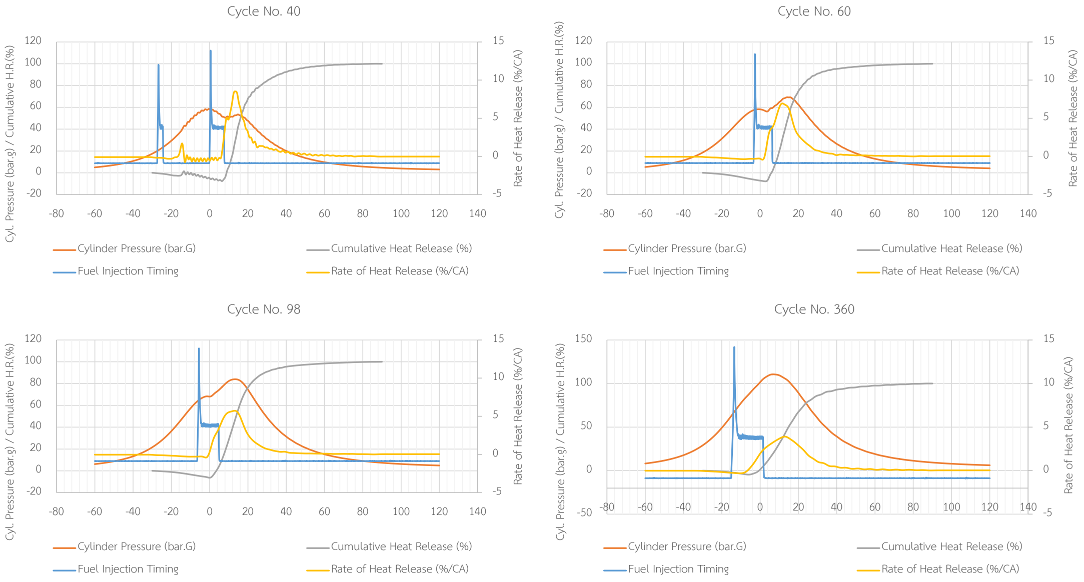


Figure 28: combustion development of transient free acceleration mode

5.3 Mild deceleration of engine test bench

Initially, the engine was running constantly at high speed of 3000 rpm with fully-pressed 100% of throttle position. Then, the engine speed and the throttle position started linearly decreasing. And 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. Within this 15 seconds period, all considered parameters were recorded.

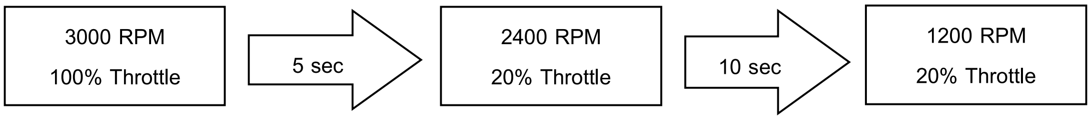


Figure 29: control condition for simulating the mild deceleration mode

From figure 30, the combustion development is like the backward of free acceleration mode by starting with the only main fuel injection with long duration. Then, the injection duration is become shorter and shorter until the injection split into 2 events such as pilot and main injection. After that the 2 injection events are moving away until reaching the target speed and load.

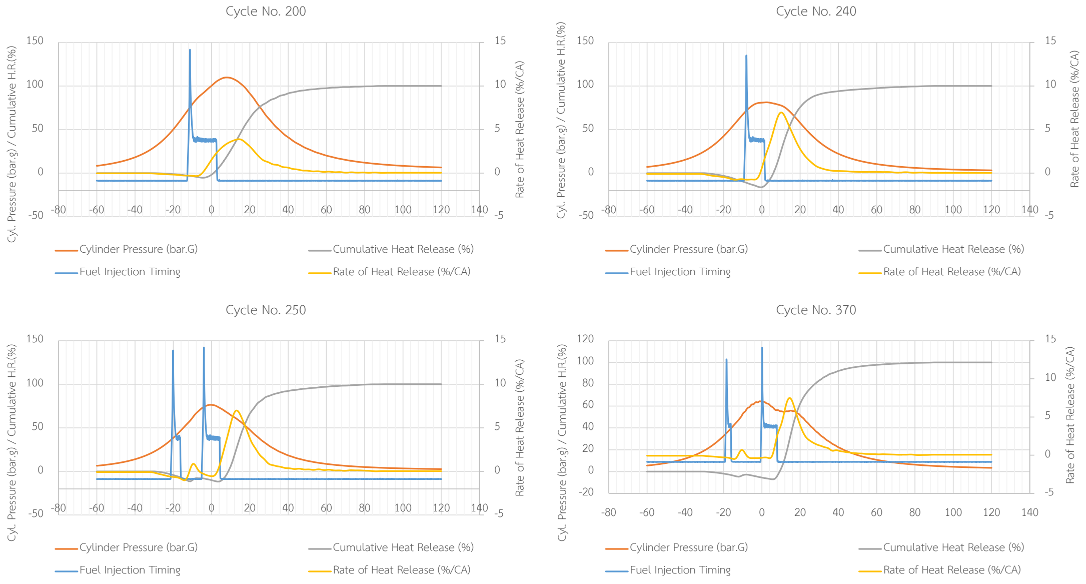


Figure 30: combustion development of transient mild deceleration mode

5.4 Load acceleration at constant engine speed

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

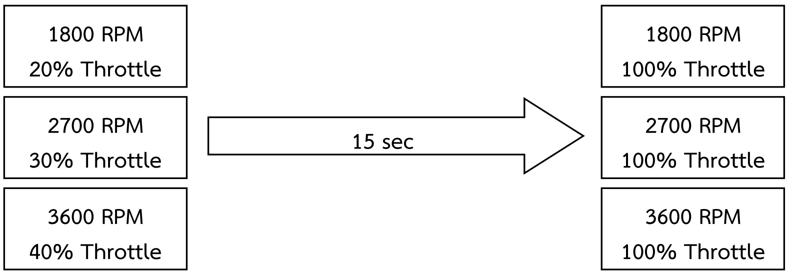


Figure 31: control condition for simulating the load acceleration mode

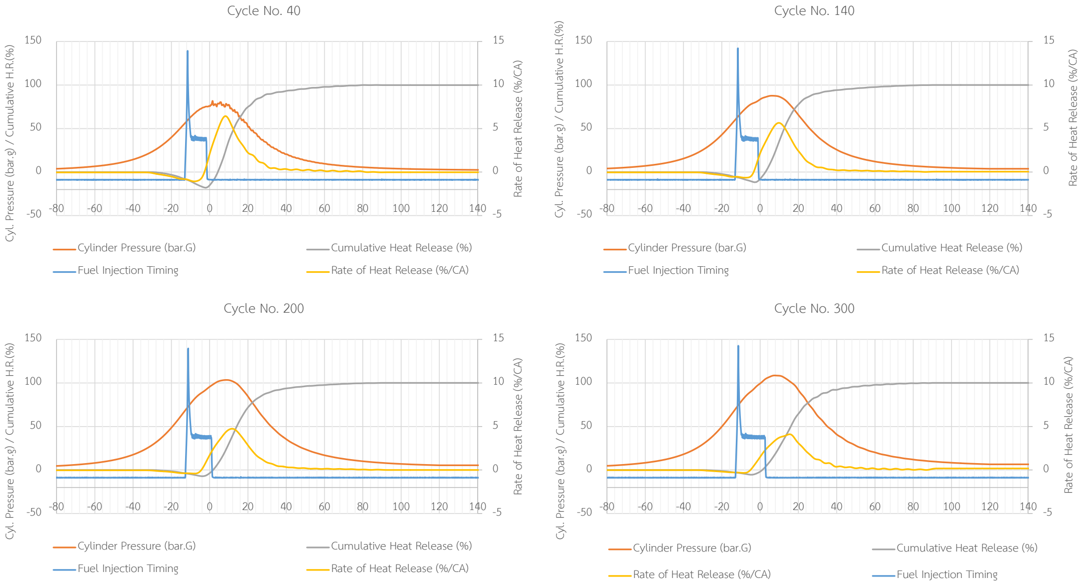


Figure 32: combustion development of transient load acceleration @ 2700 rpm

For load acceleration mode, the combustion profile is almost the same from light load to full load. The higher demand regulating the longer injection duration, which result in the higher cylinder pressure and less vaporization fraction due to the hot cylinder wall temperature.

Even if the load cannot be controlled, but the repeatable measurement could confirm it characteristic by observing the engine speed, IMEP and start of fuel injection. Please see appendix A.

5.5 Base diesel and biodiesel transient combustion comparison (B0 vs B100)

a) Free acceleration mode (refer 5.2)

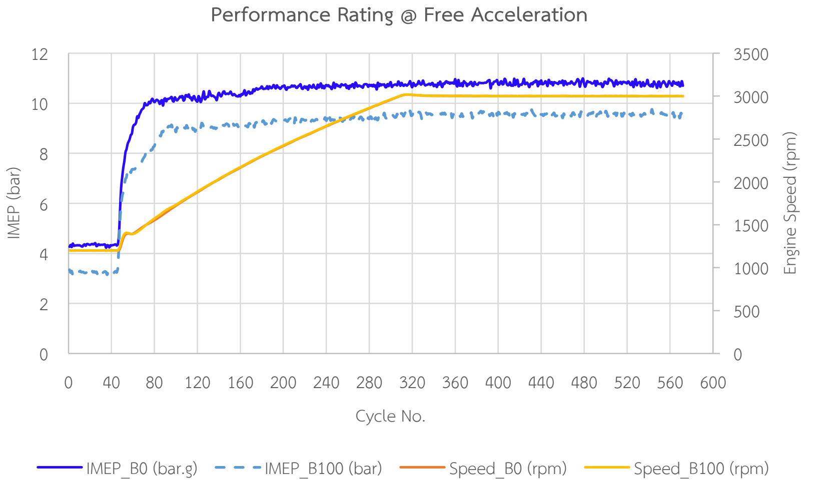


Figure 33: comparison of IMEP between B0 and B100 by free acceleration

Figure 33, the only explicit difference between B0 and B100 is the lower IMEP of B100 according to the lower heating value of B100. The IMEP of both fuels are reach to 95% of the maximum value about the same time as throttle position reach 100%. Since the common-rail DI technology has the flat torque characteristics, especially for this engine model the flat torque region range from 1600 – 3600 rpm.

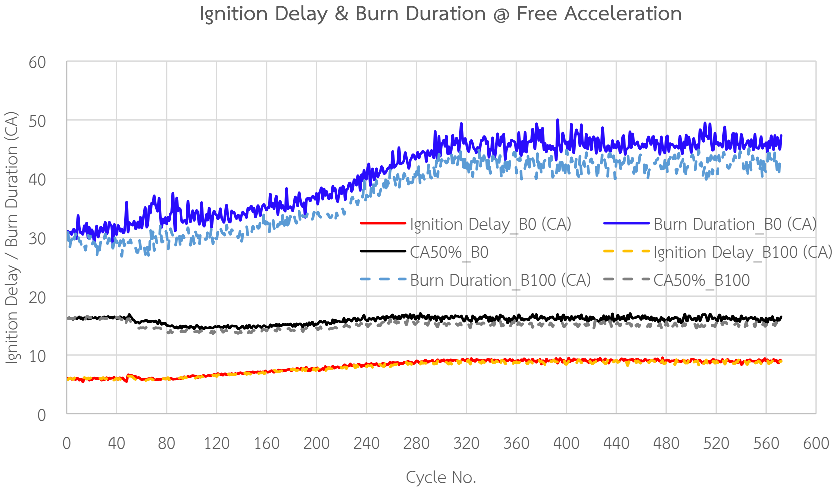


Figure 34: comparison of CA50&Duration between B0 and B100 by free acceleration

The shorter burn duration of B100 was observed by which the period from CA50 to CA90 of B100 is significantly shorter than B0. While, CA50 and ignition delay have no influence on transient combustion, regarding that the less part of premixed combustion is dominant.

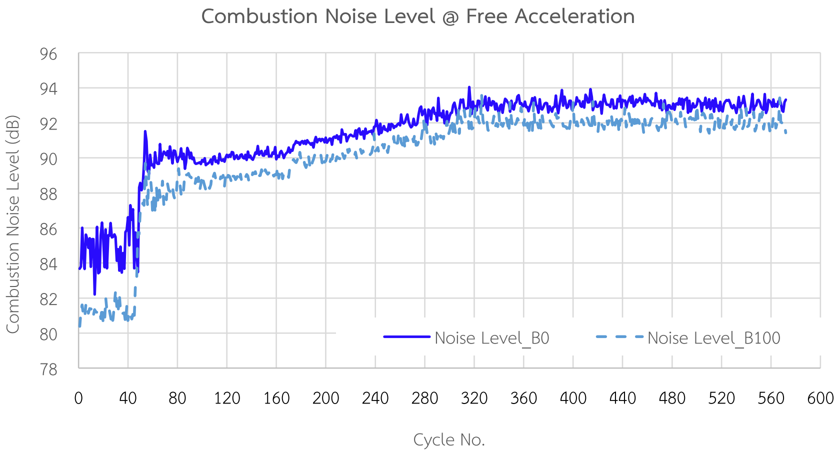


Figure 35: comparison of noise between B0 and B100 by free acceleration

Figure 35 shown that the lower IMEP of B100 will contribute to the lower combustion noise comparing with B0 as well.

b) Mild deceleration mode (refer 5.3)

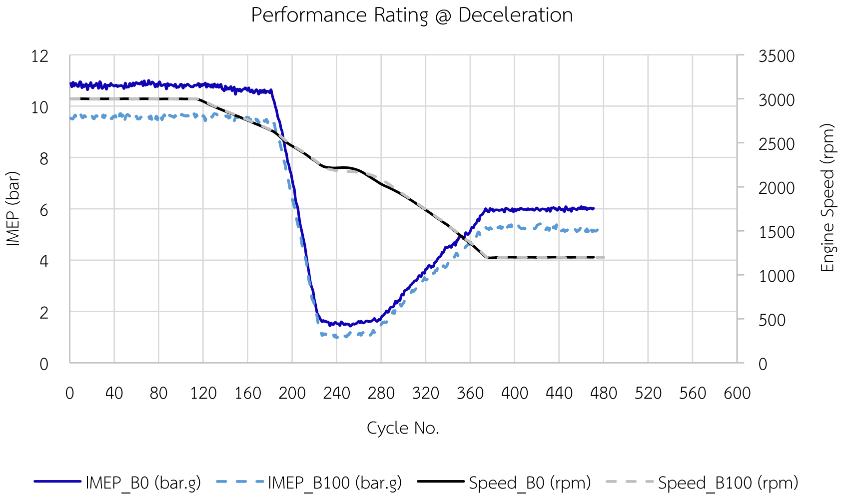


Figure 36: comparison of IMEP between B0 and B100 by mild deceleration

The engine control characteristic was almost cut the fuel shortly when receiving the high demand of slowing the engine speed and load down, before fuelling again to the new speed and load target. However, the lower heating value of B100 is affecting the lower IMEP along the test cycles.

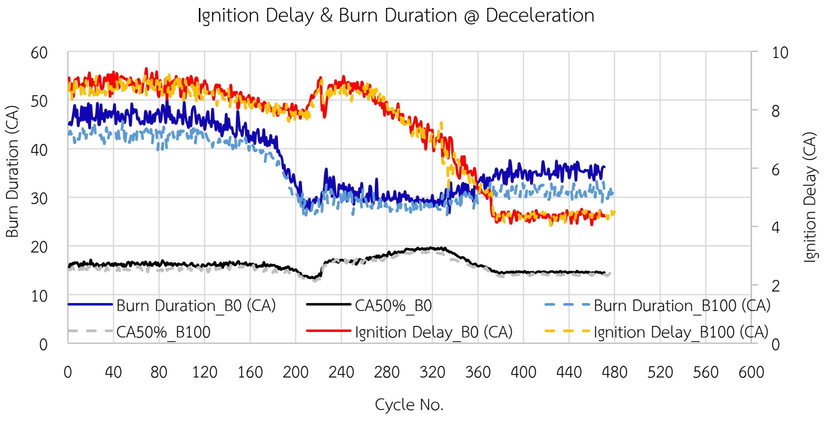


Figure 37: comparison of CA50&Duration between B0 and B100 by mild deceleration

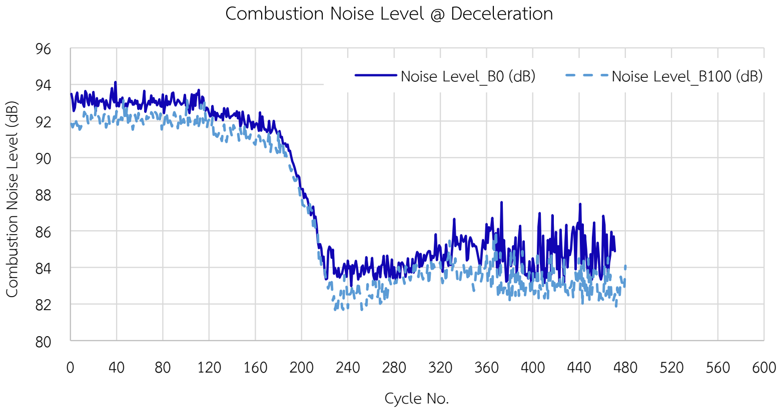


Figure 38: comparison of noise between B0 and B100 by mild deceleration

In figure 37 and 38 during the fuel cut-off period before reaching to the new target, there is no significantly difference between B0 and B100 whether burn duration, CA50 or combustion noise. Since, the fuel demand is very limit just for preventing the engine from stalling. Whenever, the engine speed re-increasing, then the combustion noise and burn duration of both fuels are being separated again.

c) Load acceleration mode @ 1800 rpm (refer 5.4)

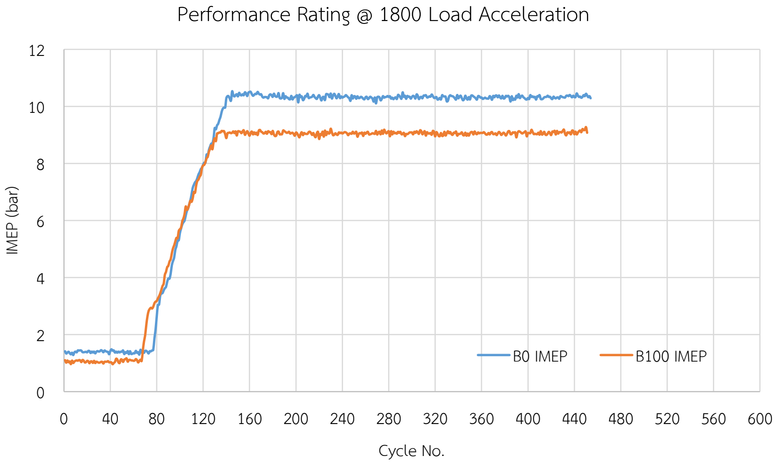


Figure 39: comparison of IMEP between B0 and B100 by load deceleration

In figure 39, the 1800 rpm load acceleration could compare better IMEP development comparing with free acceleration mode. The slope of B0 IMEP and B100 IMEP is comparable, but the heating value of B100 is about 10% lower than B0 resulting in the lower IMEP destination.

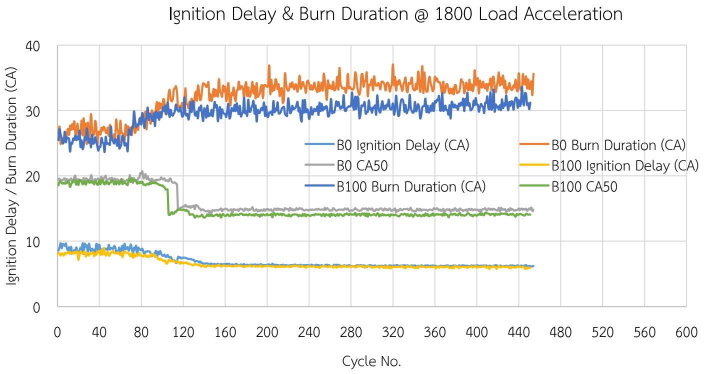


Figure 40: comparison of CA50&duration between B0 and B100 by load deceleration

The effect of B100 shorter burn duration, in figure 5.12 cannot be observed during the load acceleration until the IMEP reaching the 85% of maximum value, then the difference can be detected. The CA50 has the same characteristic with burn duration, while the ignition delay has no influence to the combustion since the acceleration start. Combustion noise in figure 5.13 shown that B100 always has lower noise than B0 except at the acceleration period, which are both comparable. The mode of load acceleration of another 2 engine speed i.e. 2700 rpm and 3600 rpm would have identical characteristics with 1800 rpm, regarding to the platform of acceleration.

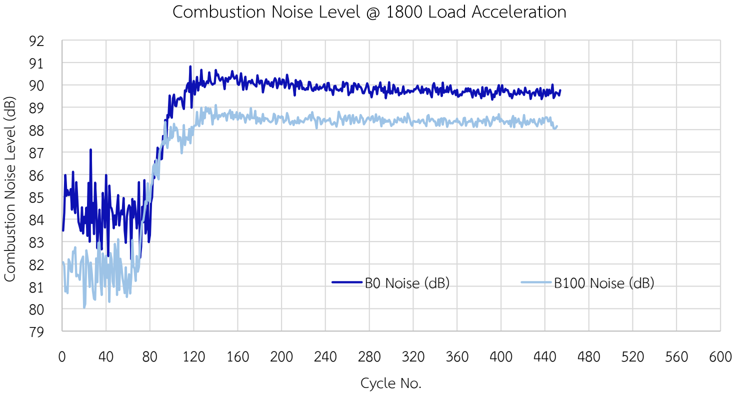


Figure 41: comparison of noise between B0 and B100 by load deceleration

5.6 Conclusion of transient combustion comparison B0 vs B100

This chapter has been devoted for the various engine – dynamometer experiments by setting up the pattern of transient conditions which are free acceleration, mild deceleration and constant speed load acceleration. The high speed combustion diagnostic instrument has been equipped with the engine for detecting the combustion characteristics, then the results of B0 and B100 combustion were investigated and compared to broaden the understanding on transient engine combustion behavior both engine control and fuel response. The result could be concluded as

Table 6: Conclusion from the 1^{st} Engine Experiment

Combustion parameter	**Free acceleration mode**	**Mild deceleration mode**	**Load acceleration mode**
Test validation	The 3 repeated measurement data shows in figure 54	The 3 repeated measurement data shows in figure 55	
Engine response	Multi-parameters change starting from pilot injection to main injection only. The IMEP reach 85% of	Fuel is temporary cut-off when ECU receiving the command of high demand speed and load	Only fuel injection duration has been changed by increasing continuously.

	maximum value since the output reach the flat torque region.	deceleration, then re-fuelling again when accelerating to the new speed and load demand.	
Performance (IMEP)	Steep increasing IMEP, should be used for comparing the acceleration time from different fuels.	Hard to compare even the IMEP during the fuel cut-off period. The comparison can be done before or after this period	Suitable to compare the 2 difference heating value of fuels, since the combustion development is smooth.
Combustion phase & duration	Can be detected the burn duration difference along the acceleration period, but none of CA50 phase difference occur.	Cannot be detected any difference in combustion phase and duration, especially during the fuel cut-off period.	The significant difference in burn duration and CA50 between B0 and B100 can be detected simultaneously in this mode.
Combustion noise	Can be detected whether speed and load acceleration, except at the initial start of transient acceleration.	Cannot be detected any difference in combustion noise during the fuel cut-off period.	Can be detected the difference during load acceleration period.

CHAPTER 6: TRANSIENT DIESEL COMBUSTION PART II [Fuels & additives]

This chapter intend to compare the combustion characteristic of alternative commercial diesel fuels and diesel blended with some advance diesel components such as biodiesel (FAME), GTL or Hydrotreated Vegetable Oil (BHD). In addition, the effect of cetane improver additive has also been taken into account. The candidate fuels comparison were divided into 3 main groups as below

Table 7: Test Fuels Sub-group and Theirs Objectives

Group I: Effect of biodiesel (FAME) blended fuels.	**Group II:** B5 with various BHD blended fuels.	**Group III:** Potential group of premium diesel fuels.
Objective: to quantify the effect of B5 and cetane improver comparing with diesel fuel.	**Objective:** to explore the possibility to improve fuel quality by blending with 2nd generation biofuel (BHD).	**Objective:** to compare the performance of expected premium fuels with regular fuel.
Conditions: Fast load acceleration @ 2,200 rpm (20% - 100% by 2 seconds)		
Test Fuels: 1) Base Diesel (B0) 2) B5: base diesel + 5% FAME 3) B5 + Cetane Improver (B5 + CI)	**Test Fuels:** 1) B5 + CI 2) B5 + 5% BHD 3) B5 + 5% BHD + CI 4) B5 + 10% BHD	**Test Fuels:** 1) Base Diesel (B0) 2) B5: base diesel + 5% FAME 3) Check Fuel High 4) B0 + 20% BHD 5) B5 + 10% GTL

6.1 Group I: Effect of FAME blended diesel (Biodiesel B5)

The base diesel and 5% FAME blended with diesel with and without cetane improver were compared in extremely short load acceleration period at 2,200 rpm. The results has shown below:

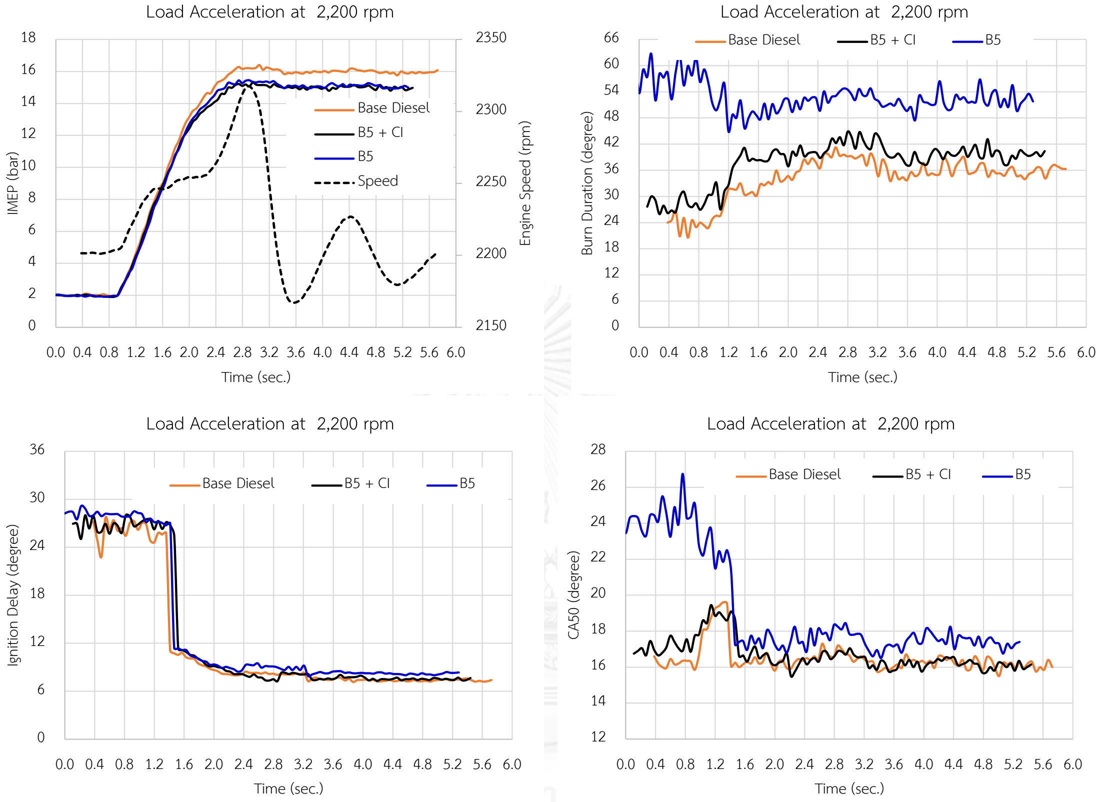


Figure 42: Group I transient combustion analysis of load acceleration at 2,200 rpm

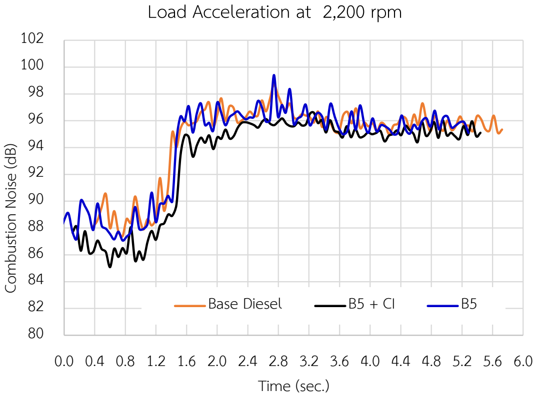


Figure 43: Group I transient combustion noise @ 2,200 rpm

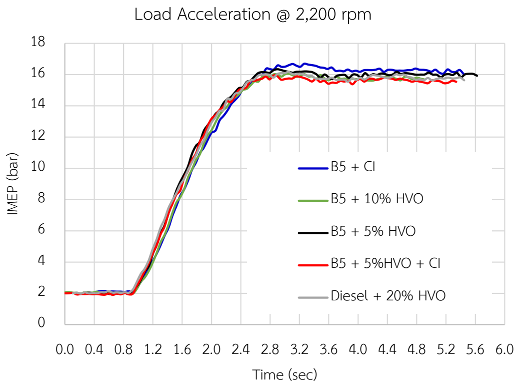
In figure 42 and 43, the engine speed fluctuation regarding to the abruptly increase in throttle position (within 2 seconds), the change of IMEP has more stability than the other calculated parameters. For Group I, IMEP of base diesel has higher value than B5 or B5+ CI especially at full load operation. Ignition delay has insignificantly difference when compared with different fuels, why 50% combustion phase seem to be the best indicator for monitoring the fuel combustion progress.

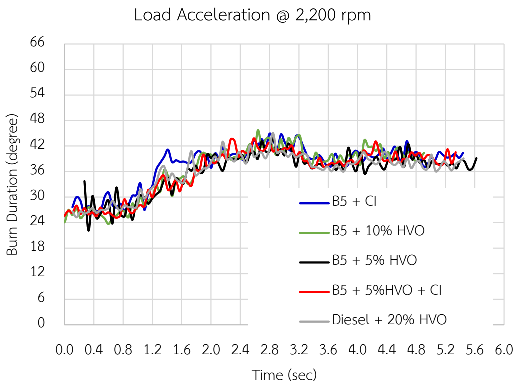
In terms of combustion period in figure 6.1, combustion progress at 50% of base diesel is faster than B5 or B5+ CI and also result in the longer burn duration. The reason is perhaps B5 or B5+CI have higher bulk modulus of elasticity according to the FAME content which result in the higher volume of fuel injected at the same injection duration period.

In figure 43, combustion noise of B5+CI is lower than base diesel and B5 therefore it could be concluded that Cetane improver (CI) can help reducing combustion noise, accelerate the CA50, but CI can't shortening the ignition delay during transient acceleration.

6.2 Group II: Effect of BHD blended diesel fuel

This group try to investigate the effect of BHD when it is blended with diesel or diesel B5 fuels. Since, the BHD has been claimed by manufacturer that it has high natural cetane quality as well as GTL which are also paraffinic hydrocarbon.





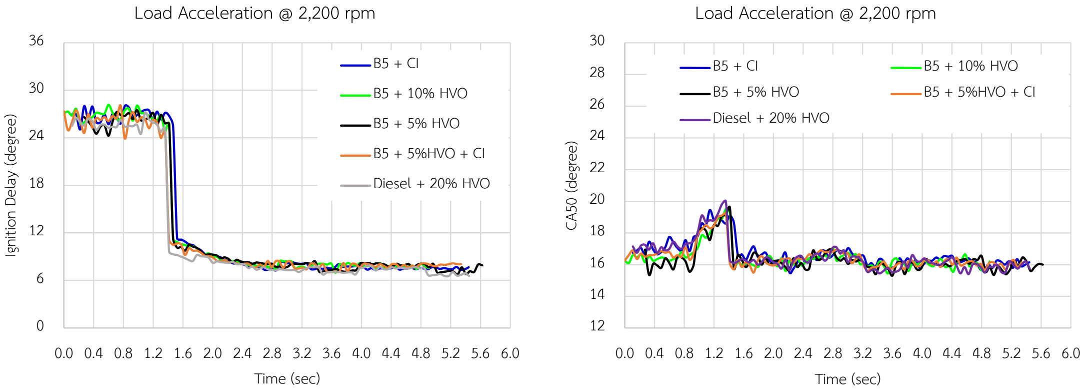


Figure 44: Group II transient combustion analysis of load acceleration at 2,200 rpm

In figure 44 the result of B5 blended with BHD and cetane improver were compared, the development of IMEP during load acceleration are comparable whether the increment rate or the target IMEP. By the way, there is slightly difference between each type of test fuels. As well as the group I comparison, the ignition delay during transient load acceleration has no significant difference. The CA50 was increased during transient acceleration, but there is no difference from those blended with small amount of BHD as well as burn duration.

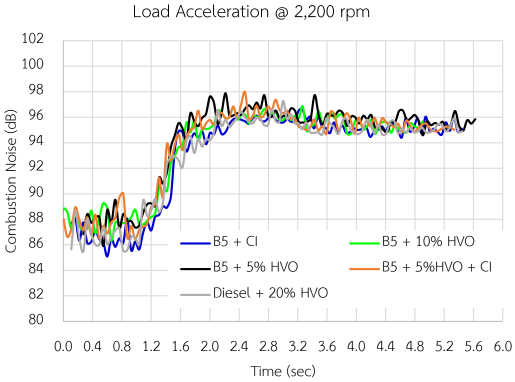


Figure 45: Group II transient combustion noise at 2,200 rpm

For combustion noise (figure 45), it can’t be discriminated the noise from B5 or B5 blended with 5% or 10% BHD. The BHD blended fuel has no effect on combustion noise improvement.

6.3 Group III: Effect of Alternative Diesels

This group try to differentiate the premium diesel with standard diesel and also the high cetane check fuel which is the simple diesel fuel which has specific cetane number (49.5).

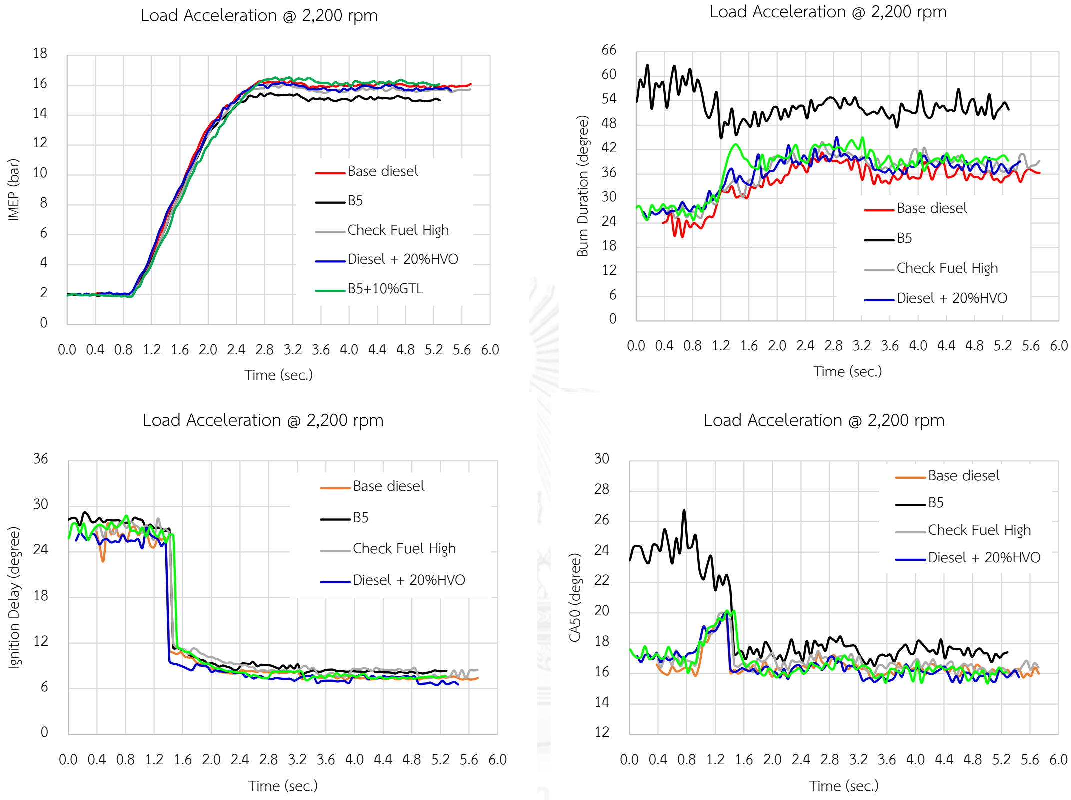


Figure 46: Group III transient combustion analysis of load acceleration at 2,200 rpm

The result shown in the figure 6.5 describing that B5 has lower IMEP, has longer burn duration and slower combustion rate regarding the longer in CA50 especially before and during load transient. In contrast, diesel +10% GTL seem to have highest benefit in transient combustion such as highest IMEP and fastest CA50. If compared by combustion noise in figure 6.6, diesel + GTL is the best fuel which tend to has lowest combustion noise.

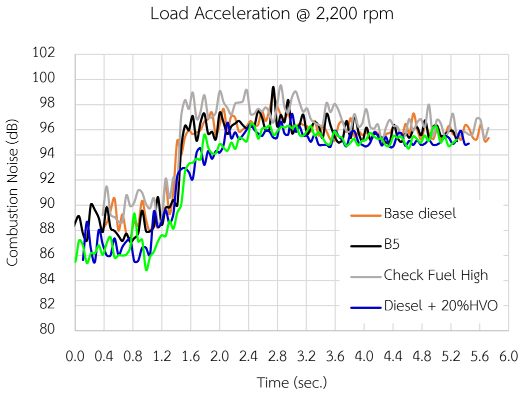


Figure 47: Group III transient combustion noise at 2,200 rpm

6.4 Conclusion of transient combustion part II.

The rapid transient load acceleration at 2,200 rpm has been set as the test condition for investigating the effect of commercial available fuels on transient combustion by detecting its performance and quality of combustion. The fuel samples are separated into 3 groups. The result can be concluded as below:

a) Concerning the rapid load acceleration method, fuel combustion mostly influenced by diffusion combustion, therefore the premixed combustion which mainly contribute to the ignition delay has less effect on combustion. The good indicator to detect transient load acceleration are IMEP development, CA50, burn duration and combustion noise.

b) For group I: the effect of FAME blended diesel fuel, the presence of FAME blended fuel result in the lower IMEP. B5 or B5 + CI tend to contribute to the slower combustion as detected by CA50 and burn duration. This is expected to be the result from the higher bulk modulus of elasticity of FAME. In addition, the combustion noise of base diesel and B5 are comparable, while the addition of cetane improver seem to help lowering the combustion noise.

c) For group II: the effect of BHD blended fuel, the BHD is actually the only 20% BHD blended in diesel fuel therefore the blend of 10% or 20% are compared as 2% or 4% of pure BHD in diesel fuel. Thus, the result is not influenced by the tiny blended of BHD fuels.

d) For group III: the effect of alternative fuels, the premium fuel such as B5 + 10%GTL seem to have better benefit than the others which are higher IMEP and lower noise. This shall be the benefit of 10% blending with paraffinic diesel (GTL) which promote higher cetane number.

From the chapter 5 and chapter 6, the speed acceleration and load acceleration were conducted on the engine-dynamometer test bench. Many parameters were controlled to have a chance for repeatable measurement for example the initial and final engine speed and load. We therefore could not get the significantly difference from engine transient experiment. In the next chapter, the vehicle acceleration on NEDC cycle will be conducted and measuring its combustion in transient mode. To get more understanding on fuel quality differentiation, the extremely difference fuels will be compared.

CHAPTER 7: TRANSIENT DIESEL COMBUSTION PART III (IN-VEHICLE)

The vehicle use in this test has different engine with the previous 2 chapters, since the test duration is long. Therefore, the new engine technology has been updated more frequent. However, the common-rail engine technology always has the same platform of technology such as injection pressure, fuel injection control strategy. This test, therefore, will use the new vehicle model for giving the information up-to-date.

The new SUV diesel vehicle model ISUZU MU-X has been equipped with cylinder pressure sensor and current clamp adapter for measuring the in-vehicle combustion, while running the NEDC reference cycle on chassis dynamometer, see figure 7.1.

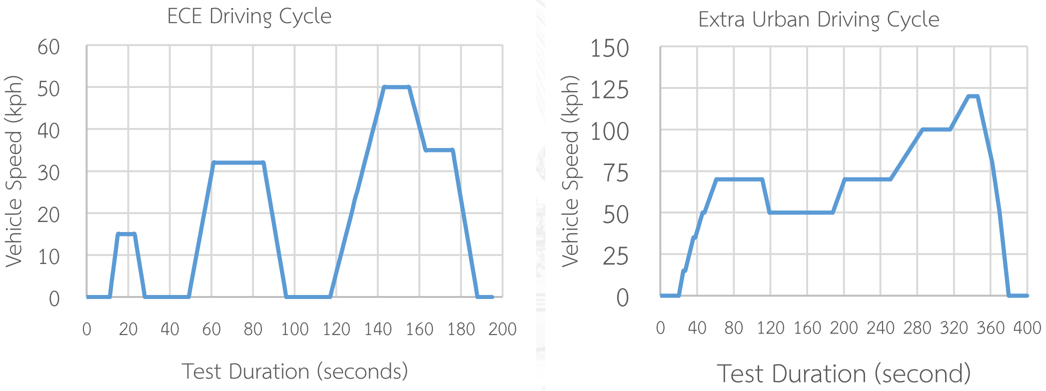


Figure 48: ECE and EUDC combined NEDC emission cycle.

Since the running condition on NEDC composed of both temporary steady-state and transient state condition, therefore the study on combustion during transient application is required to make more understanding on fuel transient response. The selected vehicle specification has shown below,

Table 8: Engine Specification of ISUZU MU-X

Engine Model	ISUZU 4JJ1
Bore x Stroke (mm x mm)	95.4 x 104.9
Engine Capacity	2,999 cc
Compression Ratio	16.5 : 1
Valve, Valve train	4 valves, Double Overhead Camshaft
Max. Torque @ speed	380 Nm @ 1,800 – 2,800 rpm
Max. Power @ speed	177 HP @ 3,600 rpm

The investigation result has been split into 5 acceleration zone covering ECE and EUDC, since the limitation on measuring data acquisition system for 300 combustion cycle only. The result will be shown in consequence order as below:

Table 9: Test Fuels Properties for In-vehicle Measurement

Properties	Standard	Diesel	GTL	HVO	FAME
Derived Cetane Number	ASTM D6890	63.5	110.5	85.5	70.0
Distillation at 10% recovery	ASTM D87	206.1	251.0	285.9	307.2
Distillation at 50% recovery	ASTM D88	293.7	295.0	291.8	326.5
Distillation at 90% recovery	ASTM D89	353.7	336.8	301.3	344.5
Density (kg/liter @ 15.6 ^{O}C)	ASTM D4052	0.8235	0.7832	0.7771	0.8759
Gross Heating Value (MJ/kg)	ASTM D240	46.18	47.23	47.28	40.17
Gross Heating Value (MJ/Liter)	Calculation	38.03	36.99	36.75	35.18
Kinematic Viscosity (mm^2/s)	ASTM D445	3.210	3.435	2.642	4.595
C Content	ASTM D5291	87.6	86.1	85.6	76.2
H Content	ASTM D5291	11.9	12.4	13.3	12.6
O Content	ASTM D5599	0.0	0.0	0.0	11.2
H/C Ratio	Calculation	1.63	1.73	1.86	1.98
O/C Ratio	Calculation	0.00	0.00	0.00	0.11

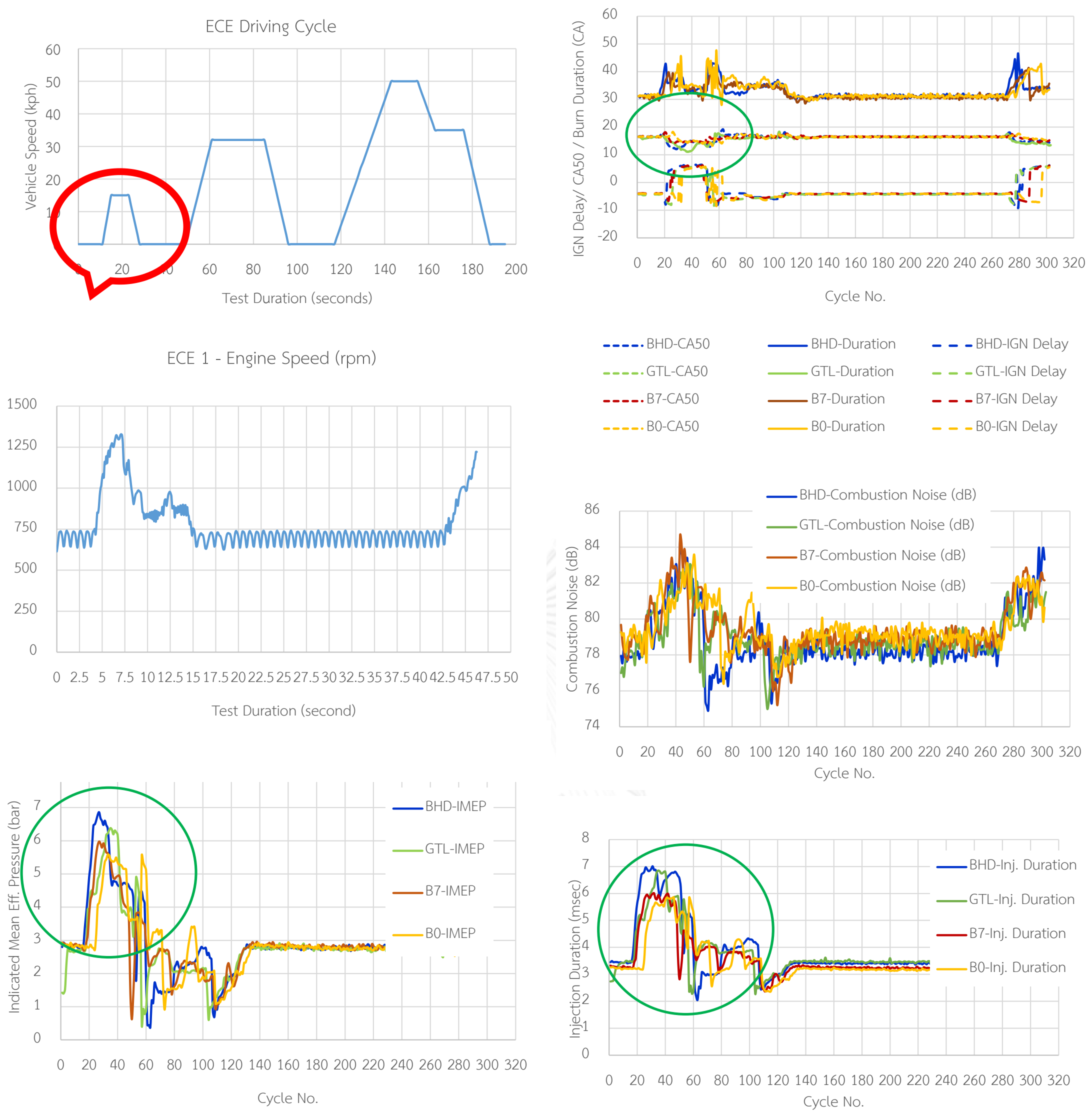


Figure 49: ECE acceleration zone 1 (In-vehicle combustion investigation)

The result from figure 49 covering the first acceleration loop of NEDC, engine speed ramp from idling at 750 rpm to 1300 rpm within 2.5 second. For combustion phase during acceleration, pure BHD and GTL have reached the CA50 before the others and tend to have lower combustion noise. The IMEP of BHD and GTL are higher than the others as well as the longer injection duration.

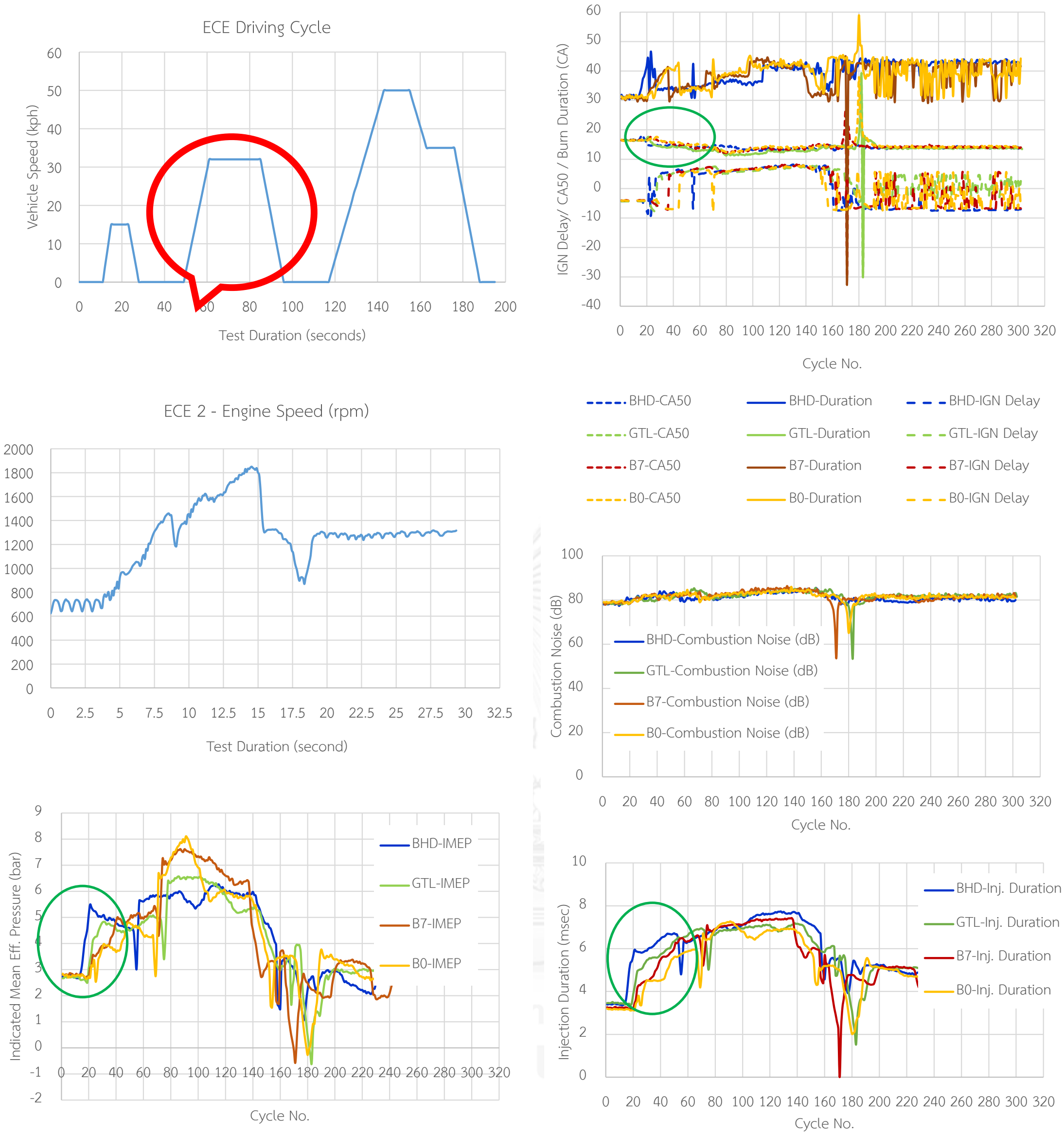


Figure 50: ECE acceleration zone 2 (In-vehicle combustion investigation)

For zone 2 of ECE cycle, the engine speed response shown that there is 1 stepping up of gear-shift (automatic transmission) when accelerate from 0 to 33 km/h. The only detectable parameters are IMEP, CA50 and injection duration for the initial acceleration. The higher IMEP indicated the potential of faster acceleration to the vehicle.

Figure 51: ECE acceleration zone 3 (In-vehicle combustion investigation)

For zone 3 of ECE cycle, the engine speed response shown that there is 2 stepping up of gear-shift (automatic transmission) when accelerate from 0 to 50 km/h. There is no chance to detect the parameter differences from the result. Since, the more severe acceleration introduce the high parameter fluctuation.

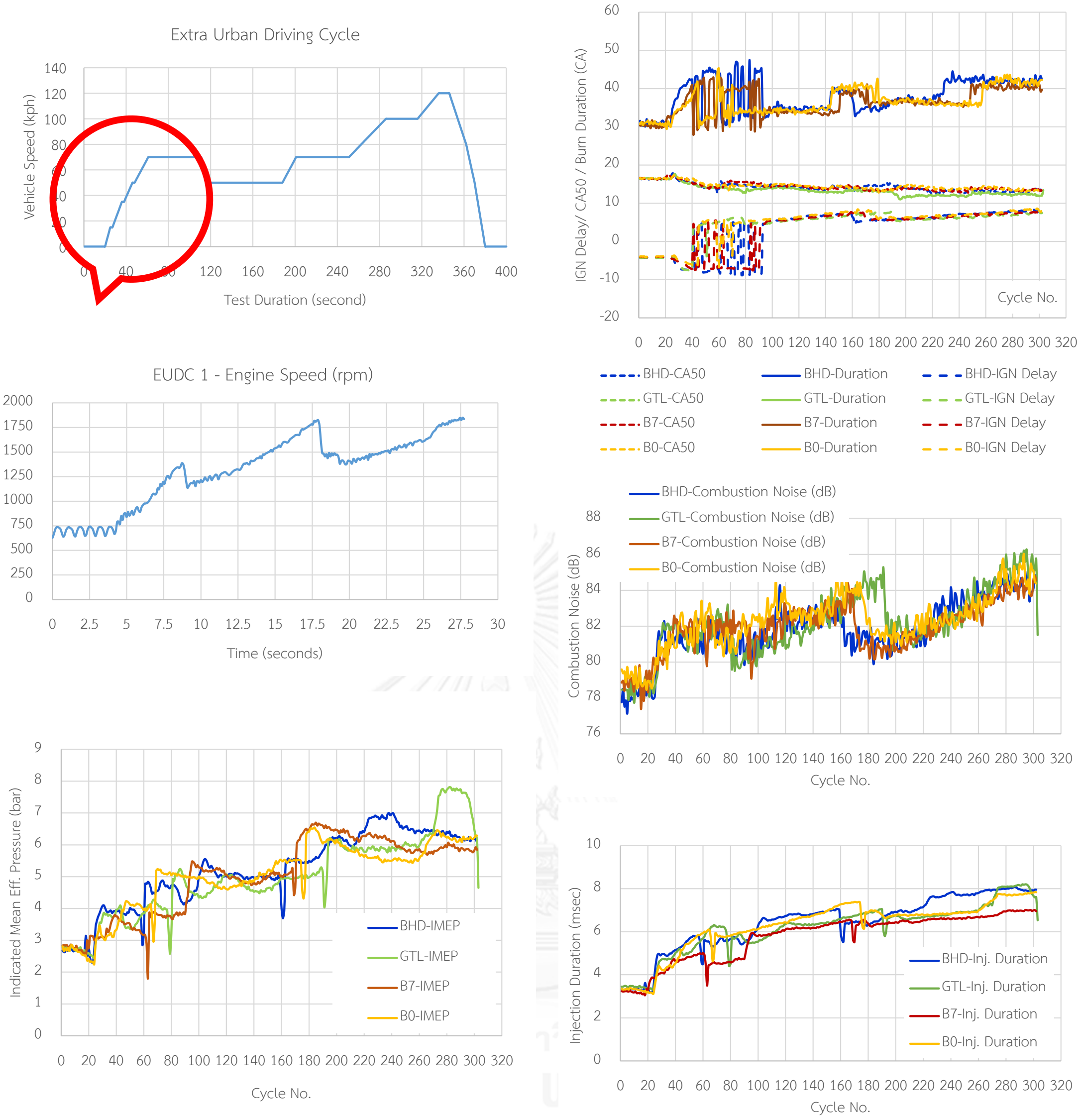


Figure 52: EUDC acceleration zone 1 (In-vehicle combustion investigation)

For zone 1 of EUDC cycle, the engine speed response shown that there is 2 stepping up of gear-shift (automatic transmission) when accelerate from 0 to 70 km/h. There is no chance to detect the parameter differences from the result. Since, the more severe acceleration introduce the high parameter fluctuation.

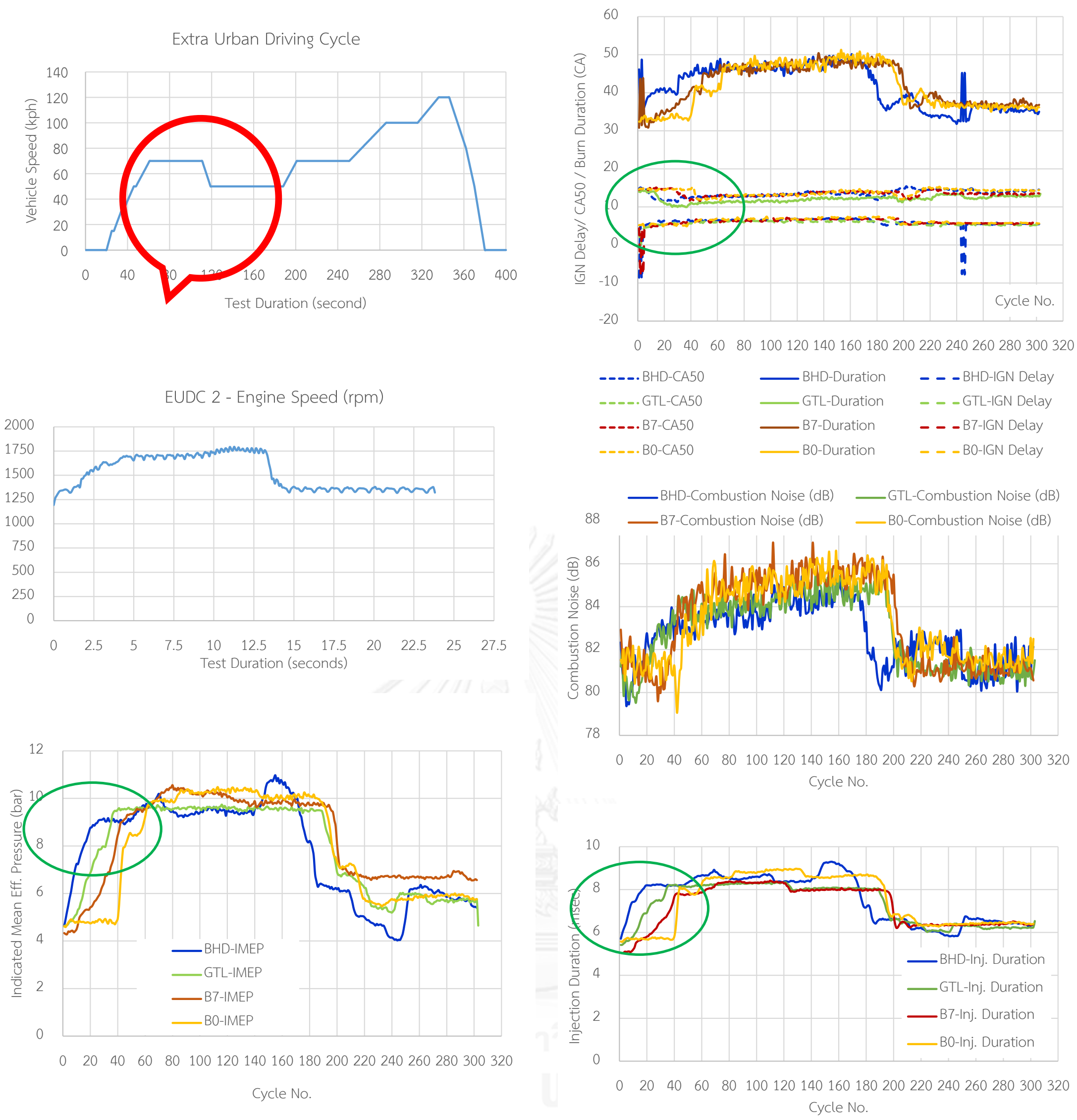


Figure 53: EUDC acceleration zone 2 (In-vehicle combustion investigation)

For zone 2 of EUDC cycle, the engine speed response shown that there is 1 stepping down of gear-shift (automatic transmission) when accelerate from 40 to 70 and 50 km/h. There is a chance to detect the parameter differences from the result. By comparing the IMEP and Injection duration at initial test cycles. In addition, CA50 is also shown some benefit of BHD and GTL.

In conclusion, testing the vehicle on chassis dynamometer by running the NEDC cycle is also a simply way to compare the fuel on transient mode by measuring its combustion while running in the acceleration phase without transmission shift. The compared parameters are IMEP, CA50 and Injection duration. The better fuel shall perform higher IMEP than the normal fuel even the vehicle speed has been controlled.

CHAPTER 8: THESIS CONCLUSION AND APPLICATION

In this study, the design of engine experiments and vehicle test on chassis dynamometer were conducted with many test conditions and test fuels, while the main important part of this thesis is the combustion indicating measurement technique which was modified to suit with transient diesel application. The result of the experiment can be fulfill the major objectives as below

a) To characterize the transient diesel combustion and propose the method of characterizing the transient diesel combustion in term of ignition delay, combustion phasing, burn duration and combustion roughness.

b) To investigate the transient combustion behavior of advance diesel fuels including new potential component as Hydrogenated Vegetable Oil (BHD) or biodiesel and the cetane improver additive like 2-EthylHexylNitrate or etc.

Since the research aims to explore the engine response to the wide variety of fuel quality, therefore the engine and ECU are the commercial engine without any modification on the system and ECU program either. The various engine experiments were conducted by designing of 3 load applications such as free acceleration, load acceleration and mild deceleration modes. The result found that the best mode for transient characterization is load acceleration, since the fuel injection pattern is remain the same for all cycles. The only change is the injection duration. This experiment result in the controllable of engine response. The detect parameters should be IMEP, CA50 and combustion noise. For example, comparing base diesel and FAME or 100% biodiesel the IMEP of B100 is lower than base diesel at the same time with lower combustion noise.

The method of combustion diagnostic in vehicle running on NEDC can also be set for transient characterization. By detecting the IMEP, CA50 and injection duration, the differences between GTL and BHD over the base diesel and B7 have been shown explicitly

Combustion phase at 10% and 90% were also investigated during the experiment and found that they are highly fluctuated. Therefore, CA10 and CA90 are inappropriate to use as the control parameter for transient engine application. This is the result why most of OEM use the CA50 as an indicator for combustion progress for the future engine (Euro 6 diesel engine).

Diesel engine technology has a big revolution from mechanical fuel injection to electronic fuel injection and then high pressure common-rail direct injection is the key technology that bring the theory of conventional diesel combustion to the new approach. The pilot fuel injection help improve the cold-run by reducing the combustion noise from the high premixed combustion.

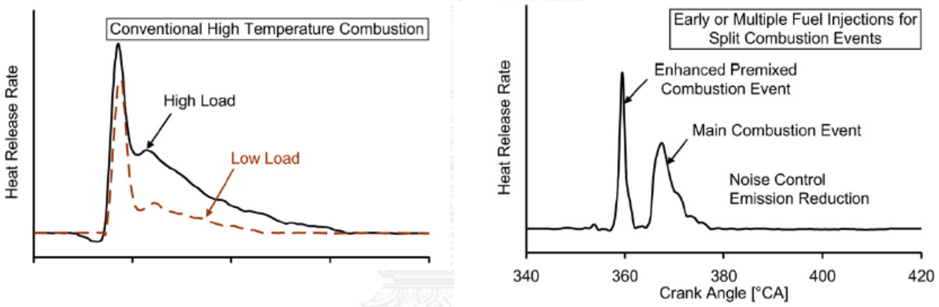


Figure 54: comparison of conventional and modern diesel combustion

From figure 54 (left) represent the conventional diesel combustion with single pulse injection, the high premixed combustion is the source of combustion noise and also the NOx emission. After premixed combustion, diffusion control combustion will be activated. For figure 54 (right) represent the modern common-rail DI which have a chance to run the small pilot injection (premixed combustion) and let the main combustion event drive by diffusion combustion. Therefore, the factor that control rate of combustion in the modern diesel engine is more likely the rate of fuel vaporization instead of the cetane number of the fuel.

The most interesting knowledge has been captured by the series of transient diesel measurement from this research is that transient diesel combustion with the wide variety of commercial fuels (the base diesel blended with some limit of biodiesel or paraffinic diesel and available in the market) give almost the same engine performance and also the output in terms of combustion parameters such as IMEP, combustion phase and combustion noise. This have been proved by the series of repeated measurement with high accuracy combustion measuring system.

International Journal Publication: this research contribute to at least 2 international journal publications which are

1) “A study of the effect of biodiesel blended fuel on diesel combustion”, edited by SAE Interntional, since 2011/08/30. The journal explained the diesel and biodiesel combustion mostly in steady-state which is the background for setting the engine and running with combustion measurement. This can help more understanding of biodiesel combustion.

2) “A comprehensive experimental study on the effect of biodiesel/diesel blended fuel on common-rial DI diesel engine technology” edited by KSAE – International Journal of Automotive Technology, which is waiting for publication. The journal has been explained the effect of using biodiesel in the common-rail DI technology in terms of combustion, performance, emission and durability. The combination of the 1st, 2nd publication and this dissertation will become the most complete research data on biodiesel/ diesel blended fuel including all aspects of diesel engine research for alternative fuel. In addition, the effect of paraffinic diesel is already included for some specific area of application.

Comment from committee:

1) **The design of experiments were focused mainly on the 2 engine models, but the author tried to conclude the effect of transient diesel combustion for the entire diesel engine? Will there be any evidence mention on the same characteristics of these 2 engine models with the others?** *Answer: It is true that the only 2 engine models may not cover all diesel engine market, but from my experience the diesel technology platform is rely mainly on the maximum fuel injection pressure and the number of events on pilot and post injections. I myself belief that for the common emission regulation level of diesel engine, the* *characteristics should be the same as experiment. However, in the future work, I may reconsider about the number of engine models.*

2) Even for the engine and vehicle experiment, why the author selected difference engine models? *Answer: For this case, the long period of time difference, result in the engine model change and the more important point is the availability of engine or vehicle in the laboratory for the time of testing. This is also related to the answer from question no. 1 that the author believe in the similar technology platform of engine.*

3) The objectives of the research is to discriminate the fuel response on transient engine combustion behavior but the result is not relevance directly to the objective. Can it conclude that the design of experiment is not suitable for objectives? *Answer: This is the most critical issue for debating that the result is not what the author expected before. By the way, this set of experiments help discovering the new understanding on transient diesel engine response to various fuels.*

4) If you have a chance to do more experiment in the future, how do you recommend to set the experiment to cover your objective? *Answer: It is the most interesting research work in this area of transient diesel combustion, if you can measure the combustion development at the same time with the emission monitoring. I do believe that even the engine ECU can control the engine performance in transient application, but the emission must be differences.*

APPENDIX

A-1: Test Method Validation by Repeatable Measurement

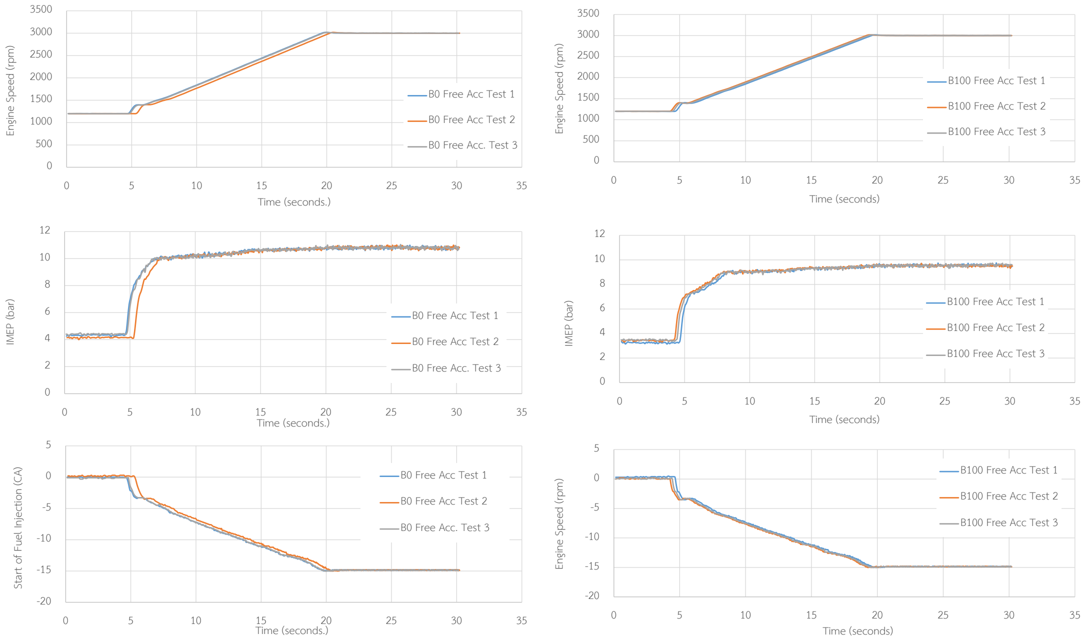


Figure 55: repeated measurement of free acceleration mode test condition

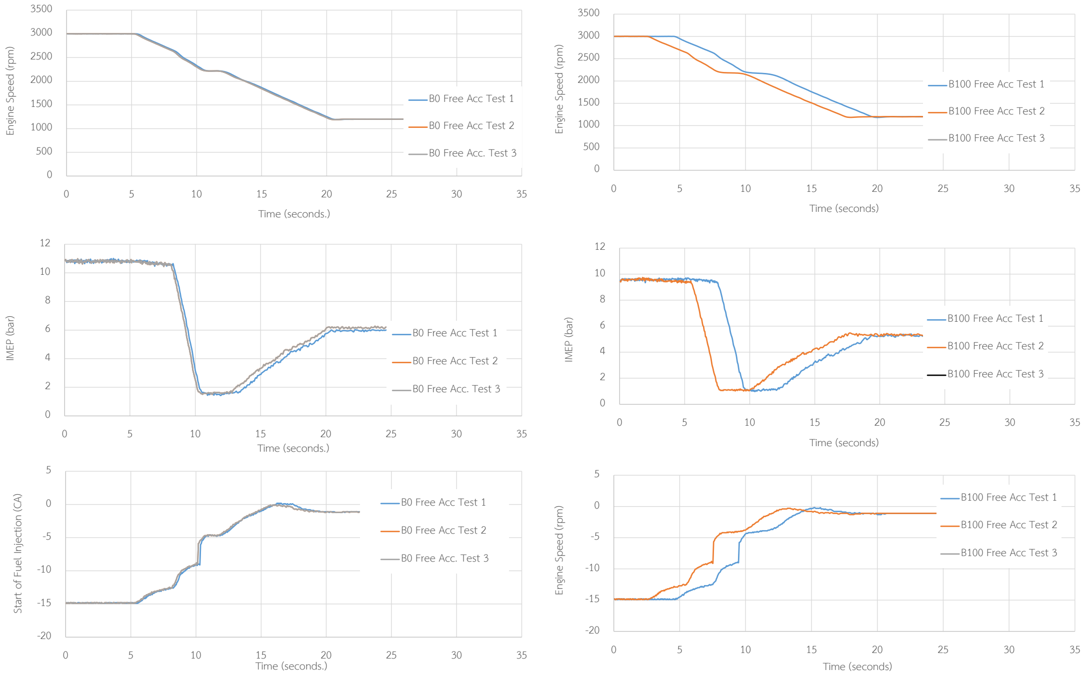


Figure 56: repeated measurement of deceleration mode test condition

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VITA

SOMNUEK JAROONJITSATHIAN has obtained his Master Degree in Mechanical Engineering since 1999. Then, he started his first professional work at National Institute of Metrology, Thailand (NIMT) as a Metrologist trainee in the Acoustics and Vibration Laboratory. Alter that in 2000, He decided to change his career as a researcher at PTT Research and Technology Institute (PTT-RTI) and continue working until now. For 15 years of his research experiences, he conducted the research on PTT fuel and lubricant products covering the area of fuel and alternative fuel combustion, effect of fuel quality on performance, emission and engine durability. He was a part of major research team to support the Thai government in gasohol and biodiesel fuel development and mandatory program during the year 2003 - 2010.

From year 2007 - 2012, he was assigned to be the member of Coordinating European Working Group for engine test and development for CEC F20-98 M111 IVD Test and CEC F-98-08 Peugeot DW-10.

In 2010, the transient diesel combustion is becoming more interesting due to the trends of premium diesel quality is increasing such as high cetane paraffinic diesel (GTL, HVO) or biodiesel blended fuel. He therefore propose this research topic for his Ph.D. work.