Engine Testing of Gasoline, E5, E10, E15 and E20 Ethanol Blends

by

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CERTIFICATION OF APPROVAL

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Last but not least, special thanks to friends and acquaintances that had helped me directly and indirectly on this project.

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMMAD ASYRAF BIN MOHAMMAD HATTA

ABSTRACT

The project is about comparing the ethanol blends with neat gasoline. The purpose of the study is to compare the performance of the engine prior to the usage of neat gasoline and ethanol blends. A study of Alvydas Pikunas et. al. however shown that there is possibility of engine performance increment due to the properties of the ethanol in the blends.

The method used in the study is to test the fuels by using the engine test bench available in the university. The scope of the study is the performance parameter such as power curve, torque curve, and specific fuel consumption using ethanol-gasoline blends of 5% ethanol content to 20% ethanol content. The study shows that there is slight reduction of engine performance and increment in fuel consumption in all range of engine speed.

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1 CHAPTER 1: INTRODUCTION

1.1 Background

The ethanol is currently one of the potential alternative fuels to replace petrol and diesel in the future. Ethanol blends that is currently available in the market as a blend of harvested sugarcane ethanol and petrol. This is referred widely as ethanol blends. As a basis, we are using the mass production engine as a test unit to gain the parameters required.

The trend of fuel price hikes and environmental concern has forced automakers to shift to alternative fuels. Ethanol is being one of the alternatives to be studied. Ethanol can be had from bio-chemical processes and petroleum product.

Universiti Teknologi PETRONAS (UTP) is equipped with many engine test bench. Centre of Automotive Research or CAR is equipped with an engine test bed that used FORD ZETEC 1.8 liter, four-cylinder engine as a base and also are having single cylinder small engines as well. These engines are connected to the computer interface that is easy for use to gain parameters such as power, torque, *Brake Specific Fuel Consumption* (BSFC) and *Brake Mean Effective Pressure* (BMEP).

It is hope that these equipments will help to further increase our understanding towards the understanding the effect of using these fuels.

1.2 Problem Statement

Fuel price hike and environmental impact of vehicle fuelled by fossil fuel such as gasoline are a huge concern nowadays. In prior to this, alternative fuels are being offered worldwide as a step to reduce emission and also to replace or compliment gasoline as fuel.

One of the alternative fuels is ethanol. It is known that ethanol is used in the early automobiles and is used today in countries such as Brazil and Sweden. Volkswagen and Volvo are two of the auto-makers that had produced the flex fuel vehicle that can run on ethanol blends and also gasoline.

However, there is concern about the performance of the engine prior to the usage of ethanol as fuel. This study is to compare and verify the usage of ethanol with gasoline. The outcome of the study should be beneficial for the local automotive industry if they are to produce ethanol fuelled vehicle in the future.

1.3 Objectives and Scope of Studies

The objective of the study is as listed below.

1. To compare the performance between gasoline and ethanol-gasoline blends
2. To determine the effect of different percentage of ethanol in the ethanol-gasoline blends
3. To verify that the introduction of ethanol in gasoline will increase engine performance

The scope of the study is to gain these parameters:

1. Torque output
2. Power output (bhp)
3. *Brake Specific Fuel Consumption*
4. *Brake Mean Effective Pressure*

All required parameters are to be gained from five different points which means that the reading of the performance parameters are done on five engine speeds; 1000, 1600, 2400, 3200, and 4000rpm. These parameters will then be translated to graphical aids to be compared and analyzed.

2 CHAPTER 2: LITERATURE REVIEW/THEORY

2.1 Literature Review

Ethanol is a pure substance compared to gasoline. It is derived from fermentation of sugar in food such as sugarcane and corn starch. Ethanol blends are the ordinary gasoline blended with ethanol. Its percentages are indicated by the volume basis. E0 means that there is 0% of ethanol in 100 ml of fuel and E85 means that the blend is the mix of 85% of ethanol and 15% of gasoline.

Ethanol (C_2H_5OH) is a pure substance compared to the gasoline C_4-C_{12} transitional properties. Furthermore, ethanol is viewed as partially oxidized hydrocarbon since there is one oxygen atom existed in the molecule. Ethanol also easily blends with water, making ethanol susceptible to water content and this would affect the engine performance and reliability. Ethanol also reacts with most rubber parts and since the engine parts consist of rubbers, especially the fuel line.

The combustion characteristics of ethanol are different from gasoline. Auto-ignition temperature and flash point are much higher. The latent heat also 3-5 times higher than that of gasoline, it is possible of having lower intake manifold temperature and higher volumetric efficiency. In term of fuel consumption, the ethanol is known to produce much lower energy output compared to the similar amount of gasoline burnt. This is due to the ethanol is having a higher latent heat and lower energy density than gasoline. [1]

On the other hand, the emission of ethanol fuelled engines was found to be better than that of gasoline. E10 found to decreases the CO emission level to 30% than gasoline fuelled. Stoichiometrically, only 2/3 of the air-fuel ratio of the gasoline is needed for the ethanol to burn.[2] Thus, less air is needed in order to combust a same amount of ethanol compared to gasoline. This is due to ethanol having one atom of

Oxygen in the molecule. Also, the higher the ethanol percentage, the lower the heating value and the higher the octane number of a given blend. Abdel Rahman and Osman[3] had proved that in their work of testing fuel with 10% to 40% ethanol blends with gasoline.

A study of a student of Lithuanian University (Vilnius Gediminas Technical University) shown that there will be increment in the engine power in about 1- 5% across the engine speed due to effect of 'manifold cooling' contributed by higher latent heat value of ethanol.

From the literature review, it is shown that ethanol blend have the potential as the replacement for the current gasoline. It is hope that this project will benefit and complement any research on the same field as well in the future.

2.2 Performance Characteristics[10]

The engine Power, Torque, *Brake Specific Fuel Consumption* (BSFC) and *Brake Mean Effective Pressure* (BMEP) are the parameters used in comparing the engines performance both in using gasoline and ethanol blends. The significance of gaining the parameters is detailed below:

2.2.1 Power and Torque

Power is the rate of which the work is done. Torque is the measure of the engine's ability to do work. The power and torque output of an engine is measured using dynamometer. An engine is clamped on a test bed with a shaft connected to a dynamometer rotor. The rotor are coupled by means of mechanical friction, electromagnet or hydraulic to a stator. This stator will absorb the torque exerted onto it and the corresponding load is exerted on the load cell.

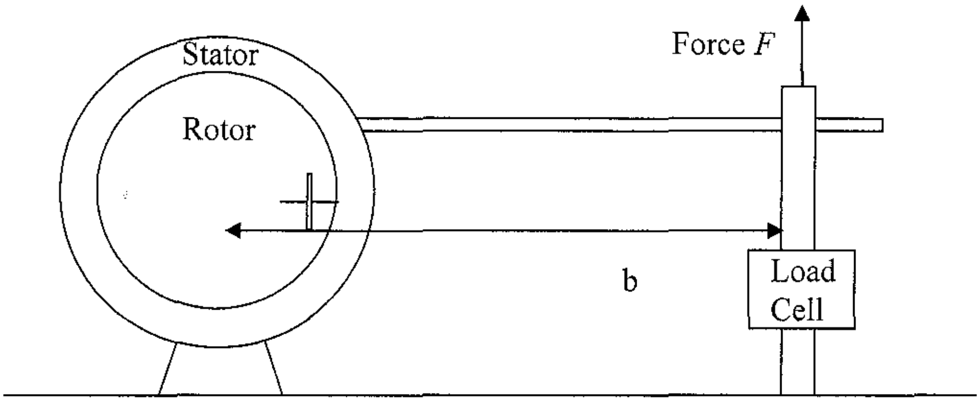


Figure 2.1: The schematic of principle of a dynamometer

Using **Figure 2.1**, the torque exerted by the engine is *T*:

$$T = Fb \qquad 2.1$$

Power P, delivered by the engine is the product of torque and angular speed:

$$P = 2\pi NT \qquad 2.2$$

$$P\ (kW) = 2\pi N(rev/sec)T(N.m)\ x\ 10^{-3} \qquad \text{(in SI unit)} \qquad 2.3$$

$$P\ (hp) = 2\pi N(rev/min)T(lbf.ft)/5252 \qquad \text{(in US unit)} \qquad 2.3$$

The typical engine using gasoline has their power building up from minimum engine speed around 500 - 700 rpm to the maximum power around 5000 – 6000 rpm. For a typical 1.8 liter naturally aspirated engines from 1990s, the power output is in the range of 100 – 130 bhp.

2.2.2 *Brake Specific Fuel Consumption* (BSFC)

One of the most important parameters to be determined in engine testing is fuel consumption. In engine testing, the fuel consumption is measured in mass flow rate per unit time, m_f. The specific fuel consumption, measured in g/kW.hr, which means how efficient the engine use the fuel to produce work.

$$BSFC = {m_f}/{P} \qquad 2.4$$

$$BSFC\ (mg/J) = {m_f(g/s)}/{P(kW)} \quad \text{(SI unit)} \qquad 2.5$$

The m_f is the fuel mass flow rate and P is the power produced for the combustion. In engine testing, the lowest value of the BSFC is desirable.

In typical BSFC versus engine speed curve, at certain engine speed, the fuel consumption is at minimum. This also means that the minimum fuel consumed to produce the maximum power output. However, this varies from engines as the type of fuel injection, injection timing and other parameters might be different.

2.2.3 *Brake Mean Effective Pressure* (BMEP)

Torque values are different from one engine to another. A useful relative engine performance measure is *Brake Mean Effective Pressure* (BMEP). It is simply the work per cycle divided by the volume displaced per cycle.

$$Work/cycle = \frac{P n_r}{V_d N} \qquad 2.6$$

where n_r is the number of crank revolutions for each power stroke per cylinder (two for four strokes, and one for two strokes cycles), then:

$$BMEP\ (kPa) = \frac{P(kW) n_r \times 10^{-3}}{V_d(dm^3) N(\frac{rev}{s})} \qquad 2.7$$

$$BMEP\ (lb/in^2) = \frac{P(hp) n_r \times 396{,}000}{V_d(in^3) N(\frac{rev}{min})} \qquad 2.8$$

BMEP can also be expressed in terms of torque:

$$BMEP\ (kPa) = \frac{6.28 n_r \times T(N.m)}{V_d(dm^3)} \qquad 2.9$$

Thus, it can be predicted that BMEP curve will be similar to the torque curve.

2.3 Stoichiometric equation and calculation [4]

Stoichiometric equation can be used to determine the requirements of the combustion process of gasoline, E5, E10, E15, and E20. Stoichometric combustion means that the fuel is burnt completely in air.

Before further physical works, here are some of the range of air-fuel ratio typically used to burn gasoline (E0), E85 and E100 (pure ethanol).

Table 1.2: The range of AFR (stoichiometric) of E0, E85 and E100

Fuel	AFRst	FARst	Eq. ratio	Lambda
Gasoline (E0)	14.700	0.068	1.000	1.000
	12.500	0.080	1.176	0.850
	13.230	0.076	1.111	0.900
E85	9.765	0.102	1.000	1.000
	6.975	0.143	1.400	0.714
	8.469	0.118	1.153	0.867
E100	9.008	0.111	1.000	1.000
	6.429	0.155	1.400	0.714
	7.800	0.128	1.150	0.870

Equivalent ratio, which is the ratio actual AFR to the stoichometric AFR can give us the intuitive way to express richer mixture. While, lambda is the ratio of leanness, which is actual AFR to Stoichiometric AFR.

Based on stoichiometric, or perfect combustion;

$$C_2H_6O + 3\ O_2 = 2\ CO_2 + 3\ H_2O$$

By adding up the molar mass of ethanol (E100);

(6 x 1.00794) + (2 x 12.0107) + (1 x 15.9994) = 46.0684 grams/mol of Ethanol

1 mol x 46.0684 g/mol Ethanol: 3 mol x 2 x 15.9994 g/mol Oxygen

46.0684: 95.9964 = 1:2.0838 for the *fuel:oxygen* ratio for perfect (i.e., stoichiometric) combustion

By knowing that Oxygen is 20.9% of air by volume, or equivalently, 23.133% of air by mass (it is assumed that atmospheric gases behave as ideal gases).

Hence, the theoretical air fuel ratio for E100 (100% ethanol) is:

(2.0838/0.23133): 1 = 9.0078: 1

So, for E85, the required air fuel ratio can be estimated as:

0.85 x 9.0078 + 0.15 x 14.64 = 9.8526

This is closer to the gasoline air fuel ratio. From these findings, it is predictable that the value of stoichiometric AFR for lower than E20 ethanol blends can be figured lower than that of E85 and should be very near to gasoline. This would give us information that the ethanol blends would not need much adjustment of its AFR rather than E85.

Other findings is that, the ethanol blends with higher than 20% of ethanol content boasts better performance from the gasoline if the engine's compression ratio are similar to the diesel engine, at 18:1 to 20:1. However, the problem is that, higher compression ratio also can cause the engine to produce higher level of NO_x gases in exhaust emission. [4]

2.4 Review on Vilnius Gediminas Technical University Findings [5]

Below are the examples of the diagrams taken from Alvydas Pikunas et al. (Vilnius Gediminas Technical University) study of E10 ethanol blends on Toyota engine.

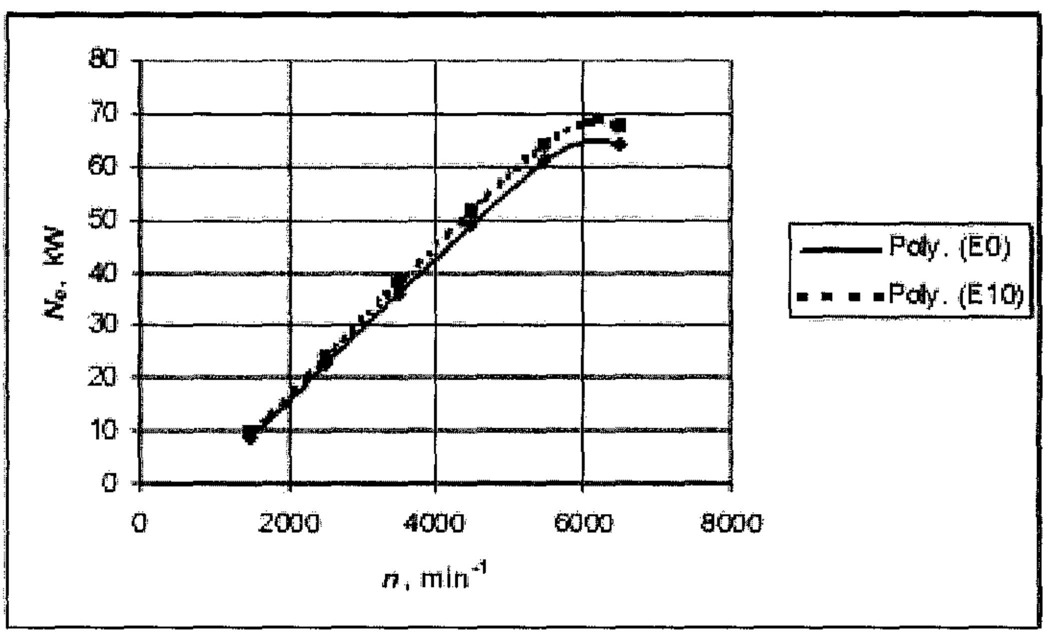


Figure 2.2: Power curve

From **Figure 2.2**, the power output of the engine is increased in the usage of E10 over gasoline. At low speed, the values are about the same until it rises to higher engine speed. The peak power at 6000 rpm is 5kW or 6% higher than gasoline.

For the higher power output, it is believed to be caused by the introduction of ethanol which has higher latent heat than gasoline. The study reported that the increment in power might due to the manifold cooling effect of ethanol in the E10 blend. It is known that the heating value of ethanol is 1.6 times higher than that of gasoline. [5] This will reduce the intake port temperature and increase the volumetric efficiency. However, this effect cannot be investigated in this project due to the engine specification where it does not have temperature sensor in the intake manifold.

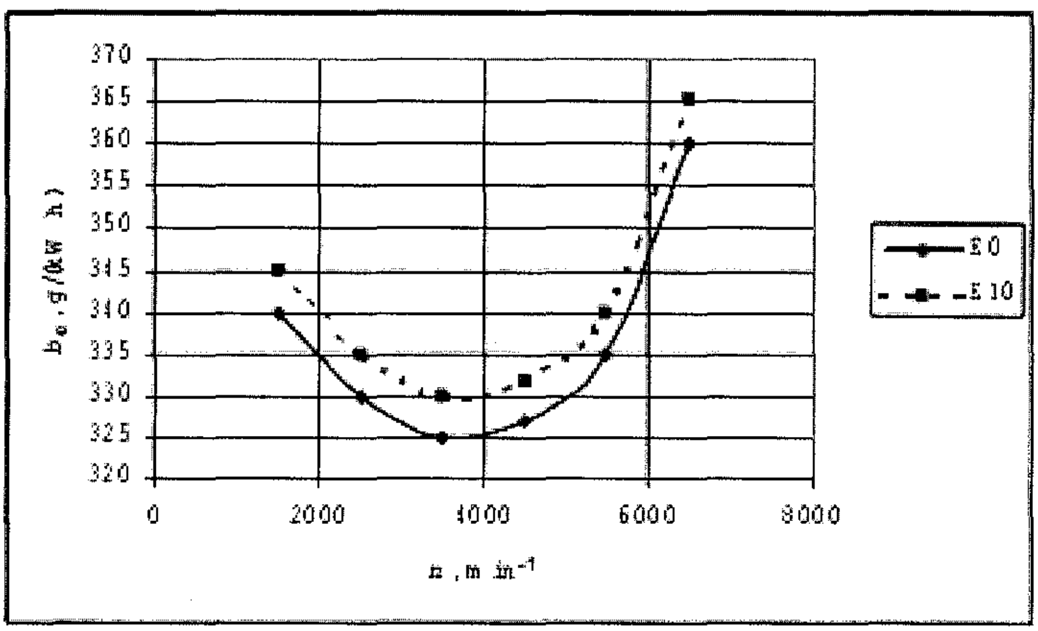


Figure 2.3: Fuel consumption over engine speed

From **Figure 2.3** the fuel consumption is higher than the gasoline. It is at higher than gasoline's about 5g/kW.hr across the engine speed from 1500 – 6500rpm or at 2% higher. The minimum is at around 3500 – 4000 rpm. This is expected as the ethanol has lower energy content and more fuel are needed in order to produce power.

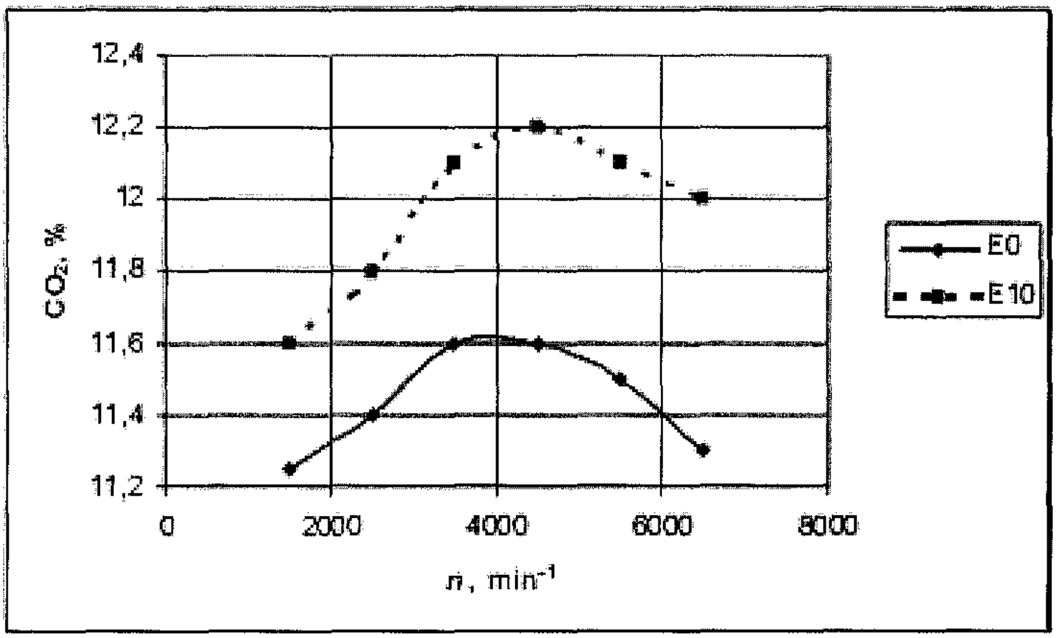


Figure 2.4: CO2 emission over speed

From **Figure 2.4**, it is found that the E10 produces more Carbon Dioxide than the gasoline. It is higher than produced by gasoline at around 0.4 – 0.7%.

From the review of the Lithuanian University findings, it is acknowledged that the finding might vary from research to another. The result however is depending on the type of engine and also the method used. From this review, other factor should be considered such as the manifold cooling effect of ethanol due to its higher latent heat value.

3 CHAPTER 3: METHODOLOGY/PROJECT WORK

3.1 Methodology

To compare gasoline performance with ethanol blended fuels, the engine test bench methodology are used. Engines are fuelled with gasoline to obtain the first data series. The engine then will be flushed and fuelled with another blend. The step repeated until all the blends are tested.

3.1.1 Engine Test Bed

The fuels are tested using educational level test bench unit based on a production engine. The engine is a 1.8 Ford ZETEC unit used in most Ford passenger car in the 1990's. It is a mass-produced engine and a good base for this project. Below are the engine specifications:

Table 3.1: The Engine specifications

Engine Name	Ford Zeta (ZETEC) 1.8L DOHC
Capacity	1796cc
Cylinders	4-Cylinder
Bore x Stroke	80.6 x 88.0mm
Compression ratio	10.0:1
Maximum Power @ Speed	85kW(115bhp)/5500 RPM
Maximum Torque @ Speed	160Nm/4400 RPM
Manufacturing Period	1991 - 1997

3.2 Project Flowchart

To further simplify the flow of the project, please refer to the flowchart below:

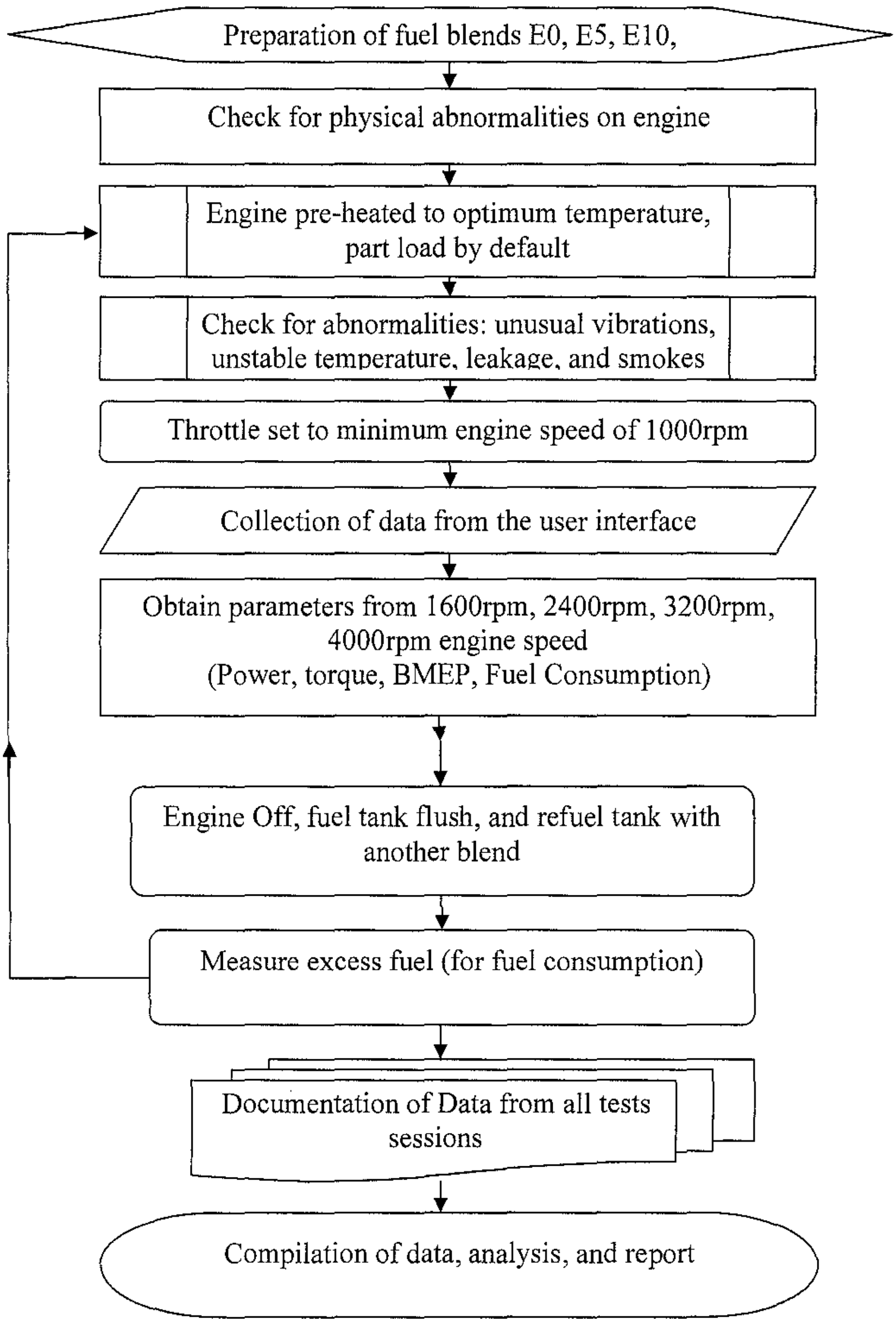
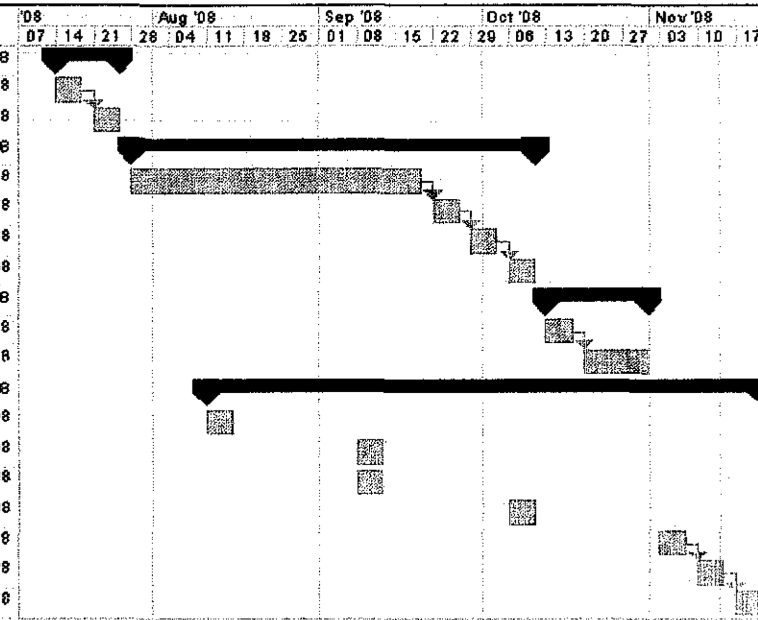


Figure 3.1: Project Flowchart

3.3 Project Gantt chart

ID		Task Name	Duration	Start	Finish
1		Fuel Blends	10 days	Mon 14/07/08	Fri 25/07/08
2		Fuel Blends Preparations	1 wk	Mon 14/07/08	Fri 18/07/08
3		Fuel Blends Test	1 wk	Mon 21/07/08	Fri 25/07/08
4		Engine Performance Test (Multi Cylinder)	55 days	Mon 28/07/08	Fri 10/10/08
5		Engine Set-up (ECU repair & Calibration)	2 mons	Mon 28/07/08	Fri 19/09/08
6		Fuel Test 1	1 wk	Mon 22/09/08	Fri 26/09/08
7		Fuel Test 2	1 wk	Mon 29/09/08	Fri 03/10/08
8		Fuel Test 3	1 wk	Mon 06/10/08	Fri 10/10/08
9		Documentations	15 days	Mon 13/10/08	Fri 31/10/08
10		Collection of Data	1 wk	Mon 13/10/08	Fri 17/10/08
11		Data analysis	2 wks	Mon 20/10/08	Fri 31/10/08
12		Project Tasks	75 days	Mon 11/08/08	Fri 21/11/08
13		Progress Report I	1 wk	Mon 11/08/08	Fri 15/08/08
14		Progress Report II	1 wk	Mon 08/09/08	Fri 12/09/08
15		Seminar	1 wk	Mon 08/09/08	Fri 12/09/08
16		Poster Exhibition	1 wk	Mon 06/10/08	Fri 10/10/08
17		Dissertation Submission (Soft Bound)	1 wk	Mon 03/11/08	Fri 07/11/08
18		Final Presentation	1 wk	Mon 10/11/08	Fri 14/11/08
19		Hard-Bound Dissertation Submission	1 wk	Mon 17/11/08	Fri 21/11/08



Project: Engine Testing FYPII.mpp
Date: Fri 14/11/08

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

Page 1

3.4 Ethanol-Gasoline Blends Preparations

The ethanol blends used are prepared in several percentages. It is to be blended in the increment of 5% starting with gasoline at 0% ethanol content or E0. Because the increment of ethanol percentage higher than 20% will not be suitable to the engine compression ratio, injection timing and also ignition timing, the ethanol percentage will be limited to only 20% or E20.[9]

The ethanol additions are prepared by volume basis. E5 means there is 5% ethanol in a unit of blend volume. It is translated to 200 ml of ethanol mixed with 3800 ml of gasoline in 4 liter of E5. It is prepared by another Mechanical Engineering student in the chemical laboratories by using the measuring tools and also with the help of chemical engineering students and technicians.

The octane rating for the ethanol is higher compared to gasoline. It is known that the ethanol octane number is around 102 - 104 RON compared to gasoline's 92 - 95 RON. This shows that the fuel can be used in higher compression ratio engines for better efficiency, lower fuel consumption and higher power/torque. [4]

Table 3.2: Table of properties of several types of fuels

	Chemical formula	Chemical weight (lb/mole)	Specific gravity	Boiling point (C)	Latent heat (Btu/lb)	Combustion energy (Btu/lb)	Vapor pressure @100F (psi)	Solubility part in 100 parts H_2O	Stoichiometric air-fuel ratio
Methyl alcohol	CH_3OH	32	0.79	65	503	10,260	4.6	∞	6.5
Ethyl alcohol	$CH_3CH_2(OH)$	46.1	0.79	78	396	13,160	2.2	∞	9
Butyl alcohol	$C_2H_5CH_2CH_2(OH)$	74.1	0.81	117	186	15,770	0.3	9	11.2
Octane	C_8H_{18}	114	0.70	210	155	20,750	1.72	-	15.2
Hexadecane	$C_{16}H_{34}$	240	0.79	287	--	20,320	3.46	-	15

Figure 3.3: The E20 ethanol-gasoline blends prepared in the lab

4 CHAPTER 4: RESULTS

After the test being done, the data obtained are then collected and documented to allow for analysis of data. The test was done in three different sessions and all the data obtained are then averaged to reduce the errors. The sessions are limited to only three sessions because of limitation of ethanol and also test time because of the unavailability of the engine earlier. The results are taken directly from the user interface of AutoTest 4 software that controls the engine test bench. Refer to **APPENDIX 4-1** to **APPENDIX 4-2** for the recorded results.

4.1 Comparison of Ethanol Blends to the Gasoline in Engine Performance

In comparing the data taken from the tests, tables and graphs are used. It is to ensure that the data are well delivered and clear to be viewed for analysis. Noted that the data gathered in the tables and the graphs are average values taken from the three (3) fuel test sessions.

4.1.1 Torque Output

The first parameter to be analyzed is the torque output. The data of torque output in every engine speed are recorded in **Table 4.1**. This is to show how the engine torque is behaving in every engine speed in prior to the usage of the blends.

Table 4.1: Average torque values over engine speed

Engine speed	E0	E5	E10	E15	E20
1000.0	111.0	107.7	106.3	102.7	101.3
1600.0	135.3	134.3	133.3	132.7	131.7
2400.0	140.7	140.0	138.3	137.7	136.3
3200.0	145.0	143.3	142.3	141.7	141.0
4000.0	144.3	142.0	141.0	140.3	139.0

A graph was constructed from the above table:

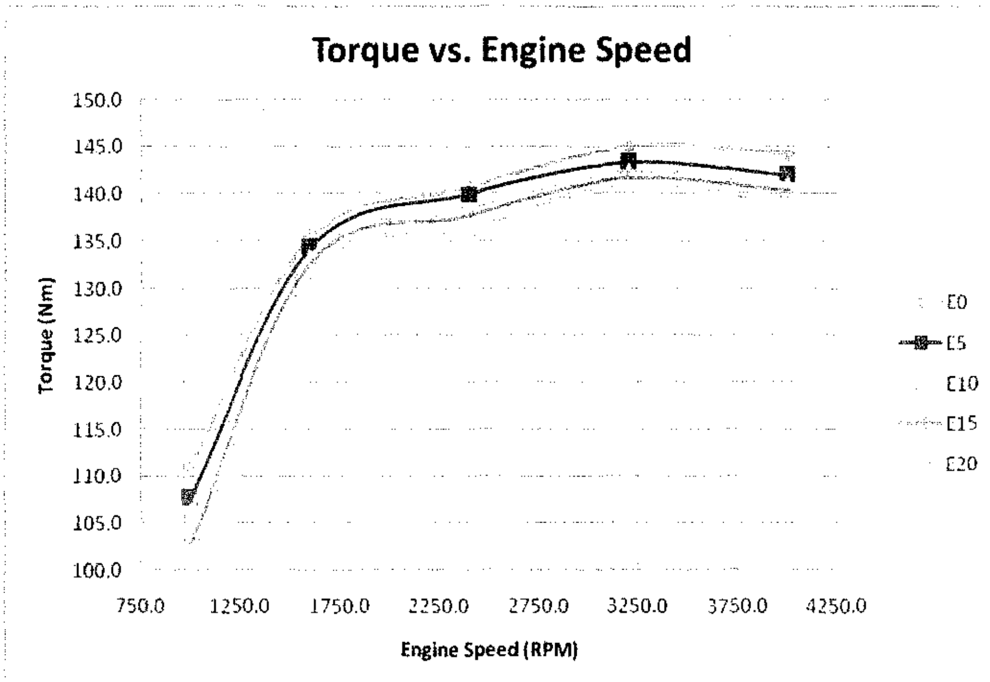


Figure 4.1: Torque vs. Engine Speed

From **Figure 4.1**, it is clear that the E0 or Gasoline gave the most torque from the rest of the blends. The other blends power values follow the E0 in descending order in all engine speed.

For low engine speed of around 1000rpm there is reduction of torque output of about 3Nm – 5Nm, from E5 to E20. For higher range of speed, around 1800rpm, the torque values are much closer together but are also decreasing in values from E5 to E20. For engine speed of 2000 - 4000 rpm, the torque output is reducing significantly. The E20 are reduced more than 5Nm from standard gasoline.

At the engine speed from 1000rpm to 4000rpm, the engine torque output is reduced as the percentage of the ethanol in the blend increased. The higher the ethanol percentage in the fuel, the lower the engine torque output. The reduction is only about 3Nm - 5Nm, or 2% - 5% from the Gasoline's.

There is an obvious characteristic of this engine. At around 2000 – 2500 rpm, the torque build slows down. The torque builds up again when approaching 3000rpm where the peak torque is. At high engine speed of 4000rpm, there is significant reduction of torque output at all blends. The torque output of gasoline is much higher at 144.3 Nm. The E5 is lower at 142 Nm and followed by E10, E15 and E20 at 139.0 Nm.

To summarize, the torque values are affected by the increase of ethanol percentage in the blends. These values are only slightly lower than the gasoline fuelled engine. The higher the ethanol percentage, the lower the torque output.

The engines torque output at higher engine speed of more than 4000rpm cannot be determined because of the engine limitation. The engine cannot be run beyond 4000rpm because of some reliability issues. It is to ensure that the engine did not blow out at high engine speed.

In relation to this, the speed where the engine torque drop which is around 5500rpm cannot be seen. Thus, the effect of the blends to the point where the torque drops cannot be determined.

4.1.2 Power Output

As what was done to the engine's torque output, the data are gathered and put into **Table 4.2**. The power curves are constructed from the values obtained. It is to be noted that these values are corrected values where pressure, humidity and also ambient air temperature are taken into consideration. The calculations are done in the Microsoft Excel where a spreadsheet programming was used. Refer **APPENDIX 4-1** to **4-5** for the data taken from the software.

Table 4.2: The power output values (corrected)

Engine speed	E0	E5	E10	E15	E20
1000.0	15.3	15.0	14.9	14.6	14.5
1600.0	32.7	30.2	29.8	29.6	29.5
2400.0	47.1	46.9	46.3	46.2	45.7
3200.0	63.3	63.3	63.3	63.3	63.1
4000.0	80.1	79.7	78.7	78.5	78.2

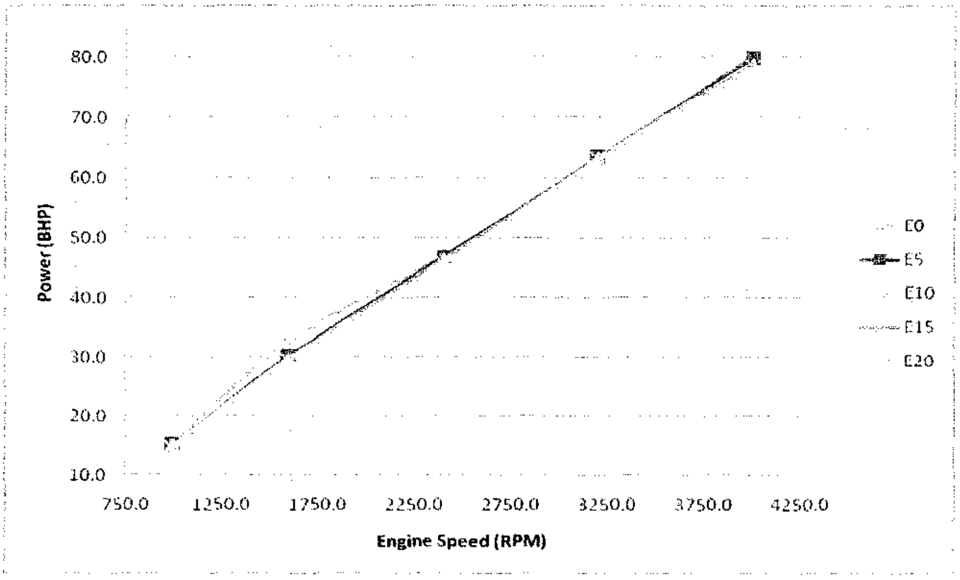


Figure 4.2: Power vs. Engine Speed (750 – 4250 rpm)

From **Table 4.2**, there is reduction of engine power across the engine speed. However, it is not clear to see on the power curve in **Figure 4.2** because the reductions are small.

In the low engine speed of around 1000rpm, the power is about the same, at 15.0 bhp. However, the gasoline has the highest power output and followed by E5, E10 and E15. E20 produces the lowest power output at 14.5 bhp. The range of power output differences are about 1bhp. The engine power reduced more as the engine speed build up at around 2000 – 3000 rpm. The values are reduced in about 1 - 2bhp.

At higher engine speed, around 3000rpm, the engine power output is similar to the gasoline. From the previous Torque Curve, the peak torque is found at this engine speed. During this speed, it is found that the engine is running quite vigorously and the sound is louder than in other engine speed.

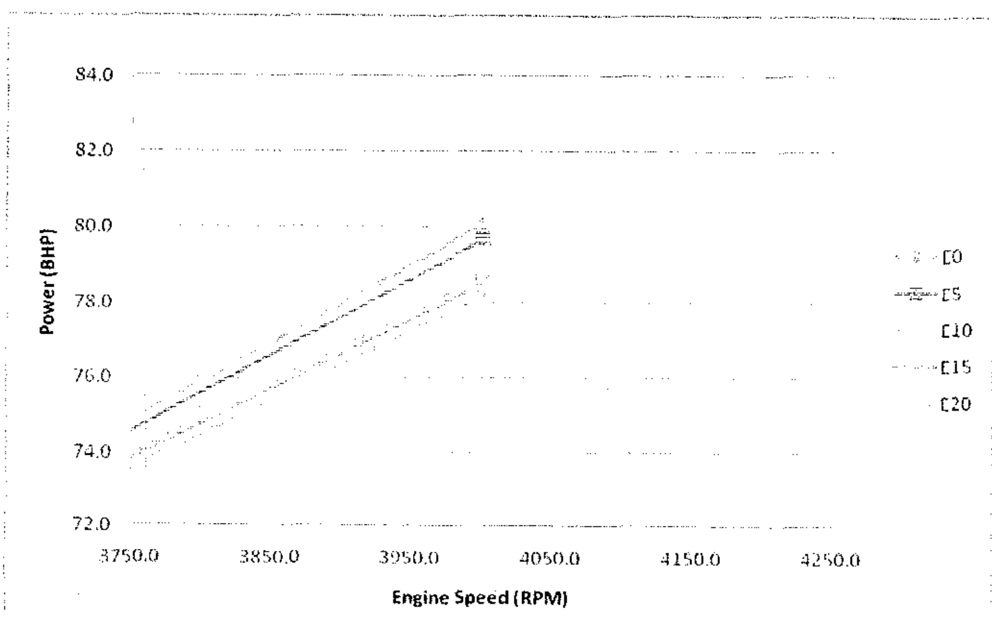


Figure 4.3: Power vs. Engine Speed (3750 - 4250rpm)

From **Figure 4.3**, at 4000rpm, the power output however exhibits reduction in all blends. The E5 power output at this speed is close to the gasoline. The E10 produces lower power output than E5 followed by E15. E20 is the lowest at 78.0bhp. These values are close to each other. It can be concluded that the effect of ethanol percentage in the blend may reduce the power output but at a slight amount.

4.1.3 *Brake Specific Fuel Consumption* (BSFC)

Table 4.3: The values of BSFC

Engine speed	E0	E5	E10	E15	E20
1000.0	0.499	0.495	0.498	0.524	0.528
1600.0	0.236	0.273	0.277	0.292	0.293
2400.0	0.162	0.270	0.278	0.287	0.295
3200.0	0.289	0.298	0.295	0.303	0.309
4000.0	0.311	0.313	0.317	0.314	0.316

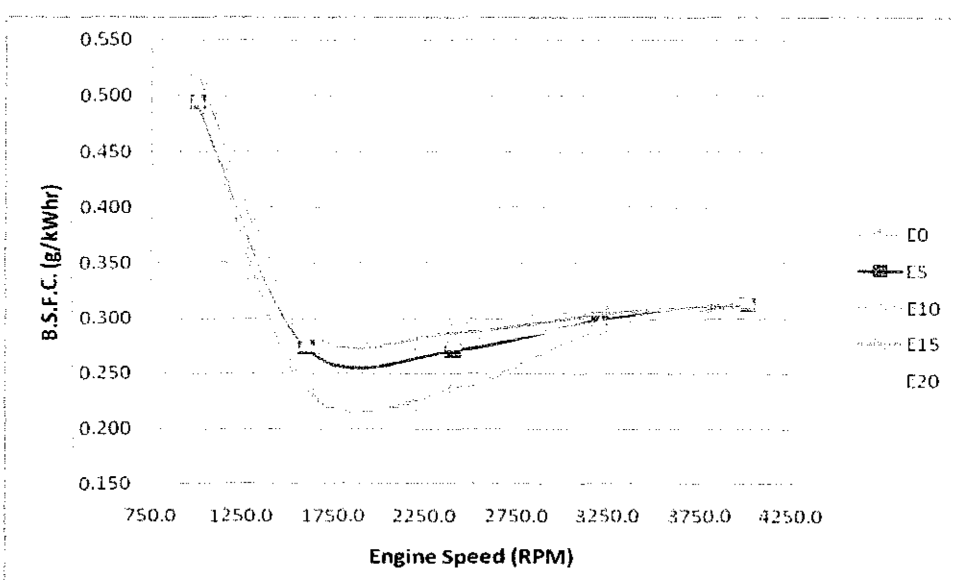


Figure 4.4: The BSFC vs. Engine Speed curve

From **Figure 4.4**, the BSFC of neat gasoline started at around 0.5 g/kW-hr and minimum at around 2000 – 2500 rpm at 0.16 g/kW-hr. The value rises again after the speed and settles at around 0.32 g/kW-hr. This is common for gasoline powered engine used in cars where the engine is usually running at 2000 – 3000 rpm during cruising. It is desirable for average fuel consumption.

The ethanol blended fuels values does not behave similarly but at higher value. For E5 and E10 blends, the BSFC are about the same of that of gasoline at low speed of 1000 rpm. For E15 and E20, the BSFC at 1600 rpm are apparently higher at 0.52 g/kW-hr. At around 1600 – 2000 rpm, the values are much higher than gasoline. All blends are closer to 0.30 g/kW-hr and does not change much until the speed elevate to 3000 rpm. All blends are close to gasoline's BSFC at the speed of 4000 rpm.

Usually, the engine has their lowest BSFC at the maximum torque. This is true to the case of gasoline. However, the resulting BSFC for the ethanol blends are not. While the maximum torque can be found at engine speed around 3000 rpm, the minimum BSFC are found at speed around 2000 – 3000 rpm. This might be due to improper calibration or maintenance and reliability issues. Further studies might be needed to investigate this.

4.1.4 *Brake Mean Effective Pressure* (BMEP)

Table 4.4: The BMEP values over engine speeds

Engine speed	E0	E5	E10	E15	E20
1000.0	7.7	7.6	7.5	7.3	7.2
1600.0	9.5	9.4	9.4	9.3	9.2
2400.0	9.8	9.8	9.7	9.7	9.6
3200.0	10.2	10.1	10.0	10.0	9.9
4000.0	10.1	10.0	9.9	9.9	9.8

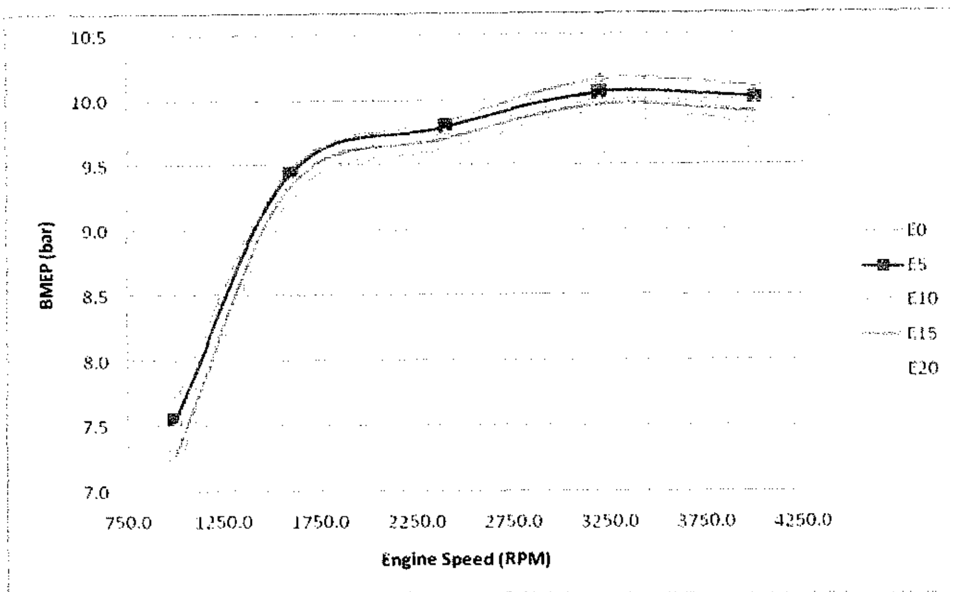


Figure 4.5: BMEP vs. Engine Speed

From **Figure 4.5**, the curves of the BMEP are similar to the torque curves because of the direct relationship between BMEP and torque. The value of gasoline BMEP are highest overall compared to the ethanol blends. It is followed by E5, E10, E15 and E20, predictably. The BMEP of gasoline at higher engine speed around 3000 – 4000 rpm are higher compared to the ethanol blends.

4.2 Discussion

The objective of this project is to determine the effect of different percentage of ethanol in the blends by volume basis. By comparing those parameters taken from the graphs, it is found that:

1. Torque output is decreasing with increasing percentage of ethanol in the blends. Torque output of the engine decreases when there is more ethanol in the blends. This might due to the fact that the more ethanol is in the blend, the lower the energy content and resulting the lower power output of the engine.

2. Power output is decreasing with increasing percentage of ethanol in the blends. The power output decreases as much as 3 – 5Nm, or 2 – 5% from the gasoline for all blends. The higher percentage of ethanol will decrease the value further. This finding is corresponding to the torque reduction in the usage of ethanol blends.

3. The *Brake Specific Fuel Consumptions* (BSFC) are increasing with increasing percentage of ethanol in the blends. The results are expected since there is more fuel needed to be burnt in order to produce the power needed. But the curve of the blends is quite different from that of gasoline in the region of 1600 – 3000 rpm where. This can be investigated in the future since engine reliability was in question.

4. The *Brake Mean Effective Pressures* (BMEP) are decreasing with increasing percentage of ethanol in the blends. These curves are similar to the torque output. The blends are exhibiting reduction in BMEP. The blends with higher ethanol content reduce the engine BMEP more than lesser ethanol content blends.

The outcome of this study is to determine also the best blend in terms of performance. For the reason, it is necessary to determine the percentage of changes (increment or decrement) of all engine performance in the usage of the blends.

If the percentage of change of performance are calculated and averaged, it is easier to analyze how every blend performs. From the values we can compare between blends, which one changes the performance of the engine the most.

In torque output, power output and BMEP, all the blends exhibit reduction in engine performance. Meanwhile, the BSFC of all blends are increased.

Table 4.5: The average percentage of reduction in torque in all blends

	% Reduction of Torque			
Engine speed	E5	E10	E15	E20
1000.0	3.0	4.2	7.5	8.7
1600.0	0.7	1.5	2.0	2.7
2400.0	0.5	1.7	2.1	3.1
3200.0	1.1	1.8	2.3	2.8
4000.0	1.6	2.3	2.8	3.7
Avg%	1.4	2.3	3.3	4.2

As shown in **Table 4.5**, the percentage of reduction in torque increase over increment of ethanol percentage in the blends. The average percentage of reduction in the E5 is small at around 1.4% over the engine speed. The value increases for E10, E15 and at E20, it is about more than twice that of E5. At low rpm, the values are the significant in all engine speed which is around 3 – 8.7 % contrast to reduction in other engine speed.

Table 4.6: The average percentage of reduction of power output in all blends

	% Reduction of Power			
Engine speed	E5	E10	E15	E20
1000.0	1.7	2.4	4.8	5.4
1600.0	7.6	8.8	9.4	9.8
2400.0	0.4	1.6	1.8	3.0
3200.0	0.0	0.1	0.0	0.4
4000.0	0.5	1.7	1.9	2.3
Avg%	2.0	2.9	3.6	4.2

As shown in **Table 4.6**, the percentage of reduction in engine's power output increase over increment of ethanol percentage in the blends. The reduction average percentage started at 2% for E5 and increases to 4.2% for E20. The highest reduction can be found in engine speed of 1600 rpm where the values are around 7 – 9.8%.

Table 4.7: The average percentage of increase of BSFC in all blends

Engine speed	% Increase of BSFC E5	E10	E15	E20
1000.0	-0.9	-0.2	5.0	5.9
1600.0	15.6	17.2	23.8	24.3
2400.0	19.4	22.7	26.8	30.3
3200.0	3.3	2.3	4.9	7.0
4000.0	0.5	1.7	0.8	1.6
Avg%	7.6	8.8	12.3	13.8

As shown in **Table 4.7**, the percentage of average BSFC increases over increment of ethanol percentage in the blend. The E5 average increment of BSFC is 7.6% followed by other blends and as expected, E20 is highest at 13.8%. All blends exhibit high percentage of increment in the speed of 1600 rpm and 2400 rpm. It is significant compared to increment at other engine speed.

Table 4.8: The average percentage of reduction in BMEP in all blends

Engine speed	% Reduction of BMEP E5	E10	E15	E20
1000.0	2.7	2.5	5.0	6.7
1600.0	1.2	1.1	1.9	2.4
2400.0	0.1	1.0	2.4	2.6
3200.0	1.0	1.6	1.4	2.7
4000.0	0.7	1.7	1.7	2.7
Avg%	1.1	1.6	2.5	3.4

As shown in **Table 4.5**, the percentage increase over increment of ethanol percentage in the blend. As expected, the reductions of BMEP are quite similar to the reduction in torque as both parameters correspond to each other. The percentage of reduction is lowest in E5 and increases in other blends. The highest percentage of reduction is at 3.4% for E20. Similar pattern from the torque reduction percentage table earlier (**Table 4.5**), where for all blends, the highest reduction percentages are in the speed of 1000 rpm. This verify the connection between BMEP and torque output.

From all blends, we can conclude that the best blend is the E5 where only 5% of ethanol content. It is the best blend in order to have the best performance out of the engine for blends up to 20% of ethanol content. However, it is not known how the blends with ethanol content higher than 20% performs.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The project is conducted with a goal to compare the performance of the gasoline engine while using gasoline and ethanol blends up to 20% ethanol content. The outcome of the project should be the verdict of the performance characteristic of the blend in term of performance across the engine speed.

From the results, the engine performances do affected by the percentage of ethanol in the blends. The performances are reduced in the increasing content of ethanol. Brake Horse Power, Torque and BMEP experienced drop in values but to a slight amount of 6%. In other case, the BSFC are increased up to 0.05 g/kW-hr, also a slight amount of increment.

It can be said that, the higher the ethanol content in the blends, the lower the performance of the engine. But this is true only to ethanol blends of up to 20% only since the project only test the fuel up to that percentage. Further increment to the ethanol percentage might have different result and should be further investigated.

The reduction in the performance is caused by the lesser energy content in the blends as the ethanol percentage increases. Thus, the energy released from the combustion process of the fuel is less compared to the gasoline. This results in having lower value of power, torque and BMEP. Furthermore, more fuel needed to be burnt in order to maintain the power output or to coup up with it.

The fuel reductions however are not huge in amount. The reduction is slight and should not affect much on how the engine will perform in a car. It is not to be realized by the drivers.

5.2 Further Work and Recommendations

The results obtained from this study are made based on the equipment and procedures used. It is to be stressed that further studies should be made in order to obtain much more accurate result. The fuel blends must be tested in more than one type of engine and should be more reliable than had been used in this project.

It is also necessary to test the engine performance to more than 4000 rpm since the engine can be run over that speed. The engine maximum power is to be found at speed of 5500 rpm using gasoline. Thus, it is yet to be found whether the engine's maximum power will be at this point for other blends as well.

It is also recommended that the study should use neat gasoline and not the one that had been added with additives. Result might be varied if the fuel had not being blended with additives before the ethanol addition. This is to ensure the accuracy of the result and to discover how the blend really works.

In this project, the emission characteristics of the fuel are not being tested. It is due to limited time available due to the engine problems and maintenance and unavailability of the gas analyzer at the time of testing. This characteristic is important to the current automotive industry since they are moving towards cleaner tailpipes emissions.

The emission of by-product such as Hydrocarbons, Nitrogen Oxide, Carbon dioxide and also Carbon Monoxide can be done to this engine. There is to study whether the proven that the blends will reduce Hydrocarbon and Carbon monoxide emission but increases in Nitrogen Oxides and Carbon Dioxide. [6]

Some study had proved that the introduction of ethanol can reduce the emissions of the engine. However, from previous chapter in this paper, Alvydas et. al. had found that the production of Carbon dioxide by the Toyota engine were increased.

It is also recommended that the engine be tested for performance of blends with higher ethanol content. For ethanol content of more than 20% has not been tested in this project. Although we can see the trend that the more ethanol content might reduce the engine performance figures more, it is not necessarily true for higher ethanol blends.

6 REFERENCE

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APPENDIX 4-1

The performance characteristics of 5% ethanol blend

Performance characteristics for Gasoline (E0)

Parameter	Engine Speed														
	1000.0			1600.0			2400.0			3200.0			4000.0		
Power(HP)	15.3	15.4	15.2	37.7	30.2	30.1	47.1	47.0	47.1	63.0	63.0	64.0	79.9	80.1	80.2
Torque	110.0	111.0	112.0	135.0	135.0	136.0	141.0	140.0	141.0	145.0	144.0	146.0	143.0	144.0	146.0
Fuel Flow Rate	0.13	0.13	0.12	0.13	0.12	0.13	0.13	0.20	0.20	0.30	0.31	0.30	0.41	0.42	0.41
BMEP	7.7	7.7	7.7	9.5	9.5	9.5	9.9	9.8	9.8	10.2	10.2	10.2	10.0	10.2	10.1
BSFC	0.51	0.51	0.48	0.21	0.24	0.26	0.17	0.26	0.26	0.29	0.30	0.28	0.31	0.32	0.31

Average, E0	Power(HP)	15.3	Power(HP)	32.7	Power(HP)	47.1	Power(HP)	63.3	Power(HP)	80.1
	Torque	111.0	Torque	135.3	Torque	140.7	Torque	145.0	Torque	144.3
	Fuel Flow Rate	0.13	Fuel Flow Rate	0.13	Fuel Flow Rate	0.18	Fuel Flow Rate	0.30	Fuel Flow Rate	0.41
	BMEP	7.7	BMEP	9.5	BMEP	9.8	BMEP	10.2	BMEP	10.1
	BSFC	0.50	BSFC	0.24	BSFC	0.23	BSFC	0.29	BSFC	0.31

The Power (HP) are Corrected Brake Horse Power with $\boldsymbol{P_{b,c} = C_F P_{b,m}}$

Where, $C_f = \frac{P_{s.d}}{P_{m-}P_v} (\frac{T_m}{T_s})^{1/2}$

APPENDIX 4-2

The performance characteristics of 5% ethanol blend

Performance characteristics for E5

Parameter	Engine Speed														
	1000.0			1600.0			2400.0			3200.0			4000.0		
Power(HP)	15.1	15.0	15.0	30.2	30.1	30.3	46.9	46.8	46.9	64.1	62.9	63.0	80.3	79.7	79.0
Torque	107.0	108.0	108.0	135.0	134.0	134.0	140.0	141.0	139.0	144.0	143.0	143.0	143.0	142.0	141.0
Fuel Flow Rate	0.12	0.12	0.13	0.14	0.14	0.13	0.21	0.20	0.22	0.31	0.32	0.31	0.41	0.42	0.41
BMEP	7.5	7.6	7.6	9.4	9.3	9.2	9.8	9.7	9.9	10.1	10.0	10.1	10.0	10.1	10.0
BSFC	0.48	0.48	0.52	0.28	0.28	0.26	0.27	0.26	0.28	0.29	0.31	0.30	0.31	0.32	0.31

Average, E5	Power(HP)	15.0	Power(HP)	30.2	Power(HP)	46.9	Power(HP)	63.3	Power(HP)	79.7
	Torque	107.7	Torque	134.3	Torque	140.0	Torque	143.3	Torque	142.0
	Fuel Flow Rate	0.12	Fuel Flow Rate	0.14	Fuel Flow Rate	0.21	Fuel Flow Rate	0.31	Fuel Flow Rate	0.41
	BMEP	7.6	BMEP	9.4	BMEP	9.8	BMEP	10.1	BMEP	10.0
	BSFC	0.49	BSFC	0.27	BSFC	0.27	BSFC	0.30	BSFC	0.31

The Power (HP) are Corrected Brake Horse Power with $\boldsymbol{P_{b,c} = C_F P_{b,m}}$

$$\text{Where, } C_f = \frac{P_{s,d}}{P_{m-}P_v}\left(\frac{T_m}{T_s}\right)^{1/2}$$

APPENDIX 4-3

The performance characteristics of 10% ethanol blend

Performance characteristics for E10

Parameter	Engine Speed														
	1000.0			1600.0			2400.0			3200.0			4000.0		
Power(HP)	15.0	15.0	14.8	29.9	29.7	29.8	46.4	46.3	46.2	63.5	63.1	63.2	78.9	78.6	78.6
Torque	107.0	106.0	106.0	134.0	133.0	133.0	139.0	138.0	138.0	142.0	142.0	143.0	141.0	140.0	142.0
Fuel Flow Rate	0.12	0.12	0.13	0.14	0.13	0.14	0.21	0.21	0.22	0.31	0.31	0.31	0.41	0.41	0.42
BMEP	7.5	7.5	7.4	9.4	9.3	9.4	9.7	9.8	9.7	10.0	10.1	9.9	9.9	10.0	9.9
BSFC	0.48	0.48	0.53	0.28	0.26	0.28	0.27	0.27	0.29	0.29	0.30	0.30	0.31	0.31	0.32

Average, E10	Power(HP)	14.9	Power(HP)	29.8	Power(HP)	46.3	Power(HP)	63.3	Power(HP)	78.7
	Torque	106.3	Torque	133.3	Torque	138.3	Torque	142.3	Torque	141.0
	Fuel Flow Rate	0.12	Fuel Flow Rate	0.14	Fuel Flow Rate	0.21	Fuel Flow Rate	0.31	Fuel Flow Rate	0.41
	BMEP	7.5	BMEP	9.4	BMEP	9.7	BMEP	10.0	BMEP	9.9
	BSFC	0.50	BSFC	0.28	BSFC	0.28	BSFC	0.30	BSFC	0.32

The Power (HP) are Corrected Brake Horse Power with $\boldsymbol{P_{b,c} = C_F P_{b,m}}$

Where, $C_f = \frac{P_{s,d}}{P_m - P_v} \left(\frac{T_m}{T_s}\right)^{1/2}$

APPENDIX 4-4

The performance characteristics of 10% ethanol blend

Performance characteristics for E15

Parameter	Engine Speed														
	1000.0			1600.0			2400.0			3200.0			4000.0		
Power(HP)	14.3	14.6	14.8	29.8	29.7	29.3	46.4	46.2	46.1	63.5	63.3	63.2	78.9	78.3	78.4
Torque	101.0	103.0	104.0	133.0	132.0	133.0	139.0	138.0	136.0	142.0	142.0	141.0	141.0	140.0	140.0
Fuel Flow Rate	0.12	0.13	0.13	0.14	0.14	0.15	0.21	0.22	0.23	0.31	0.30	0.33	0.41	0.40	0.40
BMEP	7.1	7.4	7.4	9.3	9.2	9.3	9.7	9.8	9.7	10.0	10.1	9.9	9.9	10.0	9.9
BSFC	0.51	0.54	0.53	0.28	0.28	0.31	0.27	0.29	0.30	0.29	0.30	0.31	0.31	0.31	0.32

Average, E15	Power(HP)	14.6	Power(HP)	29.6	Power(HP)	46.2	Power(HP)	63.3	Power(HP)	78.5
	Torque	102.7	Torque	132.7	Torque	137.7	Torque	141.7	Torque	140.3
	Fuel Flow Rate	0.13	Fuel Flow Rate	0.14	Fuel Flow Rate	0.22	Fuel Flow Rate	0.31	Fuel Flow Rate	0.40
	BMEP	7.3	BMEP	9.3	BMEP	9.7	BMEP	10.0	BMEP	9.9
	BSFC	0.52	BSFC	0.29	BSFC	0.29	BSFC	0.30	BSFC	0.31

The Power (HP) are Corrected Brake Horse Power with $P_{b,c} = C_F P_{b,m}$

Where, $C_f = \frac{P_{s,d}}{P_{m} - P_v} \left(\frac{T_m}{T_s}\right)^{1/2}$

APPENDIX 4-5

The performance characteristics of 10% ethanol blend

Performance characteristics for E20

Parameter	Engine Speed														
	1000.0			1600.0			2400.0			3200.0			4000.0		
Power(HP)	14.8	14.3	14.3	29.7	29.3	29.4	46.0	45.4	45.6	63.3	62.8	63.1	78.3	78.3	78.0
Torque	105.0	100.0	99.0	133.0	132.0	130.0	137.0	136.0	136.0	142.0	140.0	141.0	140.0	139.0	138.0
Fuel Flow Rate	0.12	0.13	0.13	0.14	0.14	0.15	0.21	0.23	0.23	0.31	0.33	0.33	0.41	0.42	0.40
BMEP	7.4	7.0	7.1	9.3	9.2	9.2	9.6	9.6	9.6	9.9	9.8	9.9	9.8	9.8	9.9
BSFC	0.49	0.55	0.55	0.28	0.29	0.31	0.28	0.31	0.30	0.30	0.32	0.32	0.32	0.32	0.31

Average, E20	Power(HP)	14.5	Power(HP)	29.5	Power(HP)	45.7	Power(HP)	63.1	Power(HP)	78.2
	Torque	101.3	Torque	131.7	Torque	136.3	Torque	141.0	Torque	139.0
	Fuel Flow Rate	0.13	Fuel Flow Rate	0.14	Fuel Flow Rate	0.22	Fuel Flow Rate	0.32	Fuel Flow Rate	0.41
	BMEP	7.2	BMEP	9.2	BMEP	9.6	BMEP	9.9	BMEP	9.8
	BSFC	0.53	BSFC	0.29	BSFC	0.29	BSFC	0.31	BSFC	0.32

The Power (HP) are Corrected Brake Horse Power with $\boldsymbol{P_{b,c} = C_F P_{b,m}}$

Where, $C_f = \frac{P_{s,d}}{P_m - P_v} \left(\frac{T_m}{T_s}\right)^{1/2}$

APPENDIX 4-6

Table 1: Several properties of ethanol vs. Gasoline

Property	Ethanol	Gasoline
Chemical Formula	C2H5OH	C4 to C12
Molecular Weight	46,07	100–105
Carbon	52,2	85–88
Hydrogen	13,1	12–15
Oxygen	34,7	0
Specific gravity, 60° F/60° F	0,796	0.72–0.78
Density, lb/gal @ 60° F	6,61	6.0–6.5
Boiling temperature, °F	172	80–437
Research octane no.	108	90–100
Motor octane no.	92	81–90
(R + M)/2	100	86–94
Cetane no.(1)	--	5–20
Fuel in water, volume %	100	Negligible
Water in fuel, volume %	100	Negligible
Flash point, closed cup, °F	55	-45
Autoignition temperature, °F	793	495
Lower	4,3	1,4
Higher	19	7,6
Btu/gal @ 60° F	2.378	≈900
Btu/lb @ 60° F	396	≈150
Btu/lb air for stoichiometric mixture @ 60° F	44	≈10
Higher (liquid fuel-liquid water) Btu/lb	12.800	18,800–20,400
Lower (liquid fuel-water vapor) Btu/lb	11.500	18,000–19,000
Higher (liquid fuel-liquid water) Btu/gal	84.100	124.800
Lower (liquid fuel-water vapor) Btu/gal @ 60° F	76,000[a]	115.000
Mixture in vapor state, Btu/cubic foot @ 68° F	92,9	95,2
Fuel in liquid state, Btu/lb or air	1.280	1.290
Specific heat, Btu/lb °F	0,57	0,48
Stoichiometric air/fuel, weight	9	14.7[a]
Volume % fuel in vaporized stoichiometric mixture	6,5	2

APPENDIX 4-7

Calculation example of Corrected Brake Horse Power, C_f

For engine speed of 2400 rpm, using gasoline as fuel:

Uncorrected Horsepower = 32.4 hp (taken from AutoTest4 interface)

(Average ambient pressure for data series 1 = 100.4kPa, series 2 = 101.1kPa, series 3 = 100.8kPa)

Saturated water vapor pressure at ambient temperature Tm = 25.4 Celcius;

$$Log_{10}\, P_{v,sat} = 8.10765 - \frac{1750.286}{25.4 + 235.15}$$

$$= 0.511$$

$$P_{v,sat} = 3.243\ kPa$$

Assuming relative humidity = 0.65;

$$P_v = Pv,sat \times ø$$

$$= 3.243\ kPa \times 0.65$$

$$= 2.10795\ kPa$$

Power correction factor;

$$C_f = \frac{P_{s.d}}{P_m - P_v}\left(\frac{T_m}{T_s}\right)^{1/2}$$

(Where $P_{s,d}$ = 736.6 mmHg = 98.274kPa and T_s = 29.4°C)

$$C_f = \frac{98.274\ kPa}{100.04\ kPa - 2.10795}\left(\frac{25.4}{29.4}\right)^{1/2} = 0.932732 \sim 0.933$$

Corrected Power; $P_{b,c} = C_f \times P$

$= 0.933 \times 32.4$

$= 30.2$ hp

Properties of Fuels (a)

Property	Gasoline	No.2 Diesel Fuel	Methanol	Ethanol	MTBE	Propane	Compressed Natural Gas	Hydrogen	Biodiesel
Chemical Formula	C4 to C12	C8 to C25	CH3OH	C2H5OH	(CH3)3COCH3	C3H8	CH4 (83-99%), C2H6 (1-13%)	H2	C12-C22 FAME
Molecular Weight	100–105	~200	32.04	46.07	88.15	44.1	16.04	2.02	~292(q)
Composition, Weight %									
>Carbon	85–88(b)	87(g)	37.5	52.2	68.1	82	75	0	77(g)
>Hydrogen	12–15(b)	13(g)	12.6	13.1	13.7	18	25	100	12(g)
>Oxygen	0	0(g)	49.9	34.7	18.2	–	–	0	11(g)
Specific gravity, 60° F/60° F	0.72–0.78(b)	0.85(g)	0.796(h)	0.794(h)	0.744(k)	0.508(m)	0.424	0.07(o)	0.88(g)
Density, lb/gal @ 60° F	6.0–6.5(b)	7.079(g)	6.63(b)	6.61(b)	6.19(k)	4.22	1.07(n)	–	7.328(g)
Boiling temperature, °F	80–437(b)	356-644(g)	149(h)	172(h)	131(h)	-44(m)	3.2 to -126.4(m)	-423(m)	599-662(g)
Reid vapor pressure (100° F), psi	8–15(c)	<0.2	4.6(i)	2.3(i)	7.8(l)	208	2400	–	<0.04(r)
Heating value (2)									
>Lower (liquid fuel-water vapor) Btu/lb	18,676(d)	18,394(d)	8637(d)	11,585(d)	15,091(d)	19,900(d)	20,263(d)	52,217(d)	16,131(d)
>Lower (liquid fuel-water vapor) Btu/gal @ 60° F	116,090(d)	~129,050(g)	57,250(d)	76,330(d)	93,540(d)	84500	19,800(6)	–	-118,170(g)
Octane no.(1)									
>Research octane no.	88–98(c)	–	–	–	–	112	–	130+	–
>Motor octane no.	80–88(c)	–	–	–	–	97	–	–	–
Cetane no.(1)	–	40-55(g)	–	0-54(f)	–	–	–	–	48-65(g)
Freezing point, °F	-40(e)	-40–30(4)	-143.5	-173.2	-164(h)	-305.8(m)	-296	-435(p)	26-66(g)(7)
Viscosity, mm/s									
>@104 °F	–	1.3-4.1(g)	–	–	–	–	–	–	4.0-6.0(g)
>@68 °F	0.5-0.6(f)	2.8-5.0(f)	0.74(f)	1.50(f)	0.47(f)	–	–	–	–
>@-4 °F	0.8-1.0(f)	9.0-24.0(f)	1.345(f)	3.435(f)	0.77(f)	–	–	–	–
Flash point, closed cup, °F	-45(b)	140-176(g)	52(i)	55(i)	-14(c)	-156(m)	-300	–	212-338(g)
Autoignition temperature, °F	495(b)	~600	867(b)	793(b)	815	842(m)	900-1170(m)	932(m)	–
Water solubility, @ 70° F									–
>Fuel in water, volume %	Negligible	Negligible	100(h)	100(h)	4.8(f)	–	–	–	–
>Water in fuel, volume %	Negligible	Negligible	100(h)	100(h)	1.5(f)	–	–	–	–
Flammability limits, volume%									
>Lower	1.4(b)	1.0	7.3(i)	4.3(i)	1.6(c,e)	2.2	5.3	4.1(o)	–
>Higher	7.6(b)	6.0	36.0(i)	19.0(i)	8.4(c,e)	9.5	15	74(o)	–
Latent heat of vaporization									
>Btu/gal @ 60° F	~900(b)	~710	3,340(b)	2,378(b)	863(5)	775	–	–	–
>Btu/lb @ 60° F	~150	~100	506(b)	396(b)	138(5)	193.1	219	192.1(p)	–

Stoichiometric air/fuel, weight	14.7	14.7	6.45	9.00	11.7	15.7	17.2	34.3(o)	13.8(g)
Volume % fuel in vaporized stoichiometric mixture	2.0 (b)	–	12.3(b)	6.5(b)	2.7(l)	–	–	–	–