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Statistical Analysis of the Effect of CME-Diesel Blends on the Performance of a Light Duty Common Rail Direct Injection Engine

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***Abstract*— This paper presents the effect of coconut methyl ester (CME) biodiesel blends in the performance of a light duty automotive common rail direct injection engine. Total of six fuel blends – B0 (Neat Diesel), B2 (2%CME, 98%B0), B5 (5% CME, 95%B0), B10 (10%CME, 90%B0), B15 (15%CME, 85%B0) and B20 (20%CME, 80% B0) were tested for performance at 100% load with varying speeds from 800 RPM to 2400 RPM at an interval of 400 RPM. At this typical engine speed range, no significant differences for biodiesel blends versus neat diesel were observed for torque.**

Keywords— Effect of CME blend, biodiesel, engine torque

1. INTRODUCTION

Biodiesel is a renewable fuel that can be manufactured from plant oils, animal fats, waste or recycled cooking oil, and, more recently, algae. It is considered as a good alternative fuel for diesel engines because its physicochemical properties are similar to those of petroleum diesel. Biodiesel is a cleaner fuel alternative due to its negligible sulfur content and lower greenhouse gas emission. Biodiesel can be blended with petroleum diesel at typical blend levels of 2%, 5%, 10%, and 20% by volume.

Typical performance indicators used in the evaluation of biodiesel are brake torque, brake power, brake thermal efficiency, and brake specific fuel consumption. Studies report that different biodiesel feedstocks give different results in engine performance. A study by Palash et al. [1] used Aphanamixis polystachya methyl ester (APME) and its blends in a multi cylinder diesel engine and found that 5% (APME5) and 10% (APME10) APME blend by volume with diesel showed an average 0.9% and 1.81% reduction in torque. This loss was attributed to the lower heating value and higher density and kinematic viscosity compared to diesel. Reduction in brake power (BP) by 0.9% for APME 5 and 2.1% for APME10 were also reported, as well as 0.87% (APME5) and 1.78% (APME10) increase in brake specific fuel consumption (BSFC) compared to diesel.

Celik et al. [2] used soybean oil and hazelnut oil as biodiesel raw material to determine the effect on engine performance and exhaust emissions. Soybean biodiesel and hazelnut biodiesel were added in equal amounts into the diesel fuel, at different blend levels. Engine experiments performed at a fixed engine speed of 2200 rpm showed increased BSFC with the increase of biodiesel percentage.

In a study by Santos et al. [3] engine performance and exhaust emissions using biodiesel from sunflower, safflower, peanut, canola, as well as chicken fat were compared with soybean oil biodiesel and a reference diesel. They found that at different engine speeds, BP initially increased gradually until a maximum is reached and then fall rapidly with further increase in engine speed. Torque also showed a similar trend as BP, increasing gradually at low speed and decreasing rapidly after a maximum value is reached. Peak torque were lower for some of the tested biodiesel compared to the reference diesel and that performance of the other biodiesel were similar with the reference diesel.

Chiba et al. used [4] biodiesel from waste edible oil on a naturally-aspirated in-line 3-cylinder swirl-chamber diesel engine, and reported torque differences ranging from -4.8 to +2.0% at engine speeds of 1100 to 2500 rpm, compared to diesel.

Tan et al. used an emulsion of diesel-biodiesel-bioethanol on a single cylinder direct injection diesel engine at variable speed range of 1100-. They observed lower BP and torque with the fuel blends due to their lower heating value and increased oxygen compounds, relatively higher BSFC and lower brake thermal efficiency (BTE) [5]

Hari et al. [6] compared the performance of a single cylinder diesel engine using pure diesel, coco methyl ester (CME)-diesel blends at 20% and 60% by volume, and pure CME. They found that as the blends increase, BTE decreases and BSFC increases. Various other studies [8,9] report decreasing engine torque with the increase in biodiesel content, due to the lower calorific values of biodiesel. However, there were also several studies that show increase in torque with the addition of biodiesel content. Yang et al. [10] tested waste cooking oil tested on a four stroke turbocharged Common Rail Direct Injection (CRDi) engine and observed a higher torque value for B10 compared to neat diesel fuel. Likewise, Song et al. [11] using soybean biodiesel tested on a four cylinder supercharged direct injection engine also observed increase in torque with the increase of biodiesel content in fuel blend. How et al. [7] also tested CME using a CRDi diesel engine with varying brake mean effective pressure at a constant speed and observed a similar trend. This increase in specific fuel consumption is mainly due to the combined effects of the higher density, higher viscosity and the lower calorific value of biodiesel blends. Most researches also agree [12–15] that BSFC is higher as biodiesel content in fuel blend was increased.

In a comprehensive review on the effects of different biodiesel from different feedstocks on engine performance by Wan et al. [16] mixed results are reported regarding biodiesel blends. Increase in torque and power compared to neat diesel is reported for certain blends of biodiesel from jathropa, kapok seed, thumba, algal, jojoba, soybean, as well as sunflower oil. While decrease in torque is reported for blends using waste cooking oil, cottonseed, rapeseed, palm and coconut mixture, mustard, and oils from animal fat.

In the Philippines, the primary feedstock used for biodiesel production is coconut oil. Coco-methyl ester (CME) is derived from coconut oil through a process known as transesterification. The Department of Energy claims that addition of CME, also known as coco-biodiesel, results in better and more efficient combustion, and improves fuel economy by as much as 20%.

Republic Act 9367 also known as the “Philippines Biofuels Act of 2006” mandates the use of biofuels for the development and utilization of indigenous renewable and sustainably-sourced clean energy source to reduce dependence on imported oil and mitigate emission of greenhouse gases [17]. The act also mandates the use of biofuels for all liquid fuels for motors and engines sold in the Philippines as well as the blending of biodiesel and ethanol in all locally distributed diesel and gasoline. The goal of the National Biofuels Board is that by 2025, 10% blend biodiesel is mandated in all locally distributed fuel, and 20% blend by 2030. However, given the mixed results about the effect of increasing biofuel blends in engine performance by various studies, it is but imperative to further assess the impact of the target biofuel blends set by the National Biofuels Board.

The objective of this study is to show the influence, if any, of various blends of CME when used in a four cylinder Common Rail Direct Injection (CRDI) internal combustion engine under full and half load conditions. Specifically, the effect of different blends on brake torque at different engine speeds will be analyzed.

Statistical Model

Theoretically, various factors affect torque. Even with the same engine model, parameters like speed, air temperature and density, and fuel conditions are known to greatly affect torque. In this study the experiment was performed under controlled conditions, and the effect of engine speed and biodiesel blends on torque is investigated. While the possible levels are infinite and continuous in nature, this experiment will only use 0, 2, 5, 10, 15 and 20% biodiesel blends. Blends at 2% and 5% represent small changes in fuel composition compared to the control 0%. This also represents the currently legislated blends that are required to be in all of the fuels sold in the Philippine market. The 10, 15 and 20% biodiesel blends reflect substantial changes in fuel composition. Because engines are normally operated at various speeds, this study focuses on torque data measured over the practical range of operation for diesel engines which is from 800 to 2400 rpm. The speed factor will have five levels, corresponding to 400rpm increments. While this experiment may be able to provide conclusions for specific operating speeds, a generalized conclusion is more relevant to reflect the typically varied engine operation.

2. EXPERIMENTAL PROCEDURE

The engine used was a Toyota 1kD Diesel Engine that has a 3.0 liter Common Rail Direct Injection (CRDi). The engine was coupled to an eddy current dynamometer that can be operated at a maximum power of 220 kW at 12000 RPM. Engine performance data and emissions were measured using Variable Speed Test. The diesel engine was driven at a standard cycle from 800 RPM to 4000 RPM at 100% load, keeping the throttle 100% wide open and at 50% load. Fuel blends of 2%, 5%, 10%, 15%, 20% CME mixed with neat diesel fuel (B0), were tested and the following blends were labeled B2, B5, B10, B15, and B20 respectively. B0 was also tested using the same procedures at the very start of the experiment to establish baseline data. Three trials per fuel blend per load were done and environmental conditions were almost identical during the whole testing period, with the temperature of the test cell maintained at 25ºC. For the Variable Speed Test, the engine was first ran at idle at 2500 RPM, acting as the warm up stage for the test cycle. The engine was warmed up until the temperature of the cooling water reaches 80ºC. After the cooling water reaches the target temperature, the program was started. The engine was throttled down to 800 RPM to signal the start of the test. For 80 seconds, the engine was run at constant engine speed. Data gathering for the emissions using the FTIR was done at this portion of the test to ensure an almost steady state condition on every speed. After 80 seconds, the engine speed was ramped up to the next speed. This part of the test was done from 800 RPM to 4000 RPM at an interval of 400 RPM. After the standard cycle run at 4000 RPM, the engine was throttled down to 800 RPM at idle in order for the engine to cool down. Data gathering for Torque, Fuel Mass Flow and Air Mass Flow starts after the warm up until the engine cool down.

3. DATA ANALYSIS AND DISCUSSIONS

From the data obtained, analysis was first done to determine the statistical significance of particular factors to the output response. In this case, a Design-Of-Experiment analysis was made using the biofuel blend and engine speed as factors against the engine torque.

Using a simple linear model, an R^2 value of 73.92% was achieved. The Analysis of Variance showed that the F-values of the blend factor and speed factor were 58.51 and 50,953.9 respectively. While these F-values are relatively high for most experiments, the R^2 value shows that the regression model could have been improved. The mean square value for the lack-of-fit error was 203,016 and over 11 times greater than that of the blend factor, greatly overshadowing the significance of the blend factor.

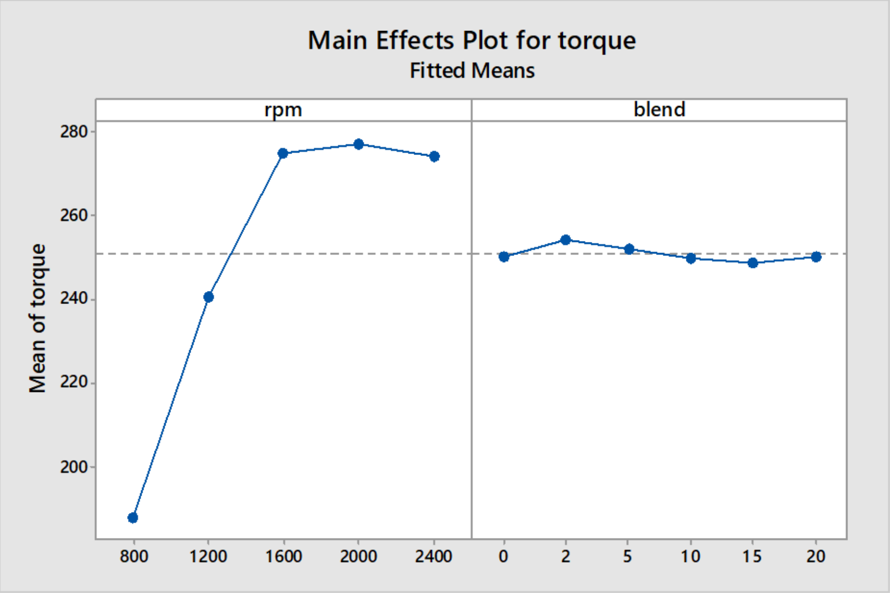

Figure 1. Main Effects Plot for Torque

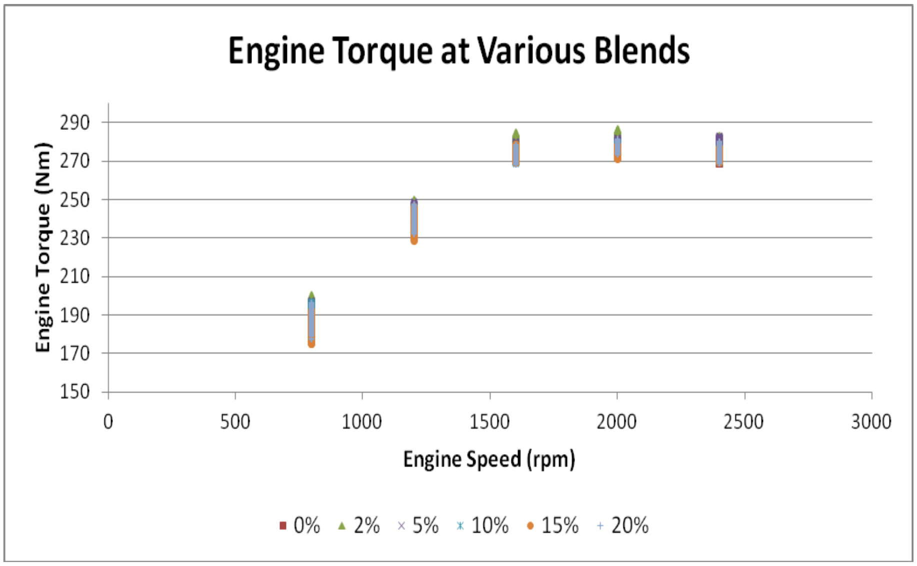

Figure 2. Engine Torque at Various Blends

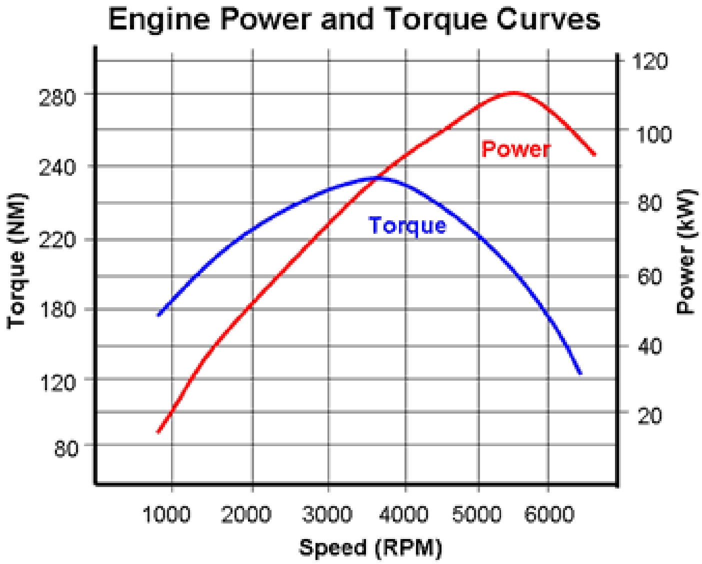

Figure 3. Typical Engine Performance Curves

Hence a different regression model was explored. From the main effects plot in Figure 1, the torque roughly follows a parabolic curve, which matches what is commonly observed for internal combustion engines, as shown in Figure 3.

Using this quadratic model, the following regression model was found.

$$T = 25.44 - 0.1411\ \text{blend} + 0.2568\ \text{rpm} - 0.000064\ \text{rpm}^2 \quad (1)$$

Analysis of Variance for the above equation provided a much improved R^2 value of 98.59%, with an overall mean-square error of 17. This time, the mean-square values for lack-of-fit error had dropped to 8178, and less than half of the mean-square value of the blend factor. Moreover, the F-value of the blend factor had risen dramatically to 1082.9. This shows the appropriateness of the quadratic model of engine speed.

However, it should be noted that the individual F-values for speed are still almost 400 times bigger than that of the blend factor. Given that this study aims to determine the influence of biofuel blends on torque, engine speed is viewed as a nuisance factor. Unfortunately, the effects of this nuisance factor are difficult to filter out.

Using engine speed as a categorical variable in another regression analysis, the following equations were determined:

Table 1. Linear Regression with Categorical Variable

RPM	Equation
800	T = 189.292 - 0.14106 blend
1200	T = 241.794 - 0.14106 blend
1600	T = 276.336 - 0.14106 blend
2000	T = 278.466 - 0.14106 blend
2400	T = 275.602 - 0.14106 blend

This new regression model produces an even better R^2 value of 99.30%. By isolating the effects of engine speed, a linear model for fuel blend versus torque was made. Based on the coefficients above, a negative sloping trend is observed. From a point of view of vehicle performance, the above equations indicate that higher biodiesel fuel blends would produce less engine torque.

Based on the main effects plot in Figure 1, this negative trend is still inconclusive. Hence, further analysis was made, this time, between the individual blends at specific engine speeds.

Simple 2-sample analysis of means was done comparing increasing fuel blends against pure neat diesel, at different engine speeds. The Table 2 below shows at which blends and speeds produced statistically higher, lower, or equal torques compared to 0% blend. The comparisons were done with a 95% confidence interval. The following graphs also show a regression made using a quadratic model of blend versus engine speed.

Table 2 Pairwise comparison of different blends

Speed	Pairwise Comparison
800	2% > 0% > 10% > 20% > 5% > 15%
1200	2% > 5% > 0% > 20% > 10% > 15%
1600	2% > 0% > 5% > 15% > 10% = 20%
2000	2% > 5% > 20% > 10% > 0% > 15%
2400	5% > 2% > 20% > 15% > 10% > 0%

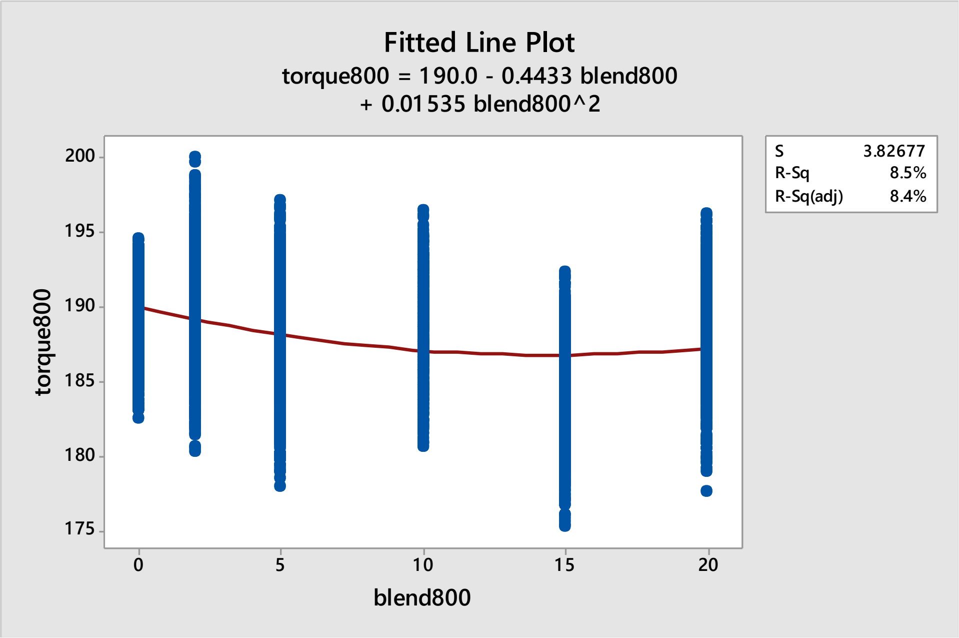

Figure 4. Regression at 800rpm using Quadratic Model

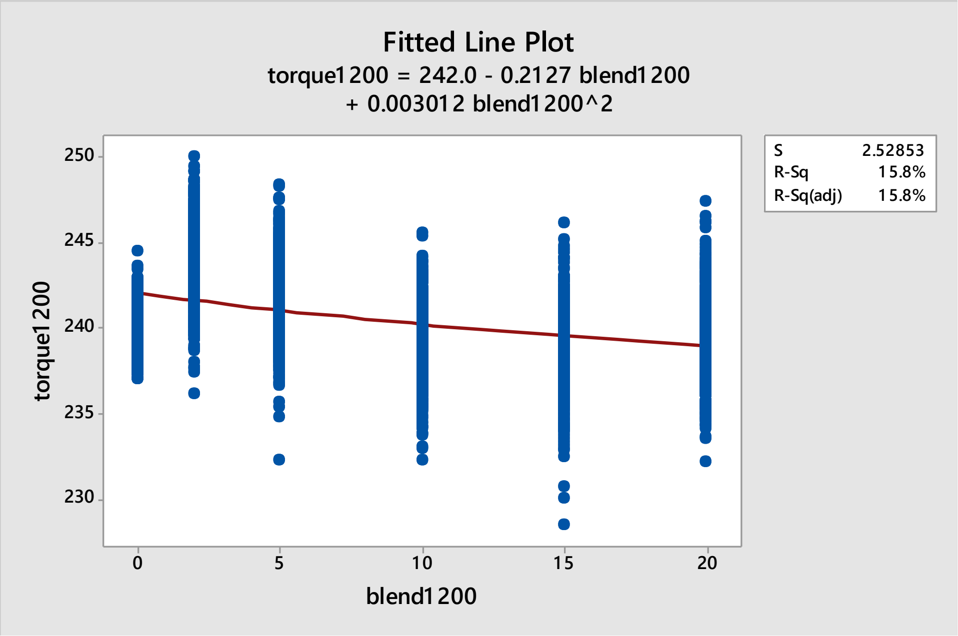

Figure 5. Regression at 1200rpm using Quadratic Model

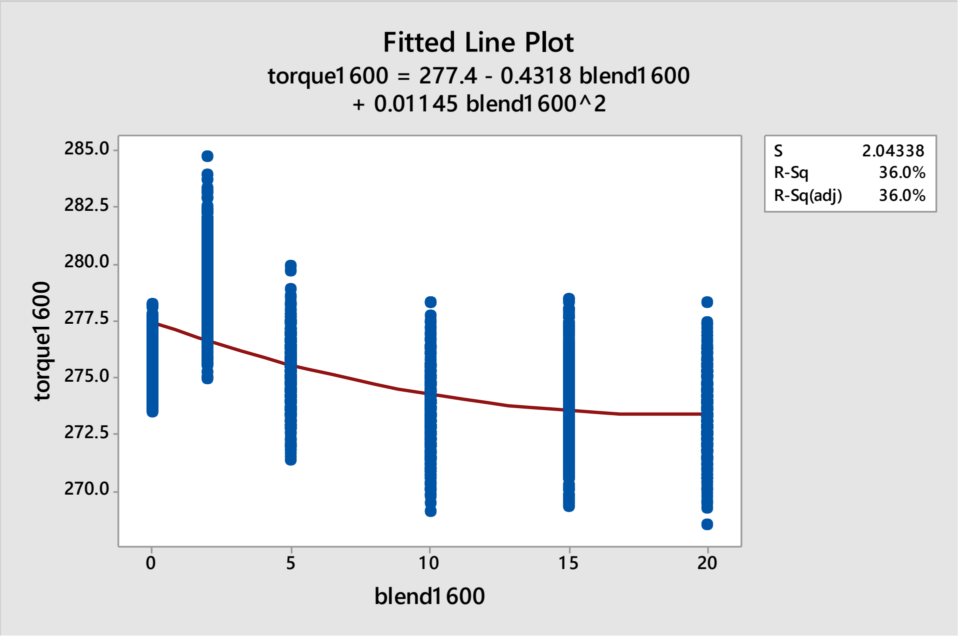

Figure 6. Regression at 1600rpm using Quadratic Model

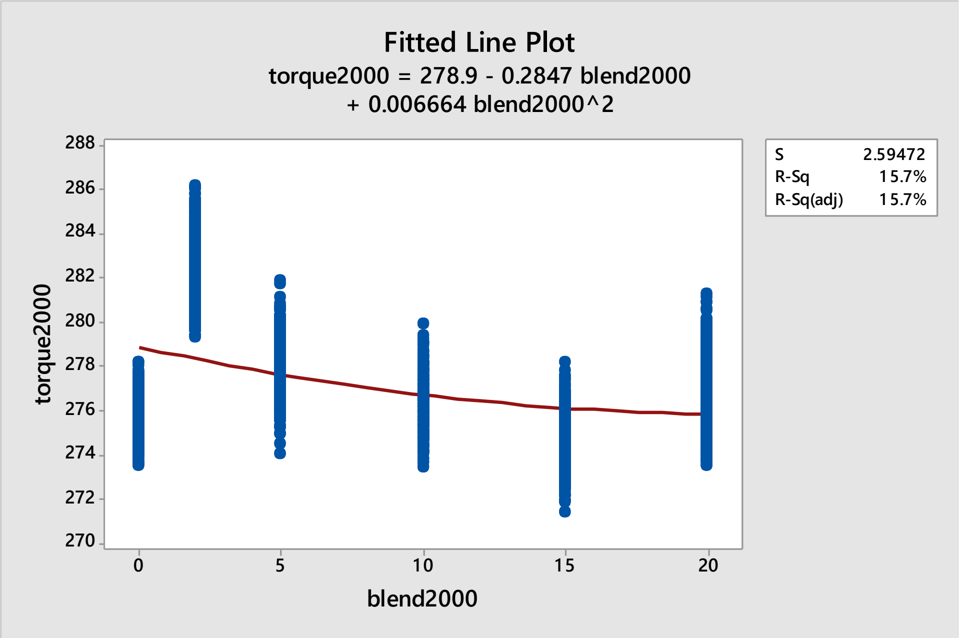

Figure 7. Regression at 2000rpm using Quadratic Model

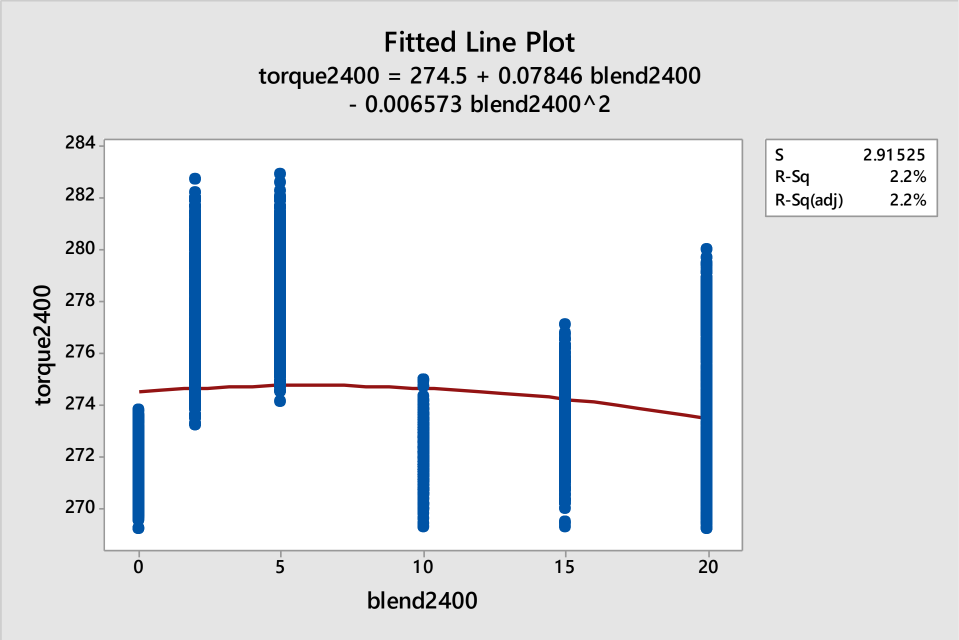

Figure 8. Regression at 2400rpm using Quadratic Model

From the above graphs and table, there does not seem to be any consistent trend between the amount of biodiesel blend and the engine torque produced. The correlations are very low, ranging only from 1.5 to 36%. For many of the engine speeds, 0~5% biodiesel blends performed similarly, and seem to produce higher torques compared to blends of 10~20%. This may be due to the fuel chemical composition changing only minimally with the addition of small blends. However, there is no pattern as the concentrations of biodiesel are made much higher. It may be inferred that a different criteria should be used to evaluate the influence of biodiesel blends. The engine's Electronic Control Unit may be responding in a highly nonlinear manner with regard to the biodiesel blend. Deeper analysis may have to be made with calorific value and chemical composition of blends, such as fuel density or viscosity, as possible factors that may provide better correlation to engine performance.

4. CONCLUSION

Based on the statistical analysis of experiment data, it can be concluded that there are no consistent and significant effects of fuel blended with biodiesel on engine torque. While the experiment data may be able to provide conclusions for specific operating speeds, there is no generalized conclusion to reflect the effect of fuel blends on the typically varied engine operation. This conclusion can be put in the context of the viability of using increasing concentrations of biodiesel in motor vehicles. Because there is no significant difference in torque, vehicle performance will be similar for the typical operating range of 800 to 2400 rpm. Further analysis may be needed to explore other chemical and mechanical factors.

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Appendix

Linear Regression Model of Torque vs Blend and Speed

Source	DF	SS	MS	F-Value	P-Val
Regression	2	15787398	7893699	25506	0
Blend	1	18101	18108	58.51	0
RPM	1	15769200	15769200	50954	0
Error	17997	5569739	309		
Lack of Fit	27	5481426	203016	41309	0
Pure Error	17970	88313	5		
Total	17999	21357137			

R^2	73.92%				
torque = 168.581 - 0.1411 blend + 0.052323 rpm					

Regression Model of Torque vs Blend and Speed using Quadratic Model

Source	DF	SS	MS	F-Value	P-Val
Regression	3	21056200	7018733	419719	0
Blend	1	18108	18108	1082	0
RPM	1	8132151	8132151	486302	0
Error	17996	300937	17		
Lack of Fit	26	212624	8178	1664	0
Pure Error	17970	88313	5		
Total	17999	21357137			

R^2	98.59%				
torque = 25.438 - 0.14106 blend + 0.256813 rpm - 0.000064 rpm2					

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Regression Model of Torque vs Blend and Speed using Categorical Variable

Source	DF	SS	MS	F-Value	P-Value
Regression	5	21206881	4241376	507929	0
Blend	1	18108	18108	2168	0
RPM	4	21188773	5297193	634369	0
Error	17994	150256	8		
Lack of Fit	24	61943	2581	525	0
Pure Error	17970	88313	5		
Total	17999	21357137			

R^2	99.30%				
800 rpm	torque = 189.292 - 0.14106 blend				
1200 rpm	torque = 241.794 - 0.14106 blend				
1600 rpm	torque = 276.336 - 0.14106 blend				
2000 rpm	torque = 278.466 - 0.14106 blend				
2400 rpm	torque = 275.602 - 0.14106 blend				

	Torque (Nm) @ Biodiesel Blend						
SUMMARY	**0%**	**2%**	**5%**	**10%**	**15%**	**20%**	Total
800 rpm							
Count	600	600	600	600	600	600	3600
Sum	113520.6	113981.2	112758.1	113183.9	110725.3	112880.1	677049.2
Average	189.2011	189.9687	187.9302	188.6398	184.5422	188.1335	188.0692
Variance	8.128218	16.40272	16.80338	11.18965	12.84475	13.01038	15.99221
1200 rpm							
Count	600	600	600	600	600	600	3600
Sum	144054.3	146270.9	145136.3	143536	143370.2	143688	866055.7
Average	240.0904	243.7848	241.8938	239.2267	238.9503	239.48	240.571
Variance	1.545729	5.353543	5.319611	4.978219	5.506377	4.956694	7.593392
1600 rpm							
Count	600	600	600	600	600	600	3600
Sum	165346.7	167618.7	165118.4	164021.2	164220.4	164081.5	990406.9
Average	275.5778	279.3645	275.1973	273.3687	273.7007	273.4692	275.113
Variance	0.956152	2.569472	1.897656	2.500552	2.652754	2.514857	6.519741
2000 rpm							
Count	600	600	600	600	600	600	3600
Sum	165346.7	169432.1	166829.6	165710.6	164639.8	166116.9	998075.7
Average	275.5778	282.3868	278.0493	276.1843	274.3997	276.8615	277.2432
Variance	0.956152	1.719943	1.347679	1.147534	1.180467	2.332656	7.986048
2400 rpm							
Count	600	600	600	600	600	600	3600
Sum	162982.3	166100.6	166779.7	163291.7	163979.5	164632.9	987766.7
Average	271.6372	276.8343	277.9662	272.1528	273.2992	274.3882	274.3796
Variance	0.820289	4.324662	3.161608	0.842396	1.991602	8.478274	8.689388
Total							
Count	3000	3000	3000	3000	3000	3000	
Sum	751250.6	763403.5	756622.1	749743.4	746935.2	751399.4	
Average	250.4169	254.4678	252.2074	249.9145	248.9784	250.4665	
Variance	1116.941	1241.246	1225.663	1125.212	1225.54	1167.471	