The Effects of Diesel-waste Plastic Oil Blends on Engine Performance Characteristics

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Abstract
The objective of this research is to present results of the performance (torque, power, thermal efficiency and specific fuel consumption) in a heavy-duty diesel engine when fueled with diesel-waste plastic pyrolysis oil (WPO) blends in full load condition. The tested engine is installed on an engine test bench and is attached with several sensors. The full factorial experimental design is performed to investigate both main and interaction effects. It is shown that fuel blends, engine speed and interaction of both factors significantly affect all engine performance parameters. The functional relationships between parameters are developed by second-order quadratic models. The result shows that the mathematical models are able to predict the performance characteristic with mean absolute percentage error (MAPE) in the range of 1.614 to 2.987%. The increase of mixing ratio to WPO 75% greatly decreases engine output torque and power approximately by 23.79%. Consequently, thermal efficiency can be reduced by 5.97% while specific fuel consumption can be increased by 31.22%. The results of error analyses, the graphical presentations, the discussions and conclusions are also presented.

Keywords*: Waste Plastic Oil, Diesel Engine, Full Factorial Design, Mean Absolute Percentage Error*

1 Introduction

The world is facing two challenges of energy insufficiency and environmental crisis, mainly coming from dependence on fossil fuels. Many researches try to make quantitative assessment with respect to the global oil remaining resources [1-3]. However, no one can accurately predict when the supplies of fossil fuels will be exhausted since there are several factors involved in the situation. However, it is believed that the production is very close to the peak and will become a global crisis. It is very urgent to strengthen the energy security of the country. Alternative energy derived from non-depleted resources is sustainable in the long term and still leaves gaps for research. Many researchers have studied the energy recovery from non-biodegradable wastes polymers such as municipal plastic wastes, waste tyres, etc. [4-6]. The method of energy recovery from plastic wastes does not give only a new alternative energy source but it is also a method of non-biodegradable waste management. Thus, this is one of the most interesting and satisfactory methods for current and future situations.

Since plastic wastes commonly have high calorific value, approximately 18,000 to 38,000 kcal/kg, this can unquestionably be an alternative energy. Pyrolysis process converts them into other useful hydrocarbon products. This process has been studied for a long time, and is sometimes called “thermal treatment” [7] or “thermal cracking” [8] or “thermo-chemical decomposition” [9]. This process heats the material to high temperature around 450 - 600°C in the absence of air [10]. Then, the plastic wastes are decomposed into smaller fractions, which can be solid, liquid and gas residues. It is found that the properties of pyrolysis oil are similar to that of diesel fuel. Therefore, researchers began to run a diesel engine with pyrolysis oil. In the beginning research focussed on the engine condition and combustion characteristic more than the engine performance and emissions [6,11,12]. The research objectives are changed in the past couple of years and show more practical data such as Murugan and group [13,14] work on waste tyre pyrolysis oil in a single cylinder diesel engine. Their works focus on the effects of different mixing ratios on the diesel engine combustion characteristic, performance and emissions. However, the tests are conducted at the engine speed of 1500 rpm.

The applications of waste plastic pyrolysis oil (WPO) in the engines are also investigated. Mani and group [15] run WPO in a single-cylinder engine which aims to compare engine performances and emissions between diesel and WPO operations without any engine modification. The experiment presents compatible engine efficiency and variety of emission results. Some more researches have worked on engine modifications such as injection timing [16] and exhaust gas recirculation system [17]. The notification of these experiments is found that they investigate only at the rated engine speed, which does not cover the actual engine operating range and becomes a significant research gap in this field.

In order to fulfil this research gap, the present investigation is aimed at determining the effects of two process parameters, which are diesel-WPO mixing ratios and engine speeds. The most outstanding benefit of this study is the practical data from a large diesel engine are revealed over wide range of engine speed, which makes researches in this field approaching to the real applications. Moreover, this research is planned by using the full-factorial experimental design (FFD), which gives a benefit of presenting the interactive effects between fuel mixing ratio and engine speed as well.

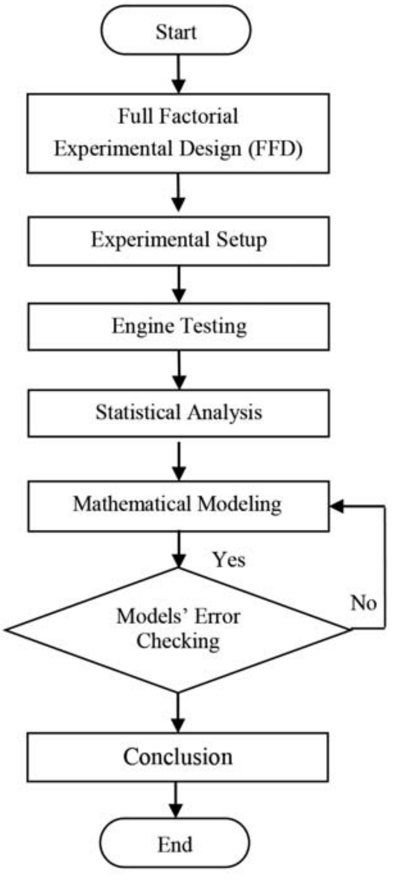

Figure 1: Research Methodology.

2 Methodology

The methodology of this research is shown in Figure 1. Since the conventional experimental design involves the one-factor-at-a-time design which cannot take account of interactive effects among variables. Moreover, almost all of previous literatures are performed by only one replicate, which is acceptable for a time and cost consuming experiment. Thus, this research is performed based on FFD with three replicates. In each replicate, thirty raw data are collected. This means, at least, ninety raw data for each parameter are recorded, according to the purpose of statistical analysis.

The experimentation is designed as follows. Four blends of diesel-WPO and six different engine speeds are tested. Consequently, twenty-four experimental runs are performed per one replicate. The most outstanding benefit of this technique, over the conventional experimental design, is to analyze both individual and interaction effects. The sequence of fuel used is randomized, and within each fuel blend, the speed sequence is randomized. Engine performance, including torque (T), power (P), thermal efficiency (η_{th}) and specific fuel consumption (SFC), are recorded. For the result and discussion purpose, average values are presented.

The engine employed for the experimental work is a four-stroke six-cylinder diesel engine developing 108 kW at 3200 rpm. The block diagram of the experimental setup is given in Figure 2. The engine specifications and fuel heating values are given in Table 1 and Table 2, respectively. The engine is installed on a Clayton water brake dynamometer, which is used to provide the engine load as shown in Figure 3. A Debimo airflow measuring blade and KIMO CP200 are fitted to the engine for airflow measurement. The fuel flow rate is measured on the geometric basis using a digital scale and a stopwatch. The cooling system has been designed as a closed loop system with a cooling tower. The system also consists of an engine coolant temperature controller. Several measuring equipments have been attached to the system throughout the investigation to collect raw data.

Table 1: Engine specifications

Model	Hino WO6D
Type	6-cylinder, 4-stroke diesel
Bore	104 mm
Stroke	113 mm
Displacement	5759 cc
Compression Ratio	16.5 : 1
Fuel System	Direct Injection

Table 2: Fuel heating values

Fuel	Heating Value (kJ/kg)	Difference (%)
Diesel (WPO 0)	45517.14	* reference
WPO 25	44990.55	-1.158%
WPO 50	44894.32	-1.370%
WPO 75	44835.74	-1.498%

The experiment is conducted at full load with engine speeds of 800, 1000, 1200, 1500, 1800 and 2000 rpm. Four fuel blends are used during experiments including neat diesel fuel (WPO 0)

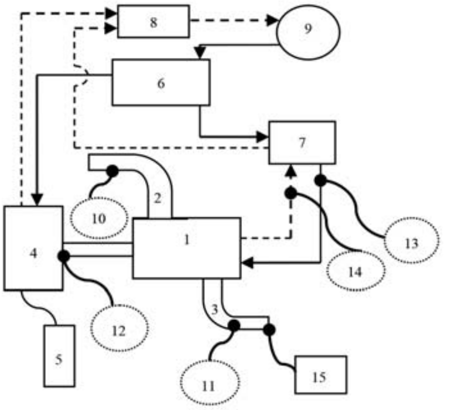

Figure 2: Experimental setup.

Figure 3: Tested engine.

and the blends of 25%, 50% and 75% with waste plastic pyrolysis oil by volume in the diesel (WPO 25, WPO 50 and WPO 75) as shown in Table 3. The engine is started by diesel and then switched to waste plastic oil for the test. At the end of the test, the engine is run for a short period with diesel to flush out the waste plastic oil from the fuel line and injection system.

Table 3: Process parameters and levels

WPO Mixing Ratio Symbol: (W)	Engine Speed Symbol: (S)
0%	800, 1000, 1200, 1500, 1800, 2000 rpm
25%	800, 1000, 1200, 1500, 1800, 2000 rpm
50%	800, 1000, 1200, 1500, 1800, 2000 rpm
75%	800, 1000, 1200, 1500, 1800, 2000 rpm
Total 4 levels	6 levels

In order to develop a functional relationship between the process and response parameters, mathematical model in the form of multiple regression equation is one of the most effective and economical techniques [18]. Each response parameter is plotted as a surface to which a mathematical model is fitted. The model for a multiple regression takes many different forms. However, it is found in previous research that the second-order models are normally applied [19,20] as shown in Equation (1) [21].

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j=2}^{k} \beta_{ij} X_i X_j \quad (1)$$

Equation (1) assumes that the response surface Y contains free term, linear term, squared term and cross product term, which have the coefficients β.

3 Statistical and Mathematical Models

The effects of diesel-WPO blend and engine speed on engine performance are assessed by using 4 × 6 full factorial design with three replicates. Engine torque data are collected from the tested engine. Power, thermal efficiency and SFC are then calculated by Equations (2) to (4) [22].

$$Power = \frac{2\pi \cdot Torque\,(N) \cdot Engine\ Speed\,(rpm)}{60} \quad (2)$$

$$\eta_{th} = \frac{Power \times 100\%}{\dot{m}_f \times Fuel\ Heating\ Value} \quad (3)$$

$$SFC = \frac{\dot{m}_f}{Power} \quad (4)$$

where $\dot{m}_f$ = Fuel flow rate (kg/hr)

The analysis of variance (ANOVA) is used to determine whether there are any significant differences between the means of three or more data set. Consequently, the significances of four levels of fuel blends and six levels of engine speeds are evaluated by ANOVA. The main results of the ANOVA are revealed in appendix A. Both process parameters, including fuel blend (W) and engine speed (S), present the probability values (p-values) of 0.000. These values are less than 0.05, which mean that both process parameters significantly affect engine performance at 95% confidence level. Moreover, the interaction between two parameters (W*S) cannot be negligible since their probability values (p-values) are lower than 0.05 as well.

The quadratic models of engine performance parameters in terms of fuel blend and engine speed are determined by multiple regression analysis, as shown in Equation (1). The results are presented by Equations (5) to (8) (see also appendix B).

$$\begin{aligned} Torque = {} & 180.347 - 1.89132W + 0.165106\,S \\ & + 0.0118775W^2 - 4.26248\times10^{-5}S^2 \\ & + 0.000216088\,WS \end{aligned} \quad (5)$$

$$\begin{aligned} Power = {} & -12.5649 - 0.246882W + 0.0579094S \\ & + 0.00259289W^2 - 1.99453\times10^{-6}S^2 \\ & - 5.66171\times10^{-5}WS \end{aligned} \quad (6)$$

$$\begin{aligned} \eta_{th} = {} & 24.4731 - 0.21395\,W + 0.019245S + 0.001142W^2 \\ & - 7.48165\times10^{-6}S^2 + 3.96271\times10^{-5}WS \end{aligned} \quad (7)$$

$$\begin{aligned} SFC = {} & 313.696 + 1.6808W - 0.15697S - 0.0081782W^2 \\ & + 6.07845\times10^{-5}S^2 - 3.3362\times10^{-4}WS \end{aligned} \quad (8)$$

In order to evaluate the reliability of developed models, each level of process parameter is placed into equations (5) to (8) and calculates the predicted values. These predicted values are then compared to the measured value as shown in Tables 4 to 7. The differences between the predicted and measured values identify the existing error. There are many available methods such as Mean absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Percentage Error (MAPE), Relative Absolute Error (RAE) and Root Relative Squared Error (RRSE) [23]. The MAPE method is used in this step for the purpose of reporting since it meets five basic criteria for a good measure of error, which are measurement validity, reliability, ease of interpretation, clarity of presentation and support of statistical evaluation [24]. The most important point is that this method is a unit free measure [25], which is easily understandable to a wide range of readers as generally seen in many researches [26,27].

Table 4: MAPE of torque characteristic model

WPO (%)	Speed (rpm)	Torque (Nm)		Absolute Deviation	Absolute Percentage of Error
		Measure	Predict		
0	800	288.00	285.15	2.85	0.990
0	1000	300.00	302.83	2.83	0.943
0	1200	309.60	317.09	7.49	2.419
0	1500	340.80	332.10	8.70	2.553
0	1800	348.00	339.43	8.57	2.463
0	2000	343.20	340.06	3.14	0.915
25	800	250.80	249.61	1.19	0.474
25	1000	261.80	268.37	6.57	2.510
25	1200	271.45	283.72	12.27	4.520
25	1500	298.13	300.34	2.21	0.741
25	1800	303.27	309.30	6.03	1.988
25	2000	298.11	311.00	12.89	4.324
50	800	243.10	228.92	14.18	5.833
50	1000	255.20	248.76	6.44	2.524
50	1200	266.49	265.19	1.30	0.488
50	1500	297.48	283.43	14.05	4.723
50	1800	299.34	294.01	5.33	1.781
50	2000	294.30	296.80	2.50	0.849
75	800	219.48	223.08	3.60	1.640
75	1000	236.50	244.00	7.50	3.171
75	1200	253.00	261.50	8.50	3.360
75	1500	286.00	281.37	4.63	1.619
75	1800	295.28	293.57	1.71	0.579
75	2000	297.77	297.43	0.34	0.114
Mean Absolute Percentage Error (MAPE)					2.147%

Table 5: MAPE of power characteristic model

WPO (%)	Speed (rpm)	Power (kW)		Absolute Deviation	Absolute Percentage of Error
		Measure	Predict		
0	800	32.34	32.49	0.15	0.464
0	1000	42.11	43.35	1.24	2.945
0	1200	52.15	54.05	1.90	3.643
0	1500	71.76	69.81	1.95	2.717
0	1800	87.93	85.21	2.72	3.093
0	2000	96.35	95.28	1.07	1.111
25	800	28.16	26.80	1.36	4.830
25	1000	36.75	37.38	0.63	1.714
25	1200	45.73	47.80	2.07	4.527
25	1500	62.78	63.14	0.36	0.573
25	1800	76.63	78.11	1.48	1.931
25	2000	83.69	87.89	4.20	5.019
50	800	27.30	24.36	2.94	10.769
50	1000	35.82	34.66	1.16	3.238
50	1200	44.89	44.80	0.09	0.200
50	1500	62.64	59.70	2.94	4.693
50	1800	75.63	74.25	1.38	1.825
50	2000	82.63	83.75	1.12	1.355
75	800	24.65	25.16	0.51	2.069
75	1000	33.20	35.17	1.97	5.934
75	1200	42.62	45.03	2.41	5.655
75	1500	60.22	59.51	0.71	1.179
75	1800	74.61	73.64	0.97	1.300
75	2000	83.60	82.85	0.75	0.897
Mean Absolute Percentage Error (MAPE)					2.987%

Table 6: MAPE of efficiency characteristic model

WPO (%)	Speed (rpm)	Efficiency (%)		Absolute Deviation	Absolute Percentage of Error
		Measure	Predict		
0	800	34.95	35.08	0.13	0.372
0	1000	36.54	36.24	0.30	0.821
0	1200	36.63	36.79	0.16	0.437
0	1500	36.82	36.51	0.31	0.842
0	1800	35.29	34.87	0.42	1.190
0	2000	33.66	33.04	0.62	1.842
25	800	30.79	31.24	0.45	1.462
25	1000	32.26	32.59	0.33	1.023
25	1200	32.49	33.35	0.86	2.647
25	1500	32.58	33.36	0.78	2.394
25	1800	31.12	32.02	0.90	2.892
25	2000	29.58	30.38	0.80	2.705
50	800	29.91	28.82	1.09	3.644
50	1000	31.51	30.38	1.13	3.586
50	1200	31.97	31.33	0.64	2.002
50	1500	32.58	31.64	0.94	2.885
50	1800	30.78	30.60	0.18	0.585
50	2000	29.27	29.16	0.11	0.376
75	800	27.04	27.84	0.80	2.959
75	1000	29.24	29.59	0.35	1.197
75	1200	30.39	30.74	0.35	1.152
75	1500	31.37	31.34	0.03	0.096
75	1800	30.40	30.60	0.20	0.658
75	2000	29.65	29.36	0.29	0.978
Mean Absolute Percentage Error (MAPE)					1.614%

Table 7: MAPE of SFC characteristic model

WPO (%)	Speed (rpm)	Efficiency (%)		Absolute Deviation	Absolute Percentage of Error
		Measure	Predict		
0	800	226.32	227.02	0.70	0.309
0	1000	216.47	217.51	1.04	0.480
0	1200	215.93	212.86	3.07	1.422
0	1500	214.84	215.01	0.17	0.079
0	1800	224.12	228.09	3.97	1.771
0	2000	234.97	242.89	7.92	3.371
25	800	259.94	257.26	2.68	1.031
25	1000	248.11	246.08	2.03	0.818
25	1200	246.33	239.76	6.57	2.667
25	1500	245.64	239.40	6.24	2.540
25	1800	257.23	249.99	7.24	2.815
25	2000	270.56	263.12	7.44	2.750
50	800	268.15	277.27	9.12	3.401
50	1000	254.50	264.42	9.92	3.898
50	1200	250.88	256.44	5.56	2.216
50	1500	246.15	253.58	7.43	3.018
50	1800	260.58	261.66	1.08	0.414
50	2000	274.03	273.13	0.90	0.328
75	800	296.98	287.06	9.92	3.340
75	1000	274.60	272.55	2.05	0.747
75	1200	264.24	262.89	1.35	0.511
75	1500	256.01	257.53	1.52	0.594
75	1800	264.14	263.11	1.03	0.390
75	2000	270.82	272.91	2.09	0.772
Mean Absolute Percentage Error (MAPE)					1.653%

The example of the absolute percentage of error calculation is shown as follows. The predicted torque of WPO 0% at 800 rpm is calculated from equation (5) by substitute $W = 0$ and $S = 800$. It gives;

$$Torque = 180.347 - 1.89132(0) + 0.165106\ (800) + 0.0118775(0)^2 - 4.26248 \times 10^{-5}(800)^2 + 0.000216088\ (0)(800)$$

Absolute deviation (D_a) and Absolute percentage of error (APE) are then calculated by equations (9) and (10) [28].

$$D_a = |\,measured\ value - predicted\ value\,| \qquad (9)$$

$$APE = \frac{D_a}{measured\ value} \times 100\% \qquad (10)$$

This gives;

$$D_a = |\,288.00 - 285.15\,|$$

$$D_a = 2.85$$

And;

$$APE = \frac{2.85}{288.00} \times 100\%$$

$$APE = 0.990\%$$

Finally, mean absolute percentage errors present very low values of 2.147%, 2.987%, 1.614% and 1.653% for torque, power, efficiency and specific fuel consumption in the bottom row of Tables 4 to 7, respectively. MAPE value of less than 10% certifies the high accuracy for forecasting of the developed quadratic models [26].

4 Results and Discussions

Generally, torque increases as engine speed increases until it reaches the maximum point. After that, it decreases at high engine speed, as shown in Figure 4. This is due to the friction loss and inability of the engine to ingest a full charge of air [22].

It is observed that the mixtures of diesel-waste plastic oil decrease engine torque significantly in Figure 4. Even the heating values of each kind of fuel are compatible as already shown in Table 2, Figures 4 and 5 show that the engine presents by average 12.92% lower torque and power than those of diesel while

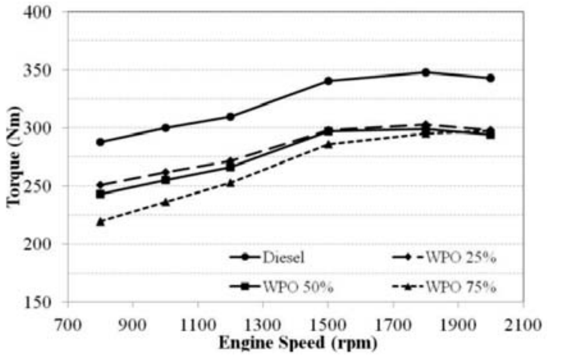

Figure 4: Variation of torque with fuel blend and engine speed.

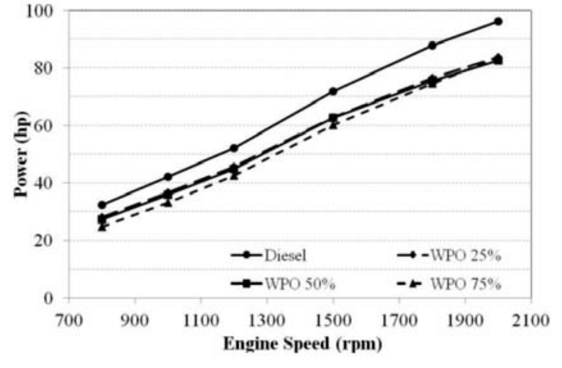

Figure 5: Variation of power with fuel blend and engine speed.

operating with WPO 25%. The differences increase up to 15.59% and 23.79% for WPO 50% and WPO 75%, respectively. The interaction between fuel mixing ratio and engine speed is markedly significant, especially in Figure 5. The graphs of diesel-WPO mixtures are getting more identical at high engine speed. Moreover, the gap between diesel and WPO graphs are getting larger as well.

This is the evidence that the Cetane number of waste plastic oil is lower and considerably brings up the longer ignition delay. Ignition delay identifies the period between the injection and start of combustion. This delay period depicts the trend to abnormal combustion in diesel engine and, consequently, leads to lower engine torque and power. This behaviour is also found in literatures [15,16]. Moreover, it is a known fact that the increment in engine speed increases the ignition delay [29]. This is the reason why the gap between diesel and WPO graphs are getting larger at high engine speed.

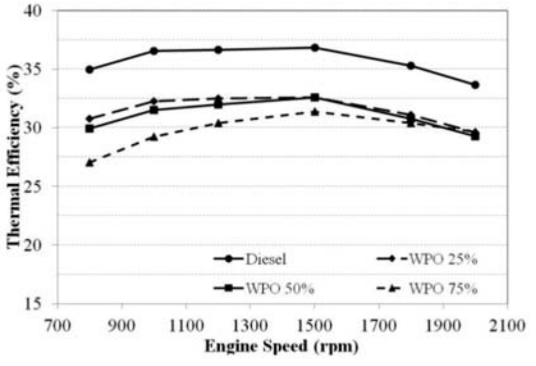

Figure 6: Variation of thermal efficiency with fuel blend and engine speed.

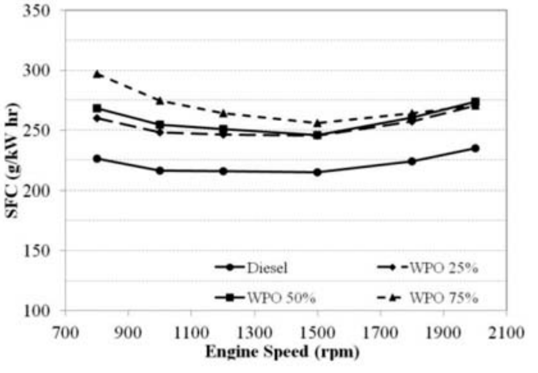

Figure 7: Variation of specific fuel consumption with fuel blend and engine speed.

Figure 6 shows that the average thermal efficiency of diesel operation is 35.65% while diesel-WPO blends produce 31.47%, 31.00% and 29.68%. This is due to two main reasons, firstly, WPOs produce less output power with almost the same amount of fuel injection. The other reason is due to the fact that, in WPO combustion, the higher cylinder pressure generates a higher exhaust gas temperature together with higher heat losses [15].

Theoretically, engine specific fuel consumption parameter is inversely proportional to thermal efficiency. Therefore, diesel presents the lowest specific fuel consumption. WPOs 25%, 50% and 75% present higher values, respectively, as shown in Figure 7.

5 Conclusion and Recommendation

The contribution of this research is to propose a model to investigate effects among diesel-WPO mixing ratios and engine speeds. Waste plastic oil is blended into diesel in several mixing ratios and run by a heavy duty engine in order to investigate the effects on engine performance characteristic. Three mixing ratios including WPO 25%, 50% and 75% are tested at a wide range of engine speed and the results compared to those of diesel (WPO 0%). The statistical analysis using ANOVA reveals that mixing ratio, engine speed and the interaction are significant at 95% confidence level. The second-order quadratic modelling is enough to fit the relations between process parameters and responses. MAPE method shows the errors in the range of 1.614 to 2.987%, which is considered very high accuracy in prediction. The benefit of this research is that the user can apply full-factorial design and quadratic modelling to practically predict the result in a number of diesel-WPO mixing ratios and engine speeds.

The experimental results show that, though the heating value of WPO is compatible to diesel, other fuel properties are also important. Lower Cetane number might lead to abnormal combustion which results in 23.79% reduction in output torque and power for WPO 75%. Thermal efficiency decreases up to 5.97% with an increment of specific fuel consumption.

Even though the overall results from this investigation can be considered that WPO blends do not have performance compatibility to that of diesel, WPO is still attractive in the waste-to-energy viewpoint. Since it is not generated from conventional fossil fuel, the cost of WPO is then unquestionably cheaper and it helps the plastic waste management process.

Operation cost and external costs, including fuel cost, pollution cost and country's energy security scenario, should be integrated in future research for the cost-benefit analysis or optimization. WPO can then be a successful alternative fuel in a similar way to biodiesel.

APPENDIX A: Results of ANOVA

Analysis of Variance for torque, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
W	3	33327.5	33327.5	11109.2	512.73	0.000
S	5	41195.0	41195.0	8239.0	380.26	0.000
W*S	15	1194.1	1194.1	79.6	3.67	0.000
Error	48	1040.0	1040.0	21.7		
Total	71	76756.7				

Figure A1: Result of ANOVA for torque.

Analysis of Variance for Power, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
W	3	1211.2	1211.2	403.7	417.01	0.000
S	5	32976.9	32976.9	6595.4	6812.24	0.000
W*S	15	121.0	121.0	8.1	8.34	0.000
Error	48	46.5	46.5	1.0		
Total	71	34355.6				

Figure A2: Result of ANOVA for power.

Analysis of Variance for efficiency, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
W	3	359.088	359.088	119.696	442.99	0.000
S	5	79.008	79.008	15.802	58.48	0.000
W*S	15	22.130	22.130	1.475	5.46	0.000
Error	48	12.969	12.969	0.270		
Total	71	473.196				

Figure A3: Result of ANOVA for thermal efficiency.

Analysis of Variance for SFC, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
W	3	23685.1	23685.1	7895.0	450.99	0.000
S	5	5155.9	5155.9	1031.2	58.90	0.000
W*S	15	1921.8	1921.8	128.1	7.32	0.000
Error	48	840.3	840.3	17.5		
Total	71	31603.1				

Figure A4: Result of ANOVA for SFC.

Appendix B: The estimated regression coefficient for response parameters from the statistical program.

Estimated Regression Coefficients for torque using data in uncoded units

Term	Coef
Constant	180.347
W	1.89132
S	0.165106
W*W	0.0118775
S*S	-4.26248E-05
W*S	0.000216088

Figure B1: Estimate regression coefficient for torque.

Estimated Regression Coefficients for Power using data in uncoded units

Term	Coef
Constant	-12.5649
W	-0.246882
S	0.0579094
W*W	0.00259289
S*S	-1.99453E-06
W*S	-5.66171E-05

Figure B2: Estimate regression coefficient for power.

Estimated Regression Coefficients for efficiency using data in uncoded units

Term	Coef
Constant	24.4731
W	0.21395
S	0.019245
W*W	-0.001142
S*S	-7.48165E-06
W*S	3.96271E-05

Figure B3: Estimate regression coefficient for thermal efficiency.

Estimated Regression Coefficients for SFC using data in uncoded units

Term	Coef
Constant	313.696
W	1.6808
S	-0.15697
W*W	-0.0081782
S*S	6.07845E-05
W*S	-3.33620E-04

Figure B4: Estimate regression coefficient for SFC.

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