Influence of blends of diesel and renewable fuels on CI engine emissions over transient engine conditions.

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Abstract

To reduce the amount of carbon dioxide released from transportation the EU has implemented legislation to mandate the renewable content of petrol and diesel fuels. However, due to the complexity of the combustion process the addition of renewable content, such as biodiesel and ethanol, can have a detrimental effect on other engine emissions. In particular the engine load can have a significant impact on the emissions. Most research that have studied this issue are based on steady state tests, that are unrealistic of real world driving and will not capture the difference between full and part loads. This study aims to address this by investigating the effect of renewable fuel blends of diesel, biodiesel and ethanol on the emissions of a compression ignition engine tested over the World Harmonised Light Vehicle Test Procedure (WLTP). Diesel, biodiesel and ethanol were blended to form binary and ternary blends, the ratios were determined by Design of Experiments (DoE). The total amount of emissions for CO, CO_2 and NO_x as well as the fuel consumption, were measured from a 2.4 L compression ignition (CI) engine running over the WLTP drive cycle. The results depicted that percentages smaller than 10 % of ethanol in the fuel blend can reduce CO emissions, CO_2 emissions as well as NO_x emissions, but increases fuel consumption with increasing percentage of ethanol in the fuel blend. Blends with biodiesel resulted in minor increases in CO emissions due to the engine being operated in the low and medium load regions over the WLTP. CO_2 emissions as well as NO_x emissions increased as a result of the high oxygen content in biodiesel which promoted better combustion. Fuel consumption increased for blends with biodiesel as a result from biodiesel's lower heating value. All the statistical models describing the engine responses were significant and this demonstrated that a mixture DoE is suitable to quantify the effect of fuel blends on an engine's emissions response. An optimised ternary blend of B2E9 was found to be suitable as a 'drop in' fuel that will reduce harmful emissions of CO emissions by approximately 34 %, NO_x emissions by 10 % and CO_2 emissions by 21 % for transient engine operating scenarios such as the WLTP drive cycle.

Keywords: biodiesel, ethanol, engine emission, ternary blend, design of experiment, WLTP.

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1. Introduction

The European Union (EU) has implemented successive emission standards to reduce the environmental impact of harmful emissions from road transport and to help the transition towards a low-carbon economy. These measures include a limit on CO_2 emissions as well as a separate Euro 6 legislation, which enforces limitations on permissible quantity of harmful gasses in the vehicle exhaust [1]. Additionally, the EU has set out climate and energy targets for 2020 to combat climate change, increase energy security and strengthen its competitiveness. These targets can be summarised as follows [2]:

- 20 % reduction in EU greenhouse gasses from 1990 levels.
- 20 % improvements in EU's energy efficiency.
- 20 % of EU energy from renewable energy.

The final target is enforced by the EU by giving all the member countries binding targets to raise their share of renewable energy in their energy consumption by 2020. These targets are determined based on the individual country's use of renewable energy and the potential to increase their production. Targets range from 10 % for Malta to 49 % for Sweden. The UK has a target of 15 %. Ultimately, all the individual targets will ensure the EU meets its target of 20 % by 2020. Included in the individual targets of each country, a 10 % share of renewable energy in the transport sector is required. This can be achieved using a combination of biofuels, hydrogen or 'green' electricity [2]. The UK government hopes to reach it's 2020 target of 10 % renewable energy in transport with the promotion of ultra low emission vehicles (ULEV) as well as increasing its use of renewable fuels in the transport sector [3].

Biofuels, which include biodiesel and bioethanol, are a renewable source of energy in the transport industry [4–6]. Currently renewable fuels, such as biodiesel, can be used as a 'drop in' fuel together with diesel up to a maximum of 7 % at pump stations [5]. Studies have been conducted on biodiesel and ethanol blends ranging from pure fuels (e.g. B100) to binary blends with petroleum diesel (e.g. B20, E10, etc.) and ternary blends with ethanol or bioethanol (e.g. B20E2, B40E5, etc.). A summary of the previous research in this area will be presented

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below.

The use of biodiesel also significantly reduces PM emissions, CO emissions as well as HC emissions due to its high oxygen content and lower aromatic compounds when compared to petroleum diesel [7]. Many studies have been conducted to study the effect of renewable fuels on harmful exhaust emissions for engines running at steady state conditions. Palash et al. [8] reported an approximate 10 % and 22 % drop in HC emissions for B5 and B10 respectively. Bannister et al. [9] also found that by increasing the blend ratio of biodiesel a reduction of approximately 22 % in HC emissions can be achieved. A drop in CO and HC emissions due to the high oxygen content of biodiesel and the absence of aromatic content was reported in several studies [7, 10–12]. Barabas et al. [13] and Kwanchareon et al. [14] reported that the reduction of CO emissions with a biodiesel binary blend is not as pronounced for low and medium engine loads, whereas for high engine loads significant reduction in CO emissions are possible. Increasing the biodiesel content also increases the NO_x emissions, as its higher oxygen content improves combustion which results in higher combustion temperatures. Lahane and Subramanian [15] found that for blends of up to B15 NO_x emissions increases marginally; beyond B15 the NO_x emissions will increase significantly. Binary blends of biodiesel with conventional diesel, especially B15 and lower, is seen as the best option for use in diesel vehicles without the need to modify the engine while still achieving a reduction in regulated emissions [15, 16].

Binary blends of diesel and ethanol also have the benefit of reducing regulated emissions. Huang et al. [17] found that binary blends of E10 reduced CO emissions by approximately 31 % and NO_x emissions of approximately 6 %. By increasing the percentage of ethanol in the blend by more than 10 %, CO emissions started to increase and NO_x emissions were reduced further by more than 34 %. Xing-cai et al. [18] reported similar trends when increasing the ethanol content in the fuel and contributed the rise in CO emissions due to ethanol's high latent heat of evaporation. By increasing the ethanol content, the cooling effect of ethanol causes incomplete combustion. High percentages of ethanol can also cause an increase in ignition delay due to its low cetane number, which also results in incomplete combustion. The cooling effect of ethanol's high latent heat of evaporation has a positive effect on NO_x emissions. By increasing the ethanol content in the fuel blend, the combustion temperature is reduced and therefore less thermal NO_x is produced during combustion [17]. Rakopoulos et al. [19] also found that the addition of ethanol to diesel increases the fuel consumption of the engine due to ethanol's lower calorific value. As the percentage of ethanol increases in the blend, the fuel consumption also increases [20]. Table 1 shows a summary of the effects of binary blends of diesel and biodiesel and diesel and ethanol and their effects on harmful emissions. In the table a '+' represents an increase, '-' represents a decrease and 'o' represents an insignificant change. From Table 1 it is evident that the benefits of using renewable fuels to reduce harmful emissions are dependent on engine operation. Biodiesel has a significant effect on harmful emissions reduction when the engine is operated at full load, but the reduction is less pronounced for part load conditions. The same applies for binary blends between diesel and ethanol. The addition of ethanol to reduce harmful emissions is only effective when the engine is operating at high loads. Emissions such as CO and HC are increased at low and medium load conditions when running with binary blends of diesel and ethanol. The summary of the literature for binary mixtures reveals that because the emissions are affected by engine load then the application of steady state tests to real world transient driving behaviour is limited.

	Biodiesel		Ethanol	
	Part load	Full load	Part load	Full load
NO_x	-	-	-	-
CO	o	- -	++	- -
HC	-	-	++	-
FC	+	+	++	+
CO_2	N/A	+	-	-
PM	-	- -	- -	- -

Table 1: Summary of effects of binary blends on harmful emissions [7, 8, 10–12, 14, 17, 19, 21].

Binary blends of ethanol with diesel have some technical barriers due to the miscibility of ethanol in diesel fuel. The addition of additives (emulsifiers) are required in order to run a CI engine with a blend of ethanol and diesel. Biodiesel acts as an emulsifier for ethanol; the addition of biodiesel drastically improves the miscibility of ethanol in diesel [16]. Studies of binary blends of biodiesel and diesel show that, generally, as the biodiesel is increased then the CO and HC emissions decrease and NO_x increases. Whereas binary blends of ethanol and diesel decrease NO_x and increase CO. Therefore the ternary blends of these fuels result in inconsistent results depending on the blend and the speed and load of the engine. The ethanol in the ternary blend also improves the atomisation performance of the fuel, because the ethanol blended fuel has a low kinematic viscosity and surface tension [22]. Ethanol's high oxygen content improves combustion which can reduce the PM emissions even further when compared to binary blends of biodiesel and diesel. Randazzo and Sodré [4] found that using ternary blends of B20E2 and B20E5 decreased CO_2 and NO_x emissions while slightly increasing HC and PM emissions. On the other hand, Zhu et al. [23] reported a slight decrease of HC, CO and NO_x emissions when adding small amounts of ethanol of up to 5 % compared to binary blends of biodiesel and diesel. Mofijur et al. [24] found that ternary blends significantly decrease the HC, PM and smoke emissions, while NO_x emissions increase slightly. An optimum amount of ethanol was found to be a maximum of E5 as per the results of Shahir et al. [20] which reduces soot and HC emissions. The lower heating value of ethanol and biodiesel as well as biodiesel's high density and high viscosity results in an increase in fuel consumption [20]. Table 2 shows a summary of the effects of ternary blends on the harmful emissions. In the table a '+' represents an increase, '-' represents a decrease and 'o' represents an insignificant change. The table shows that the chemical interaction effects between biodiesel and ethanol in a ternary blend is complex and also depends on load and/or speed of the engine. With such complex interactions between engine conditions and ternary fuel blends on the emissions, studies based on steady state results cannot be easily translated to the real world, where the engine speed and load is varied based on driver behaviour. To illustrate this, Figure 1 compares the variation of engine Brake Mean Effective Pressure (BMEP) with engine speed for the steady state engine points cited in this paper in the literature and the current transient drive cycle (WLTP) implemented on the engine used in this study. The World Harmonised Light Vehicle Test Procedure (WLTP) was implemented in 2017 and addresses the issues of it's predecessor in terms of real world driving behaviour [27]. As can be seen from Figure 1 the studies from the literature only cover a small proportion of the driving test cycle. Some attempts have been made to study the effects of engine speed and load using statistical methods [25], but the results cover a limited area of an engine's operating envelope. This study aims to address the shortcomings of previous studies by investigating both the variation of engine conditions and ternary fuel blends on exhaust emissions. In order to determine a suitable blend of diesel, biodiesel and ethanol that will reduce engine emissions a multivariate analysis is needed to provide a clear and thorough knowledge on the combustion characteristics of the engine. The use of non-linear techniques like Design of Experiment (DoE) is suitable to explore the interaction effects of diesel, biodiesel and ethanol and its effect on engine responses. DoE is the most cost effective and economical technique to evaluate the individual effects and combined effects of the blend components on the output response [28]. DoE techniques have been used successfully in other studies to investigate the effects between engine speed and load and blends between diesel, biodiesel and ethanol [25], to quantify the effects of fuel compositions on GDI-derived particle emissions using a mixture DoE [29] and to optimise a double pilot injection strategy to improve diesel performance and emissions [30]. Although multiple studies used DoE to optimise engine system parameters, the instances where mixture DoEs were used to optimise ternary fuel blends over a given drive cycle is scarce.

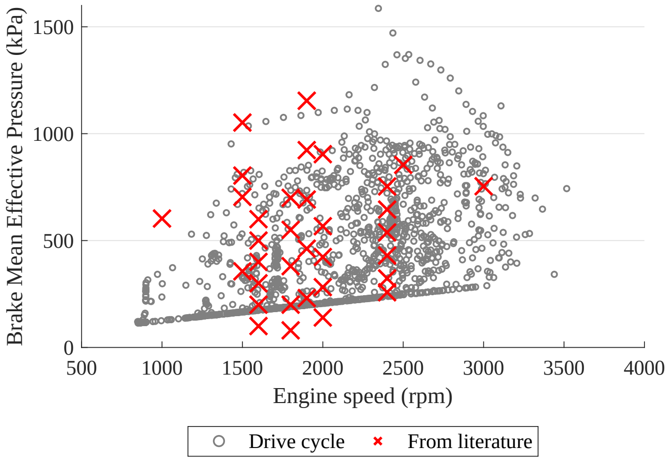


Figure 1: Comparison of engine operating points as discussed in literature compared to the operating points in the WLTP drive cycle.

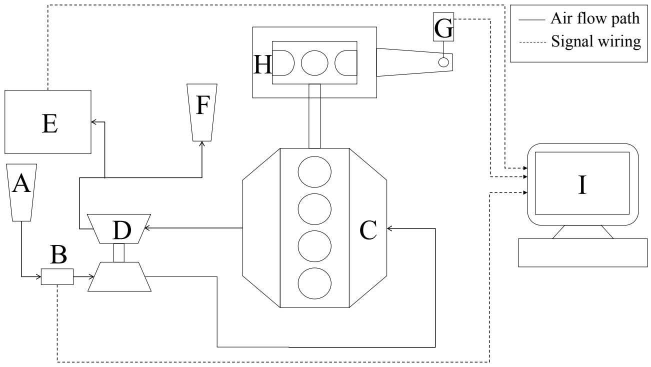


Figure 2: Layout of the engine test cell together with measuring equipment; A: air filter; B:Mass airflow sensor; C: engine; D: Turbo charger; E: gas analyser; F: exhaust outlet; G: load cell; H: dynamometer; I: DAQ.

This paper investigates the use of a mixture DoE to characterise the response of a CI engine fuelled with ternary blends of diesel, biodiesel and ethanol while being tested over the WLTP. Engine responses that were considered are CO emissions, CO_2 emissions, NO_x emissions and engine fuel consumption. The results for each exhaust emission are analysed, before the holistic improvement of the engine emissions and performance is discussed.

2. Materials and Methods

2.1. Experimental set-up

A 2.4 L Euro IV compression ignition (CI) engine with a programmable after-market ECU was used as the test engine to collect the data. Figure 2 shows a schematic of the CI engine testing facility that was used for studying the engine emissions. The engine, who's specifications are listed in Table 3, was connected to a Froude FO271 dynamometer. Two gas analysers were used; one (NOVA 7466K) for measuring CO_2 and NO_x emissions and the other (TESTO 350) for measuring CO emissions. Both were located upstream of any exhaust after treatment systems. A summary of the analysers is presented in Table 4. The factory fitted mass airflow sensor (MAF), calibrated with a Superflow SF-120 flow bench, was used to measure the intake mass air flow. Cumulative mass fuel consumption was measured by weighing the fuel before and after the test on a calibrated digital scale. Data such as engine speed, throttle position, cooling water temperature and oil sump temperature were recorded from the ECU as well as from the dynamometer control system. The fuel supplier provided physiochemical properties of diesel, biodiesel and ethanol as well as the binary and ternary blends are listed in Table 5.

2.2. Experimental design

A mixture design approach was adopted to explore the individual effects of diesel, biodiesel and ethanol and their interactions in a blend for different engine responses. The selection

	Hulwan and Joshi [16]			Zhu et al. [23]		Khoobbakht et al. [25]	Yilmaz et al. [26]	
%B	10	10	10	15	15	20	49	43
%E	20	20	20	15	15	10	3	15
BMEP (MPa)	0.2	0.4	0.6	0.2	0.7	1.15	0.37	0.37
Speed (rpm)	1600	1600	1600	1800	1800	1900	3000	3000
NO_x	o	o	o	-	-	+	-	-
CO	+	o	o	+	o	-	o	+
HC	N/A	N/A	N/A	-	o	-	-	-
FC	+	+	+	++	+	N/A	N/A	N/A
CO_2	+	+	+	N/A	N/A	+	N/A	N/A
PM	N/A	N/A	N/A	-	–	N/A	N/A	N/A

Table 2: Summary of effects of ternary blends on harmful emissions.

Engine parameter	Characteristics
Bore (mm)	89.9
Stroke (mm)	94.6
Volume (cc)	2402
Compression ratio (CR)	17.5
Number of cylinders	4
Method of cooling	Water cooled

Table 3: Engine parameters used for experimentation.

Exhaust gas	Range	Accuracy	Method
CO (ppm)	0 – 10000	< 10	electrochemical
CO_2 (%)	0 – 20	< 0.2	infra-red
NO (ppm)	0 – 2000	< 20	electrochemical
NO_2 (ppm)	0 – 800	< 8	electrochemical

Table 4: Method and accuracy of the instruments used to measure the engine emissions.

of the mixture DoE is appropriate as the sum of the input variables, in this case the blend components, must be unity [31]. As opposed to a response surface design, the factors in a mixture design is not independent from each other. If $x_1, x_2, \dots, x_p$ denote the proportions of p components of a blend, then

$$0 \leq x_i \leq 1 \quad i = 1, 2, \dots, p \tag{1}$$

and

$$x_1 + x_2 + \dots + x_p = 1 \tag{2}$$

For a mixture design with three components, the design space is a triangle with vertices corresponding to formulations that are pure blends (100 % of one blend). Figure 3 shows an extreme vertices design, where upper limits have been set to the amount of biodiesel and ethanol. The upper limits are based on previous research [15, 16] where the maximum addition without engine modification was determined:

$$x_D + x_B + x_E = 1 \quad x_B, x_E \leq 0.2 \tag{3}$$

where x_D is the fraction component of diesel, x_B is the fraction component of biodiesel and x_E is the fraction component of ethanol in the blend. Centroid and axial points have been added to the design to increase its capability to fit models for ternary blends. The composition of the centroid point and axial points were calculated using:

$$\begin{gathered} x_D = 0.83, x_B = 0.14, x_E = 0.03 \\ x_D = 0.83, x_B = 0.03, x_E = 0.14 \\ x_D = 0.86, x_B = x_E = 0.07 \\ x_D = 0.94, x_B = x_E = 0.03 \end{gathered} \tag{4}$$

The whole mixture design was replicated once and the runs were randomised to ensure experimental errors are independently distributed. The mixture design consists of one centroid point, three axial points and three vertices points. With the replication, a total of 14 runs of mixture experiments were used to analyse the data acquired from the experimental runs.

	Cetane number	LHV (MJ/kg)	Density (kg/m^3) at 15 °C	Viscosity (mm^3/s) at 40 °C	CFPP (°C)	Flash point (°C)
Diesel	51.7	42.8	831.1	2.686	-26	65
Biodiesel	52.8	38.0	883.2	4.372	-6	179
Ethanol	7.0	26.8	790.0	1.200	-38	40
B20	51.9	41.8	841.5	3.023	-22	87
E20	42.8	39.6	822.9	2.388	-28	60
B14E3	50.5	41.6	837.2	2.877	-24	80
B3E14	45.5	40.4	826.9	2.529	-27	65
B3E3	50.4	42.2	831.4	2.692	-26	67
B7E7	48.7	41.3	831.9	2.700	-25	71

Table 5: Physiochemical properties of diesel, biodiesel, ethanol and their blends.

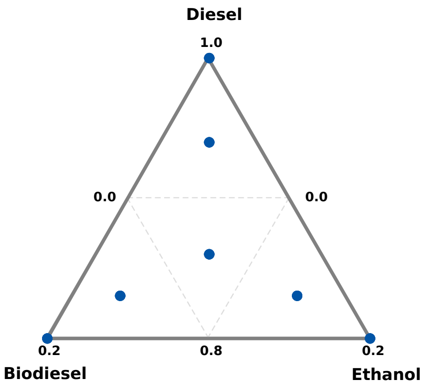


Figure 3: Extreme vertices simplex design plot of the mixture DoE.

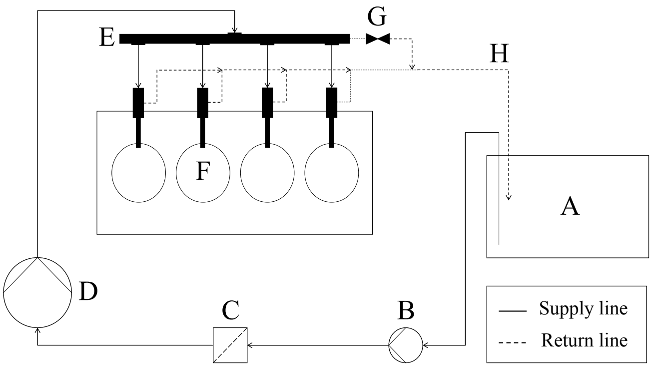


Figure 4: Layout of the engine's fuel delivery system; A: fuel tank; B: fuel primer pump; C: fuel filter; D: main fuel pump; E: common rail; F: engine; G: safety valve; H: fuel return line.

2.3. Desirability approach

The optimisation of the fuel blend is dependent on more than one engine response which include CO emissions, CO_2 emissions, NO_x emissions and fuel consumption. The desirability approach was used for the optimisation of the fuel blend parameters (diesel, biodiesel and ethanol) for the properties of the engine response mentioned above. The software transforms each response to a dimensionless desirability value d. The value ranges from $d = 0$, which indicates that the response is unacceptable, to $d = 1$ which shows that the response is more desirable. The goal of this study was to minimise all engine emissions and the desirability of each of the responses was calculated using [32]:

$$d_i(\hat{Y}_i) = \begin{cases} 1 & \text{if } \hat{Y}_i(x) < T_i \\ \frac{\hat{Y}_i(x) - U_i}{T_i - U_i} & \text{if } T_i \leq \hat{Y}_i(x) \leq U_i \\ 0 & \text{if } \hat{Y}_i \geq U_i \end{cases} \tag{5}$$

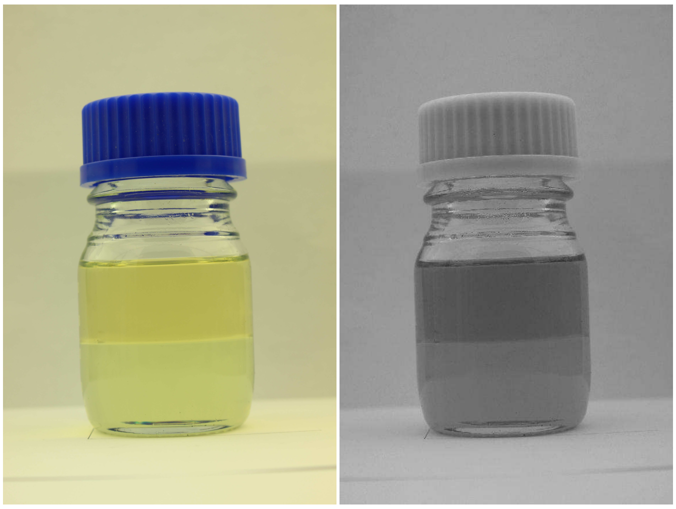
where $d_i(\hat{Y}_i)$ is the desirability function of response $\hat{Y}_i(x)$, T_i and U_i are the target and upper values respectively that are desired for response $\hat{Y}_i(x)$. For minimising the response, T_i will denote a small enough value for the response. The individual desirability functions are combined using the geometric mean, which gives the overall desirability:

$$D = (d_1(Y_1)d_2(Y_2))^{0.5} \tag{6}$$

It is noticeable that if any response $d_i(\hat{Y}_i)$ is completely undesirable, $d_i(\hat{Y}_i) = 0$, then the overall desirability is zero.

2.4. Mixture stability

The diesel, biodiesel and ethanol fuel were mixed in batches of 5 L in the determined blend ratios based on the mixture DoE. The fuels were mixed together using lab equipment with an accuracy of 10 ml to make the homogeneous fuel blends. Each blend was then kept in a sealed glass container for a maximum of 24 hours to observe its physical appearance. All blends, except E20, exhibited a stable mixture, with no observable separation between the different fuels evident. Figure 5 show the E20 fuel sample, where it is evident that the ethanol and diesel has separated from each other. Ethanol is immiscible with diesel fuel over a wide range of temperatures, leading to separation. Consequently, in many cases the presence of a surfactant and co-solvent additive in the binary blends between diesel and ethanol becomes necessary. Lapuerta et al. [33] found that the water content in ethanol, temperature of the fuel and percentage of additive used can influence the stability of the binary blend between diesel and ethanol. Binary blends with a maximum of approximately 10 % ethanol in the blend can be used



(a) Fuel sample of a E20 fuel blend. (b) Grayscale of E20 fuel sample.

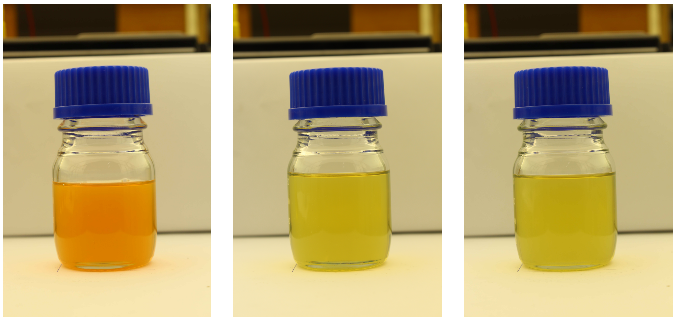
Figure 5: Qualitative check for blend stability for E20 fuel blend.

in diesel engines in countries where temperatures rarely fall below −5 °C. The addition of stability additives will increase miscibility of the fuel thus extending the use of binary blends of diesel and ethanol to colder countries. Hansen et al. [34] also found that the stability of the fuel blend depends on temperature and ethanol's water content. For blends between dry ethanol and diesel, the blend was stable for temperatures higher than 10 °C. Fernando and Hanna [35] and Kwanchareon et al. [14] found that biodiesel can be used successfully as an amphiphile (a surface-active agent) to stabilize ethanol and diesel. They reported that the addition of biodiesel to the binary blend between ethanol and diesel increases the lubricity characteristics of the blend and makes it stable well below sub-zero temperatures. For the testing of E20, no additives were added to the blend to improve its stability as the addition of additives could influence the results [36]. Qualitative checks showed that after approximately 25 minutes, signs of separation was evident in the E20 blend. The homogeneity of the blend was ensured by actively stirring the fuel blend during testing with a magnetic stirrer.

2.5. *Flushing procedure*

In order to ensure that the the old fuel blend from the previous test, in the fuel system does not influence the next test, the fuel system was flushed with the next test's blend of fuel before formal testing began. It was necessary to determine the amount of flushes required that will successfully remove all remaining fuel blend from the previous test. This was done using red fuel dye. The following procedure was followed using the engine's fuel delivery system (Figure 4):

Step 1. Run engine with fuel which contains the red dye.
Step 2. Use fuel primer pump to pump out all fuel from the fuel system.
Step 3. Replace current fuel filter with an empty fuel filter.
Step 4. Replace fuel in the fuel tank with clean fuel and run the fuel primer pump for 5 minutes.



(a) Fuel with red dye added. (b) Fuel after engine was flushed four times. (c) Fuel without any dye added.

Figure 6: Fuel samples used in compiling the flushing procedure.

Step 5. Idle engine for 5 minutes.
Step 6. Run engine at 2500 rpm for one minute.
Step 7. Use fuel primer pump to pump out all the fuel from the fuel system.
Step 8. Repeat steps 4-7.

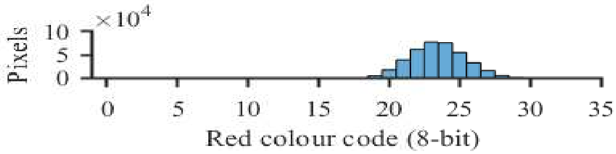
A sample of the fuel in the fuel tank was taken after each flush iteration. The samples were photographed with a Canon EOS 700D under homogeneous light conditions (Figure 6). The red spectrum of each sample was calculated using computer software. The red spectrum of the clean fuel was subtracted from the other sample's spectrum to eliminate any red colours that were already present in the clean fuel. After the fourth flush, the majority of the dye has been removed from the fuel as seen in Figure 7. For the mixture design the engine fuel system was flushed four times before every test was conducted.

2.6. *Data collection*

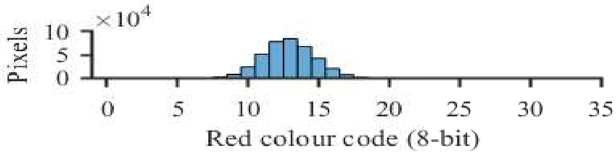
The engine was run on the WLTP as shown in Figure 8. The WLTP shows the variation of vehicle speed with time. Since only the engine and not the whole vehicle was tested it is necessary to relate the vehicle speed to the engine speed and load, based on the vehicle characteristics such as gear ratio etc. The method used is presented elsewhere [37].

3. Results

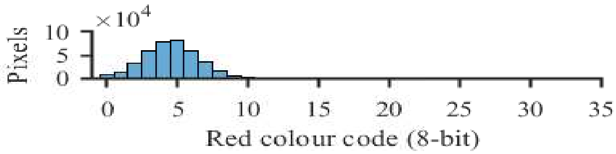
In this present study, the effects of different blends of fuel on different engine responses were considered. Fuel blends included binary and ternary blends between diesel (x_D), biodiesel (x_B) and ethanol (x_E). Engine responses include CO, CO_2, NO_x emissions as well as fuel consumption when tested over the WLTP drive cycle. The experimental response of 14 runs in the design matrix (Figure 3) along with their corresponding points of the fitted mixture design are shown in Table 6. All 14 runs were cold start runs, with the engine oil and cooling water temperature at approximately 20 °C ($\sigma = 2$) at the start of each test. The principal model analysis was based on the analysis of variance (ANOVA) which provided statistical information including the p-values of the different model terms (Table 7). P-values of less than 0.02 are deemed as highly significant, which



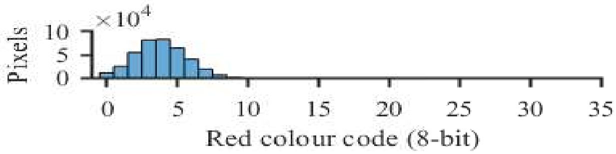
(a) Red spectrum of fuel with red dye added.



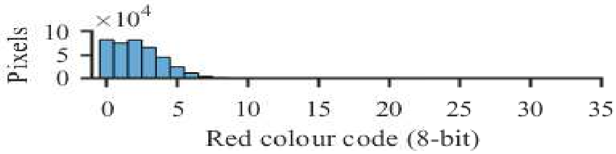
(b) Red spectrum of fuel after the first flush.



(c) Red spectrum of fuel after the second flush.



(d) Red spectrum of fuel after the third flush.



(e) Red spectrum of fuel after the fourth flush.

Figure 7: Change in red spectrum for the fuel samples taken after each fuel system flush.

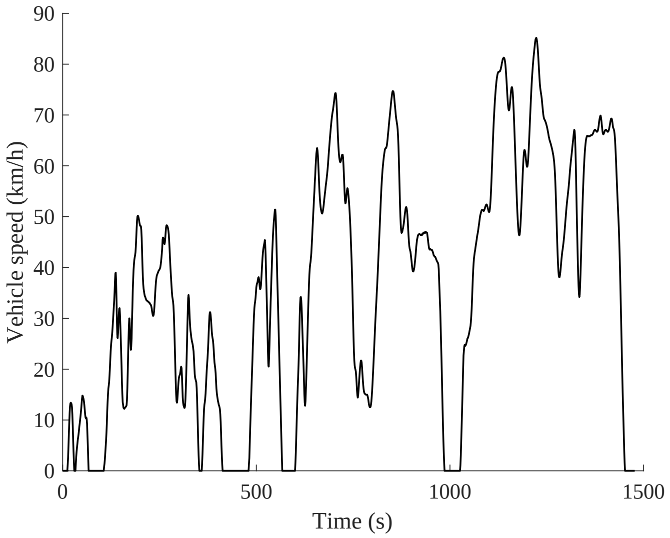


Figure 8: World Harmonised Light Vehicle Test Procedure.

means that the probability of this phenomena is due to chance, is less than 2% [38, 39]. Each engine response is discussed in more detail in the sections below.

3.1. Evaluation of CO emissions

The quadratic model developed for CO emissions as fitted based on the mixture design corresponds to:

$$
\begin{aligned}
Z_{\mathrm{CO}} = {} & x_D - 35.34 \times x_B + 70.00 \times x_E \\
& + 44.7 \times x_D \times x_B - 79.86 \times x_D \times x_E \\
& - 13.78 \times x_B \times x_E
\end{aligned}
\tag{7}
$$

where Z_{CO} is the CO emissions in the exhaust gas in grams per kilometer and the variables x_D, x_B and x_E are the fraction percentages of the components in the overall fuel blend. The effect of all the linear terms as well as the diesel/biodiesel and diesel/ethanol quadratic terms were found to be significant on CO emissions with p-values less than 0.02. Other terms such as the interaction between biodiesel and ethanol did not have a significant effect on CO emissions as indicated by a p-value of 0.249. Furthermore, the regression statistics goodness of fit (R^2) and the goodness of prediction (adjusted R^2) showed high values of 98.65% and 97.81% respectively for the presented model indicating a high correlation between the observed and the predicted values of CO emissions. The variation of CO emissions response with fuel blends based on the model developed from DoE is shown in Figure 9. As shown in the figure, there is an area of CO emissions less than 0.85 g/km for a binary blend of diesel and ethanol: for blends between approximately E2 and E10. The decrease in CO emissions can be contributed to a prolonged oxidation process even in the exhaust phase, which is possible due to the fact that ethanol has a high oxygen content.

Figure 9 also shows that for high concentrations of ethanol (>15 %) in the fuel blend, can result in CO emissions higher than 1.6 g/km. Similar studies ([26, 36]) have also found that for high percentages of ethanol in binary blends, the ignition delay can be increased due to the low cetane number of ethanol which causes the fuel to resist auto-ignition in diesel engines and inhibit complete combustion. The cooling effect of the ethanol on the gas temperature due to ethanol's high latent heat of evaporation can also influence the oxidation process, even though enough oxygen is available for combustion [16]. This is also evident for ternary blends with a high percentage of ethanol.

In Figure 9 CO emissions increase for binary blends between B5 and B15 and then start to decrease again for percentages of higher blends above approximately B16 [40]. Binary blends of diesel and biodiesel less than B20 reduce CO emissions by a small amount at low engine loads and the reduction becomes more pronounced at high load scenarios. For blends of biodiesel greater than B20, CO emission reduction is more pronounced at low engine loads[13, 14]. Engine operating conditions as well as oxygen content of the fuels play a significant part in the formation of CO emissions [26, 41]. The engine operates more regularly in the low and medium load regions

Run	Parameter settings			Experimental response (g/km)			
	x_D	x_B	x_E	CO	CO_2	NO_x	FC
1	0.80	0.00	0.20	2.0598	244.52	1.0812	134.00
2	0.83	0.14	0.03	1.2046	258.74	1.0841	122.75
3	0.83	0.03	0.14	1.4141	232.37	1.0584	128.75
4	0.86	0.07	0.07	1.1409	251.43	1.0566	119.27
5	1.00	0.00	0.00	1.0182	252.03	1.1148	120.64
6	0.83	0.14	0.03	1.0624	257.02	1.0841	121.11
7	0.80	0.20	0.00	0.8844	238.07	1.0669	123.23
8	0.83	0.03	0.14	1.2837	232.37	1.0370	129.98
9	0.94	0.03	0.03	0.9863	244.98	1.0741	121.79
10	0.80	0.20	0.00	0.8868	247.06	1.0714	126.50
11	0.94	0.03	0.03	0.9724	247.48	1.0948	126.57
12	1.00	0.00	0.00	0.9874	251.08	1.1518	116.41
13	0.86	0.07	0.07	1.0638	241.27	1.0635	121.18
14	0.80	0.00	0.20	1.9894	245.00	1.0764	135.50

Table 6: The experimental values of the engine response for the mixture DoE.

	CO	CO_2	NO_x	f_c
Linear	< 0.02	< 0.02	< 0.02	< 0.02
Quadratic	< 0.02	< 0.02	< 0.02	0.078
$x_D \times x_B$	< 0.02	< 0.02	0.351	0.973
$x_D \times x_E$	< 0.02	< 0.02	< 0.02	0.297
$x_B \times x_E$	0.249	0.392	0.894	0.030
Lack-of-Fit	0.948	0.782	0.829	0.068

Table 7: P-values of the engine response for the mixture DoE.

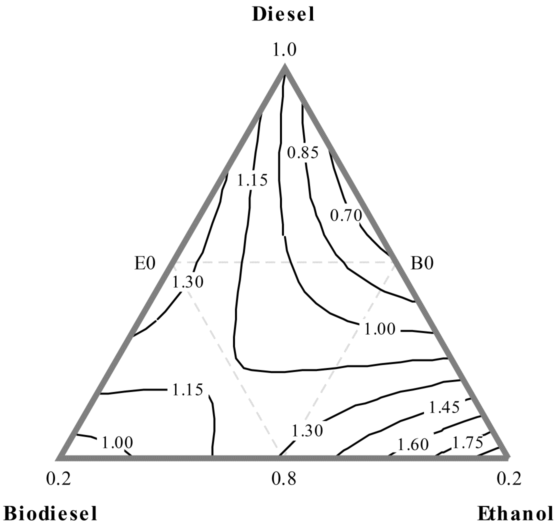


Figure 9: Contour plot of the engine response over the WLTP for CO emissions in grams per kilometer.

when tested over the WLTP, which results in minor CO emission changes for binary blends.

For ternary blends, small additions of biodiesel and ethanol will decrease the engine's CO emissions. A maximum addition of B5E5 will result in similar CO emissions compared to using just diesel.

3.2. Evaluation of CO_2 emissions

The quadratic model developed for CO_2 emissions as fitted based on the mixture design corresponds to:

$$\begin{aligned} Z_{\mathrm{CO_2}} &= 251 \times x_D - 2721 \times x_B + 3768 \times x_E \\ &+ 3660 \times x_D \times x_B - 4438 \times x_D \times x_E \\ &+ 634 \times x_B \times x_E \end{aligned} \tag{8}$$

where $Z_{\mathrm{CO_2}}$ is the CO_2 emissions in the exhaust gas of the engine in grams per kilometer. The linear terms as well as the quadratic terms in Equation 8 are significant with both having a $p - value < 0.02$. The interaction between the diesel and biodiesel terms and the diesel and ethanol terms are also significant. Interaction between the biodiesel and ethanol terms are not significant, as shown in Table 7. High values of R^2 (88.30%) and adjusted R^2 (80.99%) respectively for Equation 8 indicate a high correlation between the observed and the predicted values of CO_2 emissions. The variation of CO_2 emissions response with fuel blends based on the model developed from DoE is shown in Figure 10. A region of minimum CO_2 emissions are evident for binary blends between diesel and ethanol. For blends of approximately E5 to E15, CO_2 emissions of less than 225 g/km were predicted. Ethanol has a very low hydrocarbon atomic ratio which reduces the CO_2 emissions because of the limited carbon content per unit energy of the fuel when burned. The high oxygen content in ethanol also contributes to better combustion, which increases CO_2 emissions, yet it is offset by the smaller amount of carbon atoms available for combustion in ethanol.

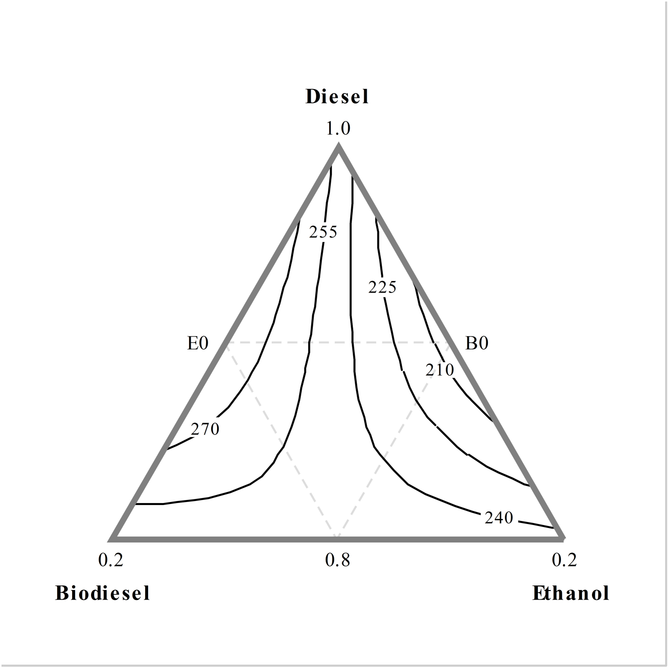


Figure 10: Contour plot of the engine response over the WLTP for CO_2 emissions in grams per kilometer.

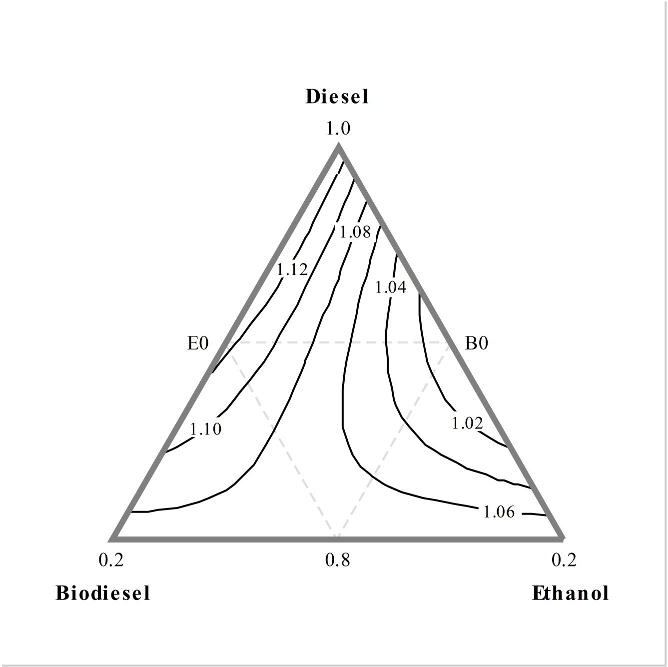


Figure 11: Contour plot of the engine response over the WLTP for NO_x emissions in grams per kilometer.

The region of highest CO_2 emissions are for binary blends of diesel and biodiesel in the region of B10. Increasing the binary blend between diesel and biodiesel beyond B10, results in a reduction of CO_2 emissions of less than 255 g/km. The higher oxygen content in biodiesel promotes complete combustion which results in an increase of CO_2 emissions. The majority of ternary blends between diesel, biodiesel and ethanol resulted in CO_2 emissions between 225 g/km and 270 g/km. An increase in CO_2 emissions towards binary blends between diesel and biodiesel as well as a reduction in CO_2 emissions towards binary blends between diesel and ethanol was also reported in other literature [24, 41, 42].

3.3. *Evaluation of NO_x emissions*

The quadratic model developed for NO_x emissions as fitted based on the mixture design corresponds to:

$$\begin{aligned} Z_{NO_x} &= 1.13 \times x_D - 1.19 \times x_B + 8.97 \times x_E \\ &+ 2.50 \times x_D \times x_B - 10.13 \times x_D \times x_E \\ &+ 0.33 \times x_B \times x_E \end{aligned} \tag{9}$$

where Z_{NO_x} is the NO_x emissions in the exhaust gas of the engine in grams per kilometer. Both the linear and the quadratic models in Equation 9 are significant with p-values less than 0.02. Interaction between the diesel and ethanol terms is significant with $p < 0.02$ whereas the interaction between the diesel and biodiesel terms and the biodiesel and ethanol terms are not significant. High values of R^2 (88.24%) and adjusted R^2 (80.89%) respectively for Equation 9 indicated that there is a high correlation between the observed and the predicted response of the engine. The variation of NO_x emissions response with fuel blends based on the model developed from DoE is shown in Figure 11. A low NO_x emissions region is evident for binary blends between diesel and ethanol of approximately E7 to E15. The decrease in NO_x emissions for binary blends between E7 and E15 can be contributed to ethanol's high latent heat of evaporation which decreases the combustion temperature as well as NO_x formation[21]. By increasing the ethanol content beyond E15, results in NO_x emissions increasing due to ethanol influencing the combustion characteristics of the engine as well as lowering the cetane number of the fuel blend considerably [16, 36].

A ternary blend between diesel, biodiesel and ethanol manages to achieve an equilibrium between the effects of better combustion due to the higher oxygen content in biodiesel and ethanol, as well as the advanced injection of the fuel because of biodiesel's increased bulk modulus. This can be seen in Figure 11 where there is a plateau of NO_x emissions between 1.06 g/km and 1.08 g/km for ternary blends with $x_D = 0.8$.

3.4. *Evaluation of fuel consumption*

The quadratic model developed for fuel consumption as fitted based on the mixture design corresponds to:

$$\begin{aligned} f_c &= 119 \times x_D + 166 \times x_B - 268 \times x_E \\ &- 18 \times x_D \times x_B + 586 \times x_D \times x_E \\ &- 1333 \times x_B \times x_E \end{aligned} \tag{10}$$

where f_c is the fuel consumed by the engine when run over the WLTP in grams per kilometer. The linear model is significant with a p-value of less than 0.02 and the interaction terms approaches statistical significance with a p-value of 0.078. Of the three interaction terms of the quadratic model, only the interaction between biodiesel and ethanol are deemed significant with a p-value of 0.03. High values of R^2 (87.48%) and adjusted R^2 (79.65%) respectively for Equation 10 show that there is a high correlation between the observed and the predicted response of the engine. The variation of the engine's fuel consumption over the WLTP with fuel blends based on the model developed from DoE is shown in Figure 12. The region of minimum fuel consumption of less than 118 g/km is achieved when approximately 10 % biodiesel and 10 % ethanol are blended with diesel. This region of improved fuel consumption can be attributed to better fuel atomisation as a result from the ethanol in the fuel [22]. The additional oxygen from the biodiesel and ethanol in the blend also contributes to improved combustion and better fuel economy. A plateau region for fuel consumption between 118 g/km and 122 g/km is evident for most of the binary blends between diesel and biodiesel as well as ternary blends with $x_E \geq 3\%$. High concentrations of ethanol in binary blends between diesel and ethanol ($x_E \geq 7\%$) and in ternary blends with the percentage ethanol in the blend being higher than 15%, results in fuel consumption of more than 126 g/km. The increase in fuel consumption when ethanol is increased in the blend has also been reported in other literature [34]. An increased concentration of ethanol in the blend reduces the energy content of the blend, which causes fuel consumption of the engine to rise. This is also true for binary blends between diesel and biodiesel with biodiesel content higher than 10 %. The biodiesel has a lower heating value compared to diesel and as the content of biodiesel increases in the fuel blend, so does the fuel consumption [11, 41, 43]. The increase in fuel consumption was minimal for concentrations of $x_B \leq 0.1$, but became significant for higher concentrations of biodiesel in the fuel blend. The plato region for ternary blends in Figure 12 is also reported in other literature [20] where small percentages of ethanol in the ternary blend does not contribute significantly to the fuel consumption increase. With higher concentrations of ethanol in the ternary blend, the fuel consumption increases significantly [16].

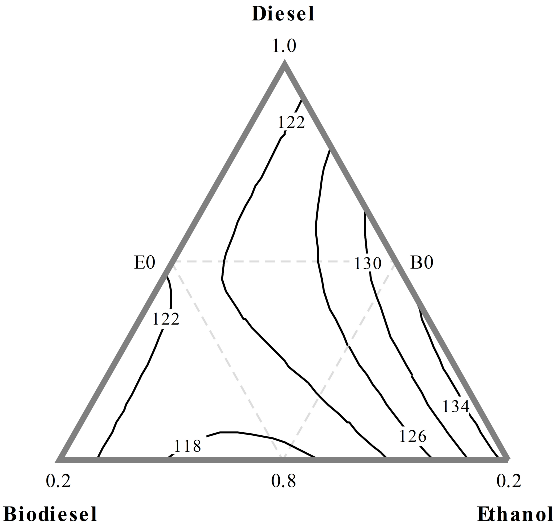


Figure 12: Contour plot of the engine response over the WLTP for fuel consumption in grams per kilometer.

3.5. Mixture optimisation

As there is more than one response to be optimised, it is necessary to set requirements for each response, that the optimisation tool will optimise towards. The desirability approach was used to determine if the optimisation was able to meet the requirements. For each response, an upper and lower value is required. If the response needs to be minimised by the optimisation tool, the lower limit is given as the target to optimise towards. The lowest and highest values of each response from the tests conducted (Table 6) where taken and set as limits for the optimisation tool. All lower and upper limits used by the optimisation tool can be seen in Table 8. Figure 13 shows the desirability plot when optimising towards a reduction in all engine emission responses. The plotted lines are known as the prediction lines of the independent variables. The vertical solid lines for each variable is the current factor setting. By changing the vertical solid line for each independent variable, the horizontal dashed lines were updated by re-computing the predicted response at the new factor setting. The horizontal dashed lines show the final predicted response according to the factor

Response	Lower limit	Upper limit
CO (g/km)	0.889	1.990
CO_2 (g/km)	232	258
NO_x (g/km)	1.04	1.15
Fuel consumption (g/km)	116	136

Table 8: Optimisation lower and upper limits.

settings. The optimisation gives a blend of E11 with the highest desirability percentage of 100 %.

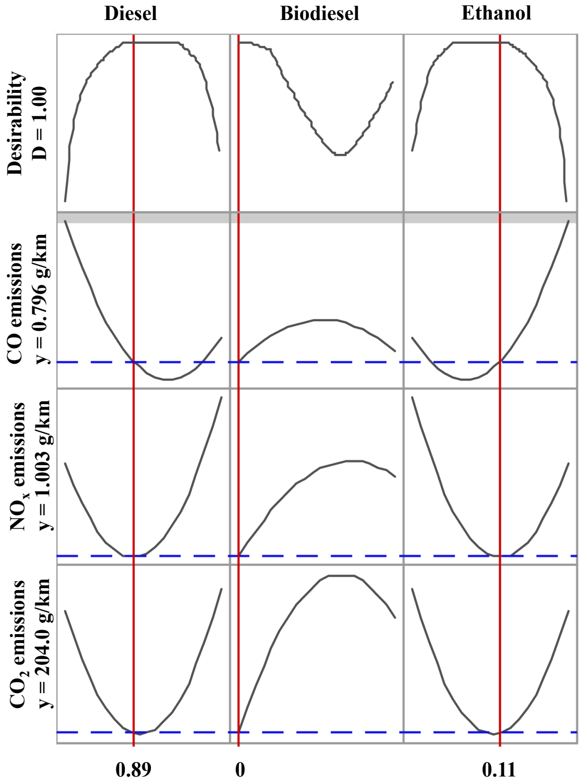


Figure 13: Optimisation plot for engine emissions for the fuel blend E11.

The 100 % desirability factor is achieved as all the responses are below the target values set out during optimisation. The comparisons between engine emissions for diesel and the engine emissions if the engine would run on a E11 blend is an approximate reduction in CO emissions of 41 %, a reduction in NO_x emissions of 12 % and a reduction in CO_2 emissions of 26 %. The E11 fuel blend, when composed of bioethanol, achieves the EU's renewable content in fuel target, but as mentioned in 2.4, blends between ethanol and diesel for percentages of ethanol higher than 10 % cannot be used in countries where ambient temperatures fall below −5 °C. Even though E11 does decrease engine emissions significantly, it will be impractical to use in European countries, due to the instability of the mixture. Another blend of B2E9 also achieved a desirability percentage of 100 % when all responses were minimised. The B2E9 fuel blend achieved engine emission responses below the targets given during the optimisation process, which resulted in the same desirability factor as E11. The comparisons between engine emissions for diesel and the engine emissions if the engine would run on a B2E9 blend is an approximate reduction in CO emissions of 34 %, a reduction in NO_x emissions of 10 % and a reduction in CO_2 emissions of 21 %. Table 9 shows the differences in emissions for the different blends compared to diesel with 5 % biodiesel in the fuel blend, that is available at most fuel pumps [44]. The addition of 2 % of biodiesel to the fuel blend improves the stability of the fuel blend with 9 % of ethanol in the fuel. B2E9 also surpasses the EU's target of 10 % renewable content in fuel as well as achieves significant reductions in engine emissions. The high content of ethanol in the blend does impact fuel consumption in a negative way, which can influence its uptake in the commercial market.

Engine Response	E11	B2E9
CO	-41 %	-34 %
NO_x	-12 %	-10 %
CO_2	-26 %	-21 %
Fuel consumption	11 %	8 %

Table 9: Comparisons of engine response for E11 and B2E9 blends compared to pump diesel.

4. Conclusion

This study investigated the effect of fuel blends between diesel, biodiesel and ethanol on the emission characteristics of a diesel engine tested over the World Harmonised Light vehicle Test Procedure (WLTP). Based on a mixture DoE, 7 different fuel blends between diesel, biodiesel and ethanol were formulated and 14 randomised runs were designed, including one replicate of each test. The main conclusions are:

1. An optimised ternary blend of B2E9 can be used as a 'drop in' fuel that will reduce harmful emissions, compared to 100 % pump diesel, of CO emissions by approximately 34 %, NO_x emissions by 10 % and CO_2 emissions by 21 % over the WLTP drive cycle.
2. This work demonstrated that the mixture DoE is a useful tool to quantify the effects of fuel blends between diesel, biodiesel and ethanol on the engine's emissions response when tested over the WLTP.
3. The addition of ethanol to the fuel blend can reduce CO emissions, but higher concentrations of ethanol in the blend can reduce the cetane number of the fuel blend, which negatively impacts combustion and increases CO emissions.
4. The addition of higher concentrations of biodiesel of more than 15 % to the fuel blend will also reduce CO emissions. Lower concentrations of biodiesel have a smaller effect on CO emissions at low engine loads and can even increase CO emissions as a result of biodiesel's poor atomisation properties.
5. Engine CO_2 emissions are reduced with the addition of ethanol to the fuel blend. The low hydrocarbon atomic ratio of ethanol results in a reduced carbon content per unit energy of the fuel which reduces CO_2 emissions. The high oxygen content in ethanol also contributes to better combustion, which increases CO_2 emissions, yet it is offset by the smaller amount of carbon atoms available for combustion in ethanol. The higher oxygen content in biodiesel also promotes complete combustion which results in an increase of CO_2 emissions for blends that include biodiesel.

6. The increase in NO_x emissions for blends with biodiesel is a result of increased combustion temperatures due to the higher oxygen content in biodiesel. The increase is also associated by the advancement of the injection timing, caused by the higher bulk modulus of compressibility of biodiesel. The decrease in NO_x emissions for blends with ethanol is contributed to ethanol's high latent heat of evaporation which decreases the combustion temperature as well as NO_x formation.
7. An increased concentration of ethanol in the blend reduces the energy content of the blend, which causes fuel consumption of the engine to rise. This is also true for binary blends between diesel and biodiesel.

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Declarations of interest

None

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