

A holistic evaluation of the impact of UK renewable strategy on emissions from compression ignition engines.

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Abstract

Reduction in fossil fuels, contributing to greenhouse gases, and improvement of air quality from vehicle emissions is of growing concern worldwide. This has led to the introduction of several binding and non-binding agreements, such as the Renewable Energy Directive to increase the renewable content of fuel for transportation, the carbon dioxide emissions standards to limit the amount of carbon dioxide emissions from vehicles and the Euro Standards to limit the amount of emissions harmful to human health in the exhaust. However, the influence of the fuel composition on hazardous exhaust emissions is a complex, and often contradictory, relationship between factors such as the fuel properties, combustion characteristics and engine load. Therefore policy implemented to improve one aspect, such as a reduction in carbon dioxide, can have a detrimental effect on another such as increased NO_x emissions.

This paper analyses, in a holistic manner, the impact on carbon dioxide and harmful emissions from transient compression ignition engines when increasing the renewable content of the fuel to meet the renewable energy targets. The analysis is based on a model developed from a rigorous Design of Experiment methodology used to determine the complex relationship between renewable fuel content and exhaust emissions (carbon monoxide, carbon dioxide and nitrogen oxides). Unlike other studies, the results were collected from a transient engine cycle, the World Harmonised Light vehicle Test Procedure, rather than steady state conditions, thus the results are more applicable to the real world.

The results generally show that as the amount of ethanol is increased then the NO_x and CO emissions decrease compared to current pump diesel. Increasing the biodiesel content

generally increases the CO and CO₂ emissions from the engine. For practical reasons a ternary blend is required to minimise the diesel engine emissions whilst meeting the UK's future renewable content target. A blend of B2.4E10 was found to be the optimum compromise between renewable content and engine emissions. However, for this to be achieved the UK will have to invest in second and third generation ethanol.

Keywords: biodiesel, ethanol, emissions, NO_x, CO₂

1. Introduction

Transportation is a significant source of greenhouse gases and harmful emissions. Consequently to address this a range of legislation is in place aimed at reducing carbon dioxide CO₂ emissions, reducing harmful emissions and increasing renewable content. Each of these will be discussed in turn. Passenger cars account for around 12 % of CO₂ emitted in the European Union (EU) [1]. EU regulation 333/2014 [2] limits the carbon dioxide fleet average emissions from passenger vehicles. Currently the target emissions level for cars sold in the EU is 130 g/km. However, this will be reduced to 95 g/km by 2020 [2]. The CO₂ limit effectively places a fuel consumption constraint on the vehicle. Manufacturers are fined an 'excess emissions premium' for each car registered that exceeds the target [3].

In addition to greenhouse gases, the exhaust contains harmful emissions such as nitrogen oxides (NO_x) and carbon monoxide (CO) which are harmful to both the environment and human health. Emissions of nitrogen dioxide alone cause an equivalent of over 23,000 deaths per year [4] and cost the UK £2.7 billion through the impact on productivity [5]. Additional regulations have been introduced to limit the emission of harmful gases. The European emission (Euro) standards state the acceptable limits for exhaust emissions for all new vehicles to be sold in the EU, currently Euro 6d [6]. Table 1 states the permissible emissions for passenger vehicles with at least four wheels (Category M). The regulation was updated to include the measurement of particulate matter by number as well as by mass

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20 [7]. Consequently, in order to curb on-road emissions a number of, sometimes contradictory, legislations have been implemented.

Table 1: Summary of Euro 6 permitted emissions for passenger cars (Category M) [6].

Emissions	Diesel	Gasoline
Carbon Monoxide (g/km)	0.50	1.00
Total Hydrocarbons (g/km)	-	0.10
Nitrogen Oxides (g/km)	0.08	0.06
Particulate Matter (g/km)	0.005	
Particulate Number (# /km)	6×10^{11}	

To reduce the impact of fossil fuel CO₂ emissions, increase energy security and strengthen its competitiveness the EU has introduced further targets. These targets can be summarised as follows [8]:

25 20 % reduction in EU greenhouse gases 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. The UK has a target of 15 % [8]. 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 [8].

35 The UK government hopes to reach its 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 [9].

A regulation [10] published in April 2018 by the Department for Transport stated that the Renewable Transport Fuel Obligation biofuel targets are to increase from the current
40 value of 4.75 %, to 9.75 % in 2020 and 12.4 % in 2032. In addition to the total biofuel targets, additional targets and caps have been introduced to ensure a sustainable supply of the biofuel. Advanced waste derived renewable fuels have a target of 2.8 % by 2032 whilst the biofuels from crops must reduce to 2 % by 2032 to ensure that the supply of crops for consumption is not compromised.

45 So far the state of play concerning targets and legislation governing the emissions from transportation and the renewable content of fuel has been presented. The rest of this section will summarise the complex relationships between the renewable fuel blends, engine loads and the impact on emissions.

Biofuels, which include biodiesel and ethanol, are a renewable source of energy in the
50 transport industry [11–13]. 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 [12]. 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 (e.g. B20E2, B40E5, etc.)

55 Table 2 shows a summary of the effects of binary blends of diesel and biodiesel and diesel and ethanol and their effects on harmful emissions, for different loads, based on the steady state studies in the literature. The metric used for engine load is the Brake Mean Effective Pressure (BMEP) since this allows comparison across engines with different displacements. Part load represents BMEP values between 0 bar and 6 bar and full load represents BMEP
60 values greater than 6 bar. Additionally, a '+' represents a minor increase and '-' represents a minor decrease (a minor change is defined as ≤ 5 %). The 'o' represents an insignificant change (≤ 1 %) and double '++' and '--' represent a significant change (≥ 5 %). The 'N/A' label indicate that for the considered literature, the specific engine emission was not considered. From Table 2 it is evident that the benefits of using renewable fuels to reduce
65 harmful emissions are dependent on the fuel blend composition as well as on engine operation. For example, generally, the amount of carbon monoxide and hydrocarbons increase

at part load but reduce at full load for ethanol mixtures. The impact of engine load on emissions is significant, since in real world driving the engine load is varied transiently (with regards to time) throughout the journey and not kept constant as per the tests in Table 2.

Table 2: Summary of effects of binary blends on harmful emissions [11, 14–18].

Harmful emissions	Biodiesel		Ethanol	
	Part load	Full load	Part load	Full load
NO _x	-	-	-	-
CO	o	--	++	--
HC	-	-	++	-
CO ₂	N/A	+	-	-
PM	-	--	--	--

70 Therefore, ternary blends of biodiesel, ethanol and diesel are being investigated to help mitigate the increase of some harmful emissions for some of the binary blends. However, the chemistry of combustion becomes even more complex with ternary blends compared to binary blends with transient engine loads and speeds, as shown in Table 3. Table 3 presents a summary of steady state studies of the impact of ternary blends on exhaust emissions.

75 It is clear from Table 3, by examining each pollutant in turn that the interaction between the pollutant and the many variables is complex. With such complex interactions between engine conditions and ternary fuel blends on the emissions, results from studies based on steady state conditions have limited value and cannot be easily translated to the real world, where the engine speed and load is varied based on driver behaviour and the local environ-
80 ment.

To try and understand how the biofuel composition is likely to impact the emissions in the real world, transient behaviour needs to be considered. Figure 1 shows the World Harmonised Light vehicle Test Procedure (WLTP) that is used, as the standard test, to ensure that new vehicles are compliant with the legislation, e.g. the Euro standards. Total test time
85 of the WLTP is 1477 seconds with an average velocity (stops excluded) of 26 km/h in the low phase, 44 km/h in the medium phase and 57 km/h in the high phase. Figure 2 compares

the variation of engine load with engine speed for the steady state engine points cited in the literature in this paper and the current transient drive cycle (WLTP) implemented on the engine used in this study. Figure 2 shows that, despite the wide range of steady state tests
 90 it does not cover the whole range of engine loads and speeds experienced in the real world as defined by the WLTP, in particular engine speeds over 2500 rpm and under 1500 rpm have not been extensively covered. Consequently, it is clear that real world driving behaviour as well as the effect of ternary blends on real world exhaust emissions cannot be accurately translated from steady-state emission tests.

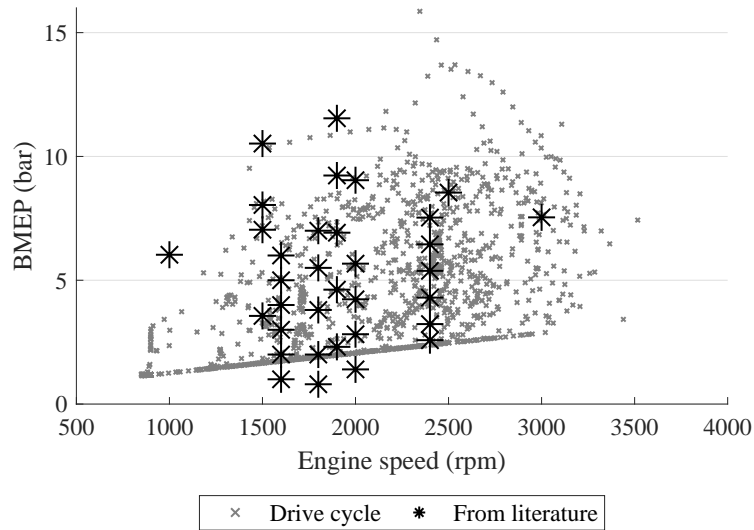


Figure 2: Comparison of engine operating points as discussed in literature compared to the operating points in the WLTP drive cycle.

95 The aim of this paper is to address these shortcomings and provide a holistic view of the complex relationship between UK policy, biofuel composition, transient engine loads and engine emissions and propose an optimal mixture suitable for compression engines, using results in previous research [22].

2. Methodology

2.1. Experimental set-up

A 2.4 L Euro 4 compression ignition (CI) engine with a programmable after-market ECU was used as the test engine to collect the data. Although the research in this paper was conducted on a Euro 4 engine, which was manufactured in 2008, this research is still highly relevant to the current UK fleet. According to the Department for Transport's statistics [23] approximately 14 % of the current diesel fleet is of this engine type. Additionally the conclusions for this paper are qualitatively relevant to more modern Euro 5 and Euro 6 diesel engines [24–27]. Figure 3 shows a schematic of the CI engine testing facility that was used for studying the engine emissions. The engine, whose specifications are listed in Table 4, was connected to a Froude FO271 dynamometer which is capable to absorbing a maximum of a 1000 kW and 4000 Nm. Two gas analysers were used; one (NOVA 7466K) for measuring CO₂ 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 5. The factory fitted mass airflow sensor (part number 6C11-12B579-AA), calibrated with a Superflow SF-120 flow bench, was used to measure the intake mass air flow in kg/s.

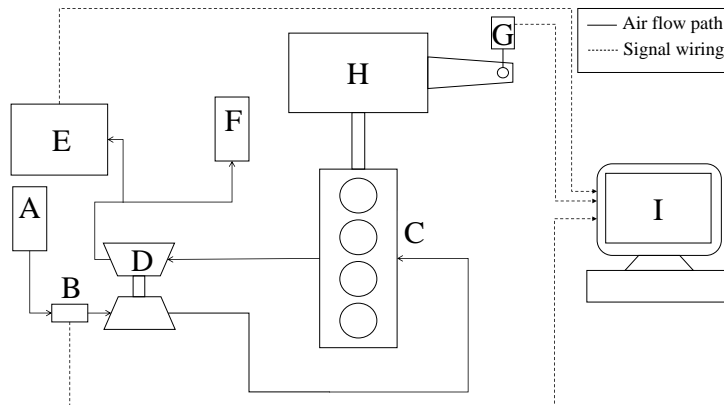


Figure 3: Layout of the engine test cell together with measuring equipment; A: air filter; B: Mass airflow sensor; C: engine; D: Turbo charger; E: gas analyser; F: exhaust outlet; G: load cell; H: dynamometer; I: Data Acquisition System.

Table 4: Engine parameters used for experimentation.

Engine parameter	Characteristics
Engine code	H9FB (Ford Transit)
Rated power (kW)	103
Rated Torque (Nm)	375
Bore (mm)	89.9
Stroke (mm)	94.6
Volume (cm ³)	2402
Compression ratio (CR)	17.5
Number of cylinders	4
Method of cooling	Water cooled (21 °C, $\sigma = 3$)

Table 5: Method and accuracy of the instruments used to measure the engine emissions.

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 6: Main fuel properties of neat test fuels.

	Diesel	Biodiesel	Ethanol
Cetane number	51.7	52.8	7.0
LHV (MJ/kg)	42.8	38.0	26.8
Density at 15 °C (kg/m ³)	831.1	883.2	790.0
Viscosity at 40 °C (mm ³ /s)	2.686	4.372	1.200
Oxygen content (%)	0	10.8	34.8
CFPP (°C)	-26	-6	-38
Flash point (°C)	65	179	40

2.2. Experimental Procedure

A mixture Design of Experiment (DoE) approach was adopted to explore the individual effects of diesel, biodiesel and ethanol and their interactions in a blend for different engine responses. The test fuels used in the DoE were B0 reference diesel, rapeseed methyl ester biodiesel (RME) and ethanol. B0 diesel was chosen as a reference fuel and benchmarked throughout the DoE. As pump diesel has biodiesel present in the fuel blend, it is necessary to use B0 diesel to make it possible to accurately control the percentage of biodiesel present in the blends used during testing. The fuel supplier provided physiochemical properties for the diesel fuel, RME and ethanol, respectively. The fuel properties of each fuel can be seen in Table 6. DoE is an established statistical tool that is used to identify the underlying complex relationships between variables whilst minimising the number of experiments necessary. The selection of the mixture DoE is appropriate as the sum of the input variables, in this case the blend components, must be unity [28]. A summary of the procedure is presented here. 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

$$0 \leq x_i \leq 1 \quad i = 1, 2, \dots, p \quad (1)$$

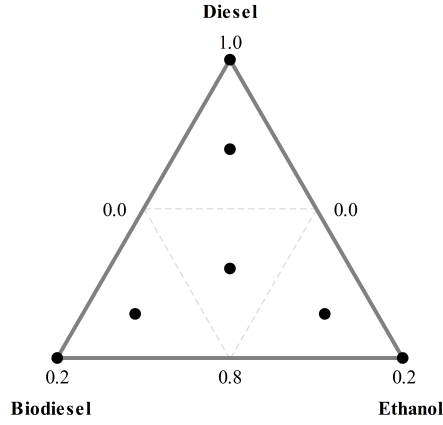


Figure 4: Extreme vertices simplex design plot of the mixture DoE.

and

$$x_1 + x_2 + \dots + x_p = 1 \quad (2)$$

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 4 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 [19, 29] where the maximum addition without engine modification was determined:

$$x_D + x_B + x_E = 1 \quad x_B, x_E \leq 0.2 \quad (3)$$

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. The whole mixture design was replicated once and the runs were randomised to ensure experimental errors are independently distributed. The optimisation of the fuel blend is dependent on more than one engine response which include CO emissions, CO₂ emissions and NO_x emissions. 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. For minimising engine emissions the desirability of each of the responses was calculated using [30]:

$$d_i(\hat{Y}_i) = \begin{cases} 1 & \text{if } \hat{Y}_i(x) < T_i \\ \frac{\hat{Y}_i(x) - U_i}{T_i - U_i} & \text{if } T_i \leq \hat{Y}_i(x) \leq U_i \\ 0 & \text{if } \hat{Y}_i \geq U_i \end{cases} \quad (4)$$

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 $\hat{Y}_i(x)$. The individual desirability functions are combined using the geometric mean, which gives the overall desirability:

$$D = (d_1(Y_1)d_2(Y_2))^{0.5} \quad (5)$$

The different blends of diesel, biodiesel and ethanol fuel were mixed in batches of 5l in the determined blend ratios based on the mixture DoE. The blend components of diesel, biodiesel and ethanol 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. In order to ensure that 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 determined that the engine fuel system needed to be flushed four times to successfully remove all remaining fuel blend from the previous test before the next test was conducted.

3. Results and Discussion

It is important to state from the outset of the discussion that the following analysis prioritised emissions reduction and meeting the renewable content target. Some argument could be made to accept a compromise on the engine emissions over renewable content, since exhaust after treatment systems are required to meet the Euro standards anyhow. However, it is commonly accepted that reducing the emissions at source (in the engine) has a knock-on positive effect on the whole vehicle. Since initial emissions reduction will result in a lighter, smaller and cheaper exhaust after treatment system [31].

It should be reiterated here that all the results discussed have been collected based on the
 135 transient WLTP drive cycle unlike previous steady state studies or transient studies on the
 now obsolete New European Driving Cycle (NEDC). Equations used to generate Figure 5
 and Figure 6 were obtained from previous research [22].

As discussed previously the addition of ethanol to diesel has a positive impact on the
 harmful emissions. Figure 5 shows the variation of CO₂, NO_x and CO with increasing
 140 amounts of ethanol in diesel. The use of binary blends of ethanol between E5 and E15 result
 in CO emissions being reduced by approximately 36 %, NO_x emissions by approximately
 11 % and CO₂ emissions by approximately 19 %. For blends greater than E15 the emissions
 tend to increase rapidly compared to pure diesel. The reduction of CO emissions, CO₂
 emissions and NO_x emissions for binary blends between E5 and E15 can assist the UK in
 145 reducing harmful emissions in CI engines as well as achieve the renewable fuel target for
 2032 of 12.4 % [10]. Therefore, assuming that the renewable biofuel content is fulfilled by

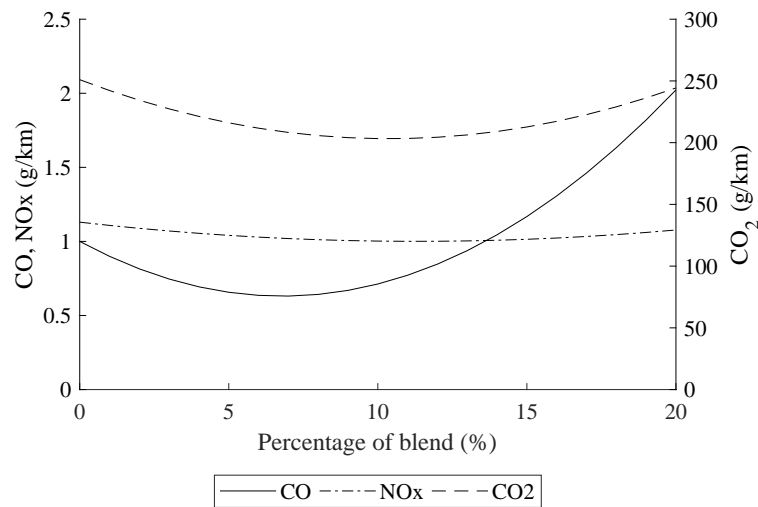


Figure 5: Variation of CO₂, NO_x and CO with increasing amounts of ethanol in diesel

ethanol alone compared to pump diesel a binary blend of E12.4 would result in a decrease
 of CO₂, NO_x and CO of 26 %, 12 % and 33 % respectively. Note the comparison has been
 made with pump diesel, which we have assumed to have a 5 % biodiesel content [32], rather
 150 than pure diesel. The reason for this is that it is now not possible to purchase pure diesel
 from a filling station in the UK, and so the comparison should be made with the fuel that

is currently available [32].

The addition of ethanol seems positive in terms of both reducing the harmful emissions from vehicles whilst simultaneously increasing the renewable content of the fuel in line with EU targets. However, there are a number of practical issues that nullify these advantages. Firstly when considering alternative fuels for vehicles, the carbon dioxide emissions from the vehicle should not be considered in isolation. All the carbon dioxide emissions along the supply chain need to be considered [33].

Table 7 shows the equivalent carbon dioxide emissions upstream of the vehicle and are often referred to the '*Well-To-Tank*' (WTT) emissions. These WTT emissions include everything upstream such as extraction, refining, purification, transportation, etc. The term '*equivalent*' refers to processes where there is a Greenhouse Warming Potential and these are then expressed as the equivalent grams of carbon dioxide. The data in Table 7

Table 7: Comparison of equivalent carbon dioxide Well-To-Tank emissions for diesel and renewable fuels. [34]

Fuel	gCO ₂ e/Litre	Percentage change
Pump Diesel	618.46	—
Ethanol	613.77	−1 %
Biodiesel (RTFO average)	312.95	−49 %

shows that the equivalent carbon dioxide emissions for pump diesel are similar compared to ethanol. This means that the net carbon dioxide saving of using ethanol comes from the displaced diesel fuel in the tank and the emissions saving from the combustion process, but there are not any upstream savings.

However, a more pressing technical barrier for a binary mixture of ethanol and diesel is that ethanol is immiscible in diesel. Therefore additives (emulsifiers) are required to improve the miscibility of the ethanol in the diesel [35, 36]. Biodiesel can act as an emulsifier for ethanol.

The addition of biodiesel also has the added benefit that it has a much lower WTT

carbon dioxide emissions compared to ethanol (Table 7). Based on current figures the WTT carbon dioxide emissions are around half that of regular pump diesel and ethanol.

175 Consequently, based on the reduced WTT carbon dioxide emissions it would be best to meet the renewable targets with biodiesel alone. However, the addition of biodiesel tends to increase emissions. Figure 6 shows the variation of CO₂, NO_x and CO with increasing amounts of biodiesel in diesel. Figure 6 shows that for biodiesel blends between B5 and B15 the CO and CO₂ emissions are at a maximum. If the renewable fuel target of 12.4 % is
180 fulfilled with biodiesel, then compared to pump diesel, this would result in an increase of CO and CO₂ of 3.3 % and 1.4 % respectively, whilst a decrease in NO_x of 1.7 %.

The changes are modest compared to pump diesel. The reason for this modest increase is because the comparison is with pump diesel, which already has a biodiesel content. There

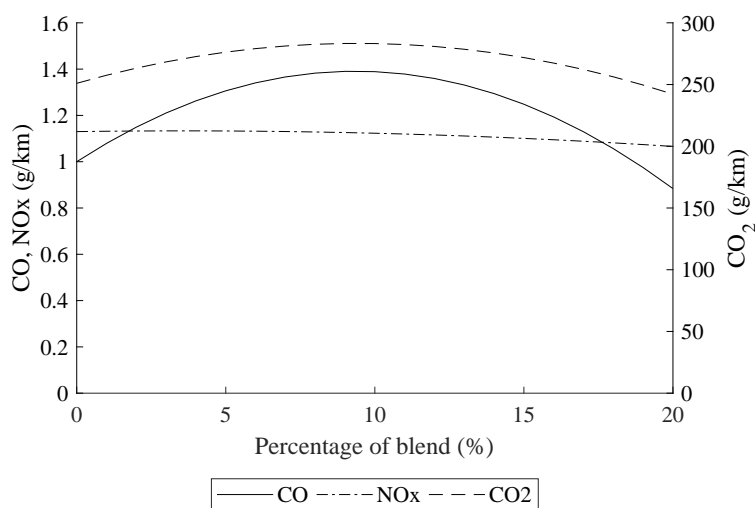


Figure 6: Variation of CO₂, NO_x and CO with increasing amounts of biodiesel in diesel

is an argument that, when considering how best to meet the future renewable targets, the
185 *well-to-wheel* (WTW) CO₂ emissions need to be considered. The WTW emissions consider the carbon dioxide emissions generated from all the upstream processes and the emissions from the vehicle itself.

To address the conflicting requirements of increasing the WTW CO₂ emissions, additional exhaust harmful emissions and practical miscibility aspects of the fuel a ternary blend of
190 diesel, biodiesel and ethanol is required. The proposed criteria for the fuel is:

A renewable biofuel content of 12.4 % to meet the 2032 UK target.

Minimise the well-to-wheels CO₂ emissions.

Minimise the harmful emissions of carbon monoxide and nitrogen oxides.

A homogeneous mixture that will not separate.

195 To minimise the WTW CO₂ emissions the maximum amount of biodiesel is required. To
minimise the harmful emissions the maximum amount of ethanol is required. Based on
previous experience the minimum amount of biodiesel to form a homogeneous mixture of
ethanol, biodiesel and diesel is 2 %. A previous mixture of B2E11 resulted in a stable blend
[22]. Other research has also found ternary blends of B10E20 to be stable [26]. Therefore a
200 mixture of B2.4E10 is proposed. This mixture satisfies the criteria in that:

it meets the 12.4 % biofuel requirement,

reduces the WTW emissions,

has a maximum ethanol content to reduce CO and NO_x emissions.

has a minimum biodiesel content of 2 % to maintain a stable mixture.

205 The predicted reduction in emissions for CO₂, NO_x and CO are 20 %, 9.6 % and 28 %.
Table 8 compares the changes in emissions for each mixture compared to pump diesel.

The proposed optimum mixture requires a 10 % content of ethanol. Therefore, if the
recommended blend were to be adopted, this would potentially impact on the UK food
industry. The UK needs to invest in second and third generation ethanol feed stocks (non-
210 edible organic matter and algae lipids) and move away from first generation feed stocks by
2032. The EU requires member states to cap feed stocks from edible sources by 2032 to
≤ 2 %. Currently 100 % of the UK ethanol is first generation.

Table 8: Summary of results showing the change in emissions compared to pump diesel

Fuel Blend	CO ₂	NO _x	CO
E12.4	-26 %	-12 %	-33 %
B12.4	1.4 %	-1.7 %	3.3 %
B2.4E10	-20 %	-9.6 %	-28 %

4. Conclusion

This paper took a holistic view to analyse the complex and contradictory relationship between UK policy, biofuel composition, transient engine loads and engine emissions. The main conclusions are:

1. The optimum mixture to meet the UK biofuel content of 12.4 % in 2032, whilst minimising carbon dioxide and harmful exhaust emissions is B2.4E10.
2. Steady state engine emission tests have limited value, compared to the real world, based on the complex relationship between engine composition and engine loads.
3. From a carbon dioxide viewpoint a binary mixture of B12.4 would be best, due to the low well-to-tank emissions of biodiesel. However, increasing the biofuel content in the range B5 to B15 maximises the harmful exhaust emissions.
4. From a harmful emissions viewpoint a binary mixture of E12.4 would be best, due to the minimisation of carbon monoxide and nitrogen oxides in the range of E5 to E15. However, ethanol is immiscible in diesel and for practical reasons biodiesel needs to be added as an emulsifier.
5. To achieve the optimum mixture, investment into second and third generation ethanol is required.

5. Future work

Future work will investigate the effect of engine emissions that did not form part of this research's scope (soot, HC and PM/PN) when the optimum blend of B2.4E10 is used. The

desired outcome will conform with future EU and UK renewable targets for 2030 and beyond.

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Declaration of interest

None

References

240 References

- [1] European Union, Reducing CO₂ emissions from passenger cars, 2018.
- [2] European Union, Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO₂ emissions from new passenger cars. [online], 2014.
- 245 [3] European Union, Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO₂ emissions from light-duty vehicles. [online], OJ L 140, 5.6.2009, p.1, 2009.
- [4] P. H. England, Air quality: A briefing for directors of public health, 2017.
- 250 [5] R. Martinez-Botas, Vehicle emissions testing programme, 2016.
- [6] European Union, Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information (Text with EEA relevance). [online], 2007.
- 255 [7] European Union, Commission Regulation (EU) No 459/2012 of 29 May 2012 amending Regulation (EC) No 715/2007 of the European Parliament and of the Council and Commission Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) Text with EEA relevance. [online], 2012.
- [8] European Union, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 260 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. [online], OJ L 140, 5.6.2009, p. 16–62, 2009.

- [9] Department for Business, Energy & Industrial Strategy, Digest of UK Energy Statistics (DUKES): renewable sources of energy, Office of National Statistics, 2017.
- [10] Department for Transport, Renewable Transport Fuel Obligation (RTFO) order. [online], 2018.
- 265 [11] M. Mofijur, M. G. Rasul, J. Hyde, A. K. Azad, R. Mamat, M. M. K. Bhuiya, Role of biofuel and their binary (diesel–biodiesel) and ternary (ethanol–biodiesel–diesel) blends on internal combustion engines emission reduction, *Renewable and Sustainable Energy Reviews* 53 (2016) 265–278.
- [12] M. Tuner, Review and Benchmarking of Alternative Fuels in Conventional and Advanced Engine Concepts with Emphasis on Efficiency, CO₂, and Regulated Emissions, Technical Report, SAE Technical Paper, 2016. doi:doi.org/10.4271/2016-01-0882.
- 270 [13] M. L. N. Carneiro, F. Pradelle, S. L. Braga, M. S. P. Gomes, A. R. F. Martins, F. Turkovics, R. N. Pradelle, Potential of biofuels from algae: Comparison with fossil fuels, ethanol and biodiesel in europe and brazil through life cycle assessment (lca), *Renewable and Sustainable Energy Reviews* 73 (2017) 632–653.
- 275 [14] N. Yilmaz, F. M. Vigil, A. B. Donaldson, T. Darabseh, Investigation of CI engine emissions in biodiesel–ethanol–diesel blends as a function of ethanol concentration, *Fuel* 115 (2014) 790–793.
- [15] S. M. Palash, H. H. Masjuki, M. A. Kalam, A. E. Atabani, I. M. R. Fattah, A. Sanjid, Biodiesel production, characterization, diesel engine performance, and emission characteristics of methyl esters from aphanamixis polystachya oil of bangladesh, *Energy Conversion and Management* 91 (2015) 149–157.
- 280 [16] J. Xue, T. E. Grift, A. C. Hansen, Effect of biodiesel on engine performances and emissions, *Renewable and Sustainable Energy Reviews* 15 (2011) 1098–1116.
- [17] T. Prakash, V. E. Geo, L. J. Martin, B. Nagalingam, Effect of ternary blends of bio-ethanol, diesel and castor oil on performance, emission and combustion in a ci engine, *Renewable energy* 122 (2018) 301–309.
- 285 [18] H. Srikanth, J. Venkatesh, S. Godiganur, B. Manne, S. Bharath Kumar, S. Spurthy, Combustion, performance, and emission characteristics of dairy-washed milk scum biodiesel in a dual cylinder compression ignition engine, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2019) 1–18.
- 290 [19] D. B. Hulwan, S. V. Joshi, Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content, *Applied Energy* 88 (2011) 5042–5055.
- [20] L. Zhu, C. S. Cheung, W. G. Zhang, Z. Huang, Combustion, performance and emission characteristics of a DI diesel engine fueled with ethanol–biodiesel blends, *Fuel* 90 (2011) 1743–1750.
- 295 [21] G. Khoobakht, G. Najafi, M. Karimi, A. Akram, Optimization of operating factors and blended levels

of diesel, biodiesel and ethanol fuels to minimize exhaust emissions of diesel engine using response surface methodology, *Applied Thermal Engineering* 99 (2016) 1006–1017.

- [22] A. van Niekerk, B. Drew, N. Larsen, P. Kay, Influence of blends of diesel and renewable fuels on compression ignition engine emissions over transient engine conditions, *Applied Energy* 255 (2019) 113890.
- [23] Department for Transport, Statistical data set Cars (VEH02). [online], 2018.
- [24] M. Lopes, L. Serrano, I. Ribeiro, P. Cascão, N. Pires, S. Rafael, L. Tarelho, A. Monteiro, T. Nunes, M. Evtuygina, et al., Emissions characterization from euro 5 diesel/biodiesel passenger car operating under the new european driving cycle, *Atmospheric environment* 84 (2014) 339–348.
- [25] L. Serrano, M. Lopes, N. Pires, I. Ribeiro, P. Cascão, L. Tarelho, A. Monteiro, O. Nielsen, M. G. da Silva, C. Borrego, Evaluation on effects of using low biodiesel blends in a euro 5 passenger vehicle equipped with a common-rail diesel engine, *Applied Energy* 146 (2015) 230–238.
- [26] C. Beatrice, P. Napolitano, C. Guido, Injection parameter optimization by doe of a light-duty diesel engine fed by bio-ethanol/rme/diesel blend, *Applied Energy* 113 (2014) 373–384.
- [27] R. Suarez-Bertoa, M. Kousoulidou, M. Clairotte, B. Giechaskiel, J. Nuottimäki, T. Sarjovaara, L. Lonza, Impact of hvo blends on modern diesel passenger cars emissions during real world operation, *Fuel* 235 (2019) 1427–1435.
- [28] J. A. Cornell, *Experiments with mixtures: designs, models, and the analysis of mixture data*, volume 403, John Wiley & Sons, 2011.
- [29] S. Lahane, K. Subramanian, Effect of different percentages of biodiesel–diesel blends on injection, spray, combustion, performance, and emission characteristics of a diesel engine, *Fuel* 139 (2015) 537–545.
- [30] NIST/SEMATECH, *e-Handbook of Statistical Methods*, 2013.
- [31] S. Dev, H. B. Chaudhari, S. Gothekar, S. Juttu, N. H. Walke, N. V. Marathe, Review on advanced low temperature combustion approach for BS VI, Technical Report, SAE Technical Paper, 2017.
- [32] The Renewable Transport Fuel Obligations Order, 2007. SI 2007/3072.
- [33] Department for Transport, New regulations to double the use of sustainable renewable fuels by 2020. [online], 2018.
- [34] Department of Business, Energy & Industrial Startegy, Greenhouse gas reporting: conversion factors 2018. [online], 2018.
- [35] M. Lapuerta, O. Armas, R. Garcia-Contreras, Stability of diesel–bioethanol blends for use in diesel engines, *Fuel* 86 (2007) 1351–1357.
- [36] P. Kwanchareon, A. Luengnaruemitchai, S. Jai-In, Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine, *Fuel* 86 (2007) 1053–1061.