Emission benefits in application of alternative fuels on racing car compression ignition engines

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Abstract. The depletion of fossil fuels, and the weather-related disasters associated with climate change and greenhouse gas emissions plus the other human health and environmental hazards related to exhaust pollutant emissions demands the use of innovative approaches to reduce fossil fuel consumption. Motorsport industry should become a test-bed, and because of its advertising potential should promote the use of alternative steps to minimize fossil fuel consumption and address associated emission issues. In the short term, some improvements to current powertrain technologies and the use of alternative fuels such as biodiesel or the primary alcohols can reduce fossil fuel dependency and partly decrease their harmful effects.

In this study a framework has been developed based on the effect of the different fuel properties to assess their suitability, performance and emission characteristics of different 'short-term' fuels such as biodiesel and primary alcohols to reduce the use of fossil fuels in motorsport industry. A database is generated to permit the construction and theoretical application of the framework to the specific case of a turbocharged, four-stroke, compression ignition engine with common-rail injection system operating in medium/high temperature engine modes.

Keywords: motorsport, biofuels, performance, regulated exhaust emissions.

1. Introduction.

The increased use of fossil fuels over the last century by society in general, and by transportation sector in particular is considered to be in part responsible for the growing scarcity of the fossil fuels, some weather-related disasters are due to the greenhouse effect [1] and certain human health and environmental hazards are linked to pollutant emissions [2],[3]. Motorsport, although only a minor element of the transportation sector, does contribute to these effects and some innovative approaches to address the use of fossil fuels should be carried out and it should change from outright performance towards efficiency. There are some approaches which can also be combined to reduce fossil fuel consumption and pollutant emissions. One of the strategies is the use of more environmental friendly fuels, which is the scope of this study. Currently, the most widely use biofuels are biodiesel, fuel for use in compression ignition engines, and the primary alcohols, especially bioethanol, for use in spark ignition engines [4].

Biodiesel is methyl or ethyl ester of the fatty acids made from virgin or used vegetable oils (both edible and non-edible) and animal fat [4]. There are some issues related to the use of edible resources such as competition over arable land, competition to grow energy crops instead of growing food and a potential increase in food prices (1st generation biodiesel). For these reasons, the used of residual feedstocks such as waste cooking oil and tallow grease and/or the transformation of lignocellulosic material to liquid fuels by means of thermochemical or biological processes are being developed. There are a large number of research articles and report papers published about the production, performance and emissions of biodiesel in compression ignition engines [4],[5],[6],[7].

At full load conditions the power using biodiesel is lower than the power using conventional diesel, mainly due to the lower heating value of the biodiesel. However, other reasons sometimes are pointed out, such as the higher viscosity of biodiesel, which makes the atomization of the fuel [8] more difficult. There are studies which obtain power losses in proportion to the lower heating value of biodiesel[9] but the majority of the studies conclude that the biodiesel power loss is less than expected being a certain power recovery at full load[10] which is mainly justified by the higher biodiesel viscosity which produces a lower back flow across the piston clearance of the injection pump [7]. In the majority of the references equal efficiency for biodiesel and conventional diesel when working under the same operating conditions is claimed [6],[11].

The tank to wheel CO_2 emission of biodiesel (mass of CO_2 per unit of fuel energy) is around 4% higher than for conventional diesel. But if the well to wheel analysis is evaluated, biodiesel has an advantage compared to conventional diesel due to the CO_2 sequestered during the plants growth. In the literature there are a majority of the studies which show a slight increase in NO_x when biodiesel is used instead of conventional diesel [11],[12]. Some reasons are given to explain the increase of NO_x emissions with biodiesel. The most important factor seems to be due to an advance in injection (because of biodiesel's viscosity, density and compressibility [13],[14] and/or electronic advance) and an advance in combustion timing (because of the higher cetane number) with biodiesel compared to the conventional diesel [13]. According to the literature review, there are other factors which could also have an influence on NO_x emissions such as flame temperature and the oxygen content of biodiesel which can promote NO formation reactions. Particulate matter (PM) from biodiesel is lower than when using conventional diesel fuel [6],[13],[15]. The oxygen content of biodiesel is the most frequently reported factor to justify the decrease in PM emissions [16]. Other factor which justifies the soot and particulate matter reduction of biodiesel respect to diesel is the absence of aromatic compounds in biodiesel. The majority of the literature agrees that the unburnt hydrocarbons (UHC) [13] ,[17] and CO [9],[17],[18] emissions from biodiesel are lower than from conventional diesel fuel. One of the most important reason to explain this trend is the oxygen content of biodiesel [9],[19], this results in a more complete and cleaner combustion process. Additionally, the higher cetane rating of biodiesel compared to conventional diesel reduces the delay period and the probability of fuel-rich zones being formed. These differences can depend on engine load conditions, for example there are some studies which report that at low load conditions these reductions are smaller or even do not appear compared to conventional diesel fuel [20].

Primary alcohols can be obtained from fossil fuels or from renewable feedstocks (bioprimary alcohols). The renewable primary alcohols are usually classified as first generation when the feedstocks are edible materials and as second generation primary alcohols when the alcohol is obtained from lignocellulosic material via a fermentation process. Taking into account fuel characteristics such as high octane rating, low cetane rating, poor lubricant properties, high flame speed and volatility, then primary alcohols are most suitable for use in spark ignition engines. However, due to their significant potential to reduce soot, they are attractive for use in compression ignition engines. In the case of compression ignition engines changes to the fuel (fuel additives to improve autoignition properties, emulsification into the diesel fuel or blending) or modifications to adapt the diesel engines to use the primary alcohols are required (alcohol fumigation, duplication of the injection system, spark or glow plugs).

In compression ignition engines reductions in output power are expected working at full load condition mainly due to the lower energy density of the primary alcohols. Brake specific fuel consumption using biomethanol [21], bioethanol [22],[23] and biobutanol [24],[25] are higher than in the case of diesel. The reason is the lower energy density of biomethanol, bioethanol and biobutanol compared to conventional diesel. Fuel efficiency of biomethanol, bioethanol [22],[23] and biobutanol [24] is similar to diesel fuel, although in some works a lower efficiency with high biobutanol percentages have been reported and are linked to the reduction in combustion temperature [25].

CO_2 emissions from primary alcohols per unit mass of fuel burnt are lower compared to the fossil fuels. These reductions are around 56, 40 and 30% for methanol, ethanol and butanol, respectively. When CO_2 emissions per unit of fuel energy are compared, the benefits are decreased due to the lower specific energy content of the primary alcohols. However, if bio-matter is used to create the primary alcohols (as in the case of biodiesel) the whole life CO_2 assessment should be better than with fossil fuels. There is no clear agreement of the effect of primary alcohols on NO_x emissions [26]. There are some properties such as the oxygen content and the lower cetane number of the primary alcohols (more premixed combustion and as a consequence higher temperature peaks) which enhance NO_x formation. But the higher latent heat of vaporisation and lower flame temperature can offset those effects and reduce NO_x formation. So most of the time the effects are compensated and the final results can depend upon injection strategies, engine operating conditions, etc. There is no doubt about the reduction of particulate matter and especially smoke opacity, with the use of the primary alcohols. General smoke opacity reductions using bioethanol-diesel blends are reported in [16],[22],[23],[27],[28] and in [24] using biobutanol, independent of the powertrain technology and combustion strategy. The most common reason to justify this particulate matter reduction using bioethanol is the oxygen content of the fuel. Although, there are other reasons, which are reported such as increased premixed combustion (lower cetane rating), lower C/H ratio, fewer carbon to carbon bonds and the reduction of aromatics compounds. The reduction in particulate matter is not as evident as in the case with soot, because the volatile organic fraction of the particulate emissions can be higher when using bioethanol, especially in low temperature engine operating conditions and when significant bioethanol percentages (higher than 20-30%) are being used [29]. With primary alcohols the total hydrocarbon emissions from are usually higher than in the case of conventional diesel fuel [16],[22],[23], especially in engine operating modes with a lower combustion temperature, where hydrocarbon emissions become significant. This results in higher hydrocarbon emissions mainly due to the higher heat of vaporisation of the primary alcohols. In contrast to the heat of vaporisation effect, the higher oxygen content of the primary alcohols compared to conventional diesel fuel reduces the hydrocarbon emissions, while the lower cetane number of the primary alcohols increases these emissions [24]. The general trend is a CO reduction when using primary alcohols compared to conventional diesel fuel [24],[26]. However, and as in the case of total hydrocarbon emissions, during certain low temperature operating conditions the most important factor which influences CO emissions can be the heat of vaporisation of the primary alcohols which reduces combustion temperature and could increase the CO emissions.

2. Methodology.

A framework to join the fuels with the powertrain technologies has been developed based on the literature review previously presented in the Introduction (see Figure 1). The philosophy of this study takes its origin in that in the assessment process of the effectiveness of each fuel, the powertrain technology and combustion strategies have to be taken into account.

The matching procedures between the fuels and the powertrains are mainly based on regulated emissions, even though performance and fuel economy are also taking into account. The process starts by evaluating the fuel's suitability for each specific powertrain technology based on certain selected properties (see Table 1). In the first step, fuels which are not suitable to the specific powertrain are discarded. After that, some fuels are pre-selected and final decisions will be made also based on emissions and performance. In this first step the following properties have been selected.

- Materials Compatibility.
- Physical fuel properties to meet regulations.
- Blending miscibility and stability (when blends are used).
- Blend physical fuel properties. (when blends are used).

In terms of emissions, diesel fuel is used as the reference fuel to evaluate the increases or decreases obtained with the alternatives fuels based on the properties comparison. The chosen fuel properties are the following:

- Oxygen content.
- Heat of vaporisation.
- Bulk modulus.
- Aromatics.
- Adiabatic flame temperature.
- C/H ratio.
- Cetane rating.

In the case of the performance, the properties which are considered to be more significant to power and fuel economy have been selected.

- Cetane rating.
- Flammability limits.
- Viscosity.
- Heating value.
- Flame speed.
- Stoichiometry.
- Heat of vaporisation.

3. Case Study: results and discussion.

In this section the framework is applied to a specific case study. The selected case study is a turbocharged, common-rail direct injection compression ignition engine. The justification for applying the case study to this powertrain technology is because of the anticipated increased use of diesel engines in motorsport. This analysis is focused on high temperature engine operating condition rather than low temperature engine modes because in motorsport high load are the most common conditions.

The matching technique starts analysing the suitability of each fuel to the powertrain technology based on the properties previously mentioned (see Table 2). Considering the majority of the properties, the most suitable biofuel for compression ignition engines is biodiesel which can be used pure, without many engine modifications. Primary alcohols have low cetane rating and are deficient in lubricant properties to be used neat in compression ignition engines without engine or fuel modifications. For this reason, blending behaviour is also analysed. In the case of methanol the stability of methanol-diesel blends is really poor [30] and only low methanol percentages can be used (lower than 5%), this represents an important drawback. Bioethanol also presents stability problems, even though these are less than in the case of biomethanol. Stability problems are worse at lower temperatures and within higher blend water content [31], so the use of high purity bioethanol is highly recommended. Blends of up to 10-15% percent, bioethanol can be used, although higher percentages may be possible with the use of additives and/or added biodiesel (e-b-diesel blends) [30]. In the case of biobutanol the miscibility and stability are better than in the case of biomethanol and bioethanol, and for this reason higher percentage of biobutanol can be used [30]. The maximum quantity of biobutanol used can be limited due to lubricity and cetane rating problems rather than stability. Comparing the three primary alcohols, biomethanol is discarded and bioethanol and biobutanol are chosen to the emissions and performance analysis (see Table 2).

The performance and emissions analysis based on fuel properties are showed in Table 3 for biodiesel, in Table 4 for bioethanol and in Table 5 for biobutanol. In the case of biodiesel the evaluation is made considering 50% biodiesel blends, while in the case of primary alcohols due to the suitability concerns it is not realistic consider the same assumption and the comparison is made with a 10% of primary alcohols. The effect of each fuel property is independently analysed and a global effect is obtained compared to a conventional diesel fuel. In this specific case study, it has to be remarked that because of the use of a common-rail injection system the effect of fuel compressibility (especially in the case of biodiesel) in injection timing is less than in the case of pump-line-nozzle and, for this reason the NOx increase using biodiesel is lower than could be expected. Also, because the chosen engine mode is a high temperature operating mode a similar trend in soot and particulate emissions is obtained and the effect of the vaporisation latent heat is lower than in a low load engine mode (especially in the case of primary alcohols).

Once each fuel is independently analysed, next stage is to compare the results of the pre-selected fuels. Although, the comparison is made with 10% in the case of primary alcohols and 50% biodiesel blends (see Table 6), it is interesting to remark that using primary alcohols are expected almost similar reductions than in the case of biodiesel, especially in soot and particulate emissions, mainly due to the higher oxygen content of the primary alcohol molecule respect to biodiesel. In the case of primary alcohols reductions are similar, and the better stability performance of biobutanol-diesel blends gives more potential to this fuel being able to increase the biobutanol percentage in the blend, although for a final decision between these two blends other concerns such as production costs of second generation of bioethanol and biobutanol should be compared. The advantage of biodiesel respect to bioethanol and biobutanol is the larger biofuel percentage that can be used in compression ignition engines, and this means a higher reduction in greenhouse gas emissions and more fossil fuel replacement, apart from the pollutant emissions benefits. However, further studies in the use of biobutanol-diesel blends seem to be interesting in order to evaluate the highest biobutanol percentage which can be used and increase the emissions and replacements benefits. So, based on this analysis, it is showed that not only the potential of biodiesel in compression ignition engines should be considered but also the use of bioethanol or/and biobutanol should be taken account and not discarded in a first instance.

4. Conclusions.

The use of alternative fuels is one of the approaches which can be applied to reduce the consumption of fossil fuels and the issues associated to them. In the transportation sector some regulations have emerged aimed at a decrease in fossil fuels consumption. More recently in motorsport alternative fuels have appeared in different competitions, but not as quickly or to the extent required. Based on an analysis of the literature review about fuel properties, regulated emissions, fuel economy, power and efficiency of some of the alternative fuels a framework has been developed. This framework can be used to assess the suitability, performance and emission behaviour of different alternative fuels compared to fossil fuel, relating to the powertrain technology and the engine operating conditions. This enables to efficiently join engines and fuels with the objective of deciding which fuel is more appropriate for each form of motorsport competition, based on the powertrain used in each race category. The framework shows that the first step should be the analysis of fuel suitability followed by the evaluation of emissions and performance behaviour taking into account fuel properties. The framework is applied to a specific case study and it is shown that key properties in engine suitability are cetane rating and fuel blend stability when pure fuels are not utilized. In emission formation the most relevant properties seem to be the oxygen and aromatic content and the properties which affect injection and combustion timing. Fuel consumption and maximum power are largely influenced by the fuel's heat value and latent heat of vaporisation if powertrain characteristics are not modified. Brake thermal efficiency is very similar with all fuels which are analysed in the case study. The application of the framework to a specific powertrain technology indicates not only the use of biodiesel in compression ignition engines but also the potential of the primary alcohols, particularly biobutanol in this powertrain technology.

5. Acknowledgments.

The authors wish to acknowledge Santander and Universia for 'Fernando Alonso' scholarship and Fuels and Engines Group from the University of Castilla-La Mancha for the extended help and their valuable suggestions in this study.

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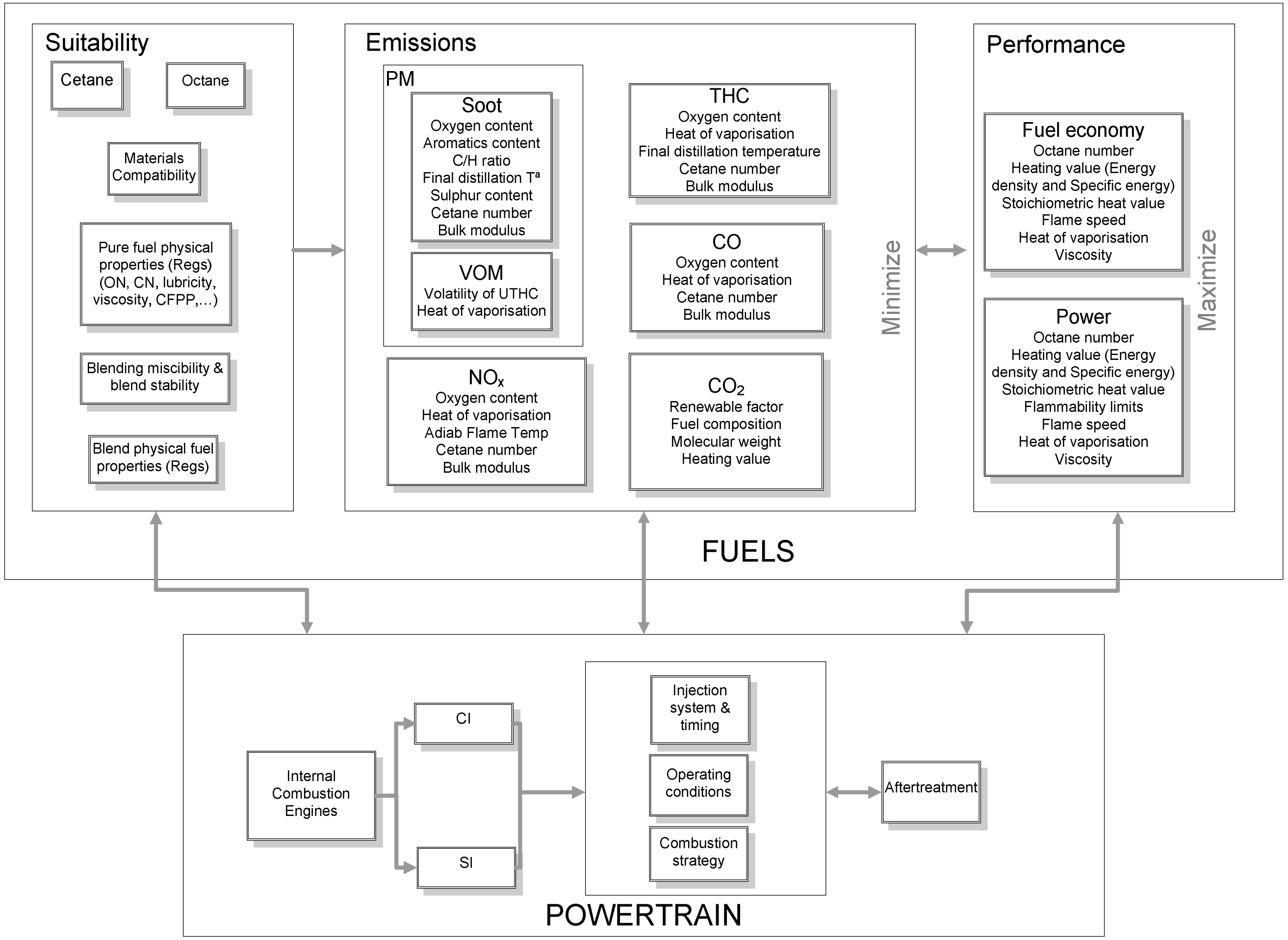

Figure 1. Framework.

Table 1. Synthesis fuel properties.

Property	**Diesel fuel**	**Gasoline**	**Biodiesel**	**Biomethanol**	**Bioethanol**	**n-biobutanol**
Composition	$C_{15.18}H_{29.13}$		$C_{18.81}H_{34.69}O_2$	CH_4O	C_2H_6O	$C_4H_{10}O$
C/H	0.521	0.538	0.542	0.25	0.33	0.4
Carbon content (% mass)	86.13			37.49	52.14	64.86
Aromatics (%)	38.68	<50	0	0	0	0
Oxygen content (% mass)	0	0	10.93	50	34.7	21.5
Stoichiometric mass (F/A)	1/14.67	1/14.6	1/12.49	1/6.45	1/9.01	1/11.19
Cetane number	52 -60	10	52-70	5	8	17
Research Octane Number	-	90-100	-	109	106-111	100
Motor Octane Number	-	80-90	-	89	87-94	
Density @ 15 ºC (kg/m^3)	835	730-760	885	791	789	810
Gas specific gravity @ 15 ºC (kg/m^3)	-	-	-	-	-	-
Viscosity @ 40ºC (cSt)	2.72	0.5-0.6	4.09	0.58	1.13	2.22
Heat value mass (Specific energy) (MJ/kg)	42.49	42.7	36.86	19.58	26.83	33.09
Heat value volume (Energy density) (MJ/l)	35.48	32.02	32.58	15.49	21.18	26.79
CFPP (ºC)	-19	-15	-3	<-51	<-51	<-51
Flash Point (ºC)	62	-40	150	11	14	29 (35)
Boiling point (ºC)	180-360	35-210	320-350	65	78.4	117
Spontaneous Ignition Temperature (ºC)	257	227-500		385	365	345 (385)
Flammability limits % volume with air	0.6-7.5	1.4-7.6		6.7-36	3.3-19	1.4-11.2
Heat of vaporisation (kJ/kg)	243	180	216	1089	858	585
Sulphur content (ppm)	10-50	10-50	0	0	0	0

Table 2. Suitability fuel comparison.

Suitability problems	**Biodiesel**	**Biomethanol**	**Bioethanol**	**Biobutanol**
Cetane Rating	↑	↓	↓	↓
Materials Compatibility	↓	↓	↓	↓
Lubricity	↑	↓	↓	↓↓
Viscosity	↑	↓	↓	↓
Miscibility/Stability	↑	↓↓↓	↓↓	↓
Modifications	No (>50%)	No (<5%)	No (<12%)	No (<20%)

Table 3. Performance and emission analysis of biodiesel.

Biodiesel diesel blend (50%) compared to conventional diesel	**Performance & fuel economy**			**Emissions**								
	Power	bsfc	Efficiency	CO_2 (/kg)	CO_2 (/MJ)	Net CO_2 (/MJ)	CO	UHC	NO_x	soot	VOF	PM
Net Effect	↓	↑	≈	↓	↑	↓↓	↓↓	↓↓↓	↑	↓↓↓↓	↑	↓↓↓
Properties												
Oxygen Content			↑				↓↓	↓↓	↑≈	↓↓	↓↓	↓↓
Aromatics	-	-	-							↓↓		↓↓
C/H				≈	≈	≈				↓		↓
Heat of Vaporisation	≈	≈	≈									
Adiabatic Flame Temperature	-	-	-						↑↓			
Final Distillation Temperature	-	-	-					↓		↓		↓
Volatility of UHC	-	-	-								↑↑↑	↑↑
Sulphur Content	-	-	-							≈		↓≈
Cetane Number	-	-	↑				↓≈	↓≈	↑≈	↓≈		↓≈
Bulk Modulus	-	-	-				≈	≈	≈	≈		≈
Density	-	-	↓									
Viscosity	↑	-	-									
Lubricity	-	-	-									
Heating Value	↓	↑	↓		↑↑	↑↑						
Stoichiometry	-	-	-	↓	↓	↓						
Renewable Factor	-	-	-			↓↓↓↓						

Table 4. Performance and emission analysis of bioethanol.

Bioethanol diesel blend (10%) compared to diesel	**Performance & fuel economy**			**Emissions**								
	Power	bsfc	Efficiency	CO_2 (/kg)	CO_2 (/MJ)	Net CO_2 (/MJ)	CO	UHC	NO_x	soot	VOF	PM
Effect	↓	↑	≈	↓	≈	↓	↓	↑	≈	↓↓↓↓	↑	↓↓↓
Properties												
Oxygen Content			↑				↓↓	↓	↑	↓↓↓		↓↓↓
Aromatics										↓≈		↓
C/H										↓≈		↓
Heat of Vaporisation							↑	↑↑	↓		↑	↑↑
Adiabatic Flame Temperature									↓≈			
Final Distillation Temperature												
Volatility of UHC												
Sulphur Content												≈
Cetane Number			↓				↑≈	↑≈	↑			
Bulk Modulus												
Density												
Viscosity												
Lubricity												
Heating Value	↓	↑			↑	↑						
Fe and MW				↓	↓	↓						
Renewable Factor						↓						

Table 5. Performance and emission analysis of biobutanol.

Biobutanol diesel blend (10%) compared to diesel	**Performance & fuel economy**			**Emissions**								
	Power	bsfc	Efficiency	CO_2 (/kg)	CO_2 (/MJ)	Net CO_2 (/MJ)	CO	UHC	NO_x	soot	VOF	PM
Effect	↓	↑	≈	↓	≈	↓	↓	↑	≈	↓↓↓↓	↑	↓↓↓
Properties												
Oxygen Content			↑				↓↓	↓	↑	↓↓		↓↓
Aromatics										↓≈		↓
C/H										↓≈		↓
Heat of Vaporisation	-	-	-				↑	↑	↓		↑	↑
Adiabatic Flame Temperature									↓ ≈			
Final Distillation Temperature												
Volatility of UHC												
Sulphur Content												≈
Cetane Number			↓				↑≈	↑	↑			
Bulk Modulus												
Density												
Viscosity												
Lubricity												
Heating Value	↓	↑			↑	↑						
Fe and MW				↓	↓	↓						
Renewable Factor						↓						

Table 6. Synthesis of performance and emission fuel comparison.

	Performance & fuel economy			**Emissions**								
	Power	bsfc	Efficiency	CO_2 (/kg)	CO_2 (/MJ)	Net CO_2 (/MJ)	CO	UHC	NO_x	soot	VOF	PM
Biodiesel (50%)	↓	↑	≈	↓	↑	↓↓	↓↓	↓↓↓	↑	↓↓↓↓	↑	↓↓↓
Bioethanol (10%)	↓	↑	≈	↓	≈	↓	↓	↑	≈	↓↓↓↓	↑	↓↓↓
Biobutanol (10%)	↓	↑	≈	↓			↓	↑	≈	↓↓↓↓	↑	↓↓↓