

Scientific Report

Project No.

Broads Hire Boat Ref:
MAST Ref.: MT-2005-052

Document title:

Investigation into environmental benefits of burning biodiesel in diesel engines

Doc. status:

Restricted

Author(s):

Jan Chirkowski, *S. K. Nanda, Prof. A. P. Roskilly

Organisation:

University of Newcastle upon Tyne

Doc. Ident. Code:

Distribution list:

University of Newcastle upon Tyne
Broads Hire Boat Federation

The project was funded from the Broads Authority's Sustainable Development Fund

No part of this document may be reproduced or transmitted in any form or by any means, not stored in any information retrieval system of any kind, nor communicated to any other person without the written approval of the Project Steering Committee in the distribution list

* Author for correspondence, e-mail: s.k.nanda@ncl.ac.uk, Tel: 0191-2223523

MAST Publication Number: MT-2005-052

Table of Contents

1. Background	3
2. Introduction	3
3. Key issues associated with biodiesel	3
3.1. Applicability	3
3.2. Biodegradability	4
3.3. Flash point	4
3.4. Lubricity	4
3.5. Exhaust emissions	4
3.6. Domestic manufacture	5
3.7. Biodiesel content	5
3.8. Stability	6
3.9. Unreliability of blend flash points	6
3.10. Corrosion	6
3.11. Cold starting	6
3.12. Warranty voidance	7
3.13. Price	7
4. Field trial details	8
4.1. Boat no.1	8
4.2. Boat no.2	9
5. Engine system modification for trials	10
5.1. Fuel line modification	10
5.2. Exhaust line modification	11
6. Experimental procedure	13
7. Results and discussion	17
7.1. NO _x emissions	25
7.2. Carbon monoxide emissions	26
7.3. Carbon dioxide emissions	26
7.4. Oxygen emissions	26
7.5. Sulphur dioxide emissions	27
7.6. Fuel consumption	27
7.7. Exhaust temperature	27
8. Conclusion	28
9. References	29

1.0 Background

The Broads Hire Boat Federation to promote environment friendly boats in the Norfolk Broads had expressed interest in using biodiesel produced from recycled frying oil sourced locally. To evaluate the environmental benefits of biodiesel in a scientific manner the School of Marine Science and Technology at Newcastle University was contracted by the Broads Hire Boat Federation to under take the work.

2.0 Introduction

In the past few years climate change due to global warming has been a key political and social issue in most developed countries. To limit this National Emission Ceiling limits have been set under the Kyoto protocol (ratified on 16th of February 2005) to reduce greenhouse gas levels in the atmosphere. This along with rising fossil fuel prices and security of energy supplies has been the key driver towards the use of renewable and carbon neutral energy sources. Limits have also been set for sulphur in liquid fuels under the European Directive 2005/33/EC for use in inland water transport. As more stringent environmental legislation come into force there is growing interest in the transport industry about the exploitation of fuels produced from the biodegradable fraction of products, waste and residues from agriculture, forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste [1]. These so-called 'biofuels' can take many forms depending on the raw material used and production process adopted. One such variation, BioDiesel, has been widely used in the UK to fuel both onshore vehicles and recreational boats. BioDiesel is produced from vegetable oils (Rapeseed, Soybean, Sunflower etc.) or industrial waste fats/oils through a process of transesterification whereby the fuel viscosity is adjusted for ease of direct injection into the combustion chamber [2].

3.0 Key issues associated with Biodiesel

3.1 Applicability

Transesterification releases fatty acids from the glycerides in straight vegetable oil to form a lower viscosity biodiesel that can be used in any direct injection diesel engine with minimum or no modification. However, due to the lower energy density of biodiesel compared with regular fossil diesel, more biodiesel must be injected into the combustion

chamber to produce the same mechanical power, increasing the injection duration through an change in injection start time. But the higher biodiesel cetane number reduces the ignition delay and the effect is minimized [3]. [4]

3.2 Biodegradability

Biodiesel is insoluble in water but is more biodegradable so does minimal damage in a marine environment in the event of a minor spill. Compared to fossil diesel which imparts 100s of ppm of aromatics into the water, Biodiesel imparts as low as 17 ppm (sea) and 14 ppm (fresh) and degrades twice as fast [5].

3.3 Flash point

The flash point (the temperature at which a minimum amount of vapour is produced to facilitate combustion) of Biodiesel ($>110^{\circ}\text{C}$ for RME) is well above that of fossil diesels (80°C for No.2 Diesel) reducing the risk of unwanted explosion. A lack of volatile organic compounds and aromatic hydrocarbons lessen the risk of releasing toxic or corrosive gases, and the fuel is considered as harmless to handle as a salad oil. [5]

3.4 Lubricity

The lubricity of BioDiesel is higher than that of fossil diesel, reducing engine component wear thereby increasing engine lifespan. When used as an additive with low and ultra-low sulfur diesel fuels, as little as a 1-2% blend of BioDiesel can impart the level of compounds needed to enhance lubricity. [6,7]

3.5 Exhaust emissions

Exhaust emissions from diesel engines fuelled with a biodiesel can vary considerably depending on the base stock used to produce it. In order to reduce the complete lifecycle environmental impact of a biodiesel it is often manufactured from local sources, which differ considerably between geographical locations. Such sources can include waste olive oil, used frying oil, rapeseed oil, soybean oil and rubber seed oil [8-12]. In general, a reduction in hydrocarbon, carbon monoxide, particulate matter emissions and an increase in nitrogen oxides is observed. The latter increase is possible as additional NO_x can be formed at low temperature due to fuel bound oxygen. Cases of a reduction in NO_x have also been reported [8, 9]. A small increase in exhaust CO_2 is observed, due to the increased oxygen content of the biodiesel, allowing for excess oxygen at combustion and therefore

CO₂ formation rather than CO. It is generally accepted that this extra CO₂ is inconsequential in the system life cycle since it is simply reabsorbed by crops and so kept in balance [13] without adding to global warming (discounting fuel production processes). The reduction in hydrocarbons and particulates is mostly attributed to complete combustion (higher oxygen content) of biodiesel bringing about more complete combustion and thus less residual contaminants in the exhaust. Biodiesel also contains trace amounts of sulfur [13, 14] allowing a dramatic reduction in SO_x emissions compared to fossil diesel. This will aid inland waterways operators to meet limits set for sulphur in liquid fuels under European Directive 2005/33/EC. There is therefore no significant contribution to acid rain formation when this fuel is in use.

Consideration should be given to the occasional wide variation in the parameters of commercial biodiesel from the same source. Notable differences in flash point, carbon residue, phosphorous content and iodine number have been reported [15] but no substantial operating differences have been observed.

3.6 Domestic Manufacture

The ability of biodiesel to be produced from animal/waste oils and fats and virtually any plant oils often enables domestic manufacture. In the UK especially this is a strong incentive since the reliance on costly foreign sources of fossil diesel can be diminished, and the agricultural economy strengthened through added demand. Also, with the biodiesel source near to the area for distribution less energy must be spent in transport. It is thought that importing the fuel from abroad will severely limit, even completely cancel out any positive environmental effects resulting from its end use. Thus the entire life cycle, from material acquisition to processing to eventual use, must be conducted locally for the greatest eco-efficiency [16]. A further, political, motivation is provided by the instalment of EU directive 2003/30, which states that 2% of the total European consumption of fuel for transport purposes should be biofuel by the end of 2005, and 5.75% by 2010, supplying the incentive for EU countries to set up the infrastructure necessary to produce biofuels.

3.7 Biodiesel Content: Raw material homogeneity, consistency and reliability are questionable and are dependant on the supplier, the nature of the raw material and production methods.

3.8 Stability

Storage and handling is difficult (particularly stability in long term storage). Evaluations using the Rancimat test [18] showed that BioDiesel ages and becomes more unstable over time in storage. Studies have shown [19] that this fuel oxidation can have beneficial effects on exhaust emissions, but some problems may occur when biodiesel is blended with fossil diesels due to the development of polymers during storage [20]. The addition of antioxidants to improve this oxidation stability in more than sufficient quantities may adversely affect other fuel parameters, such as Conradson Carbon Residue number [20] which denotes the carbon-forming ability of the fuel that if too high can lead to injector clogging.

3.9 Unreliability of blend flash points

This can vary both due to the non-homogeneity of the production process and through long-term storage and so there is difficulty in defining a maximum safe working temperature.

3.10 Corrosion

Although there have been several studies into the enhanced lubricity of biodiesel and its benefits towards engine working life [6, 7, 22] there have also been reports of the corrosion of some fuel piping through use of BioDiesel as well as the dissolution of solid deposits, such as carbon residue, left by previous fossil diesel use in older engines. The former problem can be solved by replacing the fuel pipes with inexpensive, commonly used alternatives. The latter problem simply requires more frequent cleaning and replacement of fuel filters initially and will ultimately lead to a cleaner engine [16].

3.11 Cold Starting

Since the pour point and cloud point of biodiesels are usually higher than fossil diesels, it is expected that engine starting in cold weather could be difficult. Recent efforts have been made to improve the cold flow of the fuel. The use of heating equipment at the fuel tank, fuel line or fuel filters is a basic way of reducing cold-flow problems but major engine modification is then required which nullifies one of the key advantages of the product. Also, blending with diesels causes a depression of the fuel freezing point, but the higher the proportion of biodiesel the higher the freezing point, so this does not solve the problem for neat biodiesel. Recent research has focused on the utilization of cold flow improvers,

which have been shown to be effective [26] but may add more to the cost of biodiesel usage.

3.12 Warranty voidance

In Europe at present there are three specification standards for biodiesel; EN590, DIN 51606 and EN14214. Many engine manufacturers require that one of these standards be met in order for biodiesels to be used without voidance of service warranties. However most insist on a small percentage blend, usually 5%, and any higher blend will invalidate the engine warranty unless the engine has been specifically designed for such a purpose [27].

3.13 Price

In terms of pricing, the current average cost per litre of the waste frying oil BioDiesel is 45pence/litre including an off-road duty of 3.1 pence as compared to red diesel at 34pence/litre with an off-road duty of 6.4 pence [28, 29]. In some countries on the continent duty is not charged on non-mineral hydrocarbon fuels allowing production to move swiftly ahead – the top three producers are Germany (1,035,000 t/yr), France (348,000 t/yr) and Italy (320,000 t/yr) while the UK falls far short with 9,000 t/yr. In Germany, for instance, the relative closeness of the total production capacity, 1,088,000 t/yr, to the actual production reflects the demand for the fuel, whereas in the UK the production capacity is 15,000 t/yr, indicative of the lack of demand due mainly to the non-competitive pricing [30]. A comprehensive breakdown of biodiesel costs can be found in Williamson and Badr [31], and will not be detailed further here.

4.0 Field trial details

Two boats fitted with different engine makes, a Perkins 404C-22 and Nanni Diesel 3.100HE, were selected to undergo field trials. This investigation took the form of a comparative study, with measurements of engine exhaust emissions and fuel flow being taken for engine operation on Gas Oil and BioDiesel. The BioDiesel used in this study was transesterified from waste frying oil. Details of the vessels used in the trial are mentioned below.

4.1 Boat No. 1

Vessel Name: Fair Countess

Vessel Owner: Faircraft Loynes

Vessel Length: 12.19m

Vessel Breadth: 3.66m

Power Plant: Perkins 404C-22



Figure 1- Boat No.1 'Fair Countess'

Perkins 404C-22 (Marinised) Specification

Bore and stroke: 84mm x 100mm

Number of cylinders: 4 in-line

Cubic Capacity: 2.2 litres

Cycle: 4 stroke

Aspiration: Natural

Combustion System: Indirect Injection

Compression Ratio: 22.4:1

Governing: All speed mechanical

Cooling System: Pressurised water (Outlet through exhaust piping)

Gearing: Step-down gearing facilitating direct shafting to propeller

Maximum Gross Power Output: 38kW @ 3000rpm

Maximum Gross Torque: 143Nm @ 1800rpm



Figure 2- Perkins 404C-22 Diesel

4.2 Boat No.2

Vessel Name: Aimee 2

Vessel Owner: Alexander Cruisers

Vessel Length: 7.31m

Vessel Breadth: 2.89m

Power Plant: Nanni Diesel 3.100HE



Figure 3- Boat No.2 'Aimee 2'

Nanni Diesel 3.100 HE Specification

Bore and stroke: 84mm x 100mm

Number of cylinders: 3 in-line

Cubic Capacity: 1.001 litres

Cycle: 4 stroke

Aspiration: Natural

Combustion System: Indirect Injection

Compression Ratio: 23:1

Governing: All speed mechanical

Cooling System: Pressurised water (Outlet through exhaust piping)

Gearing: Step-down gearing facilitating direct shafting to propeller



Figure 4- Nanni 3.100 HE Diesel

Maximum Gross Power Output: 21.3kW @ 3600rpm

Maximum Gross Torque: 63.5Nm @ 2400rpm

5.0 Engine system modification for trials

5.1 Fuel Line Modification

For measurement of fuel flow rate an ISO-certified graduated cylinder was used, connected to the fuel inlet piping via a 3-way valve. A second 3-way valve allowed fuel to be diverted from the fuel return line to the graduated cylinder. This forms a closed loop and ensures that only the fuel flow into the engine combustion chambers is measured. At each loading condition a pre-defined drop of fuel in the graduated cylinder is timed, enabling flow calculation.

This arrangement also aids the changeover between fuels as the fuel tank can be isolated from the engine and the second fuel type added directly to the graduated cylinder. At the changeover stage great care was taken to ensure that the engine was sufficiently flushed of the previous fuel type so as not to affect the trial results. This was accomplished by allowing several litres of the second fuel type to be fed into the engine and the excess fuel, in the return line, diverted back to the main fuel tank. The return line 3-way valve was then switched such that the closed loop was formed again. The valve arrangement is shown in figure 5 below:

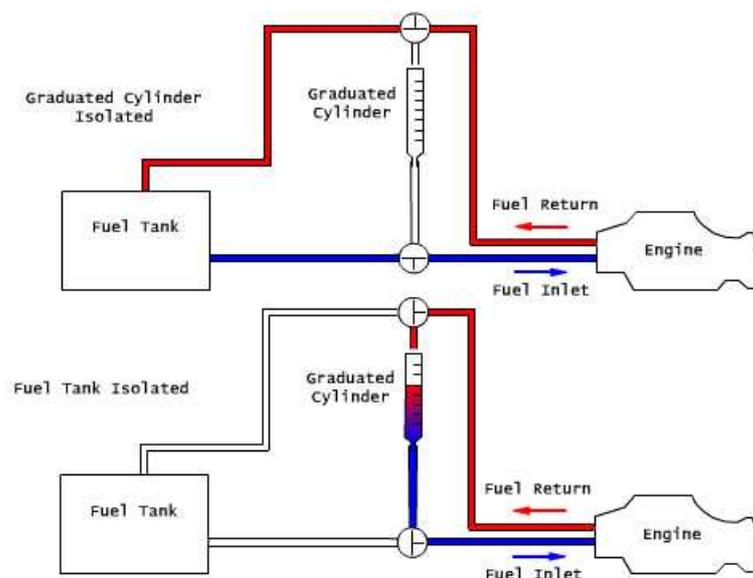


Figure 5: Fuel Line Valve Arrangement

5.2 Exhaust Line Modification

To measure temperature and pollutant concentration readings from the engine exhaust it is necessary to install a thermocouple and sampling probe on the exhaust line, as shown in figure 6. To get a representative sample the probe should span no less than 80% of the diameter of the exhaust pipe with a number of holes against the direction of flow.

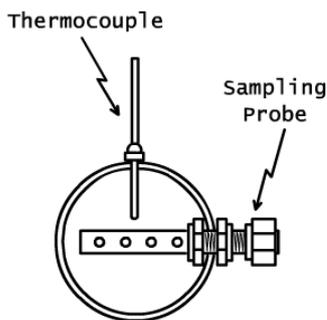


Figure 6: Exhaust Pipe Cross Section A-A

Common among pleasure boats of the type used in the trial is a wet exhaust system. The exhaust piping, usually made in part from non-metallic units, is not designed for the temperatures given off at the exhaust outlet. To maintain structural integrity of the pipe water used for engine cooling is 'injected' either into the exhaust manifold, as was the case for the trial vessel 'Aimee 2', or immediately after the exhaust manifold, as for 'Fair Countess'. As the sample extracted from the exhaust pipe would have been unrepresentative of the actual exhaust

modifications were undertaken to obtain a dry representative sample. In both trial vessels the coolant water was redirected to be added to the exhaust piping after the sample was taken (figure 7 and 8).

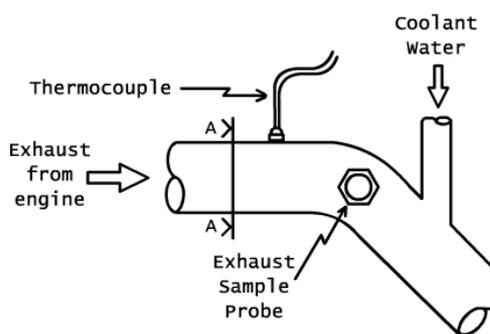


Figure 7- 'Fair Countess' Exhaust Modification

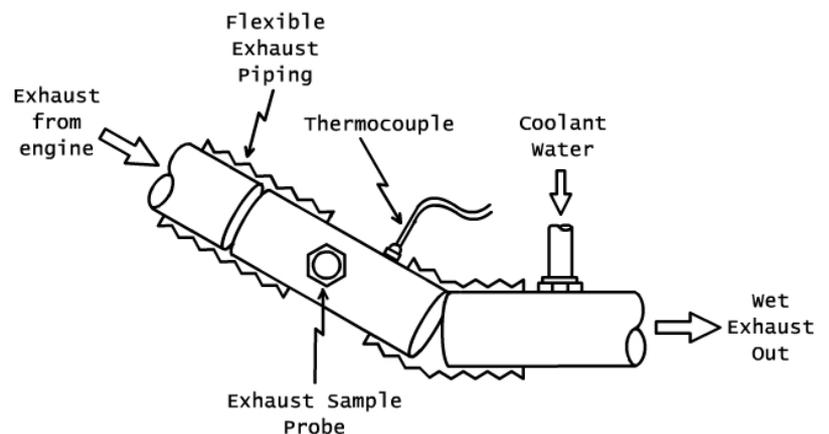


Figure 8- 'Aimee 2' Exhaust Modification



Figure 9 'Fair Countess' Exhaust Modification

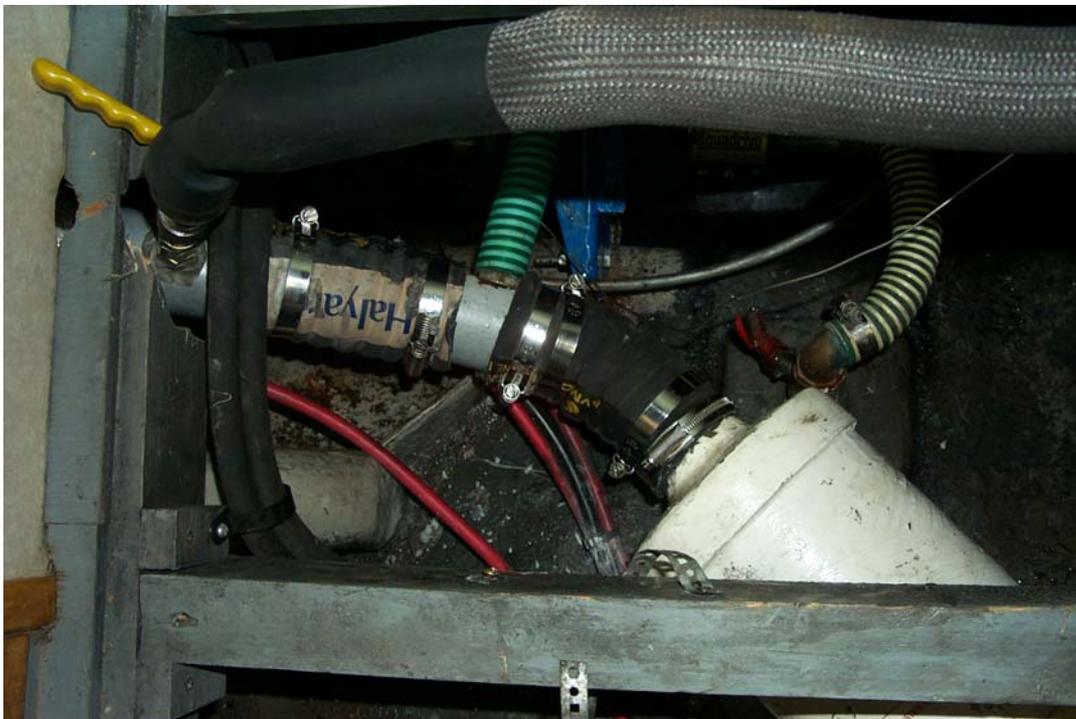


Figure 10: 'Aimee 2' Exhaust Modification

6.0 Experimental procedure

In order to obtain a standardised set of data the test procedure described in ISO 8178 was followed. The test cycle E5, for marine craft less than 24 metres in length, was used in the trial. Test load points for the cycle are shown in Table 1.

Cycle E5	1	2	3	4	5
Speed, %	100	91	80	63	Idle
Power, %	100	75	50	25	0
Weighting Factor	0.08	0.13	0.17	0.32	0.3

Table 1- ISO 8178-4 Test Cycle E5 Description

Speed and power are defined above as percentages of maximum achievable by the tested engine. The weighting factor is used when calculating specific exhaust emissions.

The trial was performed using the speed guidelines, with each boat held at the corresponding percentages of maximum engine rpm for the duration of each test mode. The course of the vessel was held as straight as possible to ensure even propeller loading and thus steady fuel consumption for a consistent engine load. Each test mode was performed twice for verification. The following readings were taken at each test mode:

- Engine fuel consumption,
- Exhaust emissions
- Exhaust temperature
- Shaft rpm
- Auxiliary current drawn

In addition ambient temperature and humidity readings were recorded at the beginning of testing each fuel type. This was performed to facilitate NO_x correction, as set out in ISO 8178-1, in order to normalise the NO_x readings to the standard ISO conditions, with a humidity of 10.71 g/kg and ambient temperature of 25°C.

6.1 Exhaust Emissions Measurement

For the scope of the trial, the exhaust components deemed most important for measurement in the trial were CO, CO₂, O₂, NO_x and SO₂. Although measurement of hydrocarbons and particulates would also have been useful, due to time constraints and for the sake of simplicity the 5 aforementioned components were recorded only, since this could be

undertaken using a single analyser. The Horiba Portable Gas Analyser PG-250 was used to perform the tests.

SPECIFICATIONS

Model	PG-250
Components Measured	NOx/SO ₂ /CO/CO ₂ /O ₂ (5 components)
Analysis Principle	NOx : Chemiluminescence(CLD) SO ₂ /CO/CO ₂ : Non-dispersive Infrared Absorption(NDIR) O ₂ : Galvanic Cell
Ranges	NOx : 0~25/50/100/250/500/1000/2500 ppm 7 ranges SO ₂ : 0~200/500/1000/3000 ppm 4 ranges CO : 0~200/500/1000/2000/5000 ppm 5 ranges CO ₂ : 0~5/10/20vol% 3 ranges O ₂ : 0~5/10/25vol% 3 ranges
Repeatability	±0.5% of F.S.(NOx : ≤ 100ppm range CO : ≤ 1000ppm range) ±1.0% of F.S.
Linearity	±2.0% of F.S.
Drift	±1.0% of F.S./day(SO ₂ : ±2.0% of F.S./day)
Response Time (T ₉₀)	45 s or less SO ₂ Only : 240 s or less
Sample Gas Flow Rate	Approx. 0.4 L /min
Display	Measured value(3 or 4digits)active, range, flow rate
Output	DC 4-20mA (Non-isolated), RS-232C interface
Ambient Temperature	5~40°C:
Ambient Humidity	85% or less
Power	100~120V AC, 200~240V AC 50/60Hz
Power Consumption	250 VA/400 VA
Dimensions	260(W)×260(H)×510(D) mm / 10.2(W)×10.2(H)×20.0(D)in
Mass	Approx. 17 kg
Sample Gas Condition	Temperature : Less than 40: H ₂ O Content : Saturated or less at ambient temperature Dust : 0.1g/m ³ or less Pressure : ±0.98kPa

Table 2- Horiba PG-250 Analyser Specification

In order to prepare the exhaust gas for entry to the analyser both a heated line and a conditioning unit are required. The heated line serves to prevent condensation occurrence

during extraction and the conditioning unit ensures that the temperature of the gas is less than 40°C and the saturation level is correct, as per the analyser specification above.

The analyser was calibrated at the start of each test day, and calibration drift measured at the end of the day. This calibration drift takes the form of zero and span drift. Zero drift is defined as the change to the zero reading of the analyser due to a change in ambient condition, while span drift denotes the change in the sensitivity of the analyser with a change in ambient conditions. To carry out zero calibration a zero gas (Nitrogen, N₂) was fed into the analyser and readings for NO_x, CO, CO₂, O₂ and SO₂ set to zero. For the span calibration, two span gases were used, one gas a mixture of Carbon Monoxide and Carbon Dioxide, the other gas containing NO_x. The readings generated by the analyser for NO_x, CO and CO₂ were then corrected to the actual concentrations of each substance in the span gases. The times of initial and final calibration were recorded and thus drift per hour computed. Pre-calibration carried out prior to use of the analyser in the trials enabled span calibration of O₂ and SO₂ to be neglected. Table 3 shows the span gas concentration.

Gas	Span Gas Concentration
CO	1390 ppm
CO ₂	13.9%
NO _x	1390 ppm
SO ₂ (pre-cal)	805 ppm
O ₂ (pre-cal)	21.2%

Table 3- Span Gas Concentrations

ISO 8178 states that both span and zero drift must not exceed 2% of full scale on the lowest range used during a 1 hour period. This will be verified in the 'Results' section of this report.

The Horiba analyser was connected to a data acquisition system that recorded emissions data averaged over 15 second intervals. This increased the accuracy level of measurements.

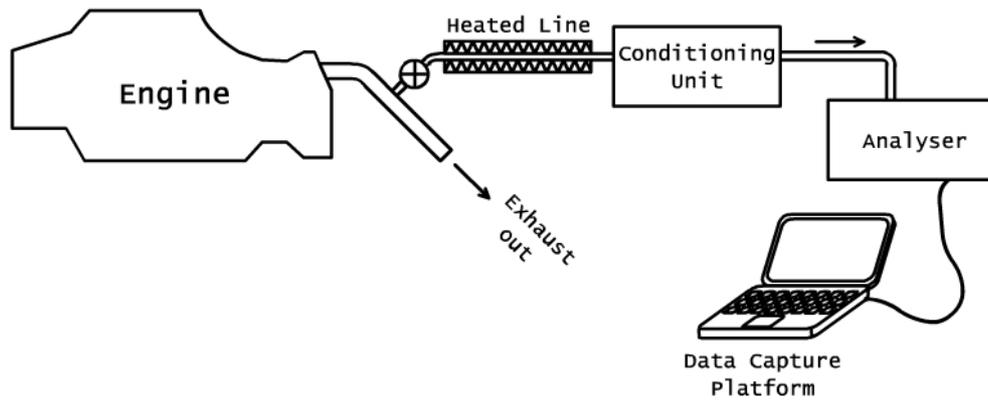


Figure 11: Exhaust Sampling Equipment Block Diagram

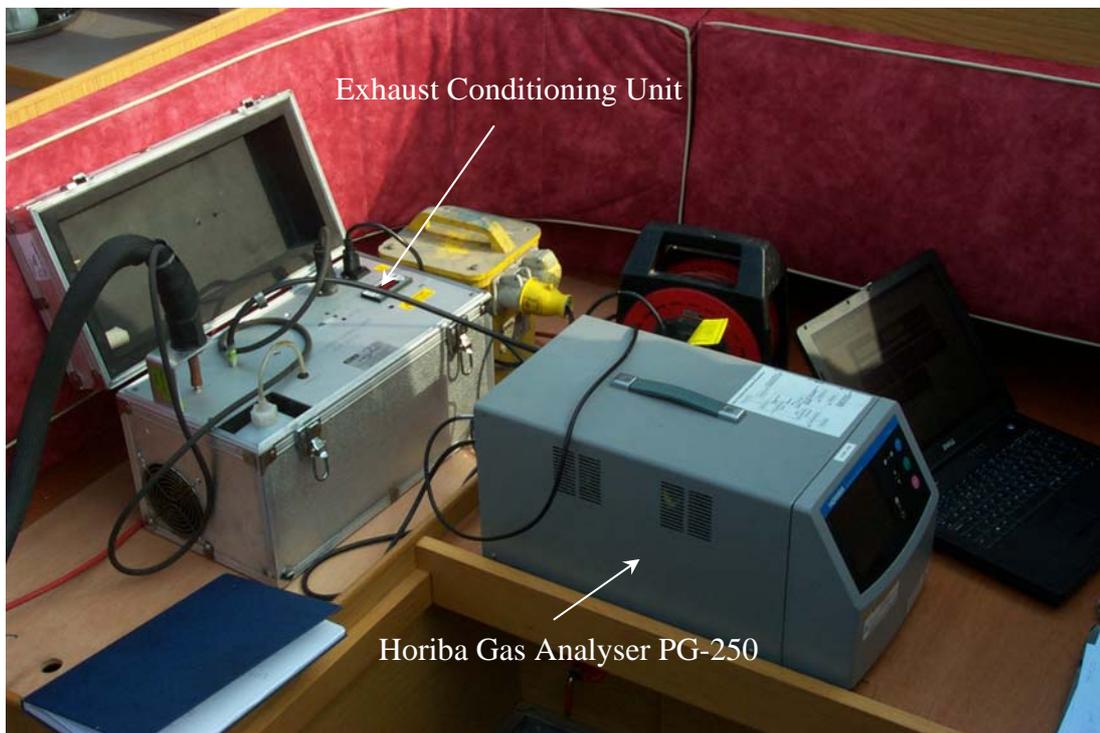


Figure 12: Exhaust Sampling Equipment

7.0 Results and Discussion

In order to compare the exhaust emissions and fuel consumption of engines running on biodiesel and fossil diesel the tested fuels must be analysed for elemental constitution and other properties. This was performed by the Lloyds Register fuel analysis service, FOBAS, and the relevant results are detailed in table 4.

		BioDiesel (Perkins)	BioDiesel (Nanni)	Red Diesel
Carbon	% (m/m)	76.76	76.61	86.19
Gross Calorific Value		39.66	39.62	45
Nitrogen	% (m/m)	0.0023	0.0024	0.1799
Hydrogen	% (m/m)	11.97	11.92	12.62
Density at 15°C	kg/ltr	0.8841	0.884	0.8608
Ash Content at 550°C	% (m/m)	< 0.010	LT 0.010	< 0.010
Sulphur Content	% (m/m)	< 0.001	< 0.001	0.13
Oxygen	% (m/m)	10.7	10.5	0.1

Table 4- Fuel Analysis Results

The raw data collected in the field must be corrected to ISO standards for comparative use. Some of these corrections are as follows:

1. The emissions readings taken at each trial mode are averaged. As a redundancy measure readings were taken on the load up and load down condition.
2. The data is corrected for zero and span drift. As mentioned earlier, for the results to be valid any drift must not exceed 2% of full-scale. The maximum drift values recorded during the trials are shown in table 5.

Gas	Max. Span Drift	Max. Zero Drift	Drift Duration	Full Scale	% Span Drift FS	% Zero Drift FS
NOx	87	0	04:30	2500	0.77	0
CO	63	1	04:41	2000	0.67	0.01
CO2	0.34	0	04:41	20	0.36	0

Table 5- Maximum Calibration Drift

3. The NO_x results must then be corrected to the ISO ambient conditions, using the formulae laid out in ISO 8178-1 in order to produce comparable results. A schematic of the calculation procedure is shown in figure 13..

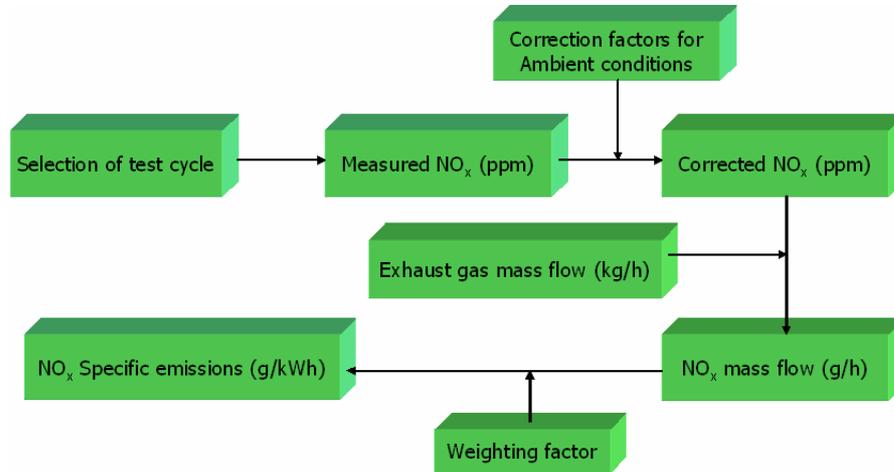


Figure 13: Schematic of NO_x emission calculation

4. The NO_x results are then corrected from dry to wet readings as the analyser measured a dry sample after being run through the conditioning unit.

The exhaust mass flow rate is determined through fuel flow data, as provided in the trial, stoichiometric air demand, and excess air factor calculated with knowledge of fuel consistency and exhaust CO_2 content. This subsequently allows determination of NO_x , CO_2 , CO and O_2 particular flow rates. The finalised results of the trial are presented below in figures 14 – 25.

Perkins Engine NO_x Flow Rate (g/hr)

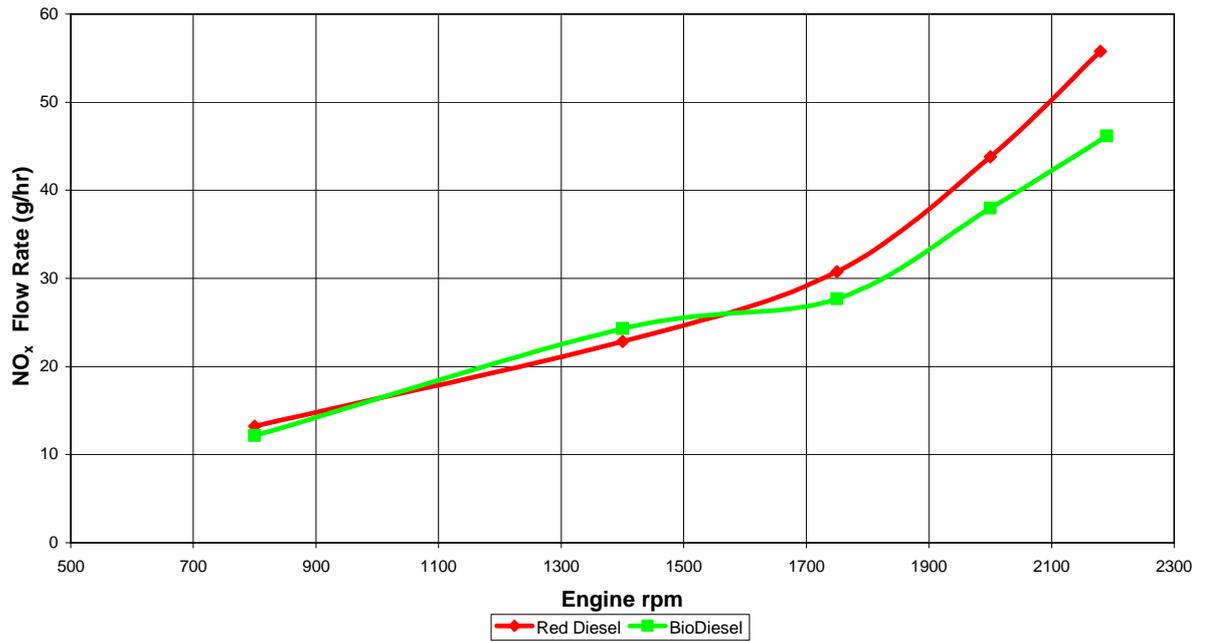


Figure 14

Nanni Engine NO_x Flow Rate (g/hr)

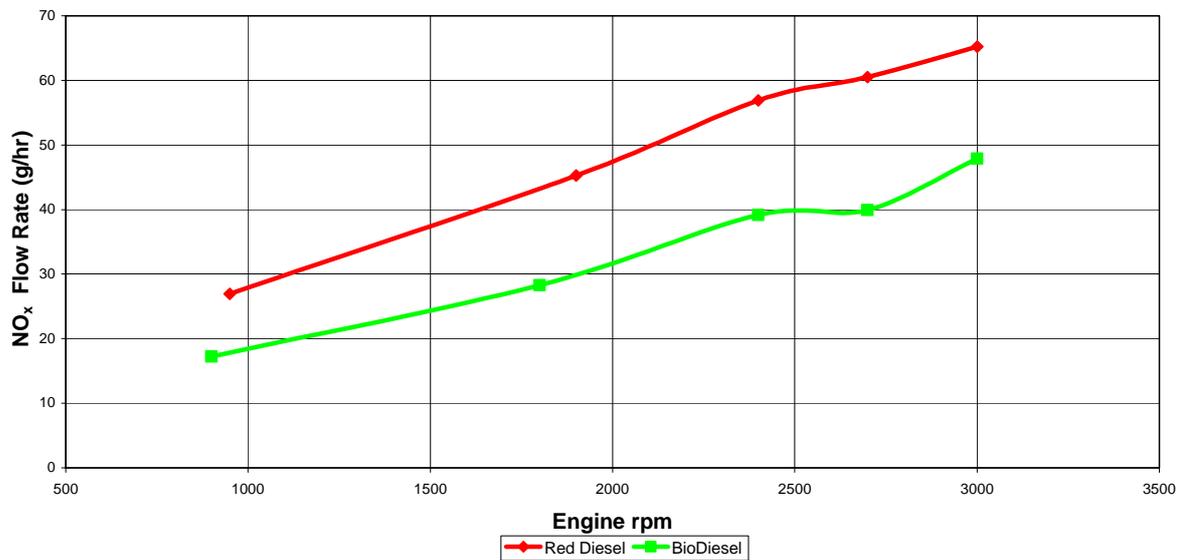


Figure 15

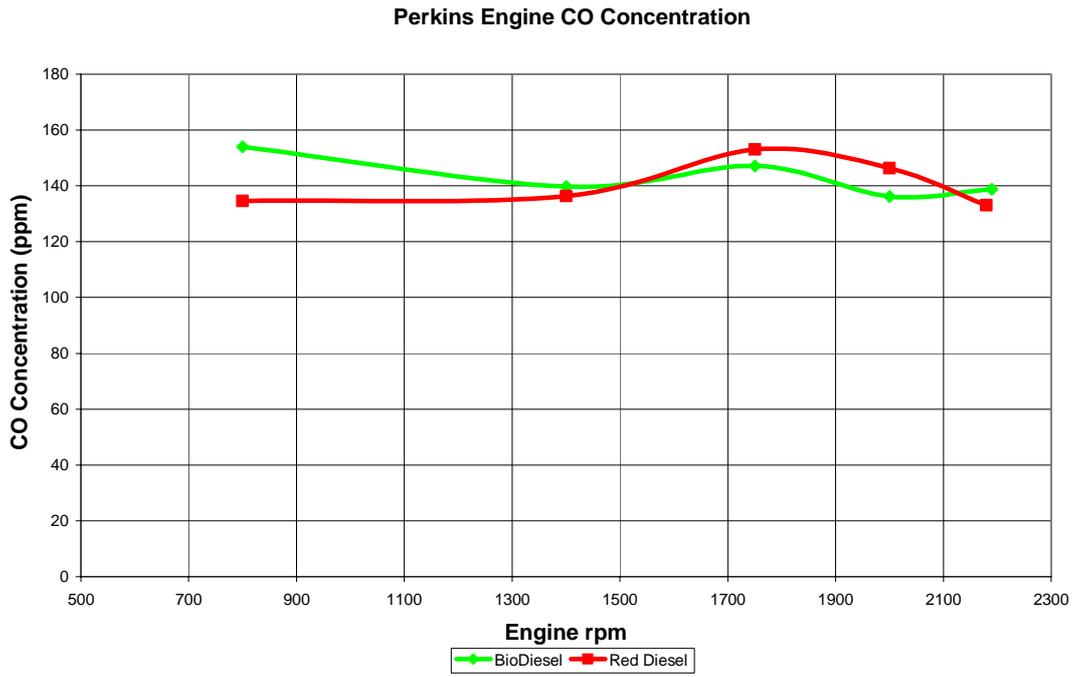


Figure 16

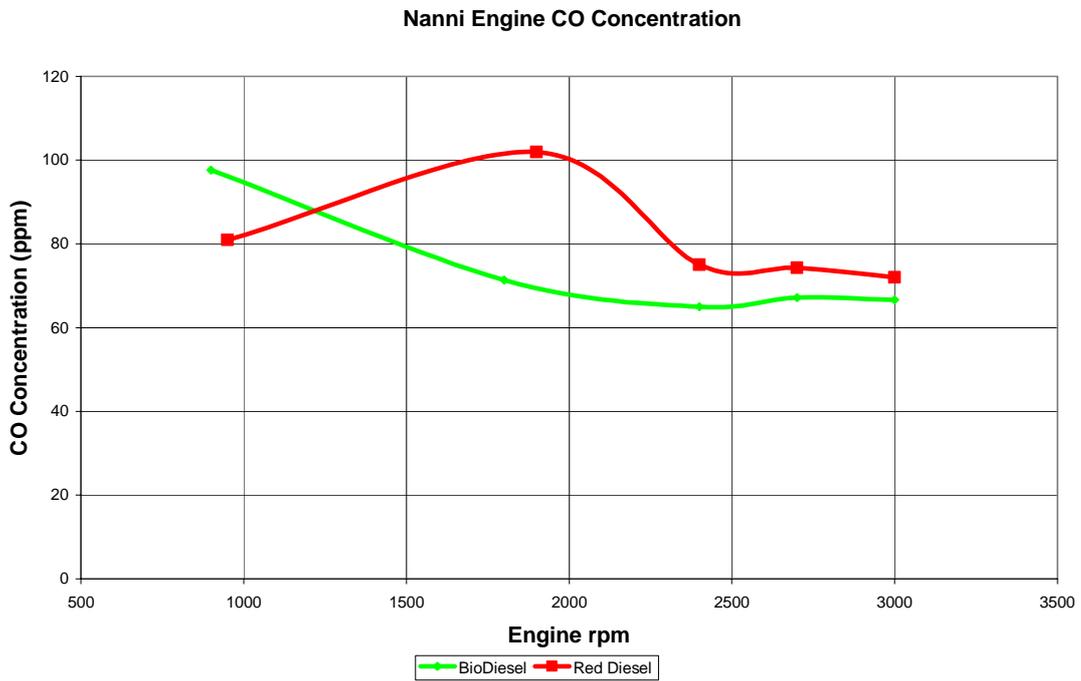


Figure 17

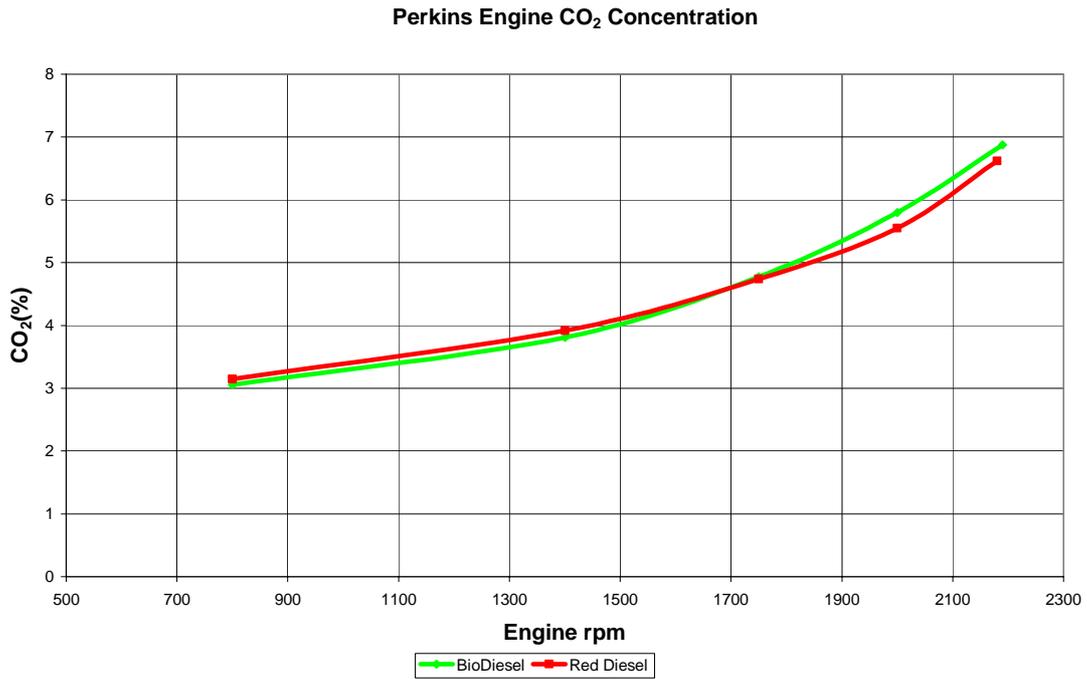


Figure 18

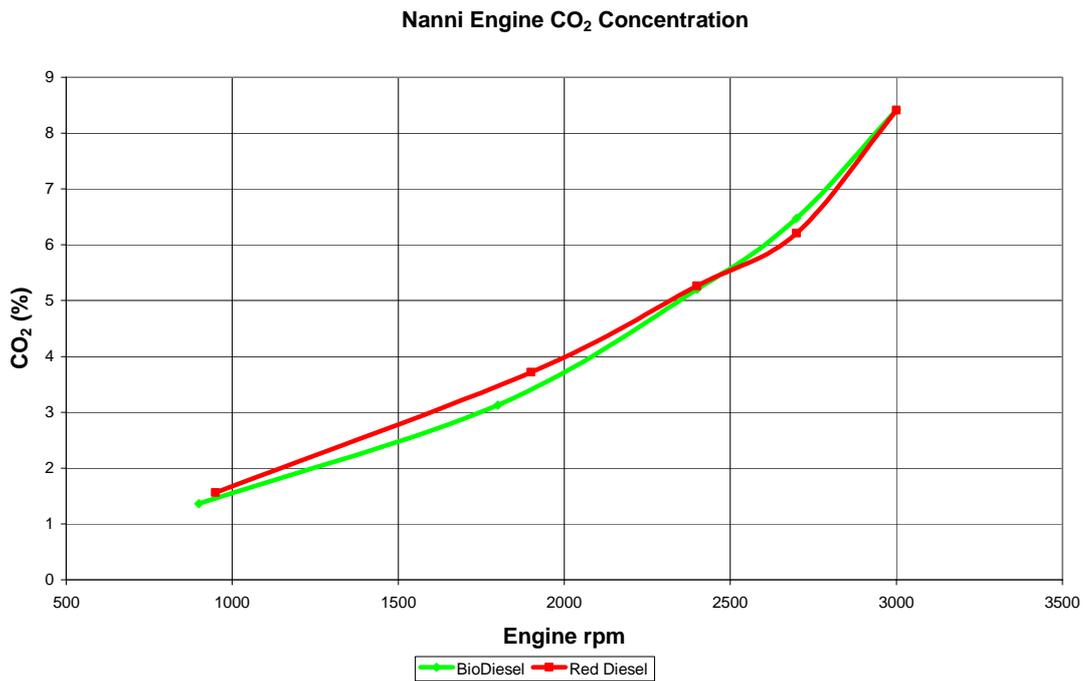


Figure 19

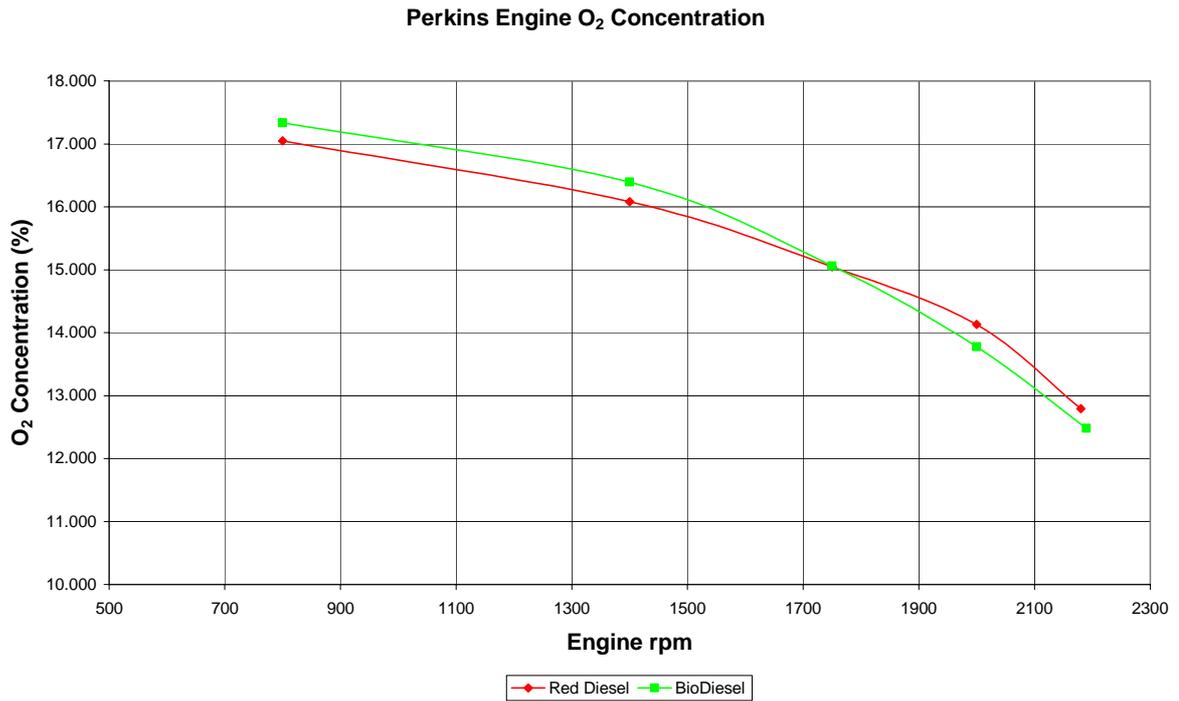


Figure 20

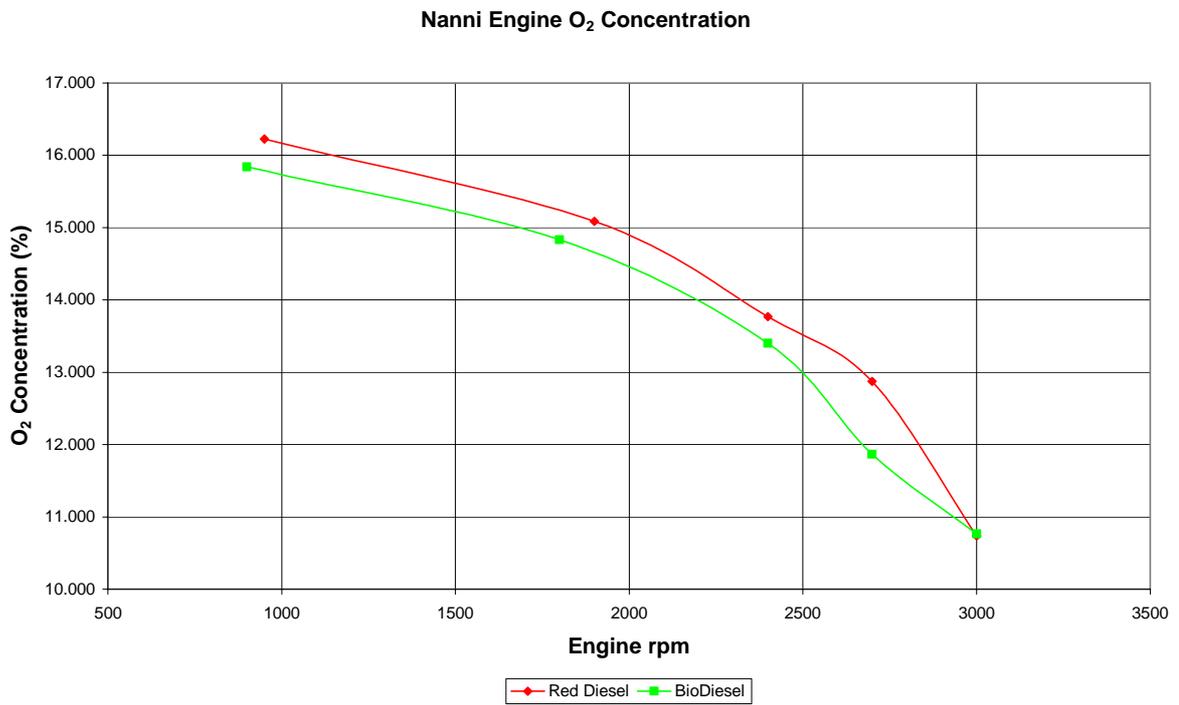


Figure 21

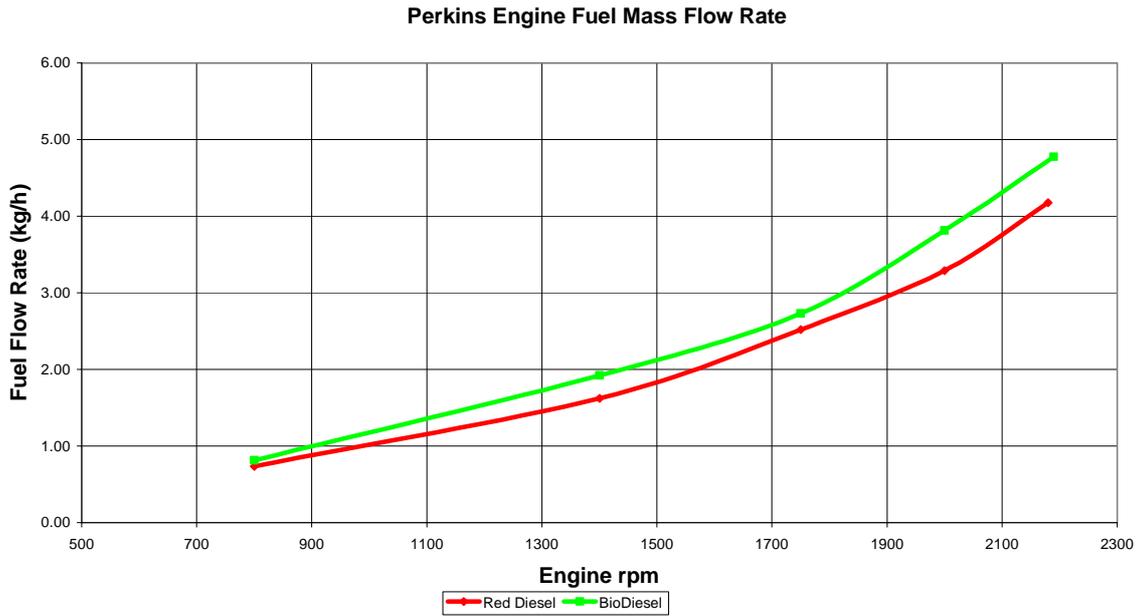


Figure 22

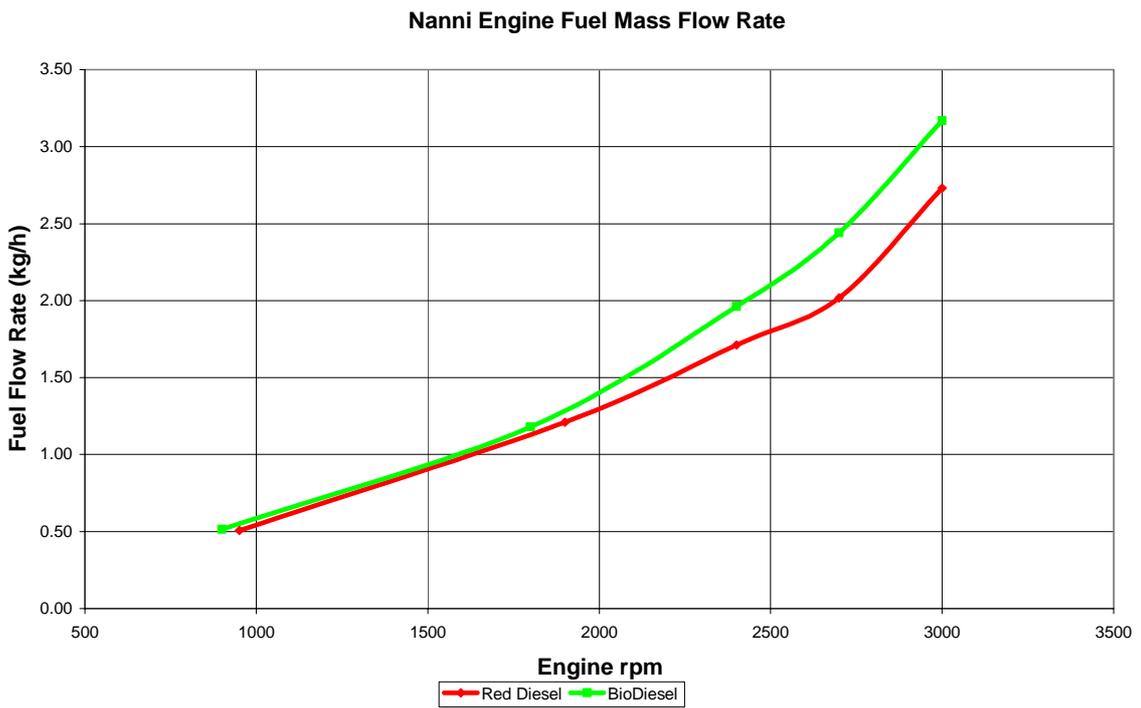


Figure 23

Perkins Engine Exhaust Temperatures

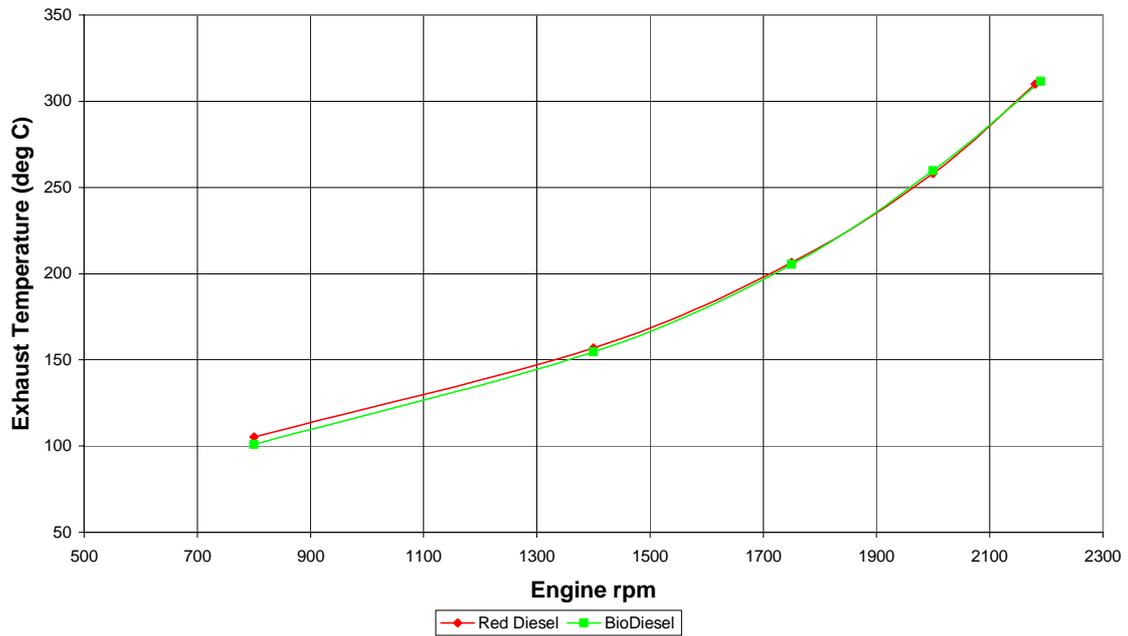


Figure 24

Nanni Diesel Exhaust Temperatures

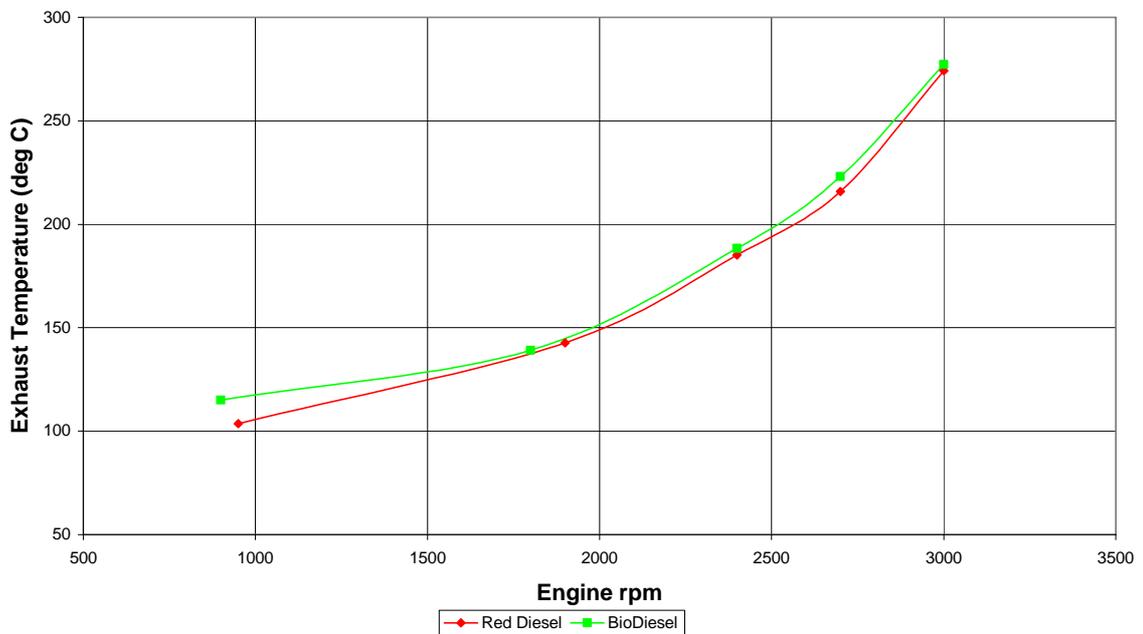


Figure 25

7.1 NO_x emissions

Figures 14 and 15 show that the NO_x emission levels for both engines running on biodiesel is lower than fossil fuel. Significant reduction in NO_x emission level is observed over the entire load range for Nanni diesel engine while reduction, only above 1500 rpm, is observed with the Perkins engine. For the latter NO_x emission levels below 1500 rpm is seen to be almost similar to that of fossil diesel. Both engines show an overall reduction in NO_x emission levels for the biodiesel produced locally in the Norfolk Broads. This suggests that it is not just engine design but fuel which also plays an important role in NO_x formation in an engine. The reduction in NO_x emission levels with biodiesel can be explained with the aid of figure 26.

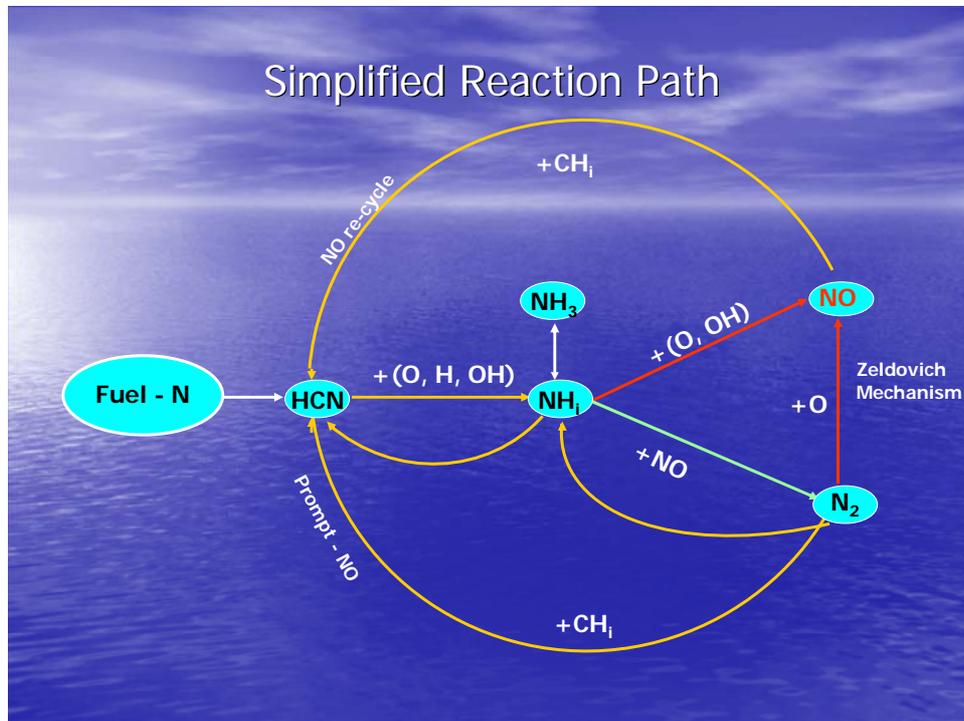


Figure 26: NO_x formation route

Of the three mechanisms i.e. thermal (Zeldovich), fuel and prompt routes through which NO_x is produced, it is the thermal NO_x that is the most dominant player in a diesel engine. It is a function of the flame temperature, residence time and partial pressure of oxygen in the cylinder. The remaining two mechanisms can occur at low temperature provided there is enough fuel bound oxygen or nitrogen. As biodiesel has high level of fuel bound oxygen we would expect higher level of NO_x from the diesel engine provided the thermal NO_x level remains constant. However, this is certainly not the case for this trial as NO_x levels

are lower with biodiesel operation. This may be due to a reduction in thermal NO_x level as the residence time for peak temperature will reduce with biodiesel as a direct consequence of fuel bound oxygen which speeds up the combustion reaction. Continuous combustion tests that have been carried out in the past have shown a shorter flame with biodiesel compared to fossil fuel for the same air to fuel ratio.

The fuel oil analysis shows higher level of bound nitrogen in fossil diesel compared to biodiesel which had trace amounts only. This may have contributed to already high thermal NO_x through the prompt NO route.

7.2 Carbon monoxide emissions

Carbon monoxide formation is principally a function of the air ratio, mixing and the temperature of combustion. It is formed during intermediate stages of combustion and low temperature may prevent conversion of CO into CO_2 . In diesel engines it is found in relatively low concentration in the higher power ranges, but in the lower power range the relative concentration tends to increase and more so in badly maintained engines. Both data (figs 16&17) sets show no significant variation, increase/decrease, in CO emissions from each engine type as the maximum difference recorded is 30 ppm. The majority of CO is formed at the intermediate combustion stage in between the Lean Flame and Lean Flame Out regions, the location of which facilitates contact with these chamber walls.

7.3 Carbon dioxide emissions

The CO_2 emission trend (figures 18 & 19) for both engines is opposite to their CO emission trend i.e. lower at part load and higher at full load. A possible explanation for this is that the CO formed during the intermediate stage of combustion undergoes complete conversion to form CO_2 .

7.4 Oxygen emissions

Residual oxygen in the exhaust is a good indicator of thermal loading of the engine. As expected (figures 20 & 21) the exhaust oxygen concentration demonstrates a clear quadratic trend reducing to minimum of about 11% at full load. The residual oxygen level with biodiesel are not significantly lower than fossil diesel suggesting that the engine is not operating under thermal overload condition at any speed.

7.5 Sulphur dioxide emissions

Biodiesel has trace amounts of sulphur in them compared to fossil diesel which has 0.13%. There is a direct correlation between the fuel bound sulphur and sulphur dioxide emissions, it is double of the fuel sulphur input into the engine. The fossil diesel will produce higher levels of sulphur dioxide compared to biodiesel.

7.6 Fuel consumption

Biodiesel has lower specific energy compared to fossil diesel so the mass of fuel injected into the engine for the same power will be higher. The lower specific energy is a direct consequence of less amount of carbon in the fuel. Figures 22 & 23 show an increased fuel mass flow rate with the use of biodiesel, by as much as 17%.

7.7 Exhaust temperature

Exhaust temperature is another indicator about thermal loading of the engine and follow a trend that is inverse to the amount of oxygen present in the exhaust. Figures 24 and 25 show this trend, however, there is not much difference between the exhaust temperatures when the engines are running on biodiesel or fossil diesel.

8.0 Conclusion

Trials were conducted on two boats in the Norfolk Broads fitted with different engine makes to evaluate the environmental benefits of biodiesel (FAME, sourced locally) compared to fossil diesel. Exhaust emissions, temperature and fuel consumption measurements were carried out on both engines after the necessary system modifications. Results from the tests can be summarised as follows:

1. NO_x emission levels from both engines for the biodiesel used were generally lower compared to fossil diesel. This indicates that the raw material used to produce the biodiesel is crucial to net increase or decrease in NO_x emission level from the engines.
2. Carbon Monoxide levels are higher at low loads and reduce with increasing load under biodiesel operation but are not significantly different than fossil diesel to have any detrimental effect on the environment. The decrease in carbon monoxide emission at high loads is attached with an increase in carbon dioxide emissions showing conversion of more CO to CO₂.
3. There is substantial amount of residual oxygen in the exhaust under biodiesel operation which suggests that the engine is not thermally overloaded within the operating envelope. Also, the exhaust temperatures are not very much different suggesting that the engine was not thermally overloaded when operating on biodiesel.
4. Biodiesel contains trace amounts of sulphur compared to fossil diesel so the sulphur dioxide emission from both engines will be negligible.
5. The fuel consumption encountered by the use of biodiesel was consistently higher than fossil diesel, since a greater amount of the fuel must be injected into the combustion chamber to produce an equivalent amount of work, as evidenced by the lower calorific value stated in the FOBAS analysis.

This study covers only a small part of the effects of biodiesel usage and further work must be undertaken on such areas as lubricity, biodegradability, cost effectiveness, storage stability and life-cycle impact for a complete assessment to be made.

9.0 References

- [1] **“Directive 2003/30/EC of the European parliament and of the council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport”**; *Official Journal of the European Union*
- [2] **“Biodiesel Impacts on Compression Ignition Engine (CIE): Analysis of Air Pollution Issues Relating to Exhaust Emissions”**; A. Demirbas; *Energy Sources Vol.27, pp.549–558, 2005*
- [3] **“Performance and emissions characteristics of biodiesel from soybean oil”**; M. Canakci; *Proc. IMechE Vol.219 Part D: J. Automobile Engineering, 2005*
- [4] **“The atomisation of Rapeseed Methyl Ester in Comparison with Diesel Fuel”**; Y.W.Wang, *University of Newcastle Upon Tyne School of Marine Science and Technology PhD Thesis, 2001*
- [5] **“A feasibility study of the use of biodiesel in recreational boats in the United Kingdom”**; P. L. Zhou, A. M. Fet, O. Michelsen and K. Fet; *Proc. Instn Mech. Engrs Vol.217 Part M: J. Engineering for the Maritime Environment, 2003*
- [6] **“Lubricity of Components of Biodiesel and Petrodiesel. The Origin of Biodiesel Lubricity”**; G. Knothe, K. R. Steidley; *Energy & Fuels Vol.19, pp.1192-1200, 2005*
- [7] **“Study on the lubrication properties of biodiesel as fuel lubricity enhancers”**; J. Hu, Z. Du, C. Li, E. Min; *Fuel Vol.84, pp.1601–1606, 2005*
- [8] **“Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil”**; M.P. Dorado, E. Ballesteros, J.M. Arnal, J. Gomez, F.J. Lopez; *Fuel Vol.82, pp.1311–1315, 2003*
- [9] **“The effect of biodiesel oxidation on engine performance and emissions”**; A. Monyem, J. H. Van Gerpen; *Biomass Bioenerg. Vol.20, pp.317–325, 2001*
- [10] **“The Engine Tests of Biodiesel from Used Frying Oil”**; Y. Ulusoy, Y. Tekin, M. Çetinkaya, F. Karaosmanoglu; *Energy Sources Vol.26, pp.927–932, 2004*
- [11] **“Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil”**; A.S. Ramadhas, C. Muraleedharan, S. Jayaraj; *Renewable Energy Vol.30, pp.1789–1800, 2005*
- [12] **“Emission characteristics of diesel engine operating on rapeseed methyl ester”**; O.M.I. Nwafor; *Renewable Energy Vol.29, pp.119–129, 2004*
- [13] **“Fuel properties and emissions of soybean oil esters as diesel fuel”**; D.Y.Z. Chang, J.H. Van Gerpen, I. Lee, L.A. Johnson, E.G. Hammond, S.J. Marley; *J Am Oil Chem Soc Vol. 73, pp.1549–55, 1996*

- [14] **“Biodiesel from set-aside land. A story of success? Sustainable agriculture for food, energy and industry”**; K. Scharmer; *London: James & James, pp.844–48, 1998*
- [15] **“Biodiesel as alternative fuel: Experimental analysis and energetic evaluations”**; C. Carraretto, A. Macor, A. Mirandola, A. Stoppato, S. Tonon; *Energy Vol.29, pp.2195–2211, 2004*
- [16] **Appendix 2: State of the Art Review**; M.J. Landamore, *University of Newcastle Upon Tyne, May 2005*
- [17] **“Use of vegetable oils as I.C. engine fuels—a review”**. A.S. Ramadhas, S. Jayaraj, C. Muraleedharan. *Renewable Energy Vol.29, 2004*
- [18] **“Biodiesel stability under commercial storage conditions over one year”**; P. Bondioli, A. Gasparoli, L. Della Bella, S. Tagliabue, G. Toso; *Eur. J. Lipid Sci. Technol. Vol.105, pp.735–741, 2003*
- [19] **“The effect of biodiesel oxidation on engine performance and emissions”**; A. Monyem, J. H. Van Gerpen; *Biomass Bioenerg. Vol.20, pp.317–325, 2001*
- [20] **“Evaluation of biodiesel storage stability using reference methods”**; P. Bondioli, A. Gasparoli, L. Della Bella, S. Tagliabue; *Eur. J. Lipid Sci. Technol. Vol.104, pp.777–784, 2002*
- [21] **“The impact of antioxidants on biodiesel oxidation stability”**; S. Schober, M. Mittelbach; *Eur. J. Lipid Sci. Technol. Vol.106, pp.382–389, 2004*
- [22] **“Wear Assessment in a Biodiesel Fueled Compression Ignition Engine”**; A. K. Agarwal, J. Bijwe, L. M. Das; *Trans. ASME Vol.125, pp.820-827, 2003*
- [23] **“Testing Waste Olive Oil Methyl Ester as a Fuel in a Diesel Engine”**; M. P. Dorado, E. Ballesteros, J. M. Arnal, J. Gomez, F. J. Lopez Gimenez; *Energy & Fuels Vol.17, pp.1560-1565, 2003*
- [24] **“Sunflower Methyl Esters for Direct Injection Diesel Engines”**K.R. Kaufman, M. Ziejewski; *Trans. ASAE, pp.1626-1633, 1984*
- [25] **“Transesterified Curcas Oil Blends for Farm Diesel Engines”**; Y. Ishii, R. Takeuchi; *Trans. ASAE Vol.30 pp.605-609, 1987*
- [26] **“Impact of cold flow improvers on soybean biodiesel blend”**; C. Chiu, L. G. Schumacher, G. J. Suppes; *Biomass and Bioenergy Vol.27 pp.485–491, 2004*
- [27] <http://www.channel4.com/4car/buying-guide/faq/biofuels/>; Accessed 15/08/05
- [28] **BioDiesel Product Specification**, *Broadland Fuels Ltd, Data provided 23/11/05*
- [29] **Hydrocarbon Duty Rates**, *Budget 2005, HM Customs and Excise, 16 March 2005*
- [30] <http://www.ebb-eu.org/stats.php>; Accessed 15/08/05

[31] **“Assessing the Viability of using Rape Methyl Ester (RME) as an Alternative to Mineral Diesel Fuel for Powering Road Vehicles in the UK”**; A. Williamson, O. Badr; *Applied Energy*, Vol. 59, No. 2-3, pp. 187-214, 1998

[32] **“Engine Emissions: Pollutant Formation and Measurement”**; G.S. Springer, D. J. Patterson, eds.. *New York, and London: Plenum Press, 1973.*

[33] **“Exhaust Emissions from Combustion Machinery”**; A.A. Wright, *Mep Series*, Vol 3, Part 20

[34] **“An Investigation into Effect of Ambient Condition on Nitrogen Oxide Emission Level from Marine Diesel Engines”**; S.K. Nanda, *MSc Dissertation, School of Marine Science and Technology, University of Newcastle Upon Tyne*