Helping to save the planet one drop at a time

ALTERNATIVE PETROLEUM TECHNOLOGIES

Reversing the increase in NO_X emissions in a diesel engine associated with B20 fuel relative to diesel and improving the overall regulated emissions.

Alex Psaila

Much of the information contained in this presentation was first published as a JSAE and SAE paper (JSAE 2011937/ SAE 2011-01-1949) entitled 'Improving Biodiesel Blended Fuels: Overcoming the NO_X Penalty and Enhancing the Engine's Regulated Emissions Profile'. Authors: Alexander Francis Psaila, Patrick M Grimes, Richard L. Ellis. This work was presented by the author at the recent JSAE/SAE conference at Kyoto on 31st August 2011.

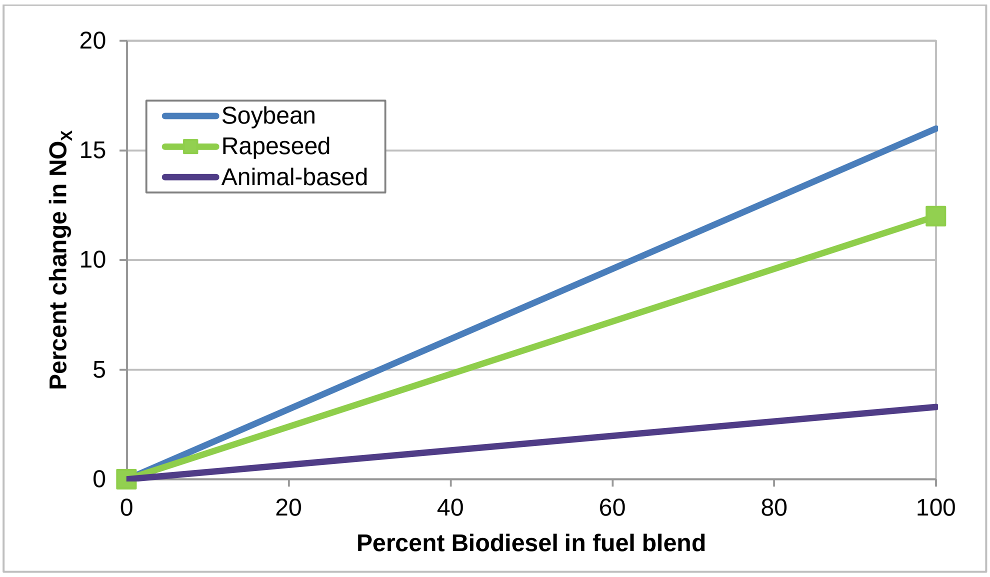
Introduction

This paper brings together two exciting technologies, biodiesel and emulsified fuels.

The concept of using atmospheric CO_2 and water to make a fuel using nature's biosynthetic processes is attractive in a developing world where our need for energy is growing and the impact of our activities on the environment is becoming increasingly apparent. It is the contention of the author that whatever the problems and challenges facing the implementation and adoption of biodiesel as a substitute for diesel will be, in time, overcome and a genuinely sustainable fuel emerges.

Several studies have been conducted which quantify the emissions associated with biodiesel containing fuels relative to diesel fuels. A much quoted study was posted by US EPA in 2002 (US Environmental Protection Agency. "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report." (October 2002), EPA420-P-01_001). In this study it was shown that PM, CO and HC are significantly reduced with biodiesel fuel whereas NO_X emissions increase. Figure 1 illustrates this increase in NO_X. It is worth noting that (1) the increase is linear with biodiesel content in the blended diesel-biodiesel blend; (2) the B20 (20% volume of biodiesel in the blend) shows an increase of around 3% NO_X in the worst case; (3) the increase depends on the origin of the fatty acid methyl ester (FAME). The soybean derived biodiesel shows the highest increase, the animal-based material the lowest with the rapeseed in between the two.

Figure 1: Effect of Biodiesel source on NO_X emissions (relative to diesel)



Initially this difference in NO_X emissions was linked to the bulk modulus of compressibility of the various biodiesel materials and the consequent impact this had on the engine's timing. However this hypothesis was not able to explain the persistence of this effect with common rail engines. The more important observation is that the ranking of the NO_X increase is the same order of increasing double bonds in the fatty acid backbone. The more highly unsaturated the parent fatty acid the greater the NO_X increase.

Emulsion fuels have been around for many years and have successfully found niche markets for both diesel and open flame applications. The ability of emulsified water in diesel fuel to reduce both NO_X and PM emissions simultaneously is a rare if not unique achievement for a single technology. Emulsified fuels have also demonstrated in practical application other advantages which flow from the fact that this diesel-like material cleans and keeps clean the engine's fuel and ignition system as well as reducing the soot loading on the lubricant and after-treatment units. This often results in observations of fuel efficiency and reduced maintenance costs.

Disadvantages associated with commercialisation of this technology in the fleet automotive heavy duty sector have also been encountered; chief among them are the logistics and distribution of the fuel and poor engine performance. However these difficulties are principally associated with high water containing emulsions (around 20% mass water). Indeed there are many examples of emulsion fuels being used successfully for many years where the water content is below 13% mass water.

This paper argues that most of the benefits of emulsion fuels come with the first few percentages of water introduced into the fuel and that virtually all the problems emerge as the water content is raised to high levels.

Engine Test Studies

Two engine tests will be presented. The scope of these studies is summarised below:

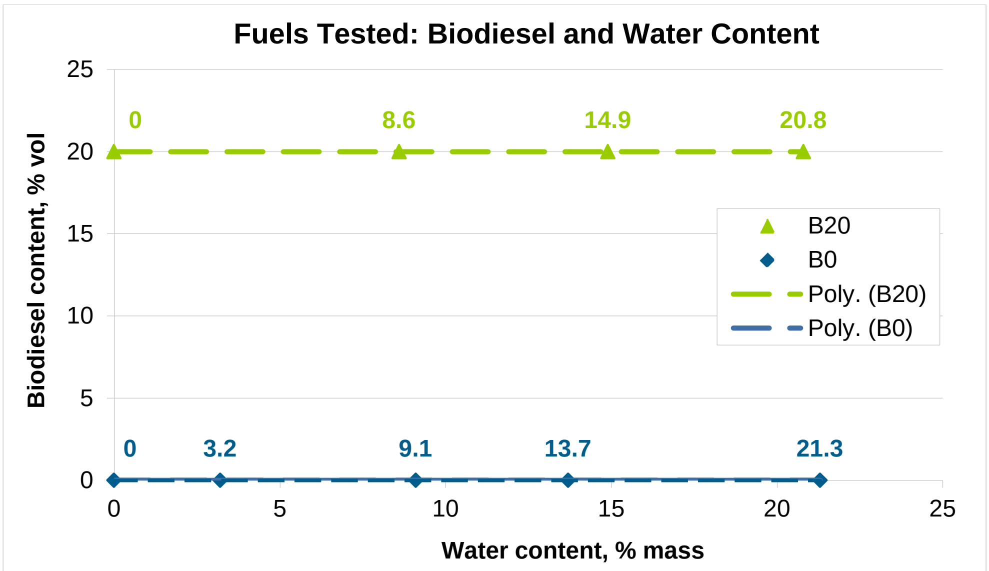
- **Study 1**: Effect on emissions of changes in Biodiesel content (B0 and B20) and water content (0 to 21%m water).
- **Study 2**: Optimisation of a biodiesel emulsion fuel with the same NO_X emissions as diesel.

Study 1: A 12.7 L Detroit Diesel Series 60 engine (1991 Model Year). The details are shown below.

Engine Parameter	Comment
Engine Serial Number	06R0038671
Make	Detroit Diesel
Engine displacement and configuration	12.7L; 1-6
Emission Family	MDD 12.7FZAK
Rated Power	365 hp at 1800rpm
Electronic Control Module	DDEC-II
Aspiration	Turbocharged

- **Test Cycle**: US Federal Test Procedure - transient cycle of 1199 seconds. Tests on each fuel were carried out in triplicate.
- **Emissions measurements**: PM, NO_X, THC, CO, CO_2
- **Fuels**: Nine fuels are discussed in this paper, five based on diesel (B0) and four on B20 base fuels. The fuel details are shown in tabular and graphical form below. The same ultra-low sulfur diesel was used in all the fuels, a 15ppm max. sulfur diesel. The B100 fuel used to blend into the B20 fuel conformed to ASTM D6751 specification.

Test No.	Code	Biodiesel %v. FAME	Water % vol.	Water % mass
1	B0-1	0	0	0
2	B0-2	0	2.7	3.2
3	B0-3	0	7.7	9.1
4	B0-4	0	11.7	13.7
5	B0-5	0	18.5	21.3
6	B20-1	20	0	0
7	B20-2	20	7.4	8.6
8	B20-3	20	12.9	14.9
9	B20-4	20	18.2	20.8



Note: B0 is diesel; B20 is a blend of 20% vol. of FAME (fatty acid methyl ester) with diesel.

ALTERNATIVE PETROLEUM TECHNOLOGIES

Study 2: A 10.8 L Cummins QSM 11C Tier 2 engine (2004 Model Year). The details are shown below. This engine was selected as it was the same type fitted to vehicles which were to be used in a three month demonstration trial.

Engine Parameter	Comment
Engine Serial Number	60420004
Make	Cummins
Model	QSM 11C
Engine Displacement	10.8 litre
Emission Family	4CEXL0661AAC
Rated Power	330 hp at 2100rpm
Aspiration	Turbocharged

- **Test Cycle**: US Non Road Transient Cycle of 1200 seconds. Tests were carried out in duplicate.
- **Emissions measurements**: PM, NO_X, THC, CO, CO_2.
- **After-treatment**: Diesel Oxidation Catalyst (DOC) supplied by Engine Control Systems.
- **Fuels**: Three fuels were tested, B0, B20 and EmB20 (6% m water emulsified in B20). The last was also tested on the engine fitted with a DOC (diesel oxidation unit) after-treatment unit. The B100 FAME fuel was specifically chosen (from soybean) for its high NO_X emissions. The 6% mass water was expected to restore comfortably the NO_X emission to the B0 level, based on the conclusions from Study 1.

Fuel	Test No.
Diesel (B0)	A1
	A2
B20	B1
	B2
EmB20	C1
	C2
EmB20DOC	D1
	D2

Results and Discussion

The expected performance of the three technologies, emulsion fuels, biodiesel (FAME) and DOC on THC (total hydrocarbon), CO (carbon monoxide), NO_X and PM emissions is summarised below in tabular form in the first three columns.

Changes relative to Diesel

	Em Water	FAME	DOC	EmB20+DOC
THC	+	-	-	-
CO	-	-	-	-
NO_X	-	+	0	-
PM	-	-	-	-

Key: Green (-) indicated a reduction in emissions;
Red (+) indicates an increase; Blue (0) indicates no change.

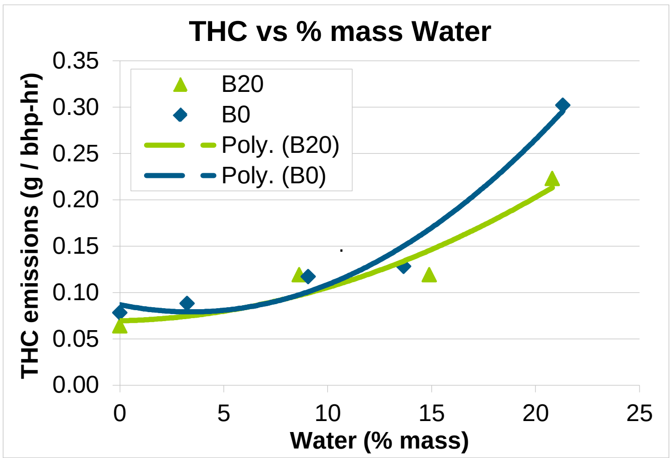
Previous studies, as well as the data reported here, concluded that emulsion fuels are effective in reducing both NO_X and PM emissions. Hydrocarbon emissions (THC) are more often than not slightly worse. Biodiesel improves THC, CO and PM but NO_X deteriorates. DOC is neutral on NO_X but improves the other three emissions. The combination of emulsified biodiesel with a DOC can be expected to show excellent improvements across all emissions.

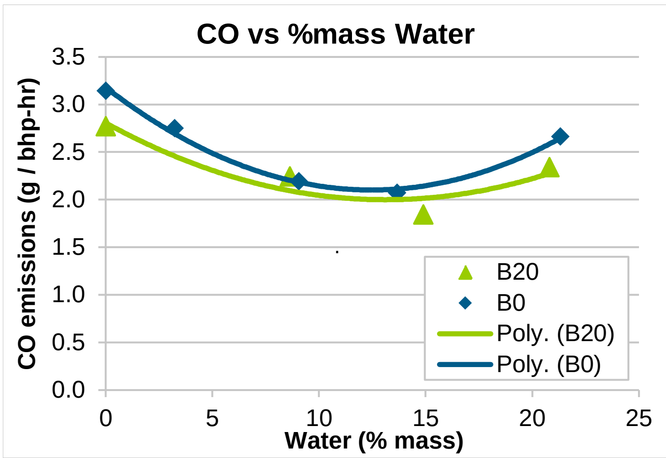
The hypothesis that this paper explores is that the benefits associated with the introduction of water into a fuel are greatest (on a percent of water basis) when the water content is low and that the adverse effects on emissions and performance are severest at high water contents.

Results of Study 1

This study address the question: What is the pattern of change in emissions (HC, CO, NO_X and PM) when water is introduced, in increasing quantities, in a B0 and B20 fuel?

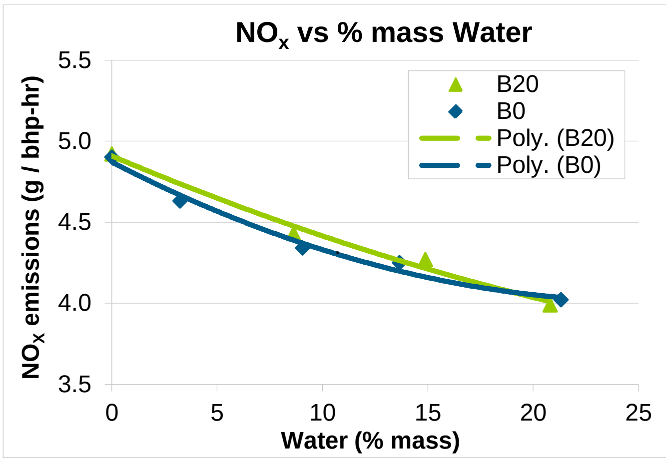
The effects on THC and CO are shown below. The emissions are plotted against the water content (x-axis). In both cases the blue graph (B0) is above the green graph (B20), indicating the reduction in emissions for the B20 fuels.

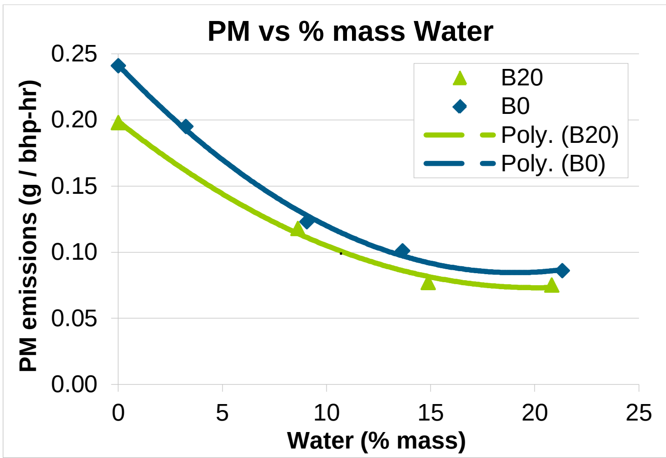




The intercepts on the y-axis are the emissions values obtained with the fuels without water. The THC data indicates that up to around 5% water the increase in emissions is slight. This deteriorates at higher water contents. The improvement in CO with increasing water content reaches a minimum around 12% and then increases.

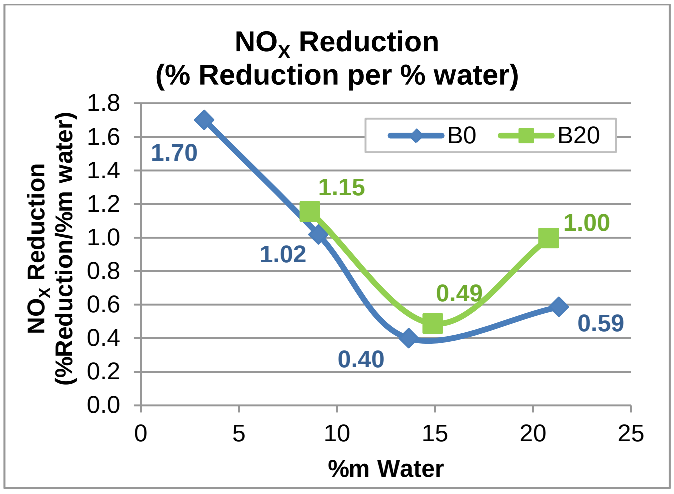
The data for NO_X and PM are shown below. The increase in NO_X with B20 is illustrated by the green graph lying above the blue (B0 or diesel) graph. As water is increased both NO_X and PM diminish. It is apparent even to the naked eye that the slopes of the graphs noticeably diminish as water content increases.

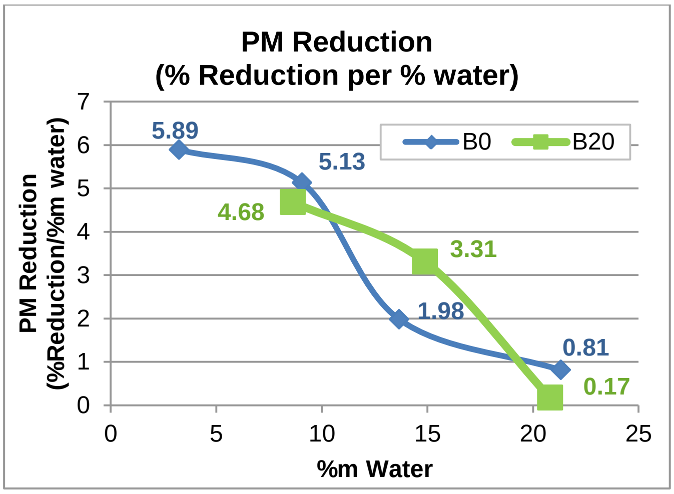




Rate of Change of NO_X and PM Emissions with Water Content

The old rule of thumb stated that for every percent of water NO_X is reduced by 1% and PM by 2%. The differential of the NO_X and PM graphs (the slope) shown above have been calculated and plotted. Non-linear relationships for both NO_X and PM reductions with increasing water contents are evident. These are shown below.



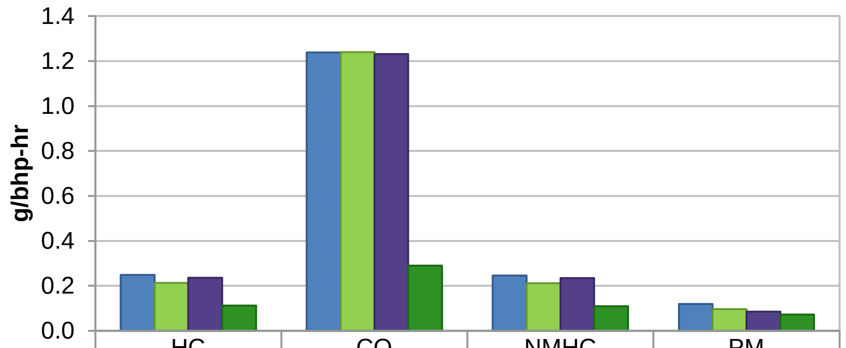


These graphs indicate a significantly higher reduction in both NO_X and PM per unit of water added when the water content is lowest. For diesel (B0) the first data point was for 3.2% water and shows a NO_X reduction of 1.7% per % water and PM reduction of 5.9% per % water. For B20 the first data point was for 8.6% water and shows a NO_X reduction of 1.15% per % water and a PM reduction of 4.7% per % water. Above 10% water both NO_X and PM reductions per % water drops drastically.

Results of Study 2

A soybean B100 fatty acid methyl ester was selected to make up B20 emulsions with an expected NO_X increase of around 3%. From Study 1, 2% to 3% water would be sufficient to reverse the NO_X increase. It was decided to make a 6% water emulsion.

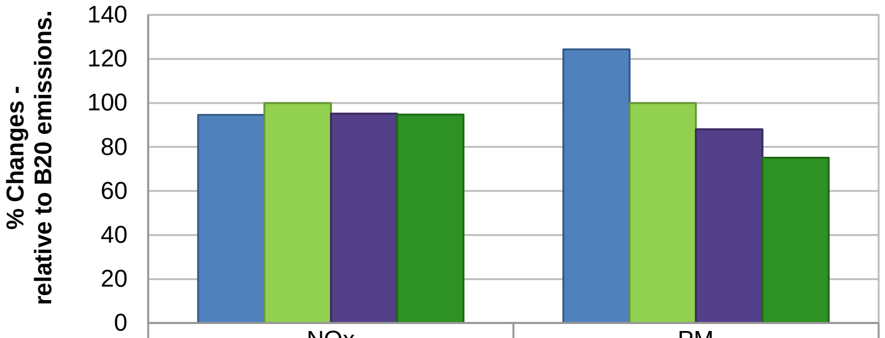
The HC (and non-methane HC, NMHC), CO and PM emissions are shown below.



	HC	CO	NMHC	PM
BLD	0.249	1.238	0.247	0.120
B20	0.214	1.241	0.212	0.097
EmB20	0.236	1.231	0.234	0.085
EmB20DOC	0.112	0.290	0.110	0.073

All the EmB20 fuel emissions are lower than diesel (B0). The DOC further reduces all emissions, except for NO_X.

The NO_X and PM results are shown below – on this occasion the emissions are shown on a % basis relative to B20 (100%). The NO_X increase associated with B20 (5.7% over B0) is higher than expected from the US EPA report (2002).



	NOx	PM
Diesel, B0	95	124
B20	100	100
EmB20	95	88
EmB20+DOC	95	75

Despite this the NO_X increase, due to the change from B0 to B20, is restored to the low level seen with diesel when the emulsified fuel is used. The stepwise reduction in PM is illustrated as the fuel is changed and DOC is introduced. The overall change from diesel to EmB20 + DOC is 40%.

Overall Conclusions

- The combination of 6% water in a B20 emulsion is able to eliminate the highest NO_X levels (5.7%) associated with inclusion of biodiesel in fuel blend;
- The low water content achieves the maximum reductions in emissions (PM, NO_X, CO) while minimising the increases in THC per unit of water; indeed ALL the regulated emissions are maintained below the baseline diesel levels;
- Optionally a DOC after-treatment unit may be used which further enhances the reductions in THC, PM and CO;
- Field Demonstration of EmB20 (6% water) with and without DOC over a 3 month period indicated satisfactory performance with no noticeable operational issues.