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ASSESSMENT OF BUS EXHAUST EMISSIONS FROM TALLOW METHYL ESTER BIODIESEL BLENDS

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25 May 2006

Summary

This report documents findings of research on two in-service buses fuelled with tallow methyl ester (TME) biodiesel blends of 20% (B20) and 40% (B40) TME in 50ppm sulphur automotive diesel fuel (ADF) referred to as the 50ppm fuel. The same batch of 50ppm fuel was used as the reference fuel for the experiments. This programme was conducted as a postgraduate research project and in co-operation with the Auckland Regional Council (ARC), BP Oil New Zealand Limited, the Energy Efficiency and Conservation Authority (EECA) and the Energy and Fuels Research Unit (EFRU) of the University of Auckland.

One bus was manufactured in 1997 and is of Japanese origin the other manufactured in 1988 and of European origin. The buses were operated on a chassis dynamometer at a number of steady state speed and load conditions along with a transient test. Fuel consumption (FC), power output and exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and particulate matter (PM) were measured and results compared between the 50ppm fuel and the biodiesel blends. Experimental results were then compared with existing published data, including the bus emissions prediction model (BEPM) [1], and a prediction made for emissions and performance of buses operating on a 5% TME biodiesel blend (B5).

Table 1-1 shows experimental results display decreasing levels of all measured exhaust emissions with increasing biodiesel content of fuel. Emissions of CO and PM matched well with existing published data and the BEPM. Experimental HC emissions reductions resulting from TME biodiesel proportion were on average less than those indicated by published data and the BEPM but inside the range of variation displayed by published data. NO_x emissions decreased with TME biodiesel usage directly opposing published data, further research into TME biodiesel effects on NO_x emissions is recommended. Power and volumetric fuel consumption on average displayed penalties of less than 2% with either biodiesel blend and the range of variation in the data does not allow a conclusive statement regarding power and fuel consumption to be made without further investigation.

Table 1-1. Summary of experimental results showing percentage change in emissions and performance of buses operating of TME biodiesel blends relative to the 50ppm fuel.

Emissions / fuel consumption	B5 (interpolated)	B20	B40
CO	-2.8%	-11.1%	-22.2%
HC	-2.4%	-9.5%	-18.9%
NO_x	-0.9%	-3.5%	-6.9%
PM	-2.2%	-8.7%	-17.4%
FC	0.2%	0.9%	1.7%

Acknowledgments

The following people and organizations supported and contributed towards the completion of this project.

BP Oil New Zealand Limited – Dr. Barry Blackett

Auckland Regional Council – Dr. Gerda Kuschel

Energy Efficiency and Conservation Authority – Andrew Smith

Stagecoach New Zealand – Allan Cannell and Warren Doel

Gough Gough and Hamer – Steve Matthews and Steve Lawn

Energy and Fuels Research Unit – Stephen Elder, Derek Hobbis and A/Prof. Robert Raine

Glossary

50ppm	The reference fuel used in the experiments, 50ppm sulphur diesel
ADF	Automotive diesel fuel
ARC	Auckland Regional Council
B20	20% biodiesel by volume in automotive diesel fuel blend
B40	40% biodiesel by volume in automotive diesel fuel blend
B5	5% biodiesel by volume in automotive diesel fuel blend
BEPM	Bus emissions prediction model
CO	Carbon monoxide
CO2	Carbon dioxide
CVS	Constant volume sample
DT80	A drive cycle emissions test for heavy duty diesel vehicles in Australia [3]
EECA	Energy Efficiency and Conservation Authority
EFRU	Energy and Fuels Research Unit
EPA	Environmental Protection Agency (USA)
Euro-0	A European emissions specification for heavy duty diesel vehicles
FC	Fuel consumption (on a volumetric basis, ie. litres of fuel per kilometre)
FID	Flame ionization detector
HC	Hydrocarbons
J94	A Japanese emissions specification for heavy duty diesel vehicles
NDIR	Non dispersive infrared
NO_x	Oxides of nitrogen
O2	Oxygen
PDP	Positive displacement pump
PM	Particulate matter
TME	Tallow methyl ester
UOA	University of Auckland

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1. Introduction

Tallow methyl ester (TME) is a liquid fuel that can be substituted for conventional petroleum based diesel in diesel engines and is part of a range of fuels commonly known as biodiesels. TME is made by reacting methyl alcohol and animal tallow in a process known as transesterification. TME biodiesel has been identified as a potential biofuel for use in New Zealand. It is anticipated that TME would probably be utilized by blending with standard petroleum based automotive diesel fuel (ADF). Biodiesel blend proportions could be variable over time and between private and commercial vehicle fleets.

This report is based on work carried out by the University of Auckland (UOA) Energy and Fuels Research Unit (EFRU) in conjunction with a postgraduate research project [2]. The report investigates the impact of TME blends on commonly regulated exhaust emissions, power and fuel consumption of two in-service buses from the StageCoach fleet in Auckland.

TME blends of 20% (B20) and 40% (B40) TME in ADF are used in this study and results are interpolated for a 5% (B5) blend. The vehicles were tested on a chassis dynamometer at a range of steady state speed and load conditions along with a power test and simple transient test similar to the DT80 drive cycle used for heavy vehicles emissions testing in Australia [3]. Results are then compared with international data collated by the Environmental Protection Agency (EPA) [4].

2. Testing overview: Equipment and methodology

2.1. Heavy vehicle research facility

The testing facility consists of two primary parts, a chassis dynamometer and exhaust emissions analysis equipment. The dynamometer provides measurement and control of vehicle speed and load parameters at the vehicles drive wheels. Single or dual drive axles up to 410 kW output at the wheels can be catered for.

The exhaust emissions measurement system is a positive displacement pump (PDP) style constant volume sampler (CVS) system that dilutes the entire exhaust gas sample in a mixing tunnel before emissions sampling. The system utilizes modal recording of dilute emissions species sampling at a rate of 1Hz. Gaseous analysis systems are calibrated in accordance with Australian [5] and USA federal standards [6] ensuring an accuracy of +/- 2%.

Gaseous emissions measurements include non dispersive infra red (NDIR) measurement of carbon monoxide (CO) and carbon dioxide (CO_2), flame ionizing detector (FID) measurement of hydrocarbons (HC) and chemiluminescent measurement of oxides of nitrogen (NO_x). In addition, raw and dilute exhaust oxygen (O_2) were analyzed using two paramagnetic oxygen analyzers.

Particulates are measured using gravimetric filter sampling through a secondary dilution system. Light scattering photometry and non-dilute exhaust opacity measurements are also recorded to provide support for gravimetric measurements and time dependant PM emissions information.

Secondary parameters recorded at the facility include; engine inlet air temperature, engine speed, fuel consumption (FC), ambient temperature, humidity and pressure.

For a detailed description of the facility, capabilities and calibration techniques see [2].

2.2. Vehicles

Two buses were tested on TME blends, these are referred to a bus A and bus B.

Bus A is a Nissan Scorpion SLF 180. The engine is of Japanese origin, manufactured in 1997 and expected to meet the J94 emissions regulations in place at the time of production. It has a tare mass of 7.4 tonne and a capacity of 38 seated passengers plus room for additional standing passengers in the aisle. The engine is an FE6 naturally aspirated 6.9 litre inline six cylinder direct injection diesel engine. This vehicle has no exhaust gas after treatment devices fitted.

Bus B is a MAN SL202. The engine is of European origin manufactured in 1988 and is expected to meet the Euro-0 emissions regulations in place at the time of production. It has a tare mass of 8.9 tonne and a capacity of 45 seated passengers plus room for additional standing passengers in the aisle. The engine is a D2566UH naturally aspirated 11.4 litre inline six cylinder direct injection diesel engine. This vehicle has no exhaust gas after treatment devices fitted.

Further specifications for each bus are included in Appendix B.

2.3. Fuels

Three fuels were used during this programme. A 50ppm sulphur automotive diesel fuel (ADF) “reference” fuel and blends of 20% and 40% tallow methyl ester (TME) in the same batch of 50ppm sulphur ADF. The three fuels will be referred to as 50ppm, B20 and B40 respectively. The reference data collected with the 50ppm fuel was taken before biodiesel fuel tests and in most cases the 50ppm fuel was re-tested after the biodiesel tests were completed. In these cases the second set of 50ppm results will be referred to as “50ppm post” if it is being singled out for discussion separate to the bulk of the 50ppm data. The purpose of the 50ppm post tests being to provide information on any changes in engine behavior over the testing period.

Specifications for the 50ppm fuel and the TME are included in Appendix C.

2.4. Testing methodology

The buses were tested at a range of steady speed and load conditions referred to as modes. Due to the nature of the bus fuel rack control systems and the dynamometer’s response behavior, some speed and load conditions were not able to be maintained in a stable fashion. Testing was only able to be conducted at either the governed maximum engine speed or at the maximum power output achieved at the full actuation position of the fuel rack. Further to this, the automatic transmissions present in both vehicles restricted the minimum engine speed that could be tested at full load. For full details of the issues encountered and the decisions made in developing this mode schedule refer to [2]. The final arrangement of test modes is shown in Table 2-1.

Table 2-1. Steady state test conditions

Mode	Bus A	Bus B
1	3000rpm at 100% load	2250rpm at 100% load
2	2800rpm at 100% load	1850rpm at 100% load
3	2200rpm at 100% load	1350rpm at 100% load
4	3200rpm at 60% load	2300rpm at 75% load
5	3200rpm at 30% load	2300rpm at 45% load
6	3200rpm at 10% load	2300rpm at 16% load
7	Idle	Idle

Each mode was maintained until the bus speed and power outputs were stable at which time emissions measurement would commence, recording over a further two minute period.

Two transient tests were also conducted to complement the steady state tests. The first was a power test also known as a lug down power test in which the vehicle is operated at maximum rack and the dynamometer used to “lug” the engine speed down in a series of steps, the power output being recorded at each step. No emissions measurements were taken during the power tests. The second is a series of accelerations to 80km/h from standstill under full rack conditions. This test was designed to simulate the DT80 test in use in Australian for heavy duty diesel vehicle emissions testing [3]. The full range of emissions was recorded during these DT80 simulations.

3. Steady state results and discussion

3.1. Brief introduction to results

The results presented in this report have been presented in a summarized format, the following information is intended to assist in the interpretation of results. For a full description of the assumptions and practices employed when analyzing and presenting the test data see [2].

The buses tested in this report have engine control systems which result in the operation of the buses at either full rack or very low rack settings. This translates to an on road driving style made up of periods of full load acceleration and periods of idle type operation with little in between. As such the most relevant test results are those taken at full rack. These full rack states are the high load or power conditions at which the majority of fuel is consumed and emissions are generated, further identifying them as the most relevant tests. Vehicles equipped with manual transmissions typically have finer engine fuelling control systems and so part load conditions become more relevant than they are in this case. As such the summarized steady state emissions results will be presented in two parts, the average for all full load tests and the average for all non full load tests. All data will be used when developing correlations and comparison with data from external sources.

Emissions have been reviewed in terms of grams of pollutant per litre of fuel consumed because this reduces minor variations in results caused by variations in vehicle operating conditions. For example a bus tested at a single test point repeated several times will have minor differences in engine speed and or fueling rate between tests. These variations will result in variations in fuel consumption and total pollutant mass. Referencing the pollutant mass by fuel consumption rate reduces the impact of these variations improving the quality of the emissions results by reducing the scatter of the data. This also reduces the statistical uncertainty of the results.

All power figures stated are brake power measured at the wheels in 3rd gear and corrected for atmospheric conditions. Oxides of Nitrogen results have also been corrected for ambient humidity using equations set out in [5].

3.2. Power and volumetric fuel consumption

For diesel engines power and fuel consumption is directly related to the energy content of the fuel consumed. Diesel fuel injection pumps are designed to deliver fuel to the engine on a volume basis, control of which is independent of the type of fuel being used. That is to say fuel with a higher energy per volume may result in more power if the injection pump calibration is unaltered. TME biodiesel has both a lower specific energy i.e. energy per unit mass, and a higher density than ADF. Combined this means that fuel energy reductions associated with TME blends are minor on a per volume basis (Table 3-1).

Table 3-1. Fuel properties

Fuel	Net energy (MJ/kg)	Density at 15ºC (kg/m^3)	Net energy (MJ/m^3)	Energy change based on MJ/m^3
50ppm	43.02	828	35620	0.0%
B20 (interpolated)	42.01	837	35162	-1.3%
B40 (interpolated)	41.00	846	34686	-2.6%
B100	37.97	874	33185	-6.8%

During the testing procedure an error was encountered with the B20 test data from bus A in the form of a signal drift from the dynamometer load cell. This has led to all B20 power results for bus A given here being corrected by applying a 4% reduction from the raw result, full details of the experimental issues are given in [2].

The experimental results are in two parts, the power tests and steady state results. Power tests are conducted with the vehicle fuel system operating at full rack As such, no difference in volumetric fuel consumption occurs between any of the tests. The corresponding power curves show minor variations in power between fuels with trends being distinct between the two buses. Bus A (Figure A 1) shows minor increases in power output for the two biodiesel blends, primarily with B20. Bus B (Figure A 2) shows minor decreases in power output for the B40 blend. Both figures show the variation in power readings during the tests, the uncertainty level of the data being around 4%. Table 3-2 summaries the power test results, displaying the change in peak power observed with each bus and fuel combination from the 50ppm fuel.

Table 3-2. Percentage change in average peak power output of buses on biodiesel blends during power tests.

	B20	B40
Bus A	5.2%	1.1%
Bus B	-0.7%	-4.4%

Table 3-3 shows the equivalent average power figures obtained from the steady state tests.

Table 3-3. Percentage change in average peak power output of buses on biodiesel blends during steady state tests.

	B20	B40
Bus A	-1.5%	1.4%
Bus B	-4.4%*	-2.5%*

* Results interpolated from engine speed points either side of peak power speed.

It is apparent that the steady state tests and the power test results do not correlate well for changes in power output. This is partly because the differences observed are in the order of 1-4% and at these levels instrument accuracy and normal variations in vehicle performance can have significant impacts. More steady state tests were taken than power tests and so the steady state data should be considered the more accurate of the two data sets.

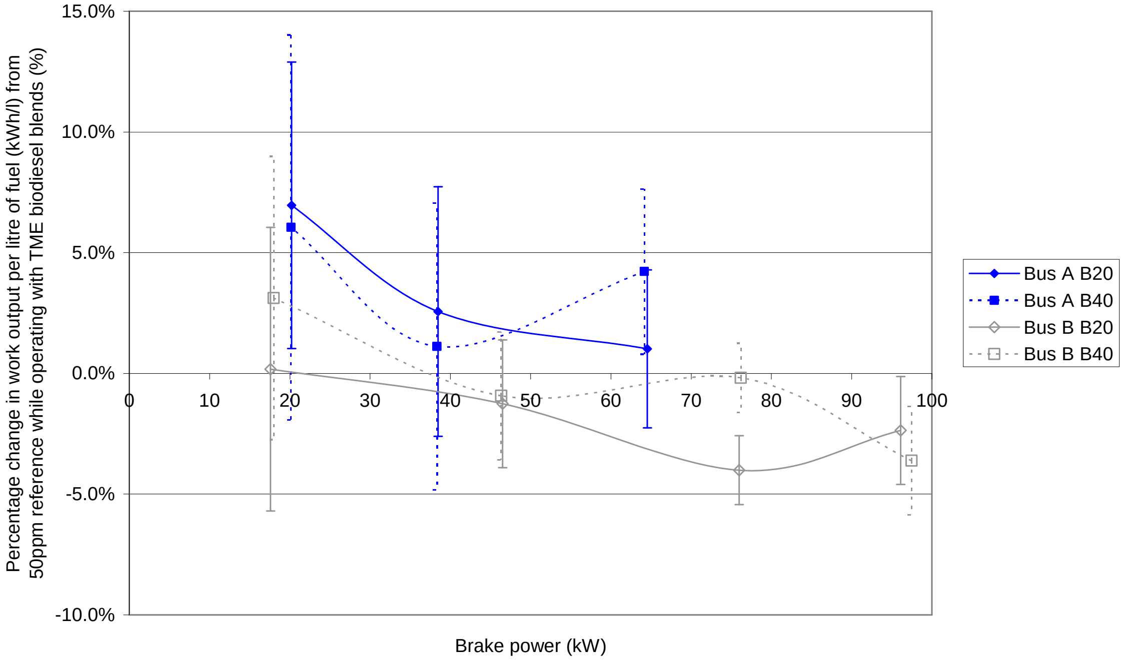

Figure 3-1. Percentage change in work output per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output compared to reference ADF. I bars indicate the 95% confidence intervals of the data.

Reviewing the steady state power results combined with fuel consumption rates provides the most accurate indication of engine performance with TME biodiesel. Figure 3-1 shows the work output per litre of fuel observed with the biodiesel blends at different engine power outputs and one engine speed. These results show an increase in overall engine output with bus A on biodiesel blends and a decrease with bus B on biodiesel blends. It is also apparent that the differences between B20 and B40 are not easily identifiable as the two fuels intersect at one or more points for both buses. A trend of decreasing biodiesel work output per litre with increasing power output is also observable but this trend is not a strong one. The vertical error bars displaying the 95% confidence intervals of the data also show a high degree of scatter in the data relative to the very small differences observed, particularly in the case of bus A.

Figure A 3 shows the equivalent data presented as a function of engine speed at maximum power output. The overall result is similar to the steady state power results and the average values for change in work output per litre of fuel are presented in Table 3-4.

Statistical analysis suggests that the difference in work output per litre of fuel results for bus B are statistically significant at all full load conditions but only for full load at maximum speed and B40 fuel for bus A. Generally the low load results are not statistically significantly different to the 50ppm fuel.

Table 3-4. Average change in work output per litre of fuel for TME biodiesel blends compared to reference ADF at maximum power output and varied engine speed.

Fuel	Bus A	Bus B	Average	Anticipated based on fuel properties (Table 3-1)
B20	-0.8%	-3.0%	-1.9%	-1.3%
B40	2.1%	-3.6%	-0.7%	-2.6%

The two buses exhibit different behavior in terms of power and fuel consumption when operated on the biodiesel blends relative to the 50ppm fuel. Bus A has shown an improvement in power and fuel economy at several test points while bus B has shown decreases in power and fuel economy. The averaged results in Table 3-4 shows that the experimental data did not produce a clear trend in power and fuel consumption behavior modification with increasing biodiesel content of fuel. The averaged results do show that the correlation with biodiesel content is a penalty to both fuel consumption and power output but that in blends of up to 40% TME such penalties are sufficiently small (in the order of 1-2%) and are likely to be within the boundaries of experimental error. More conclusive results would require further work involving sampling of a greater number of buses.

The averaged values in Table 3-4 can be interpreted as the concluding result of the steady state experiments in terms of both the drop in peak engine power output for an unmodified bus operating on TME biodiesel blends and as the decreases in fuel economy associated with such a power drop. Note the two statements above are not cumulative, if bus B were modified to produce equivalent power on B20 as on the 50ppm fuel the expected fuel economy penalty (3% in this case) would remain unchanged for an equivalent work output.

3.3. Carbon monoxide emissions results

Exhaust emissions of CO with bus B are influenced by an unexpected phenomenon. This is illustrated in Figure 3-2 which shows the CO emissions per litre of fuel consumed at varied power and governed engine speed. The data for the 50 ppm fuel shows a linear rise with increasing power from 20 kW to 80 kW. When the power output reaches 100 kW most CO emissions samples on the 50ppm fuel drop to around half of what would be expected if the linear rise in CO emissions were to continue. Only two points out of nine recorded at 100 kW are around where a solid line representing the linear rise in CO emissions would predict CO emissions to be at 100 kW. This phenomenon is not displayed by either of the biodiesel fuels, although some additional spread of the biodiesel data at full load is displayed. The result is that both TME blends record higher CO emissions than the 50ppm fuel at full load. This observation is present at all engine speeds tested. The cause of this is still unknown but possible causes are discussed in [2].

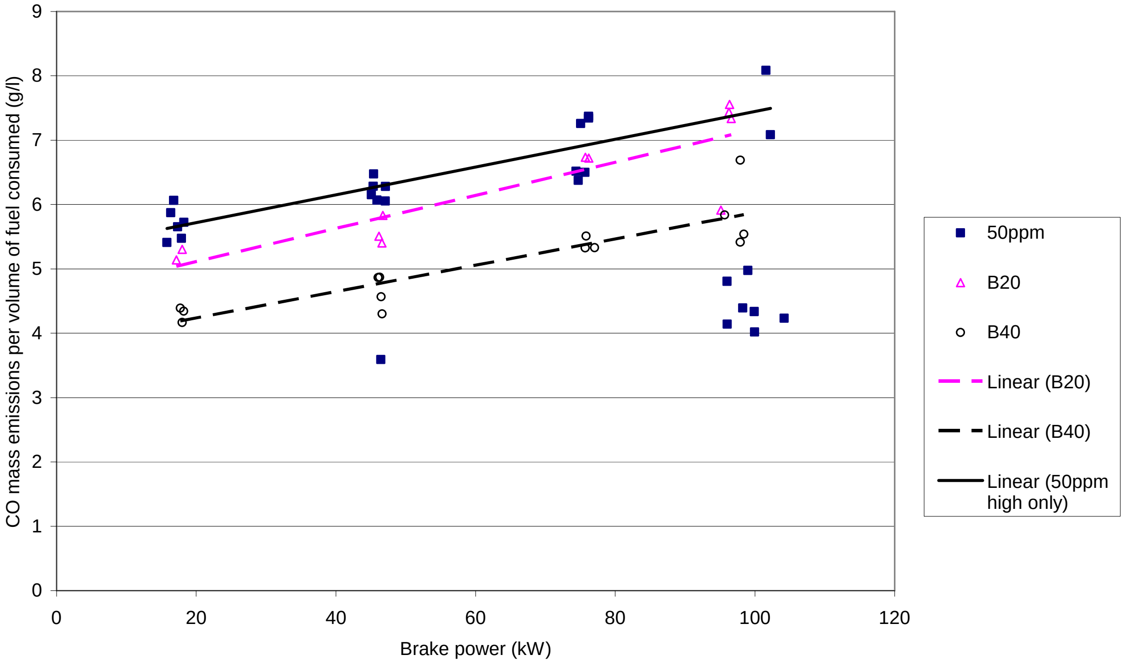

Figure 3-2. CO emissions per litre of fuel consumed for bus B operating at governed engine speed and varied power output.

Figure A 6 shows the impact of this phenomenon on the relative CO emissions rates of the results obtained in Figure 3-2. Figure A 5 shows CO emissions at varied engine speed, in the case of bus B the same phenomenon results in high relative CO emissions at all engine speeds. Similar behavior was observed during transient tests (see Chapter 4.)

The conclusion reached in [2] was that this observation was not an experimental error nor an equipment malfunction but an actual and repeatable behavior of this specific bus. It is unknown if another vehicle would exhibit the same behavior but bus A did not and no evidence has been found in other biodiesel trials to suggest that this is a normal occurrence. The CO emissions results for bus B at full engine load should therefore be considered suspect due to this unusual result specific to that bus. Figure 3-3 shows that changes in CO emissions from TME biodiesel compared to the 50ppm fuel are approximately constant across the power output range with both buses and blends, excluding the afore mentioned full load data on bus B. As such, the full load data for bus B can be omitted and the partial load data used instead.

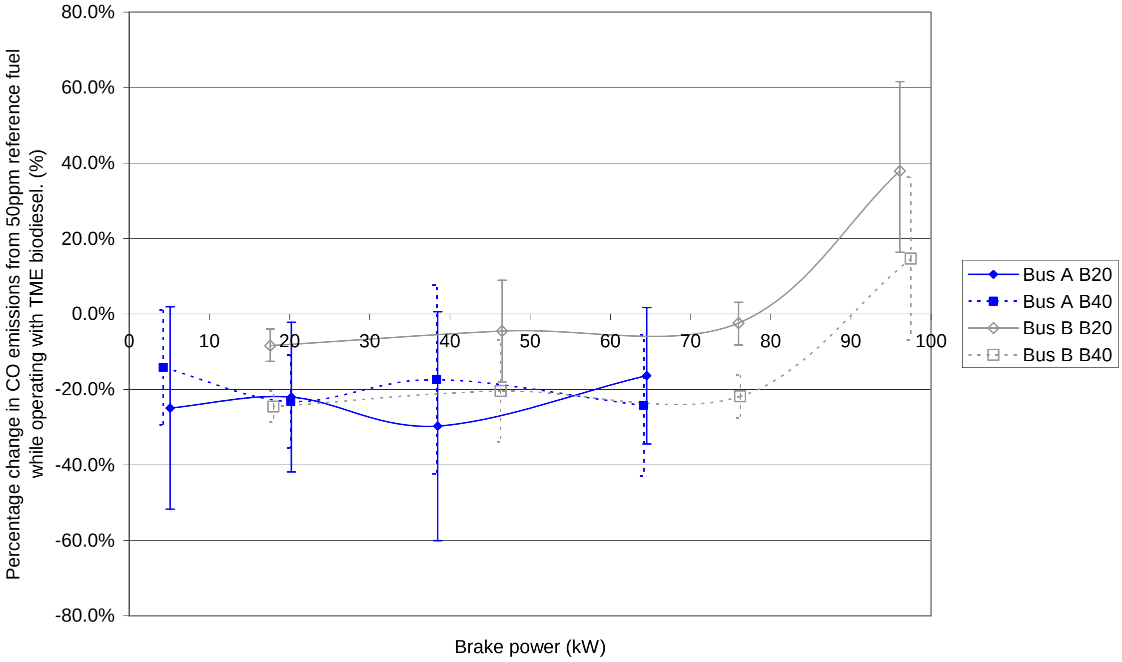

Figure 3-3. Percentage change in CO emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

Table 3-5 provides the averaged values for CO emissions changes from the 50ppm fuel for the TME biodiesel blends at both full load and varied engine speed and at the part load and governed engine speed conditions.

Table 3-5. Percentage change in CO emissions from the reference fuel while operating with TME biodiesel.

	Bus A	Bus B
B20 full load	-13.3%	28.7%*
B40 full load	-20.8%	10.2%*
B20 part load	-25.6%	-5.1%
B40 part load	-18.3%	-22.3%

* Result influenced by abnormal reference fuel results and may not be accurate.

It is apparent that in the majority of tests biodiesel blends produced less CO emissions than the 50ppm fuel and that B40 produced less CO than B20.

3.4. *Hydrocarbon emissions results*

Hydrocarbon emissions changes resulting from TME biodiesel blends vary with engine load as shown in Figure 3-4. Generally reductions in HC emissions are observed but these are most significant at low to medium engine loads, both in terms of magnitude and statistical significance. In general there was little change in HC emissions at full load when using biodiesel blends compared to 50ppm (Figure A 7).

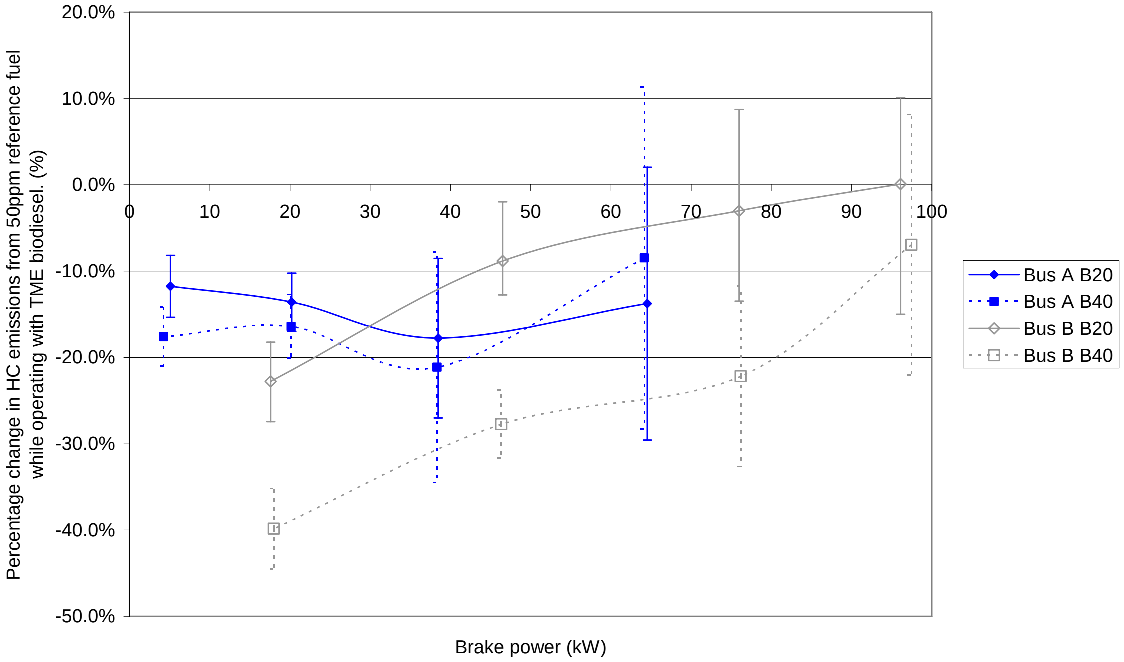

Figure 3-4. Percentage change in HC emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

Table 3-6 summarizes HC emissions results giving the average HC emissions changes resulting from TME biodiesel use compared to the 50ppm fuel separated into full load and part load test sets.

Table 3-6. Percentage change in HC emissions from the reference fuel while operating with TME biodiesel.

	Bus A	Bus B
B20 full load	-8.8%	5.0%
B40 full load	-4.0%	-10.3%
B20 part load	-14.4%	-11.5%
B40 part load	-18.4%	-29.9%

3.5. *Oxides of nitrogen emissions results*

The NO_x emission behavior of the two buses when fuelled with TME blends was an overall reduction in NO_x with the exception of full load operation of bus A. Most literature suggests that NO_x emissions typically increase when biodiesel blends are used in unmodified diesel engines. Some studies have encountered reductions in NO_x emissions and studies with biodiesel manufactured from animal sources on average show lower NO_x emissions than plant based biodiesel [4].

Figure 3-5 shows that NO_x emissions from the two biodiesel blends were very similar. The B40 blend results were only marginally higher than the B20 results at most test points suggesting that in this case biodiesel blend strength up to B40 has a limited impact on changing NO_x emissions from those encountered at the B20 level.

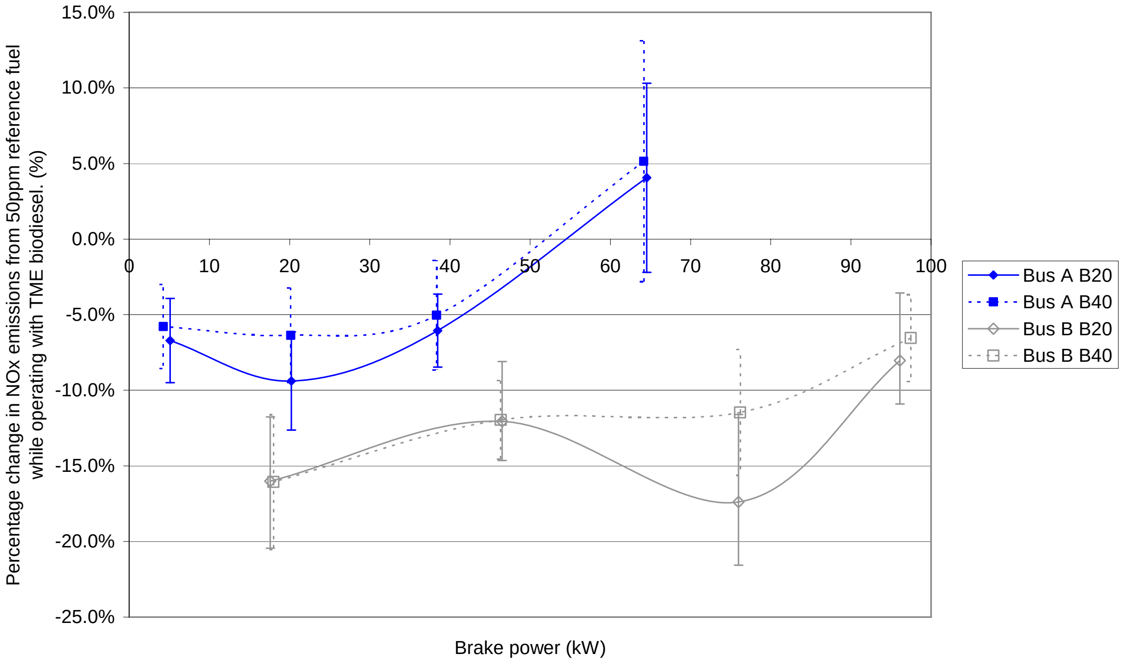

Figure 3-5. Percentage change in NO_x emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

The NO_x emissions behavior of the two buses are alike in that the greatest NO_x reductions encountered with TME blends are at lower engine loads. At high engine loads emissions benefits reduce and in the case of bus A NO_x emissions with TME blends exceed those of the 50ppm fuel. This high load behavior is relatively consistent across the engine speed range (Figure A 9). Table 3-7 provides summarized results for the steady state NO_x emissions.

Table 3-7. Percentage change in NO_x emissions from the reference fuel while operating with TME biodiesel.

	Bus A	Bus B
B20 full load	1.3%	-7.3%
B40 full load	4.6%	-6.1%
B20 part load	-7.4%	-15.2%
B40 part load	-5.7%	-13.2%

3.6 Particulate matter emissions results

Exhaust particulates are by nature more variable and more difficult to measure than gaseous exhaust emissions. Because of this two instruments were used to simultaneously measure exhaust particulates. The secondary instrument, a DustTrak™ light scattering photometer is used to provide supporting information for the primary measurements by gravimetric filter mass collection.

Figure 3-6 shows the percentage change in PM emissions for TME biodiesel blends relative to the 50ppm fuel at full load. The majority of data points show reductions in PM emissions that are statistically significant. The results also show some consistency between the two buses tested and five out of the six full load test points show that B40 produces less PM emissions than B20.

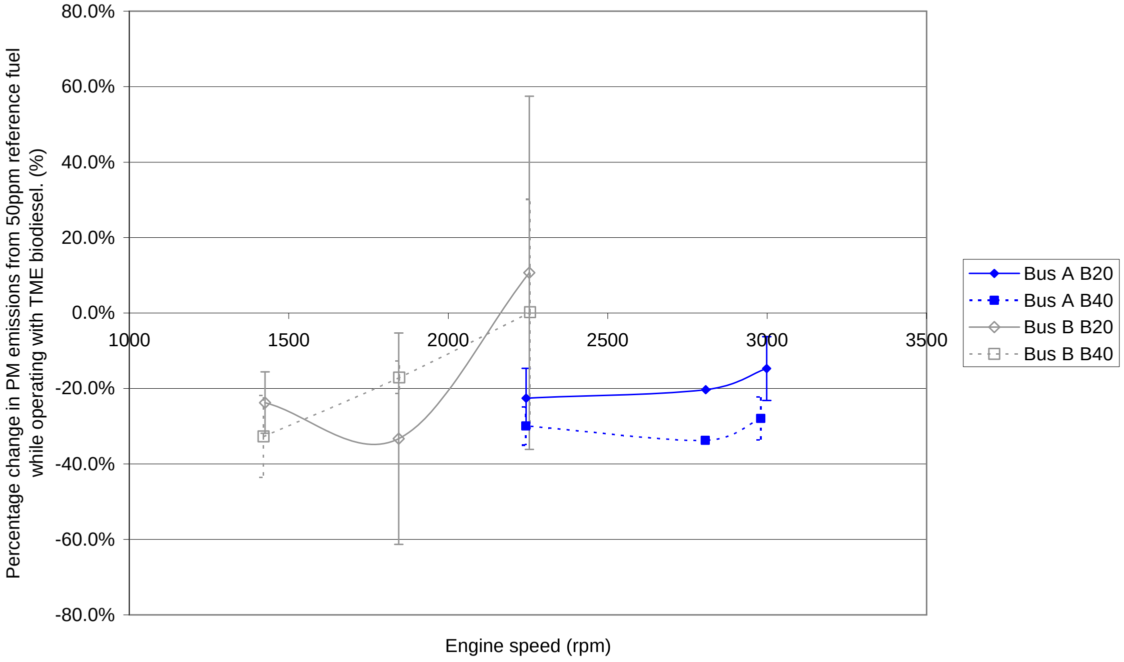

Figure 3-6. Percentage change in PM emissions per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

The partial load data is less informative than the full load data (Figure A 12). Statistical analysis of the PM changes with TME biodiesel at varied engine loads revealed that the majority of the data points collected are within a 95% confidence interval of the 50ppm data. Both increases and decreases in PM emissions were observed with the biodiesel fuels relative to the 50ppm fuel and while the B20 and B40 results are distinct from each other, neither blend had consistently lower emissions than the other across both buses.

The supporting DustTrak™ data is very similar to the gravimetric data providing significant confidence in the results given here. The DustTrak™ does suggest that the PM results for bus B at full load with both B20 and B40 are fractionally lower than those displayed in Figure 3-6.

Table 3-8 provides a summary of the PM results obtained during the steady state tests.

Table 3-8. Percentage change in PM emissions from the reference fuel while operating with TME biodiesel.

	Bus A	Bus B
B20 full load	-19.2%	-15.5%
B40 full load	-30.5%	-16.6%
B20 part load	-16.1%	6.6%
B40 part load	6.8%	-24.5%

4. Transient test results

Results from the transient test cycle consists of six full rack accelerations to 80km/h from stationary and working against a fixed power absorption. The results obtained from these transient tests correlate well with the steady state test data.

The phenomenon of inconsistent CO emissions from bus B observed in the steady state tests was also apparent in the transient data. Two of three 50ppm tests had CO emissions rates approximately half that of the third test. To maintain consistency with the steady state tests data set the two low CO results were omitted although other emissions data from the drive cycle were retained. The resulting transient test results for CO (Figure A 13), along with those for NO_x (Figure A 15) and PM (Figure A 16), produce trend lines essentially identical to the steady state results.

The primary outcome of the transient tests has been to support the results obtained in the steady state tests, however the differences between the transient data and the steady state data are apparent with HC emissions and fuel consumption although these do not appear significant. Figure 4-1 shows that the transient data produced lower overall HC emissions than the steady state data, however the scatter of results for the two data sets does not appear significantly different.

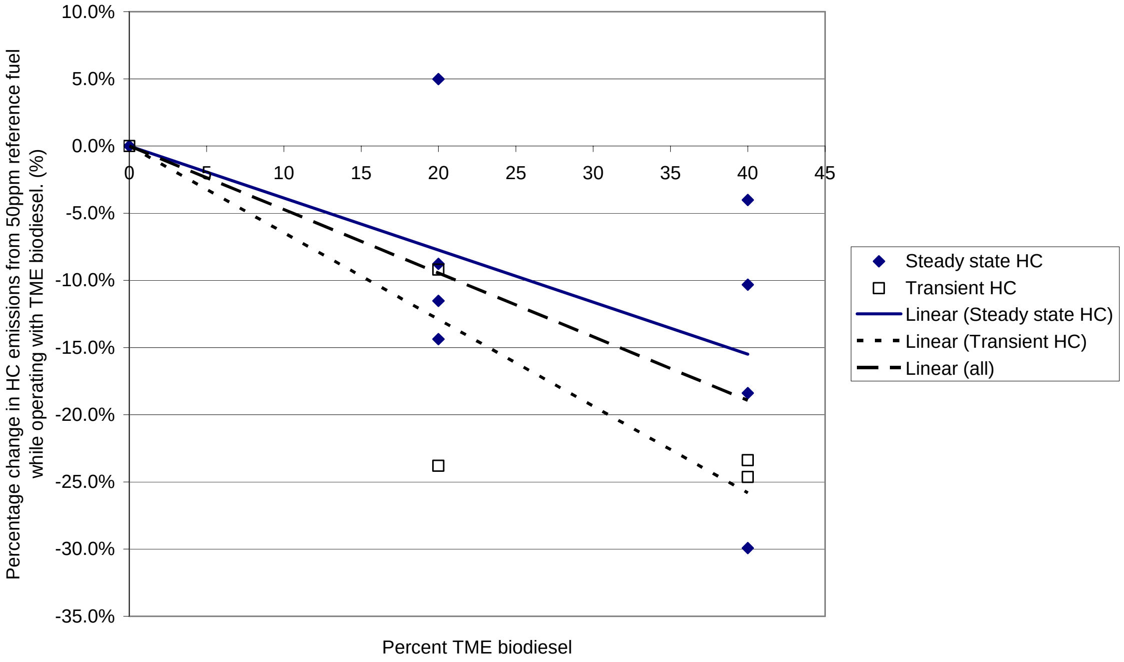

Figure 4-1. Average percentage change in HC emissions per litre of fuel consumed with TME biodiesel blends with steady state and transient test results.

In the case of fuel consumption (Figure A 17) the transient tests show reduced fuel consumption, opposite to the steady state results. The magnitude of the average change is still less than 2% with B40, as is the case with the steady state results. The scatter of the transient data greatly exceeds that of steady state data giving a greater level of uncertainty and suggesting that the steady state data is more accurate.

5. Comparison of results with BEPM.

The bus emissions prediction model (BEPM) biodiesel option [1] is based on data obtained from a 2001 study by the environmental protection agency (EPA) [4]. A direct comparison between the current experimental results and the EPA study has been carried out to evaluate the validity of using the EPA data in the BEPM.

Scatter plots and the resulting correlations from the EPA study have been overlaid with equivalent plots of the steady state data obtained in the current experiments. The data points displayed represent the average results for each operating condition with each bus on each biodiesel blend, totaling twelve data points per bus. Linear trend line approximations have been used for the experimental data and the resulting values for B5, B20 and B40 are summarized in Table 7-1 as the final result of the experiments.

Figure 5-1 shows the experimental data for CO matching the EPA data with almost no discernable difference in the observed trends or scatter of the data sets.

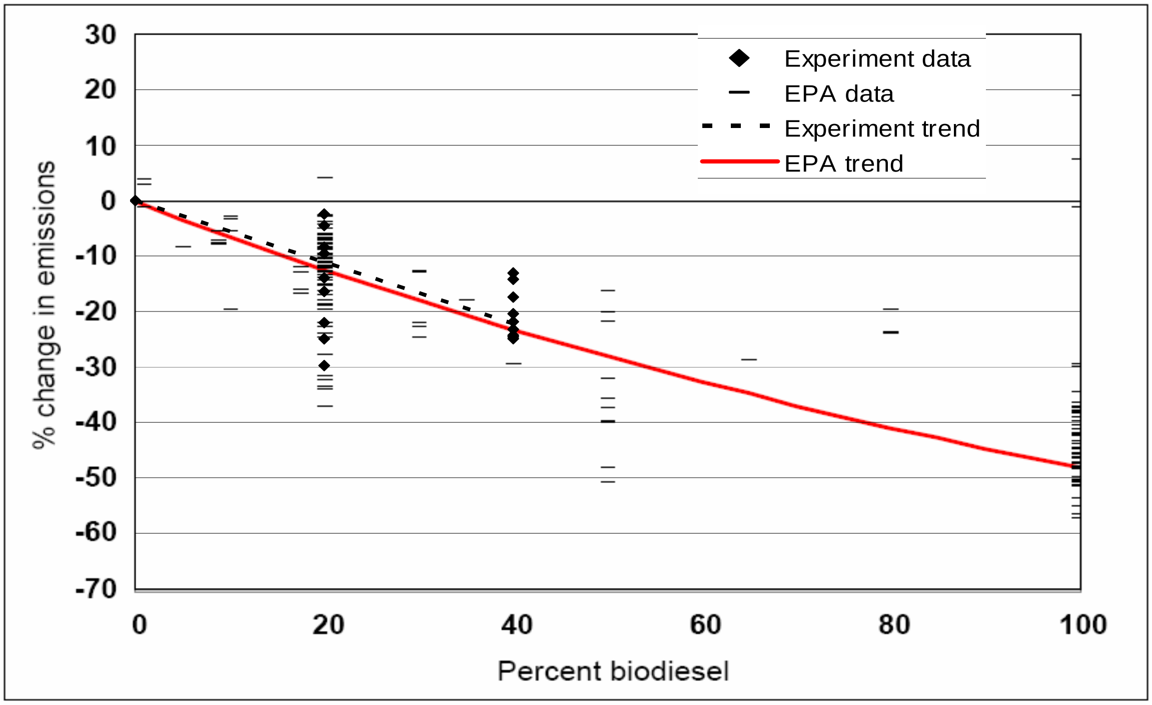

Figure 5-1. Percentage change in CO emissions with TME biodiesel blends, comparison of experimental data and EPA data. Note: full load data for bus B omitted.

Figure 5-2 show that the hydrocarbon emissions results do not present a trend as low as those found in the EPA study however the data points fall well within the scatter of the EPA data. The EPA data uses an “average” reference fuel [4], the 50ppm fuel used in these experiments would be classified as a “clean” fuel known to produce lower HC emissions and therefore smaller changes in HC from TME blends (~10% less at B40). These observations and the limited data set of two buses combined, it can be concluded that there is no strong evidence to suggest a real difference between the two data sets. Figure 5-3 shows particulates matching the EPA data both in trend and scatter. The trend line of PM results is marginally shallower than that the EPA study but this is caused by data points that were recorded at partial loads with PM results exceeding those of the 50ppm fuel. Interestingly the remaining data points fall almost symmetrically about the EPA trend line. The high results at 20% biodiesel also match a single EPA data point.

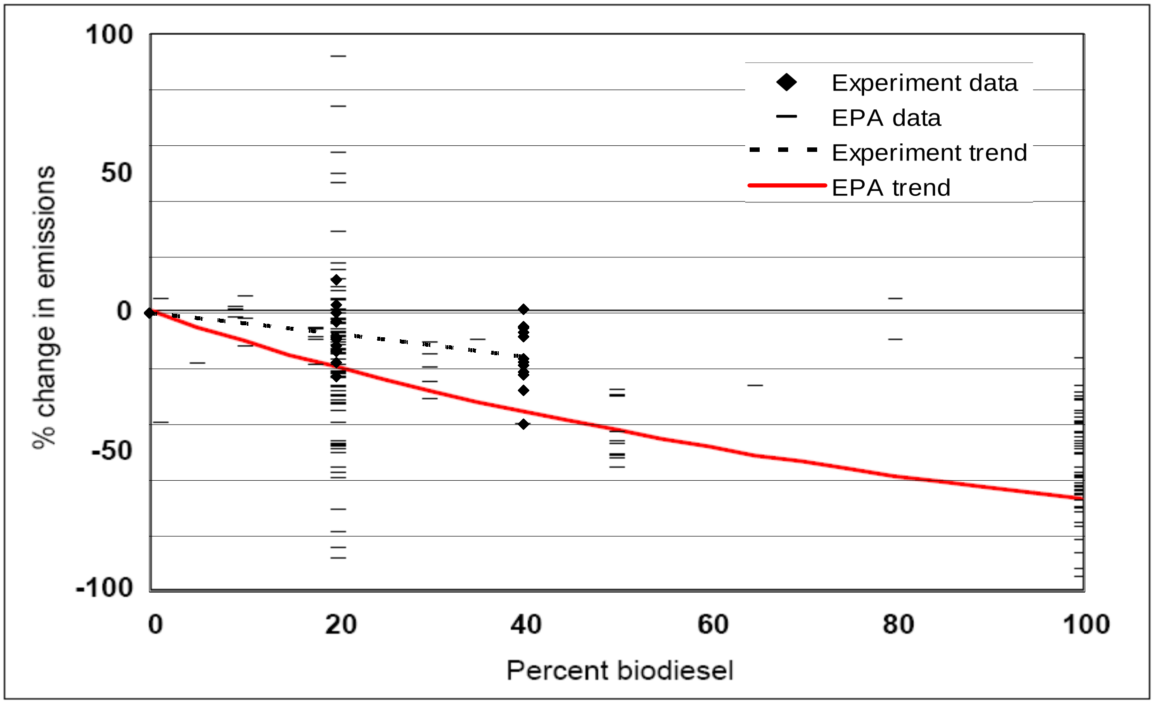

Figure 5-2. Percentage change in HC emissions with TME biodiesel blends, comparison of experimental data and EPA data. Note: full load data for bus B omitted.

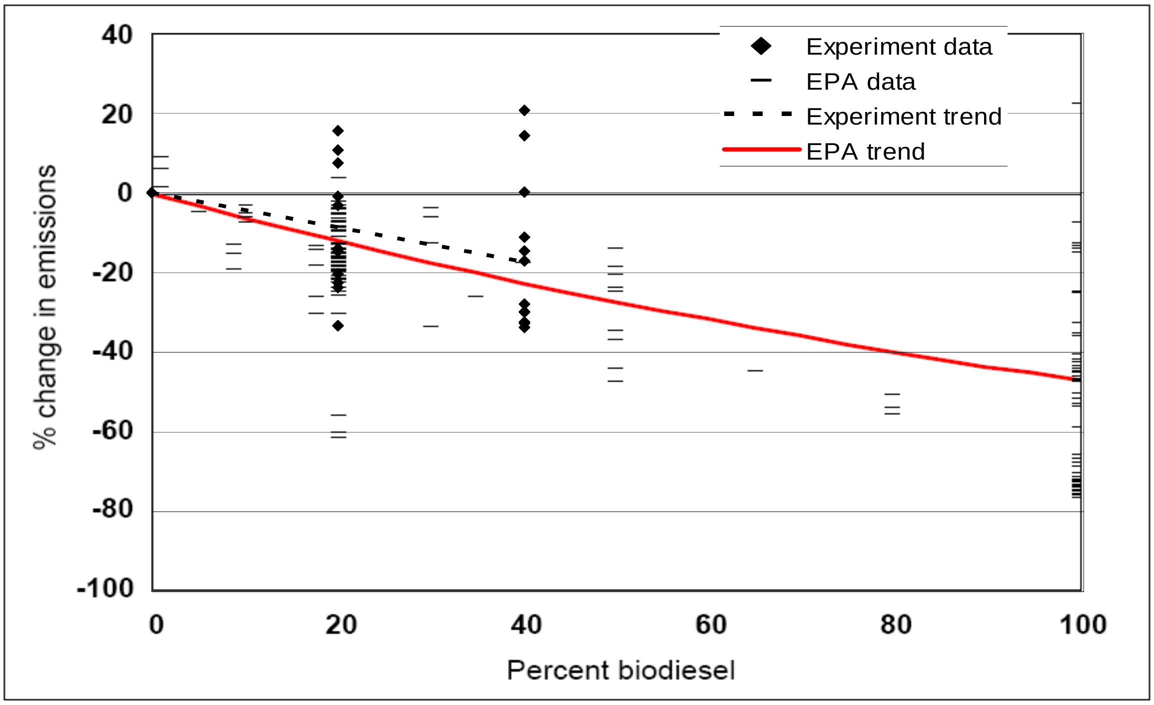

Figure 5-3. Percentage change in PM emissions with TME biodiesel blends, comparison of experimental data and EPA data. Note: full load data for bus B omitted.

Oxides of nitrogen are less impacted by biodiesel than other emissions in terms of a percentage change. This provides a tighter grouping of the EPA data than the other emissions results and makes outlying data points more visually apparent.

Figure 5-4 shows that oxides of nitrogen results appear to differ significantly from the EPA data set; most notably the test data trend is negative while the trend of the EPA data is positive. The EPA data set does display several values below zero at 20%, 50% and 100% biodiesel reaching approximately -7%. The test data exceeds this, obtaining values as low as -17%. From this it appears that a real difference is being displayed between the two data sets.

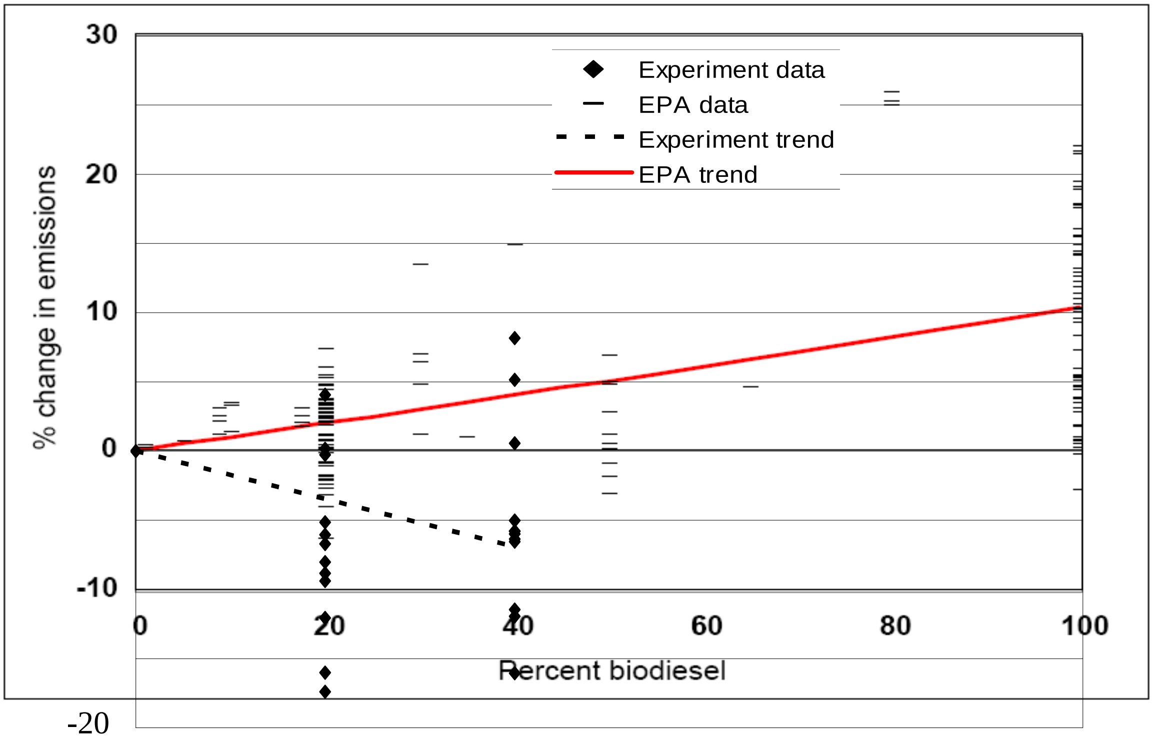

Figure 5-4. Percentage change in NO_x emissions with TME biodiesel blends, comparison of experimental data and EPA data. Note: full load data for bus B omitted.

The small sample size of the tests carried out to date and the appearance of both positive and negative results in the EPA data suggests that the new data should be used with caution. The EPA data may not provide an appropriate correlation for NO_x emissions with the TME biodiesel and buses used in this study but further work would be necessary before a new correlation could be developed with an acceptable degree of confidence.

6. Estimation of B5 results

The testing program did not include a 5% biodiesel blend (B5). This was primarily due to concerns over the likelihood that no detectable changes in emissions or vehicle performance would result from such a low concentration blend. B5 results are included in this section estimated by linear interpolation of the experimental results. In addition, B5 results were also estimated using the BEPM with an equivalent bus combination to that tested.

The BEPM uses correlations from the EPA [4] study, general data for which was displayed in Chapter 5. This data is primarily based on soy biodiesel but the BEPM also has an option for animal based biodiesel such as tallow. It should be noted that the EPA data set for animal biodiesel is considerably smaller than the general data set with approximately 11% of results (35 out of 311 data points) being from animal based biodiesel and only 26% of those (9 data points) being from tallow [4].

Table 6-1 includes percentage emissions and fuel consumption changes estimated for B5 from experimental data and the BEPM with both soy and animal based biodiesel.

Table 6-1. Percentage change in emissions and fuel consumption from a B5 blend estimated from combined experimental data and the BEPM with soy and animal based biodiesel options.

Emission / fuel consumption	B5 estimate from experimental results (linear interpolation)	BEPM B5 predicted result (Animal biodiesel)	BEPM B5 predicted result (Generic biodiesel-soy)
CO (g/km)	-2.8%	-3.6%	-2.8%
HC (g/km)	-1.9% (-2.4%)*	-5.7%	-5.7%
NO_x g/km)	-0.9%	0.0%	+0.5%
PM (g/km)	-2.2%	-3.1%	-2.2%
FC (l/100km)	+0.2%	+0.3%	+0.2%

* Value obtained from a correlation combining steady state and transient data.

As shown in Chapter 5 the experimental data matches with the generic biodiesel (primarily soy) data for CO and PM but it can also be seen that fuel consumption matches with the B5 estimate. The BEPM predicts lower emissions of CO, NO_x, PM and greater fuel consumption for animal based biodiesel compared to the generic biodiesel. With the exception of NO_x this is not shown by the experimental results. Experimental hydrocarbons results from steady state tests or combined steady and transient tests do not display the reductions predicted using the BEPM.

7. Conclusions

Final experimental results are presented in Table 7-1.

Table 7-1. Summary of experimental results showing percentage change in emissions and performance of buses operating of TME biodiesel blends relative to the 50ppm fuel.

Emissions / fuel consumption	B5 (interpolated)	B20	B40
CO	-2.8%	-11.1%	-22.2%
HC	-2.4%	-9.5%	-18.9%
NO_x	-0.9%	-3.5%	-6.9%
PM	-2.2%	-8.7%	-17.4%
FC	0.2%	0.9%	1.7%

Based on the experimental data collected the following statements can be made regarding TME biodiesel.

- TME biodiesel in 50ppm sulphur ADF blends up to 40% reduce the emissions of carbon monoxide, hydrocarbons, oxides of nitrogen and particulate matter in buses compared to 50ppm sulphur ADF.
- The two buses tested responded differently to TME biodiesel blends in terms of emissions and performance behavior in the majority of tests.
- The observed changes in emissions and performance behavior of the buses did not always correlate linearly with an increase in TME biodiesel blend strength.
- Experimental data shows trends for a reduction in power output at equivalent fuelling or an increase in fuel consumption at equivalent work output at the majority of operating conditions resulting from use of TME biodiesel blends up to 40% compared to the 50ppm sulphur ADF.
- Experimental power and fuel consumption penalties due to TME biodiesel blends up to 40% are within the level of uncertainty of measurement achievable with full scale bus testing.
- TME biodiesel blends require further investigation before definitive predictions can be made regarding power and fuel consumption effects.
- Carbon monoxide emissions reductions due to TME biodiesel blends up to 40% correlate with EPA findings for biodiesel.
- Excluding the phenomenon encountered with bus B at full rack operation carbon monoxide emissions reductions due to TME biodiesel blends up to 40% appear to be independant of vehicle load and speed conditions.
- Data for hydrocarbon emissions reductions due to TME biodiesel blends up to 40% fits within the scatter of the EPA data for biodiesel but reductions are generally less than the EPA data correlation.
- Hydrocarbon emissions reductions due to TME biodiesel blends up to 40% show a strong load sensitivity with emissions reductions being greatest at light loads and reaching comparable levels to 50ppm sulphur ADF at full rack operation.

- Oxides of nitrogen emissions changes due to TME biodiesel blends up to 40% are different to the EPA findings.
- TME biodiesel blends require further investigation before definitive emissions predictions can be made regarding oxides of nitrogen emissions.
- Particulate matter emissions reductions due to TME biodiesel blends up to 40% correlate with EPA findings for biodiesel.
- Some light load operating conditions resulted in particulate emissions with TME biodiesel blends exceeding the levels obtained with the reference 50ppm sulphur ADF.
- Emissions and performance impacts of a 5% TME biodiesel blend have been interpolated from experimental data.

8. References

[1] Boielle, N.B. (2005) *Incorporation of biodiesel scenarios into the bus emissions prediction model*, Energy and Fuels Research Unit technical report 9023.77, Auckland UniServices Limited, Auckland

[2] Boielle, N.B. (2006) *Assessment of Bus Exhaust Emissions from Tallow Methyl Ester Biodiesel Blends*. ME Thesis, The University of Auckland

[3] Anyon, P., Brown, S., Pattison, D., Beville-Anderson, J., Walls, G. & Mowle, M. (2000) *In-service Emissions Performance – Phase 2: vehicle Testing*. Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work. National Environment Protection Council. Available from: www.nepc.gov.au

[4] (2002) *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*. Draft Technical Report EPA420-P-02-001, United States Environmental Protection Agency

[5] (1989) *Australian Design Rule 37/01: Emission Control for Light Vehicles*. Australian Design Rules for Road Vehicles, Third Edition. Motor Vehicles Standards Act. Department of Transport and Regional Services, Government of Australia, Canberra

[6] (1992) *Code of Federal Regulations: Protection of Environment*, Parts 86-99. Office of the Federal Register National Archives and Records Administration, US Government Printing Office, Washington

Appendix A. Figures

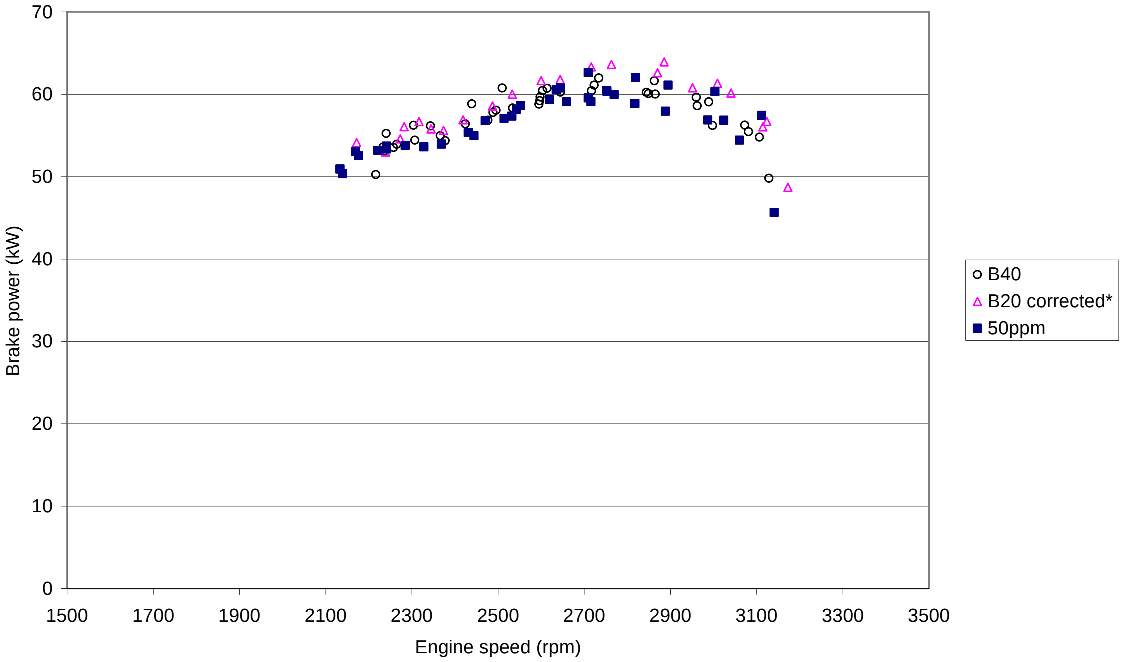

Figure A 1. Bus A, power test results: Brake power versus engine speed. *B20 results are corrected for dynamometer load cell calibration drift see [1] for a detailed explanation.

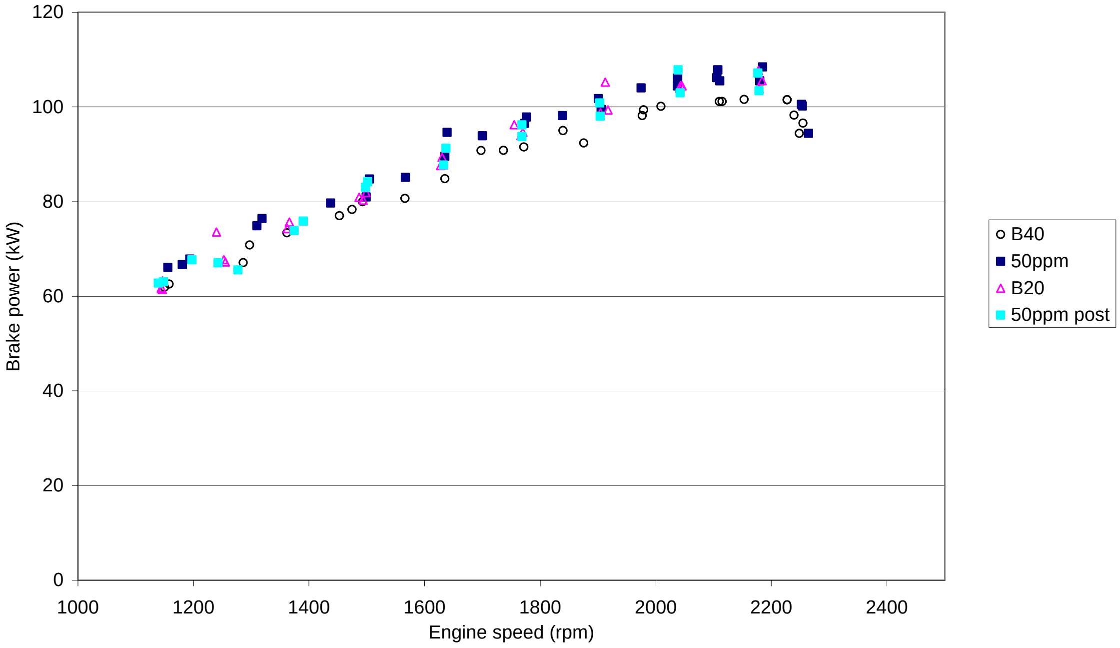

Figure A 2. Bus B, power test results: Brake power versus engine speed.

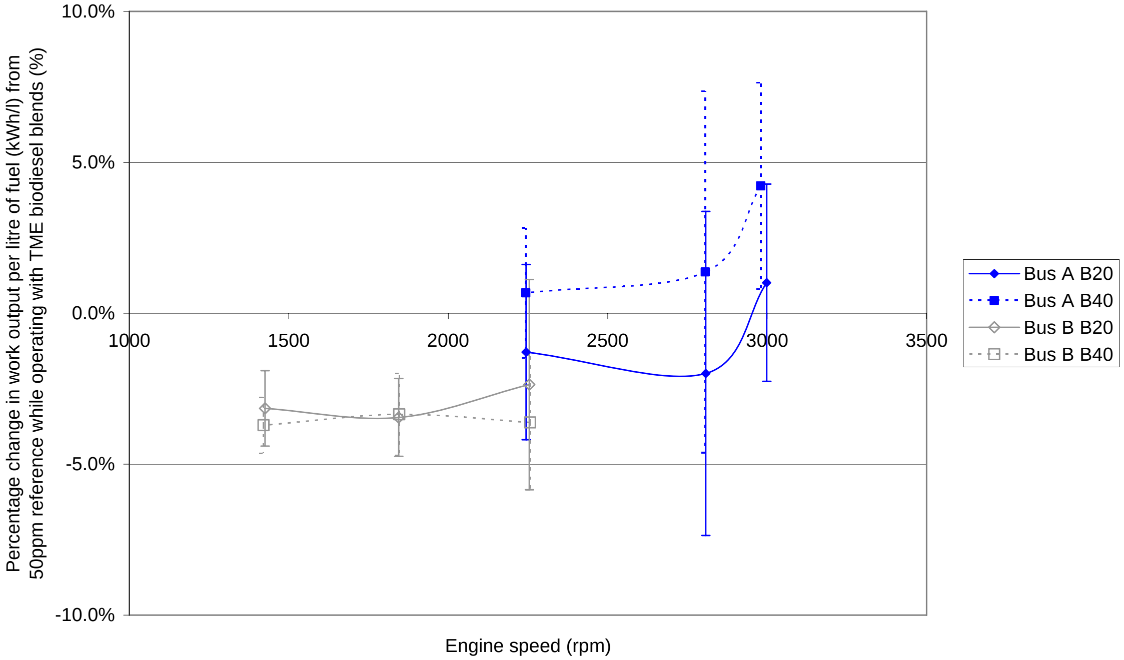

Figure A 3. Percentage change in work output per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

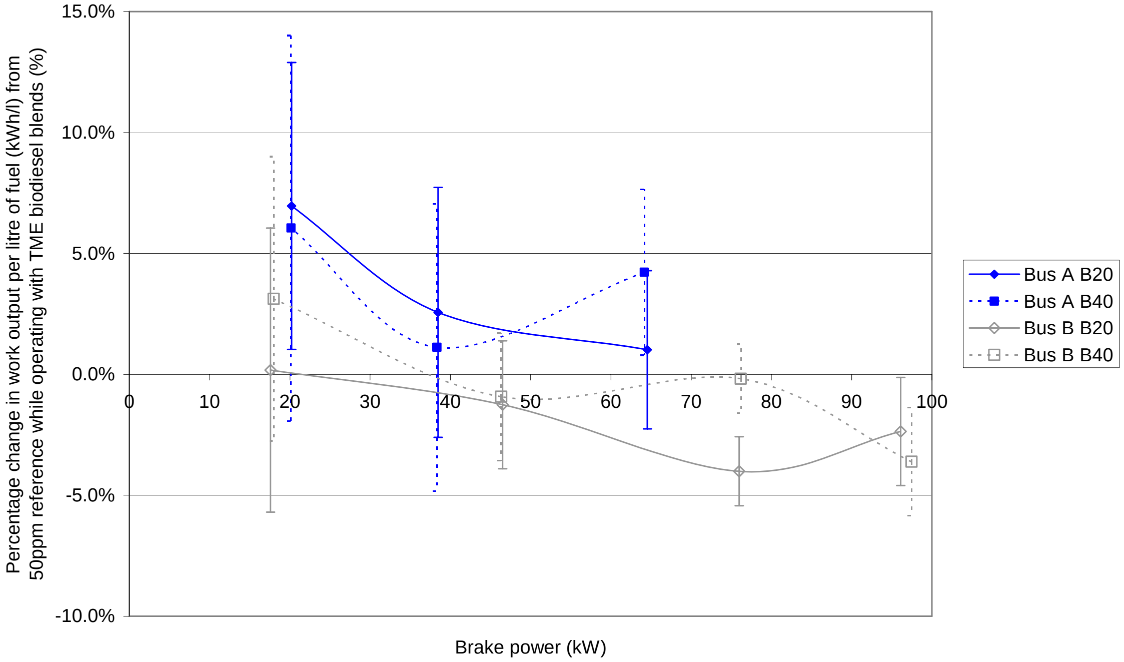

Figure A 4. Percentage change in work output per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

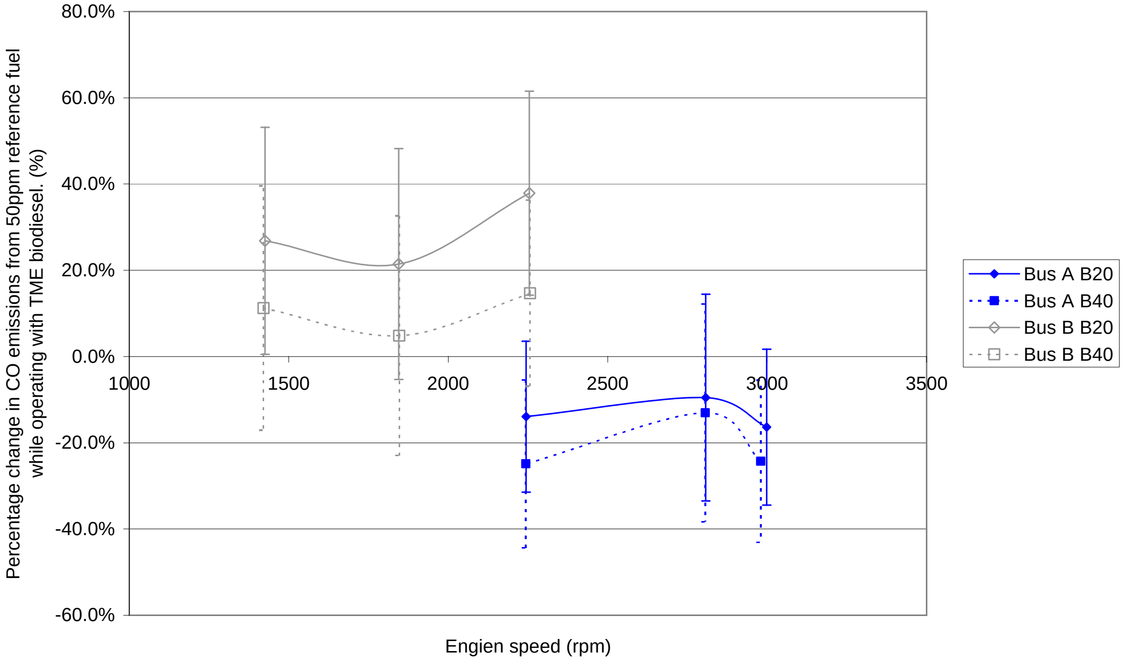

Figure A 5. Percentage change in CO emissions per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

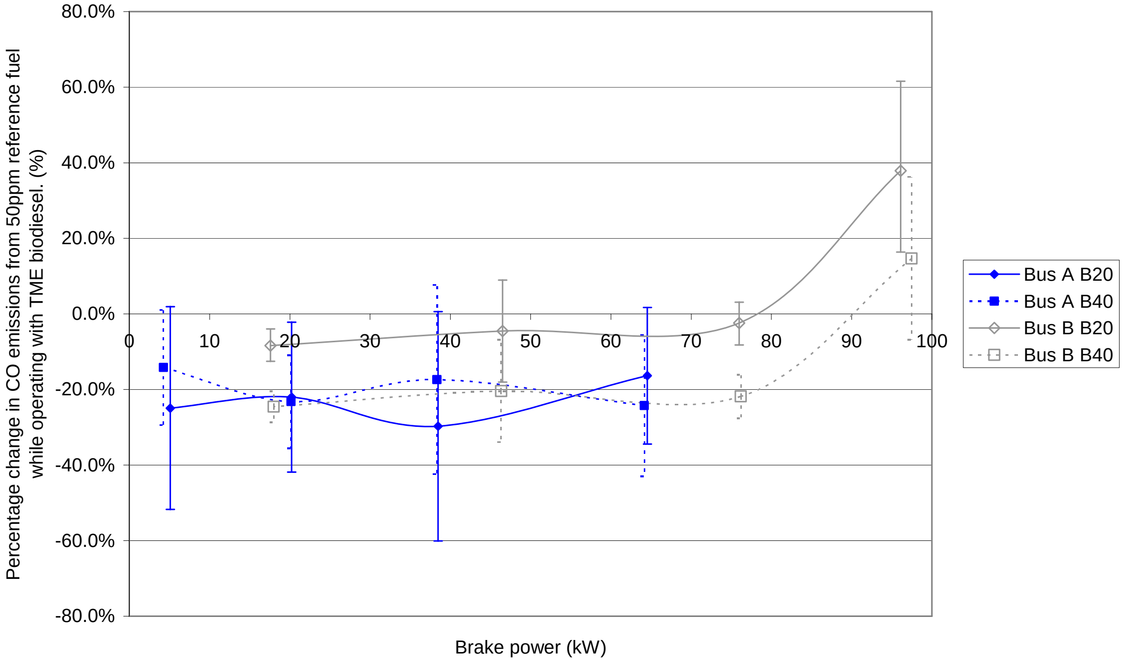

Figure A 6. Percentage change in CO emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

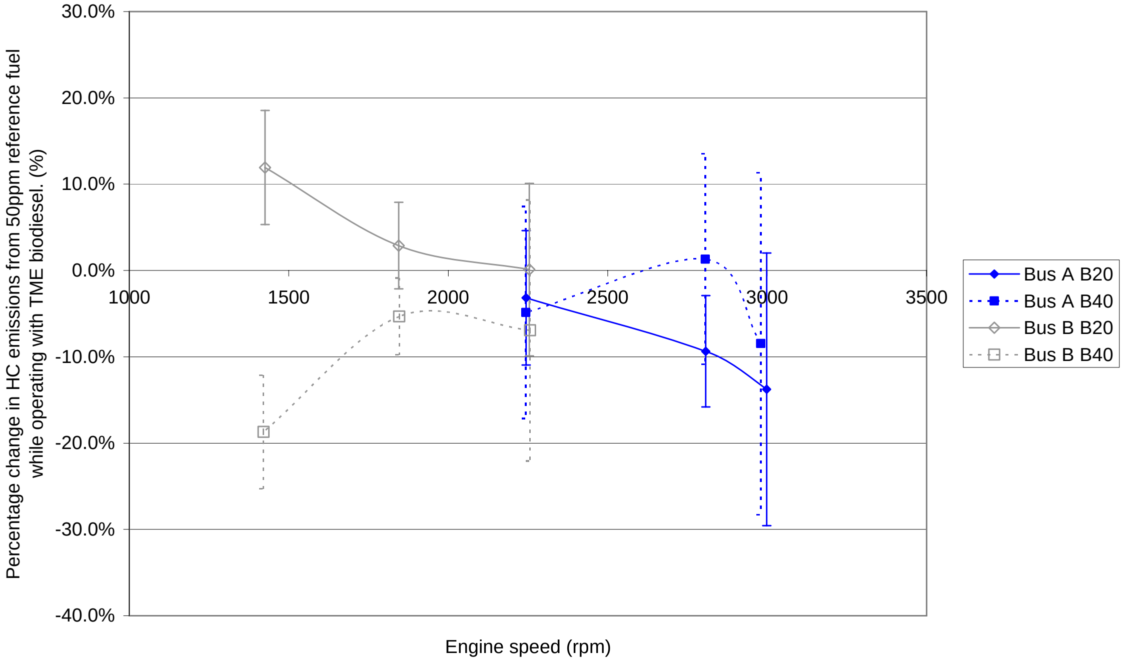

Figure A 7. Percentage change in HC emissions per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

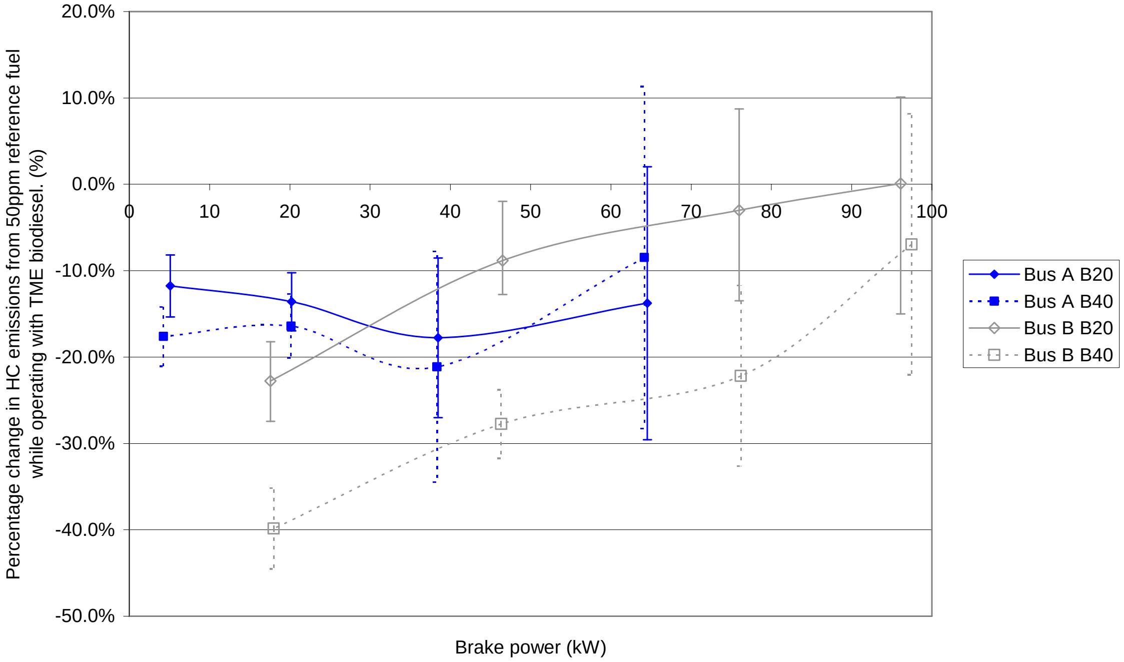

Figure A 8. Percentage change in HC emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

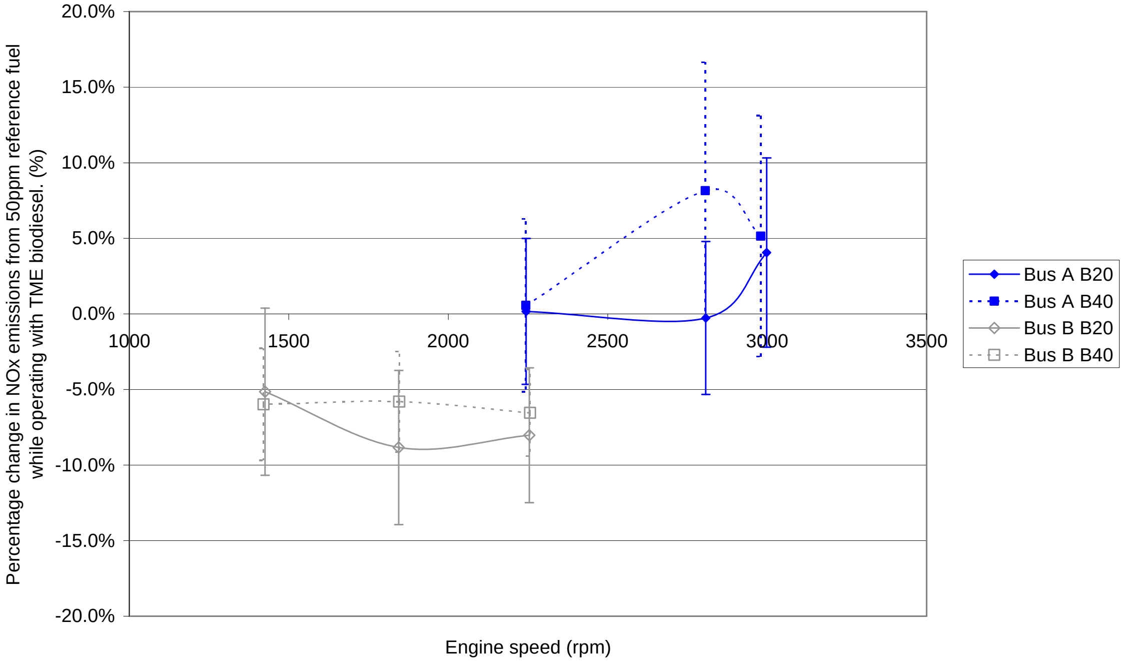

Figure A 9. Percentage change in NO_x emissions per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

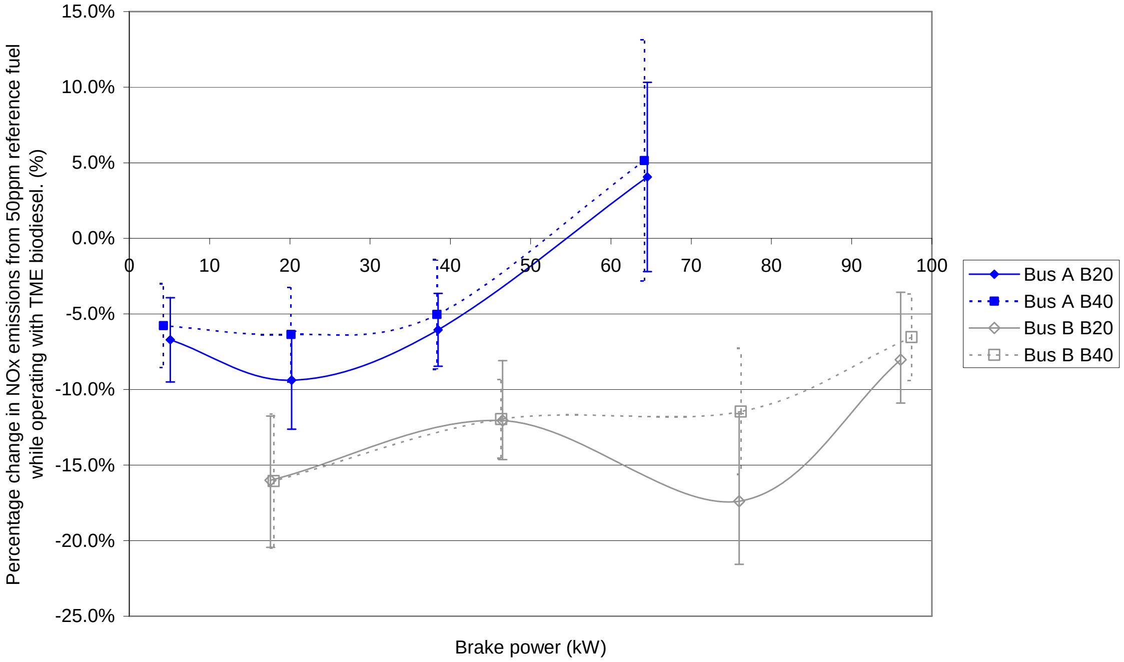

Figure A 10. Percentage change in NO_x emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

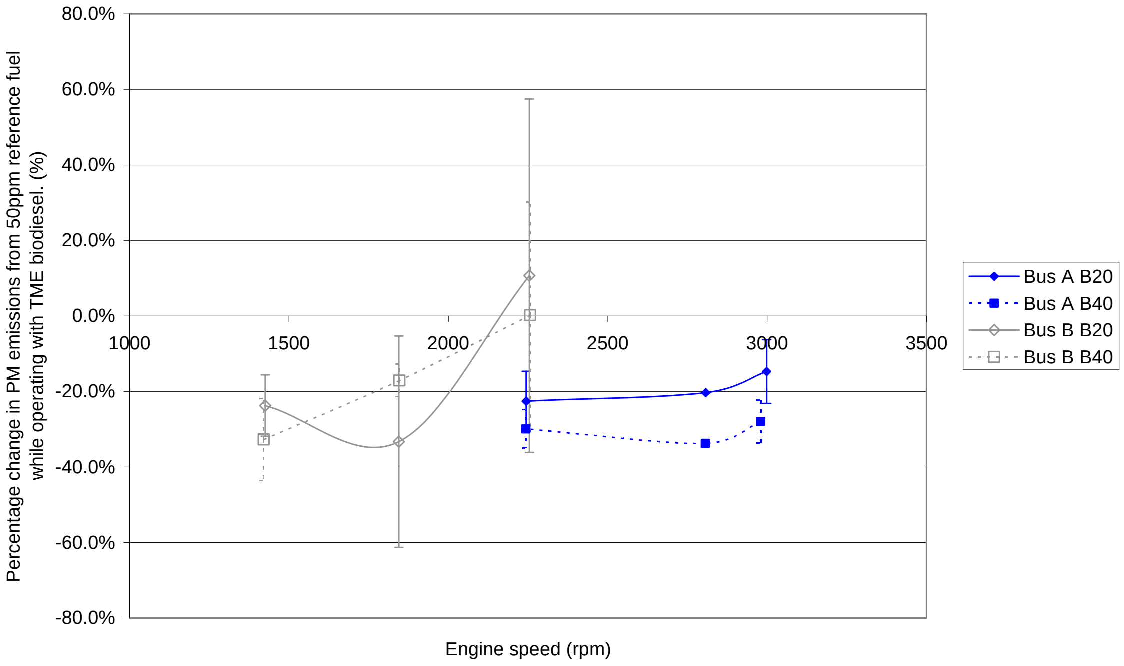

Figure A 11. Percentage change in PM emissions per litre of fuel consumed with TME biodiesel blends at maximum power output and varied engine speed. I bars indicate the 95% confidence intervals of the data.

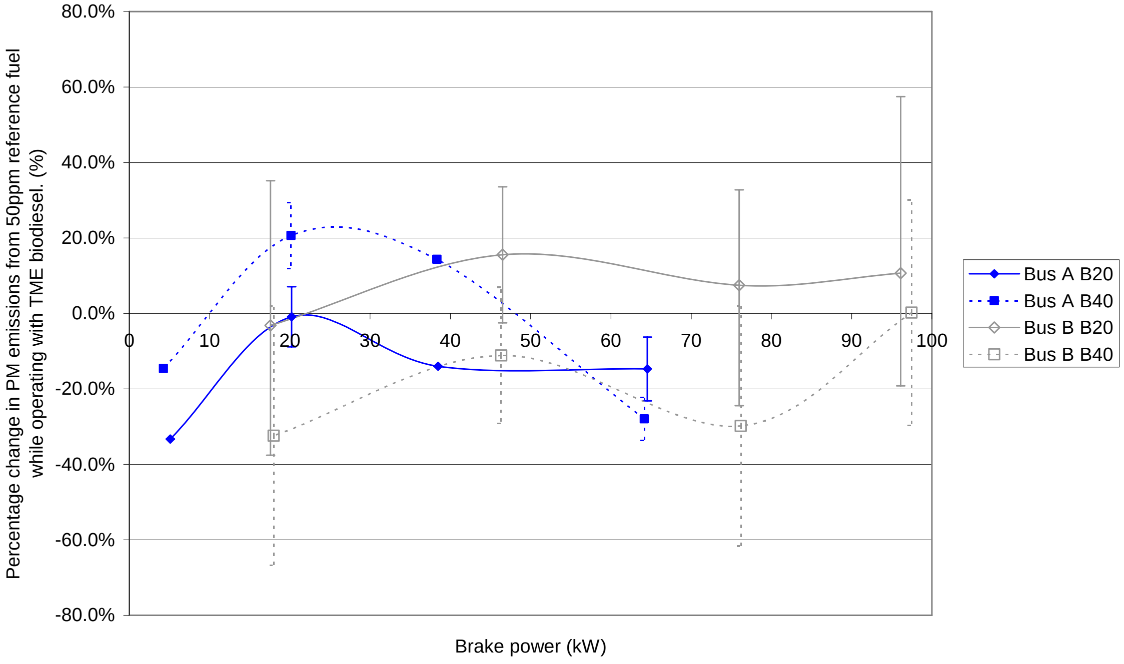

Figure A 12. Percentage change in PM emissions per litre of fuel consumed with TME biodiesel blends at governed engine speed and varied power output. I bars indicate the 95% confidence intervals of the data.

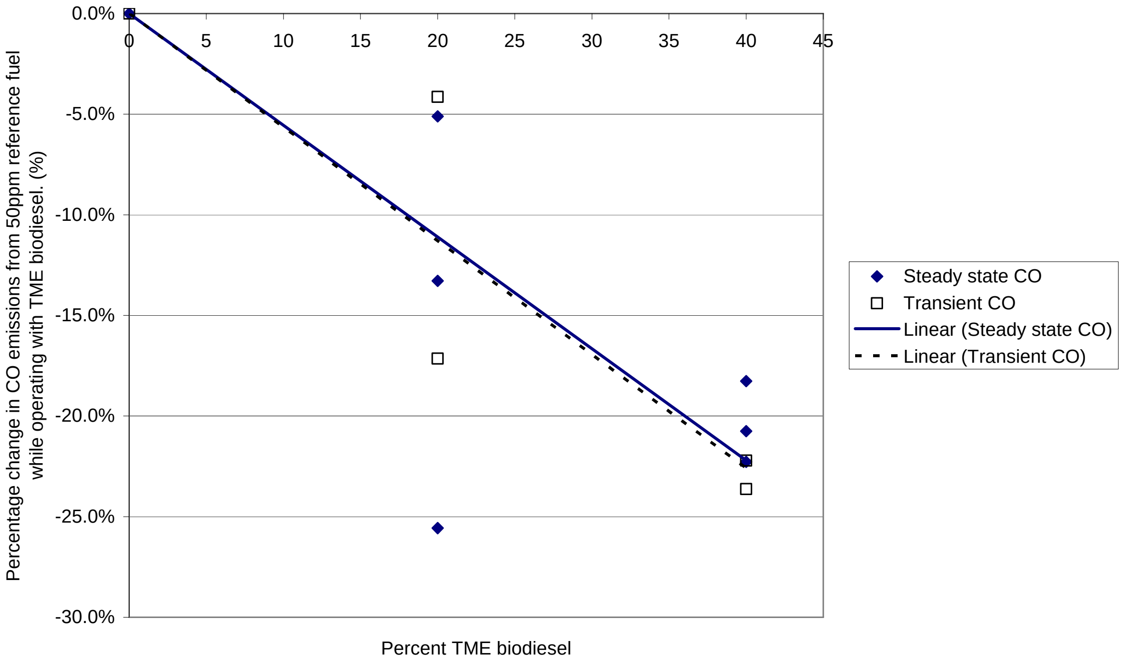

Figure A 13. Average percentage change in CO emissions per litre of fuel consumed with TME biodiesel blends with steady state and transient test results.

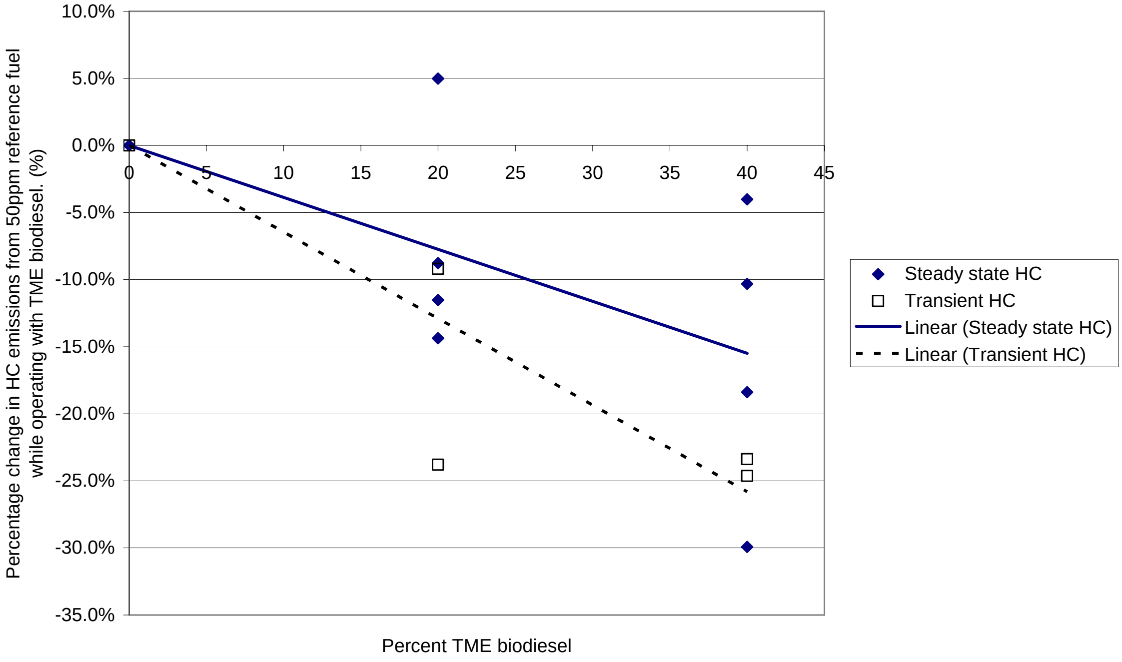

Figure A 14. Average percentage change in HC emissions per litre of fuel consumed with TME biodiesel blends with steady state and transient test results.

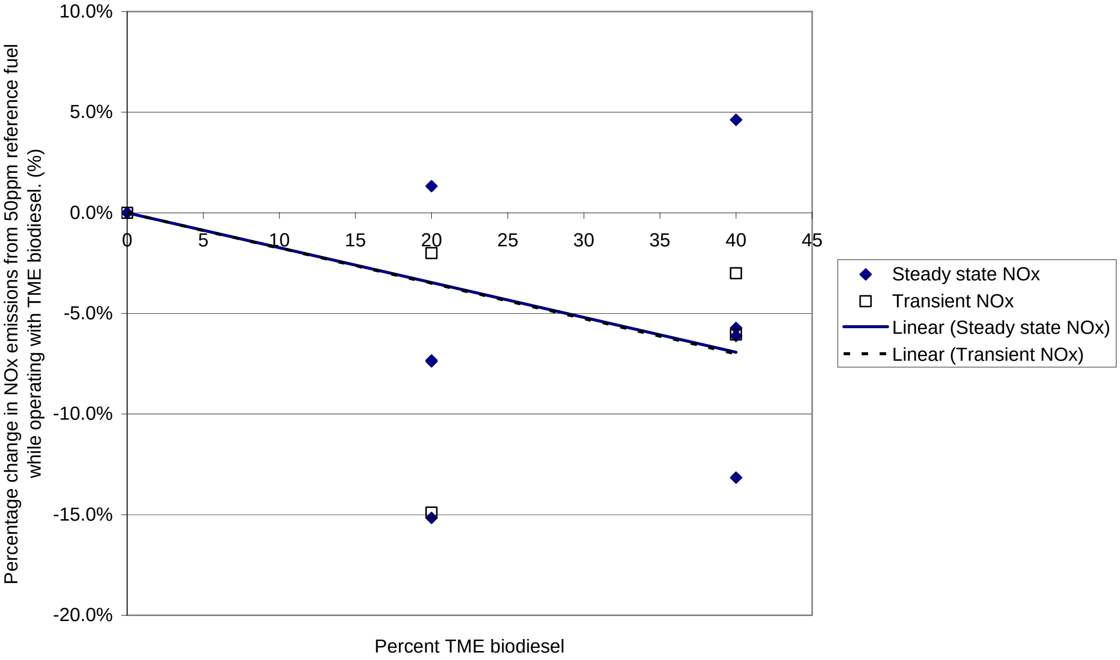

Figure A 15. Average percentage change in NOx emissions per litre of fuel consumed with TME biodiesel blends with steady state and transient test results.

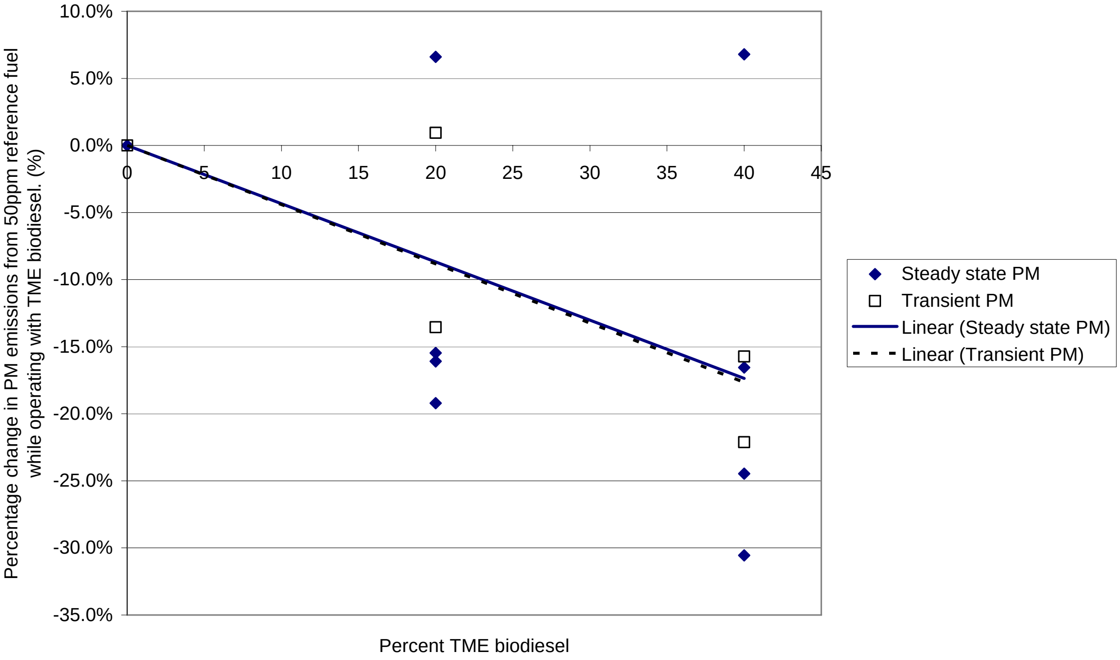

Figure A 16. Average percentage change in PM emissions per litre of fuel consumed with TME biodiesel blends with steady state and transient test results.

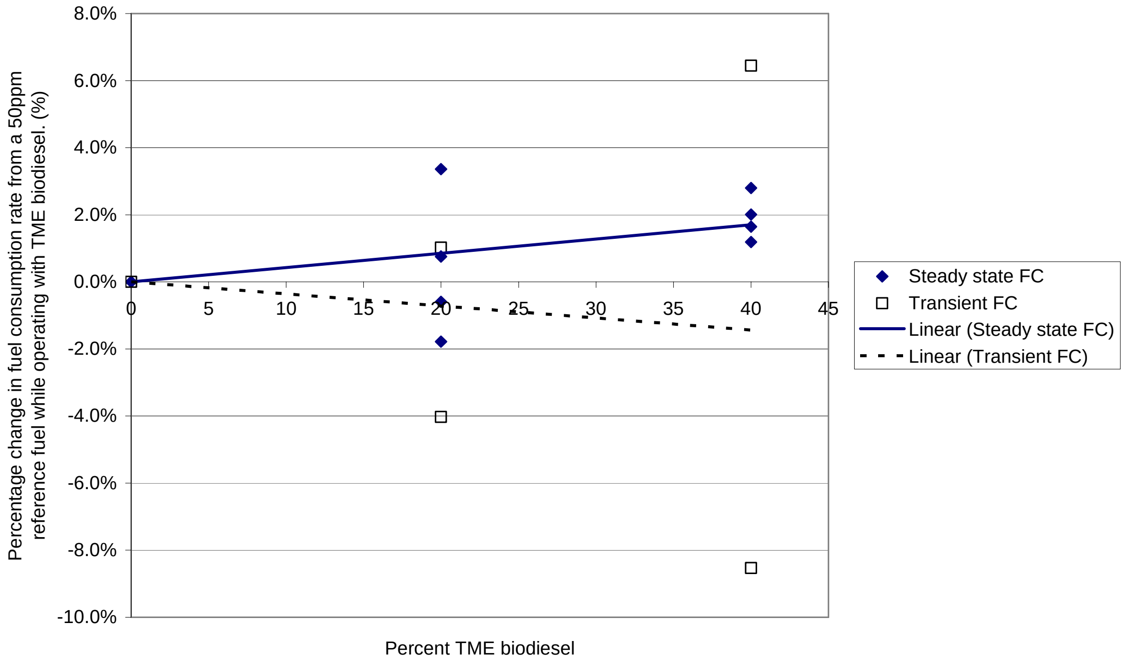

Figure A 17. Average percentage change in fuel consumption rate with TME biodiesel blends with steady state and transient test results.

Appendix B. Bus specifications

Bus	Bus A	Bus B
Manufacturer:	Nissan	MAN
Model:	Scorpion SLF 180	SL202
Model year:	1997	1988
Emissions class:	Jap 94	Pre Euro
Engine model:	FE6	D2566UH
Engine size (litres):	6.925	11.41
Compression ratio:	18:1	17.5:1
Max output (kW)	134	150
No of cylinders:	6 - Inline	6 – Inline
Injection type:	Direct	Direct
Injection pump type:	Kiki diesel Inline	Bosh 6PE 100A (Inline)
Induction type:	Naturally aspirated	Naturally aspirated
Capacity (seated/standing):	38/16	45/27
Tare mass (kg):	7380	8940
Tyre pressures (PSI):	70	75

Appendix C. Fuel properties

Table C.1. Tallow Methyl Ester fuel properties, method, result and NZS 7500 limits for batch TME #24

Method	Test	Units	NZS 7500 Spec Limit	Result
ASTM D 4052A	Density @ 15°C	kg/m3	860 - 900	874
ASTM D 1500	ASTM Colour	-	-	L 4.0
ASTM D 6304	Water Content - Karl Fischer	mg/kg	500 max	641
ASTM D 445	Kinematic Viscosity @ 40°C	mm^2/ s	2.00 – 6.00	5.146
ASTM D 664	Acid Number	mg KOH/g	0.5 max	0.39
ASTM D 130	Cu Corrosion (3 hr @ 100°C)	-	Class 1 (1a or 1b)	1a
EN 14103	Total ester	% mass	96.5 min	98.9
EN 14105	Total Glycerol	% mass	0.24 max	0.225
EN 14105	Free Glycerol	% mass	0.02 max	<0.00005
EN 14105	Monoglycerides	% mass	0.8 max	0.6
EN 14105	Diglycerides	% mass	-	0.4
EN 14105	Triglycerides	% mass	-	0.0
	Methanol	% mass	0.2 max	Note 1
ASTM D 5185-95 Mod	Sodium Content	mg/kg	5 max total	<1
ASTM D 5185-95 Mod	Potassium Content	mg/kg		<1
IP 440	Total Contaminants	mg/kg	24 max	33
ASTM D 2500	Cloud Point	°C	-	+19
ASTM D 93A	Flash Point, PMcc	°C	100 min	167.5
ASTM D 4530	Micro Carbon Residue	% mass	0.05 max	<0.1
ASTM D 5453	Sulphur Content	mg/kg	50 max	<5
ASTM D 874	Sulphated Ash	% mass	0.02 max	<0.005
ASTM D 4951	Phosphorus Content	mg/kg	10 max	<1
EN 14112	Oxidation Stability	Hours	6 min	0.77 (Note 2)
EN 14111	Iodine Value	g I/100g	120 max	Note 3
EN 14103	Linolenic acid esters	% mass	12 max	Note 3
ASTM D 6890	Cetane Number (Note 4)	-	51 min	85.52

Notes:	1 Methanol passes on flash point	2 Intertek, Clyde Refinery Laboratory (A pass was obtained using antioxidant dosing)
	3 Not measured but expected to pass	4 Intertek, Port Melbourne Laboratory

Table C.2. Tested fuel properties, methods and results for 50ppm sulphur diesel reference fuel.

Laboratory Sequence Number			**205035**
Method	**Test**	**Units**	**Result**
ASTM D 4052	Density @ 15°C	kg/L	0.8283
ASTM D 5773	Auto Cloud Point	°C	-2.5
ASTM D 93	Flash Point , P.M.C.C.	°C	67.5
ASTM D 4530	Micro-Carbon Residue (on 10% residue)	% mass	<0.1
ASTM D 6304	Water Content	mg/kg	39
IP 497	Sulphur Content	ppm(mass)	40
ASTM D 130	Copper Strip Corrosion, 3 hours @ 100°C	-	1a
IP 391	Total Aromatic Hydrocarbons	% mass	17.24
IP 391	Poly-Aromatic Hydrocarbons	% mass	1.13
ASTM D 86	Distillation , Recovery Basis	°C	
	Initial Boiling Point		180.7
	95% recovered @		342.0
	Final Boiling Point		350.6
	Recovered	% vol.	98.3
	Residue		1.0
	Loss		0.7
ASTM D 976	Cetane Index	-	55.8

Table C.3. Additional fuel properties (4 s.f.) calculated and supplied by BP Oil NZ Ltd.

Fuel	**Oxygen % by mass**	**H/C mole ratio**	**Gross energy (MJ/kg)**	**Net energy (MJ/kg)**
50ppm	Negligible (0%)	1.993	45.88	43.02
B20 (interpolated)	2.216%	1.969	44.87	42.01
B40 (interpolated)	4.432%	1.945	43.86	41.00
B100	11.08%	1.867	40.83	37.97