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ABSTRACT

A method of cleaning lubricating oil on line was investigated using a fine bypass particulate filter followed by an infra red heater. Two bypass filter sizes of 6 and 1 micron were investigated, both filter sizes were effective but the one micron filter had the greatest benefit. This was tested on two nominally identical EURO 2 emissions compliance single decker buses, fitted with Cummins 6 cylinder 8.3 litre turbocharged intercooled engines and coded as Bus 4063 and 4070. These vehicles had emissions characteristics that were significantly different, in spite of their similar age and total mileage. Bus 4063 showed an apparent deterioration on emissions with time while Bus 4070 showed a stabilised trend on emissions with time for their baseline tests without the recycler fitted. Comparison was made with the emissions on the same vehicles and engines with and without the on-line bypass oil recycler. Engine exhaust emissions were measured about every 2000 miles. All tests started with an oil drain and fresh lubricating oil. The two buses were tested in a different sequence, Bus 4063 with the recycler fitted and then removed later in the test after an oil change and Bus 4070 with no recycler fitted at first and then fitted after 29,000 miles with no oil change. The Bus 4070 was also the one with the finer bypass filter. The test mileage was 45,000 miles for Bus 4063 and 48,000 miles for Bus 4070. The air/fuel ratio was worked out by the exhaust gas analysis. The correlation between air/fuel ratio and emission parameters was determined. The results showed that the on line oil recycler cleaning system reduced the rate of increase of the NOx from 5% to 1.6% for Bus 4063 and from 4.1% to 0% for Bus 4070 per 10,000 miles. Hydrocarbon emissions increased 30 ppm per 10,000 miles with the recycler removed compared to a stabilised level with the recycler fitted for Bus 4063. There was a small decrease in hydrocarbon emissions after fitting the recycler for Bus 4070. The particulate emissions were reduced by 35% for Bus 4063 and 24% for Bus 4070 on average. The reductions on total particulate mass were due to reductions on particulate carbon and lube oil VOF emissions. The black smoke was reduced by 56% for Bus 4063 in terms of rate of increase and 40% for Bus 4070 in terms of average values

INTRODUCTION

Particulates and nitrogen oxides are main pollutants generated by diesel engines. Especially particulate emissions are greatly concerned. The formation of particulates is due to incomplete combustion of fuel and consumption of lubricating oils(1,2).

Lubricating oil forms a significant fraction of the particulate volatile fraction and can contribute to the carbon emissions. Lubricating oil also acts as a sink for carbon emissions (3,4) and unburned diesel fuel and this can lead to the deterioration of the oil (5), which results in an increase in the particulate emissions (3). For a low particulate emissions engine the work of Cooke (6) showed that lubricating oil might contribute more to the carbon emissions than to the solvent fraction at some engine conditions. His results showed that there was a variable influence of lubricating oil with no influence on particulate emissions for some engine conditions and up to a 250% increase with lube oil age for other engine conditions.

Diesel engines with low particulate emissions have very low lubricating oil consumption. There is a concern that carbon particles may accumulate to a greater mass concentration in the lube oil, as there will be a reduced dilution with top up of the oil (7). High carbon in the lube oil may then increase the contribution of the oil to the particulate emissions through the associated higher viscosity. Andrews et al (8) have shown that a Euro 1 passenger car diesel engine accumulated carbon in the oil at a greater proportion of the carbon emissions than for an older high carbon-emitting engine.

The control of combustion chamber deposits (CCD) in modern diesel engines is recognised as a part of low emission engine design. The extended service requirements are making it increasingly difficult to control deposit formation (9). The primary source of piston deposit formation is the lubricant due to its oxidation (8,11). In cylinder deposits consist of ash from the lube oil additives, carbon and absorbed unburned fuel and lubricating oil (10, 12). The CCD can be a source of wear in engines, increased friction and hence increased fuel consumption. Crownland heavy carbon has been shown to increase oil consumption (13) and deposits have been shown to increase as piston temperature increases above 250C (14). Deposits also increase with the soot content of the oil (14) and hence deposits can increase as the oil ages. The increased soot in oil as it ages results in an increased oil viscosity (15) and this increases the oil (16) and fuel consumption. The aim of the present work was to examine these influences for two Euro 2 buses fitted with Cummins engines and to determine the improvement in oil quality and impact on emissions through the use of on line recycling of the oil to remove soot, wear metals, fuel and water dilution (5). The recycler had a fine bypass oil filter and an infra-red heater to distil out water and light fuel fractions. The use of by pass filters is common in some large diesel engines, but is not usual in smaller engines of 6 litres or less.

Andrews et al (3, 8) showed that the lubricating oil age could have a significant influence on particulate emissions. Three IDI engines were tested over 100 hours to investigate the influence of lubricating oil age on the emissions. Two Ford engines, 1.6 and 1.8 litre, were low emission engines and the Petter AA1 engine was an older technology high emissions engine. For all three engines there was little influence of lubricating oil age on gaseous emissions. There was an evidence in the NOx emissions for the Petter and Ford 1.8 litre engines of an action of deposit removal, which reduced the NOx and deposit build up. This was also supported by the additive metal analysis of the lube oil. The hydrocarbon emissions increased with oil age for both of the low emission engines but only the 1.6 litre Ford engine showed a similar change in the particulate VOF. The 1.8 litre engine VOF trends were dominated by lube oil influences, which do not contribute to gaseous hydrocarbon emissions at 180 C sample temperature. The particulate emissions trends with oil age were quite different for the Ford 1.6 and 1.8 litre engines, with a continuous increase in emissions for the former and a decrease followed by an increase after 50 hours for the latter. The Petter engine also followed similar trends to the Ford 1.8 litre engine, although with much higher emission levels. It was shown that these trends were also reflected in the carbon fraction and unburned fuel fractions of the particulate VOF for the two Ford engines. However, the lube oil fraction decreased substantially over the first 50 hours for the Ford 1.8 litre engine and then remained at a stable level. The implication was that the fresh lubricating oil resulted in high unburned lube oil particulate VOF emissions and also generated carbon emissions. Once the volatile fraction of the lube oil had been burnt away in the engine, the lube oil VOF remained stable and the subsequent increase in the particulate emissions was due to increasing carbon emissions. The initial decrease in the fuel VOF fraction followed by an increase after 50 hours was possible due to the initial removal of CCD by the fresh lubricating oil followed by a build up of fresh deposits as the oil aged. Fuel fraction VOF can be contributed to by deposit absorption and desorption, which is a function of the extent of the CCD.

This work is concerned with a technique to keep oil clean, extend its life and reduce the increase in emission that occurs with aged oil. The above review has emphasised the importance of CCDs in emissions and lubricant quality. At the same time as diesel emissions regulations have come into force the trends in the diesel design, towards higher ring zone temperature and pressure, piston redesign for higher top rings, higher piston temperatures, and extended service interval requirements, are making it increasingly difficult to control deposit formation in the engine with traditional oil additive technology (9). Diesel deposits can be classified into two types: ring zone and piston skirt deposits (varnish). The higher ring zone temperatures (325-360C) promote thermal degradation of the lubricating oil and unburned/oxidized fuel components producing a ‘carbon’ deposit. At relatively low piston skirt temperatures (200-260C) a varnish type deposit predominates (9). The primary source of piston deposits is the lubricant and lubricant oxidation is the primary cause of deposit formation (9). Diesel engine deposits also increase with the oil consumption (10), the piston temperature (14) and the oil soot content (14). Engine deposits are a source of unburned hydrocarbons through absorption and they also act as a cylinder insulation, which increases NOx emissions because of the higher cylinder temperature (18).

THE ON LINE OIL RECYCLER AND BUS TEST PROCEDURE

A method of continually cleaning the engine oil on line was investigated. This was based on the combined effects of a bypass fine oil particulate filter with a 1 or 6 micron filter element followed by an infra-red dome heater which heated the oil to 135C as it flowed over a conical cascade into a drain return to the oil sump. The previous work using this system (5) used a 6 micron bypass oil filter and this was the filter used in Bus 4063 at the start of the present work. However, work was in progress to develop a finer I micron bypass filter and this had reached the prototype stage when it was decided to fit a recycler to the second bus (Bus 4070). It had originally been intended in the present work to use two nominally identical buses with the same engine and mileage. However, as will be shown in the results, the two buses had different oil deterioration rates and the accompanying emissions results showed different emissions. Bus 4063 was operating consistently 4 A/F richer for the same duty cycle for a journey with an average A/F of 35/1. Soot accumulation in the oil for Bus 4063 was also significantly higher for Bus 4070. Consequently, it was concluded that bus 4063 was in a different mechanical state to Bus 4070, possibly through different operating cycles or different driver 'harshness' of operation and the two buses could not be compared one with a recycler and one without. Thus, both buses had to be tested with and without the recycler.

The basic comparison test between the oil ageing with and without a recycler was carried out using Bus 4063 with fresh oil starting each test and using the 6 micron bypass filter. This bus was first tested with the recycler fitted and after 25,000 miles it was disconnected. This is twice the normal oil change interval for the bus. However, the oil analysis showed that the oil could have been used for longer if required. The oil was then changed and the test repeated. Bus 4070 was intended to be the comparator bus and this was tested first without the recycler for a much longer period than the normal oil change interval of 12,000miles. However, this extended test had a mechanical problem after 14,000 miles which led to a large loss of lubricating oil and this resulted in an 80% of the sump capacity oil top up. Thus the extended test without the oil change effectively had nearly a complete oil change after 14,000miles. After 29,000 miles it was decided to fit the recycler and not to change the oil. The aim was to demonstrate in an on road test that the recycler could clean-up dirty oil and reduce its rate of deterioration and make it fit for further use. It was shown (19)that this oil was still fit for continued use after 48,000miles. The normal oil change period on these buses was 12,000miles, typically about every three months. The buses were operated 7 days a week with an average mileage per day of about 140 miles. The typical route length was 10 miles repeated about 14 times per day. The bus routes in Leeds are typical of modern high density cities and Leeds is quite a hilly city, so that the journeys would involve several hills, acceleration from a stop on a hill and a bus stop on average about every 2-400m. There were no extended high speed cruise periods in the normal bus usage. Similar tests to this were previously reported by the authors (5) for a Cummins L10 and a Gardner 6LXB bus engines and both of these tests showed a reduction in oil deterioration and reduced w ear metals following the fitting of the recycler.

One of the advantages of the recycler is that it provides an improved oil quality and reduced oil consumption (5,30). The improved oil quality reduces the engine CCDs. Thus the reduced oil consumption and CCDs in the combustion chamber reduce engine emissions. Authors have shown that emissions had been reduced for a Ford1.8 litre IDI engine test as a result of improved oil quality and reduced oil consumption (17).

Other investigators of bypass filters have advocated the improvements by using filters of the order of 1 micron (25-29). The initial choice in the present work of 6 micron particle size filters was based on advice from hydraulic oil filter manufacturers that oil additives could be filtered out if the filter size was too fine. Also, very fine 1 micron oil filters that were available from hydraulic oil filter manufacturers had a rather high pressure loss. If these were used in the recycler then the bypass flow would have been controlled by the filter pressure loss and the flow rate would have decreased as soot built up in the filter. A key feature of the present recycler is that the bypass oil system oil flow rate is relatively high. In the Ford 1.8 litre IDI passenger car diesel tests (5) the recycler oil flow rate was such that oil the sump volume of the oil was passed through the recycler four times an hour. The one micron by pass filter used in this work was developed to have a fine filtration of 1 micron particles without affecting the recycler bypass flow rate, even when loaded with soot. The present results show that this new fine filter does improve the performance of the recycler. This filter is now in production and will be used in the future commercial use and evaluation work using this system.

Although a filter based bypass filter was used in the present work, centrifugal bypass filters are also quite common (29). These are of two types: powered and self-powered and the latter are more common in automotive applications. A self-powered centrifugal oil cleaner uses the dirty oil pressure to drive the cleaning rotor using centrifugal separation of the high density particles from the lower density oil. These contaminants collect as a hard cake on the inside of the rotor which can then either be cleaned off or disposed of as a unit (29). Centrifugal filters have an effective particle size removal below 1 micron and have a filtration efficiency that does not deteriorate with time (29). They are generally more expensive initially than filter based bypass filters. One assessment of bypass filters (30) has determined the average size rating (50% removal) of a centrifugal filter as 6-10 microns and hydraulic oil filters as 2 micron. They also estimated that it would take 30 bypass filter changes before the cost of bypass filtration exceeded that of a centrifugal filter. This could be 10 years of normal use. Hydraulic quality bypass filters were used in the present work with an average size rating of 6 and 1 microns.

EXPERIMENTAL TECHNIQUES

ENGINE SPECIFICATIONS

The two buses tested had the same engine specification detailed in Table 1. The two buses tested were coded Bus 4063 and Bus 4070 and operated with routine oil top ups and normal commercial duty cycles. The buses travelled around the Leeds area from early morning to late night daily. The oil and exhaust gas samplings were taken every two weeks, at about 2000 miles intervals. Each test run had travelled the same route. However, the drivers were varied and so were traffic conditions. The amount of the lubricating oil topped up and the fuel consumed were recorded at the fleet so as to track the lube oil consumption and fuel consumption.

Bus 4063 started the test with the recycler fitted and Bus 4070 started the test without the recycler fitted. For Bus 4063 after ~25,000 miles after the commencement of the test with fresh oil with the recycler fitted, the recycler was removed from this bus. The lubricating oil was then drained and the engine was refilled with the fresh oil. There was no flushing of the old engine oil, as this is not normal in an oil change. Then the test restarted and lasted for ~20,000 miles. On Bus 4070 after ~29,000 miles after the commencement of the test with fresh oil, a recycler was fitted and the test continued for a further 19,000 miles without the oil being changed. The results are shown as a function of the time from the last fresh oil change, which is given as time zero on the graphs. In some graphs that compare both buses, the time from fitting the recycler is used, even though this was done using fresh oil for Bus 4063 but not for Bus 4070. As discussed above, Bus 4063 was fitted with a recycler with a bypass particulate filter size of 6 microns and Bus 4070 was fitted with a 1 micron filter.

Table 1 SPECIFICATION OF THE ENGINES

Parameter	Spec.
Type	Cummins 6CT 8.3 turbo-charged
Maximum Power Rating	157KW(211BHP) at 2400rpm
Displacement litre	8.27
Oil pressure, low idle(min)	10 P.S.I(69 kPa)
at2100rpm(max)	30 P.S.I(207kPa)
Oil capacity litre	18.9(High), 15.1(Low)
Bore mm	114
Stroke mm	135
Cylinder No.	6
Compression ratio	17.3:1
Lube oil change intervals	3 months or 12,000miles
EGR	No
Aspiration	Turbocharged and Intercooled

FUEL AND LUBRICANTIN OIL

The fuel used in most of tests was commercially available standard low sulphur diesel with sulphur content ≤ 0.05%. The Ultra Low Sulphur Diesel (U.L.S.D) was introduced at the later stage of the tests with 30ppm of sulphur content, as the standard low sulphur diesel was not available.

The lubricating oils used in tests were 15W-40 CF-4/CE/SF mineral oil. The specifications of diesel fuels and lubricating oils were listed in Ref.(30).

PARTICULATE SAMPLING SYSTEM

A stainless steel tube (gas sampling tube) with a diameter of 7 mm was inserted into the centre of the tailpipe before the muffler (about 0.3 meter after the turbocharger). This tube was connected with a relay tube (about 2 meters long stainless steel tube), which passed through the screw hole on the back seat of bus and into the bus. The sampling kit was placed on the backseat of the bus. Thus the exhaust gases were conducted into the sampling kit. After the completion of the sampling the relay tube was taken off and a stopper used to blanket the sampling tube so as not to interfere with the bus in service.

The exhaust gases from a relay tube were conducted through a 125ml wash bottle placed in an ice bucket to condense the water and heavy hydrocarbons and then passed to a filter block with a 47 mm Whatman Glassfiber filter paper to collect the particulate samples. The residue gases were then put through a gas meter to count the volume of gases and a flow meter, and finally collected in a gas bag. This sampling process was driven by exhaust pressure. Therefore the samples collected were proportional to combustion pressure and represented real driving conditions.

GAS ANALYSIS

The exhaust gases collected in a 60 litre gas sample bag were analysed as soon as possible after sampling. The gases were passed to an oven and then transported to a heated FID at 180°C for total hydrocarbon analysis, a heated Chemiluminescence NOx analyser for NOx analysis, a Servomex paramagnetic analyser for oxygen analysis and a Hartman & Broun Uras 10E for CO and CO_2 analysis. The air/fuel ratio could be worked out by these gas analyses according to carbon balance principle.

PARTICULATE ANALYSIS

The particulate filter papers were conditioned in a constant humidity enclosure for 24 hours before and after the tests and the weights recorded after each 24-hour conditioning period. The increase in weight was the particulate mass and this was measured to 1 microgram accuracy and a minimum mass of 1 mg was collected, giving a minimum resolution of the mass of 0.2%. Only one filter paper was taken at each oil mileage as the availability of driver and vehicle restricted to take more samples.

The particulate was analysed for carbon, fuel and unburnt lubricating oil fraction using TGA technique. A round cutter with a diameter of 29 mm was used to cut the filter papers so as to get an identical area of the filter paper and minimise the interference of blank filter papers. This cut filter paper sample was wired and hung on a hook on an end of a microbalance enclosed in the oven with nitrogen atmosphere. The sample was heated up to 550°C at a rate of 20°C per minute and kept for 10 minutes where no further weight loss occurred. The weight loss represented the volatile fraction of particulates. The air was then introduced and the temperature was increased to 560°C and maintained for 20 minutes. The weight loss before and after introduction of the air was equivalent to the carbon mass. The rest of the sample was the ash mass of particulates. A blank filter paper was used to determine the weight loss of the filter paper and this was used to correct the particulate weight loss. The TGA procedure has been used for determination of fuel and lubricating oil fractions of particulates and detailed in Ref.11.

BLACK SMOKE MEASUREMENT

An OPAX 2000-II smoke meter was used in bus and refuse truck tests. This is a partial flow smokemeter or opacimeter designed for measuring the exhaust smoke of diesel engines. The principal configuration is that it has a heated smoke measuring chamber, which contains a light source (halogen lamp), a sensor (silicon photodiode with corrected spectral response similar to the photopic curve of the human eye -peak response 550nm) and a mirror. It measures the smoke(opacity) based on the visible light absorption of the exhaust gas as detected by a sensor.

The testing procedure used was the Free Acceleration Smoke (FAS) measurement required by the Vehicle Inspectorate for MOT test. This procedure has good repeatability and considered to indicate the vehicle's actual smoke emission. The details are as follows:

Smoke testing procedure on bus and refuse truck tests:

-Switch OPAX 2000-II smoke meter on to warm it up.

-At the end of the warm up period the OPAX 2000-II shows dashes on displays.

-Press the MEASURE key. The display shows "REF" and the equipment starts a new autozero. After this, the equipment is ready to operate.

-Start the engine that should already be at running temperature. Depress the accelerator pedal until engine attains its governed speed and then release the accelerator to idle. Repeat this several times in order to purge the exhaust of loose dust and carbon.

-Insert the probe in the exhaust pipe using the adapter provided. Ensure it is fixed to the tailpipe.

-Press the MEASURE key. When the display is flashing "-1-" the operator can commence the accelerations.

-For each acceleration, the operator depresses the accelerator sharply to full fuel position and on attaining governed speed remains there for approximately 2 sec, then release the accelerator. The display will delay for 5-6 sec and then prompts the operator for a new acceleration; blinking on the MEASURE display indicates the nest acceleration is required.

-Repeat acceleration and idling procedure for a minimum of six accelerations. An average value of opacity is displayed. Print it out and test is finished.

The unit measured by this procedure was K (1/m) from 0.00 to 9.99.

AIR/FUEL RATIO

As the driving patterns and traffic conditions were varied for each testing journey, the air/fuel ratio fluctuated with each sampling process. The differences in air/fuel ratio tend to have an influence on emissions measurements. So correlation between emission parameters and air/fuel ratio has to be determined before presenting emissions as a function of oil age.

The air/fuel ratio measured by exhaust gas analysis for the two bus tests is shown in Fig.1. For Bus 4063 the air/fuel ratio was around 30.5~35.1(mean value 32.5) with the recycler fitted and 32.2~37.5 (mean value 33.7) without the recycler. The mean value of air/fuel ratio for Bus 4063 during the whole test period was 33.1. For Bus 4070 the air/fuel ratio was between 33.7~38.7 (mean value 36.5) without the recycler and 34.9~38.7(mean value 37.5) with the recycler fitted. The mean value of air/fuel ratio for Bus 4070 during the whole test period was 37. It can be seen that Bus 4063 had lower air/fuel ratio than for Bus 4070. The mean value of air/fuel ratio for both bus tests was 35.

The gaseous, smoke and particulate emissions were plotted against the air/fuel ratio for each bus and the correlation coefficient was calculated using linear regression analysis. The results were listed in Table 2. It can be seen that none of the emission parameters has significant correlation with air/fuel ratio, as the maximum value of R^2 is 0.38. In general, only if the R^2 excesses 0.7 than it can be regarded as well correlated.

Table 2 Correlation between emission parameters and air/fuel ratio

Emission parameters	R^2 Bus 4063	R^2 Bus 4070
CO	0.11	0.14
HCs	0.16	0.37
NOx	0.38	0.11
Smoke	0.02	0.18
Total Particulate	0.20	0.38
Particulate Ash	0.21	0.32
Particulate Carbon	0.03	0.36
Particulate VOF	0.10	0.03
Lube oil VOF	0.00	0.09
Fuel VOF	0.19	0.00

INFLENCE OF FUEL SULPHUR CONTENT ON EMISSIONS

To minimise the effect of fuel quality on emission parameters, a same brand diesel fuel from same refinery was provided. The standard low sulphur diesel with sulphur content less than 0.05% was predominant fuel used during the tests. However, there was a change in fuel from low sulphur to ultra low sulphur fuel at the late stage of the tests due to the termination of production of the low sulphur fuel.

The Ultra Low Sulphur Diesel (U.L.S.D) started to use at around 5,000 miles of oil age for Bus 4063 without the recycler and 35,000 miles for Bus 4070 with the recycler fitted. There was no significant change on gaseous emissions with the switch of Low Sulphur Diesel to Ultra Low Sulphur Diesel. It had, however, a significant influence on smoke and particulate emissions. A simple comparison was made to see the effect of U.L.S.D on emissions as shown in Table 3. It has shown that the black smoke, total particulate and particulate carbon emissions were reduced significantly with the use of U.L.S.D on two bus tests. The reduction was greater for Bus 4063 than that for Bus 4070. This was due to that Bus 4063 had a higher emission level and ran with no recycler fitted while Bus 4070 had a lower emission level and ran with the recycler fitted when the U.L.S.D was introduced.

As the introduction of U.L.S.D had a significant effect on particulate and smoke emissions, the raw data using U.L.S.D. has been corrected by adding a parameter of 0.4 g/kg for Bus 4063 and 0.2 g/kg for Bus 4070 for TPM and particulate carbon, and adding 0.5K for Bus 4070 and 0.3K for Bus 4063 for smoke.

Table 3. Effects of U.L.S.D on emissions

Bus No.	Type of fuel	Smoke K	TPM g/kg	Particulate carbon g/kgfuel
4063	L.S.D.	1.9	1.5	1.2
	U.L.S.D.	1.4	1.1	0.8
4070	L.S.D.	1.3	1.0	0.7
	U.L.S.D.	1.0	0.8	0.5

N.B. TPM-Total Particulate Mass
L.S.D-Low Sulphur Diesel
U.L.S.D-Ultra Low Sulphur Diesel

GASEOUS EMISSIONS RESULTS

CARBON MONOXIDE – There appeared a fluctuated pattern on CO emissions for both bus tests. The average figure for CO emissions was about 300 ppm. The fitting of the recycler did not show notable improvements on CO emissions.

HYDROCARBONS - Figs.2 and 3 show the hydrocarbon emissions as a function of oil age for two bus tests.

On the Bus 4063 test with the recycler fitted, there was a peak in hydrocarbon emissions at 7,500~ 10,000 miles of oil age. This peak was due to a specific traffic condition, where a roadwork was ongoing and made bus travel slowly. This increase in hydrocarbons was associated with a decrease in NOx shown later and indicated a low speed running of the engine. During the period of 25,000 miles with the recycler fitted, the hydrocarbon emissions for Bus 4063 was maintained if ignoring the peak. After the recycler had been removed, the hydrocarbon emissions were showing an increasing trend with oil age. There was an increase of 20ppm in about 20,000 miles of use of the oil, which was about 57% increase. Hence it indicated that the recycler could prevent the hydrocarbon emissions from deterioration with oil age.

The hydrocarbon emissions were relatively stable for Bus 4070 both without and with the recycler fitted, except an abnormal data at 23,000 miles of oil age without the recycler. There was no notable reduction on hydrocarbon emissions with the recycler fitted. The average hydrocarbon emissions were about 40 ppm.

NOx EMISSIONS – NOx emissions were shown in Figs.4 and 5 as a function of oil age. With the recycler fitted the NOx emissions for Bus 4063 started at 280 ppm for the fresh oil and sharply decreased to a minimum of 200 ppm after 7,500 miles of the oil age and then increased to 280 ppm again at 11,700 miles. This decrease was due to the traffic alteration due to temporary road works, which made the bus slow down and has low engine revolutions and thus resulted in a low NOx emission. The NOx emissions were fluctuated afterwards and maintained at about 300 ppm at the end of 25,000 miles of the test. With the recycler removed the NOx emissions varied around 300 ppm.

With no recycler fitted on Bus 4070 test, there was a high initial NOx emission after fresh oil fill, which could be explained as the deposits had been built up through the previous oil change interval, which insulated the combustion chamber and thus resulted in an increase in temperature in the combustion chamber. The fall in NOx emissions after 2,500 miles of operation was due to the removal of the deposits by the fresh oil. As the oil ageing, the deposits started to build up again and resulted in an increase in NOx emissions with oil age. There was a sharp reduction in NOx at 24,000 miles of oil age, which was possibly due to the traffic variation. In general, the NOx emissions appeared to be an increasing trend without the recycler. With the recycler fitted, the NOx emissions increased and decreased periodically and showed no increase in general.

To make the NOx emissions be comparable, the NOx data has been normalised and shown in Fig.6. With the recycler fitted, NOx emissions are showing 4% increase over 25,000 miles for Bus 4063 and no increase over 17,000 miles for Bus 4070. Without the recycler, there was 10% increasing over 20,000 miles for Bus 4063 and 12% increase over 29,000 miles for Bus 4070. So with the recycler fitted, the rate of increase in NOx was 1.6% per 10,000 miles for Bus 4063 and 0% for Bus 4070. Without the recycler, the rate of increase in NOx was 5% per 10,000 miles for Bus 4063 and 4.1% for Bus 4070.

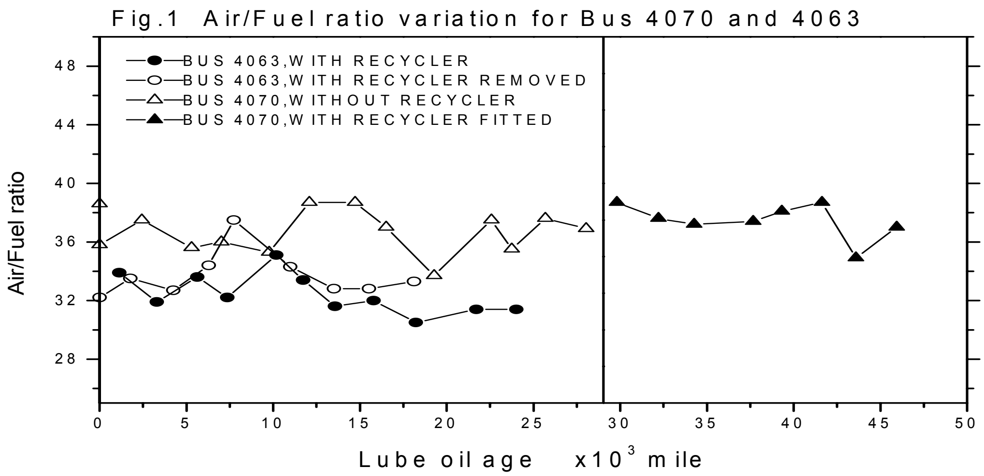


Fig.1 Air/Fuel ratio variation for Bus 4070 and 4063
BUS 4063,WITH RECYCLER
BUS 4063,WITH RECYCLER REMOVED
BUS 4070,WITHOUT RECYCLER
BUS 4070,WITH RECYCLER FITTED
Air/Fuel ratio
Lube oil age x10³ mile

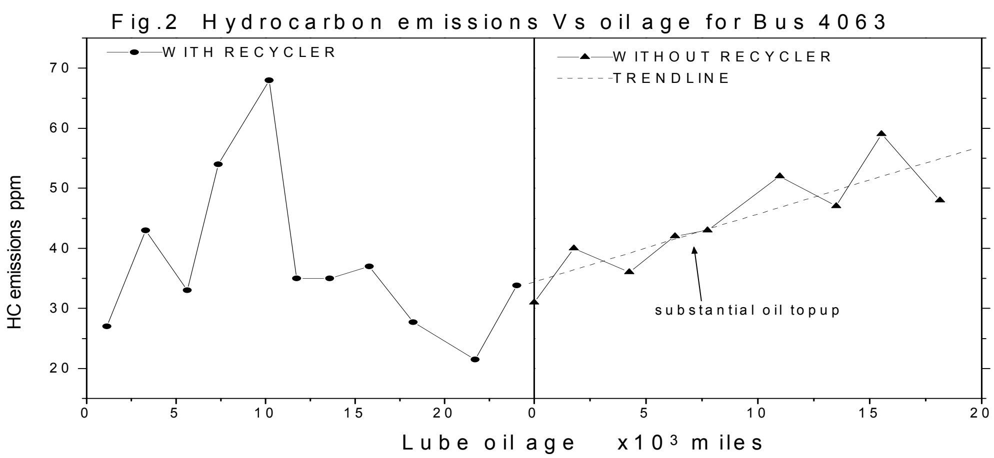


Fig.2 Hydrocarbon emissions Vs oil age for Bus 4063
WITH RECYCLER
WITHOUT RECYCLER
TRENDLINE
substantial oil topup
HC emissions ppm
Lube oil age x10³ miles

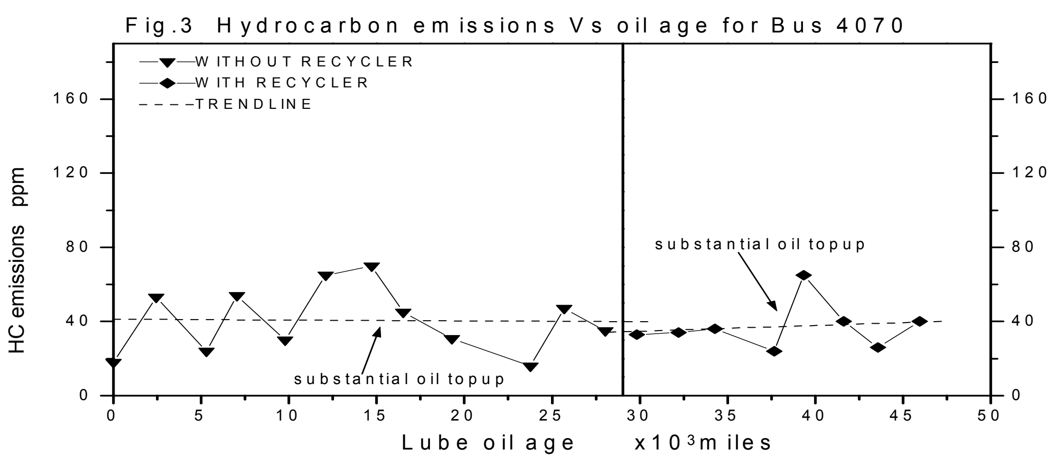


Fig.3 Hydrocarbon emissions Vs oil age for Bus 4070
WITHOUT RECYCLER
WITH RECYCLER
TRENDLINE
substantial oil topup
substantial oil topup
HC emissions ppm
Lube oil age x10³miles

Fig.4 NOx emissions Vs oil age for Bus 4063

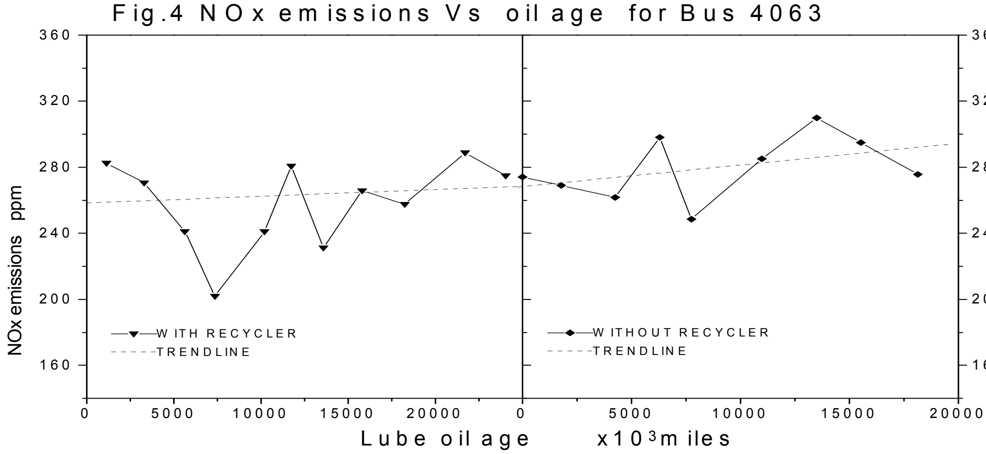


Fig.5 NOx emissions Vs oil age for Bus 4070

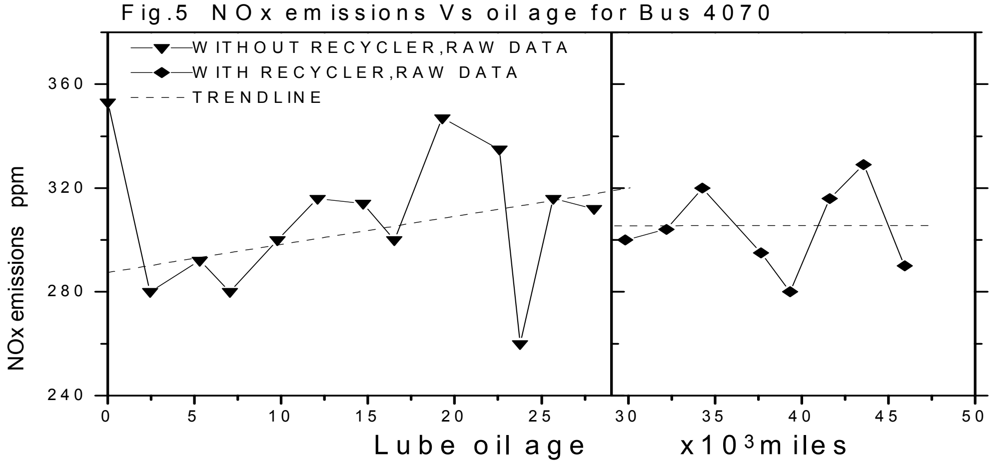
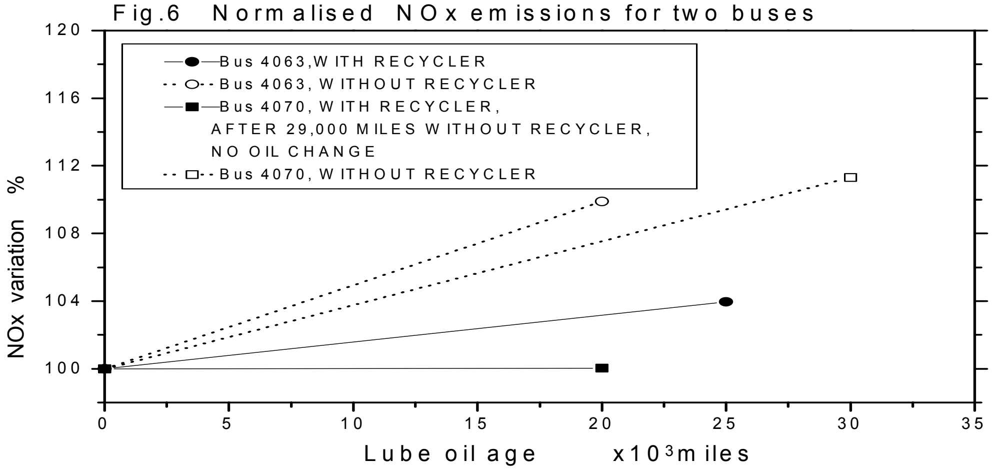


Fig.6 Normalised NOx emissions for two buses



However, The data was quite fluctuated because of the difficulty in the control of the testing conditions.

BLACK SMOKE

The production of smoke in diesel engines is predominately relied on the availability of oxygen, fuel property and temperature. The lubricating oil will, however, have a strong effect on smoke. Figs.7 and 8 show the smoke with oil age for two bus tests.

The smoke was gradually increasing for Bus 4063 both with and without the recycler with periodically increases and decreases. With the recycler, the smoke increased from 1.65 K of the fresh oil to 1.90 K after 25,000 miles of oil use on average. With the recycler removed, the smoke increased from 1.70 to 2.15 after 20,000 miles of oil age. The gradient of increase in smoke was 0.1 K with the recycler and 0.225 K without the recycler per 10,000 miles. Thus the reduction in the rate of increase by the recycler is 56% for Bus 4063.

For Bus 4070, the smoke increased and decreased periodically without the recycler. The average value is 2.0 K during 29,000 miles of the oil use. There was a fast response in smoke after the recycler was fitted without the oil being changed, which made smoke decreased from 1.6 down to 1.0 in just 500 miles. This is due to the function of the recycler on oil cleaning as the carbon in the oil was greatly reduced(28). This reduced carbon in oil could result in a reduction in oil consumption and thus reduces the smoke. The smoke was then increased a little and stabilised at an average value of 1.2 K with a slightly decreasing trend. Comparing the average values of smoke with and without the recycler (1.2K and 2.0K), it can be concluded that the recycler had reduced the smoke by 40% for Bus 4070.

These two buses had a quite different performance on smoke. The oil age had a significant effect on smoke emissions for Bus 4063 whereas there was little influence of oil age on smoke for Bus 4070. The recycler had a greater improvement on smoke for Bus 4070 because the filter on this recycler was finer.

PARTICULATE EMISSIONS

TOTAL PARTICULATE EMISSIONS - The results were shown in Figs.9 and 10.

For Bus 4063 with the recycler fitted, there was a peak in the mass of particulates at around 3000 miles of oil age, which was associated with an increase in CO, HC and smoke at the same time. The possible reason for this was an incomplete combustion process at this time. The particulates emissions after this peak decreased greatly down to a minimum of 0.76 g/kgfuel at 12,000 miles, followed by an increase. This fall in total particulate emissions was due to a reduction in particulate ash fraction primarily, where the mass of particulate ash decreased to 0 at 12,000 miles. For a further 8,000 miles of oil use, the particulate mass gradually declined and was stabilised at 1.3 g/kgfuel after 20,000 miles, which was the same value to the fresh oil.

With the recycler removed and refilled with fresh oil, the particulate mass increased consistently from 1.3 g/kgfuel to 1.9 g/kgfuel after 20,000 miles and would reach 2.0 g/kgfuel at 25,000 miles according to extrapolation. Thus by comparing the particulate emissions after 25,000 miles of oil age with and without the recycler (the doubled mileage of normal oil drain interval), it can be seen that the recycler reduce particulate emissions by 35% for Bus 4063 test.

For Bus 4070, without the recycler the particulate mass fluctuated with a peak at around 12,000 to 15,000 miles due to very high ash emissions. The average value for particulate mass emissions without the recycler was 1.70 g/kgfuel during 29,000 miles of use. After the recycler was fitted without the oil change, particulate emissions decreased rapidly from 1.55 g/kgfuel to 1.3 g/kgfuel and stabilised at this level for the rest of 18,000 miles test period. The average value for particulate mass emissions with the recycler was 1.3 g/kgfuel. Thus a 24% reduction in particulate emissions was achieved with the recycler fitted without any oil change.

PARTICULATE ASH EMISSIONS - The results were shown in Figs.11 and 12.

With the recycler, Bus 4063 had a high initial particulate ash emission. The ash decreased gradually with oil age and reached a minimum level at 12,000 miles, which was co-ordinated with a fall in total particulate emissions as discussed above. Then the ash mass had risen back and maintained at around 0.3 g/kgfuel. After the recycler was removed with fresh oil refilled, the mass of particulate ash had a lower initial value and was showing a firstly decreased and then increased trend.

Fig.7 Smoke Vs oil age for Bus 4063

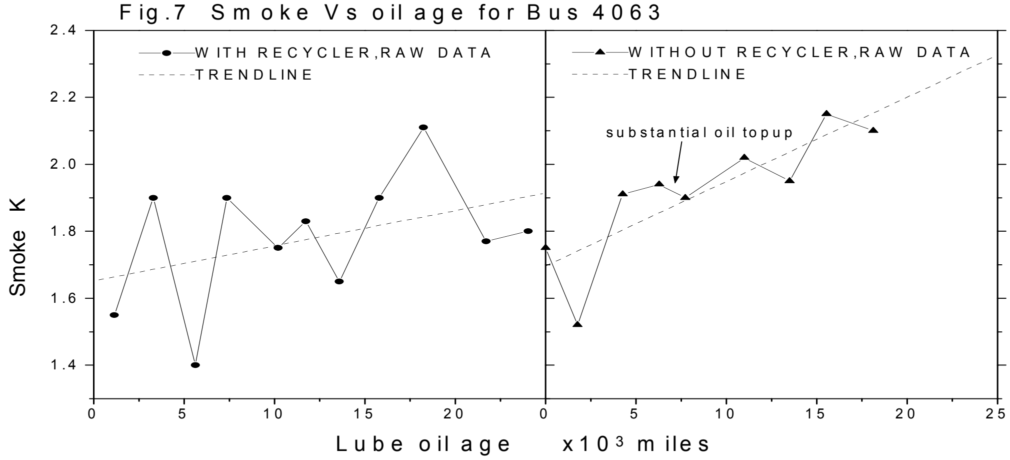


Fig.8 Smoke Vs oil age for Bus 4070

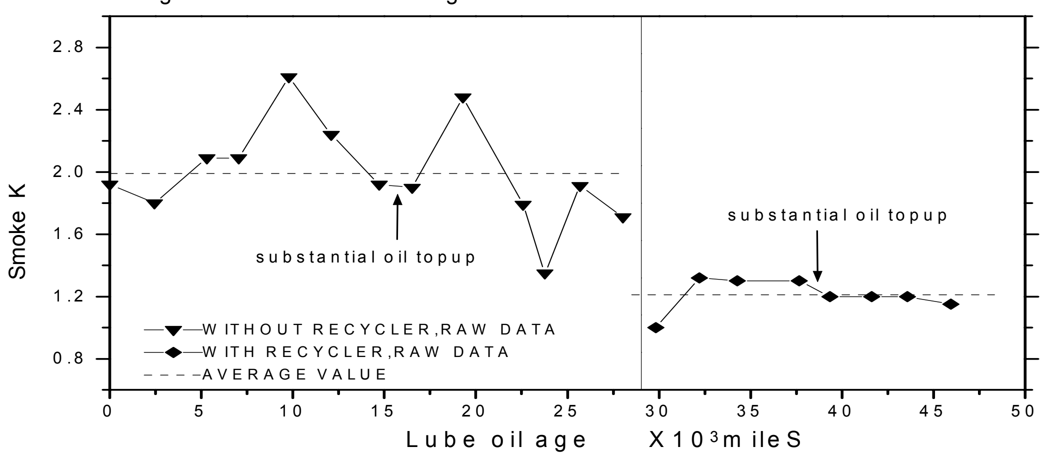


Fig.9 Total particulate mass emissions Vs oil age for Bus 4063

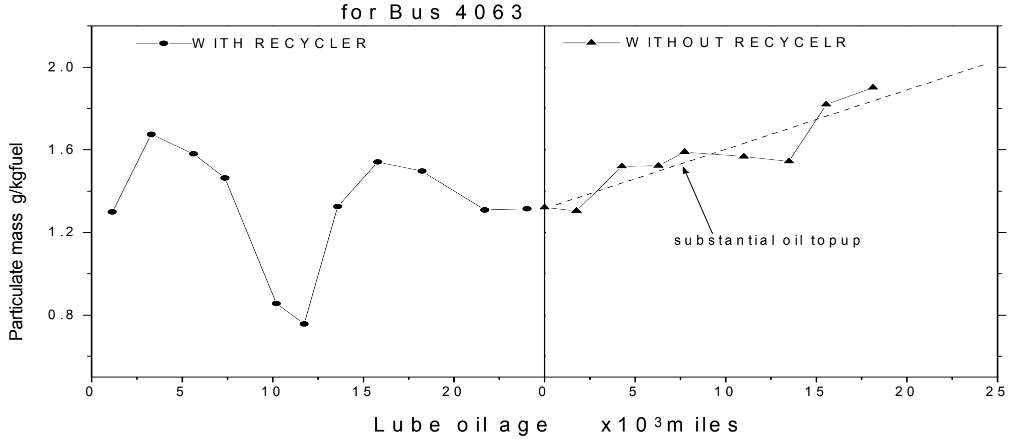


Fig.10 Total particulate mass emissions Vs oil age
Bus 4070

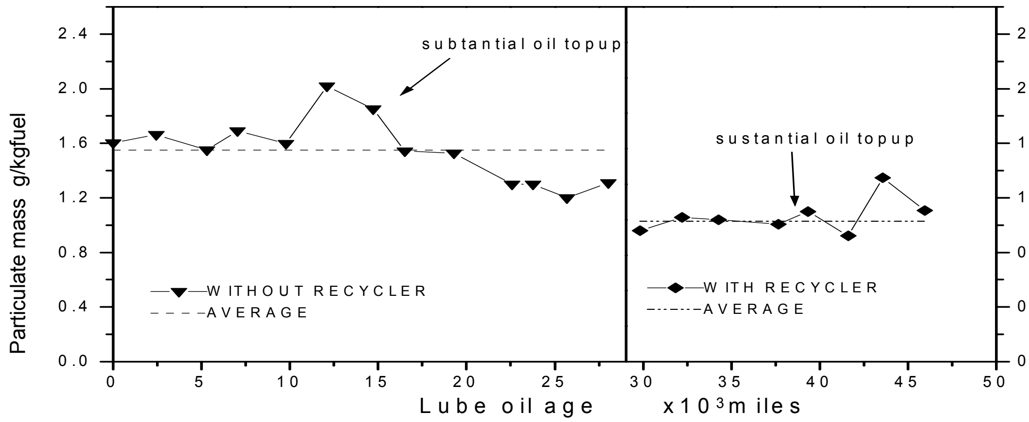


Fig.11 The mass of particulate ash Vs oil age for Bus4063 test.

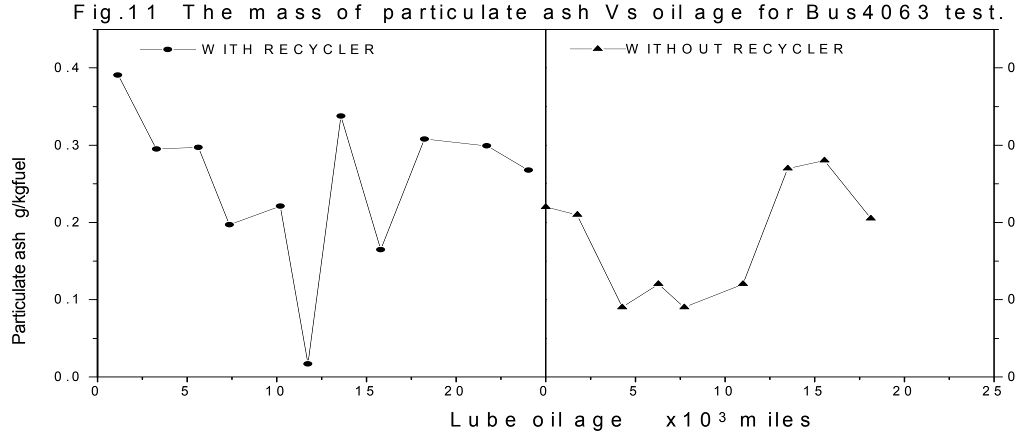
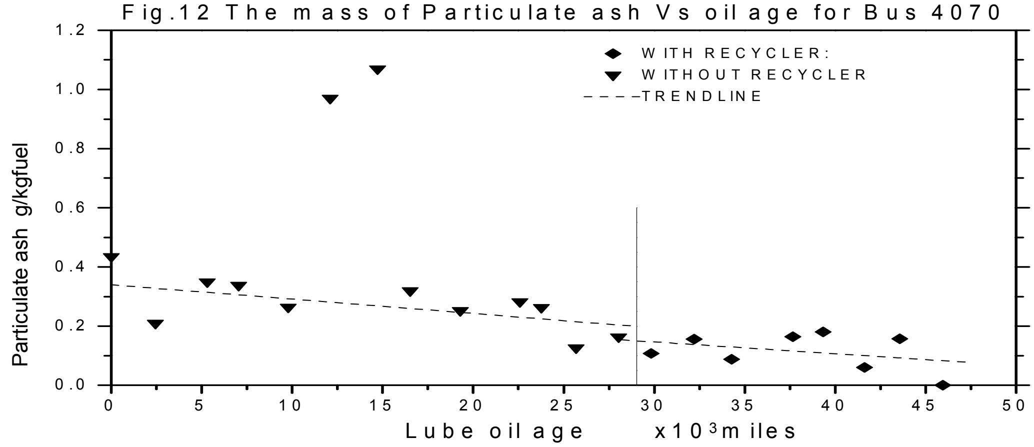


Fig.12 The mass of Particulate ash Vs oil age for Bus 4070



The particulate ash mass for Bus 4070 showed a decreasing trend through the whole test period with and without the recycler. There were two exceptional data points at the oil age of 12,000 and 14,700 miles without the recycler, where the total particulate mass was at the highest values. This was due to the very slow and more stop-start driving pattern when these samples were taken. It indicated that the low revolution and more stop-start of the engine could result in high particulate emissions due to high particulate ash emissions.

PARTICULATE CARBON EMISSIONS – The particulate carbon emissions were shown in Figs.13 and 14 as a function of oil age.

For Bus 4063 with the recycler, there was a peak in particulate carbon emissions at around 3,000 miles of oil age, which was associated with a peak in total particulate mass emissions. Particulate carbon emissions then decreased significantly down to a minimum value of 0.45 g/kgfuel at 10,000 miles, followed by an another peak at about 16,000 miles and then stabilised at 0.8g/kgfuel at the end of test. During the whole test period (25,000 miles) with the recycler fitted, particulate carbon emissions were at a similar level for fresh oil and 25,000 mileage used oil. This was mirrored by a slow increase in smoke during 25,000 miles test with the recycler. With the recycler removed, the particulate carbon mass continuously increased to 1.5 g/kgfuel after 18,000 miles. The rate of increase in particulate carbon was 0.29g/kgfuel per 10,000 miles after the recycler was removed.

For Bus 4070 without the recycler, there was also a peak for young oil (2,500 miles) followed by a series of fluctuations. Generally the mass of particulate carbon had a stabilised trend with an average value of 1.0g/kgfuel. After the recycler was fitted without the oil being changed, the particulate carbon decreased rapidly and then showed a slowly increasing trend with an average value of 0.85 g/kgfuel. The reduction in particulate carbon emissions by the recycler was 0.15 g/kgfuel by mass or 15% by percentage by comparing the average values.

PARTICULATE VOF EMISSIONS - The VOF (Volatile Organic Fraction) of the particulates was determined by the TGA technique. Figs.15 and 16 show the particulate VOF mass emissions against oil age on both bus tests.

For Bus 4063 with the recycler fitted, there was a peak in particulate VOF emissions ranging from 3,000 to 7,000 miles, which was corresponding to the peak in total particulate and particulate carbon emissions and yet the peak value for VOF emissions was at 7,000 miles whereas the peaks for total particulates and particulate carbons were at 3,000 miles. Following the peak, there was a fall in particulate VOF emissions, which was responsible for total particulates decrease at the same time along with the falls in particulate carbon and ash emissions. Then particulate VOF fluctuated through the rest of the test with an average value of 0.23g/kgfuel. With the recycler removed, there was a higher particulate VOF emission for fresh oil, compared to that with the recycler fitted. The particulate VOF emissions gradually decreased with oil age until 13,500 miles and then started to increase. The substantial oil top up did not appear to have significant effect on particulate VOF emissions. However, the variation in particulate VOF emissions was quite similar to that in the Ford1.8L, IDI engine test without the recycler (15). i.e. higher VOF emissions for fresh oil, decreased to minimum at the half of oil age and then increased again.

For Bus 4070, without the recycler there was a continuous increase in particulate VOF emissions (from 0.13 to 0.34 g/kgfuel) in the first 7,000 miles of oil age followed by a stabilised particulate VOF for 6,000 miles and then decreased to 0.22 g/kgfuel at about 16,000 miles. This fall in particulate VOF was following the peak of particulate ash that appeared from 12,000 to 15,000 miles. Thus it can be postulated that the deposits were gradually built up in cylinder and resulted in an increased VOF emissions due to storage mechanism. After a period of build up, some deposits were stripped off from the cylinder and thus resulted in a peak in particulate ash. Then the particulate VOF was reduced due to that the reduced deposits reduced the storage of hydrocarbons. The accumulation of deposits in cylinders was confirmed by the increase of NOx in the first 15,000 miles. Particulate VOF emissions were fluctuated around 0.25 g/kgfuel afterwards. The addition of the substantial amount of fresh oil did not affect the particulate VOF notably. After fitting the recycler at 29,000 miles of oil age, the particulate VOF continuously decreased from 0.3 g/kgfuel to 0.1 g/kgfuel in about 10,000 miles and then increased continuously from 39,000 miles. The increase of particulate VOF was after an addition of a substantial amount of fresh oil. This was coincident with the results of fresh oil for Bus 4070 without the recycler and Bus 4063 with the recycler that were showing the fresh oil had an increasing trend in particulate VOF emissions.

LUBE OIL VOF EMISSIONS - Lube oil VOF emissions are shown in Figs.17 and 18.

For Bus 4063, with the recycler lube oil VOF emissions increased from 0.09 g/kgfuel to 0.2 g/kgfuel for the first 7,000 miles of the oil age, similar to the total VOF emissions. The lube oil VOF reached a maximum value at around 7,000 miles and then decreased. The falls in lube oil VOF at 10,000 and 12,000 miles were accordingly to that of total particulate emissions and total particulate VOF emissions. The lube oil VOF emissions increased after the falls and stabilised at about 0.14g/kgfuel. The average value of the lube oil VOF for Bus 4063 with the recycler was 0.14 g/kgfuel. After the recycler was removed, there appeared a high initial lube oil VOF emission for the fresh oil (0.19 g/kgfuel) and continued to increase to a peak of 0.24g/kgfuel after 1,700 miles of oil age. The lube oil VOF decreased thereafter until 13,500 miles followed by an increase. The variation of lube VOF after the substantial oil top up was similar to the findings in the Ford1.8L IDI engine test. i.e. there was a high lube oil VOF for the fresh oil and decreased gradually down to a minimum at about half of oil age and then increased. The

average value for the test without the recycler was 0.17 g/kgfuel, which was 21% higher than that with the recycler.

For Bus 4070, without the recycler it showed a consistent increase in lube oil VOF emissions for the first 10,000 miles of oil age followed by a decrease, where the particulate ash emissions were at its maximum. This phenomenon of high ash and low VOF may suggest that some deposits were stripped off which resulted in a high ash emission. The lube oil VOF started to increase again after the substantial oil top up at around 16,000 miles and fall again at 22,500 miles followed by a rapid increase from 0.10 g/kgfuel to 0.23 g/kgfuel for the next 5,000 miles. The average value for lube oil VOF was 0.16 g/kgfuel. After the fitting of the recycler on Bus 4070, the lube oil VOF was reduced from 0.23g/kgfuel to 0.17 g/kgfuel on this aged oil in just about 500 miles and continuing to decrease to 0.06g/kgfuel after 9,000 miles. After the substantial oil top up, the lube oil VOF increased during the next 4,000 miles and then stabilised at ~0.1g/kgfuel. So the efficiency of the oil recycler on reducing the lube oil VOF emissions can be determined as 26% by comparing the data just before and after the fitting of the recycler, which was 0.23 g/kgfuel without the recycler and 0.17 g/kgfuel with the recycler fitted, or as 37.5% by comparing the average values, which were 0.16g/kgfuel without the recycler and 0.1g/kg with the recycler.

Lube oil fractions as percentage of total VOF mass were shown in Figs.19 and 20.

UNBURNT FUEL VOF EMISSIONS – The diesel fuel VOF emissions as a function of oil age determined by TGA technique were shown in Figs 21 and 22. The diesel VOF was fluctuated and varied around 0.11 g/kgfuel (7~10% of the total particulate mass) for Bus 4063 with and without the recycler. For Bus 4070 without the recycler it has shown that the fuel VOF mass increased by 40% with oil age for the first 5,000 miles and then stabilised at 0.14 g/kgfuel for 10,000 miles. The fuel VOF emissions decreased to 0.07 g/kgfuel after 15,000 miles and maintained at this level for 8,000 miles and then increased to 0.10 g/kgfuel at the end of the test. After the recycler was fitted to Bus 4070, the fuel VOF mass was reduced by 50%.

COMPOSITION OF PARTICULATE EMISSIONS - The mass emissions of total particulate matter, particulate ash, particulate carbon, particulate total VOF, lube oil VOF and diesel fuel VOF were discussed above. These particulate components were calculated as a percentage of total particulate mass shown in Figs.23 and 24.

For Bus 4063, with the recycler the variation of total particulate mass with oil age was mainly depending on the variation of particulate carbon and VOF mass. The particulate ash had a significant contribution to the large decrease in total particulate mass at 12,000 miles, where ash contribution to total particulate mass reduced from nearly 30% to 0%. With the recycler removed from Bus 4063, the increase in total particulate mass with oil age was due to the increase of particulate carbon, which increased from ~55% to ~75%. The mass of particulate total VOF and lube oil VOF increased slightly with the recycler removed and yet their fractions were reduced. In general, the recycler had reduced the contribution of carbon to total particulate emissions for Bus 4063, compared to that without the recycler fitted.

For Bus4070, similar to Bus 4063, the variation of total particulate mass was predominately depending on particulate carbon emissions, which took up 70-80% of total particulate mass. The reduction on total particulate mass by the fitting of the recycler on the aged oil was due to the reduction on particulate carbon and VOF (lube oil VOF) mass. The recycler reduced lube oil VOF emissions on this bus test. The diesel fuel VOF only took up 5-10% of total particulate mass both with and without the recycler. The composition of the particulate emissions did not change significantly with the recycler fitted, compared to with no recycler fitted.

The particulates from two bus tests had the similar compositions: 5~30% of ash, 55~80% of carbon, 10~30% of VOF including 5~15% (to total particulate mass) of lube oil VOF.

PYROLYSIS GAS CHROMTOGRAPHY OF PARTICULATES - Pyrolysis GC profiles of typical particulate samples are shown in Fig.25 for Bus 4063 and Fig.26 for Bus 4070 with and without the recycler.

These four traces were the last samples for each test. It shows that the particulates from two buses had a similar composition on unburnt fuel fractions and ranged from C13-C24 n-alkanes for Bus 4063 and

Fig.13 Particulate carbon mass Vs oil age for Bus 4063

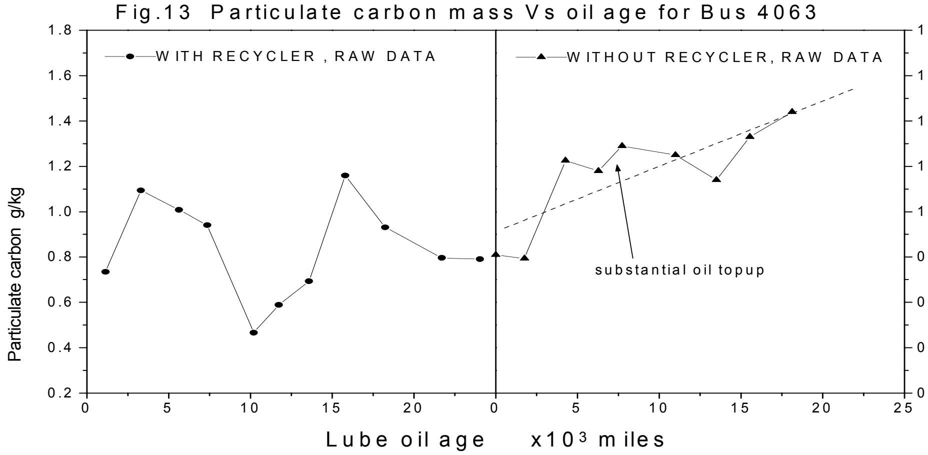


Fig.14 Particulate carbon emissions Vs oil age for Bus 4070

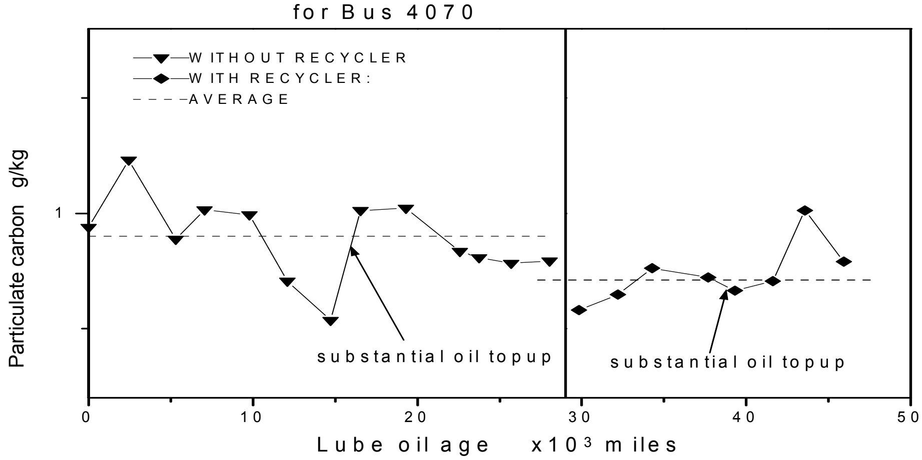


Fig.15 Particulate VOF emissions Vs oil age for Bus 4063

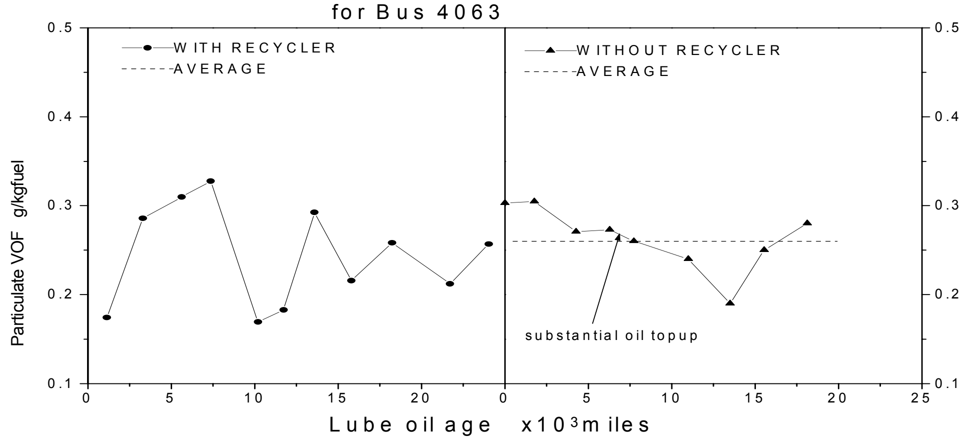


Fig.16 Particulate VOF emissions Vs oil age for Bus 4070

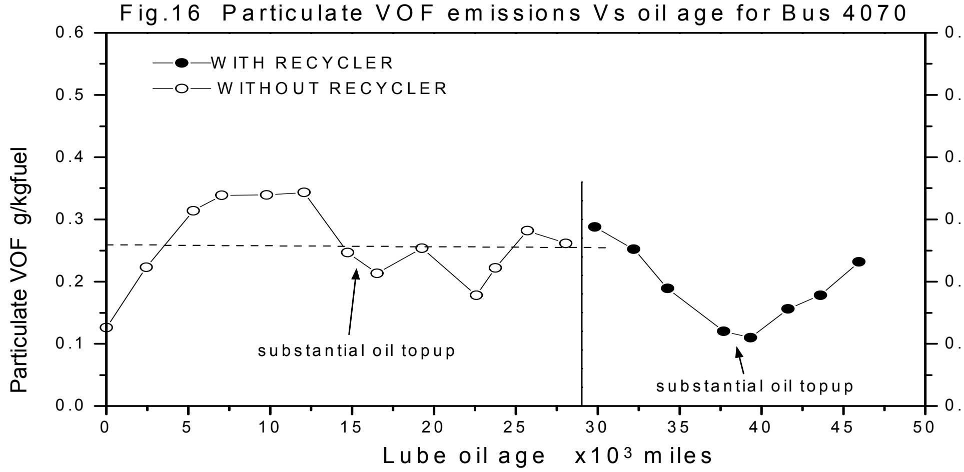


Fig.17 Lube oil VOF emissions Vs oil age for Bus 4063

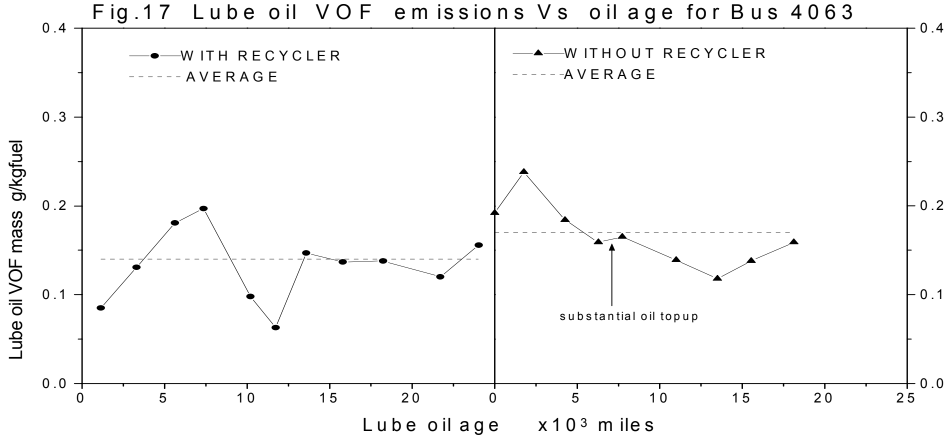


Fig.18 Lube oil VOF emissions Vs oil age for Bus 4070

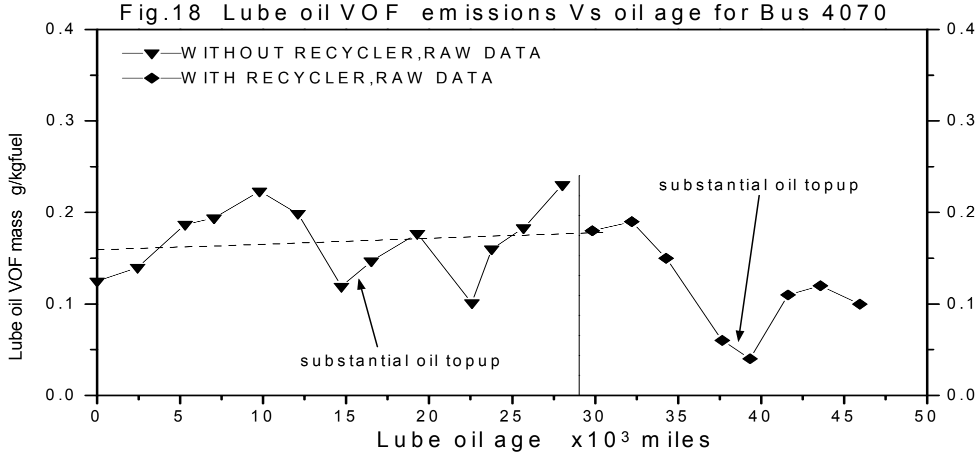


Fig.19 Fractions of lube oil VOF to total VOF Vs oil age for Bus 4063

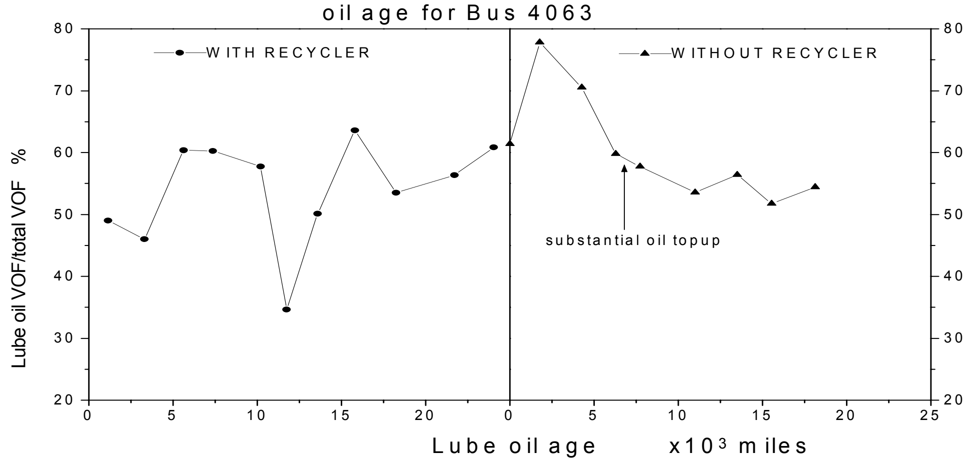


Fig.20 Fractions of lube oil VOF to total VOF Vs lube oil age for Bus 4070

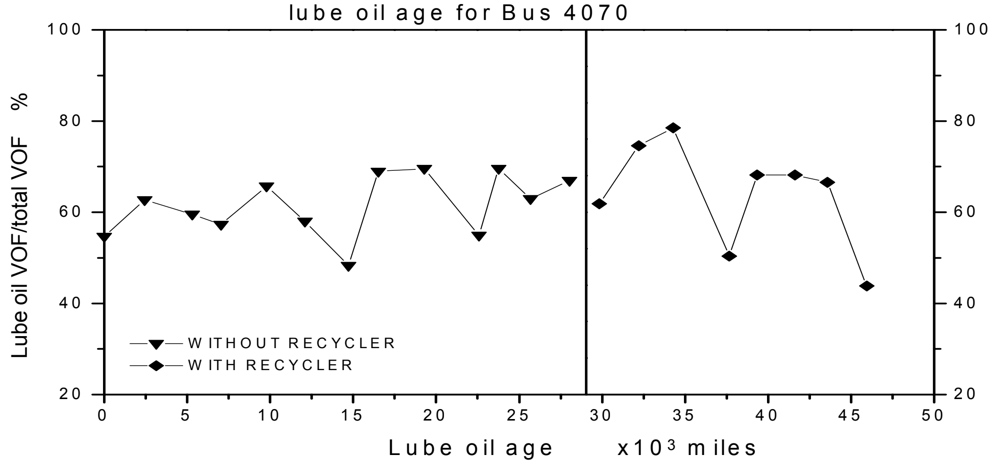


Fig.21 Diesel fuel VOF emissions Vs oil age for Bus 4063

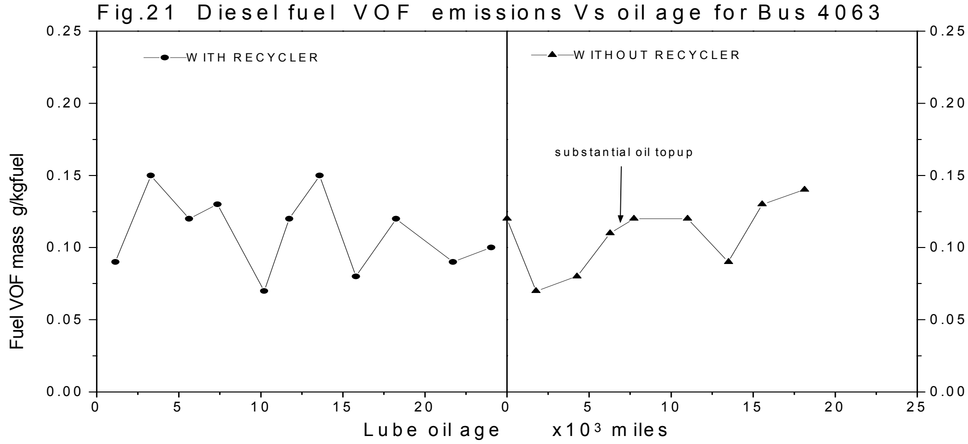
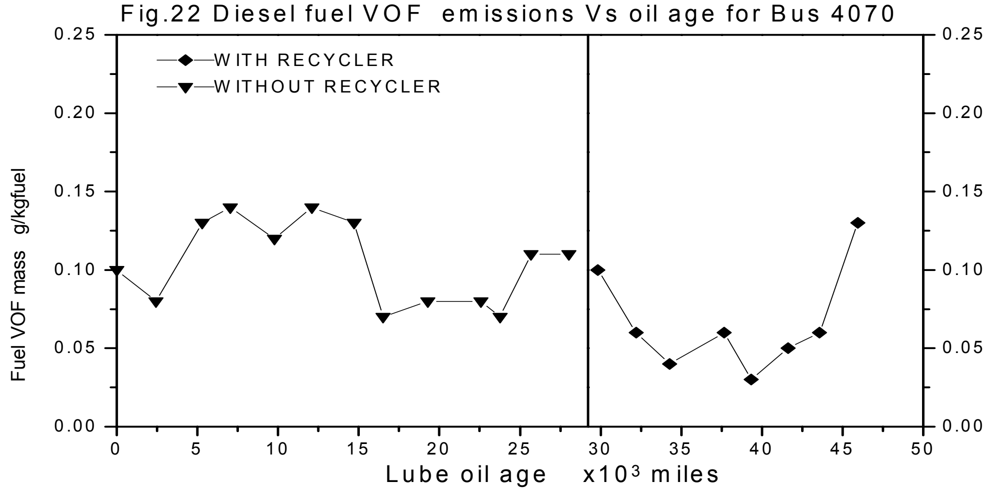


Fig.22 Diesel fuel VOF emissions Vs oil age for Bus 4070



C14-C25 n-alkanes for Bus 4070. There was no significant change in n-alkanes range with or without the recycler.

CONCLUSIONS

A bus trial has been carried out in Leeds to measure and monitor the influence of the lubricating oil recycler on exhaust emissions. Two 1995 model buses with EURO-II emissions level were used with a mineral based lubricating oil. The buses were operated on a daily routine commercial duty cycle. Exhaust gases were sampled and analysed every two weeks based on a fixed route. The results have shown:

The recycler could reduce the NOx and hydrocarbon emissions, although there were some scatterings of the data.

The recycler has shown a significant effect on the reduction of black smoke. The two buses have shown different features. Bus 4063 showed a 56% reduction on smoke by reducing the rate of increase with oil age. Bus 4070 showed a 40% reduction on smoke by reducing the average values.

The recycler can reduce the total particulate emissions by 24%(Bus 4070) and 35%(Bus 4063) due to the reductions on particulate carbon and lube oil VOF masses.

As the road tests inevitably involved some variations such as traffic condition variations, the results, therefore, have certain deviations and limitations.

The 1 micron pore size filter of the oil recycler has achieved great improvements in the oil quality. The main improvement was in the wear metals as typified by the iron content. There was no reduction in the soot in the oil using the fine bypass filter.

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Fig.23 Composition of the particulates Vs oil age for Bus 4063

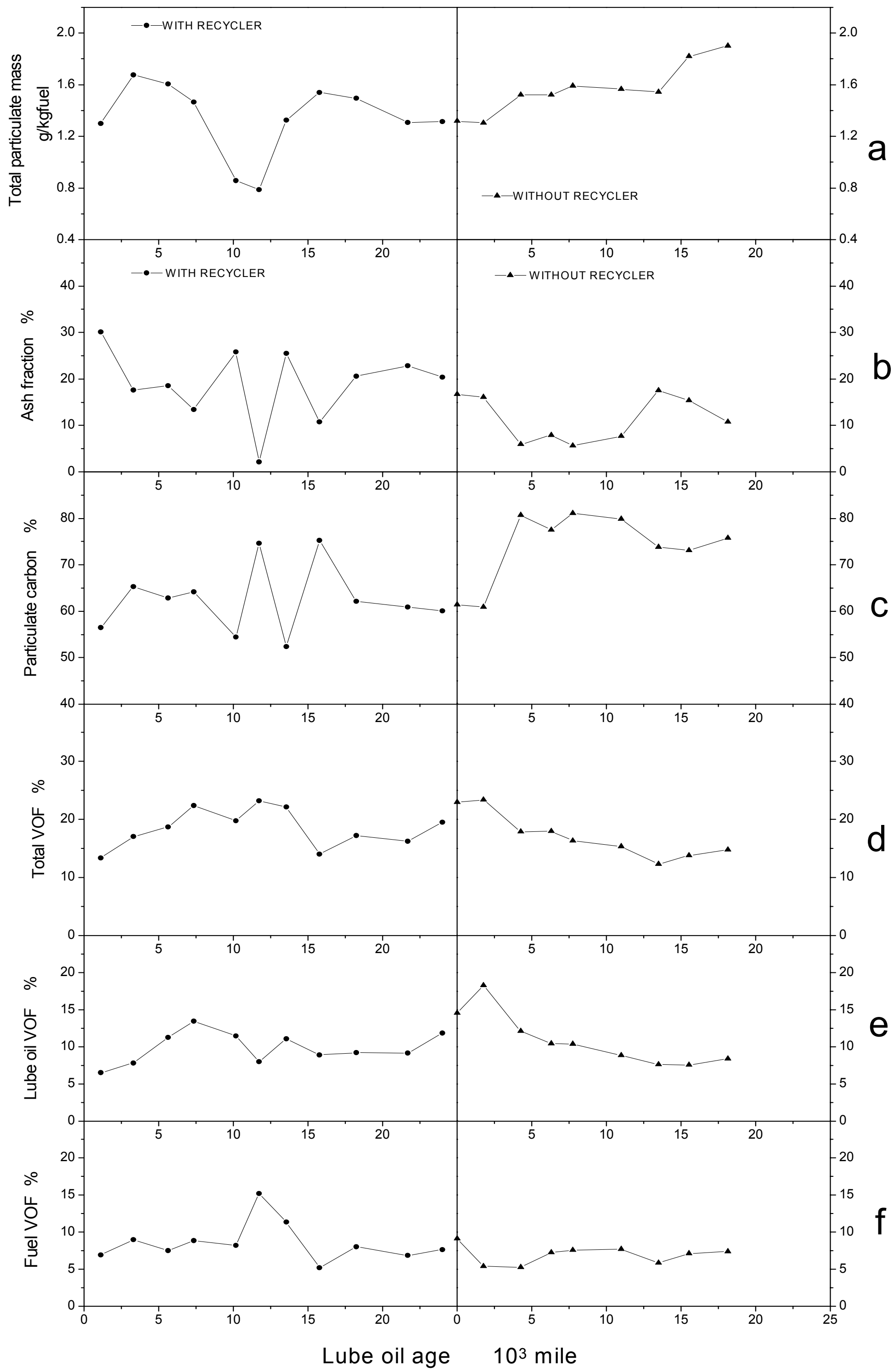
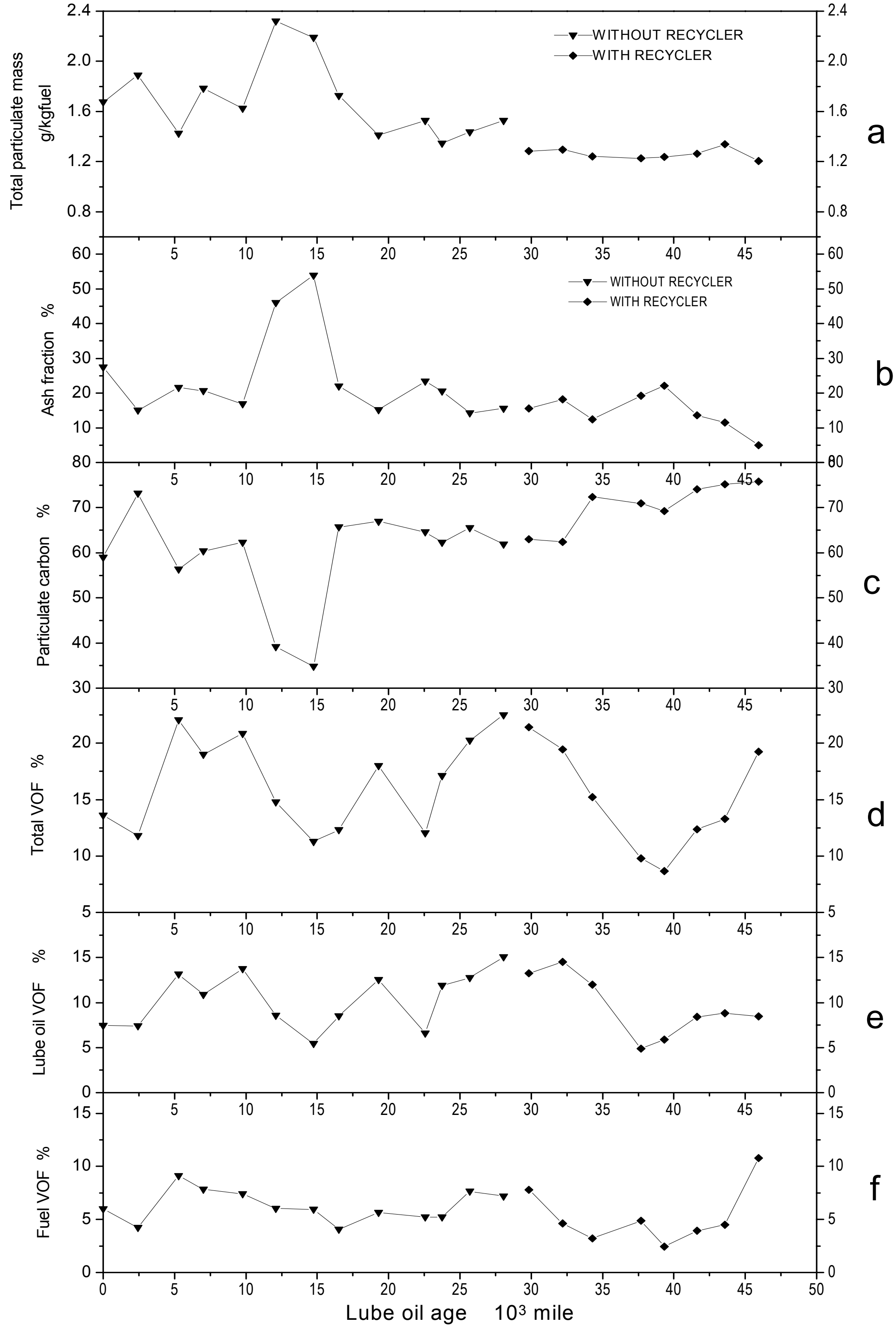


Fig.24 Composition of the particulates Vs oil age for Bus 4070



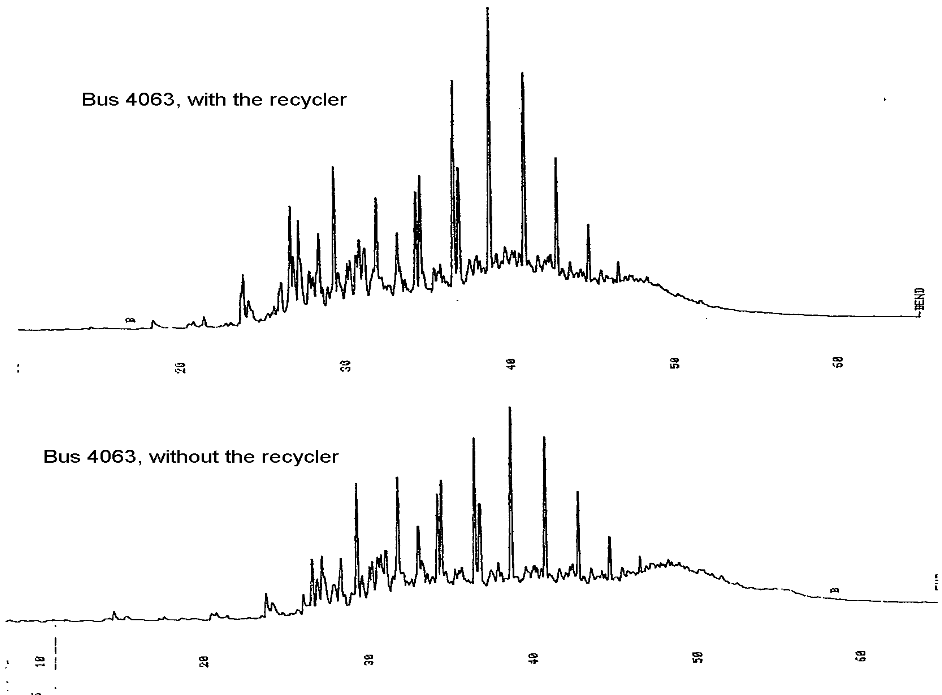


Fig.25. Pyro-probe GC of particulate samples for Bus 4063

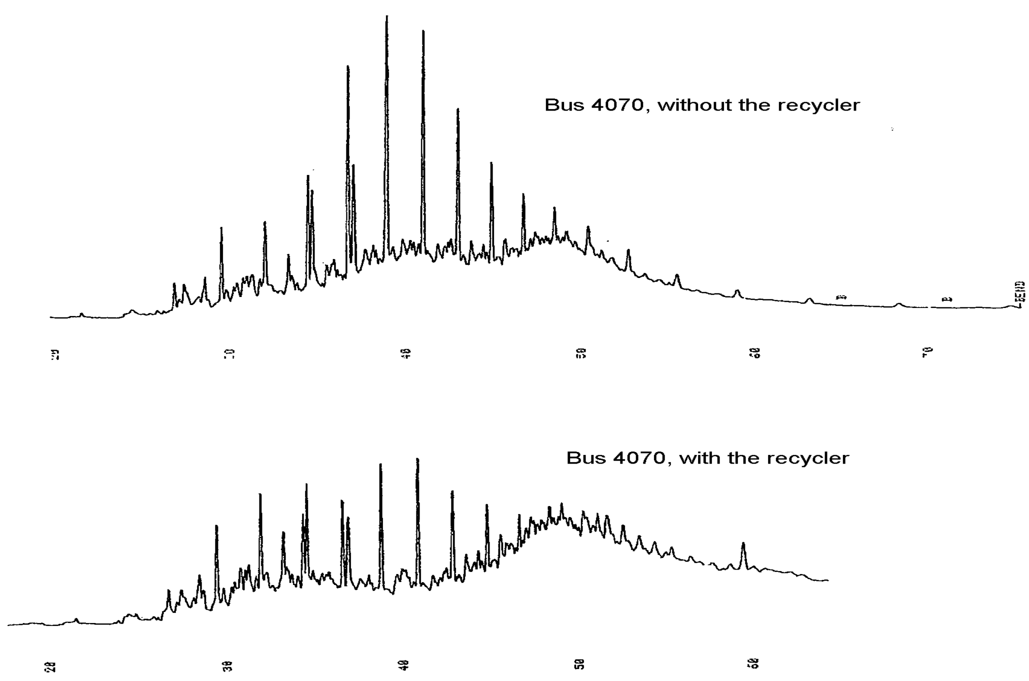


Fig.26. Pyro-probe GC of particulate samples for Bus 4070

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