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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 1 emissions compliance refuse trucks, fitted with Perkins Phazer 210Ti 6 litre turbocharged intercooled engines and coded as RT320 and RT321. These vehicles had lubricating oil deterioration and emissions characteristics that were significantly different, in spite of their similar age and total mileage. RT321 showed an apparent heavier black smoke than RT320. Comparison was made with the oil quality and fuel and lubricating oil consumption on the same vehicles and engines with and without the on-line bypass oil recycler. Engine oils were sampled and analysed about every 400 miles. Both vehicles started the test with an oil drain and fresh lubricating oil. The two refuse trucks were tested in a different sequence, the RT320 without the recycler fitted and then fitted later and the RT321 with the recycler fitted and then removed later in the test and both without any oil change. The RT320 was also the one with the finer bypass filter. The test mileage was nearly 8,000 miles both trucks. The amount of fresh oil top up was monitored and the results corrected for this dilution effect. The results showed that the on line bypass oil recycler cleaning system reduced the rate of fall of the TBN by 23% and 49% for two trucks respectively. A 73% reduction in the rate of increase of the TAN incurred for one of the trucks. The soot in oil was reduced by ~70% on average for both trucks.

The reduction in the rate of carbon accumulation in oil was 55% for the refuse truck with heavy smoke emissions. There was a 56% reduction in iron. The rate of oxidation, nitration and sulphation of oils was significantly reduced. There was an improvement of the fuel economy of about 3%. The lubricating oil consumption was reduced by 40% for 1 micron recycler filter and 30% for 6 micron filter.

INTRODUCTION

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 (1,2) and unburned diesel fuel. This can lead to the deterioration of the oil (3) and result in an increase in the particulate emissions (1). For a low particulate emissions engine, the work of Cooke (4) 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 lubricating oil age for other engine conditions.

Diesel engines with low particulate emissions have a very low lubricating oil consumption. There is a concern that carbon particles may accumulate to a greater mass concentration in the lubricating oil, as there will be a reduced dilution with top up of the oil (5). High carbon in the lubricating oil may then increase the contribution of the oil to the particulate emissions through the associated higher viscosity. Andrews et al (6) 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 and extended service requirements are making it increasingly difficult to control deposit formation (7). The primary source of piston deposits is the lubricant (8) and oxidation of the lubricant is the primary cause of deposit formation (9). In cylinder deposits consist of ash from the lubricating oil additives, carbon and absorbed unburned fuel and lubricating oil (8, 10). The CCD can be a source of wear in engines, and increased friction and hence increased fuel consumption. Crownland heavy carbon has been shown to increase oil consumption (11) and deposits have been shown to increase as piston temperature increases above 250°C (12). Deposits also increase with the soot content of the oil (12) and hence deposits can increase as the oil ages. The increased soot in oil as it ages results in an increased oil viscosity (13) and this increases the oil (14) and fuel consumption. The aim of the present work was to examine these influences for two Euro 1 refuse trucks fitted with Perkins Phazer engines and to determine the improvement in oil quality through the use of on line recycling of the oil to remove soot, wear metals, fuel and water dilution (3,15). The recycler had a fine bypass oil filter and an infrared 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 (1, 6) 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 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 that increased the NOx. This was also supported by the lubricating oil additive metal analysis. 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 lubricating oil influences, which do not contribute to gaseous hydrocarbon emissions at a 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 lubricating 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 lubricating oil particulate VOF emissions and also generated carbon emissions. Once the volatile fraction of the lubricating oil had been burnt away in the engine, the lubricating 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 (7). Diesel deposits can be classified into two types: ring zone and piston skirt deposits (varnish). The higher ring zone temperatures (325-360°C) promote thermal degradation of the lubricating oil and unburned/oxidized fuel components producing a 'carbon' deposit. At relatively low piston skirt temperatures (200-260°C) a varnish type deposit predominates (7). The primary source of piston deposits is the lubricant and lubricant oxidation is the primary cause of deposit formation (7). Diesel engine deposits also increase with the oil consumption (8), the piston temperature (12) and the oil soot content (12). 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 (17).

Oil viscosity also increases with the oil soot content (17, 18-20), that typically accumulates at a rate of 4% of the engine particulate mass emissions (1, 2, 3, 6). This results in the oil consumption increasing with the increase in viscosity (14) and also the fuel consumption increases due to the increase in viscosity. Consequently, on line oil cleaning can result in reduced soot in the oil and in reduced fuel and water oil dilution and both of these effects can result in reduced engine deposits and a reduction in oil consumption. The reduced engine deposits can also result in reduced engine friction and hence reduced fuel consumption. Thus, improved oil quality can have additional benefits apart from the extended oil life.

THE ON LINE OIL RECYCLER AND REFUSE TRUCK 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 135 ^{o}C as it flowed over a conical cascade into a drain return to the oil sump. The previous work using this system (3) used a 6 micron bypass oil filter and this was the filter used in RT321 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 refuse truck (RT320). It had originally been intended in the present work to use two nominally identical refuse trucks with the same engine and mileage. However, as will be shown in the results, the two refuse trucks had different oil deterioration rates and the accompanying emissions results showed different emissions. RT321 was operating consistently 2 A/F richer for the same duty cycle for a journey with an average A/F of 33/1. Soot accumulation in the oil and lube oil consumption for RT321 were also significantly higher. Consequently, it was concluded that RT321 was in a worse mechanical state to RT320 and the two refuse trucks could not be compared one with a recycler and one without. Thus, both refuse trucks had to be tested with and without the recycler.

RT320 was first tested without the recycler fitted and after 4,700 miles a recycler with the 1 micron bypass filter was fitted without any oil change. RT321 was first fitted with a recycler with the 6 micron bypass filter and after 5,000 miles the recycler was removed without any oil change.

5,000 miles of oil use is twice the normal oil change interval for the refuse truck. However, the oil analysis showed that the oils were still fit even for the refuse truck without the recycler fitted. This was attributed to the large amount of oil consumption and subsequent oil top up, which showed 2-5 times higher oil consumption than the FirstBus tests(15).

The aim of extended tests without the oil change for two refuse trucks was to determine the rate of deterioration of the aged oil after the recycler was removed and demonstrate in an on road test that the recycler could clean-up dirty oil and reduced its rate of deterioration and make it fit for further use. It has shown that the oil with the recycler removed needed to be changed whereas the oil with the recycler fitted was still fit for continued use. The normal oil change period on these refuse trucks was 2,500 miles, typically about every three months. The refuse trucks were operated 6 days a week with an average mileage per day of about 35 miles. These trucks had a very frequent stop-start duty cycle with many loading/unloading processes, which kept the engines in a high power output status and thus put lubricating oils in a very hostile environment.

One of the advantages of the recycler is that it provides for an improved oil quality and reduced oil consumption (3,15). The improved oil quality reduces the engine CCDs. Thus the reduced oil consumption and CCD in the combustion chamber reduce engine emissions. Authors have shown that emissions had been reduced for a Ford 1.8 litre IDI engine test as a result of improved oil quality and reduced oil consumption (16).

Other investigators of bypass filters have advocated using filters of the order of 1 micron (23-27). 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 (3) 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 1 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.

Bypass filters have two basic features: a high filtration efficiency and a high particulate storage capacity (25). They reduce the fine particulate matter in the oil leaving the main filter to remove the larger particulates. Stenhouer (26) showed that bypass filters removed organic material, sludge, varnish, resin, soot and unburned fuel. His work showed that over 80% of the contaminant removed by the bypass filter was organic. Bypass filters can remove the small pro-wear contaminant particles thus extending engine component life (27). The benefit of bypass filtration was the reduced wear and reduced in cylinder deposits. It is possible to arrange a combination filter whereby in one housing a main and bypass filter are arranged (25) with the flow between the two splitting according to their flow resistance.

Although a filter based bypass filter was used in the present work, centrifugal bypass filters are also quite common (27). 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 (27). Centrifugal filters have an effective particle size removal below 1 micron and have a filtration efficiency that does not deteriorate with time (27). They are generally more expensive initially than filter based bypass filters. One assessment of bypass filters (28) 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 refuse trucks, coded as RT320 and RT321, had the same engine specification that is detailed in Table 1.The two refuse trucks tested operated with routine oil top ups and normal commercial duty cycles. The oil and exhaust gas samplings were taken every two weeks, at about 400 miles intervals. The same route and driver were used for each test run. However, traffic conditions were varied.

Table 1. Specifications of the engines

	Refuse truck
Type	Perkins Phazer 210Ti
Maximum Power Rating	156.5KW(210BHP) @ 2500rpm
Displacement, litre	6.0
Oil pressure, P.S.I @ 2100rpm(max)	43-49
Oil capacity, litre	18
Bore, mm	100
Stroke, mm	127
Cylinder No.	6
Compression ratio	17.5:1
Lube oil change intervals	3 months
Aspiration	Turbocharge intercooled

RT320 started the test without the recycler fitted and RT321 started the test with the recycler fitted. For RT320 after 4,700 miles after the commencement of the test with fresh oil, a recycler was fitted. Then the test continued for 3,000 miles. For RT321 after ~5,000 miles after the commencement of the test with fresh oil, the recycler was removed and the test continued for 2,600 miles without the oil being changed. As discussed above, RT320 was fitted with a recycler with a bypass particulate filter size of 1 microns and RT321 was fitted with a 6 micron filter.

FUEL AND LUBRICANTING OIL - The fuel used in the tests was commercially available standard low sulphur diesel with sulphur content ≤ 0.05%. Table 2 shows the specifications of the diesel fuel.

The lubricating oils used in tests were 15W-40 CE/SF mineral oil. The specifications for the lubricating oil are listed in Table 3.

Table 2. The specifications of diesel fuel used in the refuse truck tests

Property & unit	diesel	Test Method
Colour	≤2.5	D1500/IP196
Density, @15^{o}C, g/ml	0.82-0.86	D4052
Flash point(PMCC), ^{o}C	≥56	ISO2719
Cetane Number	≥50	ISO5165/IP380/D613
Viscosity, @ 40 ^{o}C, cSt	2.0-4.5	ISO3104
Sulphur, %wt	≤0.05	ISO8754
Micro Carbon Residue: Residue wt on 10% Bottoms	≤0.3	ISO10370/IP398
Ash, %wt	0.01	ISP6245/IP4
Particulate Matter, mg/kg	≤24	DIN51419
Water, mg/kg	≤200	D1744
Oxidation stability, mg/100ml	≤2.5	D2274
Distillation		ISO3405
%Vol, @250 ^{o}C, rec	≤65	
%Vol, @345 ^{o}C, rec	≥95	

LUBRICATING OIL ANALYSIS - Oil was sampled periodically from the dipstick using a vacuum pump and syringe with the sample taken through flexible tubing located just below the oil surface in the sump and collected in a small glass bottle. The volume sampled was noted and taken into account when the oil consumption by the engine was determined by draining the sump at the end of the test. The oil sample was analysed for total base number (TBN) and total acid number (TAN), viscosity, soot by infra red and by thermal gravimetric analysis, wear and additive metals and additive depletion using FTIR. The oil analysis techniques used are summarised in Table 4. The oil used was SAE 15W/40 with the properties summarised in Table 3. The main oil analysis was carried out to current standard methodology at Swansea Tribology Services Ltd. and the TGA and FTIR work was carried out at Leeds University.

Table 3. Specifications of the lubricating oils

	Refuse truck test
SAE Viscosity Grade	15W/40
API Classification	CE/SF
Physical and Chemical properties	
Viscosity, @ 100 ^oC	14.5
mm^2/s @ 40 ^oC	110
Viscosity Index	
Flash point, ^oC	>180
Density, @ 15C, kg/m^3	<1000
TBN, mgKOH/g	13
TAN, mgKOH/g	3.7
SulphatedAsh, wt%	1.8
Elemental analysis	
Calcium, wt%	0.11
Magnesium, wt%	0.003
Zinc, wt%	0.08
Phosphorus, wt%	0.10
Manufacturer	Castrol

The lubricating oil was analysed for fuel dilution, carbon and ash content using Thermal Gravimetric Analysis (TGA). The method used a small sample size of approximately 50 mg that was placed in a small bowl hanging from a microbalance. This was then heated in an oven in a flow of nitrogen and the weight loss as a function of temperature was determined up to 600^oC temperature. The nitrogen was then switched to air and the heater increased to give 610^oC and any carbon in the oil was burnt away and the remaining weight was the ash in the oil.

Fuel dilution was determined by calibration of the TGA using mixtures of fuel and oil in different concentrations and different fuel boiling fractions. This was done on an oil volatility basis and the method cannot distinguish between oil degradation to give volatile low molecular weight components and fuel dilution. The calibration was undertaken with diesel/lube oil mixtures in the 0.5-5% fuel range and it was found that a temperature of 290^oC for the oil and fuel used in this work enabled the fuel dilution to be determined as the weight loss up to 290^oC. The boiling fractions most suitable to use were determined using pyrolysis GC of the used lube oil fractions using the fuel n-alkane distribution as the indicator of the fuel in oil distillation range. The calibration reference temperature was 290^oC throughout the present work.

The carbon content of the used lubricating oil was also determined using TGA. The used lubricating oil was heated in nitrogen to 600^oC where there was no further change in the volatile weight loss. Air was then added and the carbon in the oil was burnt out and the decrease in weight was the carbon fraction. Any remaining weight from the initial sample weight was the ash fraction of the lubricating oil. This technique was very similar to that used by Covitch et al (29), Ripple and Guzauskas (30) and was first used by McGeehan and Fontana (18) and is more reliable as a gravimetric measurement than the alternative optical or centrifugal methods for soot in the oil.

LUBE OIL AND FUEL CONSUMPTION

LUBE OIL TOP UP - Figures 1 and 2 have shown the accumulative oil top ups in terms of litre and percentage of the oil sump capacity for two refuse trucks. The RT320 had a higher rate of oil top ups with the recycler than without the recycler due to some oil leaking from the recycler. Without the recycler 80% of oils were added after 5,000 miles. With the recycler 100% of oils were topped over 3,000 miles test due to two substantial oil top ups as a result of a mechanical fault in the recycler which resulted oil leaking. For RT321 the oil top up rate was higher, indicating higher lube oil consumption on this truck.

The total amount of the oil added on the RT321 after about 5,000 miles of test with the recycler was 100% of the sump capacity. The quantity of the oil topped up was increased after the oil recycler was removed, showing an increased lube oil consumption without the recycler.

The mean value for lube oil top ups was calculated from the data in Figures 1 and 2 for two vehicles with and without the recycler. As the RT320 had an accidental leaking on the test with the recycler fitted, those two substantial oil top ups were excluded in the calculation. The mean value was 4.2 litre per 1,000 miles.

Table 4. Analytical methods for lubricating oils

Analytical items	Standard /method
Physical and chemical properties	
Kinematic Viscosity, @100, 40°C mm^2/s	ASTM D445
TBN, mgKOH/g	D4739
TAN, mgKOH/g	D664
Soot, /cm	FTIR
Water, %	FTIR
Coolant, %	FTIR
Oxidation	FTIR
Sulphation	FTIR
Nitration	FTIR
Carbon, wt%	TGA
Ash, wt%	TGA
Fuel dilution, wt%	TGA+GC
Elemental analysis	Emission spectra
Ca Mg Zn P	
Fe Pb Cu Cd Cr Al	

LUBRICATING OIL CONSUMPTION - Lubricating oil consumption was calculated and determined by the raw top up records from the fleet. Figures 1 and 2 show a pattern of regular oil top up, except three irregular oil top ups due to mechanical faults: the first one was the last oil top up for RT321 with the recycler fitted; the other two were at 6.000 miles and 6,800 miles of oil age for RT320 with the recycler fitted. These three data points were excluded when the lubricating oil consumption was calculated.

The lubricating oil consumption has been represented on average with and without the recycler in terms of litre per kilomile (l/kmile) and g/kgfuel as listed in table 5. It has shown that the reduction in lube oil consumption by the oil recycler was 31~43% in terms of l/kmile and 30~41% in terms of g/kgfuel for two refuse trucks.

The lubricating oil consumption for RT321 was about twice as the same as that for RT320. This very high lube oil consumption resulted in high smoke as shown later. Thus this engine must have some mechanical fault, which resulted in an excessive burning of lubricating oil.

It was found that the lubricating oil consumption was much higher on the refuse truck tests than that on the FirstBus tests (2-5 times, without the recycler, 2-6 times with the recycler). This indicated that the engine technology and maintenance for the buses were better (buses were 1995 model whereas refuse trucks were 1991 model). Another factor is duty cycles. Refuse trucks were operated with a pattern of very frequent stop start cycles, which also contributed to worse oil consumption.

Table 5. Lubricating oil consumption for refuse truck tests

	RT320		RT321	
	l/kmile	g/kgfuel	l/kmile	g/kgfuel
Without the recycler	3.493	2.71	6.494	4.85
With the recycler	2.000	1.61	4.462	3.40
reduction rate %	42.7	41	31.3	29.9

Figure 1 Accumulative lube oil top up Vs oil age

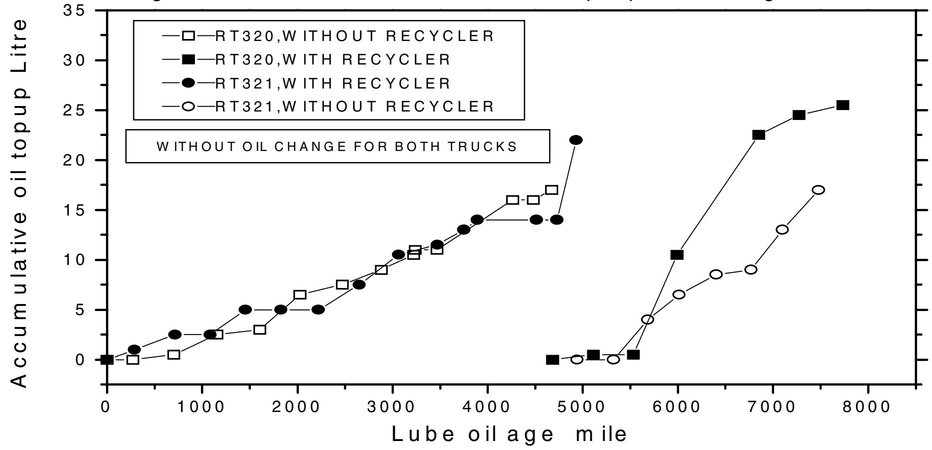


Figure 2. Lube oil top up as a percentage of the sump capacity

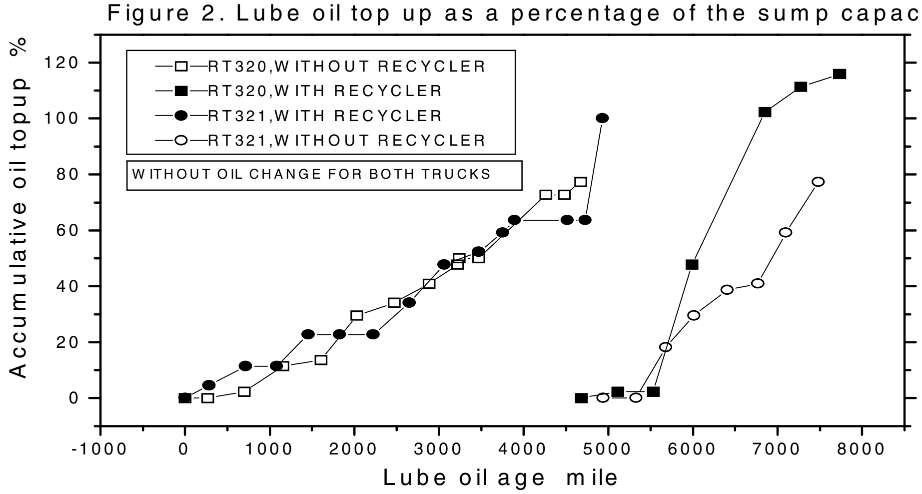
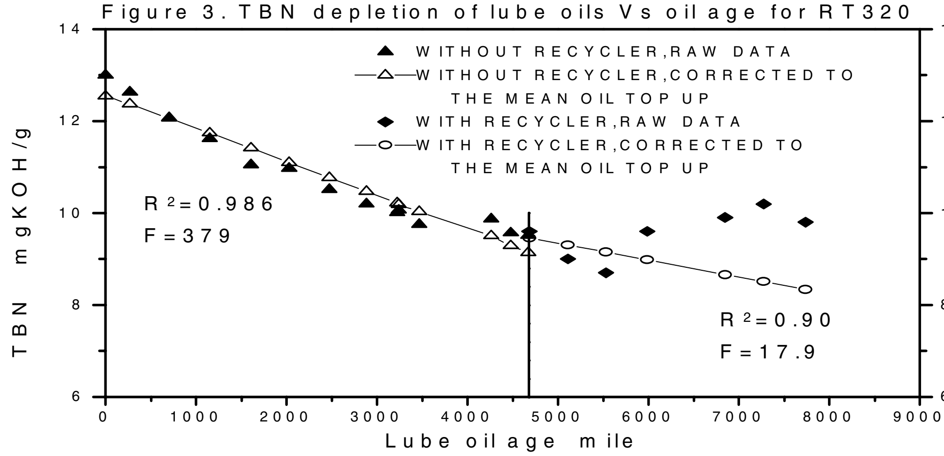


Figure 3. TBN depletion of lube oils Vs oil age for RT320



FUEL CONSUMPTION -Diesel fuel consumed was recorded by the fleet. An average value for the diesel fuel consumption was calculated from those fleet records and represented in terms of litre per kilomile (l/kmile). Table 6 shows the comparison between the results with and without the recycler for two refuse truck tests.

Table 6. Diesel fuel consumption comparison

	RT320 l/k mile	RT321 l/k mile
Without the recycler	987	1025
With the recycler	952	1004
fuel savings %	3.55	2.05

It clearly shows that the lube oil recycler has reduced the fuel consumption rate. This is attributed to the filtration of the recycler, which reduced the accumulation of the solid contaminants and formation of the deposits in cylinder. Thus the friction was reduced and energy loss due to friction was decreased.

Comparing this data with that from the FirstBus test (15), it shows that the fuel consumption for refuse trucks was 43% higher than for buses. The improvement by the recycler on fuel consumption was larger for refuse trucks. This indicated that the recycler would be more efficient if applied to older engines.

THE IMPROVEMENT IN LUBRICATING OIL QUALITY WITH THE RECYCLER AS A FUNCTION OF OIL AGE

CORRECTION FOR THE OIL TOPPING UP **-** The properties of lubricating oil are a function of the oil formulation, contamination and combustion condition. For the same engine running at a similar driving condition, the deterioration of the engine oil is a function of oil age and amount of the oil topped up. The ageing of the oil is accompanied by the gradual contamination of the oil by blow-by gases, which bring soot, water and unburned fuel into the oil. Direct contamination with soot and fuel occurs in the lubricating oil film on the liner inside the cylinder. The oil top ups have a direct dilution effect on the oil quality parameter such as soot content and fuel dilution. Therefore all the measurements of the oil's properties in the refuse truck tests were analysed as a function of the oil age and accumulative amount of the oil topped up, using the computational multiple regression tool. Then the change of the oil properties can be compared under the same oil top up rate as a function of oil age. The main correction was for the very large oil top ups that were required by component failures in the lubricating oil system, as discussed above. The procedure essentially derived a uniform rate of oil deterioration for the different oil quality parameters. This then allowed the change in the rate of oil quality deterioration to be determined.

The regression equations for oil properties are in the form of following:

oil property = a + b*G+c*Vtp

Where:

a----the intercept value

b,c ----the slope value

G----lube oil age, mile

Vtp----accumulative amount of the oil topped up, litre.

This is a two variables linear regression formula. The results from this equation have a very good correlation of the experimental data. To compare the rate of the oil deteriorate with the oil age, the rate of oil top up has to be fixed so as to see the oil's decay under an equal oil top up rate. An average rate of the oil top up from the two refuse truck tests was 4.2 l/kmile. This was used to produce oil top up corrected data as a function of the oil age in all following results. The linear fit to the experimental data that resulted from this procedure is marked on all the graphs of the oil quality as a function of oil age. This enables the linear regression line to be compared with the raw data.

The effect of the oil recycler on oil quality from this procedure is the comparison of the deterioration in the rate of change of an oil parameter with oil age. The ratio of the results with and without the oil recycler then gives a percentage improvement in that parameter due to the oil recycler. These results are summarised in Table 7 for all the oil parameters that were determined. Each parameter is discussed in detail below. However, it can be seen that for every oil parameter measured there was a very significant reduction in the rate of deterioration with oil age when the recycler was used.

TBN AND TAN - The depletion of basic component in lubricating oil additives during the use was measured by the determination of TBN (Total Base Number). Figures 3 and 4 show depletion rate of oil TBN for two refuse trucks respectively.

For RT320, the value of TBN decreased from 12.4 mgKOH/g to 9.2 mgKOH/g after 4,700 miles without the recycler. The rate of depletion was 0.7 mgKOH/g per kilomile. With the recycler fitted, TBN value decreased 1.1 mgKOH/g during a further 3,100 miles of use of the oil. The rate of depletion in TBN was reduced to 0.4 mgKOH/g per kilomile after fitting the recycler to aged oil.

Table 7. Summary of the comparison on oil qualities with and without the recycler on two refuse truck tests

Parameters	RT320		reduction by recycler %	RT321		reduction by recycler %
	w/o re	w. re		w/o re	w. re	
TBN depletion rate, % /kmile	5.7	2.9	49	5.2	4	23
TAN increase rate, %/kmile	3	-3.9		16	4.4	73
Soot increase (IR), abs/kmile	3.6	0.65	82	21	7.4	65
Carbon accumulation, %/kmile	0.19	-0.16		0.56	0.25	55
Iron increase, ppm/kmile	5.3	-2		22.8	9.6	56
Oxidation, abs/kmile	2.1	-0.32		3.2	2	37.5
Nitration, abs/kmile	0.96	0.06	94	4	2.2	45
Sulphation, abs/kmile	2	0.16	92	5	4	25

N.B. w/o re--without the recycler. w.re--with the recycler

Figure 4. TBN depletion of lube oils Vs oil age for RT321

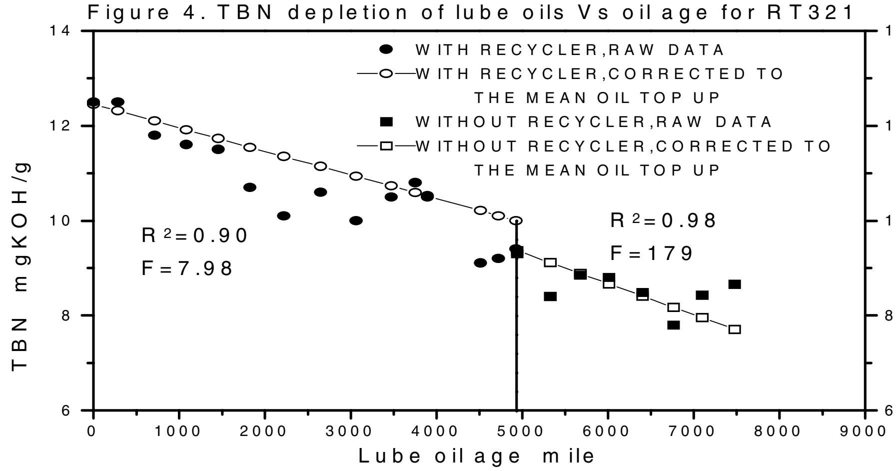


Figure 5. Normalised TBN depletion rate of lube oils

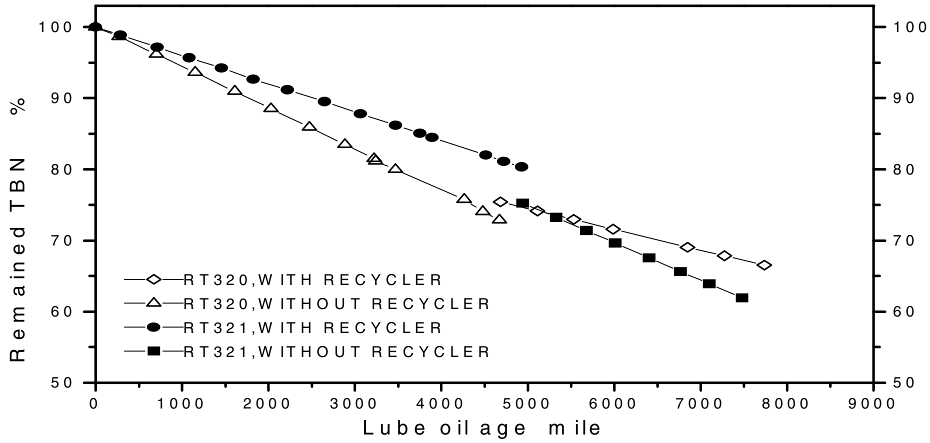


Figure 6. TAN increase of lube oils for RT320 test

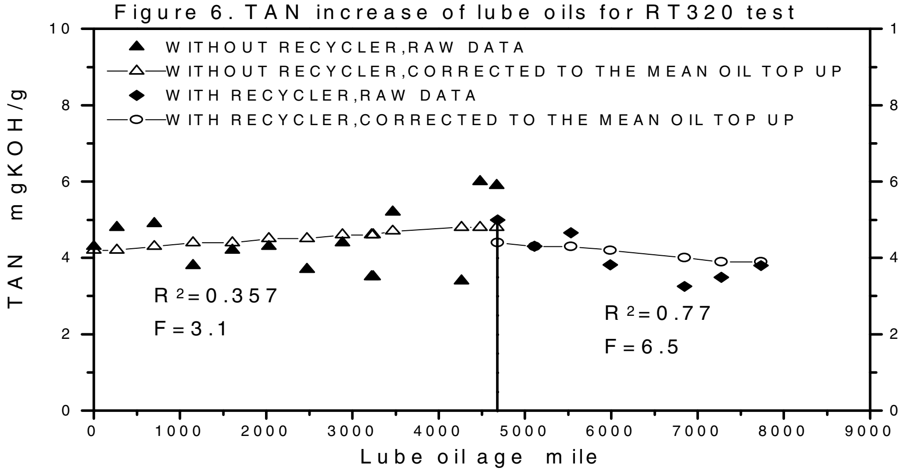


Figure 7. TAN increase of lube oils for RT321 test

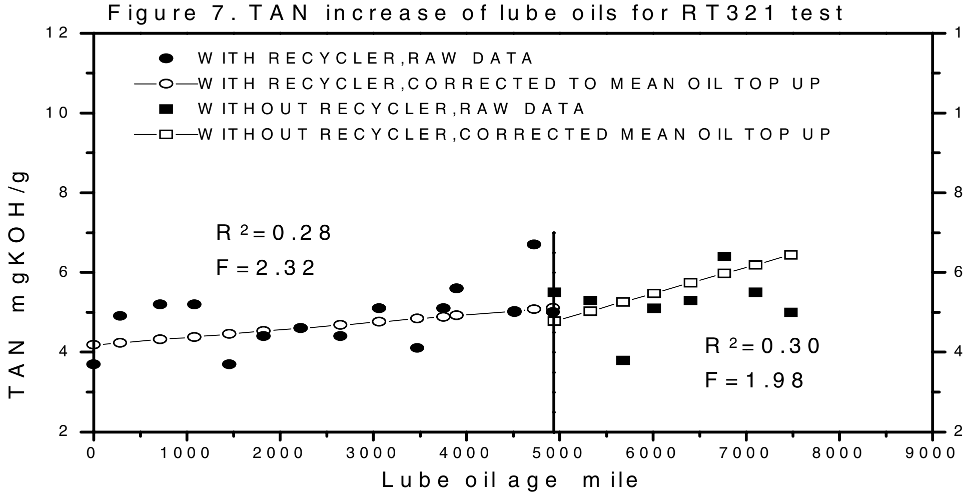


Figure 8. Normalised TAN increase Vs lube oil age

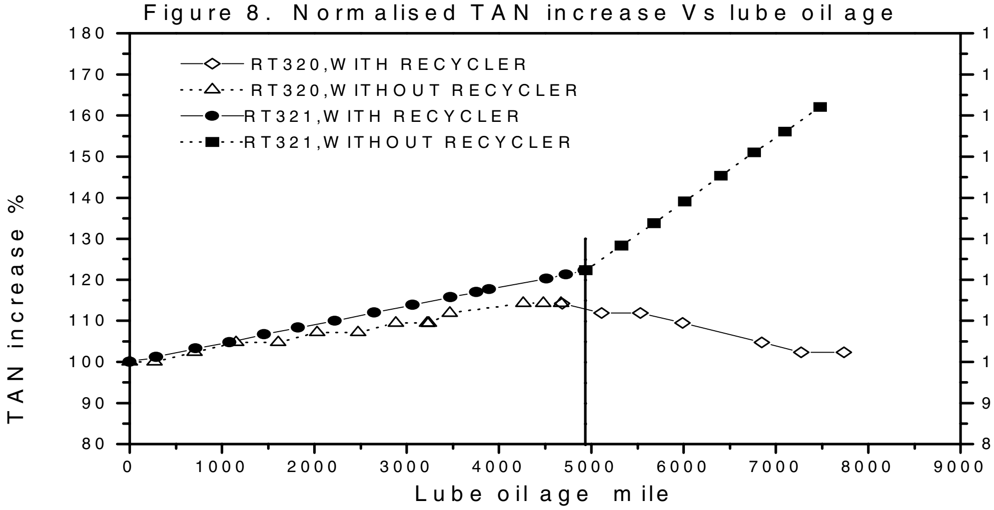


Figure 9. Variation of lube oil viscosity Vs oil age for RT320

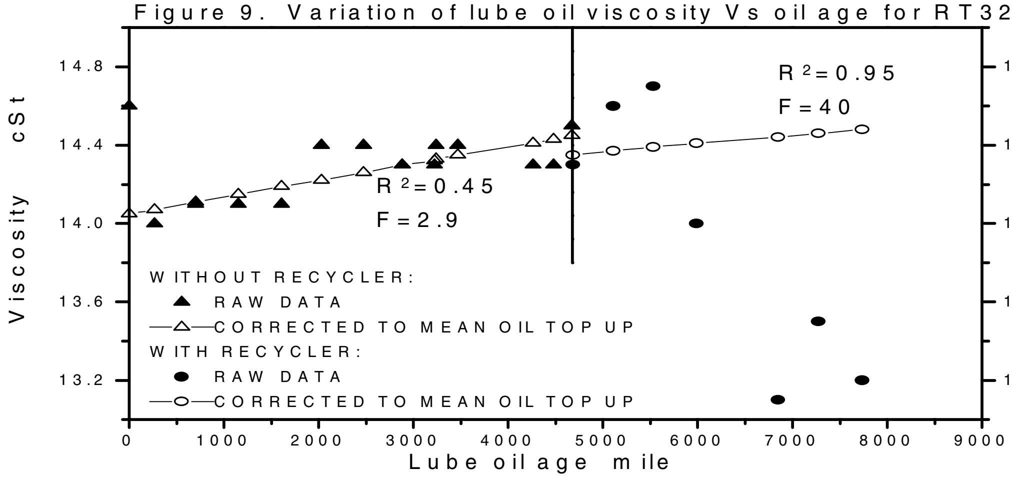


Figure 10. Variation of lube oil viscosity Vs oil age for RT321

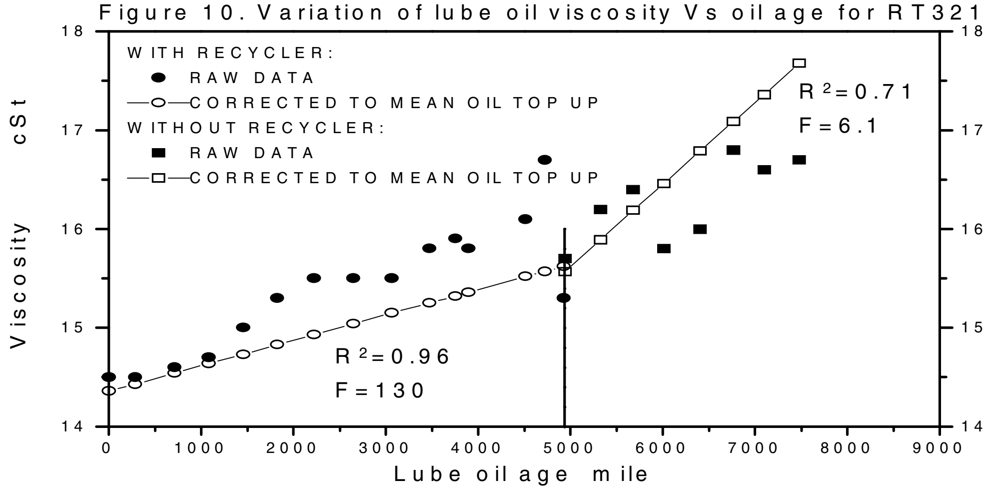


Figure 11. Soot accumulation in oil with oil age for RT320

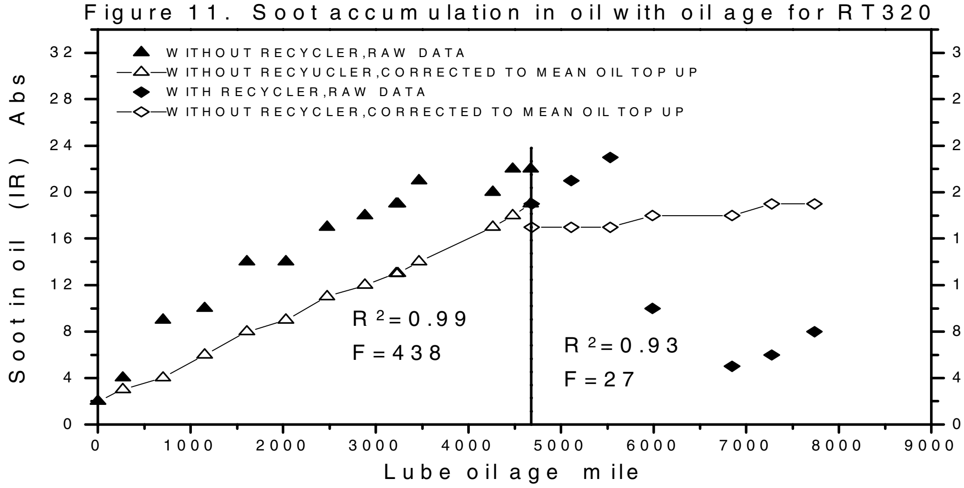
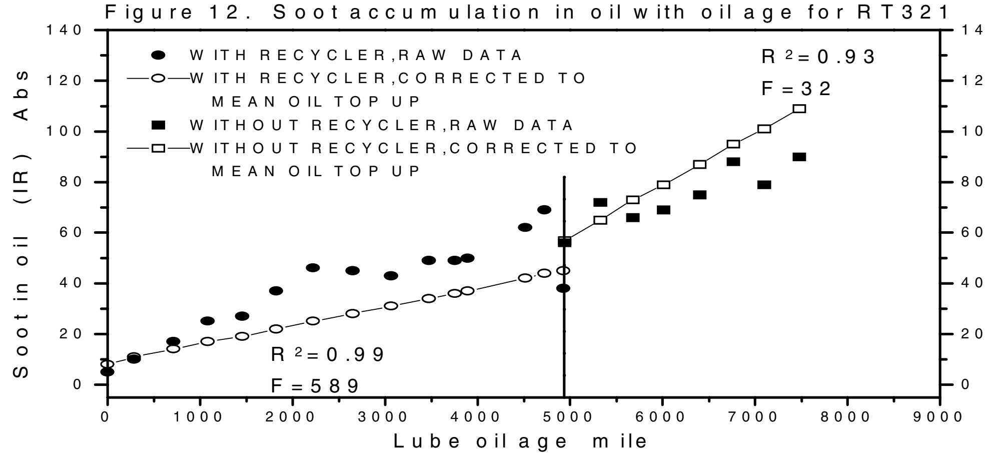


Figure 12. Soot accumulation in oil with oil age for RT321



An improvement of 43% in the rate of depletion of TBN can been seen with the recycler fitted.

For RT321, with the recycler the value of TBN decreased by 2.5 mgKOH/g from fresh oil during 5,000 miles of use of the oil. The rate of decrease was 0.50 mgKOH/g per kilomile. After the recycler had been taken off, the TBN value of the oil was reduced by 1.7 mgKOH/g in a further 2,500 miles of use. The rate of decrease was 0.68 mgKOH/g per kilomile. An increase of 36% in the rate of depletion of TBN with the recycler off or a reduction of 27 % on the TBN depletion rate with the recycler fitted was seen.

The TBN depletion data was normalised to the initial values and displayed in Figure 5. All the data was with mean oil top ups. it can be seen that for RT320 the TBN of the oil remained 73% of its original value after 4,700 miles of use without the recycler whereas only 9% further decrease after the recycler being fitted after another 3,100 miles. The rate was 5.7% without the recycler and 2.9% with the recycler per kilomile, a 49% improvement by the recycler. For RT321 the TBN remained 80% of its original value after 5,000 miles of use of the oil with the recycler. After the recycler was taken off, the remnant TBN was 67% at the end of a further 2,500 miles of use of the oil. The rate was 4% with the recycler and 5.2% without the recycler per kilomile for RT321. Hence the improvement on the depletion rate of TBN was 23%.

The TAN data fluctuated with oil age and correlation coefficients were not very satisfactory. This was due to the difficulties in the measurement of used oil TAN. Nevertheless, the trend could be found to make comparisons. Figures 6 and 7 show the TAN increase with oil age for two refuse trucks. For RT320, without the recycler the TAN values were increased slightly (0.8 mgKOH/g). In comparison, the TAN was decreased slightly with the recycler fitted due to that the declining of TAN from the addition of the fresh oil surpassed the increase from the accumulation of acidic materials. This meant that the TAN values would not have any increase if the oil top up was kept at a rate of 4.2 litre per kilomile (mean top up rate). For RT321, the TAN values increased by 0.9 mgKOH/g from fresh oil after 5,000 miles with the recycler. After the recycler was taken off, an increase of 1.7 mgKOH/g in a further use of 2,500 miles was observed. The rate of increase was 0.18 mgKOH/g with the recycler and 0.68 mgKOH/g without the recycler per kilomile.

Figure 8 shows the normalised TAN increase. It can be clearly seen that the increase rate of TAN was significantly larger without the recycler, comparing with the recycler fitted on both vehicles. The increase rate was 3% without the recycler and -3.9% with the recycler per kilomile for RT320, and 4.4% with the recycler and 16% without the recycler per kilomile for RT321. The reduction in the rate of TAN increase by the recycler was 73% for RT321.

VISCOSITY - The viscosity of oils is presented in Figures 9 and 10 for RT320 and RT321 respectively. For RT320 without the recycler there was a minor increase in the oil viscosity (0.4 cSt after 4700 miles). With the recycler fitted, there was a deep decrease in viscosity after 5,500 miles of oil age, which was due to the large amount of oil topped up with a lower viscosity. The regression analysis showed that under a mean oil top up rate the oil viscosity will be increased by 0.13 cSt in 3,000 miles of use of the oil. In general, the oil viscosity did not increase significantly for RT320 through the whole test.

For RT321 with the recycler, the viscosity of the oils increased from 14.4 to 15.6 cSt after 5,000 miles of use. With recycler removed from this truck the viscosity of the oil reached 17.7 cSt after a further 2,500 miles of use. This value, 17.7 cSt, had exceeded the maximum limit of the viscosity grade (SAE J300), which should be less than 16.3 cSt (1). This indicated that an oil change should be considered in actual use as some oil manufacturers recommend that one of the criteria for changing the oil is when the oil viscosity at 100 ^{o}C exceeded the SAE grade limit (3). The increase rate in terms of cSt per kilomile was 0.24 with the recycler and 0.84 without the recycler. The reduction by the recycler is a factor of 3.5.

SOOT/CARBON CONTAMINATION IN OIL - The soot or carbon contamination in the diesel engine oils is one of the major causes for oil deterioration, especially in old engines. The refuse trucks carry out a very frequent stop start working cycles daily and this makes the lubricating oil work under severe conditions.

The carbon contamination in oil was measured by two methods: FTIR and TGA. The FTIR measures the soot content in oil by measuring the spectra absorbency of the soot in oil. TGA determines the total carbon content in oil for both fine soot and coarse particles.

The soot in oil measured by FTIR was shown in Figures 11 and 12. For RT320 without the recycler, the soot in the oil increased from the 2 Abs of fresh oil to 19 Abs after 4,700 miles. The initial value for fresh oil was not zero because the fresh oil was inevitably mixed with the remnant used oil in the engine. After the recycler had been fitted to RT320, there was almost no increase in soot. For RT321, with the recycler the increase in soot during 5,000 miles of use was 37 Abs. The higher initial soot value (8 Abs) for 0 hour oil sample indicated more residue of used oils in the engine. After the recycler had been taken off, the soot increased by 52 Abs in 2,500 miles. Thus the rate of increase in soot in terms of Abs per kilomile was calculated as follows:

	RT320	RT321
without the recycler	3.6	21
with the recycler	0.65	7.4
reduction by the recycler	82%	65%

The data indicated 65% and 82% improvements on the reduction of soot accumulation rate by the recycler. The greater improvement for RT320 was achieved due to that the finer filter media (1 micron pore size) was used.

The total carbonaceous materials in oil were determined by TGA in terms of mass percentage, as shown in Figure 13 and 14. For RT320, without the recycler the carbon was accumulated to 0.9 %wt after 4,700 miles and showed a declined trend after the fitting of the recycler. This meant that the rate of accumulation of carbon in the oil was lower than the reduction rate due to the dilution of oil under an assumed mean oil top up rate. As a result, it revealed a declined trend with the oil ageing.

The accumulation of carbon in the oil for RT321 also showed a reduction by the recycler. The carbon in the oil was accumulated in a rate of 0.25%wt with the recycler and 0.56%wt without the recycler per kilomile of oil age.

Both soot and total carbon measurements revealed that the engine oil on the refuse truck RT321 had a significantly higher carbon contamination. This indicated that the combustion process in this engine was less complete. The air/fuel ratio measurement confirmed that the RT321 had a richer combustion condition (reported in a separate SAE paper about emissions for this refuse truck trial).

ASH CONTENT IN OIL - The ash content in oil represents the metals from lubricant additives and engine wear. It is primarily related to the lubricant additive package. As the diesel engine oils require a high detergency at high temperature a considerable amount of metal detergent is added. The ash value is influenced by the detergent content in oil to a large extent.

The ash content can also reflect the engine wear as it is also related to the wear metals in oil.

The ash in oil will be left when the lubricating oil is burnt in the combustion chamber, which can cause pre-ignition. The ash can contribute to crownland deposits above the piston rings and may lead to valve leaking so as to cause seat burning. The ash in oil also contributes a remarkable proportion to particulate emissions.

The TGA technique was used to determine the ash content in oil. The oil was firstly heated in the atmosphere of nitrogen up to $600^{o}C$ and then air was introduced to burn the carbonaceous materials. The mass left after this was the mass of ash in the oil, which are mostly metal oxides. Figures 15 and 16 show the ash in oil with oil age for two refuse truck tests.

For RT320 without the recycler, the ash in the oil increased in the first 1,000 miles and then stabilised at around 2.0%wt. After the recycler had been fitted, the ash in the oil decreased. It declined to the ash level of the fresh oil after 2,000 miles of use of the recycler. This indicated a reduction in wear metals and lubricating oil consumption.

For RT321 with the recycler, the ash content in the oil was kept at around 2%. After taking off the recycler, the ash in the oil was slight increased. The ash in the oil would increase more significantly if the mean oil top rate was applied without the recycler. The increase in ash accumulation after the recycler being taken off implied an increase in the wear metals in the oil and higher lubricating oil consumption.

WEAR METALS IN OIL - Wear metals in oil were measured by emission spectra. The iron is a primary wear metal in engine oil and the level of iron content is a general indicator for wear in an engine. The main source for iron is from liner scuffing and general wear.

For RT320 test the iron in the oil increased by 25 ppm after 4,700 miles of oil age without the recycler, as shown in Figure 17. The increase rate was 5.3 ppm per kilomile. After the fitting of the oil recycler, the iron in the oil decreased by 2 ppm per kilomile even under a mean oil top up rate. This decrease in iron meant that if the mean oil top up rate was applied, the accumulation of iron in the oil would be slower than reduction due to the dilution of the oil top up. Therefore, the difference in accumulation of iron with and without the recycler is quite apparent.

For RT321 test the iron in the oil increased by 9.6 ppm per kilomile with the recycler and by 22.8 ppm per kilomile without the recycler, as shown in Fig.18. An improvement of 58% in the reduction of iron accumulation using the recycler has been achieved.

The lead and copper contents in oil are known to be the bearing metal indicators. Both refuse trucks did not show any indication of serious bearing wear. For RT320 without the recycler, the lead and copper were slightly increased to 6 ppm and 4 ppm respectively after 4,700 miles of use of the oil. With the recycler fitted there was an increase in lead after 7,000 miles of oil age. The level of lead, however, was still well below the typical value 20~40 ppm (1). The copper level had a radical increase at the same point, which was due to a coolant leak.

Figure 13. Carbon accumulation in oil Vs oil age measured by TGA for RT320 test

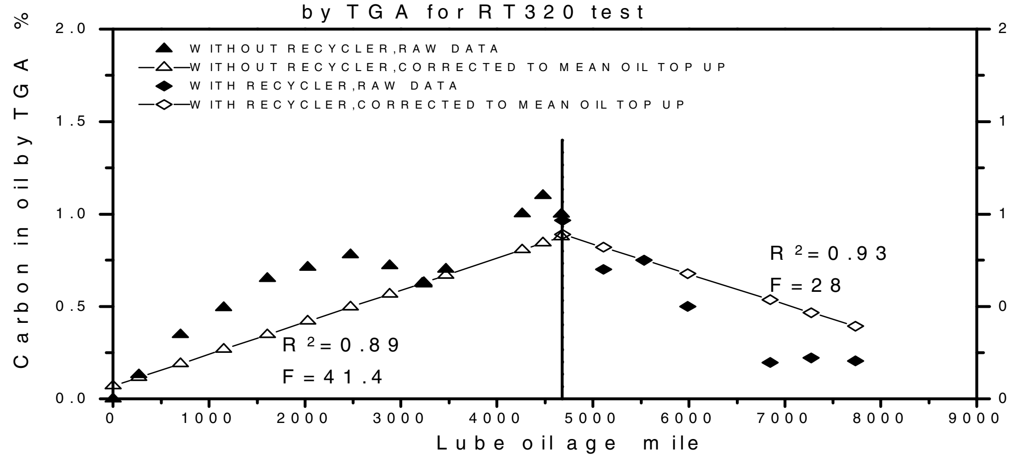


Figure 14. Carbon accumulation in oil Vs oil age measured by TGA for RT321 test

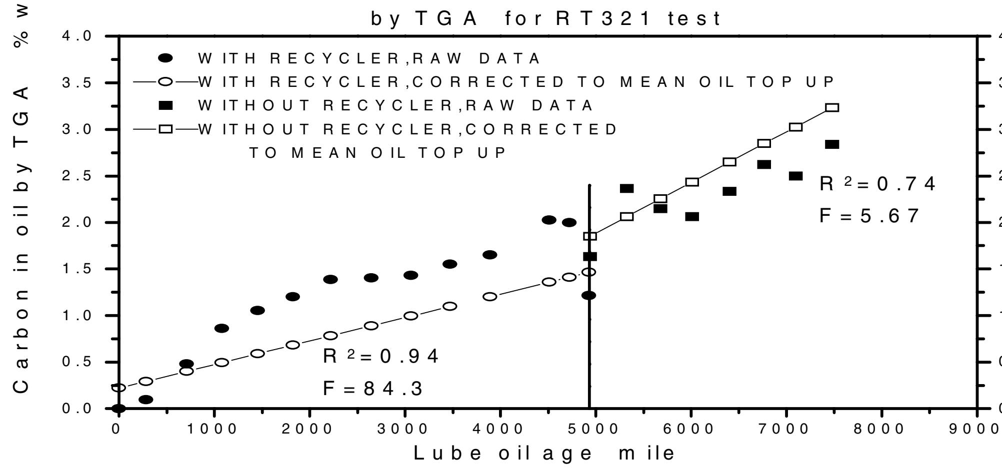


Figure 15. Ash content in oil Vs oil age for RT320 test

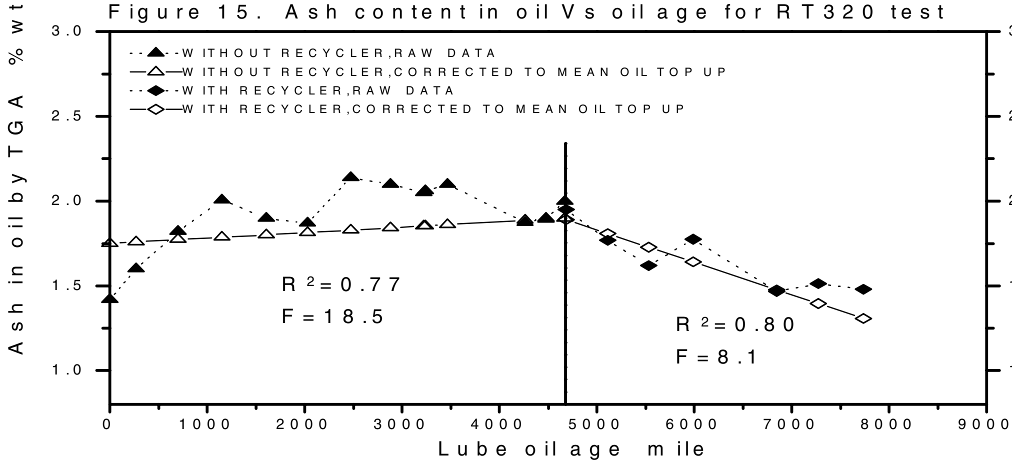


Figure 16. Ash content in oil Vs oil age for RT321 test

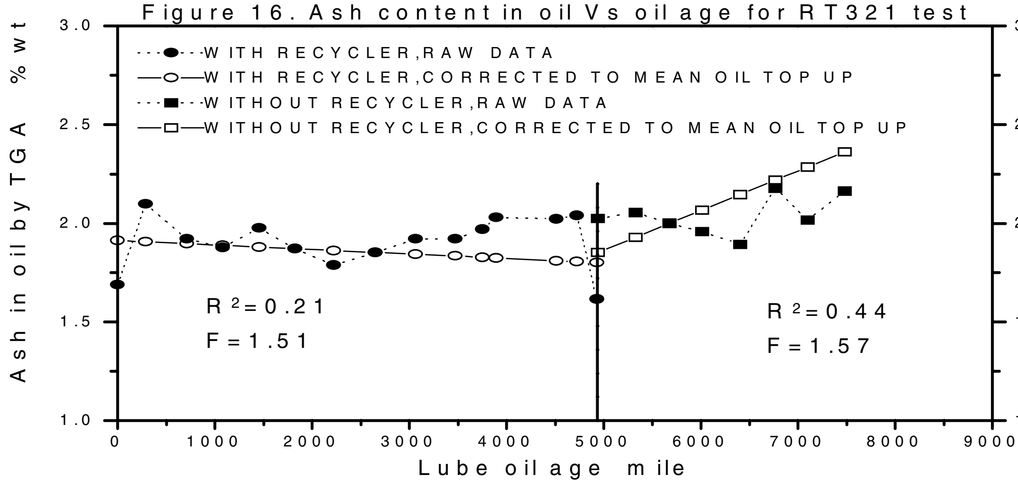


Figure 17. Iron content in oil Vs oil age for RT320 test

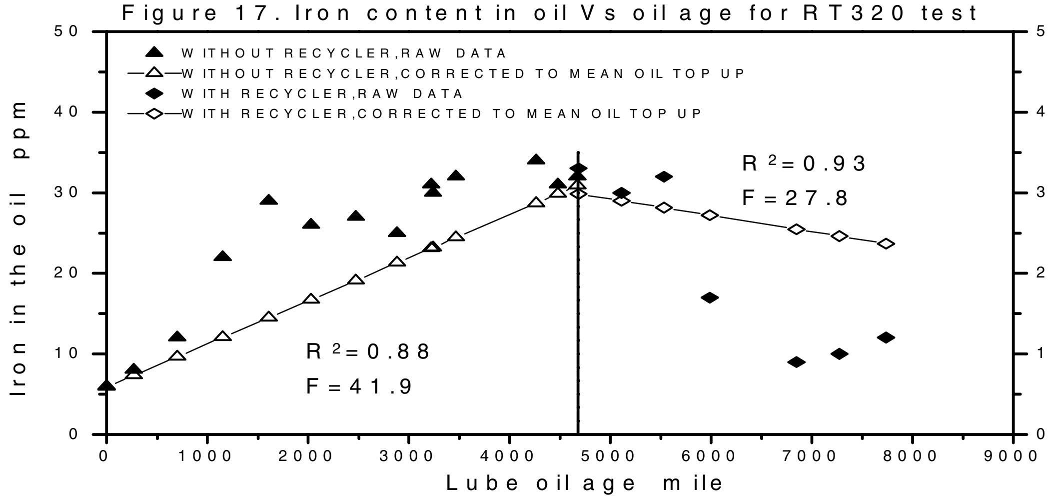
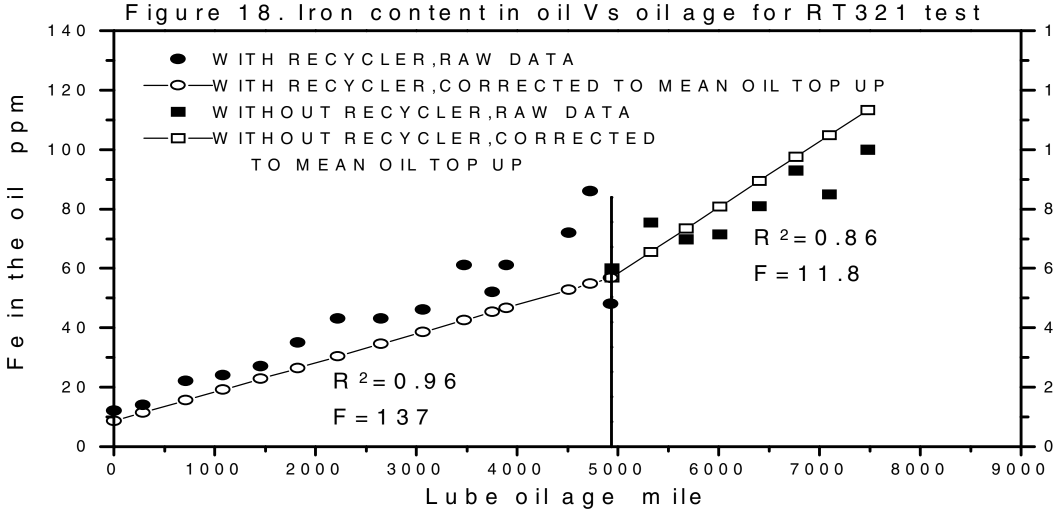


Figure 18. Iron content in oil Vs oil age for RT321 test



For RT321 test the increase rate of lead in the oil was 0.7 ppm/kilomile with the recycler and 4.8 ppm/kilomile without the recycler. The rate of increase in copper was at a similar level of 1.9 ppm/kilomile both with and without the recycler in the case of mean oil top rate.

It should be pointed out that the level of lead and copper during the whole test period for two refuse trucks were well below the warning limits, which are 50 ppm for lead or copper. They were also below the typical value: 15-25 ppm for copper and 20-40 ppm for lead. This indicated that the bearings friction was well controlled.

ADDITIVE DEPLETION:

ELEMENTAL ANALYSIS - There was no good correlation between Ca, Zn and P with lubricating oil top ups and oil age. As a result, the raw data was used to show the variation of additive elements as a function of oil age as shown in Figures 19 and 20.

For RT320 test, there were two peaks in calcium and zinc contents before the recycler was fitted and one small peak after the recycler was fitted. The content of phosphorus was stable both with and without the recycler. For RT321 test, there was a large peak in calcium and zinc after the oil recycler had been taken off, although some small peaks appeared before that. These significant peaks in additive metals indicated possible deposits burning off or dissolving in the oil and thus the calcium and zinc stored in the sediment were released into the oil. As the phosphorus is a non-metal element and not stored in the deposits and therefore its content did not change along with the calcium and zinc.

ZDDP DEPLETION - The rate of depletion of ZDDP in oil was measured by FTIR and shown in Figures 21 and 22 for two refuse trucks respectively. For RT320, the rate of depletion of ZDDP was 13% per 1.000 miles without the recycler and -1% with the recycler fitted, which showed that the content of ZDDP in oil with an average oil top up was actually increasing and indicated the decrease of ZDDP with oil age was slower than the increase due to oil top up.

For RT321, the rate of depletion of ZDDP was 5% per 1000 miles with the recycler fitted and 16% per 1000 miles without the recycler. A reduction of 69% in ZDDP depletion was achieved by the recycler.

The refuse truck RT321 showed a higher rate of depletion of ZDDP than RT320, which was associated with high smoke emissions.

OXIDATION, NITRATION AND SULPHATION OF THE OILS:

OXIDATION OF THE OILS - The engine oils are oxidised in use due to the high temperature and severe working environment. The duty cycles have a direct influence on oil oxidation. The refuse trucks carry out a very frequent stop start cycle and long time in high power output due to loading/unloading the rubbish. This would lead to a higher rate of oxidation of the oil, compared to the test results from FirstBus

Figure 23 shows the oxidation of the oil with oil age for RT320 test. The 10 units were increased after 4,700 miles of use without the recycler whereas one unit of decrease occurred with the recycler fitted under a mean oil top up rate. The rate of increase in oil oxidation was 2.1 Abs/kilomile without the recycler and -0.32 Abs/kilomile with the recycler.

The oxidation of the oil for RT321 test has been shown in Fig.24. The increase with the recycler was 10 Abs after 5,000 miles with the recycler and 8 Abs after 2,500 miles without the recycler. The rate of increase was 2 Abs/kilomile with the recycler and 3.2 Abs/kilmile without the recycler. Thus the improvement on the reduction of oil oxidation rate by the recycler was 37.5%.

The RT321 had shown a higher oxidation rate than RT320. This indicated that the engine oil in the RT321 underwent a more severe environment.

NITRATION OF THE OILS - The lubricating oil in the diesel engines is nitrified due to the contamination of nitrogen oxides from the combustion chamber. The level of nitration of the oil can indicate the tendency of deposits or varnish formation.

Figure 25 shows the nitration of the oil for RT320 test. It was increased by 4.5 Abs in 4,700 miles of use without the recycler and 0.2 Abs in 3,100 miles of use with the recycler in the case of a mean oil top up rate. The rate of increase in nitration was 0.96 Abs per kilomile without the recycler and 0.06 Abs per kilomile with the recycler. The reduction in the rate of nitration by the use of the recycler is 94%.

Figure 19. Contents of additive elements in oil Vs oil age for RT320 test

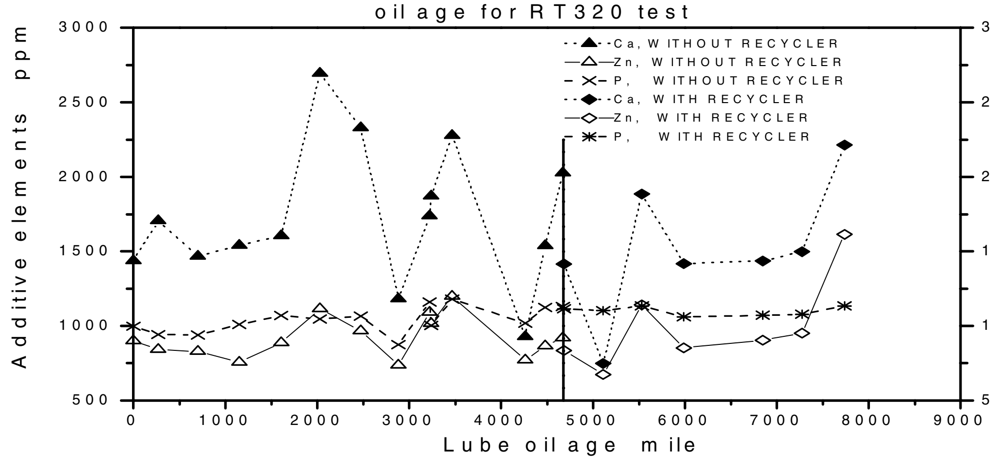


Figure 20. Contents of additive elements in oil Vs oil age for RT321 test

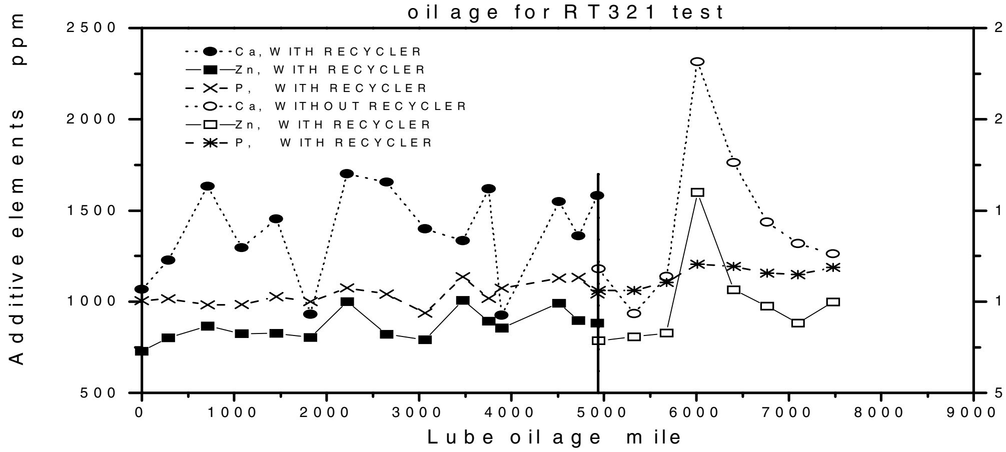
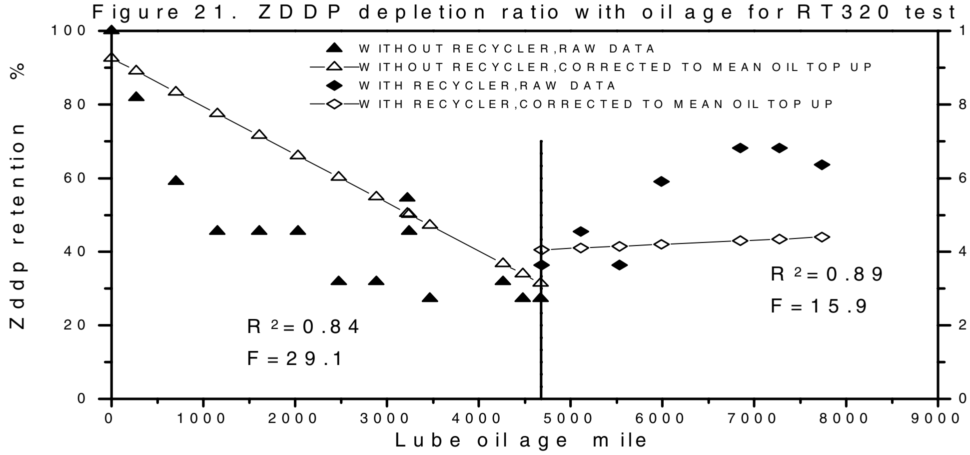


Figure 21. ZDDP depletion ratio with oil age for RT320 test



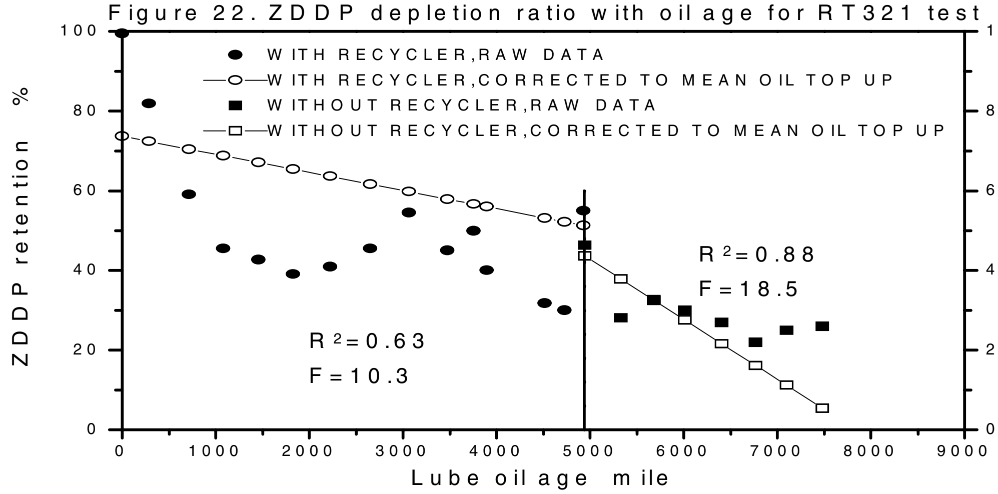


Figure 22. ZDDP depletion ratio with oil age for RT321 test

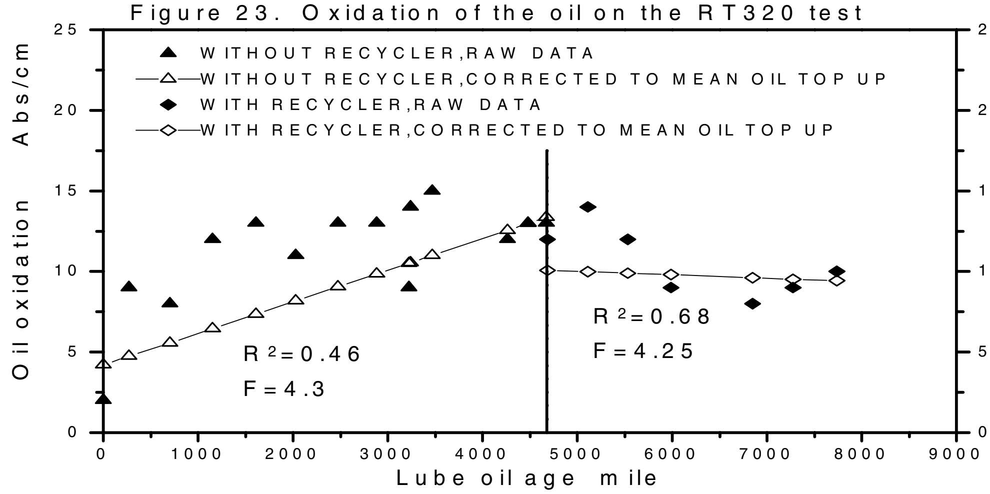


Figure 23. Oxidation of the oil on the RT320 test

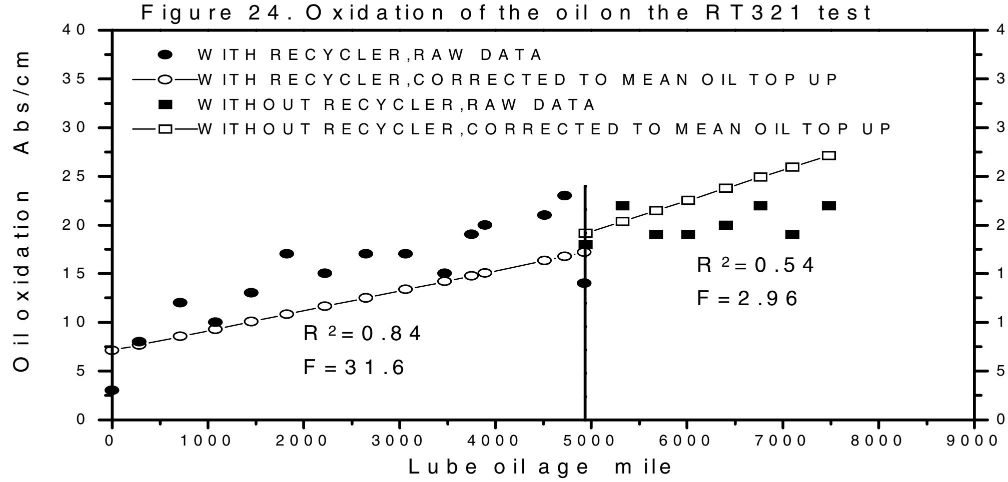


Figure 24. Oxidation of the oil on the RT321 test

Figure 26 shows the RT321 test results. The nitration of the oil showed an increase of 11 Abs with the recycler in 5,000 miles of use and 10 Abs without the recycler in a further 2,500 miles of oil age. Thus the rate of increase in oil nitration was 2.2 Abs per kilomile with the recycler and 4 Abs per kilomile without the recycler. An improvement of 45% in the reduction of oil nitration was achieved by the use of the recycler.

SULPHATION OF THE OILS -The refuse trucks use modern low sulphur diesel with ≤ 0.05% sulphur in the whole test. So there was no influence of fuel change on sulphation of the oil.

Figure 27 shows the sulphation of the oil for RT320 test. The increase of sulphation was 9.5 Abs without the recycler and 0.5 Abs with the recycler. The rate of increase was 2 Abs/kilomile without the recycler and 0.16 Abs with the recycler. Thus the reduction of sulphation by the oil recycler was 92%.

For RT321 test, the sulphation of the oil increased by 20 Abs in 5,000 miles with the recycler and 12.5 Abs in 2,500 miles without the recycler, as shown in Fig.28. The rate of increase was 4 Abs/kilomile with the recycler and 5 Abs/kilomile without the recycler. The reduction in oil sulphation rate by the oil recycler was 25%.

It has been shown above that the reductions on the oil oxidation, nitration and sulphation by the oil recycler were more significant for RT320 than that for RT321. This was considered to be due to the finer filter in the recycler for RT320. So it indicated that the finer filter has a better effect on maintaining the oil quality.

WATER IN OIL AND FUEL DILUTION - Figures 29 and 30 show the water content in oil measured by the infrared technique. For RT320 without the recycler, the water content in the oil fluctuated significantly. The maximum value for water content in the oil reached nearly 0.2%, which was reckoned as a critical value for engine oils. The water in the oil was 0.16%(1600 ppm) at the end of 4,700 miles test without the recycler. After the recycler was fitted, the water in oil was reduced from 0.16% to 0.105% instantly and continued to decrease to 0.06% after 800 miles of run with the recycler fitted. The water in the oil was then increased gradually with oil age. For RT321, with the recycler fitted the water in the oil decreased with oil age from 0.14% of fresh oil to 0.07% at the end of 5,000 miles of test with some fluctuations. After the recycler was taken off, the water in the oil continued to fall until 6,500 miles of oil age, followed by an increase. This fall in water content in oil was difficult to explain. Nevertheless, the RT320 did show an effect on removing the water from the oil with the fitting of the oil recycler and verified that the water in oil could be accumulated to a substantial amount with no recycler fitted.

The fuel dilution can be determined by TGA technique, which was shown in reference (3) on the Ford 1.8L IDI engine test. However, the determination of the fuel dilution in oil on the refuse truck tests was interfered by the oil top ups, similar to the case of FirstBus tests (15). The distillation range of the oil changed because different batches of the oils were used to top up. The weight loss of the oil samples at a calibrated temperature varied a lot and surpassed the range of calibration. Therefore the fuel dilution could not be determined by the TGA technique.

The infrared technique was also used to determine the fuel dilution of the oils. There is a limit of 2% for infrared technique. Therefore infrared technique can only detect the fuel dilution above 2% quantitatively. The data for the whole test period on the refuse truck tests revealed the fuel dilution was below 2%.

The Gas chromatography was used to analyse oil samples qualitatively, as shown in Figures 31-35. The fresh and used oil samples with/without the recycler were analysed. There was a slight increase in a range of C16-C20 peaks for used oil samples both with and without the recycler, compared to the trace of the fresh oil. It indicated that no notable fuel dilution occurred in the tests, even without the recycler.

FAST RESPONSE OF THE RECYCLER

The oil samples were taken just before and 8 miles after the fitting/taking off of the oil recyclers for two refuse trucks. The analysis results showed there was a fast response of the recycler on oil quality with and without the recycler. Table 8 summarised the results.

The recycler was fitted to the engine after 4,700 miles of use of the oil without the recycler for RT320. All parameters, except TBN, of the oil quality showed an immediate drop by the recycler. This improvement was achieved just 8 miles after the fitting of the recycler. Similarly for RT321, all aspects of the oil quality had been getting worse just 8 miles after taking the recycler off. The differences between with and without the recycler for RT321 were larger than that for RT320. This was because the engine oil in RT321 deteriorated faster than the oil in RT320. The possible source for this was the combustion process in RT321 was more incomplete and thus more contamination of the oil.

Figure 25. Nitration of the oil on the RT320 test

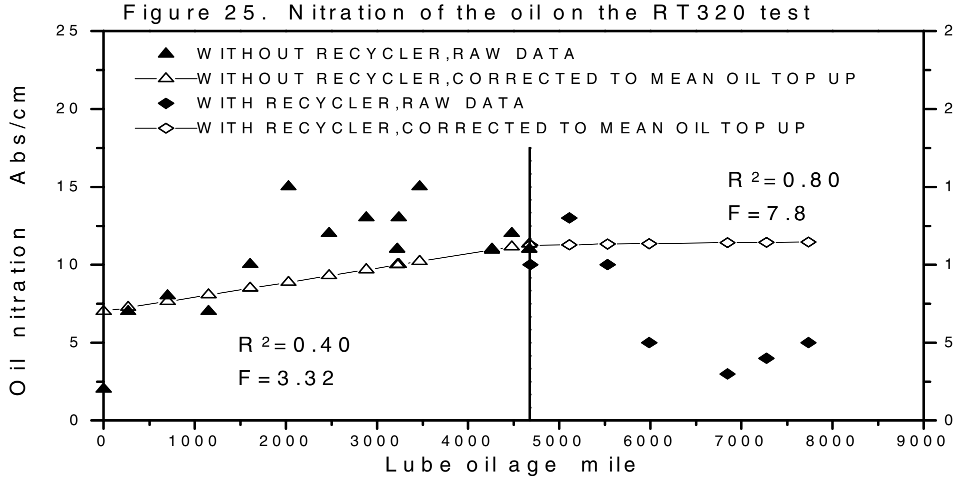


Figure 26. Nitration of the oil on the RT321 test

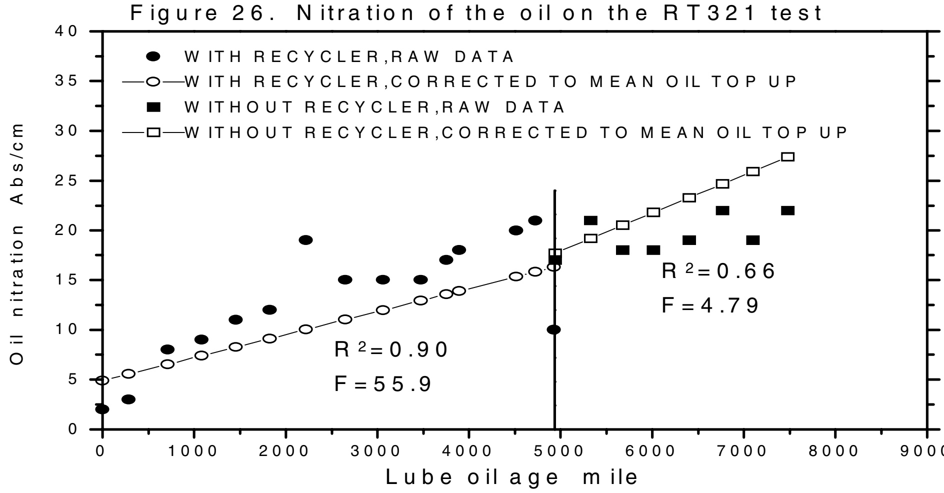


Figure 27. Sulphation of the oil on the RT320 test

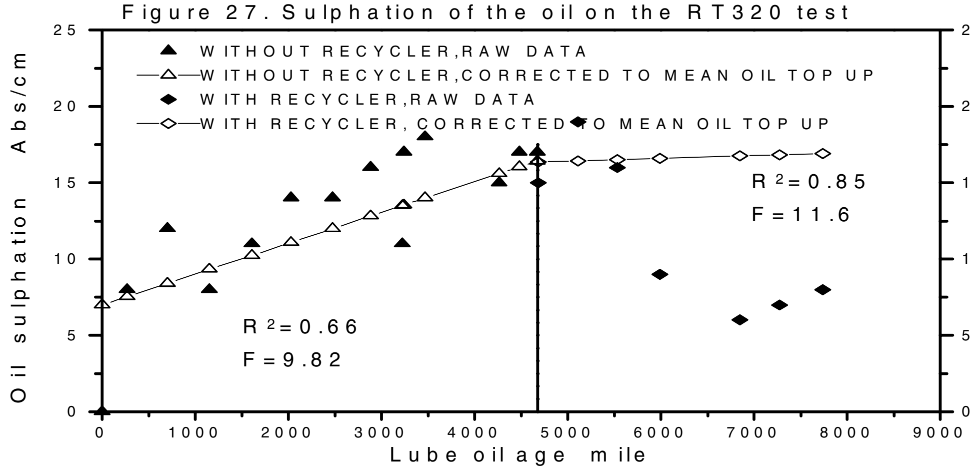


Figure 28. Sulphation of the oil on the RT321 test

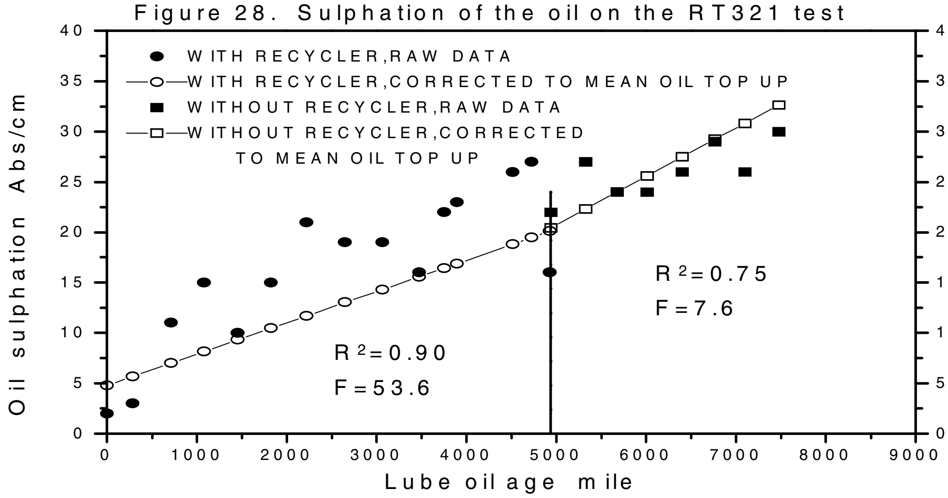


Figure 29. Water in oil Vs oil age for RT320

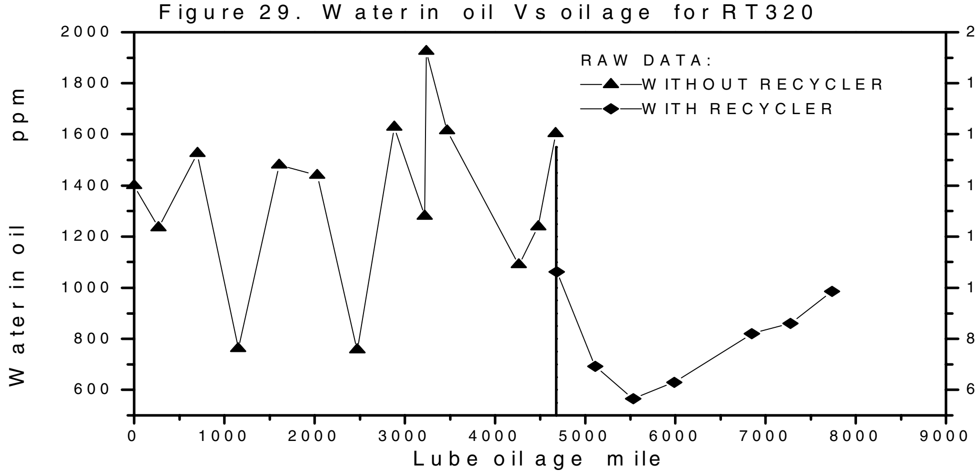


Figure 30. Water in oil Vs oil age for RT321

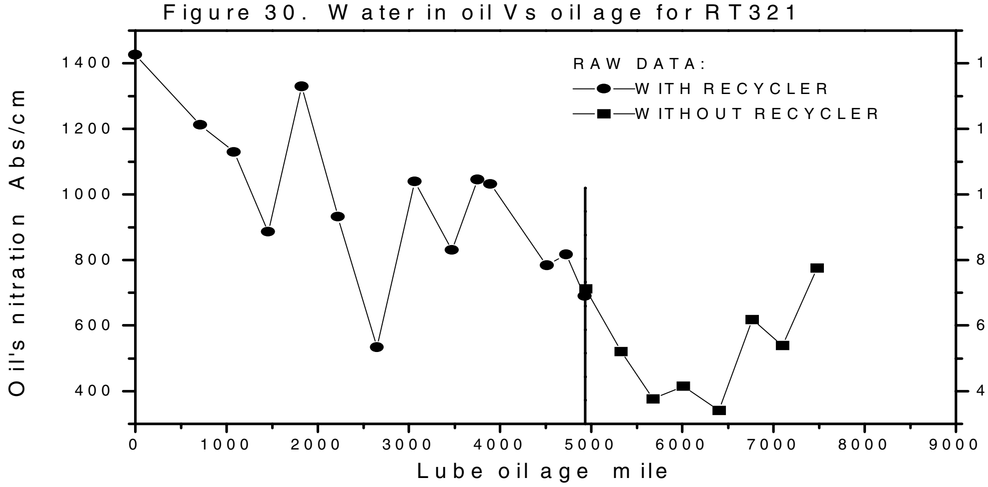


Figure 31. Fresh oil for refuse truck test

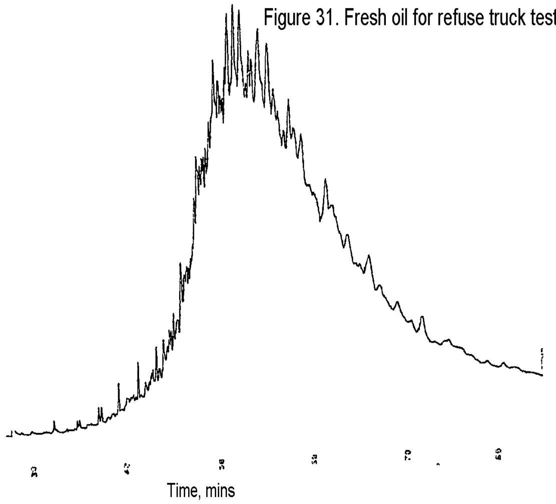


Figure 32. RT320 4,700 miles oil without the recycler

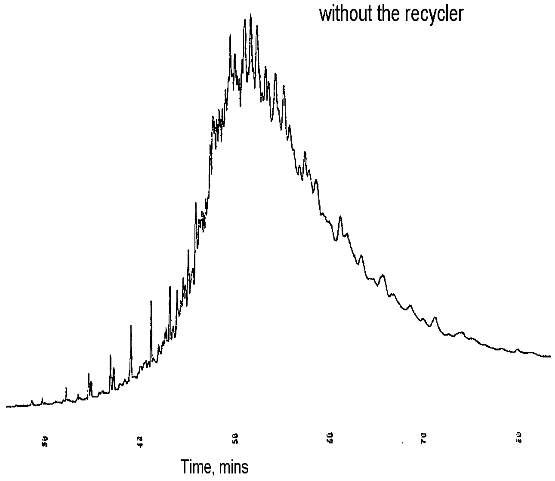


Figure 33. RT320 5,531 miles oil with the recycler

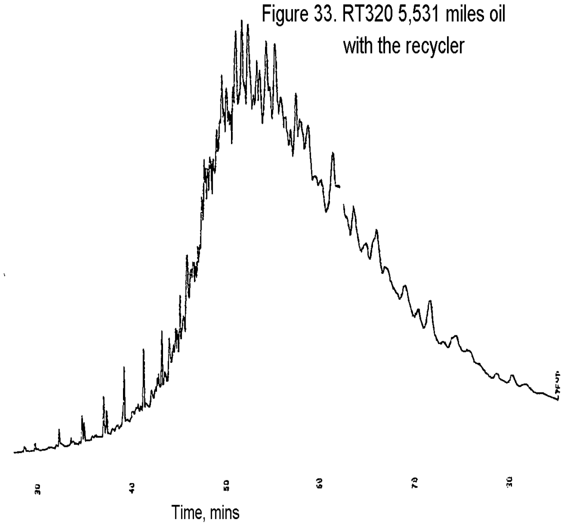


Figure 34. RT321 4,514 miles oil with the recycler

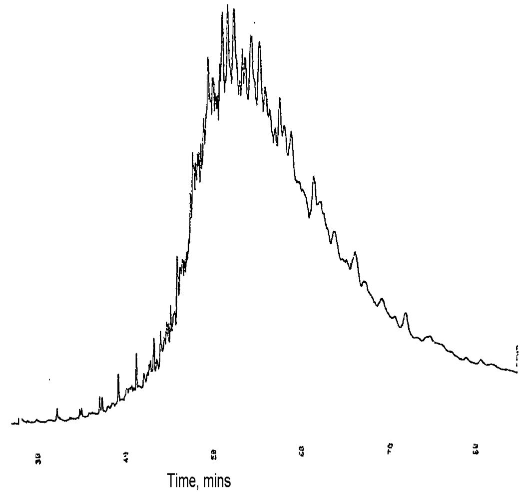
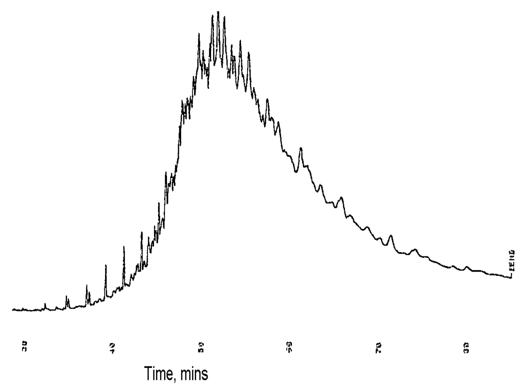


Figure 35. RT321 6,770 miles oil without the recycler



The immediate function of the oil recycler indicated the importance of filtration on improving oil quality. The flow rate of the oil through the recycler was about 0.72 l/min. Thus the recycler recycled all the oil in the sump in about 25 minutes. As the emission sampling process took about half an hour, all the oil in the sump had already been recycled once for RT320 before the first oil sample was taken after the recycler had been fitted.

ECOMONIC AND ENVIRONMENTAL BENEFITS

Refuse truck tests showed that the lubricating oil quality was well maintained with time with the recycler fitted. The better oil quality extended the oil life. The Table 7 showed that the rate of oil deterioration for most parameters were reduced by at least 50% with the recycler fitted, which indicated a doubled oil life at least. Moreover, the recycler reduced oil consumption by 30~41% (Table 5), which resulted in a further oil saving.

The improved lubricating oil quality also resulted in less deposits in the cylinders and reduced fuel consumption by 2.05 and 3.55% (Table 6) for two refuse trucks. Table 9 estimated the economies generated by the recycler for refuse trucks on average. There are four oil changes for a year operation normally. With the recycler fitted, the oil life is doubled at least and therefore the maximum oil changes are twice a year. The recycler not only extended the oil life but also reduced the amount of lube oil topped up (Table 5 showed a reduction of 37% on average). The reduction on the fuel consumption is 2.8% on average by the recycler (Table 6). The fuel savings are depending on the travel distance of the vehicles. It is assumed that a refuse truck travels 10,000 a year. So the total savings on lubricating oil and fuel are $245.6 per year for a refuse truck. Besides lube oil and fuel savings, there are other savings such as reduced maintenance cost and extended engine life. Therefore the payback time for investment is estimated less than one year for refuse trucks.

The extended oil life and reduced lube oil consumption reduced the amount of waste oils by at least 50%. Improved oil quality reduced exhaust emissions, especially black smoke and particulate emissions (reported in a separate SAE paper). These are obviously the environmental benefits generated by the oil recycler.

Table 8. The change of oil properties just before and after the fitting/taking off of the recycler

Properties	RT320		RT321	
	without recycler	after recycler fitted	with recycler	after recycler taken off
TBN mgKOH/g	9.6	9.6	9.4	9.3
TAN mgKOH/g	5.9	5.8	5.0	5.5
V100 cSt	14.5	14.3	15.3	15.7
SOOT(IR) Abs	22	19	38	56
Carbon %wt	1.0	0.96	1.2	1.6
Ash %wt	2.00	1.95	1.6	2.0
Fe ppm	33	32	48	60
Oxidation Abs	13	12	14	18
Nitration Abs	11	10	11	17
Sulphation Abs	17	15	16	22

CONCLUSIONS

Two refuse trucks with a similar age were selected and the tests were carried out to evaluate the influence of the TOP-HIGH lubricating oil recycler on emissions and lube oil quality as well as lubricating oil and fuel consumption. The two refuse trucks were 1991 model fitted with Perkins Phazer 210Ti series turbocharger intercooled engines with EURO-I emission compliance. These two refuse trucks carried out similar duties and used the same mineral lubricating oils and low sulphur diesel fuels. The lubricating oil and emissions samples were taken every two weeks or 400 miles on average and analysed. The results are showing that with the recycler:

The lubricating oil consumption has been reduced by 30~41% in terms of g/kgfuel.

The diesel fuel consumption has been reduced by 2~3.5% in terms of L/mile.

A reduction of 27~43% on TBN depletion rate has been achieved.

The increase of oil TAN has been reduced significantly.

The rate of increase in soot and total carbon in oil has been reduced dramatically. The rate of soot accumulation in oil was 65-82% lower with the oil recycler, compared to the results without the recycler. The carbonaceous materials in oil decreased with oil ageing after fitting the recycler for RT320.

The rate of accumulation of wear metals in oil has been reduced by 58% at least.

The oxidation, nitration and sulphation of the oils have been slowed down significantly.

ONGOING AND FUTURE WORK

The further development for more efficient heating dome and greater capacity filter media is ongoing. The tests on tractors and petrol vehicles are in progress. The trials for railway and marine diesel engines are planned.

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Table 9. Economy analysis for refuse trucks (for one year operation)

	without recycler	with recycler	savings
Lube oil change l	4 times/year 4x18= 72	2 times/year 2x18=36	36Lx£0.35/L = £12.6
Lube oil top up l	42[2]	26.5	15.5Lx£0.35 /L=£5.4
Lube oil Total l	114	63	£18
Fuel	1016[3]L/kmile x10=10160 L	10160x97.2% =9875.5 L	284.5x£0.8 /L=£227.6
Total saving for lube oil and fuel			£245.6
Other savings	Less engine wear and thus less equipment and maintenance cost. Fewer main oil filters required. Reduced disposal costs for waste oil and filters.		
Outlay	Initial cost for oil recycler installation and thereafter replacement of fine filters.		

N.B. 1. Assume 10,000 miles of travel a year.
2. Average rate for two refuse trucks.
3. Average fuel consumption for two refuse trucks.

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