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Preliminary Results from a Six Vehicle, Heavy Duty Truck Trial, Using Additive Regenerated DPFs

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ABSTRACT

Impending legislation will make it almost inevitable that heavy-duty trucks will have to be fitted with some form of particulate removal after-treatment device. The challenge is to provide a system that is not only environmentally acceptable and cost effective but also durable enough to meet the demands of the trucking industry. Diesel particulate filters (DPF), in conjunction with fuel borne catalysts to facilitate regeneration, are now a recognised technology for meeting future passenger car emissions limits.

Retrofitting of such systems to older technology vehicles, where specific environmental concerns exist, has demonstrated the possibility of applying this technology to the heavy-duty vehicle sector. Most of these retrofit applications tend to be to vehicles with a relatively low duty cycle. Whereas this type of duty cycle poses the greatest challenge to the successful regeneration of the filters it is not necessarily the most arduous test of the durability of the system.

To demonstrate the efficacy of the DPF additive system to a wider application range, five heavy-duty trucks were fitted with DPFs and onboard additive dosing systems. Three different DPF technologies were used and two different additive technologies. A sixth truck was also included in the trial as a reference. The trucks routinely travel in excess of 10,000 km per month. Regular sampling of the lubricating oil is used to check for adverse effects on engine durability whilst on board data logging of filter temperatures and pressures are used to monitor the performance of the filters.

This paper presents details of the installation of the systems as a direct replacement for the existing vehicle silencer, details of the effect of the filters on the regulated emissions, plus information from the onboard data logging system. The conclusion drawn is that, to date there are no indications of any problems with the durability of the DPF systems.

INTRODUCTION

Diesel combustion, i.e. where neat distillate fuel is added to compressed air, always has and always will produce soot. It is the aim of the diesel engine manufacturer to minimise the mass of this soot that survives the combustion process and leaves the combustion chamber. Where such advances have not kept pace with requirements the retro-fitting of after-treatment devices has been employed to limit the quantity of these emissions reaching the environment. However as with gasoline combustion three decades ago, it is becoming accepted, by the engine manufacturers, that there is a place for after-treatment in the control of unwanted emissions. Initially this entailed using oxidation catalysts to control unburned hydrocarbons (HC) and carbon monoxide (CO) and more recently using DPFs to control particulate (PM) emissions.

Since 1998 a heavy-duty engine manufacturer has been offering engines with a diesel particulate filter as a factory fitted option (1). In 2000 a passenger car manufacturer began to offer a passenger car complete with DPF (2) and in this case it was a standard fitment rather than an option. Both these applications rely on a fuel borne catalyst to ensure regeneration of the filter. Despite the initiatives of these manufacturers, the efforts of retrofit companies and the fiscal incentives offered in a number of countries, the up-take of DPF systems is still relatively small. An often cited reason for reluctance is concerns over reliability/durability of DPF systems.

Data has been presented (3) demonstrating the long-term durability of continuously regenerating filter systems for heavy-duty applications. However these systems were tested with fuel containing a maximum of 10 ppm of sulphur. Such fuel is not widely available at present and is not likely to be so for a few years to come. Other studies (4) have shown the efficacy of a system using a fuel borne catalyst, but over a much shorter time and distance. Although data is available (5) for a passenger car operated over a greater distance there is still a lack of data for the use of such systems over the high mileages encountered in commercial heavy-duty applications.

To generate data to fill this knowledge gap, a programme was instigated to test a series of DPF technologies on a heavy-duty truck application. For this work a haulage firm based in central Germany was chosen. The trucks used for the testing travel on average about 12500 km per month. Although the trucks are based and operate mainly within Germany the nature of the business means that the trucks can and do operate throughout Europe. This means that although fuel with a maximum sulphur level of 50 ppm is the norm in Germany the truck could be fueled with fuel containing up to the maximum limit permitted in Europe, i.e. 350 ppm.

TEST VEHICLES AND FILTERS

The trucks chosen for this work were Mercedes-Benz Actros 1835 LS tractor units. The trucks were fitted with Mercedes-Benz OM501LA engines. These are six cylinder engines with a capacity of 11.95 litres and were built to comply with Euro 2 emissions regulations. Further engine details are given in Appendix 1. A group of the trucks is shown as Figure 1. The trucks have been designated as NoSü-1 through NoSü-6.

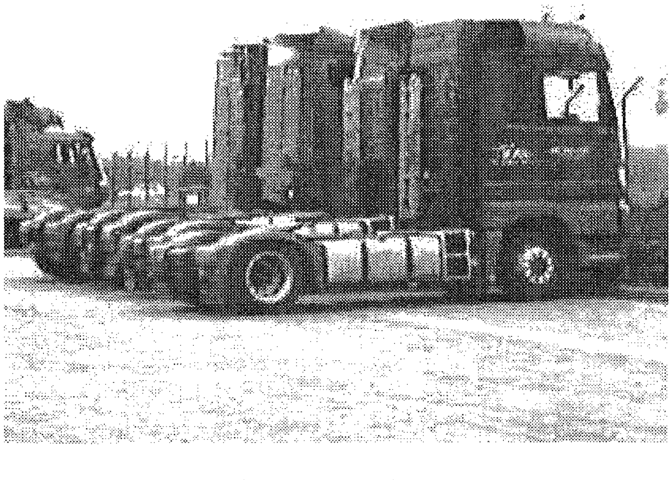

Figure 1: A group of the test trucks.

Two of the trucks were fitted with DPFs supplied by PUREM Abgassysteme GmbH & Co. KG. These filters are made from sintered metal and are designed to be more tolerant to ash build-up than the conventional honeycomb ceramic DPFs. This DPF type is referred to as D1 throughout the rest of the paper. A further three trucks were fitted with DPFs constructed by ECS and containing conventional honeycomb silicon carbide (SiC) filter elements. One of these filter elements was manufactured by Ibiden and is referred to as D2, whilst the other two filter elements were manufactured by NoTox and are referred to as D3. Further details of the DPF are given in appendix 2.

In each case the filter element was incorporated into an enclosure that matched the dimensions of the conventional exhaust silencer unit. This allowed the DPF to be mounted as a direct replacement for the standard silencer as shown in Figure 2 below. Each of the designs was tested to ensure compliance with noise limits.

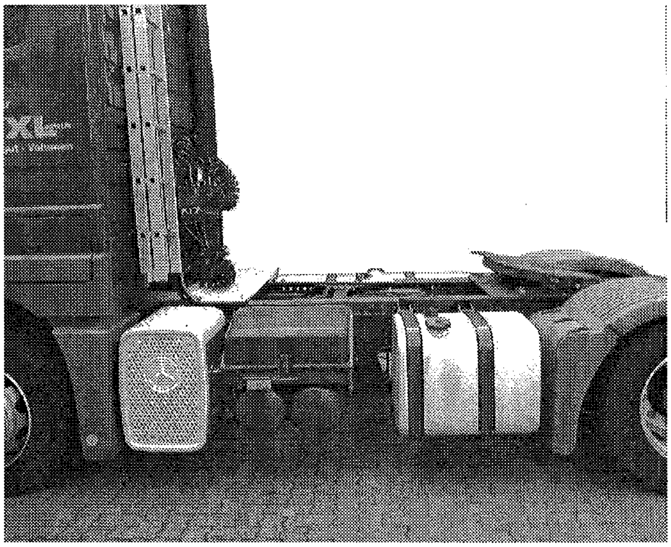

Figure 2: DPF mounted to replace standard silencer

All five trucks were fitted with an on-board additive dosing system supplied by HJS Fahrzeugtechnik GmbH & Co. The on-board additive tank had a capacity of 10 litres. The fuel additive is dosed into the fuel return line according to the quantity of fuel added to the vehicle's fuel tank. Each truck is fitted with two fuel tanks, one on either side of the chassis as can be seen from Figures 1 and 2. A balance pipe connects these two tanks so that the level in each tank falls as fuel is used. The total fuel tank capacity was 730 litres except on truck NoSü-5 where the capacity was 850 litres.

The additive used in two of the trucks is Octel Octimax™ 4804, later referred to as A1; this additive contains a 4:1 mixture of organic iron and organic strontium. The remaining three trucks used Octel Octimax™ 4820, subsequently referred to as A2, where the only metal used is iron. The target treat rate in each case was

20 mg/kg of metal. Table 1 below indicates which DPF and additive was used on each truck.

Table 1: DPF and additive allocations

Truck number	DPF type	Additive type
NoSü-1	D3	A2
NoSü-2	D1	A2
NoSü-3	D1	A1
NoSü-4	D2	A1
NoSü-5	D3	A2
NoSü-6	None	None

EMISSIONS TEST RESULTS

The trucks used for this programme had been run for some distance prior to emissions testing. This ensured that the engines were well run-in and the engine oil was stabilised. The odometer readings at the start of the emissions test programme are given in Table 2.

Table 2: Odometer readings

Truck	NoSü-1	NoSü-2	NoSü-3	NoSü-4	NoSü-5	NoSü-6
Odo'	45342	46468	39441	47113	73697	48822

All six trucks were emissions tested on a chassis dynamometer according to the European Transient Cycle (ETC), formerly known as the FiGE (Forschungsinstitut Gerausche und Erschutterungen) cycle. The ETC test procedure involves driving a vehicle for 30 minutes. The test is split into 3 phases of 600 seconds each. The three phases simulate driving in each of the following environments, urban streets, rural routes and on the motorway. The emissions from each of these three phases are sampled independently; an overall value of emissions for the test can then be calculated.

For the work reported here each vehicle was tested twice. The first test was performed on the vehicle which had been allowed to soak overnight at 20°C. The second test was then performed on a fully warmed up vehicle. The dynamometer loading was set from coast-down data obtained on the reference truck. The complete set of emissions test results is tabulated in Appendix 3. Some of the results are discussed below.

COLD START EMISSIONS TEST RESULTS

Each truck was tested after an overnight soak at 20°C. Results were determined in g/km for each of the three phases of the test procedure. The PM emissions results are plotted in Figure 3 below. For the reference truck without a DPF, labeled as Base in Figure 3, the PM emissions during the first phase (urban phase) are significantly higher, on a g/km basis, than in the subsequent phases.

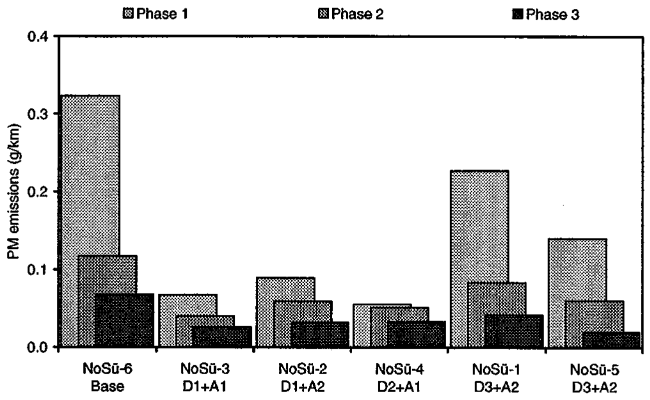

Figure 3: Cold start PM emissions results

With DPF types D1 and D2 this characteristic is not as pronounced. In terms of "filtration efficiency" DPF types D1 and D2 therefore exhibit higher efficiencies during phase 1 than during phase 2 and phase 3. For D1 the filtration efficiency during phase 1 is 72% - 79% whilst on phase 2 and 3 it is 50% - 66 % and 53% - 62% respectively. The corresponding figures for DPF type D2 are 83% during phase 1 and 56% for phase 2 and 51% for phase 3. This phenomenon has been observed before (5) and has been attributed to volatile hydrocarbons (HC) condensing in the cold filter and then being evaporated off as the filter warms up and being adsorbed onto the PM. The results for D3 are not as good with filtration efficiencies of 30% - 57% on phase 1, 29% - 49% on phase 2 and 38% - 71% on phase 3.

The HC emissions from the cold start tests are shown in Figure 4. It is interesting to note that for the base truck the HC emissions, on a g/km basis, are reduced on each successive stage of the cycle.

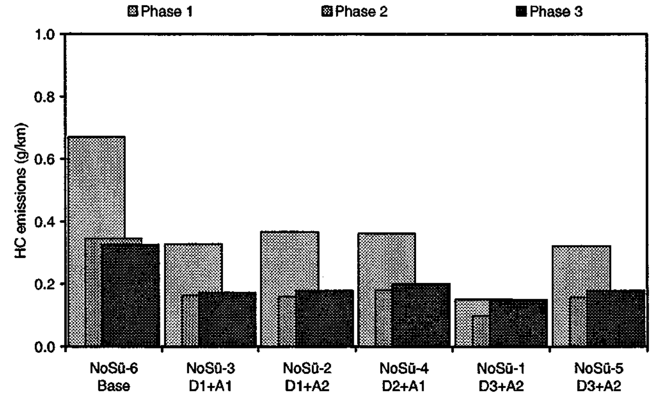

Figure 4: Cold start HC emissions

However for all of the trucks fitted with DPFs the g/km HC emissions are greater on phase 3 than on phase 2. This again may be due to HC condensation and subsequent evaporation. It is also worth noting that the truck with DPF D3 and additive A2 that gives the highest PM emissions also gives the lowest HC emissions. If the HC and PM emissions from Figures 3 and 4 are added together then the results are as shown in Figure 5.

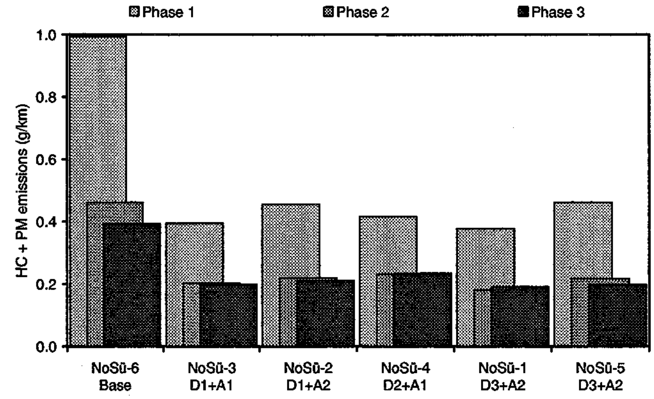

Figure 5: Cold start HC + PM emissions

Truck NoSü-1 produced significantly lower HC emissions than the other trucks, however the CO emissions for truck NoSü-1 were not significantly lower than the other trucks, see Appendix 3. This implies that the combustion process within the engine of NoSü-1 is not significantly better than the other trucks, the lower HC levels are thus assumed to be due to "trapping" within the exhaust system or on the emitted particulate matter. As this truck produced the highest measured level of post-DPF PM it is hypothesised that the HC is in fact being adsorbed onto the PM, increasing the measured mass of PM and reducing the measured mass of HC. Thus when the PM and HC are summed the difference in performance of the different trucks is reduced as shown in Figure 5. The trucks NoSü-1 and NoSü-5 are equipped with the same filter elements but with slightly different canning, the implication is thus that the emissions are effected not only by the type of DPF, but also the way in which it is canned.

The fuel consumption calculated from a carbon balance shows all of the trucks with DPFs to have a lower fuel consumption on all of the stages, than the truck without a DPF. However all the results are within experimental repeatability and no claim can be made for the DPFs reducing fuel consumption.

What is of general interest however is the magnitude of the difference between the fuel consumption during the first, urban phase and the remaining two stages. This can clearly be seen in Figure 6 which shows the fuel consumption for each truck during each stage.

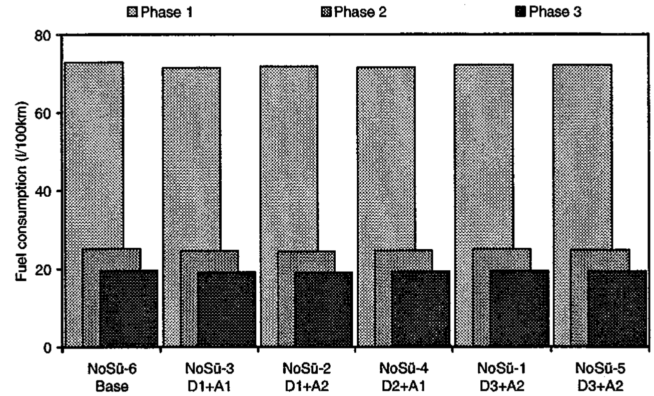

Figure 6: Cold start fuel consumption

At an average of 72 l/100km, for all the trucks, the fuel consumption during the urban phase is approximately three times that during the suburban phase and 3.7 times that on the motorway phase. The combined cycle average figure of 28.1 l/100km is closer to the consumption achieved in use than any of the individual phase results. The fuel consumption achieved in use is discussed in a later section.

HOT START EMISSIONS TEST RESULTS

After the cold start test each truck was re-tested in a warmed-up state. It is these hot start tests that comply with the EU Directive 1999/96/EC. As for the cold start tests the results were determined in g/km for each of the three phases of the test procedure. The PM emissions results are plotted in Figure 7 below.

The trends shown in Figure 7 are very similar to those shown in Figure 3. The levels of PM emissions are however noticeably lower for the hot start tests. The difference between the different stages is also reduced for the base truck, again due to the influence of condensed hydrocarbons.

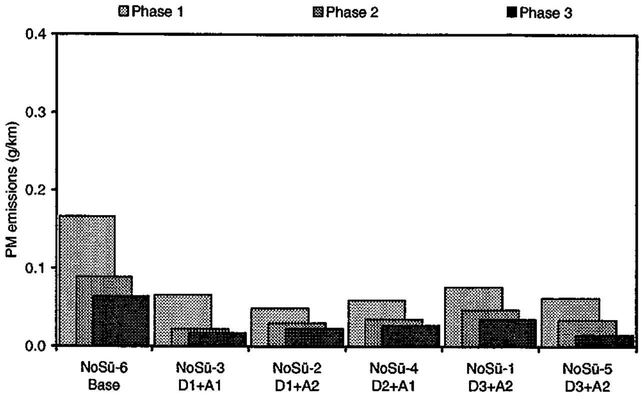

Figure 7: Hot start PM emissions

During phase 1 of the cold start tests, DPF type D3 exhibited poor filtration efficiency, particularly on truck NoSü-1. This was attributed to a peculiarity of this particular installation causing high levels of HC adsorption on the PM, and hence low measured HC emissions. This quirk is far less apparent on the hot start tests. Table 3 below shows the filtration efficiency for the different DPF types for the different stages of the hot and the cold start tests.

Table 3. Filtration efficiencies

	DPF type		
	D1	D2	D3
Phase 1 cold	72% - 79%	83%	30% - 57%
Phase 2 cold	50% - 66%	56%	29% - 49%
Phase 3 cold	53% - 62%	51%	38% - 71%
Combined cold	58%- 69%	64%	31% - 57%
Phase 1 hot	60% - 70%	64%	54% -63%
Phase 2 hot	66% - 75%	61%	47% - 61%
Phase 3 hot	64% - 73%	58%	45% - 77%
Combined hot	67% - 71%	61%	48% - 68%

As would be expected the fuel consumption is lower on the hot start test than on the cold start test, there is however still a very marked difference between the urban phase (phase 1) and the other two phases. The fuel consumption results from the hot start tests are shown below in Figure 8. Also included on this chart is the band of fuel consumption measurements taken from the trucks in service.

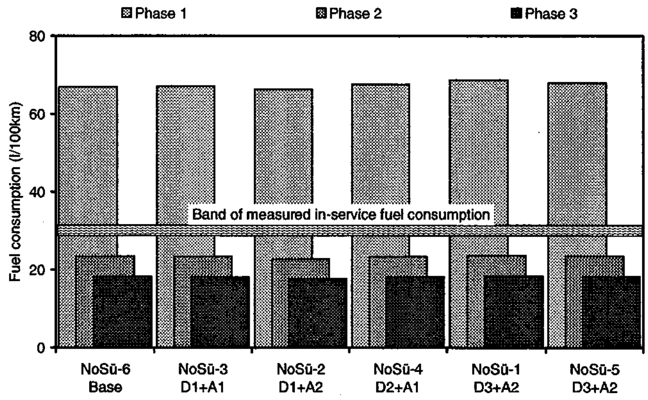

Figure 8: Hot start fuel consumption

Again there is statistically no significant difference between the results with and without a DPF. The in-service fuel consumption again is more closely represented by the combined cycle results than by the result of any individual phase. However, as the hot start results are lower than the cold start results, it is the cold start results rather than the regulated procedure results that most closely match the in-service fuel consumption.

IN-SERVICE OPERATION

The five trucks fitted with DPFs were also fitted with data loggers. The logging interval was set at 30 seconds and the loggers were powered up all the time. Thus the recorded data not only showed the temperatures and pressures whilst the trucks were operating, the data also provided information on cool down rates. This is quite clearly visible in Figure 9, which shows data from a typical day's operation. This data is in fact taken from truck NoSü-1 on 16th May 2001.

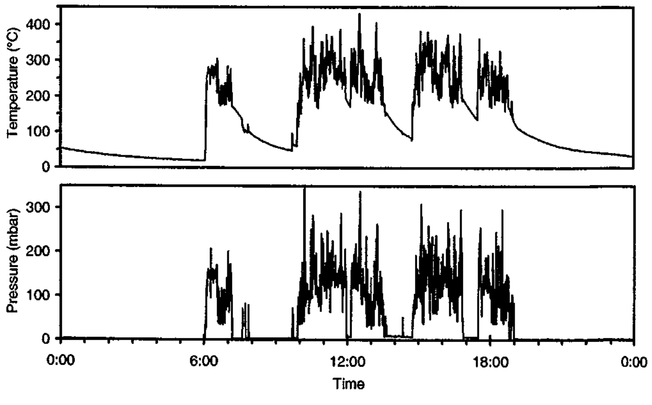

Figure 9: Typical pre-DPF temperature & pressure

From this Figure the rate of overnight cool-down is clearly visible. It is also clear from the chart that relatively high temperatures are regularly achieved.

Figure 10 shows the logger data from a more arduous day's work. In this particular case the data is for truck NoSü-2 on 18th April 2001. Again it is clear that relatively high temperatures are achieved.

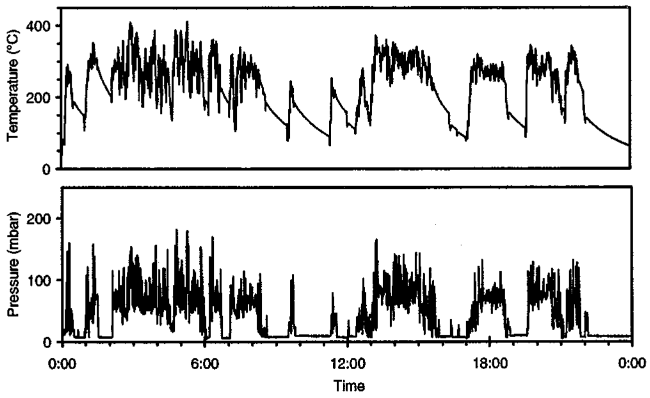

Figure 10: Pre-DPF temperatures & pressures

Figure 11 shows the proportion of data logs within certain temperature bands for a representative period of time. More precisely the data is for truck NoSü-4 for the period from 30th April to 1st June 2001. This effectively indicates the proportion of operating time spent in these temperature bands. From this chart it can be seen that the truck spent almost 5% of its time above 400°C. This time is also quite evenly distributed over the period. In fact there was only one working day during the period when the temperature did not exceed 400°C.

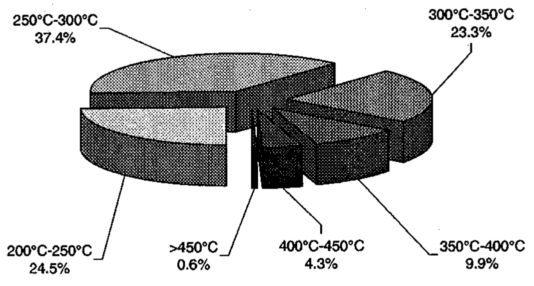

Figure 11: Proportion of data logs in a temperature range

Due to the presence of the fuel borne catalyst and the frequent temperature excursions above 400°C, regeneration of the DPF was not expected to be a problem. This did indeed prove to be the case and whilst it is not claimed that the DPF was regenerating continuously it was regenerating frequently and hence at low soot loadings. As a result of this, any exotherm produced during the regeneration was small and very difficult to detect. One instance when an exotherm could be detected is shown in Figure 12. This chart shows data from truck NoSü-3 on 28th May 2001.

The regeneration occurs under the classic conditions. The inlet gas temperature is over 400°C, the outlet gas temperature has reached this temperature indicating that the temperature of the DPF itself is in that region. The inlet temperature and pressure suddenly drop indicating a reduction in power demand, reduction in fuelling and hence increase in oxygen concentration in the exhaust.

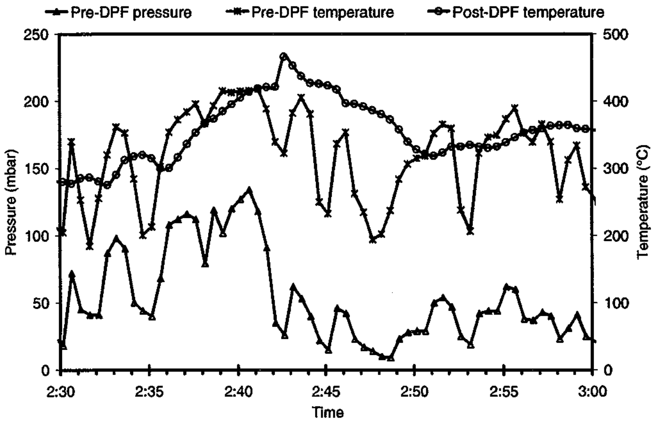

Figure 12: Regeneration event

As the inlet temperature begins to fall the outlet temperature initially remains approximately constant due to the thermal mass of the DPF, which in this case is sintered metal. After a minute (two data logs) the outlet temperature rises as the inlet temperature continues to fall. The exotherm however is limited to 45°C.

Although there is no significant variation in exhaust back pressure over time as a result of soot accumulation, ash accumulation still remains a potential source of back pressure increase. Figure 13 illustrates the daily peak exhaust back pressure. The daily peak back pressure is obviously dependent on the trucks' operating duty for that day. As the trucks will operate at close to their maximum rating at some point during most working days, this is considered a reasonable indication of the trends.

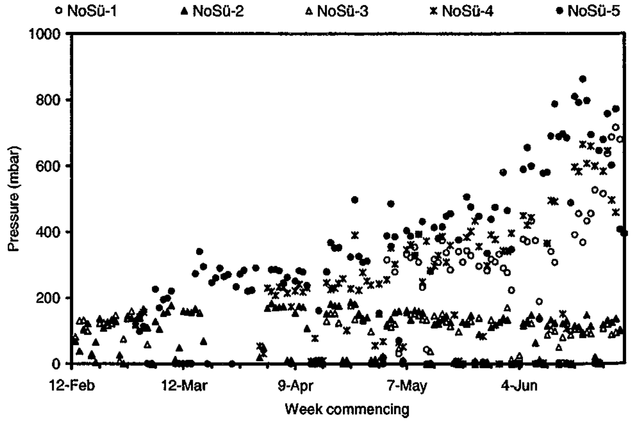

Figure 13: Peak exhaust back pressure trends

From the above Figure there is no clear trend for an increase in exhaust back pressure on trucks NoSü-2 and NoSü-3. The other three trucks do however exhibit a clear trend of increasing back pressure. From the data generated by the on-board loggers there is no clear differences in the operating histories of these trucks which could explain this and it is currently attributed to the differences in DPF technology.

Increased exhaust back pressure is of concern because there is a possibility that it can lead to increased fuel consumption, reduced lubricating oil life and increased engine wear.

Fuel consumption is not measured during vehicle operation, however the odometer reading and fuel additions are recorded each time the vehicle is refueled. As the fuel tank is not necessarily filled to the same level each time there is inevitably a high degree of variation in fuel consumption figures calculated on a per fill basis. If fuel consumption is calculated from total mileage and total fuel usage from a given point, then these variations will gradually become insignificant. This can clearly be seen from Figure 14 below.

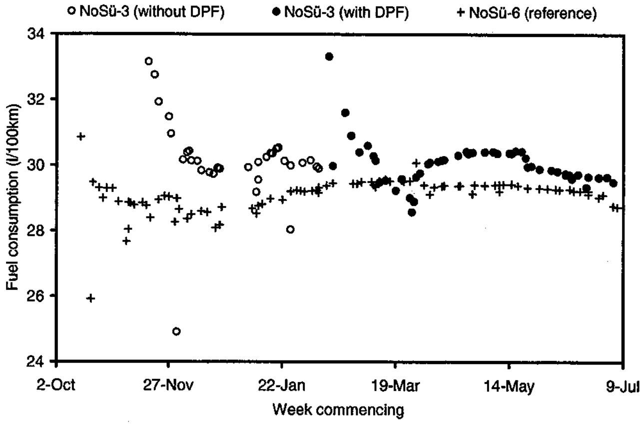

Figure 14: Fuel consumption for NoSü-3 and NoSü-6

This chart shows the fuel consumption for trucks NoSü-3 and NoSü-6, calculated in this manner. The fuel consumption data for truck NoSü-3 covers the period before and after the fitting of the DPF. Considering the data from truck NoSü-6, the reference truck, it is clear that there is some initial variation in the results but then this levels-out to give fuel consumption readings in the range of 29.0 to 29.6 l/100km with a final figure of 29.11 l/100km. This compares with a calculated fuel consumption of 28.5 l/100km for the combined cycle test result for a cold start test and 26.6 l/100km for the legislated hot start test.

Considering the measured fuel consumption for truck NoSü-3, again there is a large initial variation but this settles down to give a final value, before the DPF was fitted, of 29.91 l/100km. A new starting point is established when the DPF is fitted causing further large variation, but in this case they settle down to give a final value of 29.64 l/100 km. This is effectively the same fuel consumption as before the DPF was fitted. There is no clear trend for either of these trucks to show increased fuel consumption.

Figure 15 shows the fuel consumption data for all six trucks over the last 3 month period. Again there is no significant trend exhibited by any of the trucks.

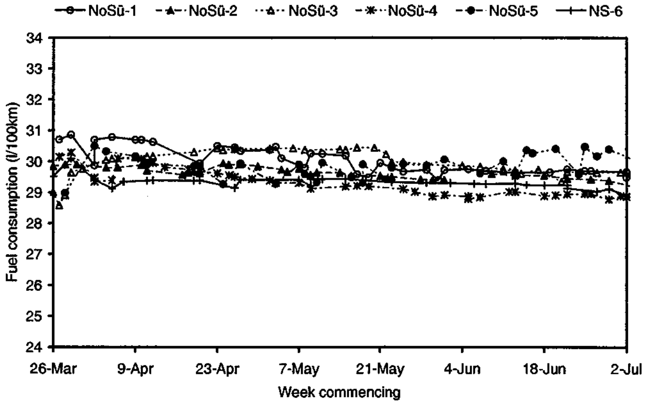

Figure 15: Fuel consumption for all six trucks

At the end of this period the truck with the highest fuel consumption is NoSü-5 which is also the truck with the highest peak exhaust back pressure. There is thus some indication that the expected relationship between back pressure and fuel consumption does exist. However the data to date suggests that the effect is not significant even for the high exhaust back pressure currently encountered.

Although it is not intended to conduct further full emissions at the end of the programme Smoke opacity tests, to the TÜV procedure, are conducted at intervals. Readings of 0.00 to 0.01 as compared with an unfiltered reading of 0.09 indicate that the DPF are still functioning in a satisfactory manner.

LUBRICANT AND FUEL ANALYSIS

LUBRICANT ANALYSIS

After fitting the DPFs fuel and lubricating oil samples were taken at intervals of approximately one month. The lubricating oil was analysed for viscosity, total base number (TBN), fuel dilution, water content, heptane insolubles and for various metals plus boron, silicon and phosphorus. The full results are given in Appendix 4. The factory fill oil was also analysed for comparison.

Figure 16 shows the TBN results.

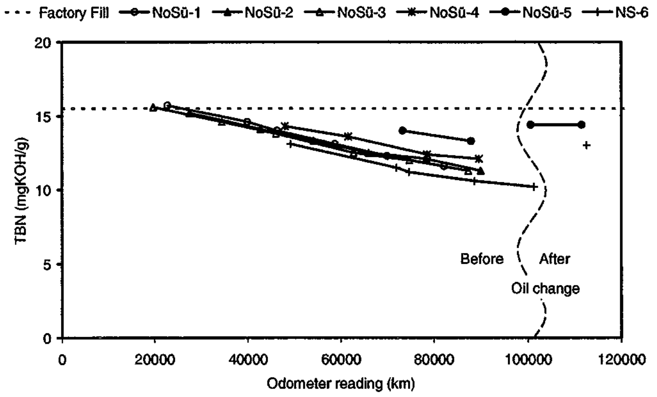

Figure 16: TBN characteristics with distance

A reduction in TBN, as a result of acidic blow-by gases interacting with the oil, would give an indication of high blow-by rates. As expected there was a fall in TBN over distance. However there were no significant differences in the TBN characteristics of any of the trucks. The step change in TBN level before and after the oil change is clearly visible. The amount of blow-by will also effect the amount of soot entering the oil. The heptane insolubles and the kinematic viscosity will both be effected by the amount of soot in the oil. These two parameters are shown as Figures 17 and 18 respectively.

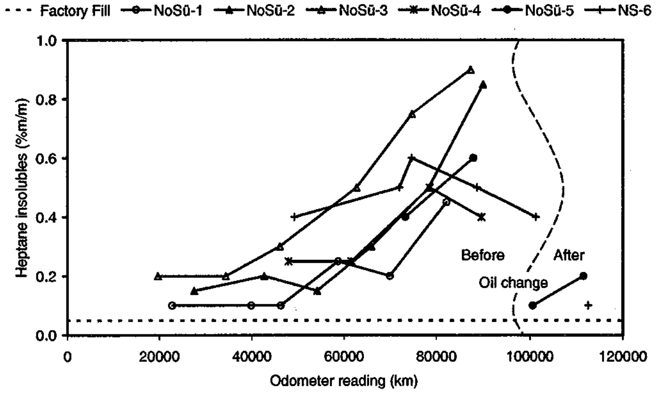

Figure 17: Heptane insolubles values with distance

The general trend is for the heptane insolubles to increase with accumulated distance. Some of the trucks show a rather erratic trend but this can probably be explained by oil top-up. For example truck NoSü-6, the reference truck had 3 litres of oil added between the samples at 74681 km and 88677 km and a further 3 litres added between 88677 km and 101313 km. As can be seen from the chart, the insolubles decrease at each successive sample. Similarly, 4 litres of oil was added to truck NoSü-4 between 78638 km and 89627 km samples. Taking this into consideration, it is not possible to identify any differences between the characteristics of any of the trucks. Truck NoSü-5 which exhibited the highest exhaust back pressure is certainly producing no higher levels of insolubles than might be expected. After the oil change on trucks NoSü-5 and NoSü-6 the level of insolubles returns to levels similar to that of the fresh oil. This is clearly visible in the chart.

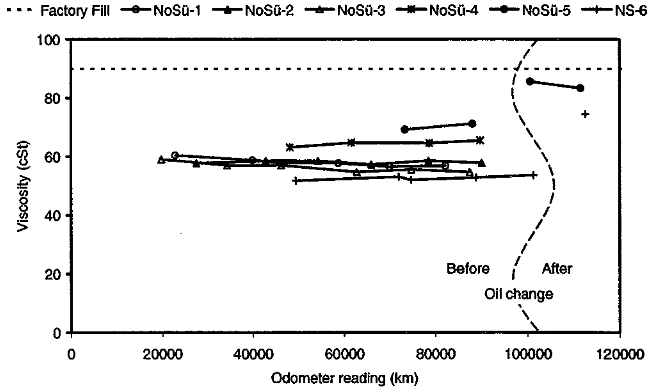

Figure 18: Kinematic viscosity with distance

Again there is no clear difference in the viscosity trends between the different trucks. Although trucks NoSü-4 and NoSü-5 show slightly different levels of viscosity these differences were prevalent when the DPFs were fitted.

Regarding the metals that were analysed for, some of the metals originate in the oil while others accumulate as a result of engine wear. The metals cadmium, vanadium and titanium were analysed for but were never detected and are not reported in Appendix 4.

Two other metals not detected in the fresh oil and normally associated with wear are manganese and tin. Both these elements were detected at one or two parts per million in the initial used oil samples but showed no tendency to increase with distance accumulated. After the first oil change these elements were not detected; it is therefore likely that they originated during the running-in period.

Elements commonly associated with wear in the combustion chamber area, i.e. cylinder liner, piston and rings, are iron, aluminium, chromium and silicon. These elements showed an increase in detected levels with accumulated distance. There was no clear difference in the rate of increase between trucks for the elements aluminium, chromium and silicon although there were differences in the absolute levels. The truck with the highest levels tended to be the reference truck NoSü-6. The levels of iron detected in the first sample of oil from the trucks fitted with DPFs were also lower than the trend for the reference truck. This "offset" could be due to differences in initial wear rates produced during the running-in period. The rate of increase in the iron content was however noticeably greater for the trucks fitted with DPFs.

Due to the fact that iron is being added to the fuel at the rate of 16 mg/kg or 20 mg/kg it would be expected that there would be some increase in the amount of iron in the lubricating oil. Figure 19 shows the level of iron in the oil samples. The rate of increase in iron content is clearly higher for all the trucks fitted with DPFs. However this additional iron is equivalent to between 1% and 1.5% of the iron added to the fuel.

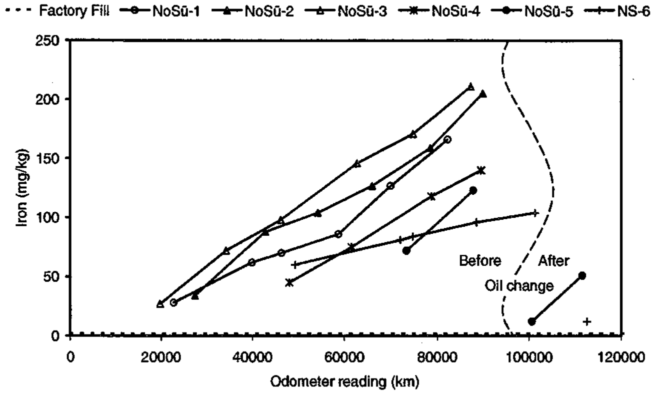

Figure 19: Iron content with distance

As there is not a corresponding difference in the rate of increase of the other elements that would be associated with iron from wear it is assumed the additional iron is in fact from the fuel additive.

The main element associated with bearing wear is lead. The levels of lead in the used oil are shown in Figure 20. This chart shows that the trucks fitted with DPFs have the expected increase in lead levels. The reference truck however has a higher level of lead, but no reason for this has been found. This will be monitored carefully over the coming months.

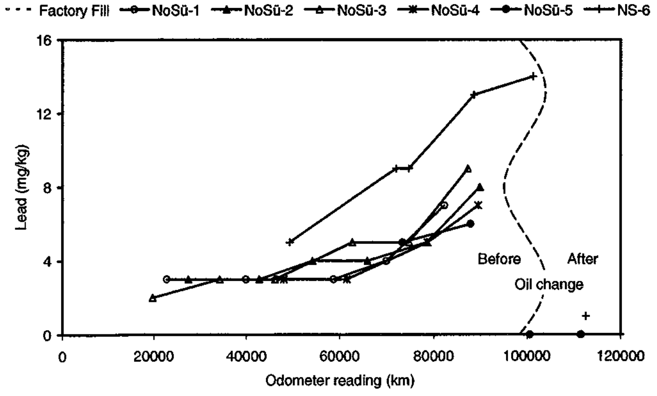

Figure 20: Lead content with distance

The overall assessment of the lubricant analyses is that neither fitting the DPF nor the use of the additive increases engine wear rates. The engines will be stripped and the wear characteristics will be fully assessed at the programme end.

FUEL ANALYSIS

A fuel sample was taken from each truck at the same time as the lubricating oil was sampled. These samples were analysed for iron content to confirm the intended additive treat rate. The results of the analyses are given below in Table 4.

Table 4. Fuel iron content

sample date	Truck number					
	NoSü-1	NoSü-2	NoSü-3	NoSü-4	NoSü-5	NoSü-6
Jan	31.9	22.4	11.4	-	-	0.6
Feb	1.6	14.6	6.4	-	-	1.8
Mar	0.2	2.5	11.3	15.1	18.6	0.1
Apr	29.0	19.2	14.8	8.5	13.0	0.1
May	14.4	19.6	7.0	11.5	13.9	0.1
Jun	2.1	17.5	7.7	10.9	14.1	0.2
Jul	13.0	13.4	7.1	10.2	7.6	-
Target	20.0	20.0	16.0	16.0	20.0	0.0

It is clear from Table 4 that either the treat rate varies widely or that the sampling technique is not rigorous enough to give meaningful data. As each truck is equipped with two tanks connected by a balance pipe and the additive is initially dosed only into the main tank it will obviously take time for a stable additive concentration to be reached. Which tank the sample is taken from and when, relative to the tank fill, it is taken will thus have a significant effect on the additive concentration.

The on-board additive dosing system records the number of injection pulses, the volume of additive delivered each pulse is also known. From this information volumetric treat rate can be determined. By measuring the density of the fuel samples an average fuel density can be determined (0.83 kg/l) in order to determine a gravimetric treat rate, the additive density already being known. The results of such a determination over a six month period are presented in Table 5.

Additive treat rate can also be determined by comparing total additions to both the additive tank and the fuel tank. This is also shown in Table 5. This result is subject to the accuracy of measuring the additive addition, as well as a small error on fuel additions. As there are no systematic differences between the results from the two methods and allowing for measurement tolerances, then from Table 5 there is confidence that a realistic additive treat rate is being maintained.

Table 5. Calculated iron treat rates (mg/kg) from pulse data (Pulse) and additive consumption data (Cons')

	Truck number					
	NoSü-1	NoSü-2	NoSü-3	NoSü-4	NoSü-5	NoSü-6
Pulse	25.2	23.8	16.9	16.0	18.2	-
Cons'	19.1	22.5	13.7	20.3	21.7	-
Target	20.0	20.0	16.0	16.0	20.0	0.0

CONCLUSION

A long distance trial was initiated to determine the reliability and durability of a DPF system using a fuel borne catalyst to ensure regeneration. A programme of data logging and sampling was put in place to highlight any potential side-effects of such a system.

At the time of writing all the trucks in the trial have covered in excess of 85000 km. The trial is continuing with the trucks covering an average of over 12000 km per month. The following points have been noted:

- The DPF units are a direct replacement for the existing silencer units and the other system components are easily mounted in the available space on the vehicle.
- Due to the vehicle duty cycle and the presence of the fuel borne catalyst the DPF's regenerate passively under every-day usage.
- The exhaust back-pressure increase due to ash accumulation within the DPF is minimised with the use of the sintered metal filter units.
- There is no measurable effect on fuel consumption due to increased back-pressure observed to this point in the trial.
- From regular lubricant analysis there does not appear to be any effect on engine wear rates as a result of using the DPF and additive.
- The DPF and additive system makes a significant reduction in PM emissions from this type of vehicle.

ACKNOWLEDGMENTS

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APPENDIX 1

Parameter	units	Value
Type		OM 501 LA
Emissions standard		Euro 2
Number of cylinders		V 6

Supercharging		Turbocharger
Intercooler		Air to air
Displacement	litres	11.946
Bore	mm	130
Stroke	mm	150
Compression ratio		17.25 : 1
Rated power	kW	260
Rated speed	rev/min	1800
Maximum torque	Nm	1730 - 1080
Injection pump		MB PLD

APPENDIX 2

	D1	D2	D3
Material	Sintered metal	Porous SiC	Porous SiC
Construction	plates	Honeycomb	Honeycomb
Cells/cm^2	NA	28	14
Wall thickness (mm)	0.9	0.4	0.8
Effective filter area (m^2)	12	15.9	11.2
Porosity (%)	49	42	45
Mean pore diameter (µm)	12	8.7	29
Thermal conductivity @ 25°C (W/mK)	14	73	11

APPENDIX 3

Test code	Truck code	Start type	Test distance km	Fuel cons' l/100km	PM g/km	HC g/km	NOx g/km	CO g/km	CO2 g/km
Phase 1:									
301010201	NoSü-6	Cold	3.79	72.89	0.323	0.670	18.053	2.749	1923.7
301010202	NoSü-6	Hot	3.84	66.99	0.166	0.940	13.843	2.338	1767.4
301021501	NoSü-2	Cold	3.74	71.83	0.089	0.367	15.756	2.989	1896.4
301021502	NoSü-2	Hot	3.76	66.33	0.049	0.414	13.277	2.808	1750.7
301021601	NoSü-3	Cold	3.79	71.48	0.067	0.328	14.137	3.343	1886.6
301021602	NoSü-3	Hot	3.81	67.16	0.066	0.418	11.867	2.869	1772.8
301030101	NoSü-1	Cold	3.82	72.24	0.227	0.151	15.836	4.025	1906.1
301030102	NoSü-1	Hot	3.79	68.69	0.076	0.670	13.052	3.473	1811.4
301030201	NoSü-4	Cold	3.77	71.57	0.055	0.362	14.625	4.632	1886.8
301030202	NoSü-4	Hot	3.79	67.58	0.059	0.669	11.984	4.098	1781.0
301030501	NoSü-5	Cold	3.79	72.20	0.140	0.322	15.797	2.751	1906.5
301030502	NoSü-5	Hot	3.80	67.92	0.062	0.600	13.115	2.473	1792.8
Phase 2:									
301010201	NoSü-6	Cold	11.25	25.12	0.117	0.345	11.153	0.941	662.6
301010202	NoSü-6	Hot	11.21	23.46	0.089	0.381	9.920	0.827	618.8
301021501	NoSü-2	Cold	11.24	24.40	0.059	0.160	9.794	1.024	644.0
301021502	NoSü-2	Hot	11.27	22.73	0.030	0.185	9.061	0.955	599.8
301021601	NoSü-3	Cold	11.24	24.59	0.040	0.163	9.115	1.147	649.0
301021602	NoSü-3	Hot	11.24	23.36	0.022	0.194	8.597	0.982	616.5
301030101	NoSü-1	Cold	11.25	25.04	0.083	0.098	10.239	1.407	660.5
301030102	NoSü-1	Hot	11.25	23.70	0.047	0.305	9.166	1.194	624.7
301030201	NoSü-4	Cold	11.25	24.65	0.051	0.181	9.120	1.579	649.7
301030202	NoSü-4	Hot	11.23	23.40	0.035	0.288	8.581	1.419	616.6
301030501	NoSü-5	Cold	11.25	24.82	0.060	0.157	9.762	0.946	655.4
301030502	NoSü-5	Hot	11.24	23.56	0.034	0.272	9.255	0.848	621.6
Phase 3:									
301010201	NoSü-6	Cold	14.60	19.59	0.068	0.326	12.216	0.745	516.7
301010202	NoSü-6	Hot	14.62	18.29	0.064	0.346	11.221	0.643	482.3
301021501	NoSü-2	Cold	14.59	19.03	0.032	0.179	10.739	0.801	502.0
301021502	NoSü-2	Hot	14.63	17.69	0.023	0.184	10.268	0.748	466.7
301021601	NoSü-3	Cold	14.61	19.13	0.026	0.173	10.158	0.891	504.7
301021602	NoSü-3	Hot	14.61	18.18	0.017	0.190	9.543	0.776	479.6
301030101	NoSü-1	Cold	14.62	19.50	0.042	0.150	11.045	1.099	514.2
301030102	NoSü-1	Hot	14.61	18.46	0.035	0.300	10.103	0.921	486.3
301030201	NoSü-4	Cold	14.62	19.27	0.033	0.202	9.895	1.221	507.6
301030202	NoSü-4	Hot	14.61	18.23	0.027	0.298	9.587	1.112	479.9
301030501	NoSü-5	Cold	14.61	19.37	0.020	0.179	10.789	0.747	511.2
301030502	NoSü-5	Hot	14.63	18.35	0.015	0.269	10.442	0.659	484.1
Total:									
301010201	NoSü-6	Cold	29.64	28.50	0.119	0.377	12.559	1.075	751.9
301010202	NoSü-6	Hot	29.67	26.55	0.087	0.436	11.068	0.932	700.2
301021501	NoSü-2	Cold	29.57	27.75	0.050	0.196	11.014	1.163	732.3
301021502	NoSü-2	Hot	29.67	25.78	0.029	0.213	10.191	1.088	680.2
301021601	NoSü-3	Cold	29.64	27.89	0.037	0.189	10.271	1.302	736.0
301021602	NoSü-3	Hot	29.66	26.44	0.025	0.221	9.483	1.123	697.7
301030101	NoSü-1	Cold	29.69	28.39	0.082	0.130	11.356	1.593	748.8
301030102	NoSü-1	Hot	29.64	26.86	0.045	0.349	10.124	1.351	708.1
301030201	NoSü-4	Cold	29.64	27.97	0.043	0.215	10.203	1.791	737.2
301030202	NoSü-4	Hot	29.64	26.50	0.034	0.342	9.512	1.610	698.2
301030501	NoSü-5	Cold	29.65	28.18	0.051	0.189	11.039	1.078	744.1
301030502	NoSü-5	Hot	29.67	26.67	0.028	0.313	10.334	0.962	703.7

APPENDIX 4

Oil analysis for truck NoSü-1

Sample number		0-0101	1-0201	2-0301	3-0401	4-0501	5-0601	6-0701
Date		21-Dec	13-Feb	3-Mar	2-Apr	5-May	9-Jun	07-Jul
Odometer reading		22728	39875	46299	58686	69930	82212	92315
Test								
Kinematic Viscosity @ 40°C	cSt	60.4	58.8	57.7	57.7	56.6	56.8	
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	
Water content	% (v/v)	0.05	<0.05	<0.05	0.1	<0.05	<0.05	
Heptane insolubles	%(m/m)	0.1	0.1	0.1	0.25	0.2	0.45	
Total Base Number	mgKOH/g	15.7	14.6	14	13.1	12.3	11.6	
Elements								
Barium	mg/kg	<1	<1	<1	<1	<1	<1	
Nickel	mg/kg	3	3	3	4	4	4	
Manganese	mg/kg	1	1	2	2	2	2	
Iron	mg/kg	28	62	70	86	127	166	
Sodium	mg/kg	18	16	16	14	13	13	
Zinc	mg/kg	1430	1420	1410	1420	1430	1440	
Aluminium	mg/kg	13	14	16	17	19	19	
Calcium	mg/kg	4910	4840	4860	4790	4800	4720	
Copper	mg/kg	13	89	92	92	89	85	
Lead	mg/kg	3	3	3	3	4	7	
Chromium	mg/kg	2	3	3	4	5	5	
Magnesium	mg/kg	20	20	21	20	20	20	
Tin	mg/kg	2	1	2	2	2	2	
Silicon	mg/kg	7	8	8	8	9	9	
Phosphorus	mg/kg	1040	1040	1040	1070	1080	1090	
Molybdenum	mg/kg	<1	10	10	22	27	33	
Boron	mg/kg	<1	8	8	18	23	30	

Oil analysis for truck NoSü-2

Sample number		0-0101	1-0201	2-0301	3-0401	4-0501	5-0601	6-0701
Date		02-Jan	05-Feb	03-Mar	02-Apr	05-May	02-Jun	07-Jul
Odometer reading		27427	42720	54157	65937	78455	89964	102751
Test								
Kinematic Viscosity @ 40°C	cSt	57.7	58.5	58.5	57.3	58.6	57.8	
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	
Water content	% (v/v)	<0.05	0.05	0.05	0.2	0.1	0.15	
Heptane insolubles	%(m/m)	0.15	0.2	0.15	0.3	0.5	0.85	
Total Base Number	mgKOH/g	15.2	14.1	13.3	12.5	12.1	11.3	
Elements								
Barium	mg/kg	<1	1	1	1	<1	<1	
Nickel	mg/kg	4	4	4	4	4	4	
Manganese	mg/kg	1	2	2	2	2	2	
Iron	mg/kg	34	88	104	127	159	205	
Sodium	mg/kg	18	17	15	15	14	14	
Zinc	mg/kg	1420	1430	1470	1410	1460	1460	
Aluminium	mg/kg	17	22	23	26	26	29	
Calcium	mg/kg	4810	4750	4790	4820	4780	4870	
Copper	mg/kg	17	64	64	62	57	59	
Lead	mg/kg	3	3	4	4	5	8	
Chromium	mg/kg	2	3	3	4	5	5	
Magnesium	mg/kg	20	20	20	20	19	20	
Tin	mg/kg	1	2	2	2	2	2	
Vanadium	mg/kg	<1	<1	<1	<1	<1	<1	
Titanium	mg/kg	<1	<1	<1	<1	<1	<1	
Silicon	mg/kg	6	7	7	8	9	9	
Phosphorus	mg/kg	1020	1050	1080	1100	1130	1150	
Molybdenum	mg/kg	<1	13	23	27	39	39	
Boron	mg/kg	<1	10	19	24	34	33	

Oil analysis for truck NoSü-3

Sample number		0-0101	1-0201	2-0301	3-0401	4-0501	5-0601	6-0701
Date		03-Jan	05-Feb	03-Mar	02-Apr	05-May	02-Jun	07-Jul
Odometer reading		19714	34252	46099	62701	74748	87335	100325
Test								
Kinematic Viscosity @ 40°C	cSt	59.1	57	57	54.7	55.6	54.7	
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	
Water content	% (v/v)	<0.05	<0.05	0.05	0.1	<0.05	<0.05	
Heptane insolubles	%(m/m)	0.2	0.2	0.3	0.5	0.75	0.9	
Total Base Number	mgKOH/g	15.6	14.6	13.8	12.5	12	11.3	
Elements								
Barium	mg/kg	<1	<1	<1	<1	<1	<1	
Nickel	mg/kg	5	6	6	7	6	7	
Manganese	mg/kg	1	1	2	2	2	2	
Iron	mg/kg	27	72	98	146	171	211	
Sodium	mg/kg	20	20	17	17	16	16	
Zinc	mg/kg	1410	1390	1410	1380	1420	1410	
Aluminium	mg/kg	10	14	16	22	23	24	
Calcium	mg/kg	4840	4820	4820	4840	4840	4860	
Copper	mg/kg	13	38	52	51	48	51	
Lead	mg/kg	2	3	3	5	5	9	
Chromium	mg/kg	1	3	4	5	6	7	
Magnesium	mg/kg	20	20	20	20	20	20	
Tin	mg/kg	1	2	2	2	2	2	
Vanadium	mg/kg	<1	<1	<1	<1	<1	<1	
Titanium	mg/kg	<1	<1	<1	<1	<1	<1	
Silicon	mg/kg	8	9	9	11	11	12	
Phosphorus	mg/kg	1030	1020	1050	1050	1090	1090	
Molybdenum	mg/kg	1	<1	13	12	26	26	
Boron	mg/kg	<1	<1	10	9	21	21	

Oil analysis for truck NoSü-4

Sample number		0-0301	1-0401	2-0501	3-0601	4-0701
Date		03-Mar	02-Apr	05-May	02-Jun	07-Jul
Odometer reading		47963	61554	78638	89627	104372
Test						
Kinematic Viscosity @ 40°C	cSt	63.1	64.7	64.6	65.5	
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	
Water content	% (v/v)	<0.05	0.1	0.15	0.2	
Heptane insolubles	%(m/m)	0.25	0.25	0.5	0.4	
Total Base Number	mgKOH/g	14.3	13.6	12.4	12.1	
Elements						
Barium	mg/kg	<1	<1	<1	<1	
Nickel	mg/kg	6	6	6	6	
Manganese	mg/kg	1	2	2	2	
Iron	mg/kg	45	75	118	140	
Sodium	mg/kg	17	15	15	14	
Zinc	mg/kg	1440	1470	1490	1510	
Aluminium	mg/kg	16	19	25	25	
Calcium	mg/kg	4930	4960	5010	5050	
Copper	mg/kg	36	39	41	40	
Lead	mg/kg	3	3	5	7	
Chromium	mg/kg	2	3	4	4	
Magnesium	mg/kg	23	23	23	23	
Tin	mg/kg	1	1	2	2	
Vanadium	mg/kg	<1	<1	<1	<1	
Titanium	mg/kg	<1	<1	<1	<1	
Silicon	mg/kg	7	8	9	10	
Phosphorus	mg/kg	1090	1130	1160	1190	
Molybdenum	mg/kg	14	31	37	45	
Boron	mg/kg	17	31	36	42	

Oil analysis for truck NoSü-5

Sample number		0-0301	1-0401	2-0501	3-0601	4-0701
Date		03-Mar	02-Apr	05-May	02-Jun	07-Jul
Odometer reading		73325	87921	100626	111592	127242
Test						
Kinematic Viscosity @ 40°C	cSt	69.2	71.2	85.6	83.3	
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	
Water content	% (v/v)	0.05	0.05	0.1	0.1	
Heptane insolubles	%(m/m)	0.4	0.6	0.1	0.2	
Total Base Number	mgKOH/g	14	13.3	14.4	14.4	
Elements						
Barium	mg/kg	<1	<1	<1	<1	
Nickel	mg/kg	3	4	<1	<1	
Manganese	mg/kg	2	2	<1	<1	
Iron	mg/kg	72	123	12	51	
Sodium	mg/kg	19	18	9	9	
Zinc	mg/kg	1520	1520	1660	1640	
Aluminium	mg/kg	29	31	3	5	
Calcium	mg/kg	5250	5400	4720	4840	
Copper	mg/kg	64	62	2	4	
Lead	mg/kg	5	6	<1	<1	
Chromium	mg/kg	5	6	<1	1	
Magnesium	mg/kg	27	27	24	26	
Tin	mg/kg	2	3	<1	<1	
Vanadium	mg/kg	<1	<1	<1	<1	
Titanium	mg/kg	<1	<1	<1	<1	
Silicon	mg/kg	11	11	6	5	
Phosphorus	mg/kg	1180	1240	1320	1330	
Molybdenum	mg/kg	26	38	106	109	
Boron	mg/kg	21	31	127	117	

Oil analysis for truck NoSü-6

Sample number		0-0101	1-0201	2-0301	3-0401	4-0501	5-0601
Date		06-Jan	23-Feb	03-Mar	02-Apr	05-May	02-Jun
Odometer reading		49218	72003	74681	88677	101313	112625
Test							
Kinematic Viscosity @ 40°C	cSt	51.7	53.1	52	52.8	53.7	74.4
Fuel dilution	% (v/v)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Water content	% (v/v)	0.05	0.1	0.05	<0.05	<0.05	<0.05
Heptane insolubles	%(m/m)	0.4	0.5	0.6	0.5	0.4	0.1
Total Base Number	mgKOH/g	13.1	11.5	11.2	10.6	10.2	13
Elements							
Barium	mg/kg	<1	<1	<1	<1	17	1
Nickel	mg/kg	2	2	2	4	4	<1
Manganese	mg/kg	2	2	2	2	2	<1
Iron	mg/kg	60	81	84	96	104	12
Sodium	mg/kg	21	18	18	17	16	4
Zinc	mg/kg	1310	1360	1370	1400	1400	1590
Aluminium	mg/kg	22	28	24	30	30	5
Calcium	mg/kg	4600	4580	4530	4540	4570	4570
Copper	mg/kg	45	52	52	50	48	4
Lead	mg/kg	5	9	9	13	14	1
Chromium	mg/kg	4	6	6	6	7	<1
Magnesium	mg/kg	28	29	28	28	27	19
Tin	mg/kg	2	2	2	2	2	<1
Vanadium	mg/kg	<1	<1	<1	<1	<1	<1
Titanium	mg/kg	<1	<1	<1	<1	<1	<1
Silicon	mg/kg	9	10	10	11	11	4
Phosphorus	mg/kg	981	1030	1010	1040	1070	1300
Molybdenum	mg/kg	1	18	18	27	34	121
Boron	mg/kg	<1	17	17	25	32	110