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ABSTRACT

Diesel particulate filters (DPF), in conjunction with fuel borne catalysts (FBC) to facilitate regeneration, are now an accepted technology for passenger car application. Retrofitting of such systems has demonstrated the possibility of applying this technology to heavy-duty vehicles. To demonstrate the efficacy of DPF/FBC systems and to assess their affect on engine durability and economy, five heavy-duty trucks were fitted with DPF/FBC systems. After the completion of over ¼ million kms four trucks underwent a full engine strip-down and rating.

This paper briefly reviews the installation of the systems and their effect on the regulated emissions, present details of the mileage accumulation and of the engine strip-downs. The conclusions drawn are that after a ¼ million km of use with the DPF/FBC systems the trucks had not suffered any abnormal deterioration and in fact there was some indication of reduced wear on the engine.

INTRODUCTION

Impending legislation will make it inevitable that heavy-duty trucks will have to be fitted with a particulate removal after-treatment device. The challenge is to provide a system that is not only environmentally effective but also durable enough to meet the demands of the trucking industry. The system must also of necessity have the minimum effect on the operation of the vehicle. Engine manufacturers are thus striving to integrate aftertreatment systems into their new engine designs. However specific legislation already exists that dictates that the current vehicle fleet for certain applications, must have particulate reduction aftertreatment. Examples of this are legislation in Japan mandating the fitting of diesel particulate reduction devises to on-road diesel engined heavy-duty vehicles that operate in certain metropolitan areas (1). For some classes of vehicle a diesel oxidation catalyst (DOC) will allow the engine to meet the requirements, but in other cases a diesel particulate filter (DPF) is required. In Europe and the USA certain off-road applications also require diesel engined vehicles to be fitted with DPFs (2,3). It is also usually necessary to demonstrate that the DPF not only reduces the particulate matter (PM) emissions by the required amount but also that it does not increase the emissions of other potentially harmful products such as dioxins (4) or nitrogen dioxide (5).

DPFs in conjunction with fuel borne catalysts (FBC) to facilitate regeneration, are now accepted technologies for passenger car application (6,7). For a number of years DPFs with an iron based FBC for regeneration have also been offered as a factory fitted option for off-road application (8). Retrofitting of such systems to older technology on-road vehicles, where fiscal incentives exist, has demonstrated the possibility of applying this technology to the heavy-duty vehicle sector.

To demonstrate the efficacy of the DPF/FBC system and to assess its affect on engine durability and fuel economy, five heavy-duty trucks were fitted with DPF/FBC systems. Different DPF technologies were used along with two different FBC technologies. Regular sampling of the lubricating oil was used to check for adverse effects on engine durability whilst on board data logging of DPF temperatures and pressures was used to monitor the performance of the DPFs. After the completion of a ¼ million kms of operation four of the trucks were removed from service and underwent a full engine strip-down and rating. The results of this programme are discussed below.

TEST VEHICLES AND FILTERS

The trucks used in this programme 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 details of the vehicles and engines can be found in reference (9). The trucks have been designated as NoSü-1 through NoSü-6.

Two of the trucks were fitted with DPFs supplied by PUREM Abgassysteme GmbH & Co. KG. This DPF type is referred to as D1 throughout the rest of the paper. A schematic of this DPF layout is shown in Figure 1.

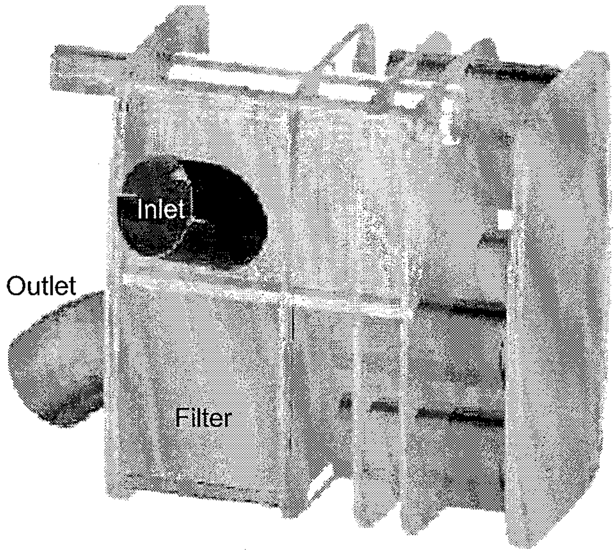

Figure 1

A further three trucks were fitted with DPFs constructed by Engine Control Systems (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. After approximately 80,000 km of use the honeycomb DPFs were removed for servicing, the D2 filter was refitted but the two D3 type DPFs were replace with alternative units. One of the D3 DPFs was replaced with a Corning RC DPF that had been canned by ArvinMeritor, this unit is referred to as D4. The other D3 unit was replaced by a lightweight sintered metal DPF from PUREM, this is referred to as D5.

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. Each of the designs was tested to ensure compliance with noise limits.

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 F1; 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 F2, 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	FBC type
NoSü-1	D3 / D2	F2
NoSü-2	D1	F2
NoSü-3	D1	F1
NoSü-4	D2 / D5	F1
NoSü-5	D3 / D4	F2
NoSü-6	None	None

EMISSIONS TEST RESULTS

The trucks used in 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 (in km) at the start of the emissions test programme are given in Table 2.

Table 2: Odometer readings for initial emissions testing

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 this programme of work here each vehicle was tested twice. The first test was performed on the vehicle that 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. Data is given in Appendix 1 and a full discussion of the results of these emissions tests can be found in reference (9).

Towards the end of the programme five of the trucks were again emissions tested. The testing was performed to the same procedure at the same laboratory, i.e. a cold start and a hot start. The full results are given in Appendix 2. The odometer readings at the start of these emissions tests along with the distance (km) covered since the start of the initial set of emissions tests, is shown in table 3.

Table 3: Odometer readings for final emissions testing

Truck	NoSü-1	NoSü-2	NoSü-3	NoSü-4	NoSü-6
Odo'	284640	283638	294805	308788	330888
Dist'	239298	237170	255364	261675	282066

Truck NoSü-5 was not retested as the honeycomb DPF had been removed for service. The DPF type D5 fitted to truck NoSü-4 had been fitted part way through the trial and had not been emissions tested around the time of fitting, no valid comparisons can thus be made with the start of programme performance. The results from this truck were however comparable with those from the two trucks fitted with the D1 type DPFs.

The type D2 DPF that was fitted to truck NoSü-4 at the start of the programme was fitted to truck NoSü-1 at the end of the programme. In the discussion of DPF emissions performance in the earlier paper (9) it was assumed that the emissions from the reference truck (NoSü-6) could be considered as representative of all the trucks. On this basis it is also considered valid to compare the performance of truck NoSü-4 fitted with the D2 DPF at the start of the programme with the performance of truck NoSü-1 fitted with the D2 DPF at the end of the programme.

Considering the results of the cold start emissions tests, from the start to the end of the programme all of the trucks produced an increase in the carbon monoxide (CO) and hydrocarbon (HC) emissions with the exception of the reference truck which showed a slight decrease in the HC emissions. All of the trucks showed a decrease in the total oxides of nitrogen (NO_X) emissions of between 3% and 6%, with the exception of truck NoSü-3 which produced a 3% increase.

The reference truck (NoSü-6) produced a 26% increase in the PM emissions whilst the trucks with the DPFs fitted showed a difference in PM emissions over the programme ranging from a decrease of 8% on truck NoSü-3 to a 23% increase on truck NoSü-1. Using the reference truck as the baseline, the PM reduction as a result of having the DPF fitted was therefore greater, on each of the three trucks considered, at the end of the programme when compare to the start of the programme. This is shown graphically in Figure 2.

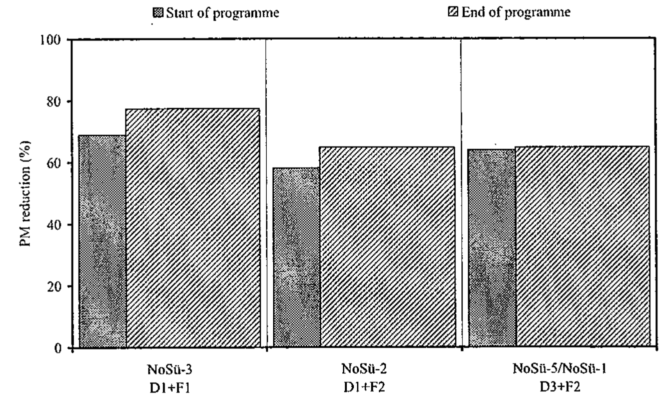

Figure 2 Cold start test PM reduction with DPF

For the hot start testing all of the trucks again showed an increase in the CO emissions from the start of the programme to the end of the programme. The effect of the distance accumulation on the hot start HC emissions varied from an increase of 50% for the D1 DPF on truck NoSü-3 to a reduction of 41% for the D3 DPF. All of the trucks produced an increase in NO_X emissions of between 4% and 7% over the distance with the exception of the D3 DPF that started the programme on truck NoSü-5 and finished on truck NoSü-1 that produced a 6% reduction.

The PM emissions showed an increase over the accumulated distance, again with the exception of the D3 DPF. Again if the reference truck is considered as representative then the reduction due to the DPF is a shown in Figure 3. For the hot start there is a slight reduction in the apparent benefit of having the D1 DPF present on truck NoSü-3 when compared to the start of the programme.

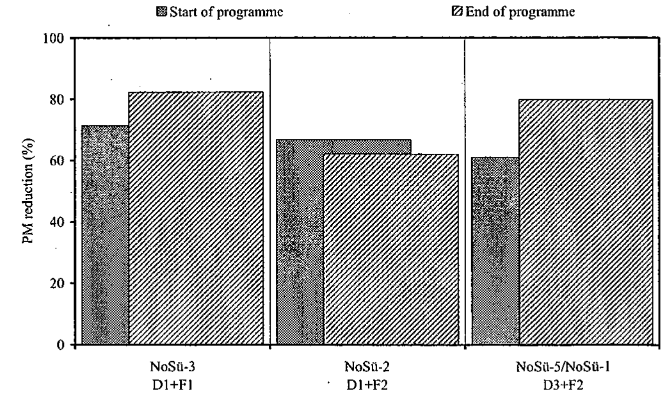

Figure 3 Hot start test PM reduction with DPF

However none of the trucks were fitted with systems containing a precious metal catalyst to reduce the HC emissions. The amount of volatile material present in the measure PM would therefore be quite high and would be influenced by the amount of volatile material adsorbed, desorbed or condensed within the exhaust system. This in turn will be influenced by the temperature profile of the exhaust gas during the testing cycle and the characteristics of the system itself, such as the thermal capacity of the DPF, the amount of soot or ash present in the system etc. This behaviour may account for the fact that the apparent filtration efficiency of the D1 DPF on truck NoSü-3 has increased when measure form a cold start but has reduced when measured from a hot start. If the cold start and the hot start results are combined then all of the trucks show increased levels of PM reduction in comparison to the reference truck.

This was not a rigorous series of experiments to determine the filtration efficiency of these devices, either when new or aged. The emissions testing was conducted in order to determine that the DPFs as fitted were functioning as intended and that they remained as such at the end of the programme. On this bases it was concluded that the DPF/FBC systems were effective at the start of the programme and that although there was an expected change in the emissions characteristics of the trucks after a ¼ million km, the DPF/FBC system continued to provide a comparable level of performance.

IN-SERVICE OPERATION

The trucks fitted with the DPFs were also fitted with data logging equipment connected to pressure transducer and thermocouples. This equipment was used to monitor the performance of the DPF in terms of pressure drop across the DPF and the temperatures before and after the filter. The data loggers were powered-up continuously, thus recording data whether the truck was operating or not. The data logging interval was set at 30 seconds. Whilst this obviously gave lower resolution to the acquired data it did allow the trucks to operate for about two months before down-loading the data loggers.

FUEL CONSUMPTION

Fuel consumption was measured by carbon balance during the emissions testing. This showed that the fuel consumption of the reference truck had improved by 0.8% on the cold start test and 3.7% on the hot start test. The change in fuel consumption on the trucks fitted with the DPF systems varied from an improvement of 3.7% to a deterioration of 1.0% for the cold start test and from an improvement of 7.6% to a deterioration of 0.6% for the hot start test. From the fuel consumption record kept by the operator the reference truck showed an average improvement of 4.3 % over the period of the trial. The truck that showed the largest improvement in fuel consumption according to the emissions testing also showed the largest improvement according to the fuel records. This was truck NoSü-2 and according to the fuel logs the fuel consumption improved by an average of 10.3% over the course of the trial. The only truck to show a deterioration in fuel consumption from the emissions testing showed a small improvement from the fuel log data. This was truck NoSü-1 and this was the truck that had experienced the highest average exhaust back pressure values. None of these differences are considered to be statistically significant.

TEMPERATURE PROFILES

Due to the fact that the data loggers were recording data continuously, information was obtained regarding cool down rates for the DPFs. It would also have provided invaluable information regarding peak temperatures should a regeneration have been initiated shortly before switching off the engine, however no such occurrences were observed. By eliminating the data when the engine was switched off it was possible to determine the temperatures at the entry to the DPF during the operating cycle of the vehicle. This is an important parameter for determining whether soot will be burned or accumulated within the DPF and whether regeneration of any accumulated soot will be initiated. Due to the presence of the FBC the rate of regeneration is usually such that the rate of heat released is sufficient to ensure that the regeneration is self-sustaining. The pre-DPF temperature profiles for the five trucks are presented in Figure 4.

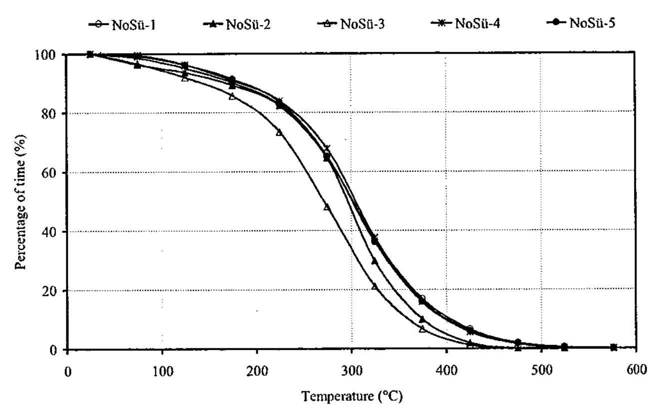

Figure 4 Pre-DPF temperature profiles

The profile for truck NoSü-3 is noticeably different to that of the other trucks. This is considered to be due to a difference in the positioning of the thermocouple rather than a difference in the operating characteristics of the truck. However it does indicate the importance of careful positioning of such devices. With the exception of truck NoSü-3, all of the trucks spend about 50% of the time with a pre-DPF temperature of below 300°C. At such temperatures it is highly likely that soot will accumulate in the DPF. However the trucks typically spent 10% of the time with a pre-DPF temperature of over 400°C and the average time between incidences of such high temperature was typically less than 3 hours.

REGENERATION PERFORMANCE

The operating temperature characteristics discussed above indicated that this application was ideally suited to an FBC aided DPF system. It was expected that soot would accumulate during the lower temperature operating periods, but that the excursions to the higher temperatures would initiate a regeneration leading to a complete burnout of the trapped soot. It was thus expected that the DPF would regenerate reliably during normal operation. This was in fact found to be the case.

With some DPF/FBC systems it has been observed that large quantities of soot accumulate before regeneration occurs (10). When such a large quantity of soot is burned with the inclusion of an FBC a clear exotherm can be observed making it easy to identify the regeneration events. In this application such exotherms were not common. It was clear from the rate of increase of exhaust back pressure that the filter was not becoming clogged with soot and by performing free-acceleration smoke tests at intervals during the distance accumulation it was possible to verify the integrity of the DPF. The combination of the above observations suggested that the DPF was indeed regenerating frequently and with lower soot loadings.

Despite the absence of frequent large exotherms it was still possible by careful processing of the data, to identify regeneration events. The temperature and pressure data for one such event is demonstrated in Figure 5. This data is from truck NoSü-4 on the 26th June 2001.

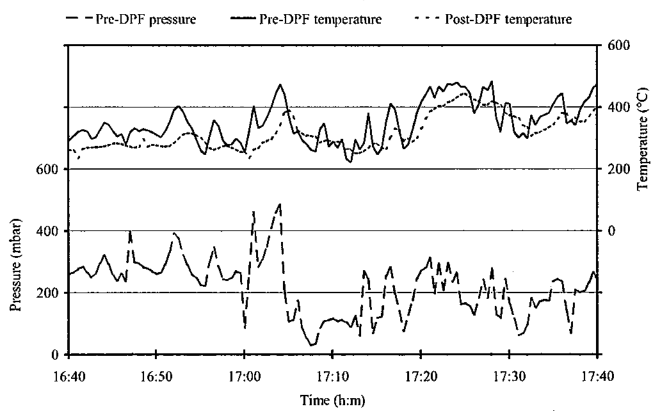

Figure 5 Regeneration event on truck NoSü-4

From the data presented in Figure 5 it is clear that there was no large exothermic event during this time period, however there is a noticeable shift in the pre-DPF pressure characteristics at about 17:05. This also corresponds to a period when the pre-DPF temperature exceeded 400°C for a period of about between 2 and 3 minutes with a peak temperature of 473°C. Although this event is followed by a further period where the temperature exceeds 400°C, after only a short period of time, it was 142 operating minutes since the last occurrence of a pre-DPF temperature of greater than 400°C for more than a minute.

Occasionally atypical operating patterns would occur resulting in larger accumulations of soot and correspondingly larger exotherms. One example is shown in Figure 6. This figure shows data from truck NoSü-3 on 9th September 2001.

Again there is a shift in the exhaust back pressure characteristic, although in this case it is less well defined. This corresponds to the pre-DPF temperature reaching a peak of 403°C, although it was noted in the previous section that the pre-DPF temperature on this truck appeared lower than on the other truck and this was probably due to the positioning of the thermocouple. Allowing for this the peak temperature was about 430°C to 440°C and it was about 8 operating hours since similar pre-DPF temperatures were achieved. The quantity of soot accumulated in the DPF prior to this regeneration event would therefore greater than for other events.

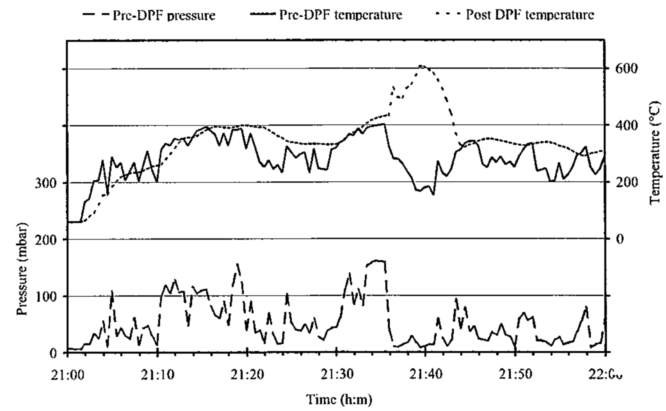

Figure 6 Regeneration event on truck NoSü-3

LUBRICATING OIL MONITORING

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.

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.

To determine the possible origin of some of the metal detected, various components were subject to X-ray analysis. The pistons were composed mainly of aluminium with some silicon and traces of nickel, copper and iron.

Aluminium worn from the piston skirt through contact with the cylinder wall would probably be the major source of aluminium in the lubricating oil, although aluminium was also found in the crankshaft thrust bearings. The other element that would derive from wear in the combustion chamber area is chromium from the piston rings.

During the life of the first oil fill there was no clear difference between trucks, in the rate of increase for the concentration of aluminium, although there were differences in the absolute levels. The truck with the highest level tended to be the reference truck °C6. During the second oil fill there was again no difference in rate of change of aluminium concentration and the absolute levels were closer. It is interesting to note that during this second oil fill the truck with the highest level of aluminium in the oil was truck NoSü-1 which was the truck with the lowest levels during the first oil fill. During the third oil fill there was again no significant difference between the trucks with the exception of the last two samples from truck NoSü-1 which were noticeably higher than the trend. The levels of aluminium detected in these two samples were approximately twice that observed for the other trucks. The evolution of the aluminium concentration in the oil is shown in Figure 7.

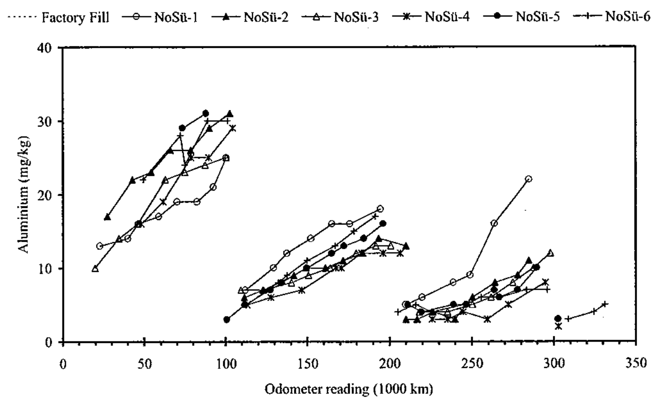

Figure 7 Aluminium concentration in the lubricating oil

The results of the analysis for chromium and silicon however did not show a similar pattern. The chromium levels increased gradually during the lifetime of each oil fill. The rate of increase diminished with each successive oil fill. There were no significant differences between the trucks. The same was true for the concentration of silicon.

X-ray analysis of the crankshaft bearings from this engine showed them to be composed of lead, tin and copper. Lead and copper were both detected in the oil samples but as noted earlier no tin was detected after the first oil change. During the lifetime of the first oil fill, the oil from the reference truck contained a higher level of lead than the oil samples from any of the trucks fitted with DPFs. Although this was a consistent trend it is probably within test repeatability. During the lifetime of the second oil fill there is no difference between the trucks, all result being within test repeatability and at an acceptable level. During the third oil fill the levels of lead were generally close to the detection limit. However towards the end of this period four of the trucks did show above trend levels of lead. The levels detected were not however considered abnormal. The engine strip-downs discussed in a later section of this report did not show any increased wear in the bearings of any of these trucks. The concentration of copper in the oil rose to high levels very quickly and then stabilised. This is indicative of initial bedding-in of some components. There were large variations between the trucks. On the trucks fitted with DPFs the concentration of copper had risen to the high level before the DPFs were fitted. The concentration of copper fell sharply after the first oil change. The concentration of copper in the oil from truck NoSü-1 was noticeably higher than that for the other trucks. However it was noticeably higher prior to the first oil change and the level after the first oil change was probably influenced by residual oil in the oil pan. During the lifetime of this second oil fill the concentration of copper rose gradually throughout the period. Again the concentration dropped after the second oil change then rose gradually during the lifetime of the third oil fill. As the history of the copper concentration during the first fill was totally different from the lead concentration history it is obvious that the copper was principally derived from a source other than the crankshaft bearings. Many of the smaller bearings are copper-based alloys and these would be a likely source.

The concentration of nickel showed a similar pattern to the copper concentration, but at much lower concentrations. On the second fill of oil the concentration of nickel was below the detection limit in the samples from all but two of the trucks. On the third fill of oil the concentration of nickel in the oil was below detectable levels in all cases.

Iron was being added to the fuel at the rate of 16 mg/kg or 20 mg/kg, depending on which FBC was used in that particular truck. Some of this treated fuel may enter the lubricating oil via the cylinder walls. Some of the combustion products will also enter the lubricating oil via the blow-by gases. It would therefore be expected that there would be a greater increase in the amount of iron in the lubricating oil, than if an iron based FBC was not used. The levels of iron detected in the first sample of oil from the trucks fitted with DPFs and using the FBC were 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 iron content was higher for all the trucks fitted with DPFs. The history of the iron concentration in the oil samples is shown in Figure 8.

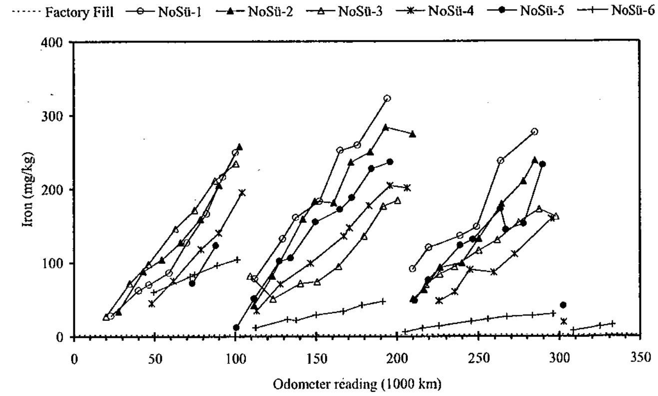

Figure 8 Iron concentration in the lubricating oil

During the first oil fill the rate of increase in iron concentration for all the trucks fitted with DPFs was very similar. During the second and third oil fills the rate of increase of iron concentration was greater for the three trucks that were run on fuel treated with FBC labelled F2. This is to be expected as F2 contains 20 % more iron than does F1. For the trucks using the FBC, the additional iron in the oil is only equivalent to between 1% and 1.5% of the iron added to the fuel. The concentration of iron in the lubricant from the trucks fitted with DPFs is approximately an order of magnitude greater than that for the reference truck without the DPF. Therefore changes in the iron concentration due to increased wear would be hard to detect within this increased iron concentration. Thus the concentration of iron cannot realistically be used as an indication of wear rates in the trucks with the DPFs fitted.

The concentration of phosphorus in the oil samples from the first batch of oil used in each truck was below the level found in the factory fill oil sample. There was a slight increase in the concentration during the lifetime of this oil fill. This may be derived from wear of some of the smaller bearings.

The concentrations of phosphorous during the second and third oil fills were consistent with the level in the factory fill oil sample and were relatively constant throughout the lifetime of each fill.

There was also an inconsistency between the concentration of molybdenum measured in the factory fill oil sample and those taken from the trucks during the trial. The oil sample from the first fill all showed low levels of molybdenum. The concentration then increase steadily throughout the lifetime of this oil fill. The concentration rose at a similar rate for all of the trucks, including the reference truck. The samples from the second and third oil fill all showed concentrations greater than the factory fill oil. The concentration only rose slightly during the lifetime of each of these oil fills. All of the trucks showed a similar trend.

The conclusion drawn from the oil sample analysis is that with the exception of the iron concentration, all of the trucks showed a similar trend in the composition and characteristics of the oil. The concentration of iron within the oil was greater for the trucks using the FBC. The increased concentration of iron was consistent with the type of FBC used and thus the amount of iron used in the fuel. The amount of iron added to the lubricating oil was between 1 % and 1.5 % of the total iron delivered by the FBC. There was no indication that this additional iron in the lubricant was increasing engine wear.

NOZZLE CONDITION

It had been suggested that the use of FBCs increased nozzle coking in direct injection diesel engines. To investigate this an injector was removed from the reference truck, a truck using FBC F1 and from a truck using FBC F2. An injector was removed from the reference truck on 13th April 2002 with an odometer reading of 250267 km. A replacement injector was installed to allow the truck to continue in service. The injector tip section was heated and put under vacuum to remove any remaining liquid diesel fuel. The injector was viewed on an SEM.

The holes exhibited varying levels of deposit formation both within the hole and around the edge of the hole. Holes 1, 3, 4 and 7 appeared to have a fairly uniform layer of light deposit within the hole. These holes did however show signs of deposit formation around the edge of the hole. Hole number 3 also had a "boulder" of deposit within the hole. This "boulder" was approximately 25 to 30 µm in diameter and appeared to be lying on the surface of the other deposits. This is indicative of an agglomeration of soot particles that has been drawn into the injector hole rather than from decomposition of the fuel within the hole.

The other four holes showed significant deposit accumulation within the holes. An example is shown in Figure 9 which depicts hole number 6. Hole 8 was particularly bad with heavy deposit accumulation over the entire visible bore. This deposit was estimated to be about 25 µm in depth. If this level of deposit was also present on the unseen side if the hole then the area of the hole would be reduced by almost 50 %.

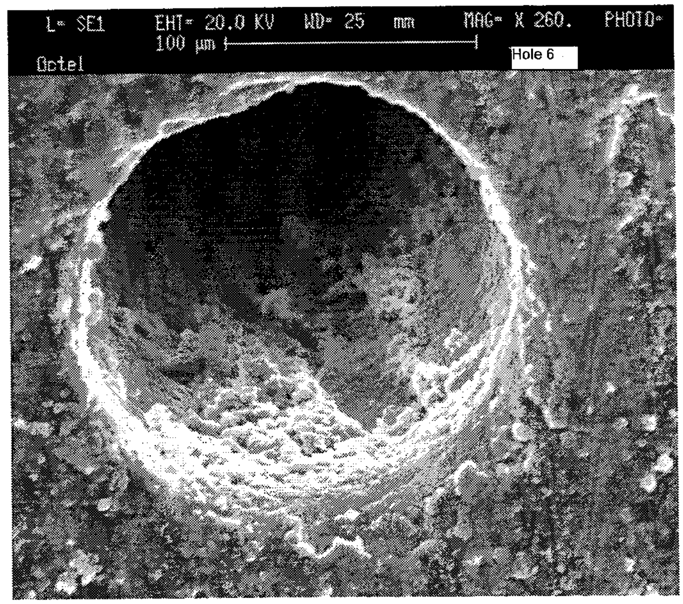

Figure 9 Hole of fuel injector from the reference truck

The deposits in and around the holes were subject to X-ray analysis. Small amounts of S, Ca, Ti and Fe were found. The sulphur could be derived from the fuel or the lubricating oil. The calcium is assumed to be derived from the lubricating oil. The source of the Ti is unknown but the Fe is assumed to be from the underlying material of the injector nozzle. It is assumed that the majority of the deposit is carbon based.

Significant levels of deposit were apparent around all eight of the holes with no bare metal visible. This was confirmed by the general view of the nozzle tip, which is shown in Figure 10. There was a uniform light deposit over the entire nozzle tip. Some of this deposit layer was removed and subject to X-ray analysis. Besides the Ca and S that were detected in the deposits within the holes there was also Zn and P present which were also present in the lubricating oil. The presence of Sr and K, as with the Ti within the holes, cannot readily be explained. Small amounts of Sr can be associated with the Ca within the lubricating oil, but at a much lower level than was detected here.

Figure 10 General view of injector from reference truck

An injector was removed from truck NoSü-3 on 1st June 2002 with the truck having covered a total of 235,040 km, 215,395 km of this was using FBC F1. The injector was analysed as for the reference truck.

This injector nozzle had generally very low levels of deposit as shown in the general view in Figure 11. There was one area where deposit was present and this deposit was subject to X-ray analysis.

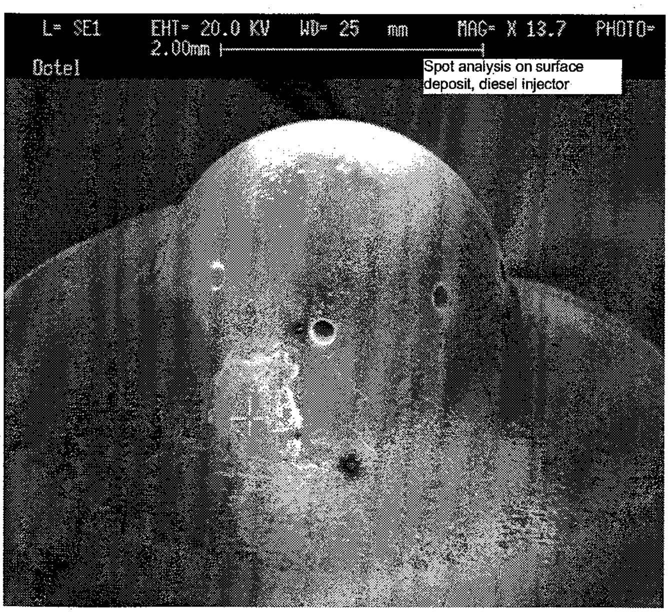

Figure 11 General view of injector from truck using F1

This deposit consisted of mainly carbonaceous material with easily detectable levels of Sr, S and Ca. The Ca was probably derived from the lubricating oil while the Sr would be derived from the FBC within the fuel, the S could be derived from both fuel and lubricant. The level of Fe within the deposit was not quantifiable due to the underlying injector nozzle being predominantly Fe with some Cr and Ni.

The 8 holes of the injector nozzle were viewed individually on the SEM. All the holes were relatively free of deposit accumulation with only a small ridge of deposit around the edge of the hole. The machining marks on the tip of the nozzle were generally visible around the holes. These can be seen as horizontal lines in the example shown as Figure 12..

Figure 12 Hole of injector using F1.

Spot X-ray analysis of the deposit in and around the holes was carried out, these spectra were generally very similar. The deposit inside the holes contained high levels of Sr, with a peak height similar to that of Fe. Very small quantities of Ca and S were also detected. The high relative levels of Sr suggest that this deposit is formed from the decomposition or evaporation of the fuel leaving residue of the FBC on the injector hole surface. Due to the underlying metal of the injector it was not possible to quantify the relative quantities of Fe and Sr within the deposit. The deposit on the edge of the hole showed much lower relative levels of Sr.

An injector was also removed from truck NoSü-5 on 3rd August 2002 with the truck having covered a total distance of 277,666 km, of this distance 213,341 km was using fuel treated with F2. A replacement injector was installed to allow the truck to continue in service. The used injector was analysed as before.

All the holes were relatively free of deposit accumulation. There was a light deposit over the external surface of the injector nozzle. However there was no indication of deposit build-up around the edge of the injector holes.

The deposit in and around the holes was subject to spot X-ray analysis. The X-ray analysis of the deposits within the holes showed Fe and Sr as the main metals present. There were also trace amounts of Ca, Cr and Ni with S and P also present. As the fuel used in this truck was treated with F2 the presence of Sr was surprising. However further investigation showed that the truck had been inadvertently treated with F1 at some time. The Ca and P would be derived from the lubricating oil, although no Zn was detected. The analysis of the deposit around the holes showed much lower levels of the non-Fe elements. There was a general light covering of deposit over the nozzle tip with very little bare metal visible. There was an area of slightly heavier deposit and this deposit was subject to X-ray analysis. The deposits on the main body of the injection nozzle contained Ca, P, Sr and S. There was a significant amount of Fe detected but due to the fact that the nozzle is made of predominantly Fe based material it was not possible to quantify the amount of Fe in the deposit.

For the reference truck that had run without the use of the FBC, there was however a greater amount of deposit on the injection nozzle and in particular in the nozzle holes. The small volume within the nozzle holes cannot be considered as part of the combustion chamber volume. The fuel that remains in this volume at the end of the injection event will tend to evaporate but in the absence of any oxygen within the hole will not burn. Any residue from the fuel will inevitably be left adhering to the walls of the hole. During the combustion stroke the increased cylinder pressure would force combustion gases into the hole allowing combustion gases to react with these residues. This can explain the presence of metals from the lubricating oil being present in the deposits from within the injector holes. During the subsequent exhaust and induction strokes the pressure of this remaining vapour would fall, then during the compression stroke fresh charge air would be forced into the hole, compressing any remaining vapour and allowing low temperature oxidation of any material present in the hole. By contrast the deposits found on the external surface of the injector nozzle are combustion products that have been deposited on the nozzle either by impaction or by thermophoresis.

The trucks running on fuel treated with FBC showed a lower level of deposit inside the holes and outside the holes on one of the injectors examined. The lower level of deposits on the external surface could be explained by the FBC acting as a catalyst within the combustion chamber, so as to produce less soot and also acting as a catalyst within any deposits that are formed. The reduced level of deposits within the holes is less easily explained as the FBC dose not contain any surface active materials to remove the deposits in what could be considered a "wet" region. The temperatures encountered and the time for which oxygen is available make it unlikely that the FBC is acting to catalyse the oxidation of these deposits. It is possible with such a limited number of injectors to analyse, that this is simply injector to injector variation.

The general conclusion from this investigation however must be that the use of FBC was not contributing to injector deposits. In this particular application the level of deposits on the surface of the injector tip were considered low. This is thought to be due to a combination of good engine design and the operating duty of these trucks.

ENGINE CONDITION

Four of the trucks were selected for a complete engine strip-down. The reference truck NoSü-6 was obviously included. The two trucks with DPF type D1 were included as these two trucks had been running with the same DPF units throughout the programme but with the two different types of FBC. The fourth truck that was included was truck NoSü-1 which had run with SiC honeycomb type DPFs throughout and had thus experienced the highest average exhaust back pressure. The engines from the four trucks were removed and stripped down to the bare crankcases. All of the components were removed for inspection and photographic recording.

The most obvious difference between the condition of the engines running on fuel treated with FBC and the reference truck was the colour of the combustion chamber deposits. The reference truck had light to medium combustion chamber deposits that were black in colour. The truck running on the fuel treated with the iron based FBC had deposits that were red in colour due to the iron oxides form from the combustion of the FBC. Again the deposit thickness was considered light.

The components from each of the four trucks were very similar in wear condition and apart from the increase in bore polish evident for truck NoSü-6 there were no specific areas where increased wear was apparent in comparison to any of the other engines. The amount of bore polish in each of the six cylinders, along with the average value, for each of the four engines is presented graphically in Figure 13.

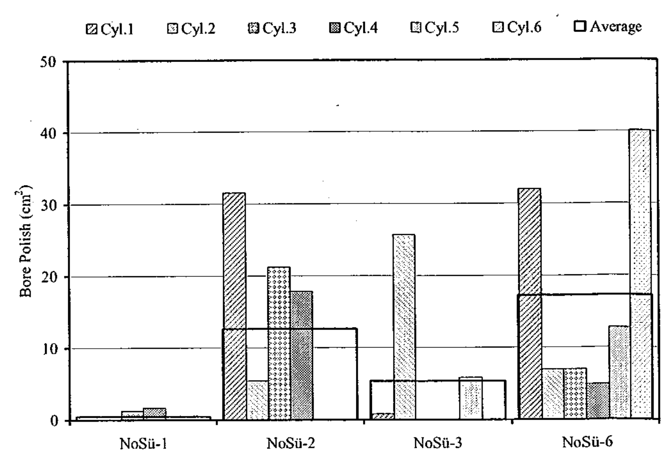

Figure 13 Cylinder bore polish results

The piston cleanliness results show marked differences in the levels of the groove and second land deposits. These deposits can vary according to the level of bore polish present in the cylinder liners. Where there is a high level of bore polish present then more oil will tend to pass up the cylinders and clean the piston grooves. If there is little or no bore polish present and there is a controlled oil supply in place then deposits tend to accumulate and the pistons will be given a lower rating. This was evident in comparing the results from the reference truck NoSü-6 with truck NoSü-1, as NoSü-6 had 96.7 cm^2 of total bore polish and NoSü-1 had only 2.8 cm^2 of total bore polish. The piston rating results from truck NoSü-3 had one cylinder with 25.7 cm^2 of bore polish in cylinder No 2 and as can be seen from the graph this piston had the highest rated No1 groove of the six cylinders.

All of the piston rings were found to be free from ring stick. All trucks showed similar wear and deposits. The running surfaces of the 1st rings showed light wear patterns with just visible light scratches, the sides were free from deposits and the lower sides were deposit free and had light to medium wear with lightly polished surfaces. The running surfaces of the 2nd rings showed light wear with a maximum 30% light contact. The surfaces were all deposit free. The upper sides had a high degree of light to medium carbon deposits with an average of 70% of the total area affected. The lower sides had light carbon deposits with an average of 30% of the total area affected. The running surfaces of the 3rd (oil control) rings were all lightly worn and deposit free. The sides were very lightly worn and had light oil deposits around the ring slots.

The wear rates on the main bearings were typical for the accumulated distance. The lower bearings from all the engines had small areas of worn overlay. The fourth bearing from the reference truck NoSü-6 was worn to reveal 2.5 cm^2 of bronze. This was the only bearing on any of the trucks that had been worn to reveal bronze. The upper main bearings on all the trucks were all lightly worn and had a matt finish. The upper crankpin bearings were all lightly worn with a light matt finish. The lower bearings were lightly worn with small areas of light polish and a matt finish. All four crankshafts were in good condition with the journals lightly worn and all fit for further service.

The camshafts from all four engines were in good condition. The valve cam-lobes had light wear patterns with more pronounced contact at maximum lift position. The fuel injector cam-lobes were shown to have medium wear with all surfaces intact and clearly visible contact patterns around the circumferences. All of the camshafts were fit for further service.

The inlet and exhaust valve rockers had light to medium wear with surface intact and all were fit for further service. All valve bridge pieces were lightly worn and fit for further service. The valve roller followers were in good condition with just visible contact lines around the outside diameters. The injector rollers had light to medium contact patterns with light discolouration. The exception was the roller for cylinder number 3 injector from the reference truck NoSü-6 which was showing signs of light incipient scuffing.

CONCLUSION

To demonstrate the efficacy of DPF/FBC systems and to assess their affect on engine durability and fuel economy, five heavy-duty trucks were fitted with DPF/FBC systems. A sixth truck was used as a reference. These trucks were run for ¼ million km. The performance of the DPFs was monitored and monthly oil samples were taken to monitor wear rates. At the end of the distance accumulation four engines underwent a complete strip-down to confirm wear rates. At the end of the programme the following conclusions have been drawn:

> The DPF units were a direct replacement for the existing silencer units and the other system components are easily mounted in the available space on the vehicle.
>
> The DPF/FBC system made a significant reduction in PM emissions from this type of vehicle.
>
> Due to the vehicle duty cycle and the presence of the FBC the DPF's regenerated passively under every-day usage.
>
> The exhaust back-pressure increase due to ash accumulation within the DPF was minimised with the use of the sintered metal filter units.
>
> The use of the FBC appeared to reduce the level of deposits on the tip of the fuel injectors.
>
> From regular lubricant analysis there was no apparent effect on engine wear rates as a result of using the DPF and FBC. This was confirmed by a complete engine strip-down.

ACKNOWLEDGMENTS

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APPENDIX 1

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 2

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:									
302103001	NoSü-6	Cold	3.54	45.03	0.304	0.604	16.945	2.853	1188.0
302103002	NoSü-6	Hot	3.52	40.21	0.202	0.672	14.291	2.831	1060.0
302102901	NoSü-1	Cold	3.52	42.54	0.116	0.800	13.945	4.165	1119.1
302102902	NoSü-1	Hot	3.54	36.50	0.057	0.374	11.799	3.191	961.9
302103101	NoSü-2	Cold	3.51	44.76	0.108	0.429	15.799	2.922	1181.2
302103103	NoSü-2	Hot	3.55	39.82	0.081	0.369	13.787	2.082	1051.6
302110101	NoSü-3	Cold	3.54	44.00	0.054	0.449	15.215	2.226	1162.2
302110102	NoSü-3	Hot	3.54	38.54	0.042	0.637	13.119	1.480	1017.9
302110401	NoSü-4	Cold	3.55	42.81	0.076	0.437	13.541	2.677	1129.9
302110402	NoSü-4	Hot	3.55	38.44	0.041	0.505	12.562	2.055	1014.8
Phase 2:									
302103001	NoSü-6	Cold	10.51	27.14	0.168	0.259	10.616	2.452	715.2
302103002	NoSü-6	Hot	10.51	26.22	0.217	0.298	10.201	2.412	690.8
302102901	NoSü-1	Cold	10.51	26.25	0.049	0.199	8.220	4.956	687.8
302102902	NoSü-1	Hot	10.50	24.82	0.028	0.162	7.656	4.793	653.0
302103101	NoSü-2	Cold	10.50	26.98	0.057	0.243	9.183	2.615	710.7
302103103	NoSü-2	Hot	10.52	26.22	0.074	0.207	9.294	2.046	691.7
302110101	NoSü-3	Cold	10.52	26.10	0.040	0.273	9.113	2.243	687.8
302110102	NoSü-3	Hot	10.52	25.03	0.033	0.283	8.818	1.948	659.8
302110401	NoSü-4	Cold	10.51	26.26	0.027	0.228	8.426	3.143	690.8
302110402	NoSü-4	Hot	10.52	25.62	0.035	0.246	8.221	2.626	674.6
Phase 3:									
302103001	NoSü-6	Cold	13.55	25.72	0.096	0.273	12.204	0.566	680.5
302103002	NoSü-6	Hot	13.54	25.23	0.101	0.289	11.796	0.566	667.3
302102901	NoSü-1	Cold	13.64	24.96	0.041	0.171	9.478	1.218	659.5
302102902	NoSü-1	Hot	13.59	24.81	0.028	0.187	9.275	1.288	655.4
302103101	NoSü-2	Cold	13.56	26.01	0.036	0.268	10.326	0.633	688.1
302103103	NoSü-2	Hot	13.55	25.75	0.043	0.227	11.105	0.706	681.0
302110101	NoSü-3	Cold	13.57	24.88	0.024	0.281	10.559	0.590	658.1
302110102	NoSü-3	Hot	13.56	24.43	0.021	0.288	10.325	0.560	646.3
302110401	NoSü-4	Cold	13.62	25.43	0.020	0.248	9.635	0.669	672.6
302110402	NoSü-4	Hot	13.63	25.20	0.017	0.262	9.599	0.751	666.4
Total:									
302103001	NoSü-6	Cold	27.60	28.74	0.150	0.310	12.208	1.578	758.9
302103002	NoSü-6	Hot	27.57	27.52	0.158	0.341	11.506	1.559	726.4
302102901	NoSü-1	Cold	27.66	27.69	0.053	0.262	9.569	3.013	728.7
302102902	NoSü-1	Hot	27.63	26.35	0.032	0.202	8.983	2.864	693.7
302103101	NoSü-2	Cold	27.57	28.77	0.053	0.279	10.587	1.679	759.4
302103103	NoSü-2	Hot	27.62	27.73	0.060	0.238	10.759	1.393	732.6
302110101	NoSü-3	Cold	27.62	27.79	0.034	0.299	10.604	1.429	734.0
302110102	NoSü-3	Hot	27.62	26.47	0.028	0.331	10.109	1.206	699.0
302110401	NoSü-4	Cold	27.68	27.98	0.030	0.265	9.678	1.866	738.2
302110402	NoSü-4	Hot	27.69	27.06	0.027	0.287	9.455	1.630	714.1