SAE TECHNICAL PAPER SERIES

2005-01-0669

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P. Richards and M. W. Vincent
Associated Octel Company

J. Chadderton
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Reprinted From: Diesel Exhaust Emission Control 2005 (SP-1942)

ISBN 0-7680-1635-5

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SAE International™

2005 SAE World Congress
Detroit, Michigan
April 11-14, 2005

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760 Web: www.sae.org

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

Printed in USA

2005-01-0669

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ABSTRACT

A dosing system has been developed to facilitate the addition of a fuel borne catalyst (FBC) to a vehicle's fuel supply. The on-board dosing system was primarily designed to reduce cost and complexity. One embodiment of the design provided an additional benefit, namely the automatic adjustment of treat rate according to duty cycle. For high duty operating cycles where average exhaust gas temperatures are high, a low treat rate of FBC is supplied. Conversely at low duty where the exhaust temperature is lower, a higher treat of FBC is delivered. Data from field applications are presented to demonstrate this feature.

INTRODUCTION

Increased pressure to improve ambient air quality, specifically with regard to suspended particulate matter, coupled with the classification of diesel particulate matter as a possible human carcinogen, has resulted in the introduction of various incentive schemes and/or legislation to bring about the retrofit of diesel particulate filter (DPF) systems. This has widened the range of vehicles and accompanying duty cycles requiring retrofit, which in turn has increased the demands on the DPF systems. The use of a fuel borne catalyst (FBC) allows the DPF to accumulate significant quantities of soot or particulate matter and then allows regeneration of the DPF in a short period of time. This makes such a system eminently suitable for applications where the duty cycle includes large periods with low exhaust gas temperatures and only short excursions to higher temperatures.

One of the perceived shortcomings of a DPF/FBC system is the added complexity of dosing the FBC into the fuel. If the vehicle is always refuelled from one or more known refuelling points then the fuel can be treated at the refuelling point, for example municipal vehicles that return to the depot on a regular basis and are refuelled from a dedicated supply tank. If all the vehicles using this dedicated tank require FBC then the bulk fuel can be treated with FBC. If however some of the vehicles using this supply do not have DPFs fitted, and do not require FBC, then an automatic system that determines which vehicles do, and which vehicles do not require FBC, and blends the FBC and fuel at the point of fuel delivery can be utilised (1). If the vehicle is to be refuelled at an indeterminate location then the FBC must be added to the fuel from an on-board supply. This is the approach that was taken for the first serial production passenger car to be equipped with a DPF system (2) and has been adopted for numerous retrofit applications.

A characteristic that is shared by all of these methods of adding the FBC to the fuel is that they aim to provide a fuel with a known and constant concentration of the FBC. For an on-board dosing system this can lead to a high degree of complexity (3). The required concentration of FBC is known to vary both with FBC type and the engine/vehicle type in which it is to be used. However detailed experimental investigation (4, 5) has shown that one of the key parameters is the metal to soot ratio of the trapped material. From such experiments it is possible to determine the required concentration of catalyst in the soot to ensure reliable regeneration of the DPF.

However it was also known that the soot emission rate was not proportional to fuel consumption, but this relationship varied with engine operating point (6). Thus to maintain a constant metal to soot ratio would require an FBC treat rate that was mapped to engine operating condition. This was blatantly not practical; moreover it had been demonstrated many times that running with a constant FBC treat rate produced satisfactory regeneration of the DPF. It was thus concluded that the highly transient nature of the engine operation would produce soot particles with varying metal to soot ratios but that the DPF "averages" this out. On this basis it was assumed that it was not important to ensure a constant metal concentration in the fuel, but to produce an average metal to soot ratio in the DPF should be satisfactory. Knowledge of the average soot emission rate and the average fuel consumption rate would allow this to be achieved.

At the SAE 2003 World Congress a novel FBC dosing system, was presented (7). The system was intended as an on-board device and was designed for simplicity and low cost. A major feature of the design was that it removed the need to accurately measure the quantity of fuel added to the fuel tank in order to meter an appropriate quantity of FBC into the tank. The simplest manifestation of the design concept added FBC to the fuel tank at a fixed rate while the engine was running. This was achieved by injecting a small fixed quantity of FBC into the fuel feed or return line at a fixed time interval. The recirculation of the fuel ensured that the FBC was mixed with the fuel in the tank. The injection frequency was set to provide the required average treat rate.

This paper summarises the salient features of the dosing system and presents data from field applications that demonstrate how this approach will produce an FBC concentration in the fuel that varies with the engine/vehicle duty and hence with the exhaust temperature.

SYSTEM OVERVIEW

The dosing system comprises three essential components namely the FBC storage tank, the solenoid operated injection unit including an in-line filter, and the electronic control unit (ECU). These major components are shown in Figure 1.

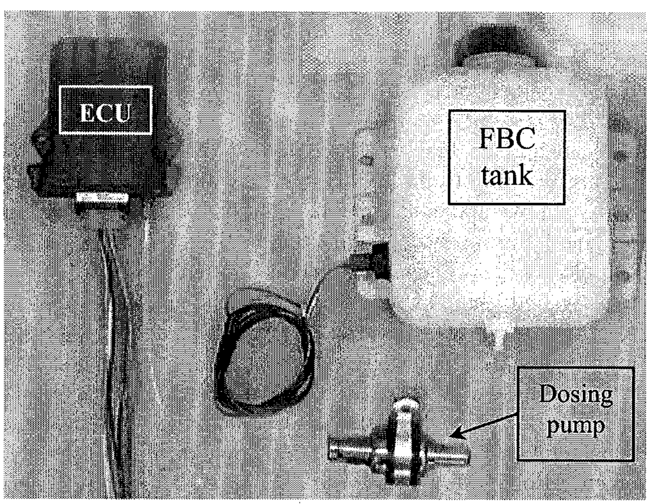

Figure 1. Dosing system, major components.

Additional components are included for safety and diagnostic purposes, including an FBC low-level sensor, which can be seen in the left side of the FBC tank in Figure 1, an exhaust back pressure sensor, the connection to which can be seen entering the lower right side of the ECU in Figure 1, and a dash mounted warning lamp. The warning lamp is used to indicate the system integrity, low FBC level and high exhaust back pressure. The ECU is connected in to the vehicles "ignition" switch. When the engine is running the ECU activates the dosing pump solenoid at a pre-set time interval, thus injecting a fixed amount of FBC into the fuel line. Treated fuel is then returned to the fuel tank causing the concentration of FBC in the tank to increase with time.

With the dosing strategy outlined above the average rate of FBC usage is fixed; the average rate of fuel usage will however vary with the average engine duty. The average FBC treat rate will therefore also vary with engine duty. By simple mathematics the average FBC treat rate will be inversely proportional to the average rate of fuel usage. This is shown in a later section of the paper. If the rate of fuel usage doubles then the FBC treat rate will be halved. The implication of this is that if the engine is operated consistently at low duty then the FBC treat rate will be higher than if it is consistently operated at high duty. This is illustrated in Figures 2 and 3, which are taken from reference (7). Figure 2 shows a computer simulation of an engine operating consistently at low duty. The low part of the graph shows that it takes many hours for a tank full of fuel to be used, and that over time the average FBC treat rate is such that the average metal concentration in the fuel is about 30 mg/kg.

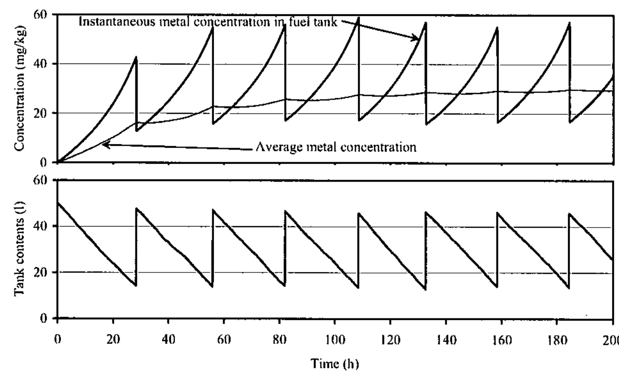

Figure 2. Simulation of low duty operation.

Figure 3 shows the simulation of the same system operating at a higher duty. The time taken to consume a tank of fuel is greatly reduced as shown in the lower part of the graph. The upper part of the graph shows that the average FBC treat rate is also significantly reduced. It should be noted that the scale of the upper part of Figure 3 is different to that of Figure 2. In this example the average FBC metal concentration is reduced to about 7 mg/kg.

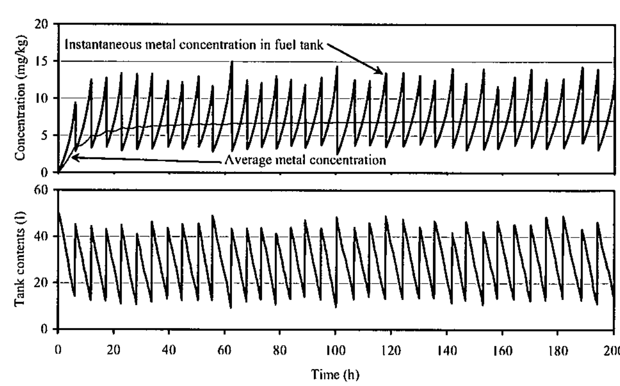

Figure 3. Simulation of higher duty operation.

It can be see from Figure 2 and Figure 3 that whereas the average FBC concentration has been reduced by a factor of a little over four, the frequency of tank filling, i.e. the fuel usage rate has also changed by a factor of approximately four.

This characteristic is advantageous in that if the engine is operated consistently at low duty then the exhaust gas temperature entering the DPF will also be low and a higher treat rate of FBC may be required to ensure reliable self-regeneration. Conversely if the engine is operated consistently at high duty then the exhaust gas temperature will be higher and the need for FBC will be lower. The effect on regeneration performance of varying the FBC treat rate has been demonstrated in previous work (7, 11).

This simple FBC dosing strategy automatically adjusted the average FBC treat rate to match the average engine duty cycle. Over treatment of the fuel at high operating duties can thus be avoided and FBC usage minimised. Despite the efforts of DPF manufacturers to increase the ash holding capacity of their filters (12-14), the ash removal frequency is still a consideration for the operator. Minimising FBC usage obviously also directly reduces the operating cost of the system.

SYSTEM PERFORMANCE

The analysis presented here is of data taken from three buses fitted with the same type of engine. The first bus was a Leyland Olympian double deck bus. This bus was first registered in 1991 and is operated by Warrington Borough Transport for regular municipal transport services. The bus is shown in Figure 4.

Figure 4. Leyland Olympian double deck bus.

The other two buses were MCW Metrobus double deck buses that were being used as open topped tour buses, operated by Ensign Bus in Stratford-upon-Avon. One of the buses is shown in Figure 5. These two buses later referred to as Metrobus #1 and Metrobus #2 were first registered in 1980 and 1981 respectively. All three buses were therefore homologated prior to the Euro series of emissions regulations and are thus designated as pre-Euro.

Figure 5. MCW Metrobus

Each of the buses was fitted with a Gardner 6LXB engine. This is a naturally aspirated, direct injection engine that was very commonly fitted to buses in the UK, of which many are still in regular service. Further engine details are given in Table 1.

Table 1 Gardner engine details

Type	Gardner 6LXB
Cylinder arrangement	6 In-line
Bore	120.7 mm
Stroke	152.4 mm
Capacity	10450 cm^3
Compression ratio	15 : 1
Peak Power	134 kW @ 1850 rev/min
Peak Torque	727 Nm @ 1000 rev/min
Emissions specification	Pre-Euro

The engine is mounted transversely at the rear of the bus with the exhaust silencer running parallel to it, beneath the chassis rails. The original silencer was replaced with a filter system; the DPF was Liqtech SiC element to the Stobbe design (8). The size of the DPF substrate was 25.4 cm x 30.5 cm (10" x 12"), giving 15.4 litres of DPF volume for the 10.5 litres of naturally aspirated engine volume. The DPFs were given a proprietary base metal catalytic coating, applied by Haldor Topsøe A/S, which had been shown not only to reduce emissions of HC and CO, but also to significantly reduce the emissions of NO_2 (9). The activity of this catalyst towards the oxidation of soot is such that it will not influence the regeneration behaviour of the DPF, i.e. the DPF would not be expected to regenerate without the inclusion of the FBC.

The DPF systems were also equipped with a pre- and post-DPF thermocouple, plus a pre-DPF pressure transducer, which were connected to a Grant 1000 series Squirrel data logger. The data loggers were set to log data every 10 seconds. To minimise the amount of recorded data the loggers were also connected through the vehicle's "ignition" circuit such that the logger would only log while the engine was operating.

A 5 litre tank of FBC was mounted in the rear engine compartment along with the dosing system ECU. The FBC dosing pump is mounted by the chassis rail close to where a tee piece feeds the FBC into the fuel feed line from the mid mounted fuel tank. A second pressure tapping in the pre-DPF canning was connected to the pressure transducer integral with the dosing system ECU. The layout of the dosing system component ensured that the connection between the DPF housing and the ECU was short and ran uphill to the ECU to prevent the formation of condensation in the pressure transducer within the ECU.

The data from the three buses is discussed in more detail in the following sections.

DATA FROM THE LEYLAND OLYMPIAN

The data presented in this paper covers the period from November 2003 to July 2004, a total of over 1350 operating hours. From the logged data it was possible to determine the amount of time for which a given exhaust gas temperature prevailed in the DPF inlet canning. The percentage of the time spent with an exhaust gas temperature in each 10°C temperature band is shown graphically in Figure 6

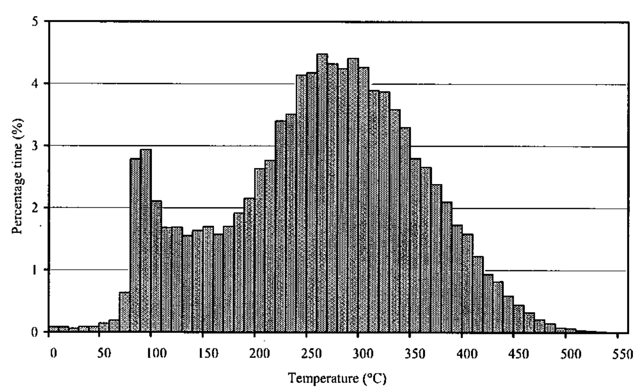

Figure 6. Pre DPF temperature distribution.

From this chart the time the bus spends with the engine at idle is clearly visible from the amount of time for which the DPF inlet temperature is in the window of 80°C to 110°C, a total of 7.8% of the operating time. It is also evident from this data that the bus spends only 37% of the time with a DPF inlet temperature above 300°C. The implications of this temperature profile have been discussed in more detail in reference (10).

The temperature data can obviously also be used to determine the temperature-time distribution on a daily basis. A chart equivalent to Figure 6 could be produced for each day the bus was operating. Figure 7 shows the maximum and the arithmetic mean temperature on a daily basis. The grey columns indicate the maximum DPF inlet temperature observed whilst the black diamond markers indicate the mean temperature on that day.

From Figure 7 it is clear that there is some variation in the daily mean temperatures. As this is not a systematic variation it is assumed that this variation is due to the day to day variation in the duty cycle of this particular bus. If the fuel consumption and FBC consumption were also known on a daily basis it would be possible to test the hypothesis that the FBC treat rate varied automatically with duty cycle.

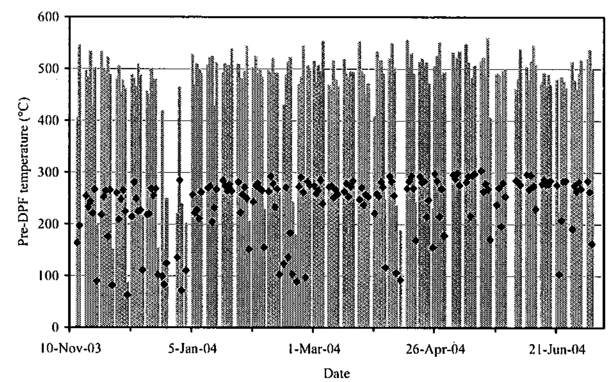

Figure 7. Daily mean and maximum pre-DPF temperatures.

As the dosing system is adding FBC at a known time interval during engine operation, and the data logger is recording data at a fixed time interval, it is possible to calculate the amount of FBC added. Unfortunately, although the FBC consumption can be calculated with a good degree of accuracy the fuel consumption is not known on a daily basis.

However, as fuel used is a major parameter in the operating costs, the operator keeps careful note of fuel used. The quantity of fuel added to the vehicle tank is carefully recorded every time the fuel tank is topped up. The fuel tank is usually topped up to the automatic cut-off on the delivery nozzle. It is therefore assumed, to a fair degree of accuracy that the fuel added is equal to the fuel used since the last top-up.

The data presented in Figure 7 can thus be recalculated on a "per fill" basis as opposed to a daily basis. This is plotted in Figure 8. The grey columns indicate the maximum DPF inlet temperature observed between successive fuel tank top-ups, whilst the black diamonds indicate the arithmetic mean temperature in the same period. The data is plotted against the date of the top-up, i.e. at the end of the calculating period.

From this chart it can be seen that some of the variability evident in Figure 7 has been removed. This can be explained by the fact that when the temperatures are calculated on a daily basis, low values of mean and maximum temperatures are calculated for days when the bus has only operated for a short period of time. However on these days no tank filling will be necessary, thus when the data is recalculated on a "per fill" basis the data from these days is included with that of subsequent days when longer periods of operation dictate that a tank refill is required.

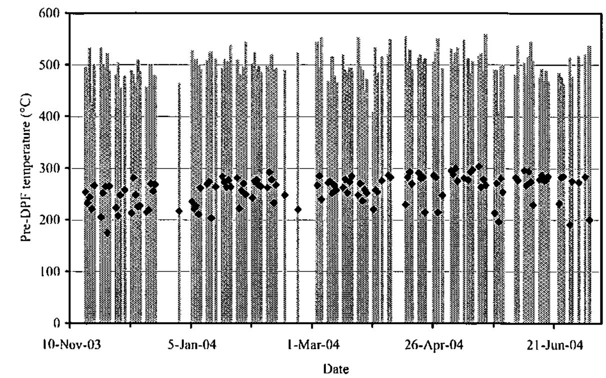

Figure 8. Mean and maximum pre-DPF temperatures per fill.

Despite this "smoothing" of the data there is still a significant variation in the mean operating temperatures observed. A mean pre-DPF temperature of 175.4°C was observed between the 26th and 27th November 2003 whilst a mean pre-DPF temperature of 303.9°C was observed between 14th and 17th May 2004. The bus did not operate on the 15th and 16th.

As the odometer reading was also recorded when the fuel tank was filled it was possible to calculate an average fuel consumption between consecutive tank fills. There was also a significant variation in fuel consumption from fill to fill. However, this variation was found not to correlate with either the average or the maximum temperature observed during the same period. As the data logger was configured only to log data while the vehicle was operating, it was possible to determine the average fuel consumption in terms of the volume of fuel used per unit of time. This is shown in Figure 9 below.

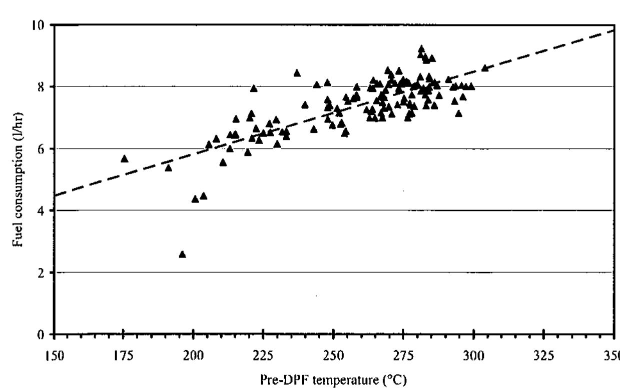

Figure 9. Average volumetric fuel consumption rate per fill

From Figure 9 there is some correlation between fuel consumption expressed as volume per unit time, and the mean pre-DPF temperature. From this data the correlation is not particularly strong, with an R^2 value of only 0.59. This may be partly due to the assumption that the fuel tank was filled to the same level at each refill. Due to the frequency of data logging the possible error in the calculated operating times is typically less than 0.05%.

The volumetric fuel consumption per unit time as shown above was calculated as:

$$FC_t = c_1 * F / n \qquad [1]$$

Where F is the volume of fuel added to the tank, n is the number of data logs between tank filling and c_1 is a constant. The FBC dosing system was configured to deliver a fixed volume of FBC at a fixed time interval. Thus the amount of FBC added between tank filling is given by:

$$FBC_t = c_2 * n \qquad [2]$$

where C_2 is a constant determined from the FBC dosing interval and the amount of FBC added at each injection of the dosing pump. The FBC treat rate is thus given by:

$$TR = c_3 * FBC_t / F \qquad [3]$$

where c_3 is a constant to give consistency of units. Rearranging gives

$$TR = (c_1 * c_2 * c_3) / FC_t \qquad [4]$$

It was thus possible to determine the quantity of FBC added to the system in any given period from equation [2]. If the fuel tank was always run from full to empty then the quantity of FBC added would equal the quantity of FBC used and an exact measure of dose rate could be calculated. However, as the dosing system relies on the fact that fuel is constantly being re-circulated and that the concentration of FBC within the fuel tank varies, the fact that the fuel tank is refilled from different levels introduces some uncertainty into the treat rate of the fuel used by the engine. With this in mind the average dose rate was calculated based on the amount of FBC added and the amount of fuel added between tank refills. The constant of proportionality was chosen to give an overall average treat rate of 1. The calculated values of treat rate have been plotted against average pre-DPF temperature in Figure 10.

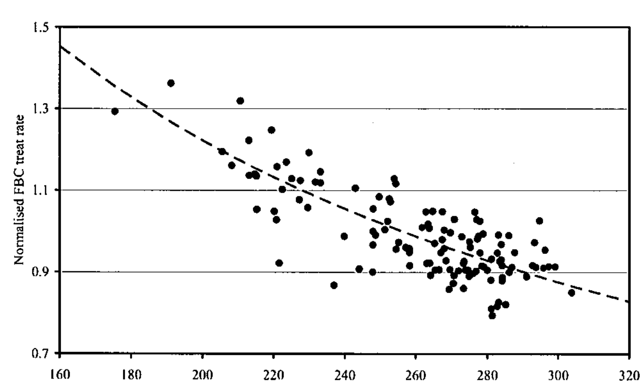

Figure 10. Relationship between FBC concentration and mean pre-DPF temperature.

If it is assumed that the weak linear correlation between time based volumetric fuel consumption and mean pre-DPF temperature shown in Figure 9 holds true, then the FBC treat rate will be inversely proportional to the pre-DPF temperature. The least squares best fit regression line for this inverse proportionality is shown as a dashed line in Figure 10. From the data presented in Figure 9, a change in average pre-DPF temperature from 175°C to 300°C results in fuel consumption increasing by a factor of 1.6. From the arithmetic and Figure 10 this results in a decrease in FBC usage of a factor of 1.6.

It is thus clear that when the engine/vehicle is on average operating at a lower duty, which can be defined as a low fuel usage rate which would be expected to produce low exhaust temperatures, the FBC treat rate will be higher than it would have been if the engine/vehicle was operating at high duty.

DATA FROM THE MCW METROBUSES

Although both of the Metrobuses are still in regular use with the DPFs fitted it was only possible to install the data loggers for a limited period of time. The data considered in this paper was recorded between October and November 2003 for bus #1 and between January and April 2004 for bus #2. The available data for these two buses is therefore more limited.

For both of the Metrobuses the accumulated data was analysed to show the overall time spent with a pre-DPF temperature in each 10°C temperature window. This is shown in Figure 11.

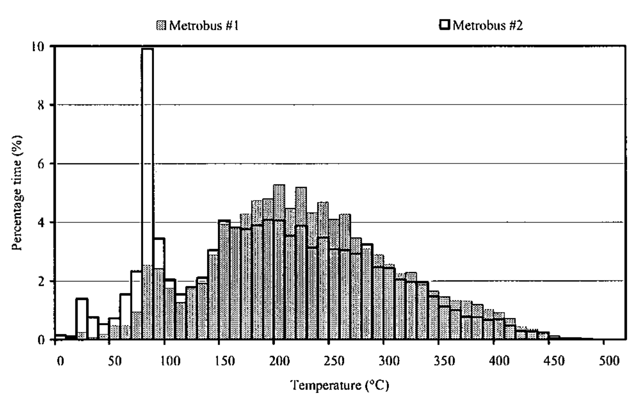

Figure 11. Pre DPF temperature distribution for Metrobuses

From this chart it is evident that both these buses have a similar temperature distribution although bus #2 clearly spent more of its time at idle. Almost 10 % of the operating time was spent with a pre-DPF temperature in the 80°C to 90°C window and a total of 20.9% of the time with a pre-DPF temperature below 100°C. The corresponding value for Metrobus #1 was 7.5% and for the Olympian 8.8%. Comparison with Figure 6 also indicates that the Metrobuses which were being used as sightseeing buses tend to have a lower operating temperature profile compared to the Olympian bus, which is being used for regular city centre service. The DPFs on both of these buses were regenerating at regular intervals. This is discussed in more detail in other publications (9, 10).

The lower overall temperature profile that is evident on the Metrobuses is also reflected in the mean and maximum temperatures when plotted on a daily basis. However as discussed above for the Olympian bus the data is more useful if converted into mean and maximum values on a "per fill" basis as it can then be correlated with fuel usage. The data is presented in this form in Figure 12 for bus #1 and Figure 13 for bus #2.

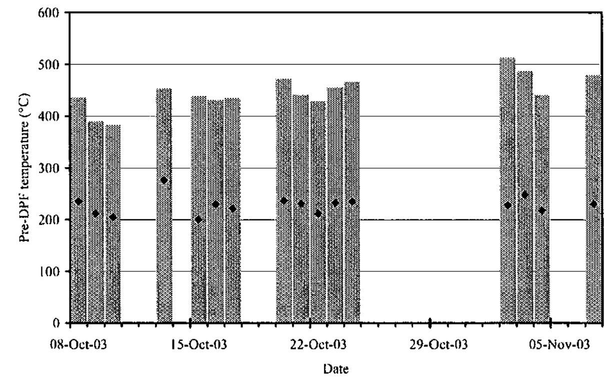

Figure 12. Mean and maximum pre-DPF temperatures per fill for Metrobus #1

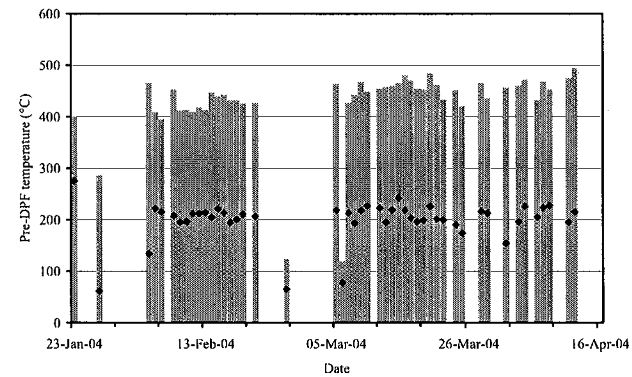

Figure 13. Mean and maximum pre-DPF temperatures per fill for Metrobus #2

For Metrobus #1 the majority of the mean pre-DPF temperatures are in the range of 200°C to 240°C. For Metrobus # 2 these figures become 190°C and 230°C. In comparison the Olympian produced figures in the range 200°C to 300°C. The maximum pre-DPF temperatures are also correspondingly lower for the Metrobuses compared to the Olympian.

As discussed in the previous section, it was possible knowing the fuel usage and the number of data logs during the fuel tank refill period, to determine an approximate average FBC treat rate during that period. The results of these calculations are then plotted against the "per fill" arithmetic mean temperature. This data has been combined with the data from the Olympian to produce Figure 14.

There is clearly more scatter in the data from the Metrobuses, which is indicative of a poorer correlation between the pre-DPF temperature and the fuel usage rate. The reason for this is not currently known, although it must be remembered that the recorded temperatures are in the inlet canning to the DPF and are thus susceptible to the vagaries of heat loss in the exhaust system when compared to the engine-out exhaust gas temperature.

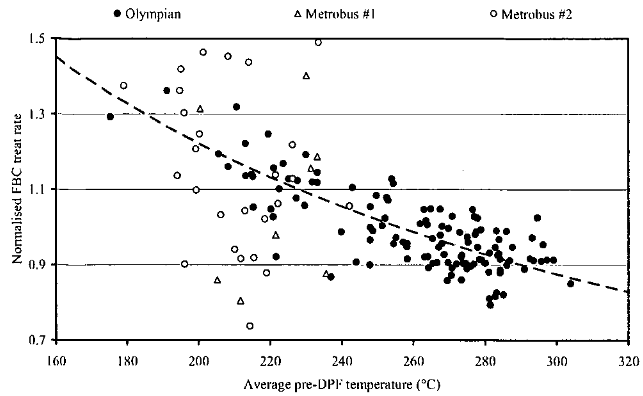

Figure 14. Relationship between FBC concentration and mean pre-DPF temperature for all three buses.

Whilst the data presented and discussed above shows that the dosing system does automatically adjust the FBC treat rate in accordance with the average pre-DPF temperature, it does not show how this strategy effects the regeneration performance of the DPF. In the earlier work (7) it was shown that this type of dosing system did result in similar DPF regeneration performance to a system that ensures a constant and on average equal FBC treat rate. Laboratory tests have shown the effect of FBC treat rate on DPF regeneration performance (7, 11). If the engine operation to produce the average temperature were steady state, then the dosing system under discussion would clearly be most advantageous. However further work is required to demonstrate that under the highly transient conditions encountered on the buses described here, the simple inversely proportional relationship is the optimum, or whether additional control over the dosing frequency could further optimise the FBC usage.

CONCLUSION

An on-board dosing system was developed to add fuel borne catalyst (FBC) to a vehicle's fuel tank to enable the regeneration of a diesel particulate filter (DPF). The system was conceived primarily as a retrofit device and was designed to eliminate the need for costly and complex sensing of the quantity of fuel added to the fuel tank. Instead the system was designed to add FBC on a pseudo-continuous basis.

It was postulated that by configuring the system to add the FBC pseudo-continuously, and at a fixed rate with time, then the system would automatically adjust the average concentration of FBC to match the average duty cycle of the vehicle.

By subdividing the operating time of urban buses into a number of events defined as the time between fuel tank refills, it was concluded that;

- There is a correlation between average volumetric fuel consumption rate and average pre-DPF temperature.
- As the FBC usage rate is constant, this results in the average FBC treat rate being inversely proportional to the average volumetric fuel consumption rate.
- The average FBC treat rate was thus inversely proportional to the average pre-DPF temperature.

Further work is required to show that this is the ideal relationship between FBC treat rate and average DPF temperature to provide optimum DPF regeneration performance whilst minimising FBC usage.

ACKNOWLEDGEMENTS

The authors are indebted to Steve Hiser at Adastra for his assistance in downloading data from the vehicles and liaising with the operators to acquire additional operational data. The authors are also grateful to Tim Meade of Ensign Bus, for supplying the fuel data.

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CONTACT

For further information contact

Paul Richards Tel: +44 1908 273 638
Fax: +44 1908 376 033
Email: richardsp@octel-corp.com

Matthew Vincent Tel: +44 1908 273 620
Fax: +44 1908 376 033
Email: vincentm@octel-corp.com

Associated Octel Company
Fuel Technology Centre
Watling Street
Bletchley
Milton Keynes
MK1 1EZ
England

http://www.octel-corp.com

John Chadderton Tel: +44 151 348 5776
Fax: +44 151 348 5778
Email: chaddertonj@octel-corp.com

Adastra House
Cheshire Manufacturing Park
PO Box 17
Ellesmere Port
Cheshire
CH65 4HF
England

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