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ABSTRACT

Forthcoming emissions legislation is driving the passenger car manufacturers towards the fitting of Diesel Particulate Filters (DPFs) as original equipment. In areas with a particular problem such as heavily congested city centres, retrospective legislation has also been introduced, for example in Hong Kong and Tokyo. Legislation mandating the retrofitting of DPFs obviously has an immediate effect on particulate emissions. Other authorities are thus investigating the efficacy of such measures.

However with the increasing use of DPF technology concerns are now being raised over some currently unregulated emissions such as ultra fine particulate and NO_2, although total particulate mass and oxides of nitrogen are regulated.

To add to the data base for such issues a programme of work was run using London Black Cabs. Four cars were fitted with a DPF, an on-board dosing system to meter a fuel borne catalyst (FBC) into the fuel and a data logger to monitor the DPF performance. Emissions measurements were taken before and after fitting the DPF. The cars were then run on the road conducting normal taxi duties.

This paper presents an analysis of the results of some non-regulated emissions testing including particle size analysis and NO_X speciation. A companion paper describes the results of the regulated emissions testing plus the operation aspects of the programme.

INTRODUCTION

"Polluted air damages health and quality of life, particularly affecting the most vulnerable in society - the very young and the old. Up to twenty four thousand people die prematurely in Britain each year from the effects of air pollution. The week-long period of high pollution in December 1991 is estimated to have caused 160 premature deaths in London." (1)

Two of the air pollutants causing the most concern are oxides of nitrogen (NO_X) and particulate matter with a diameter of less than ten micro meters (PM_{10}). In 1999 it was calculated that road transport contributed 52.1 % and 68.5 % to the NO_X and PM_{10} emissions respectively in Greater London. These figures rose to 56.6 % and 92.5 % respectively in Central London (1). Of these numbers it was estimated that taxis contributed 1.0 % and 3.9 % to the NO_X and PM_{10} emissions respectively within Greater London and 6.0 % and 18.0 % respectively in Central London. In 2001 values of 66 tonnes/year of NO_X and 13 tonnes/year of PM_{10} were attributed to taxis in Central London (1).

The oxides of nitrogen consist mainly of nitric oxide (NO) and nitrogen dioxide (NO_2), NO_2 being considered the major concern to health (1,2). Due to the combustion temperatures and chemical equilibrium considerations it is expected that most of the NO_X formed within the diesel engine will be in the form of NO. However it has been postulated that NO_2 can be formed in the flame zone by reaction with HO_2 and then quenched before being reduced back to NO (3). Typical values of NO_2/NO ratios of 0.1 to 0.3 have been quoted, but it is acknowledged this is very load dependent (3,4). Exhaust NO will however then readily oxidise to NO_2 in the atmosphere in the presence of ozone (1).

Efforts by engine designers to reduce NO_2 emissions have concentrated on reducing NO_X emissions. This has traditionally been achieved by the use of exhaust gas recirculation (EGR) which acts to reduce inlet charge oxygen concentrations (5) with a small additional contribution from the thermal and chemical effect of introducing carbon dioxide CO_2 (6). The use of EGR can be incorporated into new engine designs but unfortunately does not readily lend itself to retrofitting.

A very effective way of reducing the particulate emissions from diesel vehicles is to fit diesel particulate filters (DPFs). Since 1998 a heavy-duty engine manufacturer has been offering engines equipped with a diesel particulate filter as a factory fitted option (7). In 2000 a passenger car manufacturer began to offer a passenger car complete with DPF (8). Both systems employed a fuel borne catalyst (FBC) to ensure regeneration of the filter. Such a DPF system does however lend itself to retrofit application.

There have been numerous demonstrations of the retrofitting of DPFs to larger vehicles (9-11). Transport for London has also embarked on a retrofit programme for the London Bus Network Fleet. However, the limitations of the systems being fitted to buses means that they are not suitable for use on the taxi fleet. Other studies have however shown that DPF/FBC systems can be successfully retrofitted to passenger cars (12-14).

In the UK, the Department of the Environment, Transport and the Regions (DETR), in conjunction with Society of Motor Manufacturers and Traders (SMMT) and CONCAWE, ran a particle research programme (15). As part of this programme, the performance of different particulate emission control devices was compared. Two vehicles used in this programme were retrofitted with DPF/FBC systems, work on these two vehicles has been reported elsewhere (13-14). Particulate emission levels were shown to be exceedingly low, even for a system which had already accumulated a distance of 60,000 km. Significantly, the filter was also very effective in lowering not only the mass but both the ultra-fine particulate fraction and number of particles.

A programme of work was thus undertaken to investigate the practicalities of retrofitting London Black Cabs with DPF/FBC systems. This paper presents the findings from some initial non-regulated emissions testing. An accompanying paper (16) considers the impact of fitting the DPF/FBC systems on the regulated emissions and discusses the operation of the vehicles in regular use on the streets of London.

VEHICLE SELECTION AND REGULATED EMISSIONS RESULTS

In order to quantify the benefits of using a DPF/FBC system on the London taxi fleet a small number of vehicles were selected as being representative of the fleet. The salient details of the vehicles used are given in Table 1 below.

Table 1. Vehicle details

Taxi	Registration	Type	Engine	capacity	Trans'
1	M680 MUC	LTI	Nissan	2664 cc	Auto
2	R925 SLD	MetroCab	Ford	2496 cc	Auto
3	N505 PUL	LTI	Nissan	2664 cc	Auto
4	K127 LNJ	LTI	Nissan	2664 cc	Man'

Each of these vehicles was independently tested at Millbrook Proving Ground Limited. Triplicate emissions tests were performed on each vehicle as supplied, with a standard exhaust system. As these vehicles were taken from service they were of different ages, manufactured to different emissions specifications and had covered different mileages. The accumulated mileage at the start of the emissions testing is shown in Table 2 along with the relevant emissions specification for each taxi.

Table 2. Odometer reading and emissions specification

Taxi	Registration	Type	Odo' reading	Emissions specification
1	M680 MUC	LTI	74759	EURO I
2	R925 SLD	MetroCab	99144	EURO II
3	N505 PUL	LTI	211096	EURO I
4	K127 LNJ	LTI	329873	EURO I

After these base-line emissions tests the vehicles were fitted with appropriate DPF exhaust systems, on-board FBC dosing systems and data loggers. Details of the selection and fitting of the DPFs can be found in reference (16). The vehicles were again independently tested in triplicate with the DPF fitted and with fuel containing the FBC. An analysis of the results of the regulated emissions testing is provided in reference (16). For completeness the average results from the regulated emissions testing is also given below as Table 3.

Table 3. Regulated emissions test, average results

Taxi	DPF	Emissions				Fuel Consumption
		CO (g/km)	HC (g/km)	NO_X (g/km)	PM (g/km)	(l/100km)
1	No	1.197	0.024	1.435	0.247	10.3
1	Yes	1.502	0.036	1.297	0.004	9.6
2	No	1.121	0.110	1.365	0.148	8.9
2	Yes	0.676	0.085	1.441	0.009	9.3
3	No	0.304	0.023	1.460	0.076	9.8
3	Yes	0.491	0.023	1.375	0.006	9.9
4	No	0.727	0.182	1.297	0.172	8.5
4	Yes	0.781	0.200	1.273	0.029	8.8

NO_X SPECIATION ANALYSIS

With the increased use of diesel after-treatment systems containing a precious metal catalyst concerns are now being raised regarding the amount of NO_2 produced by such systems. As the DPF/FBC system employed on the taxis within this programme did not contain any precious metals it was considered unlikely that there would be any additional NO_2 produced. To quantify any effect of the after-treatment system upon the NO_2 emissions NO_X speciation was performed whilst the vehicles were being driven to the regulated emissions test procedure.

The NO_X speciation was performed using a Nicolet FTIR analyser. The equipment was configured to analyse the dilute exhaust gas providing a second by second analysis of the major NO_X species. This technique allows identification of which parts of the driving cycle produce which species of NO_X and during which parts of the cycle the NO_X emissions are affected by the DPF/FBC system.

Figure 1 shows the total NO_X and vehicle speed for the first elemental urban drive cycle for taxi # 3. This data is the average of the triplicate testing and clearly shows NO_X peaks during accelerations and troughs during decelerations. It is also evident that the exhaust system and the dilution tunnel have a damping effect (delay and diffusion in time). This phenomenon has been studied in detail with regard to heavy-duty vehicle emissions testing (17) by other researchers. Whilst the behaviour is thought to be the same for all gaseous species the behaviour may change significantly for particulate matter as discussed later in the paper.

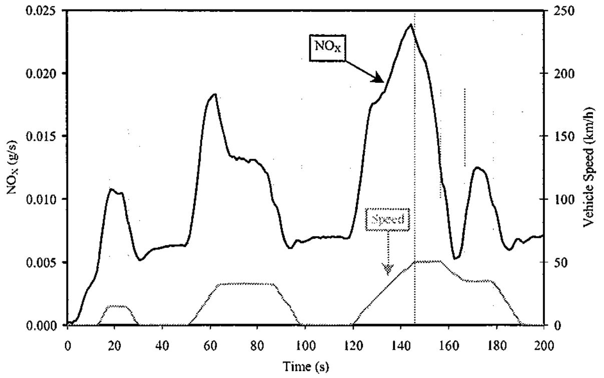

Figure 1: Average NO_X emissions at start of cycle

Figure 2 shows the total NO_X emissions over the complete urban drive cycle (UDC) and extra urban drive cycle (EUDC). Again the data are for taxi # 3. The data from each of the three emissions tests are presented along with the vehicle speed. This chart clearly shows the excellent test to test repeatability of the technique.

It is also apparent from Figure 2 that there is little change to the total NO_X emissions as the vehicle warms up, i.e. there is little difference between each elemental urban drive cycle. It is also evident that a large portion of the total NO_X emissions occur during the extra urban drive cycle, in fact approximately half of the total NO_X emissions occur during the EUDC. For taxi # 3 the averaged FTIR results show 52.9% of the total NO_X emissions occur during the UDC and 47.1% during the EUDC. From the regulated test bag analysis 50.0% of the total NO_X emissions occur during the UDC.

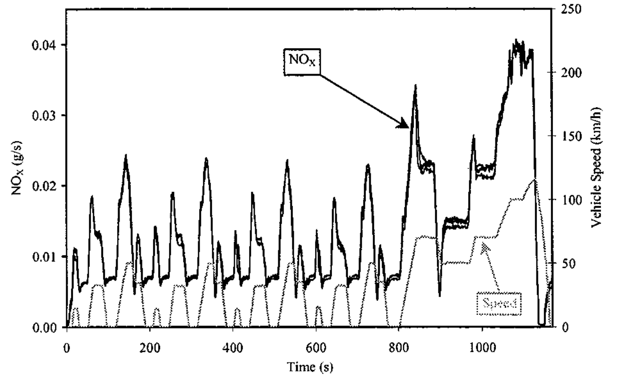

Figure 2: Repeatability of NO_X measurements

Figure 3 shows the corresponding NO_2 data. Again there is excellent test to test repeatability. However, with the NO_2 data there is an obvious warm-up effect and a greater proportion of the NO_2 is produced during the UDC. For taxi # 3, 67.9% of the NO_2 was produced during the UDC and only 32.1% during the EUDC.

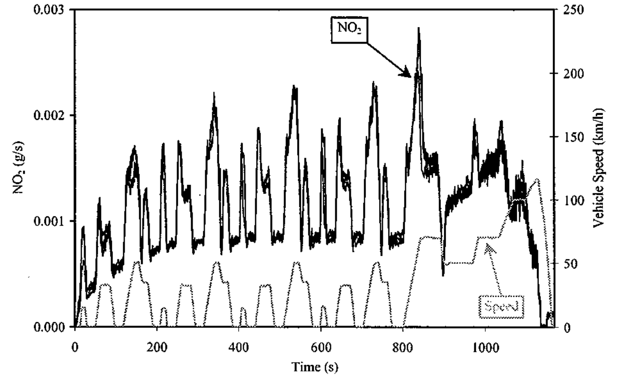

Figure 3: Repeatability of NO_2 measurements

As the test to test repeatability of the FTIR measurements was so high it was considered reasonable to take the average of the three tests at each one second interval in order to determine an average profile. This has been done and further discussion will be based on the average values for each vehicle configuration. Summing these values over the test cycle gives a value of total mass for the complete cycle which can be compared with the total mass per cycle from the bag analysis used for the regulated test. This has been done for CO and NO_X and the results of this comparison are presented in Table 4 along with the NO_2 values from the FTIR analysis.

As can be seen from Table 4 there is generally good agreement between the two methods and there is no systematic error. Taxi # 2 with DPF/FBC and taxi # 4 are the exception with significant differences between the two methods. No explanation for this can be given.

Table 4. Comparison of FTIR and bag average results

Taxi	DPF	Bag values		FTIR values		
		CO (g)	NO_X (g)	CO (g)	NO_X (g)	NO_2 (g)
1	No	13.09	15.63	13.22	16.20	1.33
1	Yes	16.34	14.11	15.17	14.30	1.06
2	No	12.18	14.82	11.68	14.79	1.57
2	Yes	8.64	14.08	7.24	15.71	0.74
3	No	3.32	15.92	3.28	16.29	1.34
3	Yes	5.34	14.95	5.31	15.61	0.87
4	No	8.03	14.33	11.48	11.20	1.70
4	Yes	7.34	15.65	8.37	13.60	1.76

VEHICLE TO VEHICLE VARIATION

Taxi # 1 and Taxi # 3 had the same type of engine and transmission and as can be seen from Table 3 and Table 4 these two vehicles produced very similar NO_X emissions levels. With the standard exhaust Taxi # 3 produced less than 2 % more NO_X mass than Taxi # 1 by either the FTIR method or bag analysis.

Taxi # 4 had the same engine type but had a manual transmission and was an older and much higher mileage vehicle. Again the basic emissions profile was the same but Taxi # 4 showed much lower emissions levels. From the regulated emissions test bag analysis Taxi # 4 produced 8.3 % lower NO_X emissions than Taxi # 1, however by the FTIR method the NO_X emissions were 30.9 % lower, this being one of the examples of a significant discrepancy between the conventional bag analysis and the FTIR.

The NO_X comparison between Taxi # 1 and Taxi # 2 is shown in Figure 4. Although by comparing Taxi # 2 to Taxi # 1, gives a reduction of 5.2 % and 8.7 % by the bag analysis and the FTIR method respectively, there were significant differences in the NO_X emission characteristics. Taxi # 2 had a slightly smaller capacity engine and was equipped with EGR. During a large portion of the test cycle the EGR operated to reduce the NO_X, typically by about 50%. However during the initial start phase and the idle phases of the cycle Taxi # 2 produced noticably higher NO_X emissions than Taxi # 1.

Also during the accelerations in the EUDC phase of the cycle the NO_X emissions from Taxi # 2 were significantly higher than for Taxi # 1. On a second by second basis Taxi # 2 produced anything from 8% to 348% of the NO_X emissions of Taxi # 1.

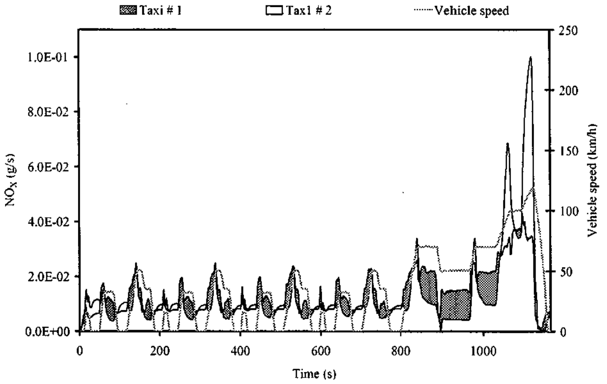

Figure 4: Taxi # 1 v Taxi # 2 NO_X measurements

As with the total NO_X, Taxi #1 and Taxi # 3 exhibited very similar trends and levels of NO_2 emissions, but with Taxi # 3 again producing marginally lower levels. From the FTIR analysis Taxi # 3 produces 0.55% lower NO_X and 0.75% lower NO_2.

Whereas Taxi # 4 produced lower levels of total NO_X emissions compared to Taxi # 1 and 3, but produced a similar emissions profile, Taxi # 4 produced significantly higher NO_2 with a different profile. Taxi # 4 produced far higher levels of NO_2 during the high speed portion of the EUDC phase.

The NO_2 emissions profile for Taxi # 4 was more akin to the profile for NO_X emissions than to the profile for NO_2 for Taxis # 1 and 3. This is illustrated by plotting the NO_2/NO ratio for the three taxis as shown in Figure 5.

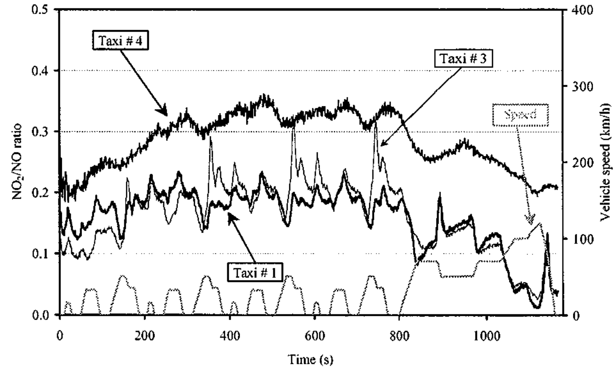

Figure 5: NO_2/NO ratios for Taxis # 1, # 3 & # 4

Taxi # 1 gave a NO_2/NO ratio of approximately 0.15 to 0.25 during the UDC, dropping to 0.1 to 0.2 during the first part of the EUDC and finally falling to less than 0.1 over the higher speed portion of the EUDC. Taxi # 3 showed a similar trace with 0.15 to 0.30 during the UDC and producing very similar values to Taxi # 1 during the EUDC phase. Taxi # 4 however was significantly different with NO_2/NO ratios generally above 0.2 during the entire cycle. There was a general upward trend during the UDC phase followed by a general downward trend during the EUDC phase, however there was not the significant drop in the NO_2/NO ratio during the high speed portion of the EUDC phase that was seen with Taxi # 1 and # 3.

As with the NO_X there was a significant difference between Taxi # 2 and Taxi # 1. Overall Taxi # 2 produced 18% more NO_2 than Taxi # 1 despite producing 9% less NO_X. This was not totally unexpected as the lower combustion temperatures produced by the EGR tend to shift the equilibrium of the $2NO_2 \leftrightarrow 2NO + O_2$ reaction in favour of the NO_2. Thus Taxi # 2 produced higher levels of NO_2 during most of the cycle. Taxi # 2 produced lower levels of NO_2 emissions on the lower speed accelerations and on the cruise parts of the EUDC cycle.

This phenomenon can clearly be seen in Figure 6 which shows the NO_2/NO ratio for Taxi # 1 and # 2.

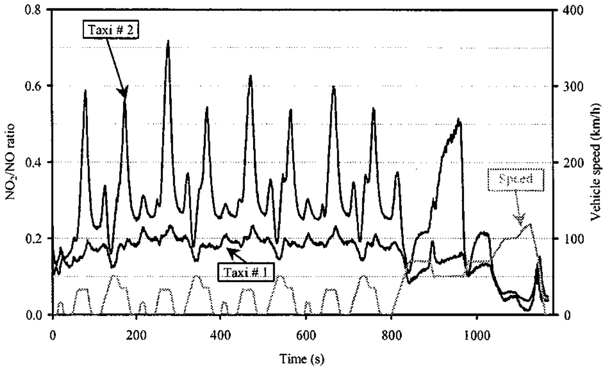

Figure 6: NO_2/NO ratios for Taxis # 1 & # 2

As noted above Taxi # 1 gave a NO_2/NO ratio of approximately 0.15 to 0.25 during the UDC, dropping to 0.1 to 0.2 during the first part of the EUDC and finally falling to less than 0.1 over the higher speed portion of the EUDC. Taxi # 2 however was significantly different with NO_2/NO ratios generally above 0.25 during the UDC with a peak value of 0.72. Again during the first part of the EUDC Taxi # 2 produced NO_2/NO ratios of about 0.2 to 0.5 but matched those of Taxi # 1 during the high speed portion of the EUDC phase.

BENEFIT OF USING THE DPF AND FBC

The taxis were re-tested after fitting the DPF and using the FBC. The results over the combined cycle are given in Table 4 above whilst the data throughout the cycle are analysed below.

For Taxi # 1, using the DPF/FBC reduced the total NO_X emission by 10% and 12% by the regulated and FTIR methods respectively. Figure 7 shows that this benefit was distributed evenly throughout the cycle.

Using the DPF/FBC system on Taxi # 3 produced a benefit, 6% and 4% by the regulated and FTIR methods respectively. Again the differences were fairly constant throughout the cycle. As these two vehicles used the same engine and transmission systems this similarity is to be expected.

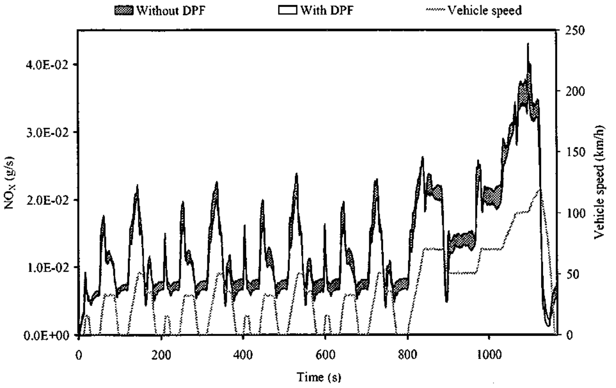

Figure 7: Taxi # 1, NO_X emissions with and without DPF

Taxi # 4 however showed an increase in NO_X mass emissions by both the regulated test and the FTIR method when the DPF/FBC system was used. The increase in NO_X emissions occurred throughout the cycle as shown in Figure 8. It is interesting to note however that although Taxi # 4 produced a higher mass of NO_X in the bag of the regulated test the NO_X emission rate in terms of g/km were actually lower when the DPF/FBC system was fitted, see Table 3. As correcting the mass of NO_X in the regulated bag to g/km shows a reduction in NO_X from fitting the DPF/FBC system it is assumed that if the FTIR result could also be corrected there would also be a benefit from the DPF/FBC system. However, on balance it must be assumed that the effect of the DPF/FBC system is neutral on NO_X emissions when applied to this particular vehicle.

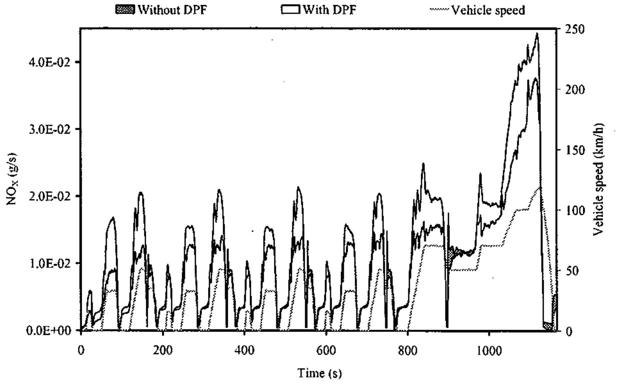

Figure 8: Taxi # 4, NO_X emissions with and without DPF

Taxi # 2 showed a 5% reduction in NO_X mass by the regulated method. This corrected to a 5% increase in terms of g/km, as shown in Table 3, so again it must be concluded that the effect of the DPF/FBC is neutral on this vehicle also. The second by second trace showed no major variations in the profile and it is assumed that such small differences in overall mass are within the workings of the test method.

Figure 9 shows the NO_2 data for Taxi # 1 with and without the DPF. From Table 4 the benefit of using the DPF/FBC was a 20% reduction in NO_2, however from the chart it is clear that the reduction was not uniformly distributed through the cycle.

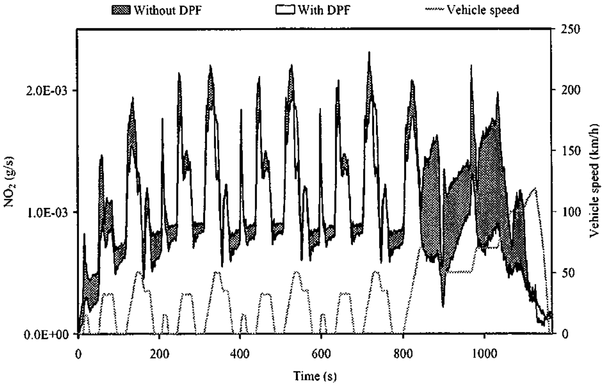

Figure 9: Taxi # 1, NO_2 emissions with and without DPF

There was clearly a far greater reduction in NO_2 emissions during the EUDC phase of the cycle. For Taxi # 3 the benefits were even greater, using the DPF/FBC reduced the NO_2 by 35% and again the benefit was greatest during the EUDC phase of the cycle. This is clearly illustrated in Figure 10, which shows the reduction in grammes of NO_2 throughout the cycle along with the corresponding speed trace.

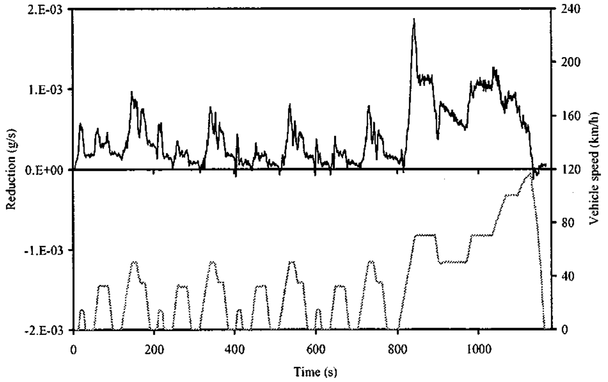

Figure 10: NO_2 reduction for Taxi # 3

Taxi # 4 produced a 3.5 % rise in NO_2 emissions with the fitting of the DPF/FBC system. Again the differences were not uniformly distributed throughout the cycle. There was an increase in NO_2 emissions during the UDC phase but there was a reduction in NO_2 during the EUDC phase. This is shown in Figure 11.

A possible explanation for the significant benefit during the EUDC phase is that at the higher temperatures experienced during the EUDC phase of the cycle the NO_2 is acting as an oxidising agent on the trapped soot within the DPF. However as the favoured reaction mechanism is $2NO_2 + C \rightarrow 2NO + CO_2$ a corresponding increase in NO emissions would be expected. This did not occur, moreover there was in fact a slight decrease in NO emissions over the combined cycle and the EUDC cycle. Another possible mechanism is that the FBC affects the combustion process so as to generally reduce the NO_X production whilst also shifting the equilibrium of the $2NO_2 \leftrightarrow 2NO + O_2$ reaction in favour of the NO.

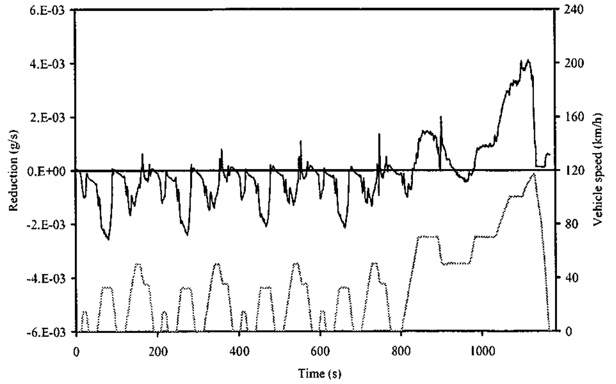

Figure 11: NO_2 reduction for Taxi # 4

Taxi # 2 however produced a reduction in NO_2 emissions throughout the cycle with only a marginally greater reduction during the EUDC phase. This is shown in Figure 12. It should be noted however that this vehicle produced a significantly different NO_2/NO ratio profile in standard form as shown in Figure 6. When the DPF/FBC system was fitted the large "spikes" in the NO_2/NO profile were reduced.

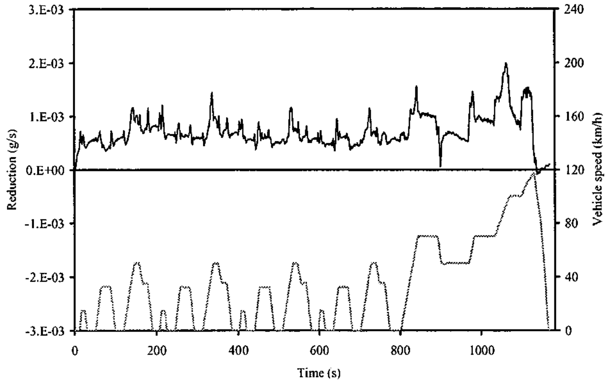

Figure 12: NO_2 reduction for Taxi # 2

Thus despite the fact that the regulated emissions test showed a 5.5 % increase in NO_X emissions as a result of fitting the DPF/FBC system and modifying the EGR rate, the NO_2 emissions were actually reduced by over 50 %. The average NO_2 reduction for the four taxis was 26 %.

PARTICLE SIZE AND NUMBER ANALYSIS

At present emissions of particulate matter from diesel engines is only regulated in terms of total mass. Particulate emissions from gasoline engines are not regulated in any way. However it is now well known that this particulate matter consists of particles of different sizes and composition and work has been done that suggests the health effects of these particulates is heavily dependent on their size (18).

To quantify the effects of fitting a DPF/FBC system to the taxis used in this study measurements were made of the number of particles emitted within a number of discrete size ranges. Measurements were made using a Dekati Electrical Low Pressure Impactor (ELPI) device.

The ELPI was used to determine the number of particles in each of twelve stages. The mean particle size for each of the ranges is indicated in Table 5 below. Also shown in Table 5 is the reduction in particle emissions or the filtration efficiency, in each of the stages for each of the taxis, as a result of using the DPF/FBC system.

The ELPI technique proved, in general to be reliable and repeatable. The instrument provides a second by second record of the particle number concentration for each of the twelve stages. One of the three tests with the standard exhaust on Taxi # 1 and one of the tests with the DPF/FBC system on Taxi # 3 and Taxi # 4 have been eliminated from further analysis. In these three cases the signal from the ELPI was lost partway through a test. This was not immediately apparent from the overall result, which only appeared low, but the loss of signal was readily apparent from the second by second trace.

Table 5 Particulate concentration reduction

	Size µm (D50%)	Taxi # 1	Taxi # 2	Taxi # 3	Taxi # 4
Stage 1	0.030	98.61	99.92	98.54	92.08
Stage 2	0.060	99.53	>99.99	99.11	99.87
Stage 3	0.105	99.65	>99.99	99.71	99.74
Stage 4	0.169	99.58	>99.99	99.49	99.51
Stage 5	0.259	99.52	>99.99	99.87	96.80
Stage 6	0.399	99.72	>99.99	99.79	92.82
Stage 7	0.647	99.73	>99.99	99.97	94.71
Stage 8	1.010	99.75	99.99	99.72	98.05
Stage 9	1.630	98.77	99.99	99.61	99.92
Stage 10	2.490	99.78	99.99	99.79	98.99
Stage 11	4.030	99.82	>99.99	99.92	98.88
Stage 12	6.690	99.71	>99.99	99.80	98.98

Figure 13 illustrates the repeatability of the method and also the difference between vehicles. The chart shows the particle emissions rate for stage 5 over the first 200 seconds of the test cycle, for two of the vehicles fitted with the standard exhaust system.

Taxi # 1 and Taxi # 3 showed similar characteristics but with Taxi # 3 emitting about a half an order of magnitude less particles than Taxi # 1. This was generally true throughout the particle size range. Also with these smaller particles (stage 5 has a mean aerodynamic diameter of 250 nm) there was relatively little variation in particle emissions rate through the cycle.

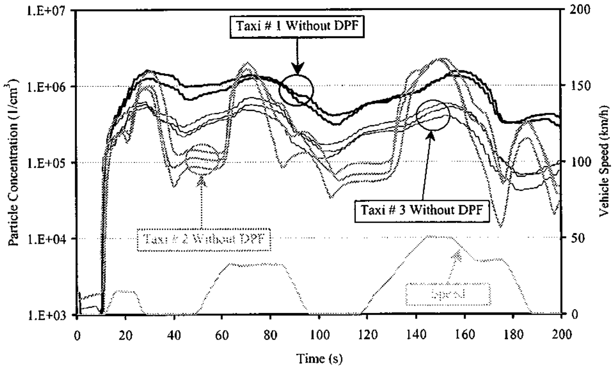

Figure 13. Particle emissions rate for standard exhaust

Taxi # 2 produced larger variations in particle emissions rate throughout the cycle for all size ranges. It is not yet understood whether this was as a result of the exhaust system geometry or was a result of the EGR valve operation, or both.

BENEFIT OF USING THE DPF AND FBC

Figure 14 shows the effect of using the DPF/FBC system on the particle emissions rate through the size range. The chart shows the sum of the emissions over the full emissions test cycle. These data are for Taxi # 1 and Taxi # 3 which had the same engine/transmission configuration and would thus be expected to produce similar results. However it should be noted that in terms of particulate mass emissions by the regulated procedure Taxi # 3 produced only 31 % of the emissions of Taxi # 1. In terms of the number of particles emitted, when averaged over the size range, Taxi # 3 produced only 22 % of the number of Taxi # 1.

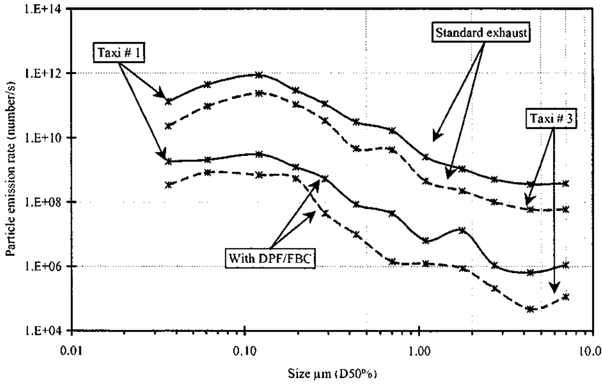

Figure 14: Taxi # 1 & Taxi # 3 with and without DPF/FBC

Both Taxi # 1 and # 3 showed a maximum emissions rate on stage 3 of the ELPI, i.e. with a mean diameter of approximately 120 nm, with the standard exhaust. With the DPF/FBC the number peak appeared to remain at stage 3 for Taxi # 1 but moved to stage 2, i.e. a mean diameter of approximately 60 nm, for Taxi # 3.

Taxi # 4 had the same engine type as Taxis # 1 and # 3 but had a manual transmission and was a far higher mileage example. Figure 15 shows the comparison between Taxi # 1 and Taxi # 4. The level of particulate numbers was actually closer between these two vehicles than between Taxi # 1 and Taxi # 3. This was in agreement with the regulated PM emissions, Taxi # 4 produced 70 % of the PM emissions of Taxi # 1. However there was a slight difference in the characteristics of the emissions in that there was an indication on Taxi # 4 of a bi-modal distribution with the DPF/FBC system in place, this may have been due to a higher volatile component in the emissions from the higher mileage vehicle.

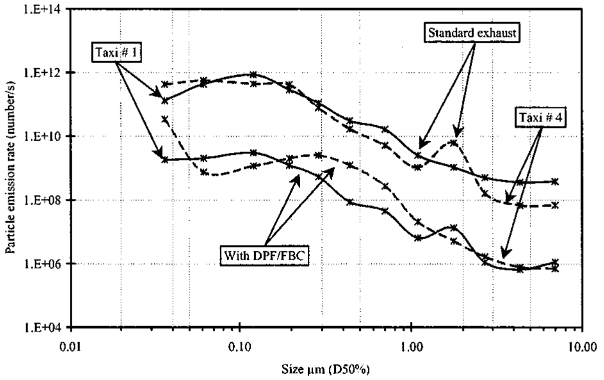

Figure 15: Taxi # 1 & Taxi # 4 with and without DPF/FBC

Figure 16 shows the comparison of particle size distribution for Taxi # 1 and Taxi # 2. In terms of particulate numbers Taxi # 2 with the standard exhaust produced far higher levels than Taxi # 1, yet by the regulated test procedure Taxi # 4 produced only 60 % of the PM mass emissions of Taxi # 1.

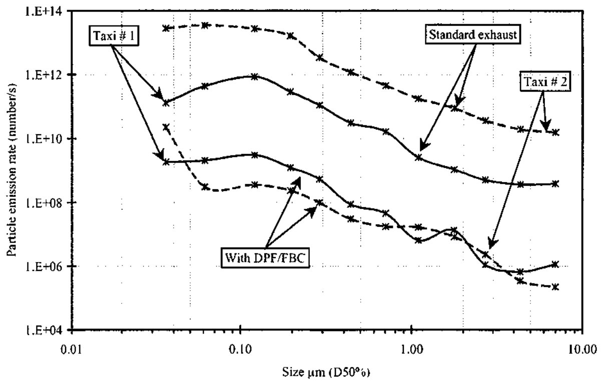

Figure 16: Taxi # 1 & Taxi # 2 with and without DPF/FBC

With the DPF/FBC system fitted the particulate numbers from Taxi # 2 were comparable with those of Taxi # 1, thus there was a higher filtration efficiency on Taxi # 2, as is clear from Table 5. Whether this improved filtration efficiency was a result of different morphology of the PM from the vehicle fitted with EGR, or was due to the fact that this vehicle had an 11.8 cm x 20.3 cm DPF as opposed to the 14.4 cm x 20.3 cm DPF fitted to the other three vehicles, is not yet fully understood.

How the DPF/FBC system affected the particulate emission rate throughout the test cycle is illustrated in the following two charts. Figure 17 shows the particle concentration for stage 3 throughout the cycle. Considering the without DPF situation, i.e. the standard exhaust, there were clear peaks and troughs in the emissions corresponding to the drive cycle. Peaks in the particle emissions tend to correspond to accelerations whilst troughs tend to correspond to periods of deceleration and idle.

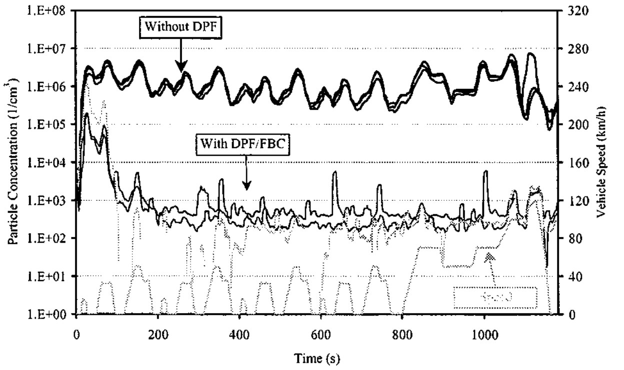

Figure 17: Taxi # 3 with and without DPF/FBC, stage 3

Due to the way in which a diesel fuel injection pump operates there will be no fuel supply, and hence no combustion during a deceleration. It would therefore be expected that the particle emissions would also drop to zero. This was evidently not the case for the particles measured in stage 3. For some of the higher stages this was the case, an example is shown in Figure 18, which presents data for stage 8. These data are for Taxi # 1.

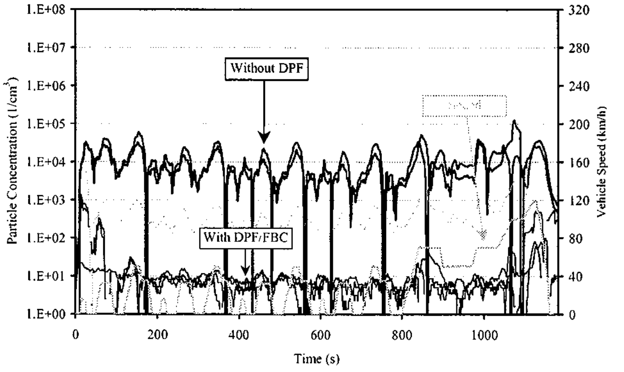

Figure 18: Taxi # 1 with and without DPF/FBC, stage 8

For stage 8 the concentration did drop to zero on occasions throughout the cycle, e.g. the deceleration at the end of each elemental urban cycle and at a number of points during the EUDC phase. The exact mechanisms producing these phenomena are not yet fully understood. One possible mechanism is that the smaller the particle the more it behaves as a gas and exhibits the same time diffused behaviour previously observed for gaseous emissions (17). Also due to the transient nature of the test it is likely that smaller particles will be deposited within the exhaust system due to thermophoresis (19) and later re-entrained as the exhaust gas temperature drops below that of the exhaust system. The deposition of particles is more likely to occur under acceleration or higher load conditions when the gas temperature is higher and engine-out particulate levels are also higher. Re-entrainment is then more likely to occur during decelerations when gas temperatures drop and engine-out emissions levels also drop. The trapping and release of particles within diesel exhaust systems has previously been observed for systems containing an oxidation catalyst (20) but systems containing DPFs have not been studied as extensively.

Considering the case where the DPF and FBC was used, it is clear from Figure 17 that not only were the levels of particulate emission lower by two to three orders of magnitude but also that the emissions were more constant, i.e. the damping effect previously mentioned is more pronounced. This was also the case for the larger particles as shown in Figure 18. This may be due to the increased surface area and thermal mass of the exahust system containing the DPF.

Similar patterns were shown by the other taxis. Figure 19 shows the data for ELPI stage 6 from Taxi # 2. As can be seen from this figure, Taxi # 2 produced larger variations in the concentration during the cycle. This again may be due to a difference in the morphology of the particulate from the vehicle equipped with EGR.

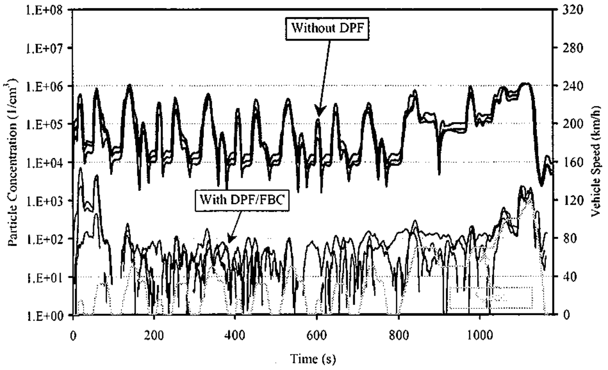

Figure 19: Taxi # 2 with and without DPF/FBC, stage 6

CONCLUSIONS

Four London taxis were tested with standard exhaust systems, they were then fitted with DPF/FBC system and re-tested. Fitting the DPF/FBC system reduced the NO_X emissions by up to 9.6 % on the taxis without EGR but produced an increase in NO_X emissions of 5.5 % on the taxi with EGR. However speciation of the NO_X emissions from this vehicle showed a reduction in the more harmful NO_2 emissions of greater than 50 %.

Although the benefit of fitting the DPF/FBC system was only a small reduction in NO_X the effect on NO_2 was generally much greater. The major reduction in the NO_2 emissions occurred during the high speed portion of the EUDC phase of the test cycle.

Fitting the DPF/FBC systems reduced the regulated PM emissions by between 83.3 % and 98.5 %. Particle size measurements showed that fitting the DPF/FBC system reduced the number of particles by between 92.1 % and over 99.99 %. These reductions also applied to the sub 100 nm particles.

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