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# Practical Experience of Fitting DPFs to Buses in Chile

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## ABSTRACT

Continuing research into the effect of vehicle emissions is driving legislation, which is increasingly being enacted to encourage the retrofitting of emissions control devices. Of particular concern are emissions of diesel particulate matter and nitrogen oxides. More recently the adverse effects of nitrogen dioxide in particular, have been highlighted. A programme of work is underway in Santiago to demonstrate the suitability of retrofitting diesel particulate filters (DPF) to urban buses. This paper presents data, including regulated and unregulated emissions, from a bus fitted with a DPF that relies on a fuel borne catalyst (FBC) to facilitate regeneration of the DPF.

## INTRODUCTION

The City of Angels, or Los Angeles in California, USA is infamous for its smog. Less well known is that Santiago, Chile suffers from a similar problem for similar reasons. The city is nestled in a basin formed by the foot hills of the Andes to the east and the Cordillera de la Costa to the west. This topography produces relatively stable atmospheric conditions which include winds of low velocity resulting in a fairly stagnant atmosphere. In the late autumn and winter this is exacerbated by an inversion layer which develops at about 600-900m above the city, and effectively traps the Santiago atmosphere, thus preventing the dispersion of pollution created within the city.

The population of Santiago is now approximately 5 million, with almost 1 million motor vehicles. Approximately 15,000 of these are urban buses to serve this increasing population. Many of these buses are diesel powered, with the engines designed to older emissions standards. This results in the majority of suspended particulate matter being attributable to mobile sources. Due to the combination of traffic density and topography, the airborne particulate concentrations in Santiago are amongst the highest in any urban environment, the annual average concentration for 1999 was  $74\mu\text{g}/\text{m}^3$  (1). An earlier study (2) showed that the  $\text{PM}_{10}$  concentration exceeded

$150\mu\text{g}/\text{m}^3$  throughout the winter. Figure 1 shows the 24 hour average  $\text{PM}_{10}$  concentration in Parque O'Higgins, Santiago on an hourly basis from 1997. This figure clearly shows the seasonal variation in  $\text{PM}_{10}$  concentration.

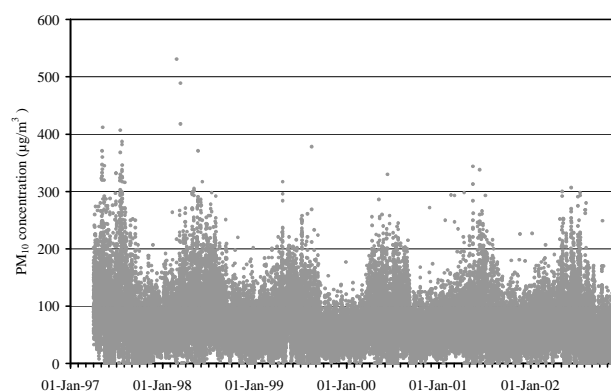


Figure 1.  $\text{PM}_{10}$  concentration in Santiago

Approximately 80% of the population of Chile is concentrated in the central valley region around Santiago with the metropolis of Santiago accounting for about a quarter of the total population of Chile. The impact of ambient air quality in Santiago thus has significant implications for the Chilean population as a whole.

A study of the relationship between air pollution and mortality in Santiago (3) concluded that a  $10\mu\text{g}/\text{m}^3$  change in  $\text{PM}_{2.5}$  was associated with a 0.8% change in all-cause mortality. An earlier study (4) had found a 0.75% increase in all-cause mortality for a  $10\mu\text{g}/\text{m}^3$  change in  $\text{PM}_{10}$ .

Another air pollutant of concern due to the low rates of atmospheric dispersion and the high levels of sunlight in this region is ozone. Ozone is not emitted but is formed in the atmosphere by the effect of sunlight on the other pollutants emitted to the atmosphere, particularly volatile hydrocarbons, often referred to as volatile organic compounds (VOC). Ozone is removed from the atmosphere by reactions with nitric

oxide (NO). This reaction reduces the ozone back to oxygen and oxidises the NO to nitrogen dioxide (NO<sub>2</sub>). The evidence for health effects of long term exposure to low levels of ozone are scant due to the difficulty of removing compounding factors such as the other pollutants that are inevitably present. However some studies (3) have suggested a significant association between high ozone levels and mortality. Another study has indicated a 5% increase in daily morbidity (upper respiratory illness) in association with a 25µg/m<sup>3</sup> increase in ozone levels (5). However it is accepted that reducing VOC and NO<sub>2</sub> emissions will reduce ozone levels and reduce possible health problems.

Nitrogen Dioxide in itself is of concern to epidemiologists. At high concentrations NO<sub>2</sub> is a poisonous gas, but even at low concentrations it is a strong oxidising agent. It is these strong oxidising qualities that encouraged its production in some diesel exhaust aftertreatment systems (6). It is likely that this high reactivity has also resulted in the association between exposure to NO<sub>2</sub> and increased incidences of bronchitis, pneumonia and other respiratory illnesses. Brazilian studies have also shown an association between exposure to NO<sub>2</sub> and intrauterine and child mortality (7, 8). A more recent study has also shown that high NO<sub>2</sub>/NO ratios increase the toxicity of particulate matter (9).

Given the concerns linked to the proven air quality results and the mortality projections, the Chilean authorities have acted to improve air quality by tackling mobile source pollution. Announced in January 2004, changes include giving responsibility to Transantiago, in the Ministry of Transport and Telecommunications, within the Government of Chile, for a complete overhaul of public transport in Santiago. The measures announced by Transantiago include:

- Changes to bus routes following analysis of traffic and passenger movements. Ten key routes resulted from the analysis
- Reduction in the number of bus operating companies from about 250, many with very few buses, to fifteen much larger organisations
- Removal of very old buses from the road, and a regulated age/use programme to monitor vehicles in service. The overall numbers of buses in use to be reduced from about 15,000 to a maximum of about 8000
- Programmes to test and approve appropriate filter technology, and implement the use of diesel particulate filters on all buses not meeting Euro III emissions standards
- Programmes to require new buses on certain routes passing right through the city centre.
- All new buses offered extended use/life arrangement where fitted with an approved particle filter system

- Provision of low sulphur diesel fuel during 2005 in Santiago to assist the operation of diesel particulate filters

The timetable for this ambitious programme of reform and air quality improvement required that companies offering emissions abatement equipment, generally DPF technology, were invited to take part in a vehicle trial during the middle of 2004. The trial was set up to demonstrate that candidate systems would achieve a reduction of at least 70% in mass of particulate matter (PM) in vehicle emissions tests carried out in Santiago, and in addition, that vehicles equipped with DPF systems would operate satisfactorily over a distance of at least 8000km, before emissions tests were repeated. Systems therefore had to meet the PM reduction target both at the beginning and end of test.

## VEHICLE SELECTION

A group of nine buses were selected from the Transantiago fleet. These buses were monitored to assess their normal operating exhaust temperature and back pressure profiles. The fuel and lubricant consumption of these buses were also measured, as was the opacity of the exhaust gas, and exhaust noise which is also closely regulated in Santiago. These buses operated over different routes leading to a wide variation in fuel consumption. Six of the nine buses monitored were of the same type. These were Mercedes-Benz MB OH 1420 buses with OM 366 LA engines rated at 140 kW. Despite the fact that all these buses were of the same type they exhibited significantly different levels of fuel consumption. This is shown in Table 1. Also shown in table 1 is the lubricant consumption of each of the buses as a percentage of the fuel consumption. Again there was a significant variation between the buses.

Table 1. Fuel and lubricant consumption and smoke opacity.

Licence Plate Route	Fuel consumption L/100 km	Lubricant consumption % of FC	Opacity m <sup>-1</sup>
UZ 2582 L 379	41.4	0.06	1.49
NR 4362 L 705	54.5	0.11	1.27
TE 3779 L 388	37.6	0.07	0.92
RR 1547 L 681	40.5	0.13	0.24
TF 5204 L 136	48.2	0.34	2.08
TT 2191 L 388	50.5	0.13	1.13

This information was used to match DPF technologies to the specific buses. It is known that some DPF technologies do not work well on vehicles with high lubricant consumption and high smoke emissions (10). However, it must also be remembered that although the trial was to be conducted using fuel with less than 50 mg/kg of sulphur, engine lubricating oil

frequently has a high sulphur content. A high lubricant consumption thus implies a significant burden of sulphur entering the DPF in the exhaust gas stream. This is potentially at least as big a problem as sulphur in the fuel, and may affect the durability of DPF systems employing platinum based catalysis.

With the above considerations in mind it was decided that the most suitable technology for the bus with the highest relative lubricant consumption and the highest smoke emissions was an uncatalysed DPF in combination with a fuel borne catalyst (FBC) to facilitate regeneration.

The selection and performance of DPFs for the other buses will be presented at a later date. The following sections describe the application of the DPF/FBC system to the “dirtiest” bus and demonstrate the emissions reductions available using DPF technology.

## SYSTEM OVERVIEW

The vehicle chosen for this investigation was the Mercedes-Benz OH 1420 bus shown in Figure 2.



Figure 2. Test bus

The bus was fitted with a Mercedes-Benz OM 366 LA engine. This unit is a 6 litre, turbocharged, direct injection engine. Further details are given in Table 2.

Table 2. Engine details.

Type	OM 366 LA
Cylinder arrangement	6 In-line
Bore	97.5 mm
Stroke	133 mm
Capacity	5958 cm <sup>3</sup>
Compression ratio	16.5 : 1
Peak Power	140 kW @ 2600 rev/min
Emissions specification	Euro II

These buses are fitted with a high level exit exhaust system to help disperse the soot emissions of the conventional vehicle. The external part of the exhaust system at the rear of the bus can be seen in Figure 3.



Figure 3. High level exhaust exit.

A photograph of the DPF installed in place of the original silencer unit, with vertical discharge tailpipe connection, is shown in Figure 4. The FBC container can be seen in the top right hand part of the picture.



Figure 4. DPF system installed in the bus

The DPF used in this application was a 28.6cm x 25.4 cm (11¼” x 10”) SiC honeycomb element comprising 7 segments, one central cylindrical segment and six segment cemented around it. The sleeved DPF element is fitted with ring clamps at either end to allow for easy removal and refitting at maintenance intervals. The filter centre body is incorporated into a combined silencer-DPF unit which also includes inlet and outlet end canning to match the dimensions of the original silencer unit.

The DPF system was fitted as a direct replacement for the original equipment silencer. Noise pollution from the bus traffic in Santiago has also been identified as a problem (11), therefore great care was taken to ensure that the DPF did not

increase the noise emitted by this bus. The inlet canning thus contains appropriate noise attenuation. The noise of the bus without DPF was checked using a Sonómetro Cirrus CR251B meter, and the noise was reassessed shortly after the DPF was fitted. The exercise was then repeated at the end of the trial, after completing 8000km. The results of these noise measurements are given in Table 3.

Table 3. Noise measurement results.

	Without DPF	With DPF
First measurement	98.4 dB(A)	94.3 dB(A)
Second measurement	98.4 dB(A)	93.4 dB(A)

As can be seen from the table above, the DPF system initially reduced the noise by 4.1 dB(A), i.e. it more than halved the noise emissions. This is because the dB scale is by definition logarithmic, thus a doubling of the sound pressure level results in an increase of 3dB(A). On the second set of measurements the reading without the DPF remained the same whilst the reading with the DPF showed a slight reduction in noise. It is postulated that this further reduction with the DPF system was due to a stabilisation of the soot cake deposited on the inlet canning of the DPF system, which would slightly reduce the resonance within the system.

The DPF system relied on a FBC to facilitate regeneration, but was to operate on the same ultra low sulphur diesel fuel as the rest of the fleet. For maximum operational flexibility and reliability, it was necessary to install an on-board dosing system for the FBC. A five litre FBC tank was installed in the engine compartment of the bus, with a proprietary electronically controlled dosing system. The FBC used was a commercial iron-based organometallic product. The target treat rate of the FBC was such as to yield an average of 20mg/kg of metal in the fuel. It was thus estimated that the FBC tank would need refilling at intervals of approximately 25,000 km to 30,000 km. Due to the high lubricant consumption of this particular bus it is also estimated that the DPF will need to be serviced at 50,000km to 60,000 km to remove the accumulated ash.

## EMISSIONS TEST RESULTS

Emissions testing was performed at the test laboratories of the centre for control and certification of vehicles (abbreviated generally to 3CV) in Santiago. Testing was conducted on a chassis dynamometer with a PDP dilution system and a Pierburg AMA 4000 gas analyser. As well as the regulated pollutant gases, NO<sub>2</sub> levels were also measured during the emissions tests. Particulate mass measurements were made using a Tapered Element Oscillating Microbalance (TEOM). Particulate number measurements were also made using a Scanning Mobility Particle Sizer (SMPS) and a Diffusion Charger (DC).

Measurements were made at a steady state operating condition of 60 km/h road speed with a dynamometer load of 30 kW. Smoke measurements were made under free acceleration and under load using a partial flow opacimeter.

As with the noise measurements given above, the emissions measurements were conducted on two occasions separated by a distance of 8000km, or about six weeks. The filtration efficiency of the DPF was defined as the reduction in mass or number as a percentage of the value without the DPF, the results are summarised in Table 4 below.

Table 4. DPF filtration efficiency

	First measurement	Second measurement
Particulate (Mass)	98.3 %	94.53 %
Particulate (SMPS)	99.9 %	N/A
Particulate (DC)	99.9 %	99.85 %

The filtration efficiency is defined as the reduction in emissions divided by the without filter emissions. The filtration efficiency in terms of mass is determined from the mass of particulate collected on a filter paper. This mass includes volatile material such as adsorbed hydrocarbons, sulphates and condensed water etc. Because the DPF is not designed to trap material in the vapour phase, some of which will subsequently condense out, the apparent filtration efficiency when calculated by mass is lower than when the number of solid cored particles is counted as determined by the DC and the SMPS. It should be noted that the SMPS will also count particles formed by the spontaneous nucleation of volatile materials if the sampling conditions are conducive to their formation. These phenomena are discussed more fully in various references such as (12, 13).

Although this data above is for a single steady state test point it is consistent with the result found by other authors using data from the ISO 8178 test method (14).

When the bus was tested without the DPF system the percentage of the NO<sub>x</sub> present as NO<sub>2</sub> was 1.7 % in the first test and 2.7 % in the second test. With the DPF fitted there was no NO<sub>2</sub> detected in either of the emissions tests. It has previously been shown (15) that an uncatalysed DPF using FBC for regeneration can significantly reduce NO<sub>2</sub> emissions. The fact that this system appears to eliminate NO<sub>2</sub> totally, is attributed to the low percentage of NO<sub>2</sub> in the engine-out NO<sub>x</sub> coupled with the fact that no Pt is employed in this DPF system. It is well established that the use of Pt to assist DPF regeneration results in the production of NO<sub>2</sub> within the DPF system, and can cause significantly increased NO<sub>2</sub> tailpipe emissions.

Fitting the uncatylised DPF also showed a significant reduction in unburned hydrocarbon (HC) emissions. Reductions of 60% were observed on the first set of tests. No HC results were available for the second set of tests. The combination of reduced NO<sub>2</sub> and HC emissions should help to reduce ozone levels. It has been shown that further reductions in HC and NO<sub>x</sub> emissions can be achieved by the use of a base metal catalytic coating applied to the DPF (16).

Although fuel consumption was not measured directly during the testing and the bus has not been back in service long enough to provide a definitive answer, the CO<sub>2</sub> measurement taken during the emissions testing showed a 4.2% and 4.6% reduction in CO<sub>2</sub> emissions with the DPF fitted, on the first and second test respectively.

## OPERATIONAL SERVICE

At this point in time the bus has been in service for only a limited time. Data from the dosing system control unit indicates that the system is functioning correctly. The instantaneous exhaust back pressure rises and falls with operating duty and tends to mask the trends due to soot accumulation. An hourly maximum of the exhaust back pressure over the first 500 hours of operation is shown in Figure 5.

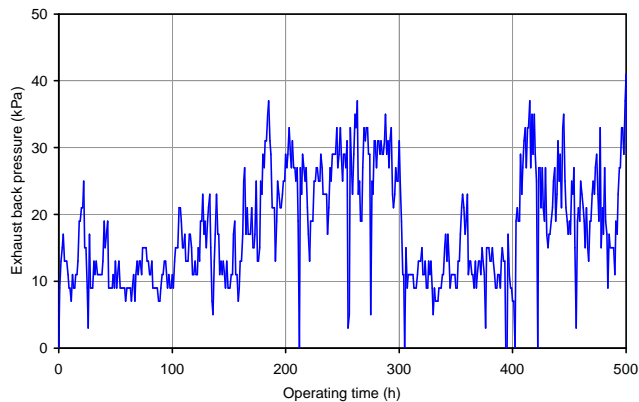


Figure 5. Hourly maximum back pressure values.

As can be seen from the chart in Figure 5 the back pressure tended to rise for the first 300 hours. This suggests that when the DPF regenerated during this period the regenerations were not complete, i.e. not all of the trapped soot was oxidised. After about 300 hours of operation it appears that a complete regeneration has taken place and the back pressure has fallen back to the level of the new DPF. The bus then undergoes about a further 100 hours of operation with fairly regular regenerations returning to the almost clean condition. There then follows a period of time where the regenerations do not run to completion resulting in higher levels of back pressure. At present the maximum exhaust back pressure is comparable to that measured on the bus before the DPF was fitted.

## CONCLUSION

Previous work has indicated that soot emissions from diesel powered vehicles in Santiago are probably causing increased

mortality. The retrofitting of DPFs to diesel vehicles in other countries has been shown to reduce the emissions of the fine particles which cause these problems by over 90%. An exercise is underway to demonstrate that similar results can be achieved in Santiago. This paper has considered the retrofitting of a FBC based DPF system to an urban bus in Santiago and from this work the following conclusions are drawn:

- The fitting of a DPF can reduce the mass of particulates emitted by over 90%
- The DPF can reduce the number of particles emitted by over 99%.
- The DPF/FBC system can significantly reduce NO<sub>2</sub> tailpipe emissions.
- There is no apparent fuel economy penalty from use of the DPF/FBC system.
- The DPF system is a direct replacement for the original equipment silencer and shows a meaningful reduction in noise emissions.
- The system appears durable even though it has been fitted to one of the most polluting buses in the fleet.

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