NO₂ Emissions From A CRT® Filter-Equipped Truck in Simulated Public Environments

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Summary

The control of Particulate Matter (PM) emissions from Heavy Duty Diesel (HDD) vehicles represents an important challenge, both in terms of improving the environment and in terms of meeting incoming legislation. The Continuously Regenerating Technology (CRT® filter) system provides a large number of environmental benefits, including reductions in Carbon Monoxide (CO), Hydrocarbon (HC) and Particulate Matter (PM) emissions of between 80 and 100%. This technology also reduces the emissions of the so-called nanoparticles (ultrafine particles) from diesel exhaust by between two and three orders of magnitude. These nanoparticles have been linked in some studies to mortality in humans.

The CRT filter system operates by converting a proportion of the engine-out NO into NO₂; this NO₂ then combusts the PM at temperatures much lower than those at which oxygen combusts this PM. This principle enables the continuous removal of PM from diesel exhaust under normal operating conditions for most applications. (Combustion in oxygen only occurs at temperatures significantly above those experienced in normal driving cycles.) During the reaction between the NO₂ and the PM, the NO₂ is converted back into NO.

However, under certain conditions, some of this NO₂ can pass unconverted through the CRT filter system and is subsequently released into the environment. These emissions are the subject of this report. Johnson Matthey commissioned IVL, the Swedish Environmental Research Institute, to perform a series of tests on a truck equipped with a CRT filter system. These tests were designed to determine the level of exposure to NO₂ that may be experienced by the public in a traffic environment.

Two traffic situations were simulated. The Drive-by test simulated the NO₂ levels that a pedestrian might be exposed to as a truck or bus, fitted with the CRT filter system, drove by. The Truck stop test simulated the exposure associated with a prolonged time (45 seconds) at idle following a period of city driving; such a situation corresponds to a bus collecting passengers from a bus stop, or a vehicle stopping at a set of traffic lights.

Measurements of the NO₂ concentration were made at a number of fixed positions as the truck drove by or idled. In every case, the NO₂ emissions from the system, when averaged according to the prescribed legislated protocol, were substantially below the European NO₂ exposure guideline levels (which are based upon World Health Organisation (WHO) recommendations).
**Introduction**

The control of Particulate Matter (PM) emissions from heavy duty diesel vehicles is an important issue, both in terms of improving the environment and in terms of legislation. The progressive tightening of the emissions standards for heavy duty diesel vehicles worldwide (Europe, North America and Japan) presents challenges for the engine development and emissions control communities. One system which has been developed to control PM emissions is Johnson Matthey’s CRT filter system. This works on the principle that NO\(_2\) combusts PM at much lower temperatures (approx 275-300°C) than does O\(_2\) (approx 550°C) [1, 2], which enables continuous removal of PM at temperatures which are readily accessed on most heavy duty applications. However, since the majority of the NO\(_x\) which is generated within the engine is in the form of NO, this NO must be oxidised into NO\(_2\) before it can react with the PM at such low temperatures. Therefore, the CRT filter system comprises an oxidation catalyst in front of a Diesel Particulate Filter (DPF) – the oxidation catalyst converts a portion of the NO into NO\(_2\) which reacts with the PM trapped on the downstream DPF. This oxidation catalyst also oxidises CO into CO\(_2\) and oxidises Hydrocarbons (HC) into water and CO\(_2\). The performance of the CRT filter system on a typical Euro I/II engine over the European Stationary Cycle (ESC) is summarised in Table 1.

**Table 1: Performance of the CRT filter system over the ESC on a Euro I Engine**

<table>
<thead>
<tr>
<th>Technology</th>
<th>HC</th>
<th>CO</th>
<th>NO(_x)</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Baseline</td>
<td>0.162</td>
<td>0.989</td>
<td>7.018</td>
<td>0.163</td>
</tr>
<tr>
<td>Engine + CRT</td>
<td>0.003</td>
<td>0.002</td>
<td>6.874</td>
<td>0.008</td>
</tr>
<tr>
<td>EU 2005 Limits</td>
<td>0.460</td>
<td>1.500</td>
<td>3.500</td>
<td>0.020</td>
</tr>
</tbody>
</table>

It can be seen that the CRT filter system removes almost all of the PM emitted from the engine, as well as removing almost all of the CO and HC. In addition, a small amount of NO\(_x\) conversion is also observed (typically between 2 and 10%, depending upon the engine type and test cycle etc), but it should be noted that the vast majority of the NO\(_2\) which reacts with the PM is converted back to NO, not into N\(_2\). However, the critical feature is the outstanding conversion of PM, CO and HC, with the concomitant improvements in the environment.

There has also been speculation that it is the very small ("ultrafine") particles within the particulate emissions which pose most risk to human health. It has been shown that the CRT filter is highly effective at removing PM all across the particle size range, including these ultrafines [3].

Therefore, there are numerous benefits, both to the environment and, potentially, to human health, associated with the fitment of the CRT filter to heavy duty diesel vehicles.

The CRT filter system has been fitted to over 10,000 heavy duty diesel vehicles in Europe as a retrofit technology over the last six years. One requirement of the CRT
filter system is that the sulphur level in the fuel must be very low (ideally below 10ppm) for optimum performance. As the fuel sulphur level increases, the ability of the catalyst to generate NO\textsubscript{2} decreases (which affects performance, particularly at low temperatures), and the sulphate emissions from the system also increase [2]. This requirement for very low fuel sulphur levels meant that the first CRT filter field trials were carried out in Sweden, where MK1 diesel fuel, with a sulphur level of 2-4ppm was introduced in 1991. Following on from the success of these trials CRT filter usage spread within Sweden; this rate of CRT filter application was increased by the introduction of the Swedish environmental zones, which require that all heavy duty diesel vehicles operating within the cities of Stockholm, Gothenburg and Malmo must have better than Euro II emissions or have at least 80% PM and 60% HC conversion (with reference to the engine-out levels).

As outlined above, a major feature of the CRT filter system is its ability to convert NO into NO\textsubscript{2} to enable the low temperature conversion of PM. Under some conditions a proportion of this NO\textsubscript{2} can pass unconverted through the CRT filter system and is subsequently released into the environment. This effect has been discussed by a number of authors [4, 5], and is the subject of this report.

Johnson Matthey commissioned IVL, the Swedish Environmental Research Institute to perform a series on tests to investigate the NO\textsubscript{2} emissions from the CRT filter system. These tests were designed to determine the level of exposure to NO\textsubscript{2} that may be experienced by the public in a traffic environment.

As a guide, the recommended European ambient air quality guidelines for NO\textsubscript{2} (based on World Health Organisation (WHO) recommendations) are shown in Table 2, along with the Swedish NO\textsubscript{2} ambient air quality guidelines.

<table>
<thead>
<tr>
<th>NO\textsubscript{2} Guideline Level</th>
<th>Averaging Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Guidelines</td>
<td></td>
</tr>
<tr>
<td>200 µg m\textsuperscript{-3}</td>
<td>1 hour, not to be exceeded &gt; 8 hours/year (2010)</td>
</tr>
<tr>
<td>40 µg m\textsuperscript{-3}</td>
<td>Annual by 2010</td>
</tr>
<tr>
<td>Swedish Guidelines</td>
<td></td>
</tr>
<tr>
<td>110 µg m\textsuperscript{-3}</td>
<td>Maximum 88 hours per 6 months</td>
</tr>
<tr>
<td>75 µg m\textsuperscript{-3}</td>
<td>Maximum 4 days per year</td>
</tr>
<tr>
<td>50 µg m\textsuperscript{-3}</td>
<td>Winter mean</td>
</tr>
</tbody>
</table>

Table 2: Comparison of Recommended NO\textsubscript{2} Air Quality Guidelines for Europe (based on WHO Guidelines with EU DC/DG XI Recommendations) and Swedish Ambient Air Quality Targets
Experimental Details

All tests were carried out using a truck equipped with a CRT system. The CRT filter was installed on the truck several days before the test, and was therefore in a fresh state. In this state the amount of NO$_2$ generated by the catalyst will be at its highest. In addition, during these tests the filter will have been in a clean state, which again will maximise the amount of NO$_2$ released by the CRT filter system (since the NO$_2$ generated by the catalyst has very little carbon to react with, so it will pass through unreacted). Therefore, these tests represent a “worst case” scenario for NO$_2$ release from the CRT filter system. Two simulations were devised to assess the NO$_2$ concentration generated by such a vehicle as it drove by a specific spot (Drive-by simulation) and as it stopped after a period of city driving (Truck stop simulation). These tests were intended to simulate the NO$_2$ concentrations which could be experienced by a pedestrian as a bus or truck drives by on the road, and as the bus or truck comes to rest (eg at a bus stop or a set of traffic lights).

The tailpipe of the truck was located 1.0m behind the left front wheel of the truck, and was 0.5m above ground level. It was angled at 45° to the truck body, pointing backwards with respect to the direction of travel. The diameter of the tailpipe was 127mm. The tailpipe was on the side of the truck facing the analysers.

The NO$_2$ concentration was measured at specific sites in an area surrounding the truck and in this way it was intended to determine the events of highest NO$_2$ concentration and their location within the measurement grid. For the Drive-by and Truck stop simulations measurements were made at 1m intervals to a maximum of 3m away from the vehicle and at 5m intervals along the direction of travel of the truck. All measurements were made at a height of 1.5m above ground level. Figure 1 shows the layout of the measurement grid.

**Figure 1: Schematic Representation of the Analysis Positions Within the Measurement Grid**

Wind Direction

<table>
<thead>
<tr>
<th>Truck Stop</th>
<th>1 metre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of Travel</td>
<td>TRUCK</td>
</tr>
<tr>
<td></td>
<td>1 metre</td>
</tr>
<tr>
<td>5A</td>
<td>4A</td>
</tr>
<tr>
<td>4B</td>
<td>3B</td>
</tr>
<tr>
<td>4C</td>
<td>3C</td>
</tr>
</tbody>
</table>

| 5 metres |

---
Catalyst temperature and engine driving parameters were logged continuously during the tests to ensure that successive tests were reproducible. NO\textsubscript{2} concentration in the ambient environment is affected by atmospheric conditions, eg temperature, wind speed, humidity and light intensity. The wind speed was measured during the tests, and had an average value of around 2.5 m s\textsuperscript{-1}; the average humidity was 87\% and the temperature during the tests varied between \(-1.3\) and \(-1.7^\circ\text{C}\). Background NO\textsubscript{2} measurements were taken at regular intervals during the testing in both indoor and outdoor sites.

NO\textsubscript{2} measurements were made using an Eco Physics CLD 700 AL chemiluminescence detector, which enabled measurement of NO, NO\textsubscript{2} and total NOx. (The NO\textsubscript{2} levels were determined in the standard way, by subtracting the NO level from the total NOx value, since in this context NOx is defined as the sum of NO + NO\textsubscript{2} concentrations.) Data were logged continuously with a time resolution of 1 second using a Campbell model CR10 data logger. A chart recorder was also used as a back-up.

(a) Drive-by simulation
This test was designed to simulate the local concentration of NO\textsubscript{2} as a bus or truck accelerates past a given point. Measurements were made once a conditioning lap had been completed; this lap comprised a circular route of approximately 90m diameter, and ensured that the CRT filter system achieved a reproducible temperature prior to each measurement. The catalyst inlet temperature attained during these tests was between 300 and 350\degree\textsuperscript{C}, with some spikes to higher temperature (up to 400\degree\textsuperscript{C}). These temperatures are around the point at which the CRT filter catalyst converts the highest amount of NO into NO\textsubscript{2}. During these tests the truck approached the testing/measurement grid at a constant speed and then accelerated when level with the first measurement point in the grid. NO\textsubscript{2} was measured continuously during both the conditioning lap and the Drive-by simulation. Fourteen repeat measurements were performed to check the reproducibility of the measurements.

(b) Truck stop simulation
This test was designed to assess the levels of NO\textsubscript{2} generated as a truck or bus comes to idle after a period of city driving, before accelerating away. This test simulates the NO\textsubscript{2} levels which might be generated at a bus stop or a set of traffic lights. The truck completed the conditioning lap and was then brought to rest half-way between two of the measurement points in the grid. The truck then idled for a period of 45 seconds before accelerating away, driving at a distance of 1m parallel to the measuring grid. NO\textsubscript{2} was measured continuously during both the conditioning lap and the Truck stop simulation. Four repeat measurements were performed to check the reproducibility of the measurements.
Results and Discussion

The aim of the testing was to determine the average NO$_2$ concentration over averaging periods of 1 second, 10 seconds, 30 seconds and 2 minutes for comparison with the Guideline Levels shown in Table 2. These were determined by calculating running averages over the whole data set for each measurement point during each experiment. The maximum average NO$_2$ levels at each measurement point (i.e., the highest levels measured during the 14 repeat tests) for the Drive-by simulation are shown in Table 3.

Table 3: Maximum Average NO$_2$ Levels During the Drive-by Simulation

<table>
<thead>
<tr>
<th>Gridpoint</th>
<th>Maximum Average NO$_2$ Concentration (µg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 second</td>
</tr>
<tr>
<td>1A</td>
<td>6910</td>
</tr>
<tr>
<td>2A</td>
<td>1150</td>
</tr>
<tr>
<td>3A</td>
<td>420</td>
</tr>
<tr>
<td>4A</td>
<td>2300</td>
</tr>
<tr>
<td>1B</td>
<td>110</td>
</tr>
<tr>
<td>2B</td>
<td>360</td>
</tr>
<tr>
<td>3B</td>
<td>920</td>
</tr>
<tr>
<td>4B</td>
<td>1040</td>
</tr>
<tr>
<td>1C</td>
<td>90</td>
</tr>
<tr>
<td>2C</td>
<td>290</td>
</tr>
<tr>
<td>3C</td>
<td>640</td>
</tr>
<tr>
<td>4C</td>
<td>1130</td>
</tr>
</tbody>
</table>

Note that the time taken to drive the circuit between measurements was less than one minute, so the 2 minute average NO$_2$ values reported in Table 3 (which are already at low levels) represent exposure to two CRT filter-equipped vehicles.

The European NO$_2$ exposure guideline level is 200 µg m$^{-3}$ averaged over a period of one hour (not to be exceeded for more than 8 hours in a year). It can be seen that even when the measured values are averaged over just a 2 minute period (with the passing of two CRT filter-equipped vehicles), the NO$_2$ concentration levels at every point in the measurement grid (apart from gridpoint 1A) are well below this guideline level. The level at gridpoint 1A is slightly above this guideline value, but it has been averaged over only two minutes, not the full hour. It is clearly the case that averaging over one hour would lead to levels well below the European guideline figure. In addition, as stated above, the average NO$_2$ concentration levels reported in Table 3 represent the highest average levels measured in all 14 repeat tests of the Drive-by simulation. The average NO$_2$ concentration levels measured at gridpoint 1A (the point at which the highest levels of NO$_2$ were measured) during each of the 14 repeat experiments are shown in Figure 2. Note that gridpoint 1A is directly in the exhaust plume of the truck; it was, therefore, not surprising, that the NO$_2$ levels recorded here were significantly higher than those measured at any other position.
It can be seen that one data set gives NO₂ levels which are much higher than those measured during the 13 other tests so it seems reasonable to regard this one test as unrepresentative. Consideration of all 13 other experiments shows that even the 30s average is very close to the European one hour average exposure guideline of 200 µg m⁻³ (and is clearly below this level for some of the measurements), and the 120s average is well below the one hour guideline level. So for all positions, averaging over one hour would give levels massively below 200 µg m⁻³. Therefore, for the Drive-by tests the average NO₂ levels are well below the European guideline figures.

Table 4 shows the maximum average NO₂ levels at each measurement point (ie the highest levels measured during the 4 repeat tests) for the Truck stop simulation.

Table 4: Maximum Average NO₂ Levels During the Truck Stop Simulation

<table>
<thead>
<tr>
<th>Gridpoint</th>
<th>Maximum Average NO₂ Concentration (µg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 second</td>
</tr>
<tr>
<td>0A</td>
<td>1720</td>
</tr>
<tr>
<td>1A</td>
<td>7100</td>
</tr>
<tr>
<td>2A</td>
<td>2130</td>
</tr>
<tr>
<td>3A</td>
<td>850</td>
</tr>
<tr>
<td>4A</td>
<td>1850</td>
</tr>
<tr>
<td>5A</td>
<td>770</td>
</tr>
<tr>
<td>0B</td>
<td>850</td>
</tr>
<tr>
<td>1B</td>
<td>1990</td>
</tr>
<tr>
<td>2B</td>
<td>3910</td>
</tr>
<tr>
<td>3B</td>
<td>270</td>
</tr>
<tr>
<td>0C</td>
<td>410</td>
</tr>
<tr>
<td>1C</td>
<td>1480</td>
</tr>
<tr>
<td>2C</td>
<td>1390</td>
</tr>
</tbody>
</table>
Note that the time taken to drive the circuit between measurements was less than one minute, so the 2 minute average NO$_2$ values reported in Table 3 (which are already at low levels) represent exposure to two CRT filter-equipped vehicles.

Once again, it can be seen that, in general, the NO$_2$ concentration levels, averaged over a 2 minute period, are already below the European guideline of 200 µg m$^{-3}$ averaged over one hour. However, the NO$_2$ level at gridpoint 1A is significantly higher than this recommended level. The results shown in Table 4 represent the highest average values from the 4 repeat experiments performed using the Truck stop simulation. The average levels observed in each of the four experiments are shown in Figure 3.

Figure 3: Average NO$_2$ Concentrations Measured at Gridpoint 1A During 4 Repeat Truck stop Measurements

It can be seen that the NO$_2$ levels observed in the experiment giving rise to the highest concentrations were significantly higher than the levels obtained in the other experiments, but even in the experiment in which the lowest NO$_2$ levels were recorded, the 2 minute average is slightly higher than the European guideline level. It must, of course, be remembered that these data were recorded in a situation in which two CRT filter-equipped vehicles were passing the measurement point within 2 minutes. In addition, it is important to note that the European guidelines are for exposure over a one hour period. The data set containing the highest measured concentrations of NO$_2$ has been plotted against time, to assess the rate of decay of the NO$_2$ concentration. Figure 4 shows the trace as a function of time, and shows two fits to the data – one trendline has an exponential form, while the other has a logarithmic form.
It can be seen that the anticipated average NO\textsubscript{2} concentration over a 200-300 second period is expected to be significantly below the one hour European guideline level for NO\textsubscript{2}.

**Conclusions**

Experiments have been performed to determine the NO\textsubscript{2} levels associated with a CRT filter-equipped truck or bus in two scenarios: driving past a fixed position and resting at idle at a fixed position for 45 seconds after a period of city driving. In both cases the CRT filter catalyst temperature was between 300 and 400\textdegree C, which represents the temperature range over which the catalyst converts the highest proportion of NO into NO\textsubscript{2}.

These tests have shown that the measured NO\textsubscript{2} levels, when averaged over the prescribed one hour period, are substantially below the European NO\textsubscript{2} guideline level of 200 µg m\textsuperscript{-3}. Indeed, for the Drive-by simulation the NO\textsubscript{2} levels were below the European guideline when averaged over just 2 minutes. As expected, the average NO\textsubscript{2} levels were higher for the idling Truck stop simulation, but even here extrapolation of the measured NO\textsubscript{2} decay profile demonstrated that the concentration would fall below the European guideline level after between just 200 and 300 seconds.
References

1. BJ Cooper and JE Thoss, SAE 890404, “Role of NO in Diesel Particulate Emission Control”.

2. R Allansson, CA Maloney, AP Walker and JP Warren, SAE 2000-01-1875, “Sulphate Production over the CRT Filter: What Fuel S Level is Required to Enable the EU4 and EU5 PM Standards to be Met?”

3. PN Hawker, G Huthwohl, J Henn, W Koch, H Luders, B Luers and P Stommel, SAE 980189, “Effect of a Continuously Regenerating Diesel Particulate Filter on Non-Regulated Emissions and Particle Size Distribution”.
