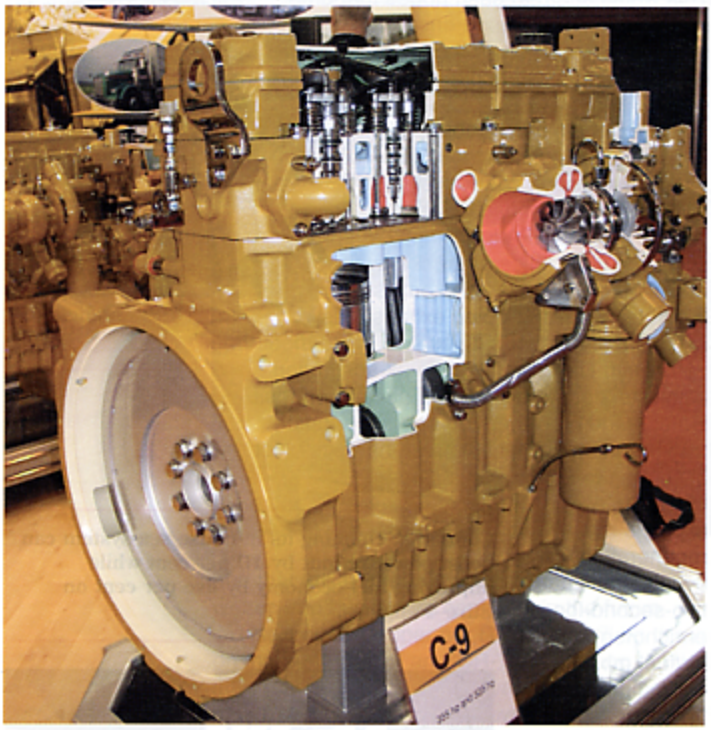
In November 1999 when the European Parliament signed off the legislation that fixed Euro-3, -4, and –5 emissions standards for heavy-duty diesel engines the one figure not cast in stone was the Euro-5 limit on oxides of nitrogen (NOx), applicable to newly type-approved vehicles from October 2008. But it was agreed that 2g/kWh should be the provisional figure, to be reviewed by 31 December 2002 so that account could be taken of technological developments. Germany in particular was keen to push for faster progress towards lower NOx.

But last December's deadline came and went with no Euro-5 NOx limit finalised. As *Transport Engineer* went to press this month there was still no news. It is scarcely surprising that engineers at vehicle and engine manufacturers are growing more and more impatient, and increasingly worried that the 2g/kWh pencilled-in more than three years ago is about to be rubbed out, to be replaced by a much lower number, in ink. Germany's federal environmental agency, the *Umweltbundesamt* (UBA), has suggested a figure below 1g/kWh could be necessary if its national NOx target is to be met. This compares with the current (Euro-3) limit of 5g/kWh, to be cut to

Caterpillar: paying hefty penalties in the US now, but confident that its strategy will prove right in the long run, with "camless engines" already on trial.



3.5g/kWh by the Euro-4 legislation that comes into force in October 2005. The UBA is also pressing for far lower particulate emissions, and wants the Euro-5 limit cut to one tenth of the agreed published figure even though in theory the time for discussion is long past. Any change at this stage would involve complex and controversial manoeuvring by European Union law-makers.

But Euro-5 is by no means the end of the road. Euro-6 is under construction and likely to arrive between 2010 and 2012, almost certainly including a tougher NOx limit (echoing a US limit due in 2010) and a limit for the first time on total number of individual particles in the exhaust in addition to total mass of particulates emissions. This is concentrating engineers' minds on the number of very small particulates that are reckoned to be most harmful to health because they penetrate deeply into the lungs. There is also speculation that Euro-6 could introduce targets (not limits) on hitherto-unregulated exhaust emissions: ammonia and carbon dioxide (CO_2). Ammonia is in the spotlight already as a result of the introduction of urea- or ammonia-based selective catalytic reduction (SCR) de-NOx systems for Euro-4 and beyond. An excess of NOx-reducing ammonia gives rise to so-called "ammonia slip", so a limit on tail-pipe emissions of this toxic irritant could be on the cards, probably no higher than 10 parts per million (ppm). Proposals for a CO_2 limit are more straightforward, simply reflecting concern about climate change. Car emissions of this "greenhouse gas" have long been the focus of reduction targets, so it seems illogical to go on ignoring it with heavy-duty diesel engines.

A Euro-5 NOx limit lower than 2g/kWh would be unlikely to cause much engineering upset. Selective catalytic reduction (SCR) systems, the most popular means of cutting NOx for Euro-4 and –5, have proved themselves capable of getting into 1g/kWh territory, according to several published bench tests. And most after-treatment manufacturers voluntarily include catalysts to guard against ammonia-slip in SCR systems with high NOx-conversion rates. So an ammonia limit for Euro-6 probably would be similarly uncontroversial.

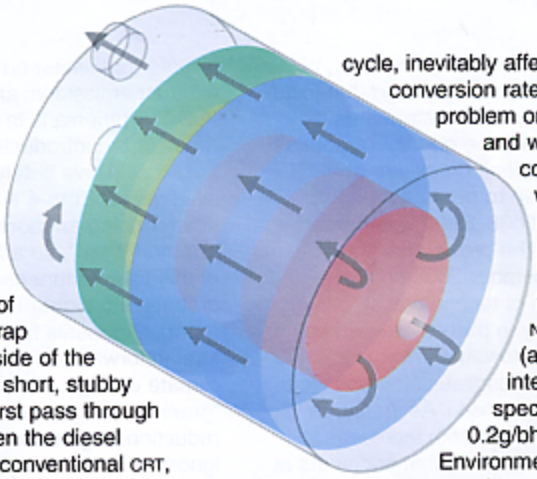
The ramifications of particulate numbers and lower particulate mass at Euro-6 are harder to predict, not least because legislators are still trying to find reliable ways of measuring ultra-fine particulates. Oxidation catalysts and traps are already good at reducing both the mass and number of particles above 10-microns in diameter (largely carbon) but PM2.5 particles (four times smaller) represent a much tougher technical challenge.

Compact and cheap

A more pressing problem facing engine manufacturers and exhaust after-treatment suppliers is how to translate impressive test-bench results into commercially-viable systems in good time for Euro-4 (taking effect in October 2005). This means minimising the equipment's capital cost; optimising its effect on fuel economy; and packaging it to take up as little space as possible while adding little or nothing to maintenance costs.

At the influential Society of Automotive Engineers international congress in Detroit, Michigan two years ago Johnson Matthey presented its SCRT system, a combination of the well-established particulate-reducing CRT (continuously-regenerating trap) and urea-injection selective catalytic reduction de-NOx equipment. The system's linear layout is not a problem on US truck and bus chassis with their generous dimensions. But Barry Cooper, vice president of Johnson Matthey's diesel emission control systems division (and co-inventor of the original CRT) admits that "you need a more compact arrangement for Europe because the truck chassis are so much shorter." At last month's SAE congress, Johnson Matthey's technical manager for heavy-duty diesel engines, Andrew Walker, was upbeat about the progress being made towards commercially-feasible exhaust after-treatment capable of meeting Euro-5 and US 2007 legislation. Dr Walker, based at Johnson Matthey's plant in Royston, Hertfordshire, is leader of a team of engineers from Johnson Matthey, Volvo Powertrain Corporation, Eminox and Bosch brought together to show what is possible with a compact, working

Exhaust emissions management in the round: Johnson Matthey's compact SCRT-trap wraps selective catalytic reduction and ammonia-slip catalysts around a particulate filter.



version of SCRT, in a single enclosure small enough to take up no more chassis space than a tractive unit's original exhaust silencer.

To shorten the linear SCRT into a stainless steel enclosure (made by Eminox) no longer than 620mm (24.4in), the last two stages of the Johnson Matthey SCR-Trap are wrapped around the outside of the first two stages to produce a short, stubby cylinder. So exhaust gases first pass through the oxidation catalyst and then the diesel particulate filter, much like a conventional CRT, running down the centre of the unit. Emerging from the filter, they pass into the end section of the enclosure, where the urea injection equipment (made by Bosch) is situated. Then the gases are turned through 180 degrees to be re-directed back around the outside of the central core to pass through a pair of encircling SCR catalysts mounted one after the other. Just before exhaust gases exit they pass through a fifth stage, an ammonia-slip oxidation catalyst.

Peter Lambe of Dinex: "Strength from flexibility to serve the aftermarket."

What effect does all this have on exhaust back-pressure? None, according to Dr Cooper. "The filter and the soot that accumulates on it is the main influence on back pressure, and that is no different from a CRT," he explains. The filter in the Eminox stainless steel enclosure can be withdrawn for cleaning.

Bench testing was carried out in Sweden, using a 12-litre Volvo D12C engine. This was a year-2000 engine, without the exhaust gas recirculation fitted to the latest US-specification engines, but recalibrated to minimise particulate emissions at the expense of higher NOX. Engine-out emission figures (before any after-treatment) highlight the effect of being able to abandon the normal NOX/PM balancing act. The PM figure was a mere 0.022g/kWh on the 13-mode European steady-state cycle (ESC), only 10 per cent above Euro-4 and –5 limits. But the flip side of this is a NOX figure pushing 7g/kWh, well above even the current Euro-3 limit of 5g/kWh. One benefit of the low PM figure is that the CRT section in the core of the enclosure can be small.

The high-NOX/low-PM calibration gives the SCR section ample opportunity to prove itself, while the CRT is coasting. Two set-ups were tried, one with two annular SCR catalysts, another with three. On the ESC test cycle NOX emissions were cut by 84 per cent with two SCR catalysts to just over half the provisional 2g/kWh Euro-5 limit. Adding a third SCR catalyst resulted in a 92 per cent reduction. Both arrangements produced PM figures more than 50 per cent below the Euro-5 limit. Emissions of hydrocarbons and carbon monoxide were almost too small to measure. Evidently the Bosch urea injection system (controlled by engine-mapping rather than NOX sensors) was finely tuned. Ammonia-slip never rose above 10ppm even ahead of the final catalyst, and was almost entirely eliminated downstream of it.

The US transient test cycle proved a tougher nut to crack, chiefly because of the cold-start section. Urea injection does not start immediately because the chemical reaction in the SCR catalyst cannot convert the urea solution into ammonia until the temperature is at least 160 degrees Celsius. This took 625 seconds in the cold-start cycle, inevitably affecting the total NOX-conversion rate. But there is no such problem on the hot-start cycle, and when the two are combined to give a weighted average, the system cuts NOX by 79 per cent, taking the Volvo engine below the notional US 2007 NOX limit of 1.2g/bhp-hr (a statistical interpretation of the specified 2007 NOX limit of 0.2g/bhp-hr). US Environmental Protection Agency rules say that only 50 per cent of a manufacturer's production has to satisfy the 0.2 figure by 2007, so achieving 1.2g/bhp-hr for all production would suffice under the so-called "averaging, banking and trading" arrangement. The 0.2g/bhp-hr figure kicks in for 100 per cent of production in 2010.

Andy Walker of Johnson Matthey: leading the team developing the compact SCRT-trap.

Ammonia-slip at the tailpipe was greatest during the US hot-start test, averaging 9ppm but with spikes of up to 60ppm. This would seem to dash hopes that urea injection is already good enough at high-NOX conversion rates to mean the slip catalyst can be avoided to keep costs down.

"Presenting these results at the SAE is powerful evidence that you can design effective emission control using SCR systems," says Johnson Matthey's Dr Cooper. Yet the EPA is unhappy about SCR because it relies on truck drivers refilling urea tanks to keep emissions within legal limits. Cooled exhaust gas recirculation cannot cut NOX enough to meet the 2007 limit. The EPA favours NOX-adsorbtion catalysts that store oxides of nirogen on their surface and burn them off during periodic "regeneration events." Simpler than SCR? Not according to Dr Cooper. He explains that regeneration events entail a two-second-long enrichment of the air/fuel mixture, once a minute. "The problem is how to make the engine run rich for a couple of seconds every minute without a torque fluctuation," says Dr Cooper. "There are driveability and fuel consumption issues."

Dr Cooper hopes the EPA will remain "technology neutral" and permit either SCR or NOX adsorbers for 2007 and beyond. He believes that the

Cummins: claiming its in-house SCR system can boost power output by 10 per cent while improving fuel economy by five per cent on Euro-4 engines.

fuel consumption penalty of adsorbers may swing the argument in favour of SCR, at least for heavy-duty diesels. "Any fuel penalty greater than three per cent is seen as totally unacceptable," maintains Dr Cooper. Mack Trucks (Volvo's US subsidiary) is urging the EPA to accept SCR. Cummins is in the same camp. But International Truck and Engine Corporation believes there is little or no chance of a urea re-filling network being set up in the US before 2007.

In Europe, SCR is emerging as the best long-term option ahead of EGR because of its greater NOX-reduction potential. There is also an SCR fuel economy benefit estimated at between three and five per cent by virtue of an engine's high-NOX/low-PM calibration. Dr Cooper agrees that SCR alone could handle Euro-4, and Euro-5 too, subject to any rule changes that may yet emerge. So where does that leave the compact SCR-Trap and its apparently redundant CRT ? Dr Cooper certainly does not regard it as simply a stake in the ground for Euro-6 or US 2007, pointing out that there are bound to be retrofit opportunities for lowering exhaust emissions on existing vehicles,

Dinex space module: a new clamping system allows Dinex to offer interchangeable cores, so a conventional acoustic silencer can be upgraded to an oxidation catalyst or DPX catalyst and particulate filter.

and that this sort of requirement may well be written into bus tender contracts in the future.

Neither Dr Cooper nor Dr Walker will be drawn on the likely cost of an SCR-Trap, pointing out that it is not yet ready to go into production. At last month's Birmingham CV Show there was nothing more tangible than a transparent plastic model. A two-year field trial involving Volvo tractors is now under way in the US, designed to prove durability over 350,000km (220,000 miles) with service intervals no shorter than 50,000km (31,250 miles).

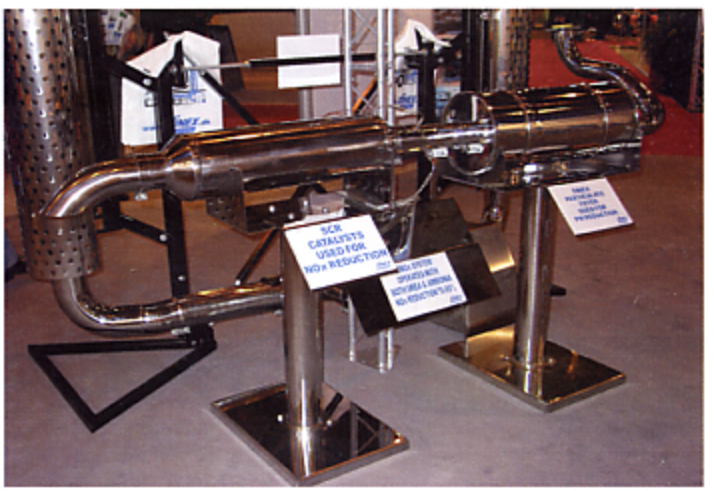
Dr Cooper meanwhile emphasises that Johnson Matthey is exploring various other emission technologies so it can be ready to move fast in whatever direction is chosen by the legislators. "There is a race to deliver the most cost-effective emission control system to the end user," says Dr Cooper. "All our eggs are not in one basket."

Another supplier of a combined NOX-reduction and particulate system is promising quicker results: order a system now and it can be on the vehicle in six to eight weeks. The bold claim is made is made by Peter Lambe, former managing director of Warrington, Cheshire-based Dinex Exhausts and recently promoted to director of group business development by its Danish parent company, Dinex AS. Last December Dinex signed an agreement with KleenAir, an emissions control company based in California, to distribute KleenAir's NOX-reduction system in Europe. NOxMaster is an SCR system that can use either ammonia (contained in a quick-change gas-bottle) or urea solution as a reducing agent to convert NOX into nitrogen and water vapour. Following trials in London taxi cabs, the KleenAir SCR system is the first to qualify for grant funding under the government's Energy Saving Trust CleanUp scheme. The grant is restricted to London taxis at present, but Dinex is hoping it will be extended to other vehicles following further tests. The London Borough of Hounslow is running a trial with NOxMaster fitted to a 16-seat Mercedes-Benz Sprinter minibus and a Dennis Eagle refuse-collection vehicle.

Ammonia or urea

Dinex has now married its Engelhard-supplied DPX particulate catalyst/filter to the NOxMaster system to tackle both NOX and particulates, rivalling the Johnson Matthey system with one called DiNOx. The first stage is the DPX catalyst/filter, followed by injection of either ammonia gas or urea solution ahead of the SCR catalyst, with the final oxidation catalyst to deal

Anglo/US coalition: KleenAir's NOxMaster plus the Dinex DPX adds up to DiNOx, available right now.



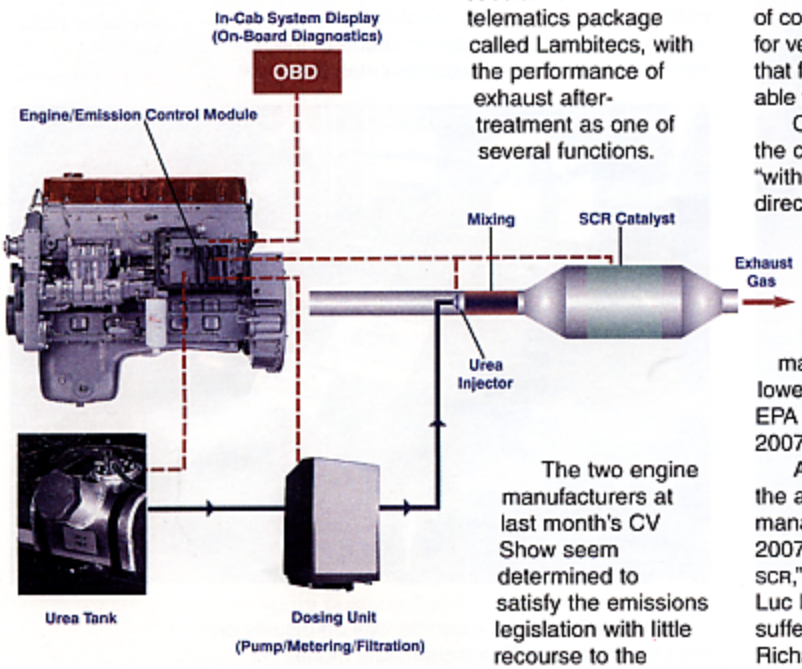
with ammonia slip. An example was on display on the Dinex stand at Birmingham last month.

"Our strength comes from being used to serving the aftermarket – we are very flexible," explains Mr Lambe. He claims that the ability to offer either ammonia (in a quick-change gas bottle) or urea for the SCR stage is unique. Although urea solution is the choice of truck and bus manufacturers in Europe, Mr Lambe contends that ammonia's advantage lies in its "lower light-off temperature" – the point at which it begins to react in the catalyst and convert NOX. In recent Millbrook tests on a Dennis Dart SLF bus with a four-cylinder Cummins ISBe engine using a London bus test cycle (a transient cycle) the ammonia-based SCR achieved an average NOX reduction of 88 per cent, compared with 68 per cent for the urea solution.

Mr Lambe says the aftermarket selling price of the DiNox system is likely to be between £6,000 and £8,000, depending on engine displacement, power output and installation. But what commercial vehicle operators are willingly going to shell out that sort of money for a comprehensive exhaust clean-up before it becomes mandatory? Mr Lambe points to London taxis, local authorities and bus operators

persuaded to do so by tender agreements written by the like of Transport for London. He agrees that any retrofit business in the wider haulage business would be driven by grants. He is hopeful of winning an Energy Savings Grant CleanUp grant for DiNOx that could cover up to 75 per cent of the capital cost. Ideally, the remaining 25 per cent would be covered eventually by something akin to the Reduced Pollution Certificate excise duty concession or perhaps by another sponsor, such as Transport for London in the case of London buses.

In return for forking out hefty capital sums for exhaust after-treatment, organisations like this could hardly be blamed for wanting some form of proof that the systems are delivering on their promises. Both Johnson Matthey and Dinex are preparing for this. Johnson Matthey has been developing a diagnostic module for its CRT that logs up to a month's temperature and back-pressure data. Dr Cooper says the graphed results can be used to fix cleaning intervals and help fault diagnosis. Dinex has taken things one step further, unveiling a substantial vehicle telematics package called Lambitecs, with the performance of exhaust after-treatment as one of several functions.



Cummins "integrated emissions management": geared up for Euro-4 and Euro-5.

The two engine manufacturers at last month's CV Show seem determined to satisfy the emissions legislation with little recourse to the external after-treatment industry. Cummins revealed that UK field trials of its own in-house-designed urea-injection SCR system (*Transport Engineer* May 2002) went so well that it will become its route to Euro-4 and Euro-5. It has been christened "integrated emissions management" (IEM) and has several features that suggest that it should incur minimal on-cost. Electronic control of the SCR has been integrated into the engine's own electronic control module so there is no separate control device. Second, as expected, Cummins has been able to minimise particulates purely through combustion and injection calibration, achieving the 80 per cent cut needed to satisfy the Euro-4 PM limit without any form of catalyst or trap. The SCR control is close enough to hit the Euro-4 NOX-reduction target without needing an ammonia-slip catalyst at the end of the system. And the whole system comes direct from the Cummins organisation, principally the Fleetguard Emissions Solutions and Nelson-Burgess (an exhaust system manufacturer in Hinckley, Leicestershire) subsidiaries.

If the capital on-cost of Cummins IEM looks modest, the claimed spin-off benefits aside from meeting Euro-4 are anything but modest. Cummins anticipates a fuel consumption improvement of five per cent over current Euro-3 levels, and power increases of the order of 10 per cent. If that is realised, it would for example, take the 5.9-litre ISBe up to 300hp and the 11-litre ISM to 460hp. The company says this would answer the criticism that it lacks a high-power 12-litre engine for the European market. (There has been insufficient demand to justify Euro-3 certification for its 15-litre ISX.) Operators will also be able to look forward to longer oil drain intervals, apparently extended by up to 50 per cent, presumably because of the hugely reduced particulates.

Opportunities ahead

"For Euro-4 we are effectively moving from an engine supplier to an integrated engine/after-treatment system supplier, which will position us for new business opportunities," says general manager of Cummins automotive business in Europe, John Carroll. "All elements of the IEM system, from air intake to engine and exhaust after-treatment, will be covered by a single warranty with a single point of contact at Cummins. That's a major advantage for vehicle builders and operators and a capability that few – if any – other engine companies will be able to provide."

Cummins says the IEM system will also take the company into the Euro-5 legislation in 2008 "with only minor modifications." But Cummins' director of European engine business Alex Savelli declines to elaborate on those modifications until the Euro-5 limits are confirmed. "IEM is best suited for UK and Europe for Euro-4 and –5," says Mr Savelli. "Choosing the right technology matters if you are going to deliver it at the lowest possible cost." Mr Savelli hopes that the EPA in the US will accept SCR in time for the 2007 limits.

Arch-rival Caterpillar is full of confidence in the ability of its ACERT electronic engine management system, both for Euro-4 and the US 2007 legislation. "We could meet 2007 without SCR," says European engine account manager Luc Richard. "But the fuel consumption is likely to suffer." So Caterpillar too is testing SCR. Mr Richard says that pro-SCR pressure is being brought to bear on the EPA by the likes of European/US players such as DaimlerChrysler. He says that while Caterpillar had to pay some non-compliance fines because its ACERT non-EGR engines failed to meet the 1 October 2002 deadline for the latest EPA emissions legislation, it has proved a shrewd move. "The latest figures from the US show we have a 38 per cent share of the engine market for class 6, 7 and 8 trucks. Six months ago it was 34 per cent. Operators are suspicious of EGR. Our research shows that it cuts engine durability by as much as a third."

Another reason for Caterpillar's optimism turns out to be its progress towards the "cam-less" engine, with electronically-controlled valves to give variable valve timing. According to Mr Richard, Caterpillar already has some of these engines operating in US field trials and he claims that everyone who drives them is impressed. Low NOX and particulate emissions are just two of a wide range of benefits promised by these engines, including higher power outputs and better fuel economy. Maybe this helps explain why European emissions legislators continue to procrastinate over future limits. ■