Clearing the air on exhaust chemistry sets

Huge disparity between rules and regulations on commercial vehicle exhaust emissions in Europe, the US, Japan and elsewhere could soon be a thing of the past, we are promised, as engine designs and exhaust after-treatment technologies converge. That is not exactly how it seems at the sharp end of vehicle operation. David Wilcox reports.

So far, so good. That seems to be the guarded consensus among European operations engineers looking back on the 12 months since Euro-3 exhaust emissions limits came into force for newly-registered vehicles. There has been remarkably little to report about the new low-NOx (oxides of nitrogen) engines, which is exactly as it should be, fleet operators would argue, when engine manufacturers are given ample time to plan their strategies.

The current upheaval in the US truck market is testament to how different things can be when there is a widespread perception that engineering development of engines and emissions-control systems has been rushed. The so-called "pull-ahead agreement" drawn up by the US government's powerful Environmental Protection Agency is forcing most manufacturers of heavy-duty diesel engines to satisfy 2004 low-NOx limits by this month, 15 months ahead of the original deadline. This has frightened the pants off US truck buyers. Their fear is that these new low-NOx engines with exhaust gas recirculation (EGR) have been inadequately field-tested. The upshot is that new truck sales have been soaring in the US in recent months as buyers clamour to get the last of the well-proven pre-2004 EPA regulation engines. A survey of truck operator purchasing intentions conducted by the American Trucking Associations (ATA) four months ago suggests that US hauliers are now planning to hold back on vehicle replacement for as long as possible. Respondents to the ATA survey say that they will buy only half the average number of new vehicles next year. The ATA sees this as clear evidence that operators are anxious to "avoid new untested technologies".

After-treatment potential

Back here in Europe meanwhile, though manufacturers and operators seem to have taken Euro-3 in their stride, nobody is assuming that Euro-4 limits will be anything like as easy to deal with. And scarcely anyone ever mentions Euro-5 legislation without using the prefix "tough", not least because it sets demanding limits for both NOx and particulate matter (PM) emissions, leaving no room for the familiar trade-off between the two.

But the potential for combining several downstream exhaust after-treatment technologies into a package that allows current, Euro-3 engines to crack the Euro-5 standard was demonstrated at an automotive engineering congress in Helsinki, Finland in June. Engineers from Ricardo, the prominent Shoreham, West Sussex-based consultancy, and the Association for Emissions Control by Catalyst (a Brussels-based body representing the catalytic after-treatment industry) jointly presented a paper at the congress run by FISITA, the International Federation of Automotive Engineering Societies. By adding comprehensive catalytic exhaust after-

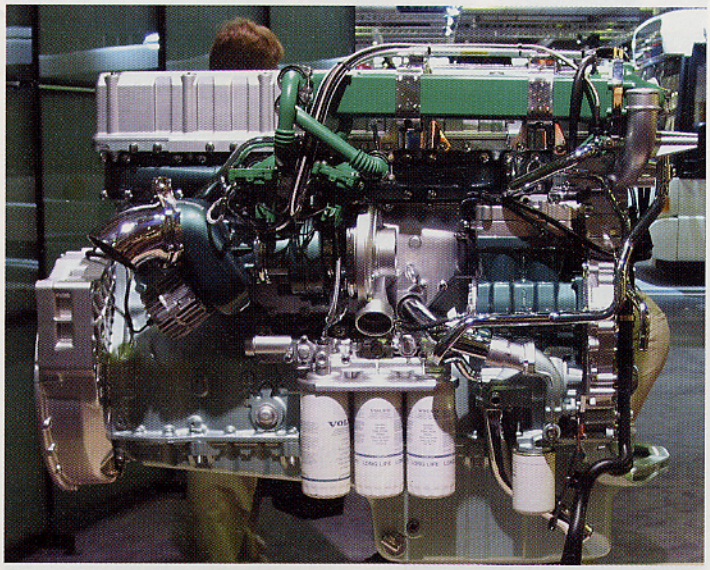
Horses for courses: exhaust gas recirculation is being used to cut NOx emissions from Detroit Diesel engines in the US. But in Europe DaimlerChrysler prefers selective catalytic reduction for the Euro-4 limits of 2005.

treatment to a Euro-3 Iveco Cursor 7.8-litre engine the Ricardo/AECC team not only met Euro-5 standards for all four regulated emissions, but bettered them by a comfortable margin.

The Cursor engine was first run in unmodified form in the test cell to establish a set of baseline emission values, using both the European Transient Cycle (ETC) and European Stationary Cycle (ESC). The test fuel had a sulphur content of less than 10 parts per million, defined as "zero-sulphur" in the European specification that will be in use well before Euro-5 arrives.

Exhaust after-treatment for the Ricardo/AECC trial comprises three main components. First in the line is a combined oxidation catalyst and diesel particulate filter, already a well-proven means of cutting particulate matter (PM) emissions, carbon monoxide (CO) and hydrocarbons by around 90 per cent. Next comes the selective catalytic reduction (SCR) system, spraying urea into the exhaust stream. The resultant chemical reaction in the catalyst chamber converts NOx into nitrogen and water vapour. This method of catalytic NOx reduction (an alternative to cooled-EGR) is pivotal to the case being made by AECC on behalf of catalytic system manufacturers.

The final link in the chain is a clean-up catalyst designed to deal with "ammonia slip" - any excess of ammonia produced by the mix of urea and NOx that is unreacted in the SCR catalyst. The system includes two NOx sensors; one immediately before the urea injection, the other right at the back to monitor tail-pipe NOx emissions.



Pulsating development: Volvo's V-Pulse 12.1-litre engine (with cooled exhaust gas recirculation) was on show in Hanover last month. But it is available ony in the US from this month to satisfy the latest EPA limit on NOx.

The Ricardo/AECC team also ran an accelerated ageing test, formulated by Iveco and designed to compress 250,000km of real-world operation into 1,000 hours on a test bed. It comprises 125 repetitions of an eight-hour cycle, made up of one hour of simulated city driving and seven of highway driving. There were repeated engine speed and load changes, but the continuous nature of the test meant that the temperature in the particulate filter was always between 330 and 380 degrees Celsius, so filter regeneration was never a problem.

This 1,000-hour ageing test was run using 40ppm sulphur diesel, similar to current UK-specification ultra-low-sulphur diesel (ULSD), and included two deliberate "mis-fuelling incidents" when 250ppm sulphur diesel was used for 50 hours on each occasion. The ETC and ESC tests were repeated once more after the ageing procedure.

In a nutshell, the Ricardo/AECC set-up achieved tailpipe emissions 50 per cent below Euro-5 limits. There was no significant deterioration in system performance after 1,000 hours, though sulphate was stored in the particulate filter as a result of the high-sulphur fuel used in the ageing test. This was gradually released during the high-temperature ESC testing at the end of 1,000 hours. It is claimed that sulphate-storage will not be a problem with zero-sulphur diesel.

Sceptics will point out that as a trade body for the catalytic after-treatment industry, the AECC is hardly an impartial source of test data. But the margin by which Euro-5 limits were beaten in the test is impressive by any standards. So why all the talk about tough legislation?

Ammonia slip

Engine and emissions experts at last month's huge Hanover show provided answers. They make it clear that the sort of after-treatment kit used by Ricardo/AECC is not going to be popular with vehicle manufacturers and operators. One key reason is that it requires three catalytic treatments -oxidation, SCR and the final clean-up catalyst for ammonia slip - all demanding expensive precious-metal coatings. The ammonia-slip catalyst is avoidable if the NOx-reduction target is more modest. This is because the amount of ammonia generated by the SCR system needs to be in direct proportion to the NOx-reduction target. Once that exceeds 80-85 per cent there is a chance that some ammonia will be unreacted in the SCR catalyst and find its way out of the tailpipe. Ammonia is a toxic irritant, and the consensus among emissions experts is that tailpipe ammonia concentrations should not exceed 10 parts per million. In the Ricardo/AECC test the figure was a creditable 4ppm most of the time (with occasional spikes up to 9ppm), but the final catalyst was needed to achieve that figure while hitting the half-Euro-5 target.

One way of sidestepping ammonia-slip stumbling blocks is to aim for a NOx reduction of less than 80 per cent. This strategy already looks feasible, according to Karl-Viktor Schaller, engineering chief at MAN's heavy trucks business unit. "We are already achieving NOx levels of 4g/kWh with our Euro-3 engines," says Mr Schaller. "If we aim for a 60 per cent reduction we could meet the Euro-5 limit of 2g/kWh with a low urea dosing rate and no ammonia-slip catalyst." He is assuming that the proposed 2g/kWh NOx limit will be confirmed, as expected, by the European Commission in the next three months.

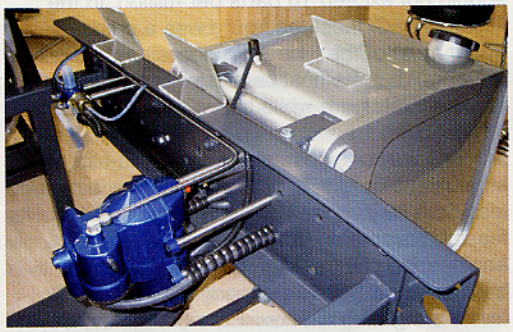
On the contentious issue of NOx sensors, the Ricardo/AECC engineers say that the two in their system worked reliably throughout the 1,000-hour test. But vehicle manufacturers and operators continue to question their long-term reliability in the harsh working environment of truck and bus exhaust systems. Drift in accuracy is a particular concern. Yet Volkswagen is sufficiently satisfied with NOx sensor performance already to employ one in its fuel-efficient, low-emission Lupo FSI, powered by a 1.4-litre common-rail direct-injection petrol engine using stratified-charge injection. The sensor here

is used to control a NOx storage catalytic system. NGK, the Japanese company of spark-plug fame, is reckoned to be leading the way in NOx sensor design and is focusing on those likely to be needed for the on-board diagnostics equipment that will soon be mandatory in Europe to prove that emissions-control remains effective in service. But NOx sensors are not essential for controlling urea dosing in SCR systems. MAN's Dr Schaller explains that combustion data from the engine map are sufficient for a mathematical calculation of the NOx emissions going into the SCR catalyst.

Some operators fret about the life expectancy of NOx-reducing catalysts in SCR systems. Siemens reported last year in a Society of Automotive Engineers (SAE) paper that catalytic activity had been found to decline most quickly in its early life but that the trend line levelled out after about 300,000 miles at just over 90 per cent per cent of its starting value. The catalyst's NOx-reduction rate is sensitive to temperature, so emission test cycles involving cold starts will give inferior NOx reduction figures.

Increased exhaust back-pressure, three times the norm, is one of the snags of all the after-treatment catalysts in the Ricardo/AECC test. A fuel consumption penalty of two per cent was measured with the Euro-3 Cursor engine. But the Ricardo/AECC engineers point out that there is potential to balance engine tune and catalyst performance for better fuel consumption at Euro-5.

The general aim would be to calibrate the engine to minimise both particulates and fuel consumption, leaving the SCR system to deal with the resultant higher NOx emissions. Exactly how much fuel can be saved this way? Opinions vary. MAN's Dr Schaller talks of three per cent. Bosch, developing urea injectors for SCR systems, says it is up to five per cent. Eckhard Cordes, DaimlerChrysler's commercial vehicle boss, was quoting up to six per cent at Hanover



Good in parts: SCR systems are best split into three separate units - electrical pump, air-pressure control, and dosing - at least according to Purem.

last month. A Cummins/Siemens Sinox SCR trial for the UK's Energy Savings Trust (*Transport Engineer* May) produced a 1.5mpg improvement (close to 10 per cent) on a 7.5-tonne Daf LF45.150 operated by Royal Mail. There is scarcely any reason to doubt that the fuel consumption of SCR-equipped Euro-5 engines will be measurably better than that of their Euro-3 equivalents.

These fuel savings will be prized by operators seeking to offset the cost increases associated with Euro-5 limits. Urea solution costs about €0.5 (32p) a litre, and a typical truck is expected to consume it at the rate of about 4-6 per cent of diesel fuel consumption. So urea will add about three per cent to a typical UK operator's fuel bill. Development of a European urea-refilling infrastructure is thought to be well advanced, including pallet-mounted urea tanks and pumps for hauliers' premises. The liquid is now the subject of a draft DIN standard (DIN 70 070) for a urea concentration of 32.5 per cent, and a consortium of producers including Hydro and BASF is producing it under the AdBlue name.

Ricardo/AECC test results (ETC)

emission (g/kWh)	Euro-5 limit	engine out	catalysts out	conversion efficiency (%)
HC	0.4	0.29	0.07	76
CO	3.0	0.78	0.01	99
NOx	2.0	5.83	0.85	85
PM	0.03	0.064	0.011	83

These are the emission reductions obtained by the Ricardo/AECC team running the Euro-3 Cursor engine on the European Transient Cycle (ETC) after a 1,000-hour accelerated ageing test. They are little different from the first set of tests run before ageing.

EUROPE	NOx (g/kWh) ESC/ETC	PM (g/kWh) ESC/ETC
Euro-3 (2000)	5.0/5.0	0.1/0.16
Euro-4 (2005)	3.5/3.5	0.02/0.03
Euro-5 (2008)	2.0/2.0*	0.02/0.03

European emissions standards, to European Stationary Cycle (ESC) and European Transient Cycle (ETC): the dates refer to the year in which Type Approval applies. The date applicable for vehicles first registered for the road is one year later. For all cases, the exact date is 1 October in each year.
** Provisional figure for Euro-5 NOx level: to be confirmed by the end of 2002.*

US	NOx (g/bhp-hr)	PM (g/bhp-hr)
2002	4.0	0.1
2004*	2.5**	0.05
2007	0.2	0.01

US emissions standards, measured using the Federal Test Procedure, a transient test cycle.
** The 2004 limits applied from 1 October 2002 for the seven engine manufacturers who signed a consent decree after the so-called "cycle-busting" episode (Transport Engineer February 2001).*
*** This NOx level includes non-methane hydrocarbons (NMHC)*

JAPAN	NOx (g/kWh)	PM (g/kWh)
2000	4.5	0.25
2003	3.38	0.05
2005	2.0	0.027

Japanese emission standards, measured using a 13-mode steady state cycle.

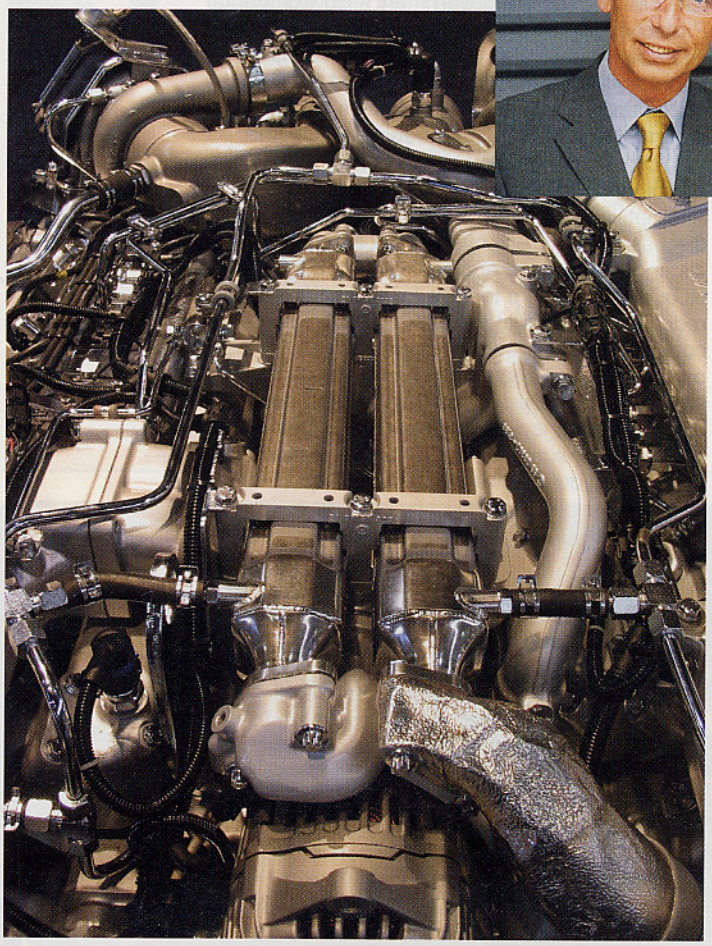
Punishing particulates

Emissions of particulates have be cut to only one fifth of the current Euro-3 limit to satisfy Euro 5. Indeed the same low PM level is demanded by Euro-4, which comes into force in only three years from now. But this may well be a less onerous target than it seems because it is believed that many Euro-3 engines are already comfortably below the current particulate limit. MAN's Dr Schaller says adoption of second-generation Bosch common-rail fuel injection is helpful when aiming to cut PM emissions

because secondary injection burns some of the carbon that is at the heart of particulates emissions. Dr Schaller even dares to suggest that a simple oxidation catalyst, without a particulate filter like a CRT (continuously-regenerating trap), may be enough to meet the Euro-4 and -5 PM standard. Oxidation catalysts are normally credited with PM cuts of up to 50 per cent. Whether that would be enough depends on how NOx emissions are managed. If the combustion is optimised for very low particulates the higher NOx level may call for an 85 per cent-plus urea dosing rate, making an ammonia-slip catalyst essential.

But when combined oxidation catalysts and particulate filters such as Johnson Matthey's CRT are already demonstrably capable of cutting PM by 90 per cent, why would any truck maker choose a less effective solution? Cost is one reason, but more significant still is the need to guarantee reliability on every type of commercial vehicle on every type of operating cycle. Dr Schaller refers to a 300-strong CRT-equipped bus fleet that is failing to regenerate its filters adequately because of low exhaust temperatures. The conclusion in June from a two-year Danish experiment involving 120 buses in Odense equipped with various particulate filters (*Transport Engineer* October 2001) was that 80 per cent of the filters "worked well or were acceptable". Half the remainder failed because of low exhaust temperatures. The others failed because of poorly-maintained engines. The Danish engineers reason that a fuel-borne catalyst additive or actively-heated exhausts would solve this filter-regeneration problem.

MAN's Karl-Viktor Schaller: "Euro 5 is not due until 2008. Who knows what will happen in the meantime?"



Wide choice: there is just enough room between the two cylinder banks of MAN's 18.3-litre 90-degree vee-10 engine to shoehorn in exhaust gas recirculation heat exchangers.

Cummins engineers in the US also think that active regeneration of particulate filters will be needed to meet US 2007 exhaust legislation by vehicles such as urban buses on stop/start operations, and even for those with extended idling periods or regularly operating in low ambient temperatures.

Manufacturers of particulate filters are working hard at reducing the limitations of their systems, with metallic instead of ceramic catalyst substrates and filters emerging as a recurrent theme at Hanover. Advocates of metallic substrates include ArvinMeritor's European air and emissions technologies division, based at Warton, near Preston, Lancashire. It can supply metal substrates for uses including diesel oxidation catalysts and SCR systems. Better durability, greater surface area and more flexible shapes for manufacturing are some of the plus points. This month ArvinMeritor starts to supply Caterpillar in the US with diesel oxidation catalysts using these metallic substrates. Like many automotive suppliers, ArvinMeritor recognises that exhaust emission legislation all around the world is steadily converging, changing a quirky European taste into a huge global market. So it is stepping up its vehicle exhaust emissions business, emphasising that it already has a solution to the problem of low exhaust temperatures hindering particulate filter regeneration. A long-established exhaust diesel-burner system developed by ArvinMeritor subsidiary Zeuna Stärker has been rechristened "I R Tech" (intelligent regeneration) and is giving this technology fresh impetus. Because the burner intermittently raises exhaust temperature to 650-700 degrees Celsius, its particulate filter does not need the help of a precious-metal catalyst to reduce the temperature at which sooty particulates will burn. The downside is the cost of fuel consumed during each burning event, reckoned to be two per cent of overall vehicle fuel consumption.

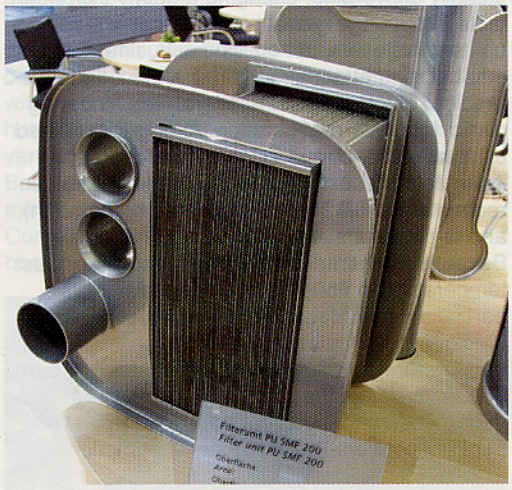
Less frequent vacuuming

Purem, a German joint-venture company set up by DaimlerChrysler and HJS, Johnson Matthey's CRT-canning partner in Germany, has achieved some notable results using a sintered metal filter in place of the usual ceramic filter in a CRT. It is made of a fine stainless-steel mesh sheet with a coating of metal powder mixed with an unspecified additive. These sheets are cut to fit the cross-section of the filter can, then welded together to form a series of sandwich-like pockets. This construction is no cheaper than a ceramic silicon carbide filter but can accommodate more soot and ash before clogging. Purem points out that this not only helps where filter regeneration is infrequent but also means that the gradual increase in back pressure is less marked as deposits accumulate. The chore of vacuuming the filter to remove the ash also becomes less frequent. A German field trial using different particulate filters in combination with Octel's Octimax fuel-borne catalyst on several Mercedes-Benz Actros tractors run by a Dortmund haulier is proving the theory. After close on 200,000km, exhaust back-

pressure on two units equipped with the Purem sintered metal filters was the same as at the start of the trial, despite the extra ash from the fuel-borne catalyst and the absence of cleaning. Purem says it can supply the sintered metal filters in any shape, replacing existing ceramic ones in CRTs.

Ventures into SCR

But DaimlerChrysler did not get involved with Purem to sell metallic filters. The real prize is SCR systems. The original Sinox SCR co-operation project between Siemens, Mercedes-Benz, MAN and Iveco has ended. Two months ago Iveco announced that it had formed an alliance with Hexadex, the parent group of UK-based exhaust and emissions company Eminox. The new company, called Ivedex, is focusing on the development of NOx and particulate reduction after-treatment. This appears to parallel what DaimlerChrysler has done in setting up Purem with HJS. Purem will not only supply DaimlerChrysler with its SCR system but hopes to find customers in the wider commercial vehicle world. Other vehicles manufacturers are said to have prototypes already. What distinguishes the Purem SCR from its rivals is that it is split into three separate components. The electric pump to draw the urea solution from the tank is chassis-mounted next to the tank. Next in line, mounted further up the chassis, is the air pressure control



Sinter of attention: at the heart of the Purem particulate filter is a sandwich of sintered-metal sheets.

unit. This taps into the vehicle's air system to carry urea solution forward at the right flow rate and pressure. The third part is the dosing unit, mounted on the engine so there is a short line to the point of injection into the exhaust stream. Purem claims that this modular approach is preferable to the neater, one-box layout because each part, particularly the critical dosing unit, is in its optimum position. The whole system, including the urea tank and all the pipework, has to be lagged and heated because urea solution (67.5 per cent water) freezes at minus 11 degrees Celsius.

With an in-house customer the size of DaimlerChrysler, Purem seems to be in a strong position among the growing band of SCR system suppliers and "integrators" jostling for position in a market poised for take-off. Puzzlingly, Siemens has just ended its long-standing involvement in the business by selling its Sinox SCR business to a management buy-out team backed by a US private equity company. Sinox bosses deny that this is bad timing or disenchantment with the business, even though attempts to sell Sinox SCR systems as an option on MAN TG-A units last year fell on stony ground. They say it is just part of a grand Siemens plan to sell off subsidiaries and refocus on its core electronics business.

The new owners of Sinox and other SCR suppliers can be confident of strong demand for their products in the run up to Euro-5 in 2008. There is widespread acceptance that SCR is unavoidable for this tier of NOx legislation, though one dissenting voice is that of Swedish emissions systems manufacturer, STT Emtec. It suggests that its EGR-based DNOx system has the potential to take Euro-3 diesel engines down to Euro-5 NOx limits. That remains to be proven in tests but is an attractive prospect because EGR is cheaper than SCR and does not need a urea-refuelling infrastructure to support it. The US market for SCR to satisfy 2007 legislation is less certain. The US government's Environmental Protection Agency is leaning towards NOx adsorbers rather than SCR (*Transport Engineer* February 2001). In Europe, assuming SCR does materialise as expected, the choices centre around which path to steer between NOx and PM, choosing the most cost-effective combination of catalysts and engine calibration. Alternative approaches are already under discussion. Vehicles covering low annual distances may have engines calibrated for low NOx, allowing them to have low-cost NOx-reduction systems at the expense of poorer fuel consumption and more comprehensive particulate after-treatment. Long-distance or highly-utilised vehicles could be tailored quite differently, with low engine-out particulates for good fuel consumption but a heavier reliance on high NOx reduction with an extra catalyst to deal with ammonia slip.

Lure of improved fuel economy

The more pressing debate concerns Euro-4 in 2005. Until quite recently it had been assumed that SCR would be needed to take NOx down from the Euro-3 limit of 5.0g/kWh to Euro-4's 3.5g/kWh. But increasing refinement of combustion and EGR control means there is growing confidence that EGR is good enough to meet Euro-4 too. Recent work on EGR systems to satisfy the US 2004 NOx limit that came into force this month for most of the big engine-builders is likely to reinforce that belief. MAN and Volvo are the two European-based makers who look closest to backing EGR for Euro-4, though neither has yet committed itself (in public at least). DaimlerChrysler is following a different route, confirming at Hanover last month that Euro-4 Mercedes trucks, buses and coaches will be SCR-equipped. A German emissions industry insider tells us that two other (un-named) truck and bus builders are on the brink of following suit. They are said to be persuaded by the lure of improved fuel consumption - always a strong marketing tool - and the knowledge that they will have to get into SCR sooner or later. Those in the EGR camp will doubtless wince at the capital cost of an integrated SCR and particulate reduction system. Latest quotes estimate this at €6,000 (£3,800). This is far cheaper than in the past, but anything that cuts it - like leaving out the SCR section - would give EGR a price advantage for the duration of Euro-4. As MAN's Dr Schaller observes: "Euro-5 is not due until 2008. That is still a long time away. Who knows what will happen in the meantime?" ■