Update on Diesel Exhaust Emission Control

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August 26, 2003

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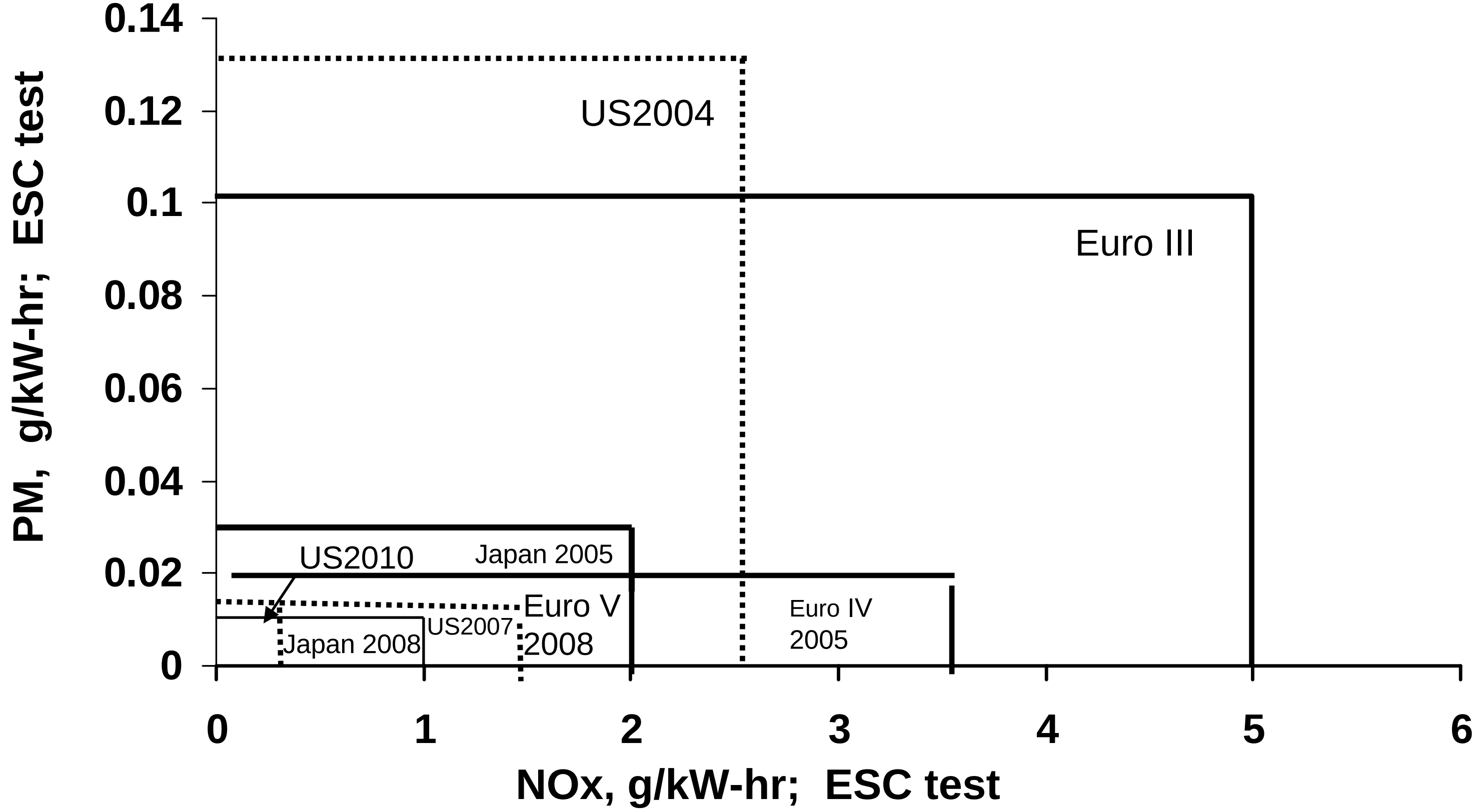
Discovering Beyond Imagination

Regulations and Approaches

Euro IV and Japan 2005 are coming next, with significant PM and NOx tightening; US2007 goes further; US2010 very low;



New: German/French Euro VI (2010) proposal is 0.5 g/kW-hr NOx and 0.002 g/kW-hr PM

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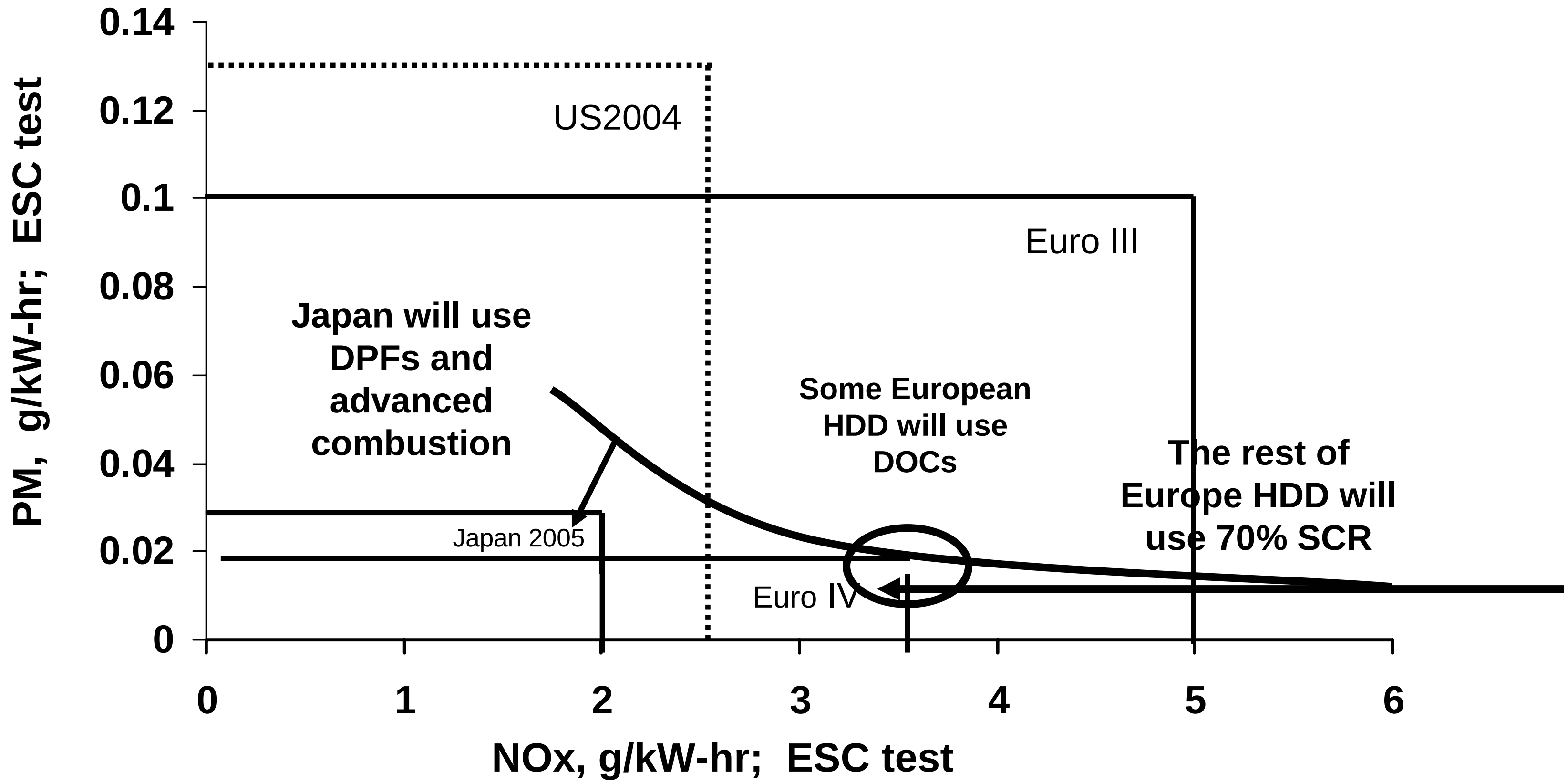
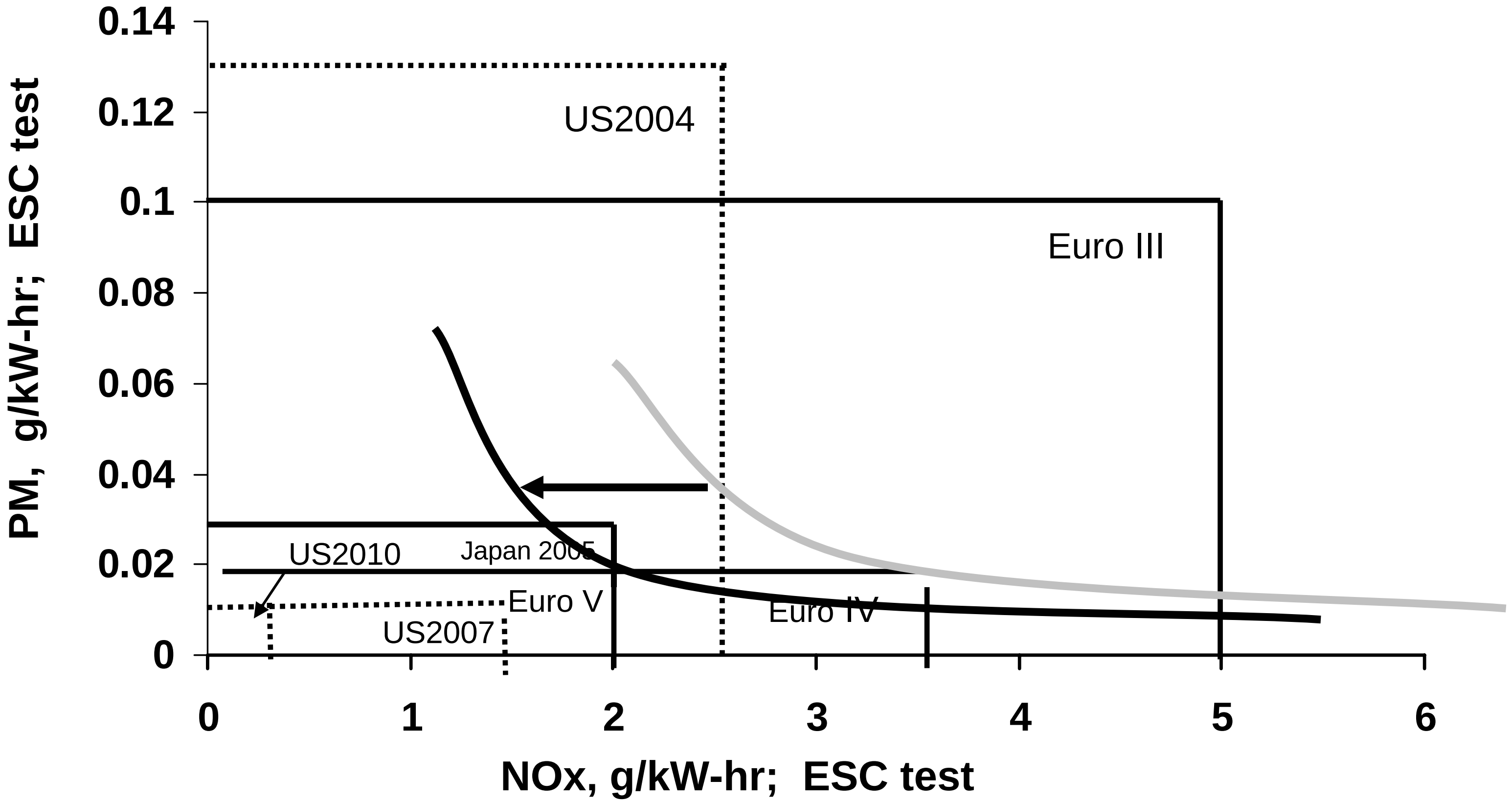
In 2005, filters, DOCs, and SCR will be used



By 2007+, engine technologies are expected to make significant advances



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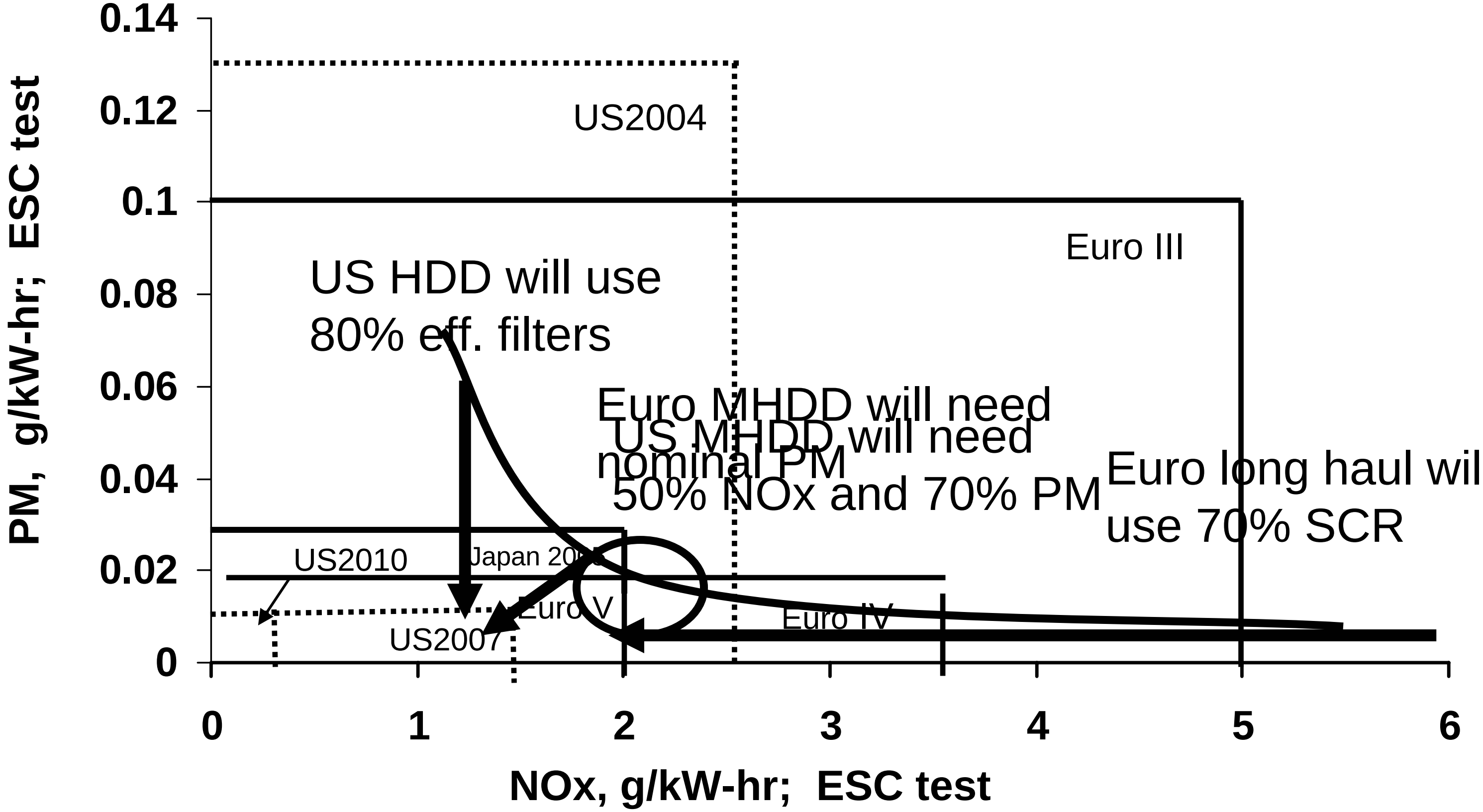

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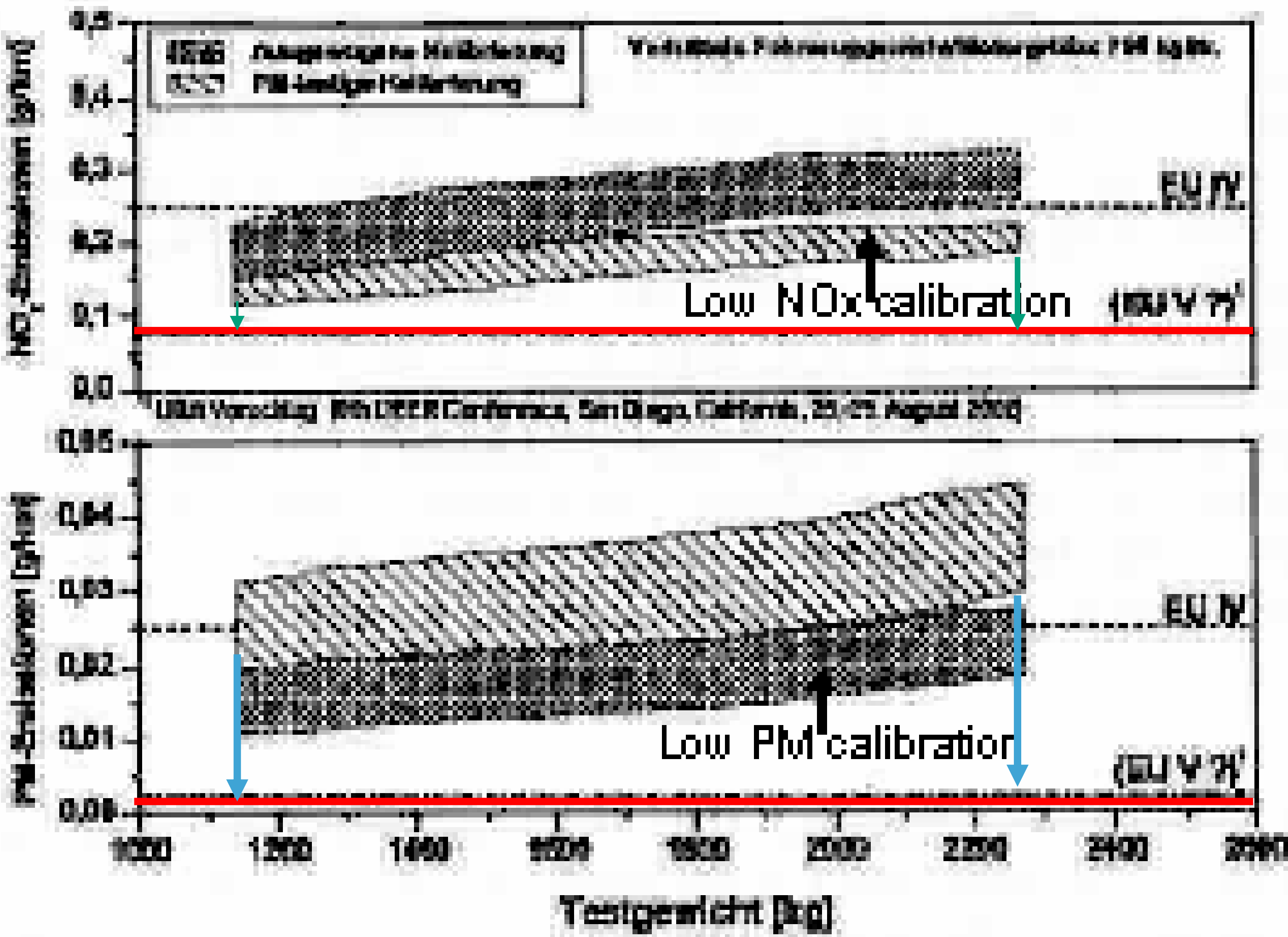
Depending on weight and calibration, Euro LDD will need 25 to 80% NOx and 80 to 95% PM emission control reductions.



Low NOx calibration: 25% NOx reduction for 1150 kg vehicle; 55% NOx reduction for 2250 kg vehicle; **LEV2: 70% and 82% NOx, respectively**

Low NOx calibration: 90% PM reduction for 1150 kg vehicle; 95% NOx reduction for 2250 kg vehicle

FEV, Vienna Motorsymposium 5/03

Recent developments in filters

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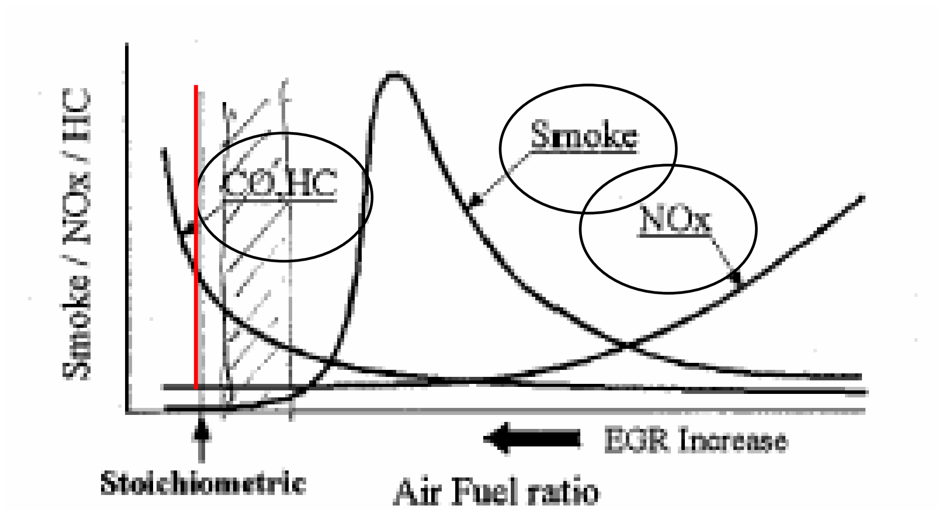
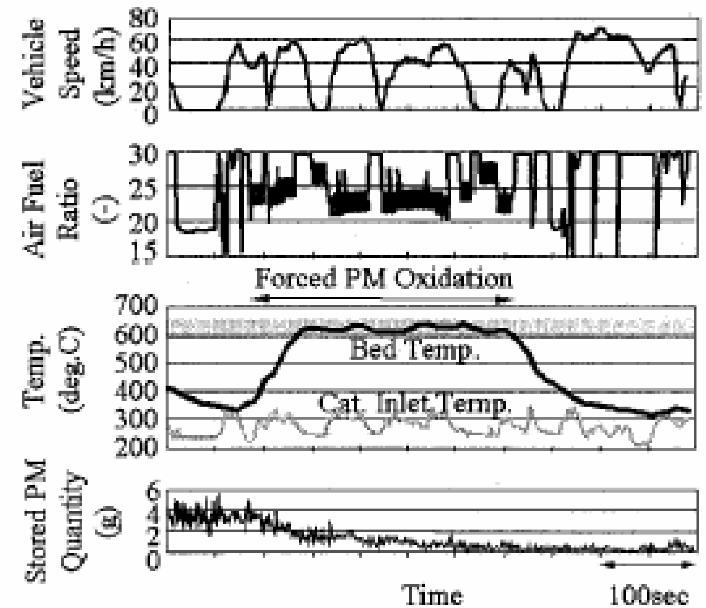
Low temperature combustion is being used in LDD to regenerate DPFs



Low load combustion strategy uses high EGR to burn slightly lean to generate CO&HC with low NOx and PM



Catalyst inlet temperatures of 200 to 320C are reported that will heat CDPF (DPNR) to >600C under low load

• This strategy, HCCI, and VVT offer attractive LT DPF regeneration options.

•They will not be implemented widely until 2007 or beyond in HDD

•LTC is being used in LDD this year.

Toyota, JSAE 5/03

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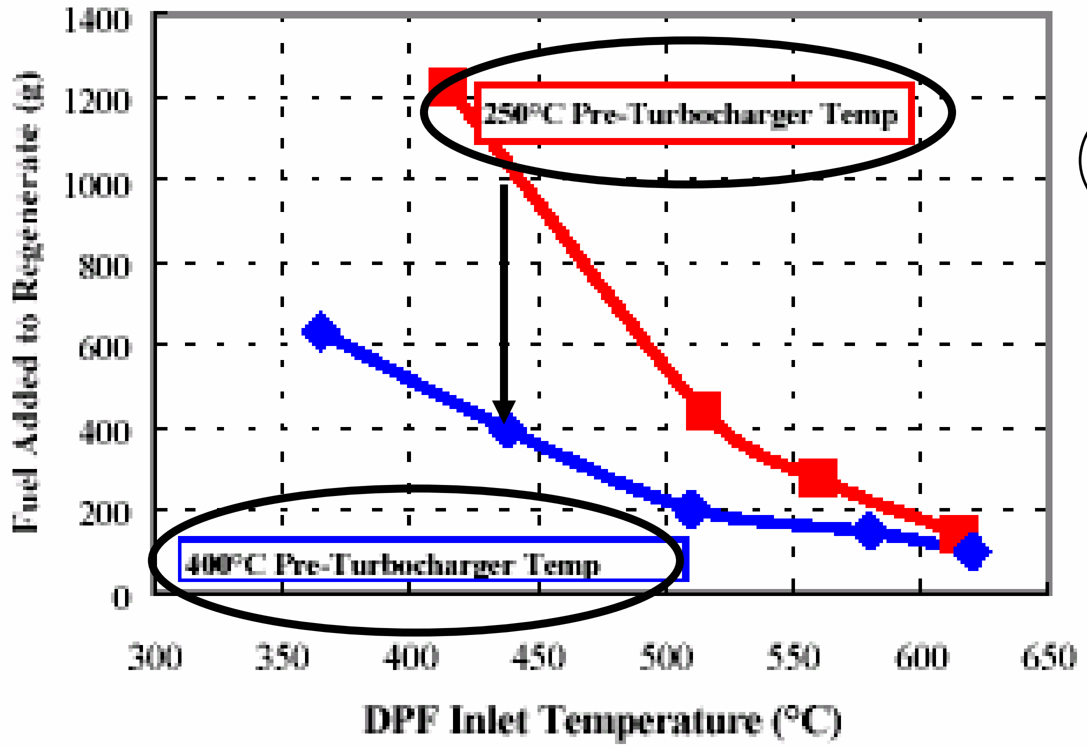
DPF regeneration fuel savings can be realized with post injection using higher exhaust temperatures

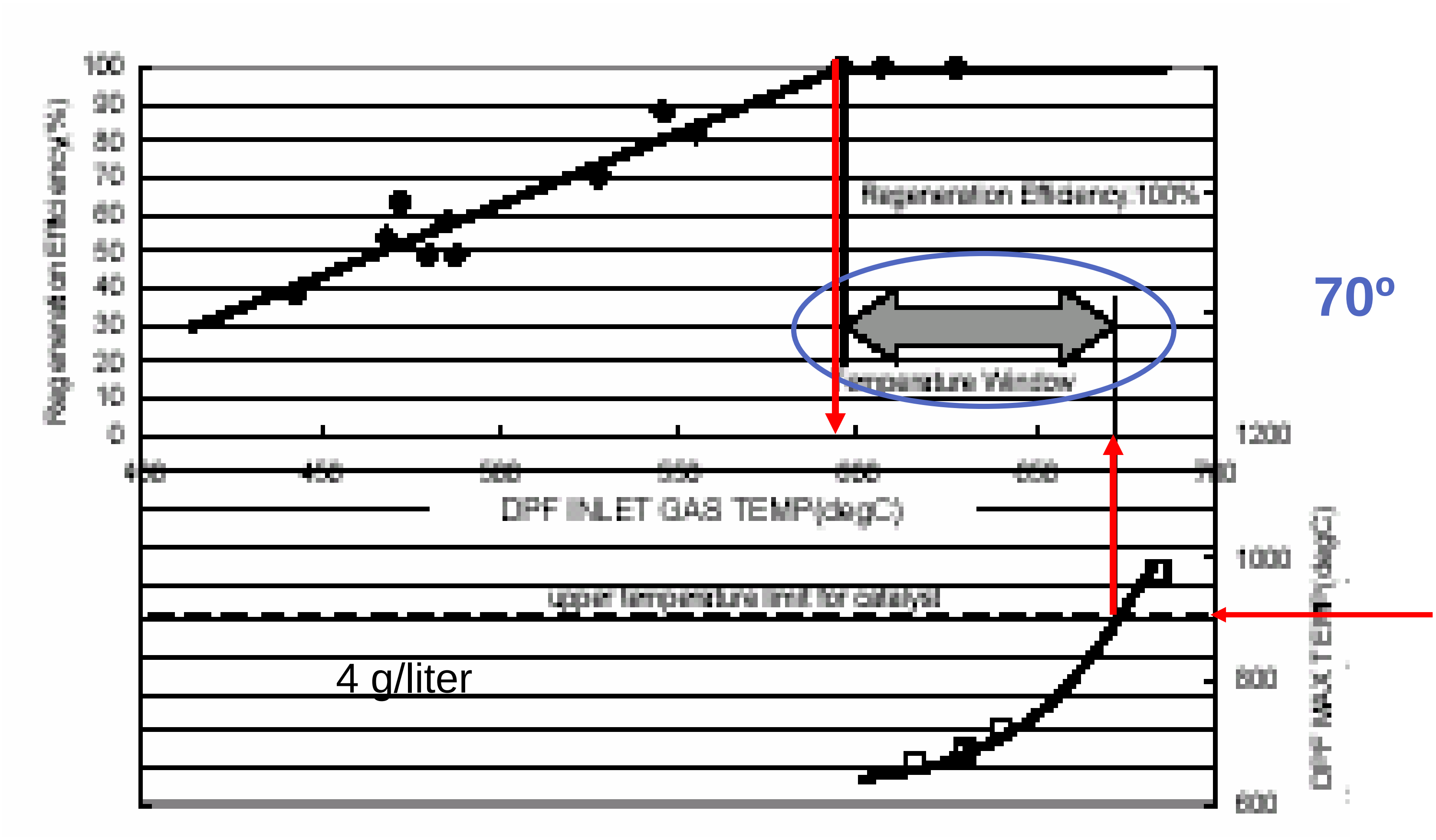


Auxiliary exhaust port injection of fuel

Although it takes more fuel to increase exhaust temperature, a net fuel savings is realized for DPF regenerations at higher T.

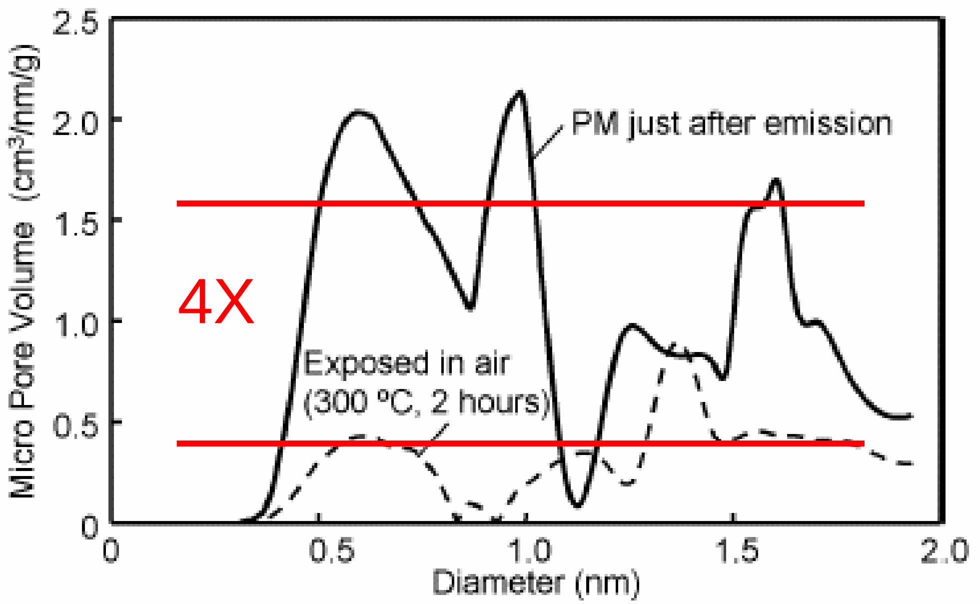
Ford SAE 2003-01-0047

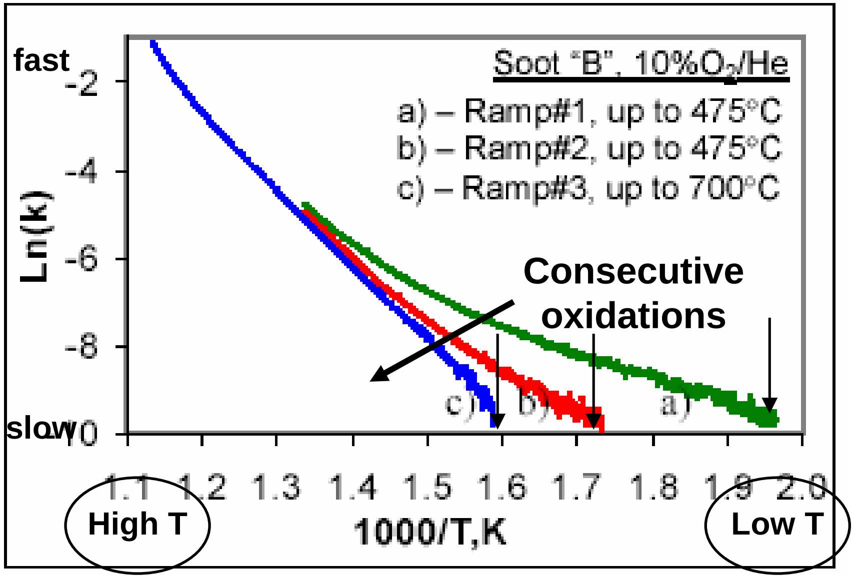
Safe regeneration characteristics of catalyzed SiC filter systems are characterized



NGK 2003-01-0383

Perhaps filter regenerations should be done more frequently to take advantage of highly reactive, fresh soot





Fresh soot has more micropores than older soot

Fresh soot is more reactive than older soot

Toyota SAE 2002-01-0957

Cummins, SAE 2003-01-0833

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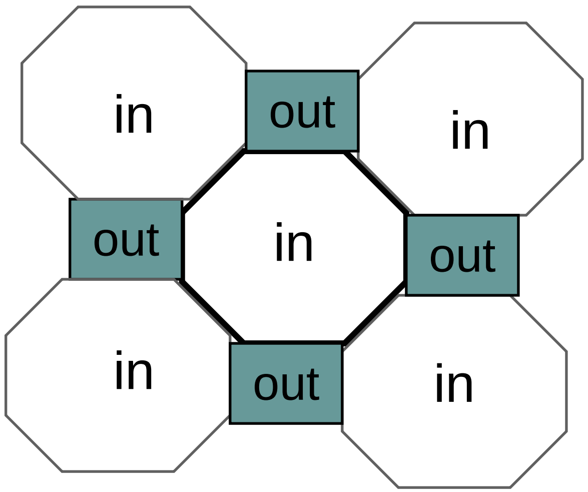
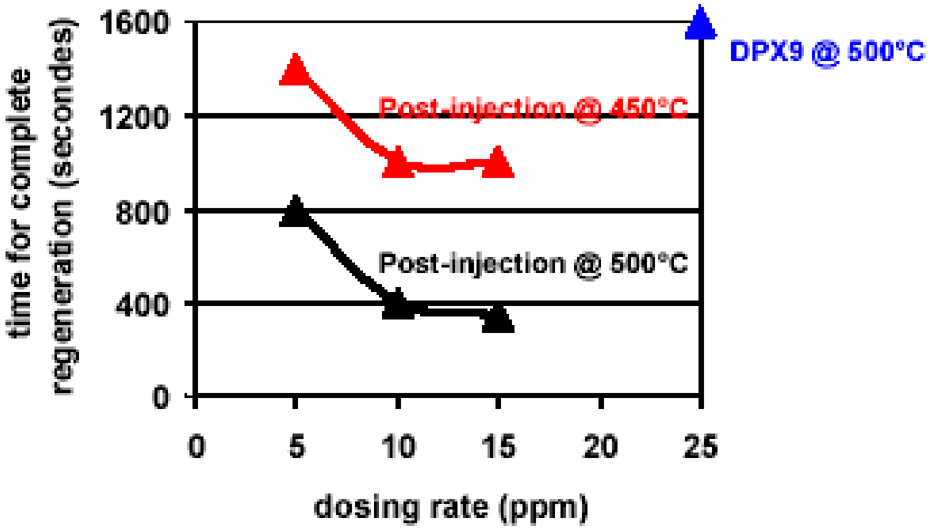
Ash cleaning not needed for life of vehicle with new filter design; 2nd generation Ce-based FBC performs better at lower dose rate;



Ash storage capacity increases 2X with larger inlet:outlet ratio in DPF

(PSA, ETH Particulate Conf. 8-03)



Reservoir requirements dropped from 5 to 1.5 liters, lasts 50% more (120,000 km)

Rhodia SAE 2002-01-2781

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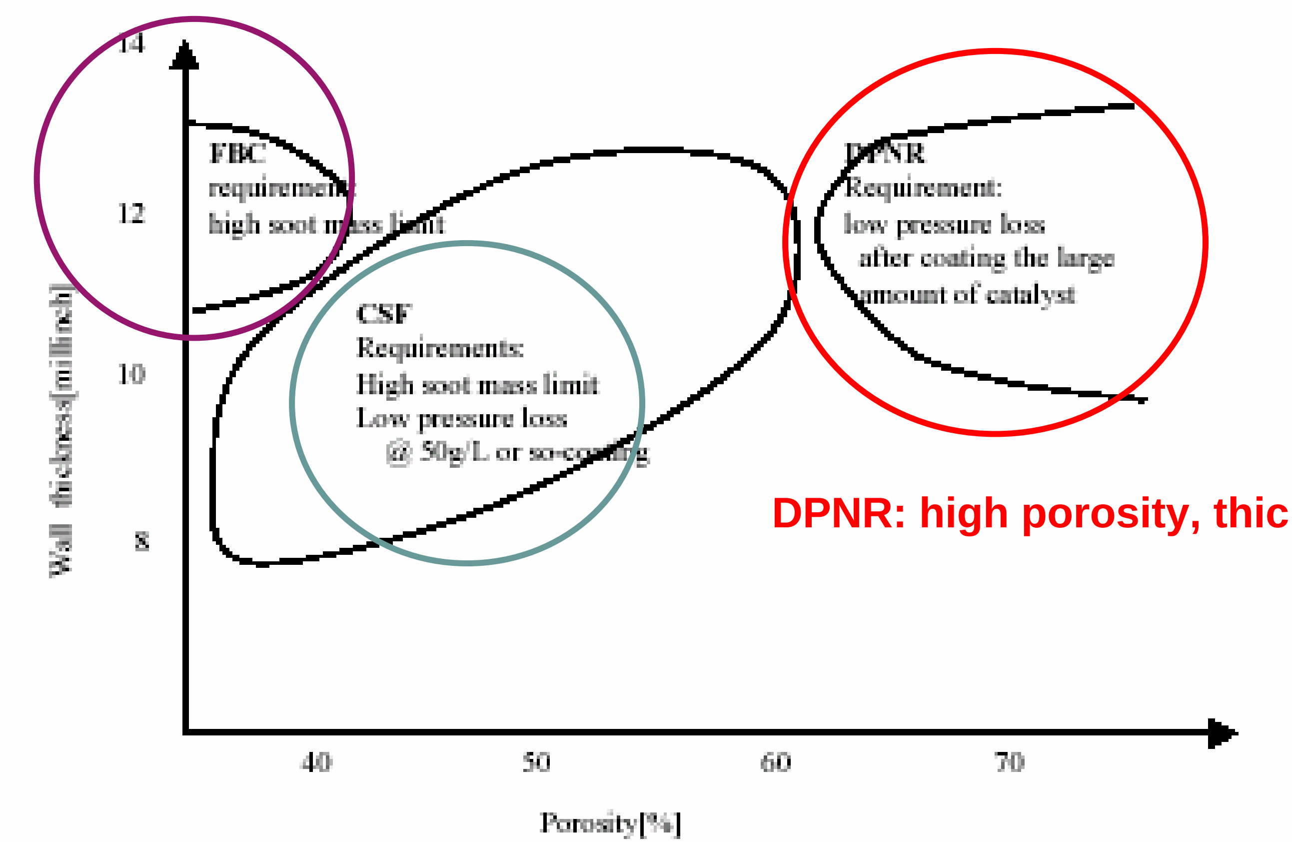
Pore structure can be engineered for the application

Uncatalyzed: narrow pore size, low porosity, thick walls

Catalyzed: broad size distribution and porosity, range of wall thickness



DPNR: high porosity, thick walls

Ibiden SAE 2003-01-0377

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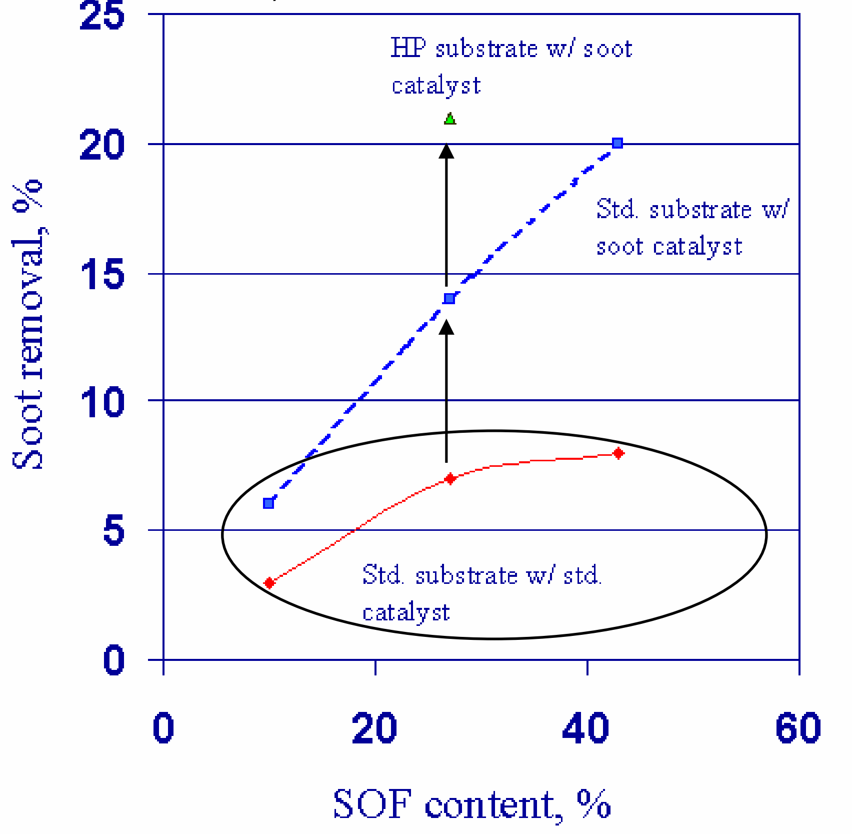
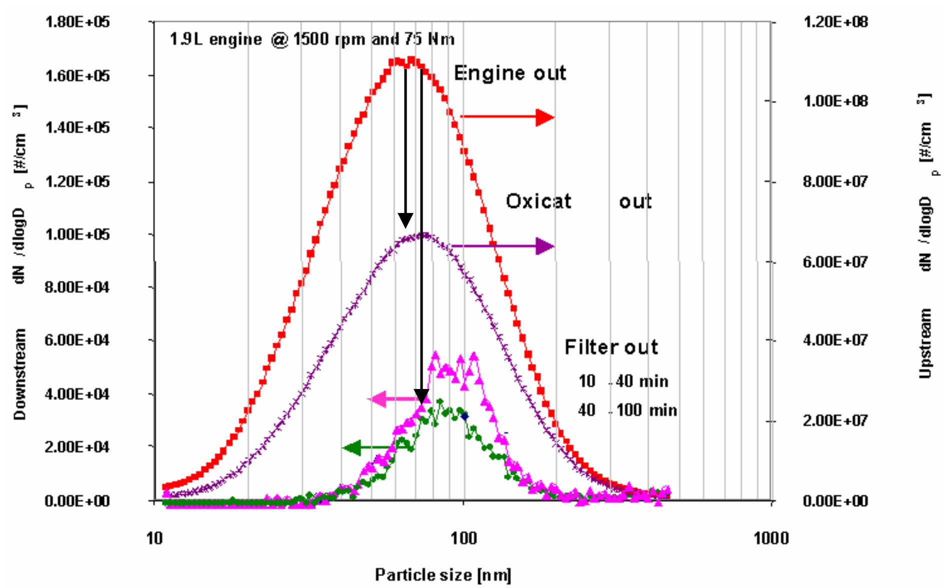
Optimized flow-through oxidation catalysts can remove soot

ICT, OMG SAE 2003-01-1862



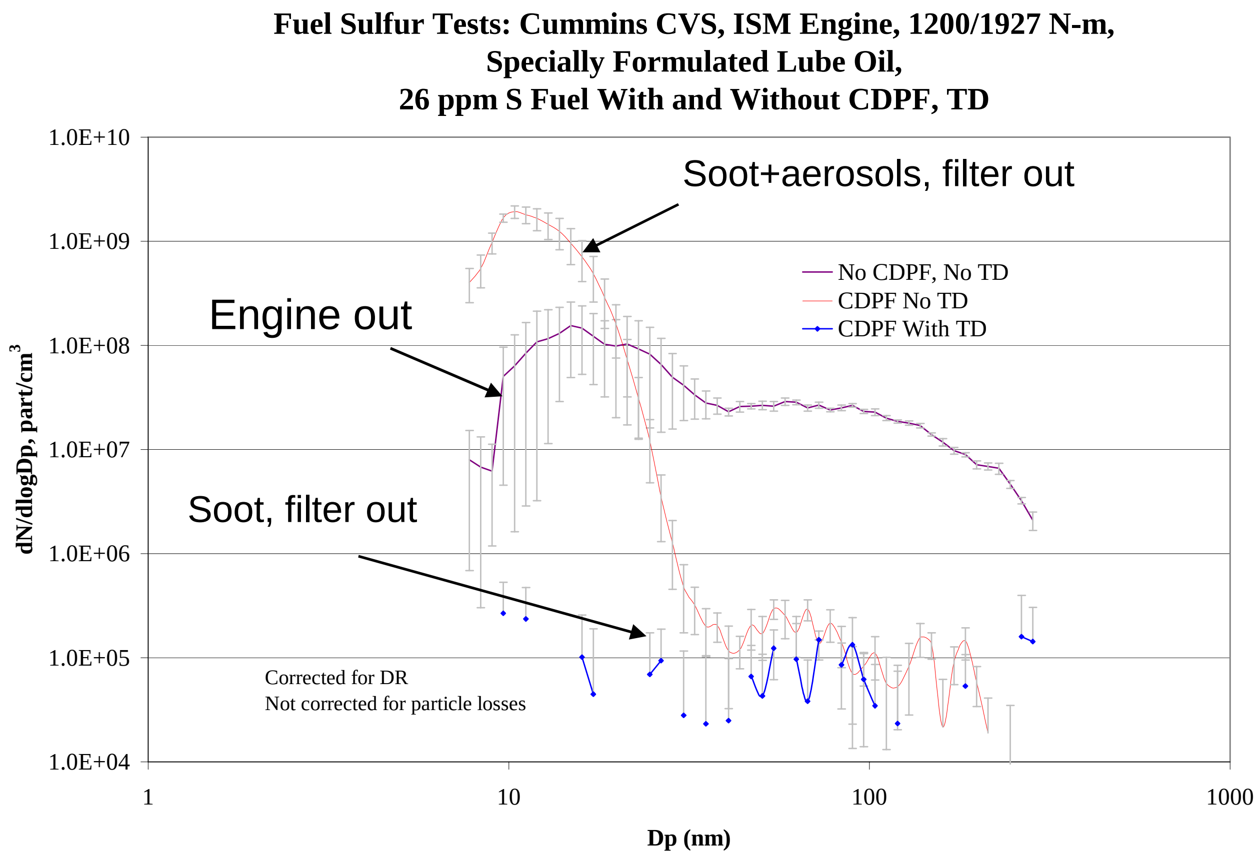
Soot removal efficiency depends on exhaust SOF content. Hypothesis is SOF condenses on catalyst and brings soot with it. High porosity substrate (65%) enhances soot/catalyst contact.



Oxidation catalysts drop ultrafines by about 30%. DPFs by 99.9%.

CERTH/CPERI, ETH Particulate Conf. 8-03

Filters are very effective in removing carbon ultrafines; under high load conditions, DPF can form nanoparticles



With TD (thermal deneuder), carbon ultrafines are removed 2.5 orders of magnitude. However, emissions of aerosol nanoparticles goes up.

Univ. of MN, CTA Monterey 3/03

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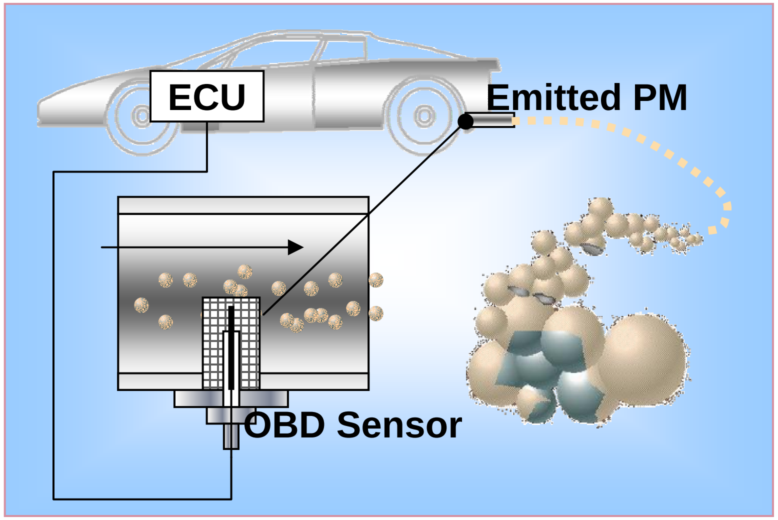
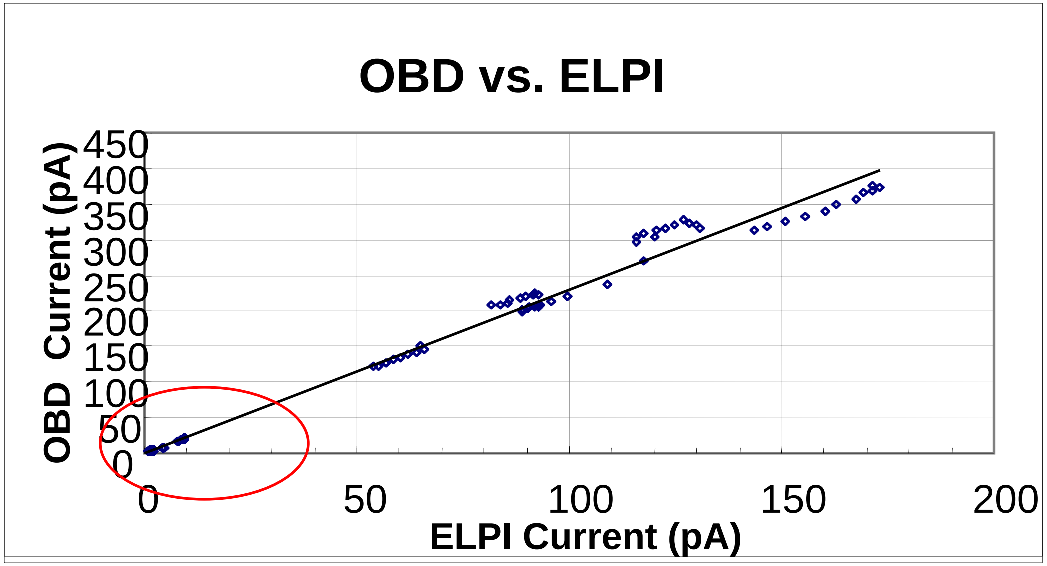
PM OBD sensor is in early stages of development





Operation: Electrical potential across flow charges particles. Difference between input current and ground is indicative of PM

Good correlation between OBD device and ELPI, even at very low PM levels

Dekati 8-03

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Thoughts on ash management

- Some HD vehicles: 240,000 to 400,000 km without ash cleaning

  (BP SAE 2002-01-0433).
- Lube oils are reducing ash loadings by 30%
- Washing is okay to clean uncatalyzed filters.
  - Catalyzed filters: washing questioned and TBD.
- Central facility is okay for uncatalyzed filters.
  - problematic for catalyzed filters
- Filter design can minimize ash cleaning intervals

NOx Control

LNT and SCR lead the field on effective NOx control, but LNC showing improvement

System	Transient Cycle NOx Efficiency	Effective Fuel Penalty	Swept Volume Ratio	Notes
SCR, 400-csi	85-90%	2-3% urea or about **1.5%** penalty in US	1.7 emerging	Being applied and specs being finalized; low temp. performance issues;
LNT	80-95%	1.5 – 4% total regen. + desulf.	1.3 to 2	Desulfation strategy and durability issues; integrated DPF/LNT components emerging; PGM cost issues
DeNOx catalyst	20-60%	2 to 6%	0.85 to 4	Generally not sensitive to sulfur; HC slip issues; durability needs proving

SCR

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SCR is emerging as a possible solution to US2007

- Two engine manufacturers recently announced serious intentions, subject to internal review
  - ATA seems interested
- EPA concerns
  - 150,000 mile maintenance-free emission control systems
    - might be addressed by certification with empty urea tank
  - undo hardship on operators in filling with urea
    - need viable infrastructure

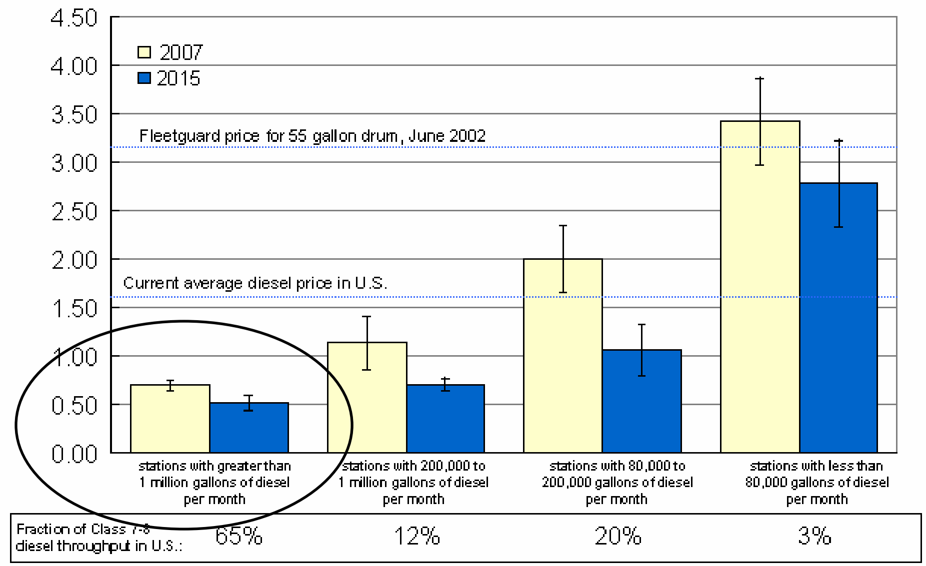
77% of diesel is pumped at 2200 stations

Profiles of Fueling Stations Serving the Class 7 & 8 Truck Market

Station Size (Monthly Diesel Consumption)	# of Public & Private Stations	Diesel Consumption
Large (2,000,000 — 1,000,000 gal/month)	2,200	77%
Medium (200,000 – 80,000 gal/month)	3,500	20%
Small (<80,000 gal/month)	>25,000	3%

2200 stations pump 77% of fuel; additional 3500 bring total to 97%

Retail Urea Cost By Diesel Station Throughput



Urea could cost $0.70/gal at the largest 65% of truck stops

To make infrastructure viable, estimates are that about 50% of 2007 trucks would need SCR

EMA study by Tiax 6-03

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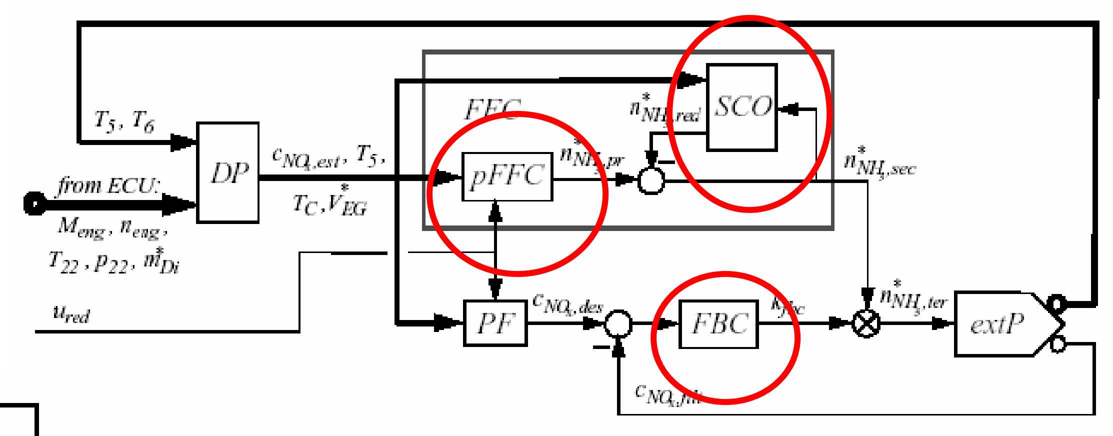
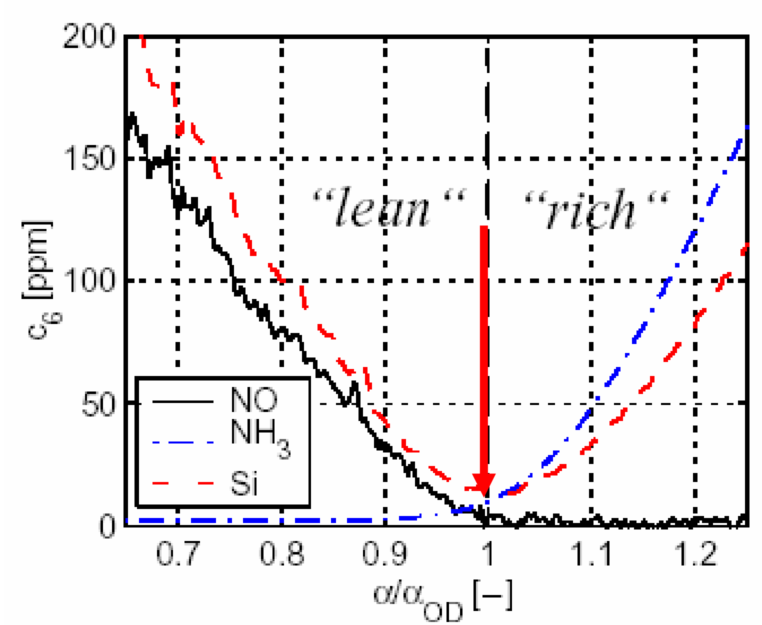
A urea control strategy incorporates feed forward and feed back control

ETH, SAE 2003-01-0776

10 liter turbocharged intercooled engine; 2 liters coated SCR catalyst; NOx sensor at exit





Feed Forward Control using flowrate and catalyst temperature inputs

Surface Coverage Observer is kinetic model

Feed Back Control uses the NOx sensor; useful in transient conditions

Given temperature constraints, FBC is not needed for ESC; all aspects are used for ETC; >80% efficiency, <10 ppm slip

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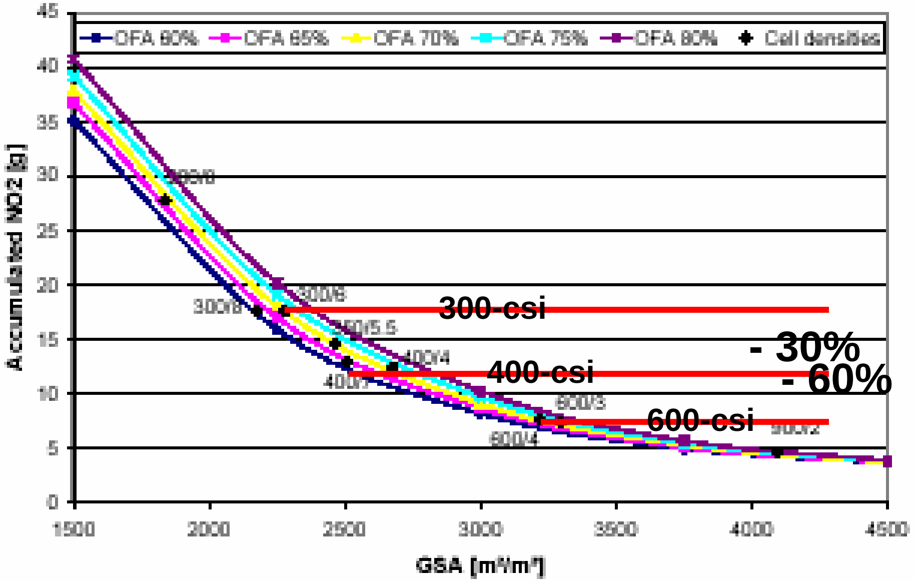
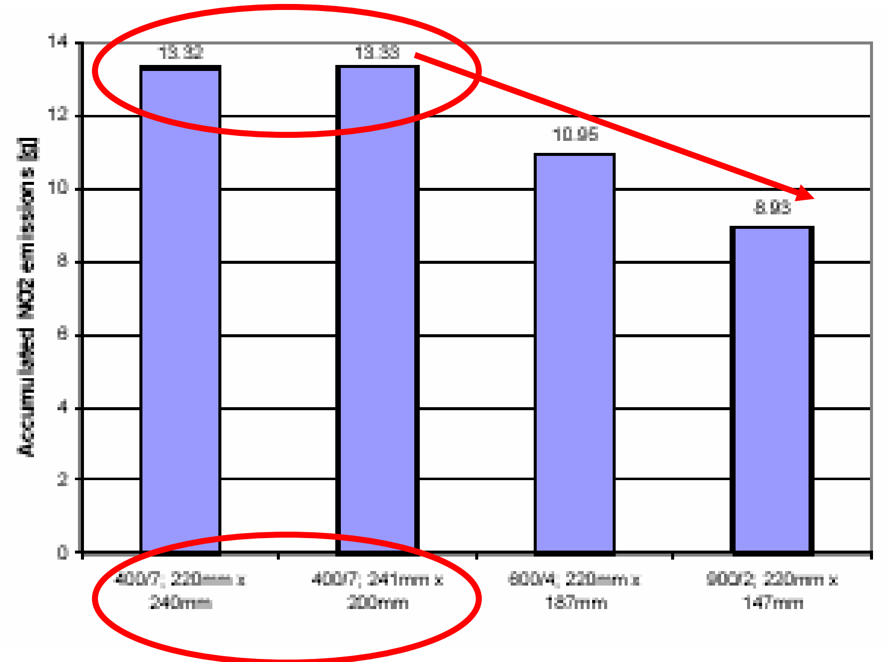
A dynamic model is developed to optimize the cell density of SCR systems

Same volume, increasing cell wall area



Same cell wall area, decreasing volume



400-csi:
Shorter, larger diam., same emissions

600-, 900-csi:
-22% and -40% volume,
-18% and -33% lower emissions

Corning, OMG SAE 2003-01-0845

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Lean NOx Traps

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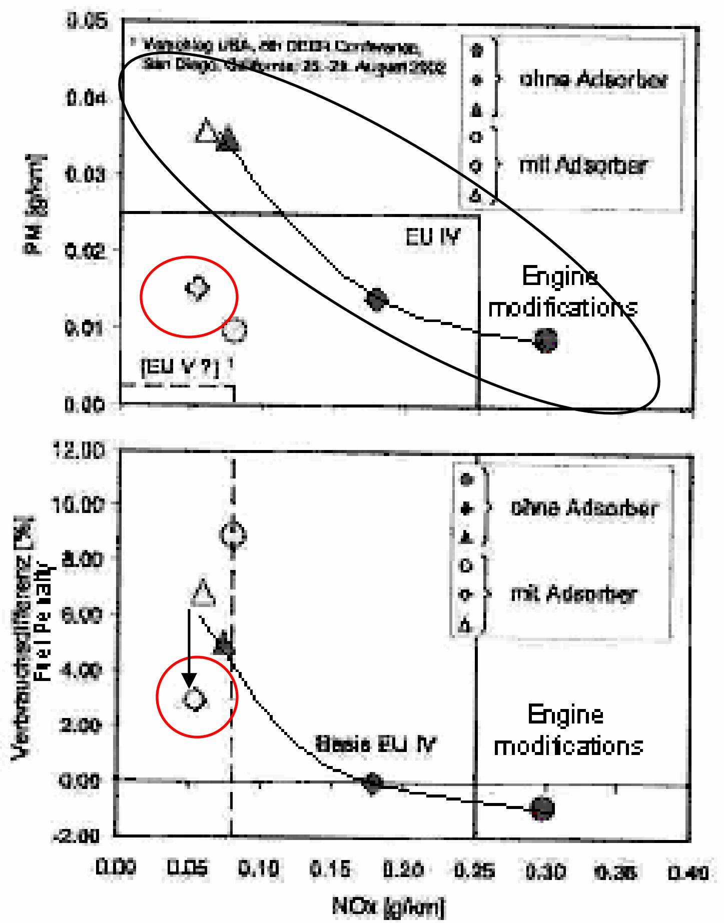
LDD Emission requirements and fuel penalties are described for Euro V (Proposal)

SCR has about a 7% effective fuel penalty to hit Euro V LDD



FEV, Vienna Motorsymposium 5/03

To hit Euro V NOx with LNT, a 3% FP is obtained, 5% via engine means.

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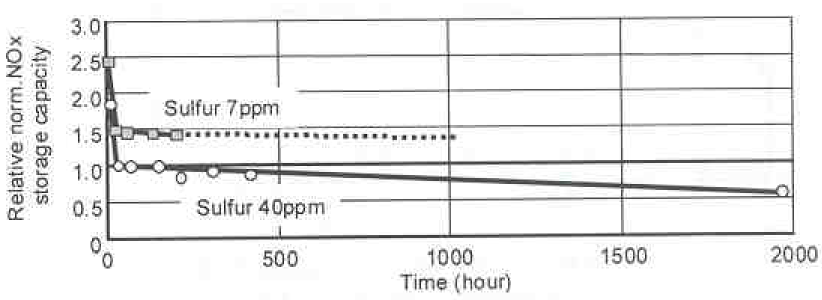
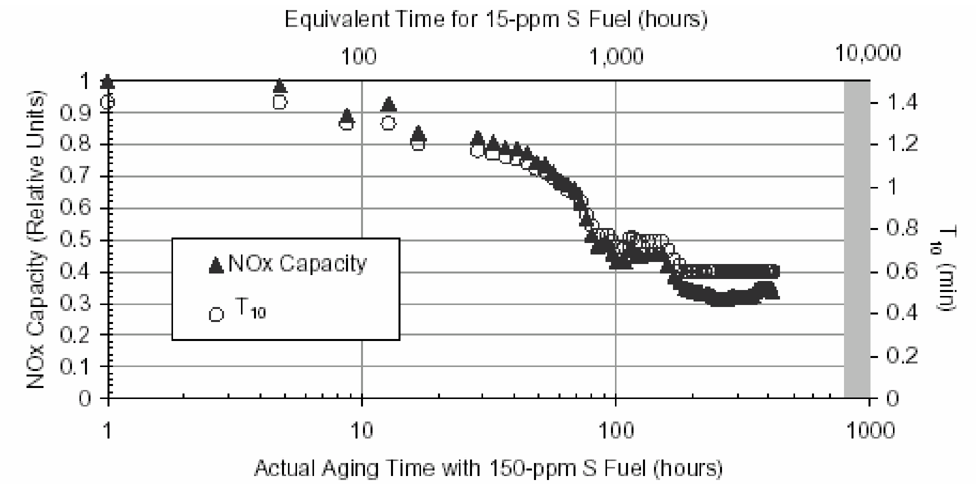
LNTs may deteriorate upon desulfation, but later stability is observed



Sulfur aging is characterized although not optimal 40-50 PPM is sufficient.

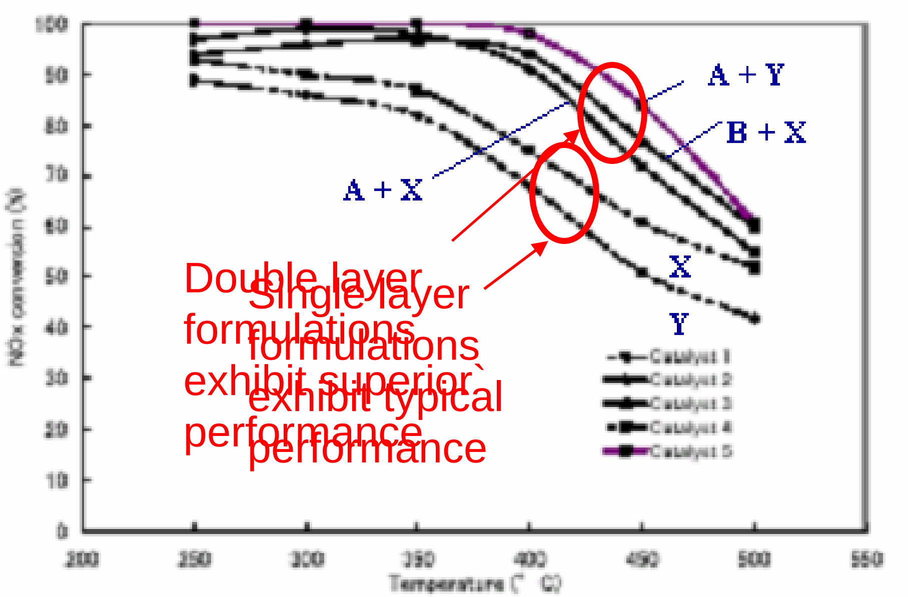
Toyota, Vienna Motorsymposium 5/02

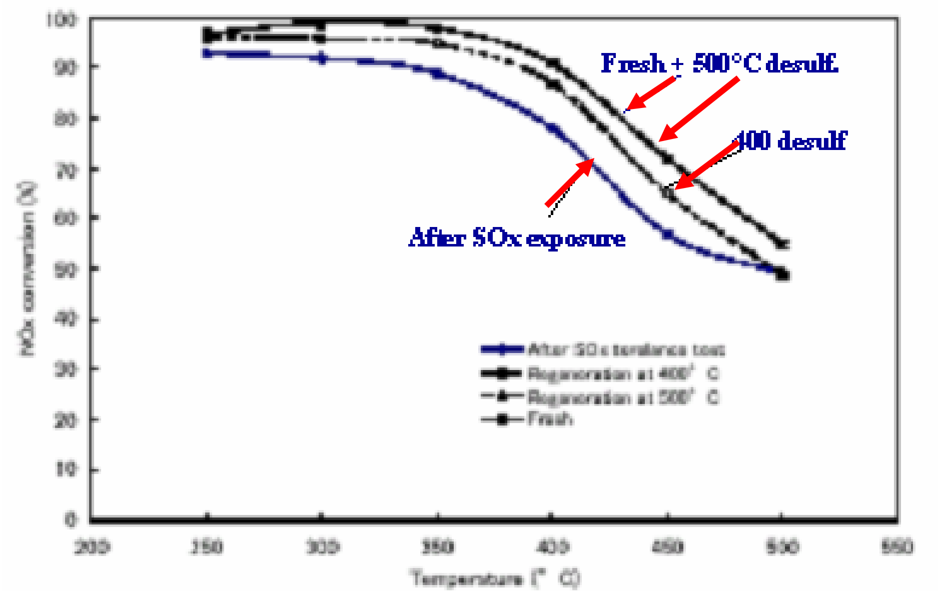


Emerachem DEER 8/02 and SAE 2002-01-2880

Other studies show no deterioration with up to 20+ desulfations. OMG Aachener Kolloquium 10/02; Delphi SAE 2002-01-0734

A new double-layer LNT is developed that keeps SOx off the adsorbing material





Top layer adsorbs SO_2 for moderate storage capacity, but quick release.

VTT, Mitsubishi SAE 2003-01-1158

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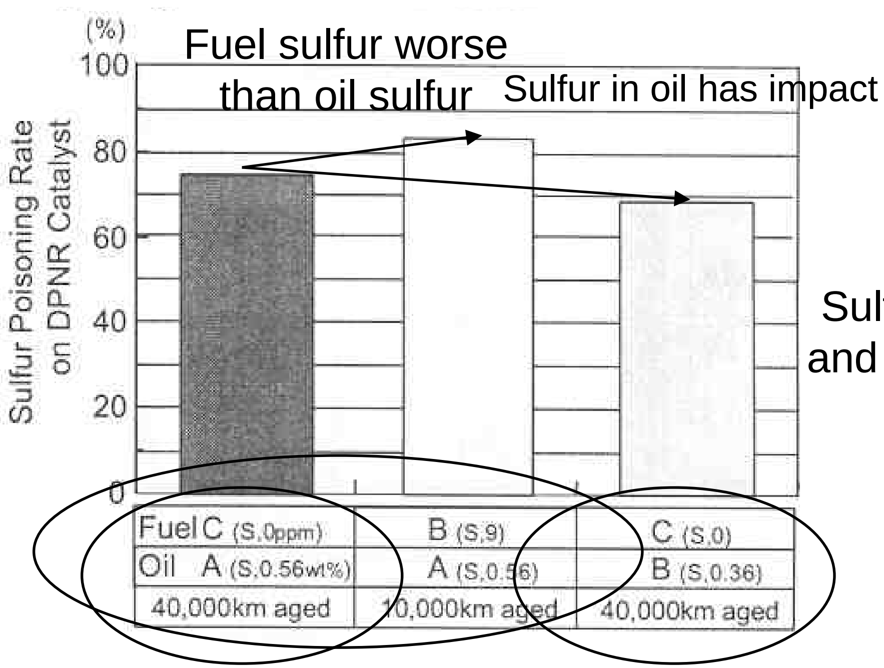
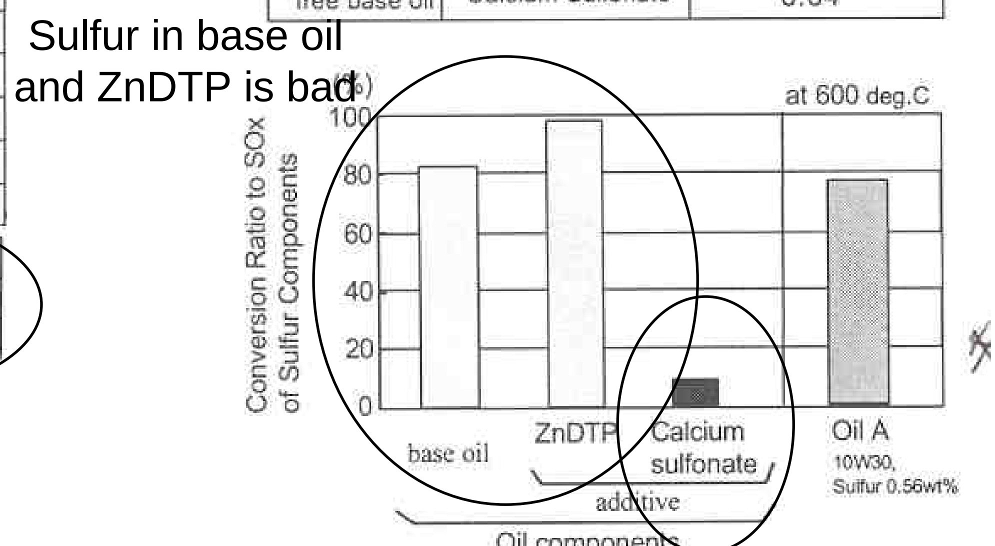
Effects of sulfur in lube oil on LNT are quantified



LNT efficiency is impacted by sulfur in the lube oil. Sulfur in base lube oil affect LNT more than sulfur in oil additives. A + B have same additive package.

Table 4. Test Oil Sample

		Sulfur (wt%)
Base Oil		0.42
Additive with sulfur free base oil	ZnDTP	0.24
	Calcium Sulfonate	0.04



SOx formation from lube oil varies on where the sulfur resides.

Toyota, SAE 2003-01-1865

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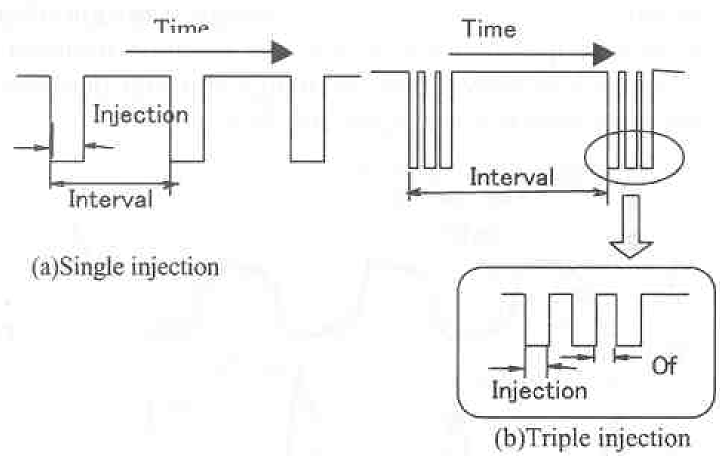
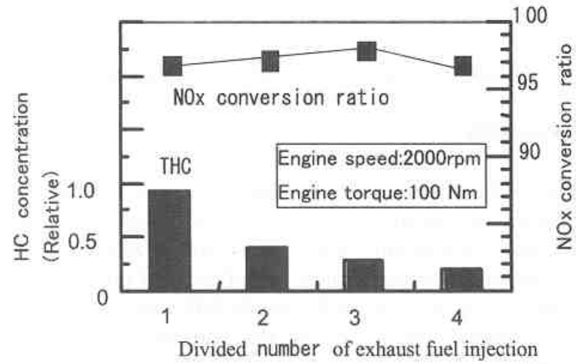
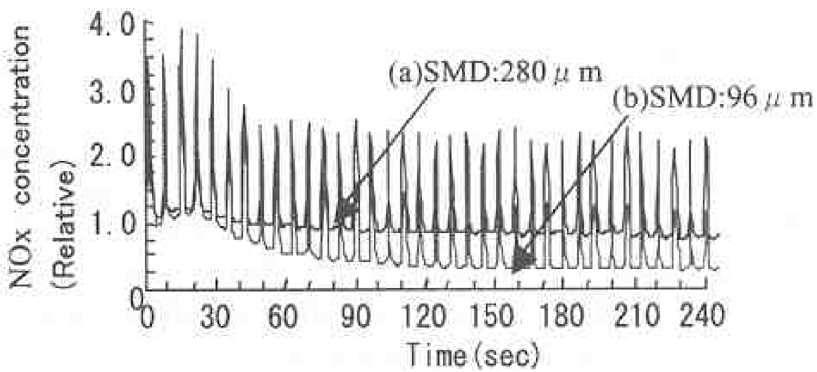
Injection strategy for fuel is described for DPNR

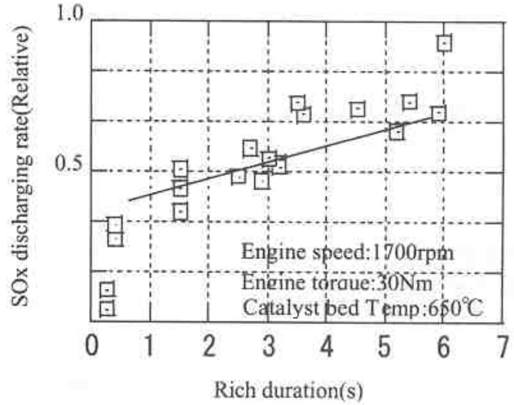




Split injections result in better utilization of reductant and lower HC slip.



Smaller droplets from port injector evaporate faster, and are more easily utilized.



Given constant total desulfation fuel, it is better to have a longer rich pulse.

Toyota, SAE 2003-01-1880

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Integrated systems

DPF/SCR systems are on the road - 5 trucks in the US

SCR: extruded 200-csi, SVR=3.8

Exhaust Emission	Baseline (eng.-out)	SCR/DPF (cat.-out)	% of change
NOx g/bhp-hr)	5.80	1.06	-82%
HC (g/bhp-hr)	0.055	0.00	-100%
PM (g/bhp-hr)	0.094	0.010	-89%
CO (g/bhp-hr)	0.71	0.40	-44%

Combined FTP hit US2007 blended NOx and PM; 82% NOx efficiency, 89% PM efficiency

Exhaust Emission	Baseline (eng.-out)	SCR/DPF (cat.-out)	% of change
NOx (g/bhp-hr)	5.89	0.85	-86%
HC (g/bhp-hr)	0.01	0.00	-100%
PM (g/bhp-hr)	0.033	0.018	-55%
NH3 (ppm Ave.)	N/A	0.4	N/A

OICA hit US2007 transition NOx, but missed on PM due to sulfates

- 3 Mack highway tractor/trailers
- 2 refuse trucks
- started mid-2002

Ceramics LLT, SAE 2003-01-0774

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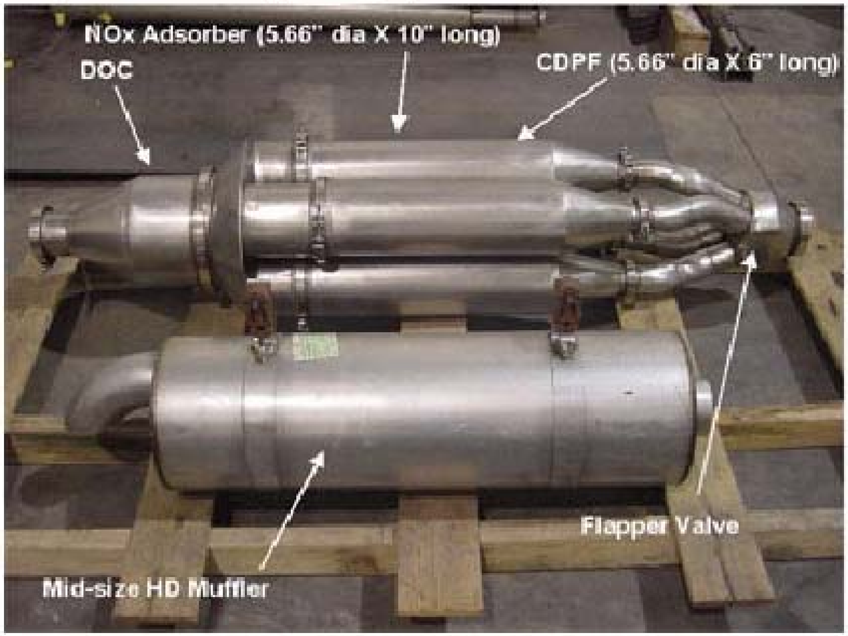
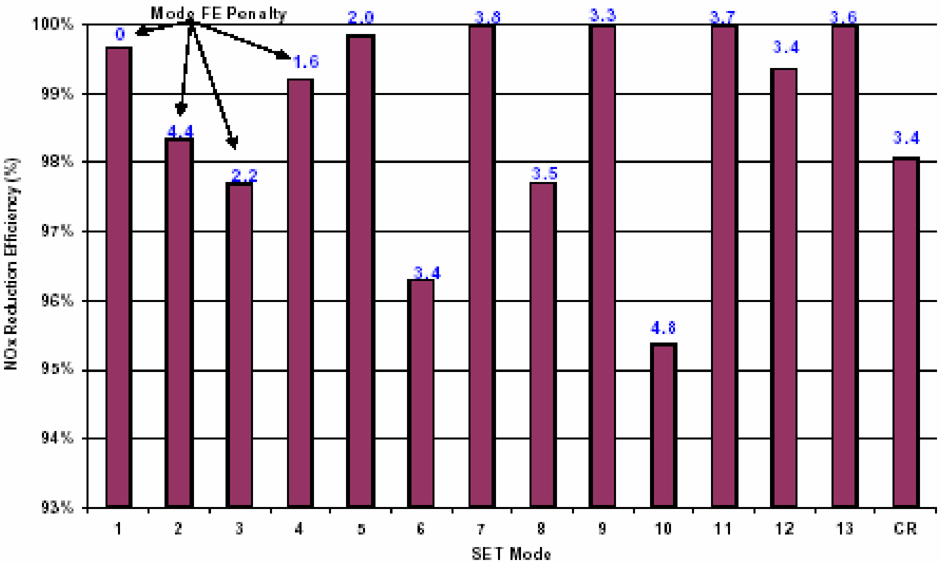
The large EPA 2-leg LNT/DPF system is replaced with a more “efficient” 4-leg system





NOx efficiencies are >95% at all S.S. modes and fuel penalties are 1.6 to 4.8%.

In the EPA four-leg system, one leg is being regenerated while three legs are in collection mode. The regeneration gas is throttled and uses a fuel injector to minimize fuel penalty. SVR (LNT) = 2.8; SVR (filter) = 1.7

EPA Non-road NPRM 4-03

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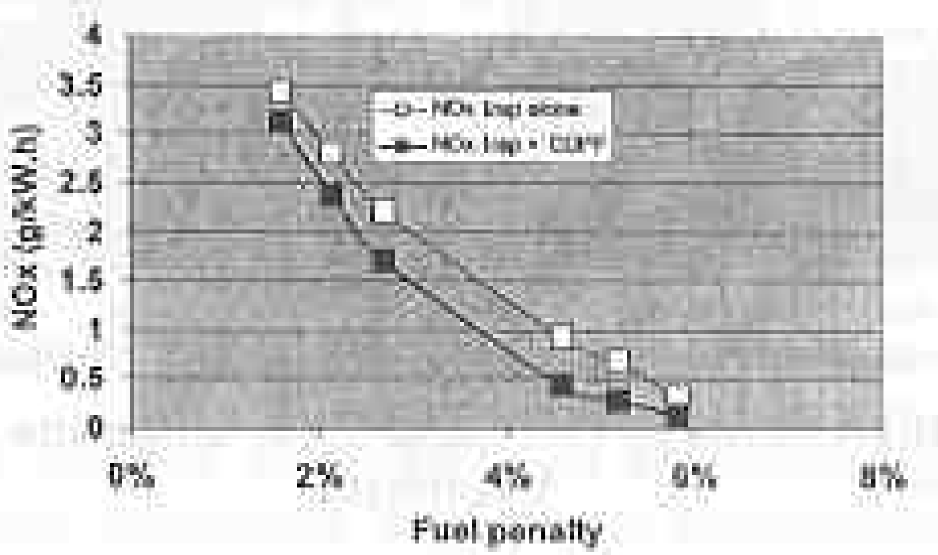
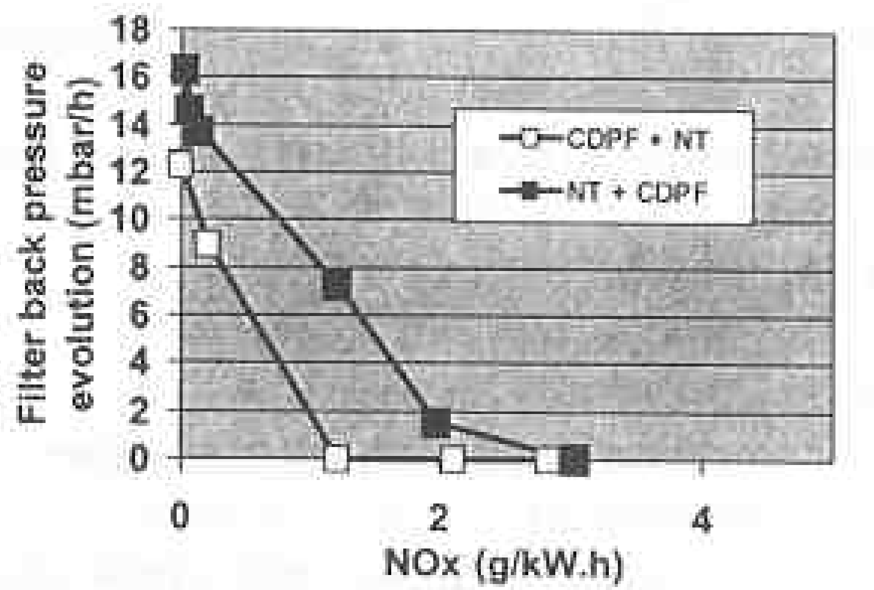
6.2 liter Euro III HDE equipped with CDPF + LNT hit HDD Euro V; 1.8% FP





FC is lower with CDPF due to some downstream NOx conversion in it.

With CDPF in the front, NO_2 can oxidize soot, giving lower back pressure.
Back pressure goes up with decreasing NOx due to more LNT regenerations and resultant soot.

<u>NOx Trap + CDPF</u>

CDPF + LNT + DOC chosen; 1.8% FP

Issues: Keep soot from building up given low NOx target; control regeneration to keep LNT T<700°C

IFP, RVI, Vienna Motorsymposium 5/04

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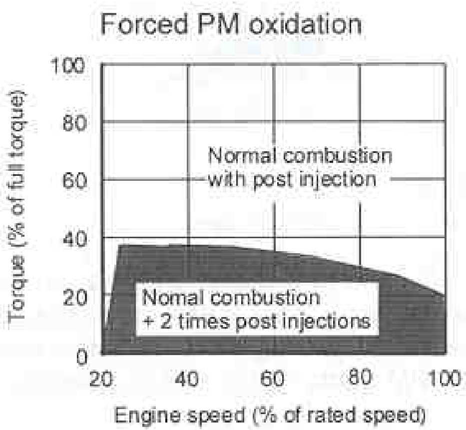
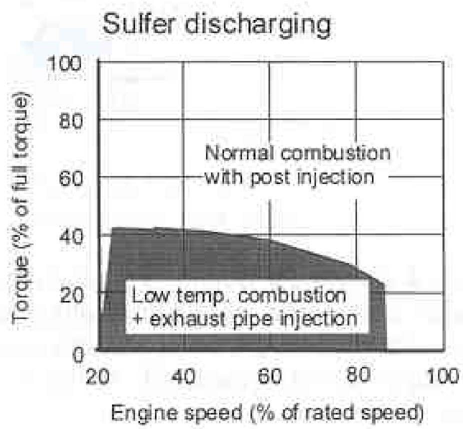
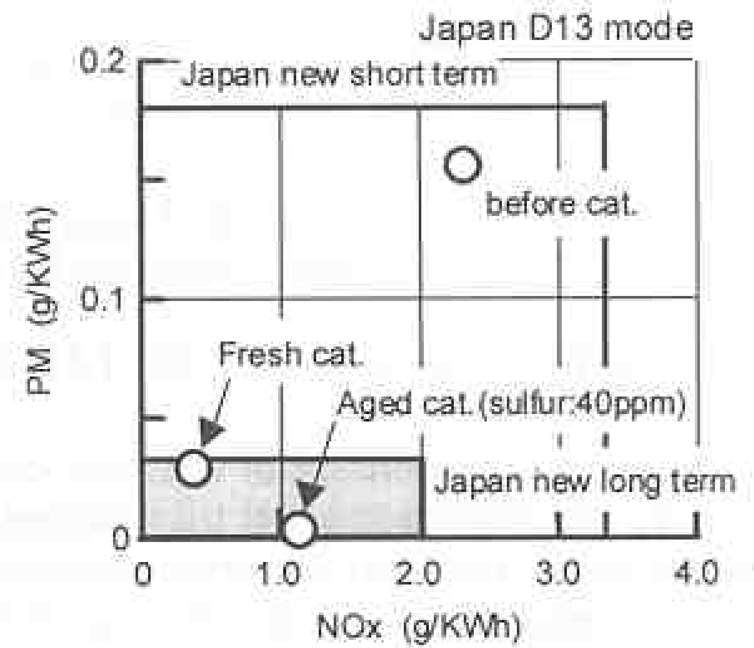
A 4.0 liter light duty commercial truck is fit with the DPNR system







Temperatures from 4l TSI-CR are sufficient to use only auxiliary injections to regenerate filter. Desulfation requires low-temperature combustion control.

- **PM efficiency increases from 90% to 96% after 2000 hrs.**
- **Ash back pressure increases 30%**
- **In Japan Transient Cycle, temperatures are too low, necessitating low temperature combustion at low load.**

65% NOx aged efficiency.
NOx emission more than doubles upon 2000 hrs of aging in 40 ppm sulfur fuel (200,000km);

Toyota, Vienna Motorsymposium 5/02

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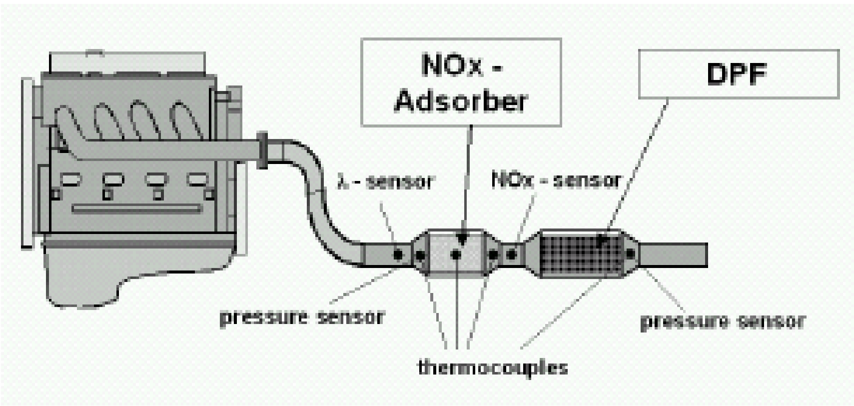
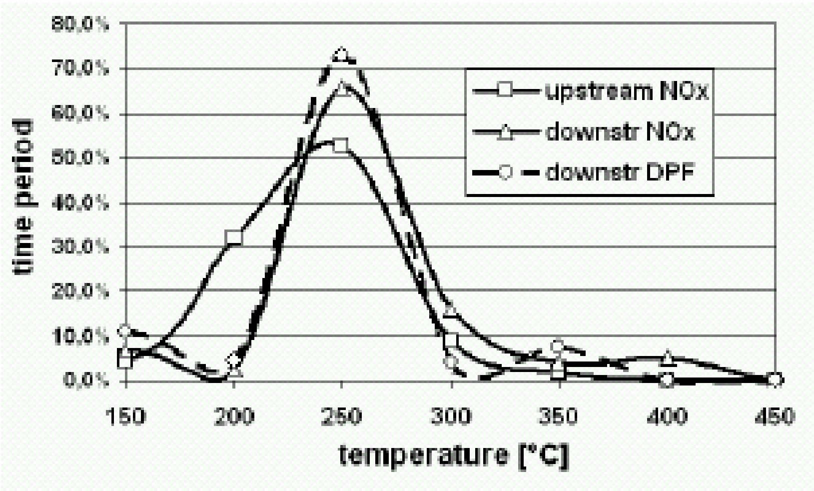
LNT / DPF synergies show on LDD



1750 kg vehicle with 2.0 l engine; Ce-FBC, uncat. 4.6 l DPF



During 660 km of mixed driving, the DPF never exceeded 450°C and was hotter than LNT inlet.

- High LNT exotherms and NO_2 slip may have burned soot.
- Cordierite DPF could work well with LNT
- High cell density LNT might minimize NO_2 slip
- Oil dilution with fuel is a problem: 7.7% over 15,000 km
- 55 to 65% NOx eff. With 4.5 to 5% FP in certification cycle testing

AVL   SAE 2003-01-0043

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Exhaust emission control systems are part of the solution

- DPFs, DOCs, SCR will be applied in 2005 in Japan and Europe
  - some LNT in 2007 in the US
  - LNT in LDD this year
- Filters are in the optimization stage
  - understanding improving regeneration
  - filter properties
  - ash management issues
- NOx solutions are available at +70%
  - SCR is being optimized
  - LNT is on dynos
- Integrated solutions are making HDD the environmental benchmark

THE END

Thank you.

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