Review of Diesel Emission Control Technology

Tim Johnson

August 2002

CORNING
Discovering Beyond Imagination

Outline

- Introduction
  - Regulatory update and technology approaches
- Ultrafines
- Filters
- NOx
  - LNC
  - SCR
  - LNT
- Integrated approaches
  - EGR+filters
  - LNT+filters
  - SCR + filters

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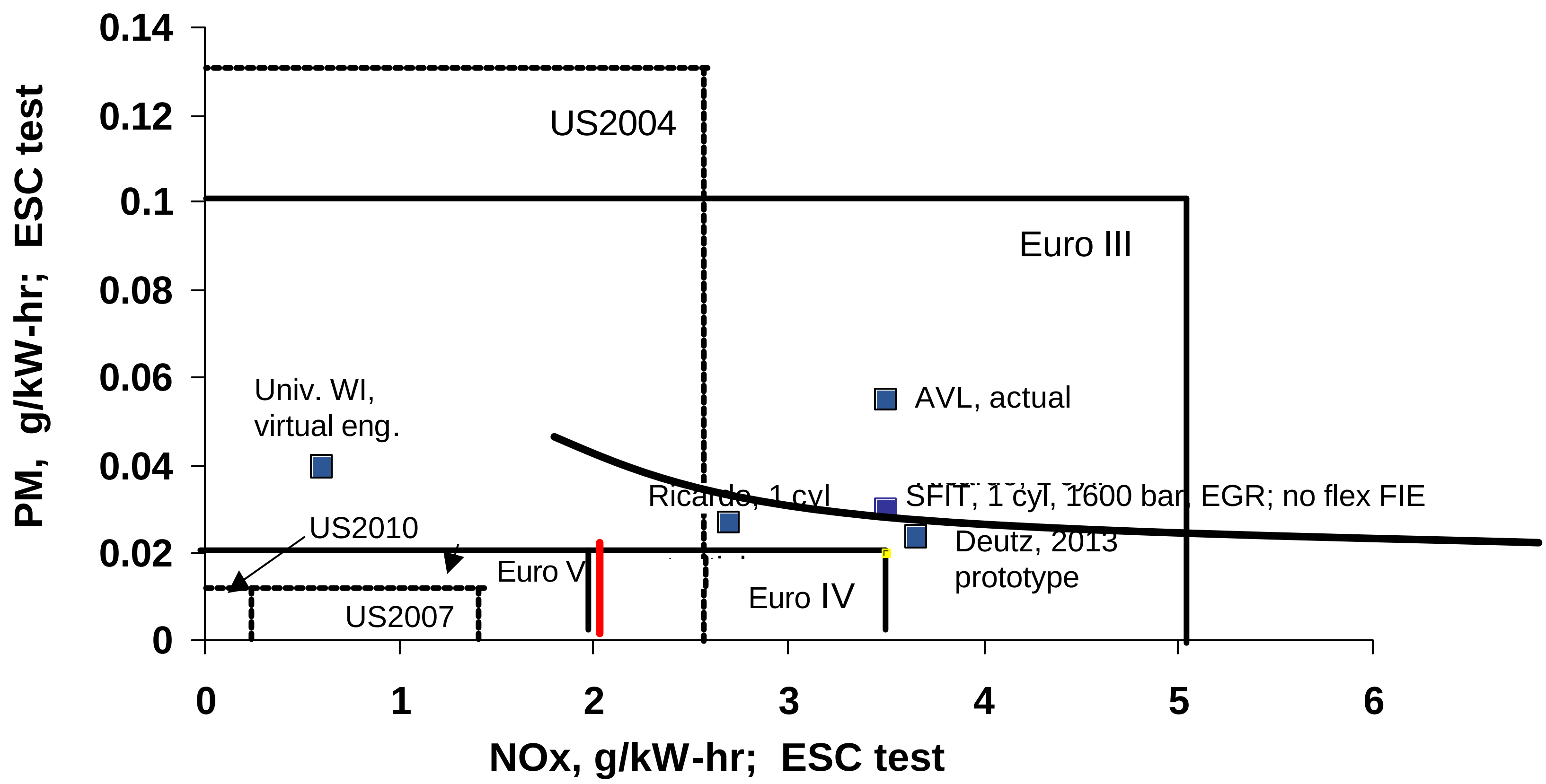
Where will HDD engines be in 0 to 2 years?



•Prototype Engines have cooled EGR, combustion optimization, fully flexible fuel injection, staged turbocharging, multi-hole injectors, high pressure injection.

Japan 2005 = Euro V (2008)

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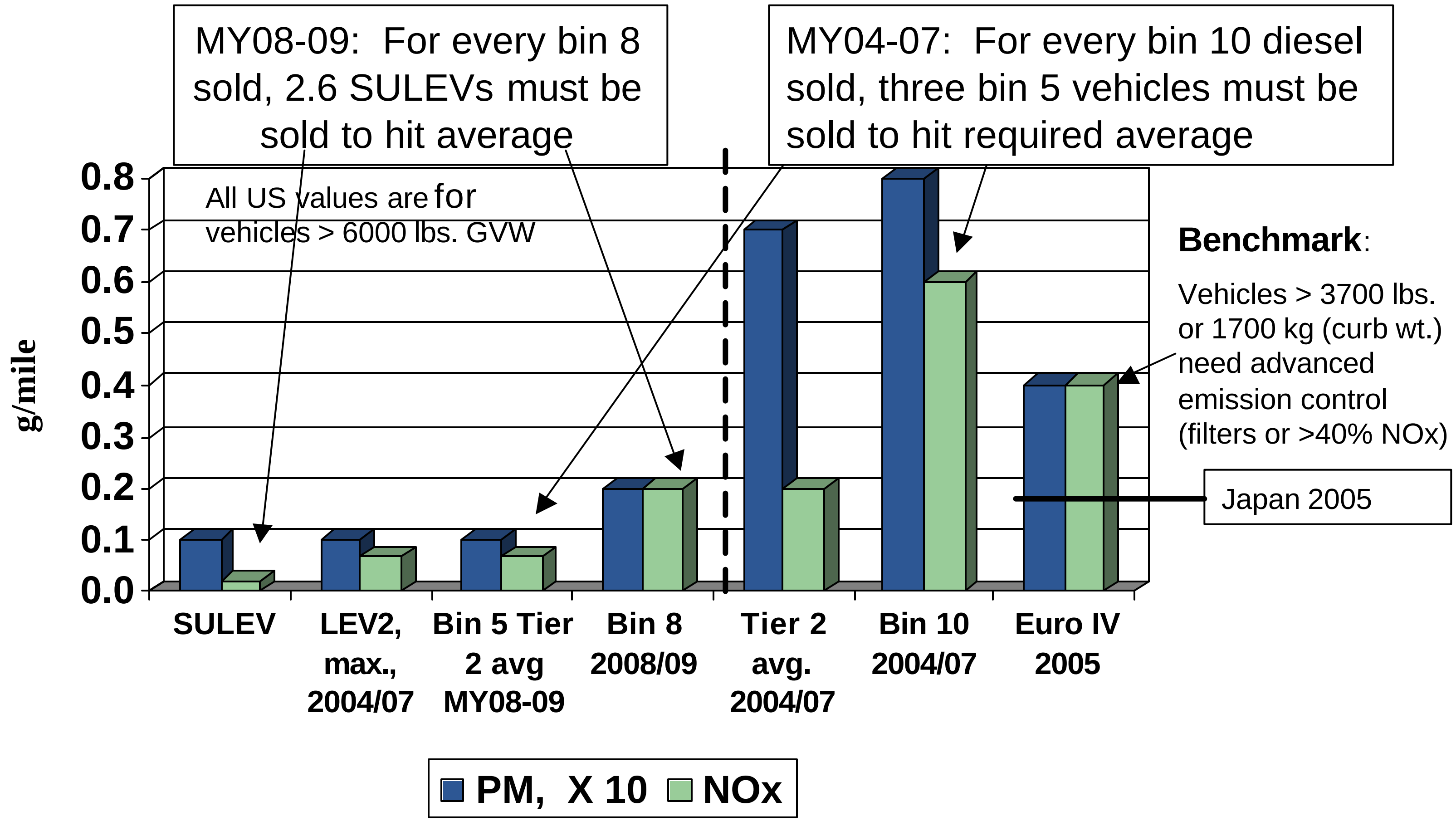
LDD regs: Only heavier PC in Europe will need advanced technology; US has options for less emission control, but “price” is steep; SULEV charges for gasoline are really diesel charges



- US: Until fuel is available, look for DOCs; After that: strategy (LNT+DPF)
- Nissan “hit” Bin 5 with 5000# GVW; Cummins and DDC optimistic by MY07 GVW>6000#

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Ultrafine particle studies

- HDE technology advances over years has resulted in lower ultrafine particulates
- Contrary to previous hypotheses, nanoparticle fraction appears to be comprised primarily of lube oil or other heavy HCs

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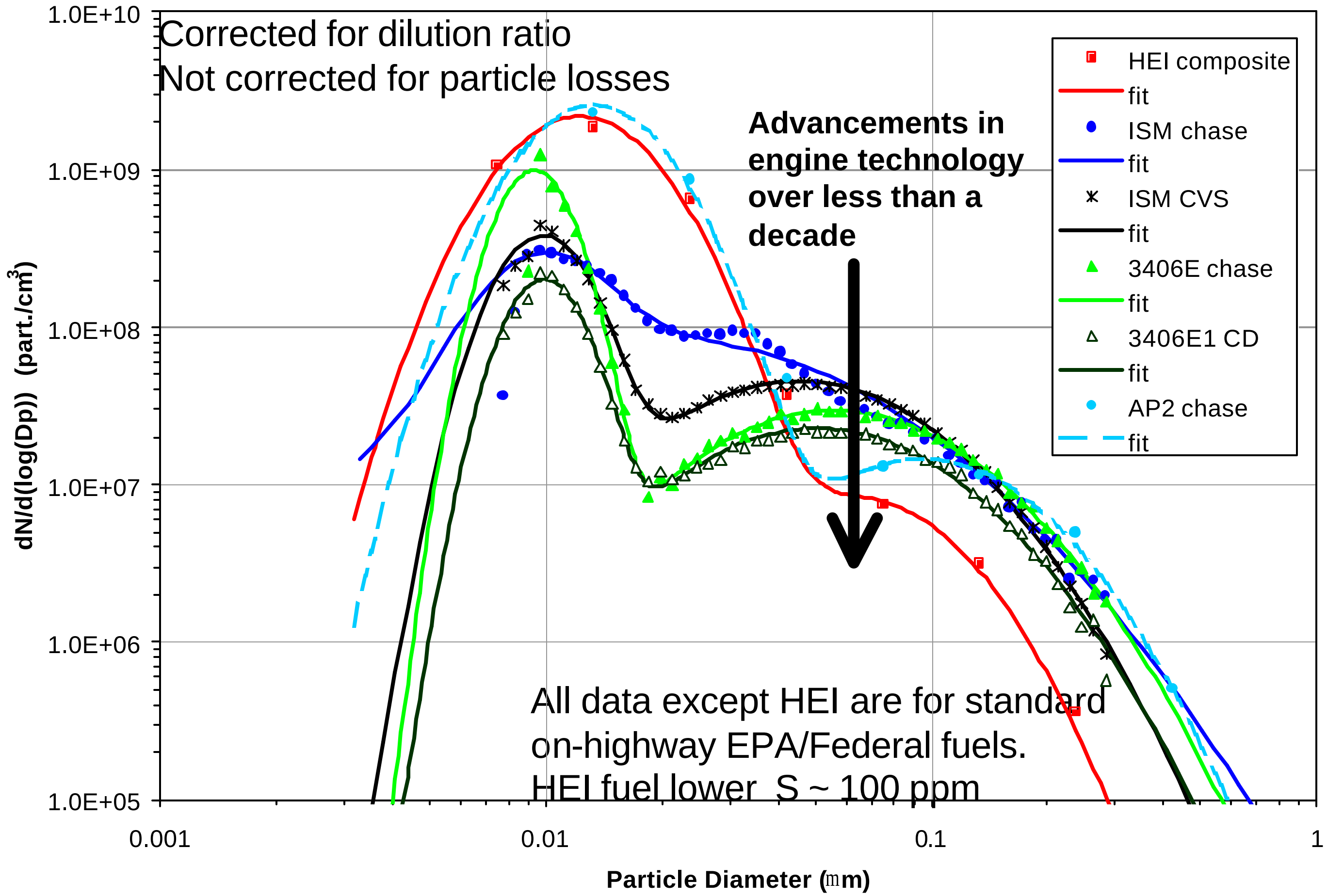
Critical evaluation of ultrafine emissions from current and previous engine technologies shows continuous improvement



Other key results: Developed effective means of duplicating exhaust plume studies in the laboratory

Univ of MN, CRC, DEER 8/02

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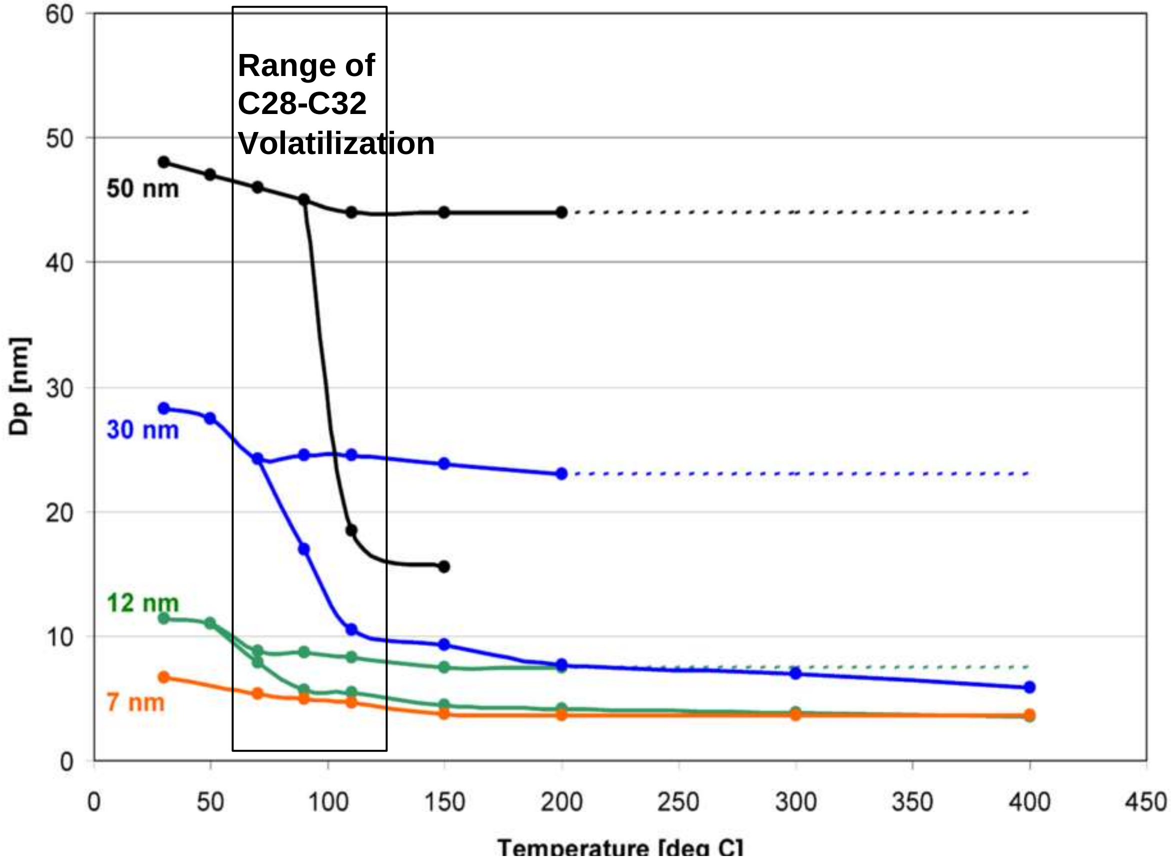
Nanoparticles are likely primarily composed of lube oil components, or other heavy HCs



University of MN, DEER 8/02

When nanoparticles from diesel exhaust are heated, they begin losing much mass at a temperature range that indicates large HCs. A non-volatile portion remains in all but the smallest particles. Hygroscopicity studies show very little sulfuric acid, except at upwards of 300 ppm fuel sulfur.

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Recent developments in filters

- Filter literature prior to 2000 was on feasibility
- Current literature is on optimization
  - regeneration strategy
  - filter properties
- New filter types are described

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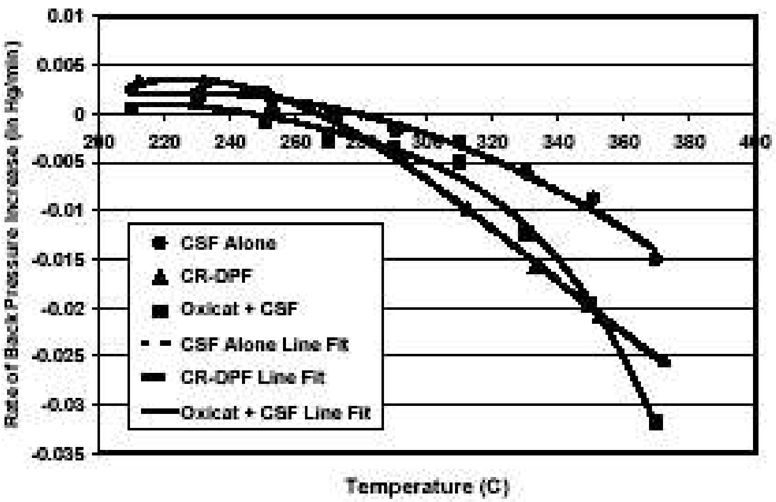
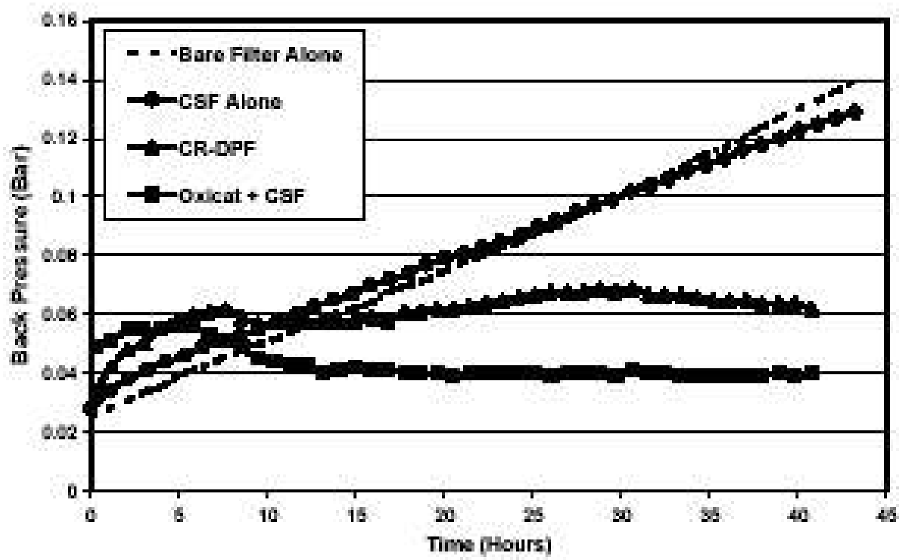
A DOC+CSF gives improved regeneration relative to std. CRT system



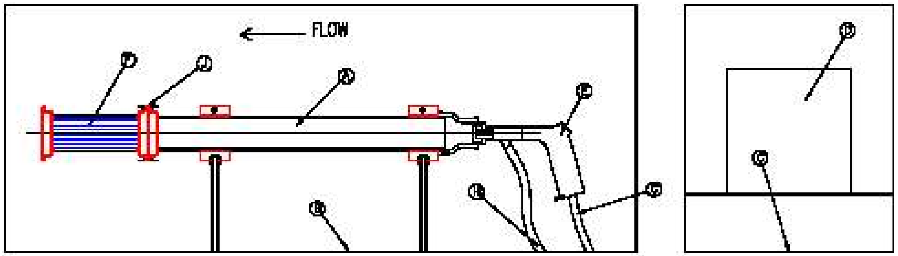
9 liter, 250 hp engine, 1580 rpm, soot preloaded at 225C



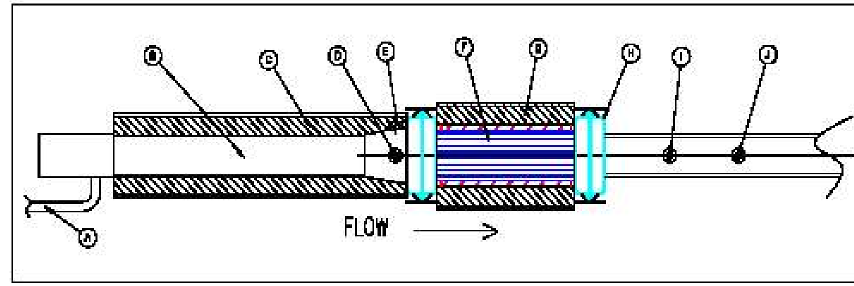
System	Balance Point Temperature
CR-DPF	265°C
CSF Alone	280°C
Oxicat + CSF	250°C

New DPF system gives lowest back pressure in low temperature testing. LT cycle gives 160C<T<265C; mix of steady state and transient; 10 liter 210 kW turbo bus

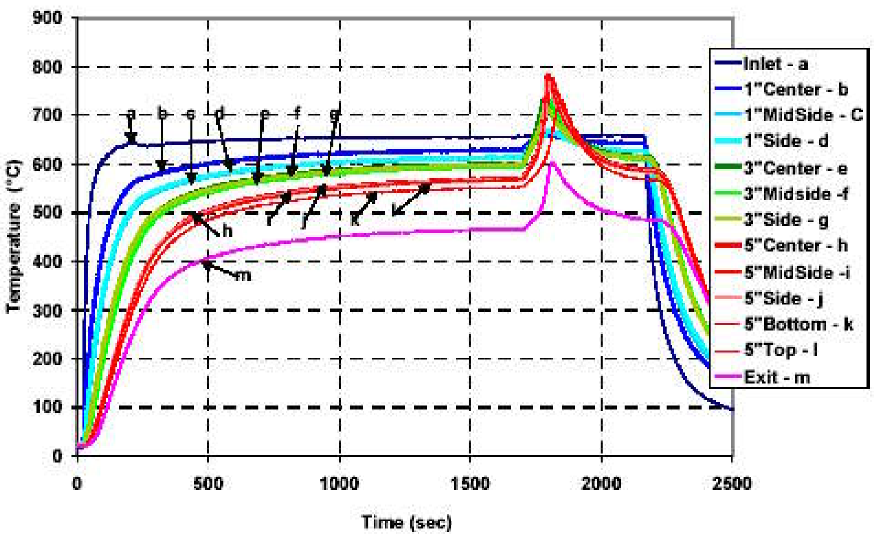
An experimental method was developed that enables rapid evaluation of regeneration conditions. High flow rate, lower oxygen and soot loadings, and optimal inlet temperature can be used.



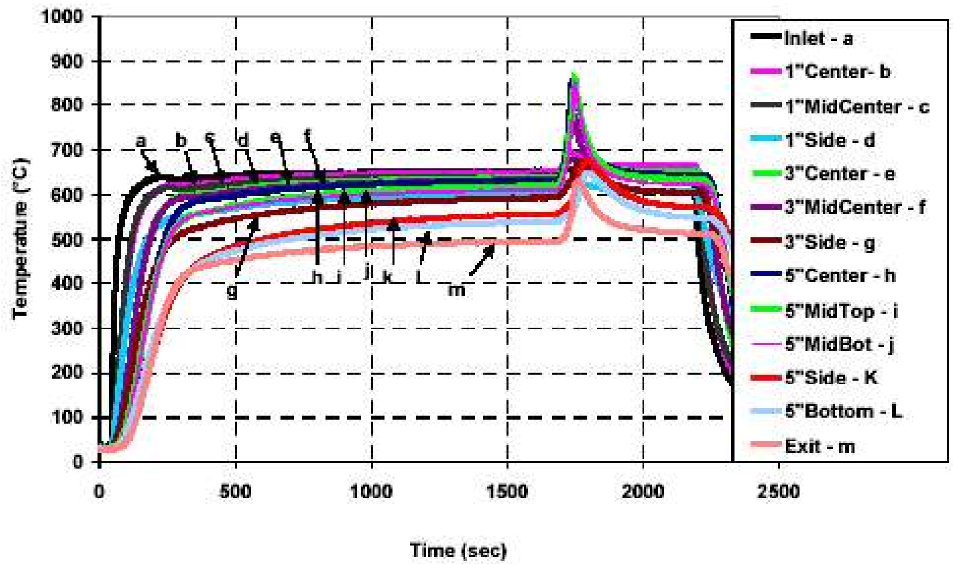
Artificial soot from a container (D) is quickly loaded into the filter (F) using compressed air (G). Photocopier toner is used.



The loaded filter (B) is then preheated with hot gas (B) to equilibrium, and regeneration gas is fed in.



SiC filter loaded to 10 g/l soot, preheated to 650C and then regenerated in 18% O2.



Cordierite filter under same conditions. Higher peak temperatures, broader T range.

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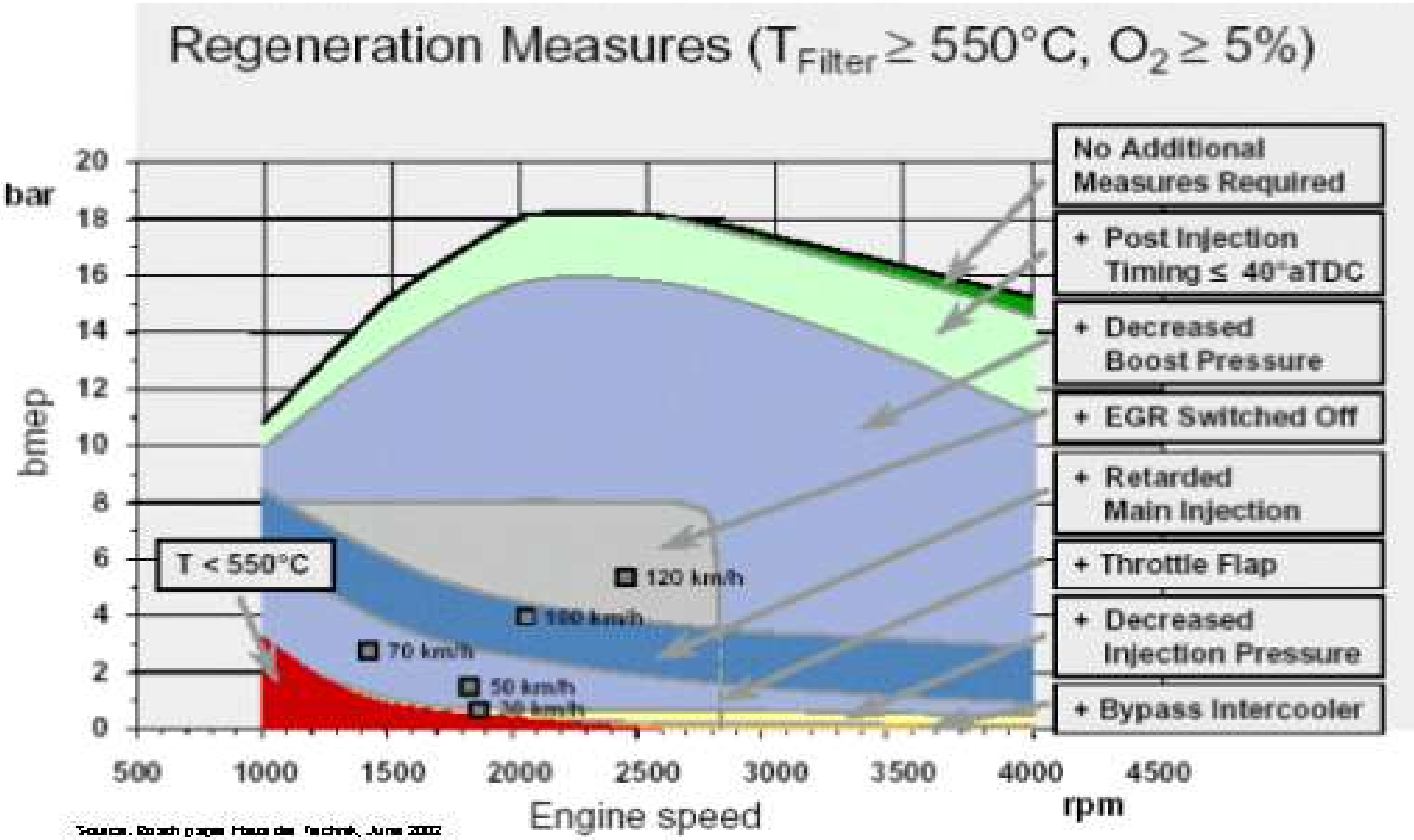
Corning SAE 2002-01-1009

Regeneration strategies are being refined for better reliability



Bosch, Vienna Motorsymposium 4/02

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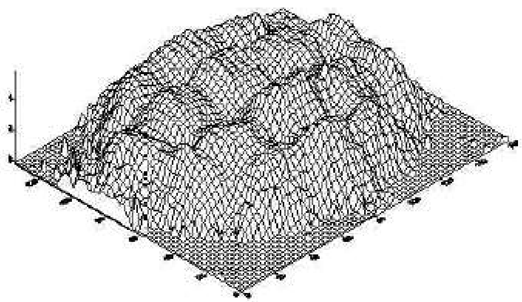
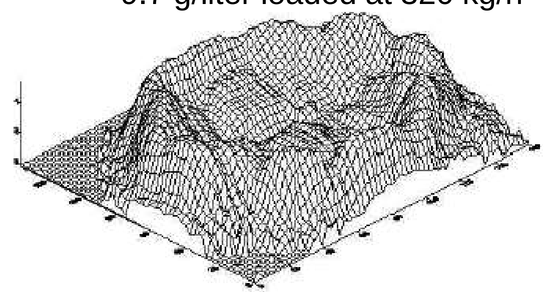
Flow rate over a DPF cross section depends on soot loading flow rate. This can impact peak regeneration temperatures

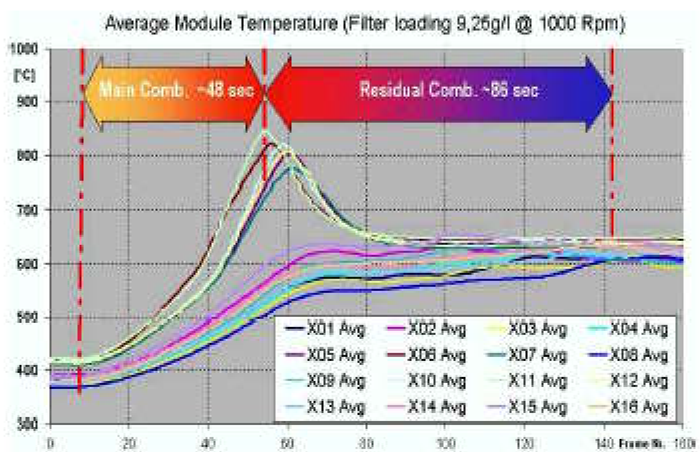
9.3 g/liter loaded at 60 kg/h

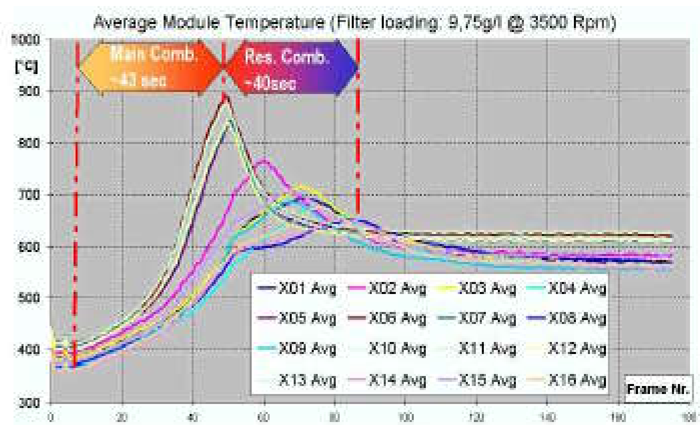


9.7 g/liter loaded at 320 kg/h



Flow distribution for filters loaded at low and high flowrate with soot (about 9.5 g/liter). At low flowrate, flow is even across the face meaning the soot is evenly distributed in the filter. At high flowrates, flow is eventually (at about 6 g/liter) diverted to the outside. Measurements at 150 kg/h.





In both cases the regeneration begins in the central segments. However, the peak temperature is higher for the filter loaded under high flow rate (right). Perhaps this is due to lower flow rate (less heat removal) in the center sections. Regeneration with a burner and at 350 kg/h.

Zeuna Staerker SAE 2002-01-2158

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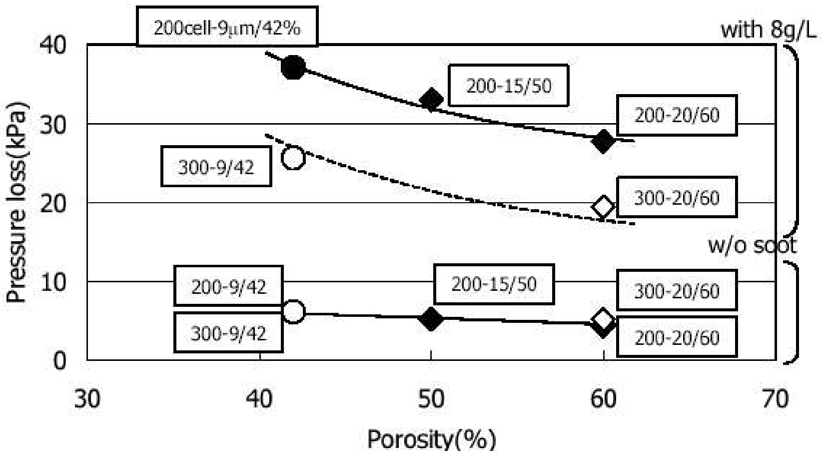
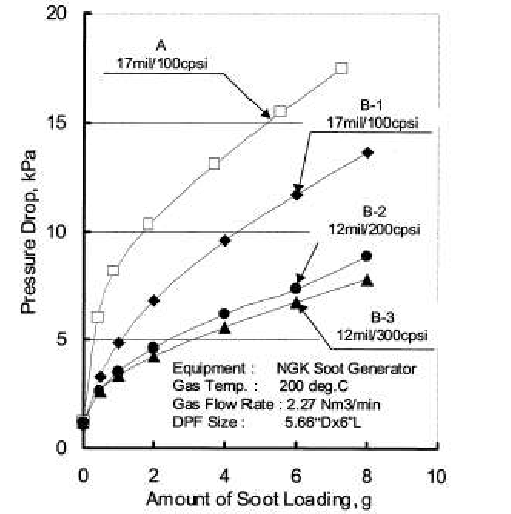
DPF properties are being optimized to significantly reduce pressure drop

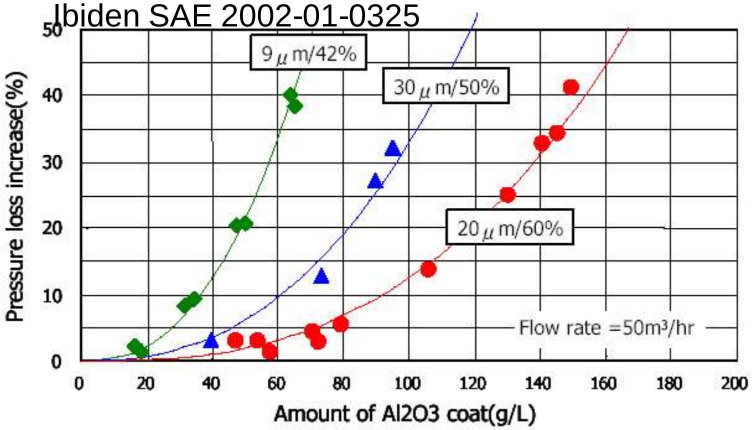


Pressure drop dependency on cell geometry and porosity is different for loaded and unloaded SiC filters.



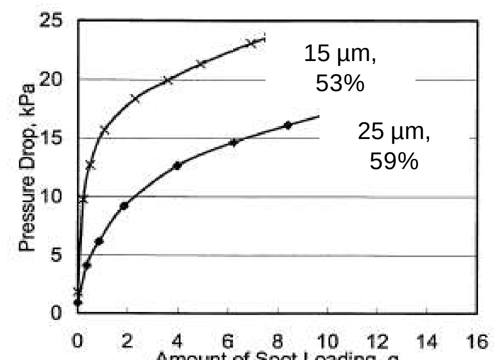
At higher cell densities, back pressure is strongly dependent on wall thickness. Porosity is 59% w/ 25 μm avg. (Type A is 53% and 15 μm)

Ibiden SAE 2002-01-0325



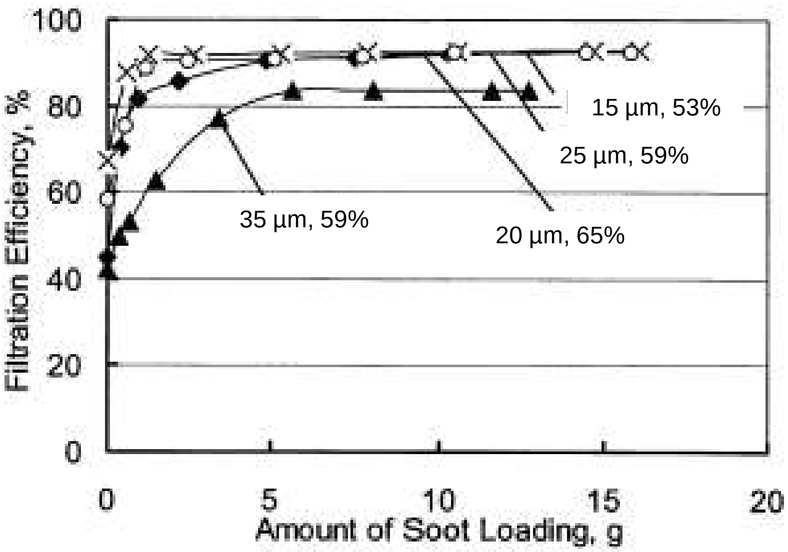
Pressure drop of washcoated filters is more dependent on percent porosity than average pore size. With large pores, WC is impregnated into filter, dropping effective pore size.

NGK 2002-01-0322



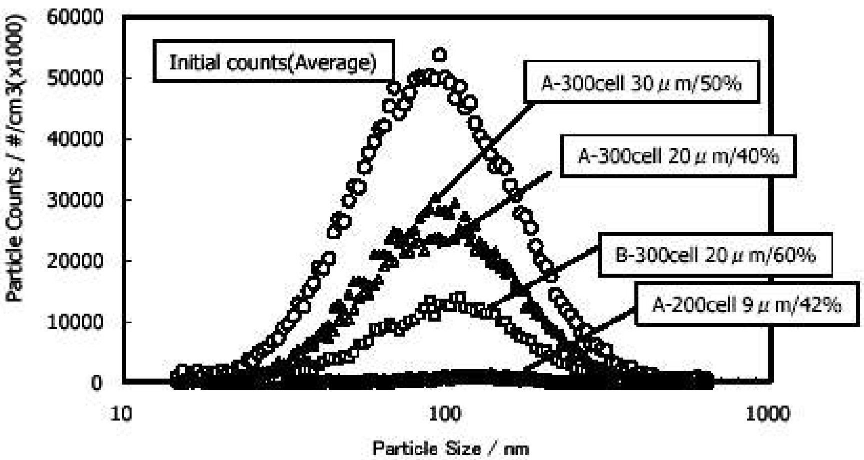
Pressure drop of washcoated filters can be dropped with pore engineering, 300/12, 100g/liter

Filter porosity can affect filtration efficiency by mass and number



Filtration efficiency by mass is dependent on pore size if > 25-30 µm

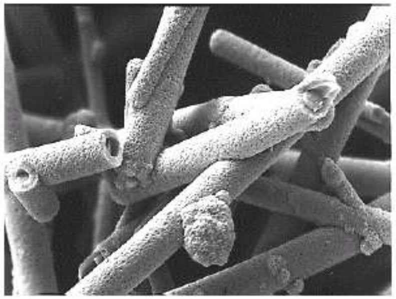
NGK 2002-01-0322



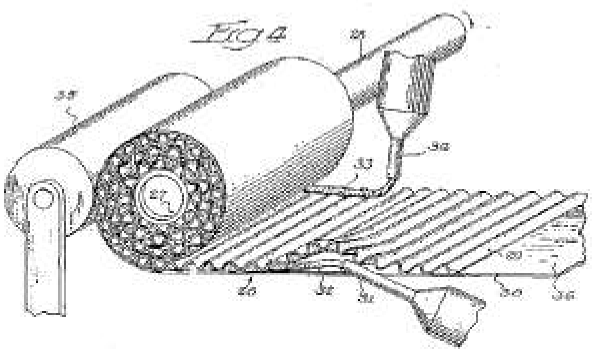
Initial filtration efficiency for filters. Ultrafine particulate efficiency will increase as filtration proceeds or if washcoat is added. Uncoated filters.

Ibiden SAE 2002-01-0325

New filter materials and concepts are emerging



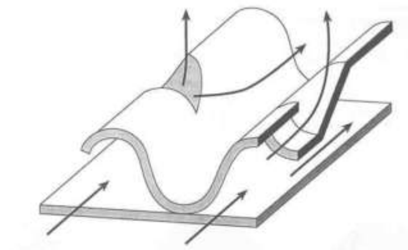
Alumina fibers are CVD coated with SiC. 3 µm diameter



Fibers are made into paper and rolled into a plugged honeycomb.

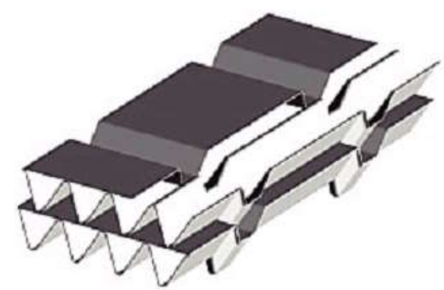
Filtration efficiency is marginally better than standard filters, but standard filters can hold more soot at given pressure drops.

Fleetguard, 3M SAE 2002-01-0323



MAN, Emitec Vienna Motorsymposium 4/02

- Only 50% ultrafine soot removal
- Not suitable for dirty engines
- Ash goes through
- Soot trapping mechanism is via a metal screen; or diffusion to catalyst via thermophoresis and then NO_2 oxidation for concept below



Another concept that does not use screens for filtration; performance not yet reported

Source:http://www.kemira.com/metalkat/emissionNews/1_4.html

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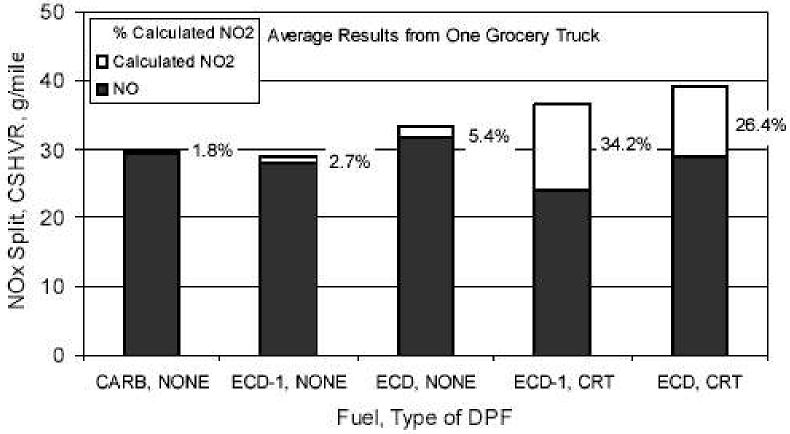
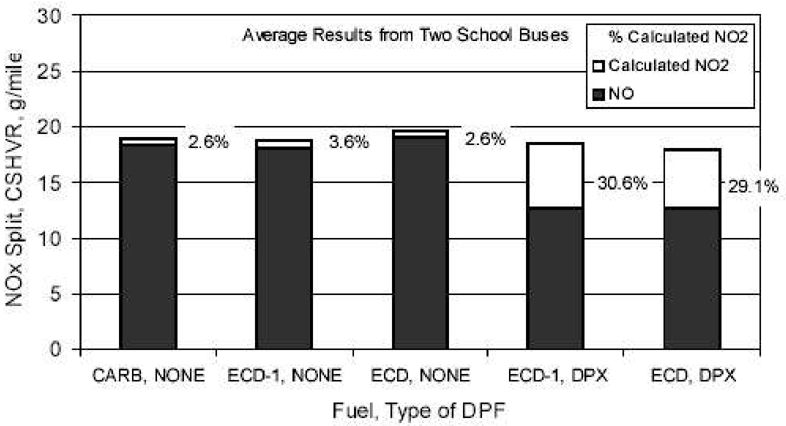
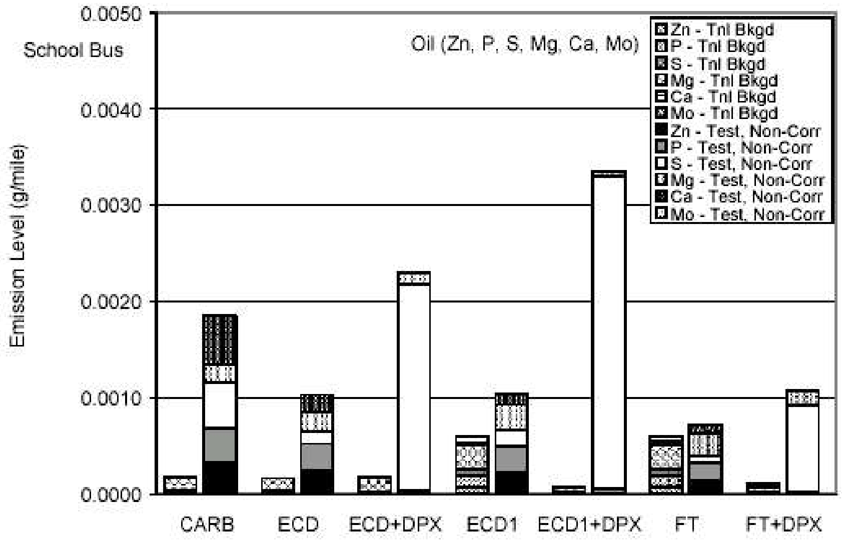
Some filters are not perfect. They have NO_2 emissions and can store and release sulfates.





Both leading filter systems generate NO_2 to facilitate PM oxidation. NO_2 emissions are increased.

BP SAE 2002-01-0433



Lube oil elements in PM from school bus. DPX filter system likely stores and releases sulfur. CRT did not exhibit this behavior.

BP SAE 2002-01-0432

Also, catalyzed filter systems will convert sulfur to sulfate, which condenses as PM, and perhaps nanoparticles under the right conditions. (various studies)

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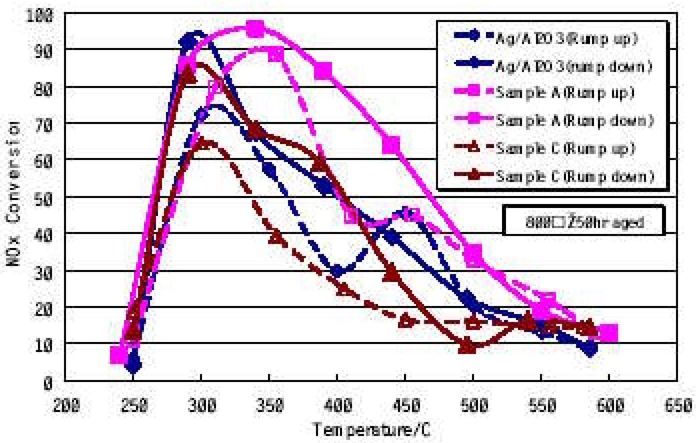
NOx Control

- SCR leads the technology field in terms of maturity and reliability of performance
    - secondary emissions are now being tackled
- LNT is making rapid progress, and is a very attractive technology that could overtake SCR
- LNC could be a viable option in some situations - less favorable efficiency/fuel penalty tradeoff, but has attractive features

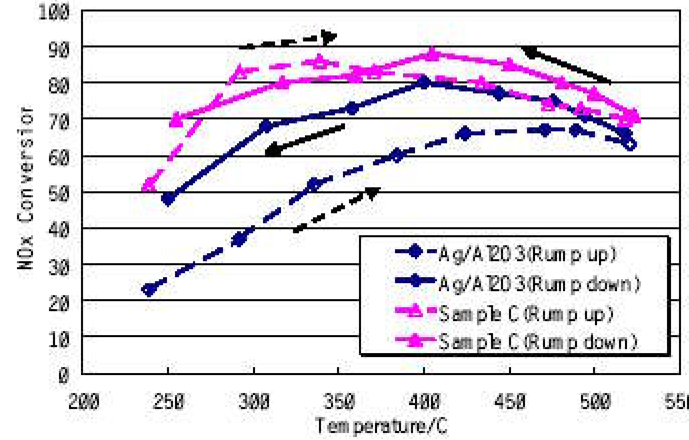
LNT and SCR lead the field on effective NOx control, but LNT is young and moving faster

System	Transient Cycle NOx Efficiency	Effective Fuel Penalty	Swept Volume Ratio	Notes
SCR, 400-csi coated catalyst	85-90% emerging	5-7% urea or about **2.3%** in Europe or **4.7%** in the US	1.7 emerging	Secondary emissions issues emerging; systems with oxicats still need ULSD fuel; durability well-proven for vanadia systems
LNT	80-95% not exposed to sulfur	2 – 6% total regen. + desulf.	2 to 5	Key issue is proving durability within realm of an effective desulfation strategy; integrated DPF/LNT components emerging
DeNOx catalyst	25% 50-70% emerging	2 to 6%	0.8 to 4	Marginal improvement with increased cell density and perhaps better fuel management; HC slip issue
Plasma/deNOx catalyst system	80%	6%	4	Bench scale work; 2001 saw a relatively large step change in improvement.

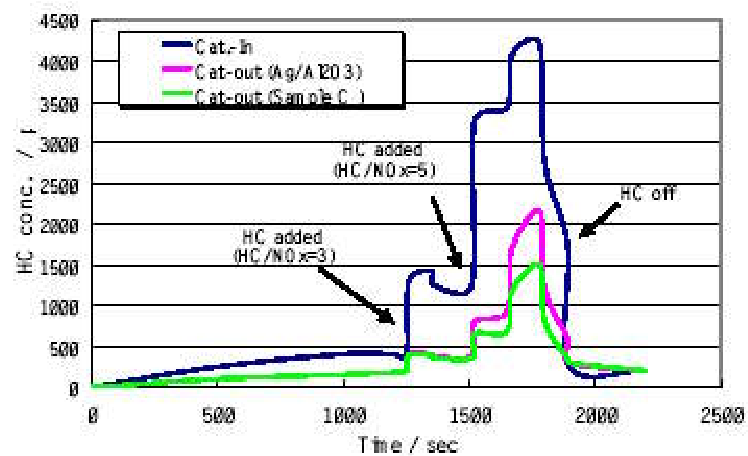
Additives to Ag/Al2O3 catalysts improve performance



Improved catalyst has less ramp-up / ramp-down hysteresis due to better clean-up of adsorbed HCs. Aged at 800C for 50 hrs.Model gas: NO 500ppm, CO 300ppm, CO2 6%, O2 10%, HC 3,000ppmC1, H2O 6%, balanced N2, **SV=40,000h-1**. Symbol: filled; ramping down., open; ramping up.



Engine results show impressive efficiency. Unaged. HC/NOx=5, **SV=15,000h-1**, 2L diesel engine(NA; SVR=2.5).



- Additives improve HC/NOx reactions, possibly through an isocyanate intermediary
- Sulfur durability (50 ppm SO2, 400C) up to about 15 hours

N. E. Chemcat SAE 2002-01-1724

HC slip is improved, but still an issue. 225C. Engine tests

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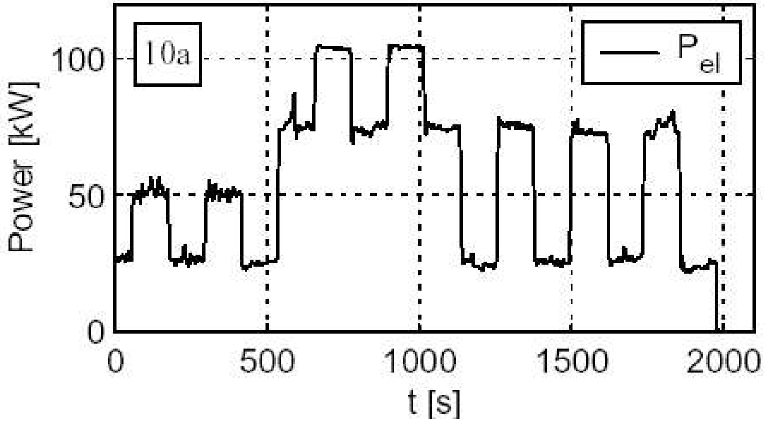
SCR technology is summarized

(Paul Scherrer Inst. SAE 2001-01-3625)

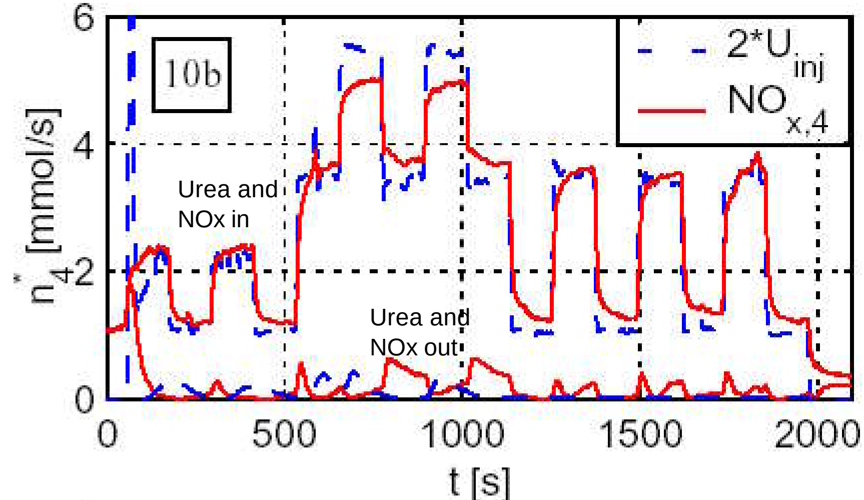
- Efficiency is up and size is down due to improved catalysts and substrates
  - 1995: 18% efficiency
    2000: 96% efficiency
    Same NH_3 slip, T, and size
- NO to NO_2 conversion helps efficiency, but
  - sulfate formation becomes problem
  - ammonium nitrate can form
- Ammonia slip from catalyst is high in rapid transients without closed loop control
  - Slip catalysts can form N_2O
- Iso-cyanic acid (HCNO) is problematic for low SVR-systems
  - not enough time for three step dissociation of urea
    (see also Ford SAE 2001-01-3621)

Authors are optimistic on the prospects for SCR

An SCR model for catalyst and urea injection is developed that is effective and uses simple inputs



Transient cycle used to test urea injection model. Liebherr D926 6.6 liter engine, 10 liters of washcoated vanadia-based catalyst.

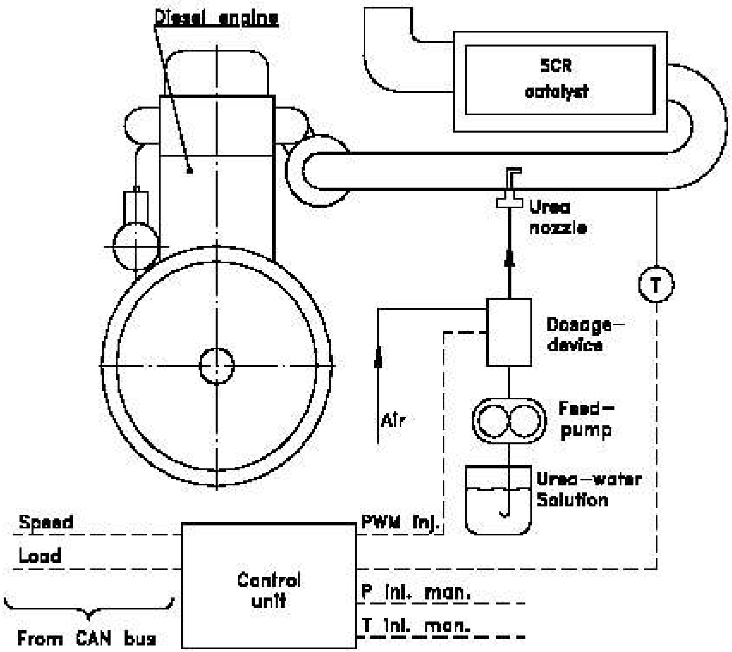


Results obtained using engine power and catalyst temperature inputs. **NOx efficiency is 93%. Ammonia slip is 3%.**

- By reducing urea injection, NOx efficiency dropped to 86%, but ammonia slip was negligible at 0.5%
- At high power, it was found that upwards of 20%+ of urea is oxidized and wasted.

ETH, FISITA 6/02

An SCR system is reported that uses engine parameters to calculate urea injection. Hits Euro IV&V on dyno, misses in real life.



		CO [g/kWh]	HC [g/kWh]	PM [g/kWh]	NO_x [g/kWh]	NH_3 aver. [ppm]	NH_3 peaks [ppm]
ESC Renault V.I.	upstream	0.26	0.11	0.035	7.13		
	downstream	0.33	0.02	0.033	1.34	1	10
	change	(+27%)	(-82%)	(-6%)	(-81%)		
ESC DAF	upstream	0.62	0.09	0.049	6.75		
	downstream	0.71	0.01	0.042	1.05	6	20
	change	(+15%)	(-89%)	(-14%)	(-84%)		
ETC Renault V.I.	upstream	5.80	0.11	0.341	7.33		
	downstream	6.57	0.01	0.328	2.05	2	37
	change	(+13%)	(-91%)	(-4%)	(-72%)		
ETC DAF	upstream	2.12	0.10	0.124	6.58		
	downstream	2.09	0.01	0.095	1.81	0	6
	change	(-1%)	(-90%)	(-23%)	(-72%)		

Euro IV NOx (3.5 g/kW-hr) was hit in all cases. Euro V NOx (2.0 g/kW-hr) is very close. PM is missed in all cases (0.02 - 0.03 g/kW-hr). Both engines are Euro 2 calibrated, about 12 liters and 350 kW, turbo, intercooled.

Urea injection strategy based on engine operating parameters and uses twelve 3D engine maps (Bosch).

- 34 liters of coated catalyst on 400-csi substrates
- No pre-oxidation, hydrolysis, nor ammonia slip catalysts.

Trip type	Calculated NOx [g]	Urea consumption [g]	Predicted NOx Conversion [%]	Average catalyst temp.
Sub-urban	462	432	45%	230
Highway	1261	1573	61%	248
Mountain	873	905	50%	230

However, in real life, conversion efficiencies are too low due to low average load and temperatures. New catalysts and oxidation cats will help.

TNO, Engelhard SAE 2002-01-0286

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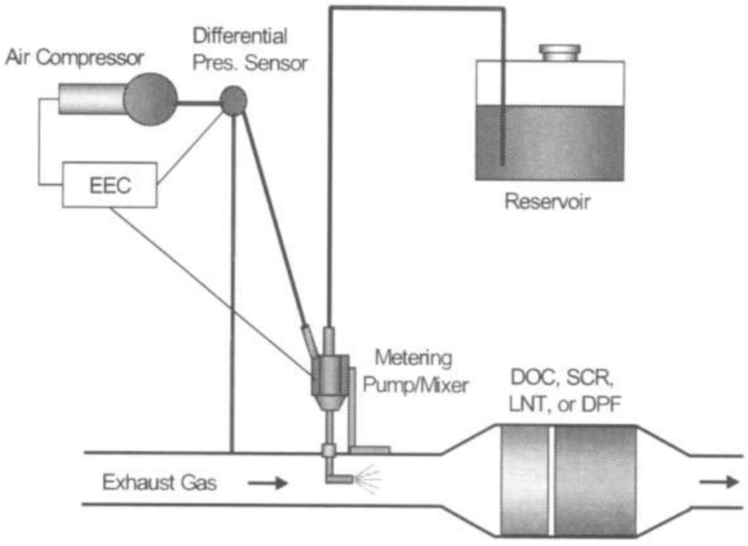
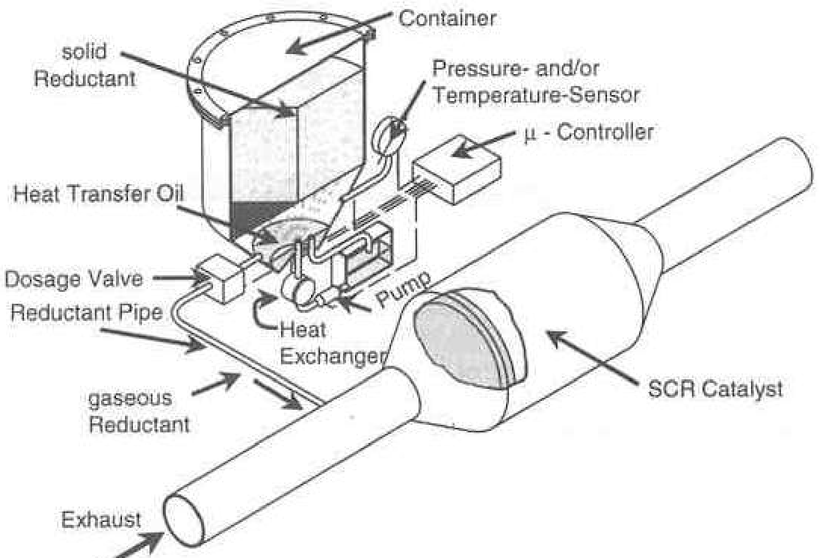
Improved urea injection devices for the exhaust are making SCR more attractive



Simple urea injection system uses compressed air and combined metering/mixing pump

Ford SAE 2001-01-3622



Solid urea is vaporized using hot oil. 6.1 liters of carbamate is good for 10,000 km for 2.0 g/kW-hr NOx drop.

AVL Vienna Motorsymposium 4/02

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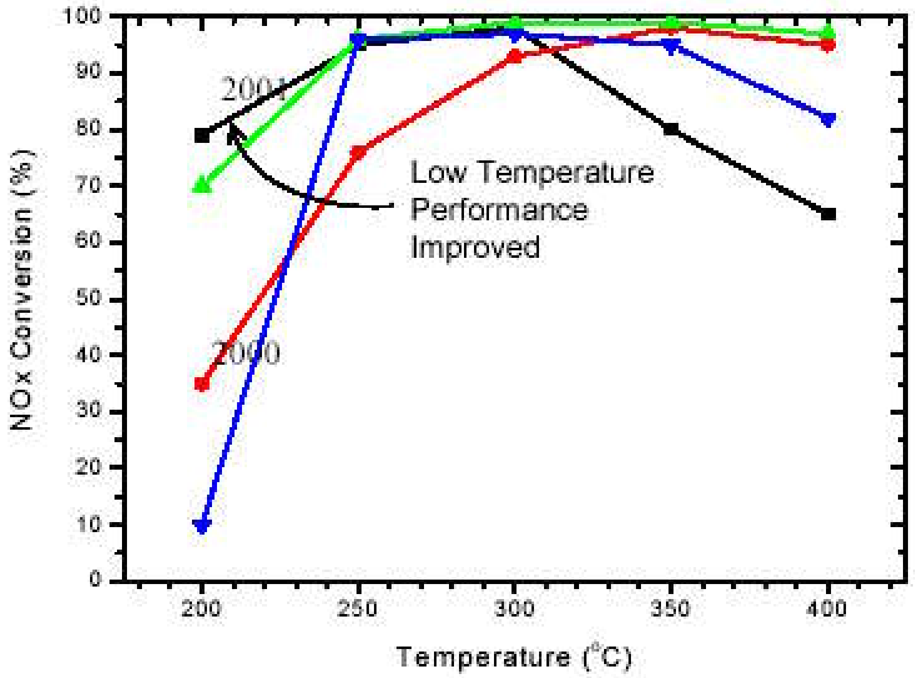
Continuous Improvements in Low Temperature Performance of NOx Adsorber Catalysts Are Realized while Maintaining HT Performance



EPA CDIRP Technology Review, 6/02

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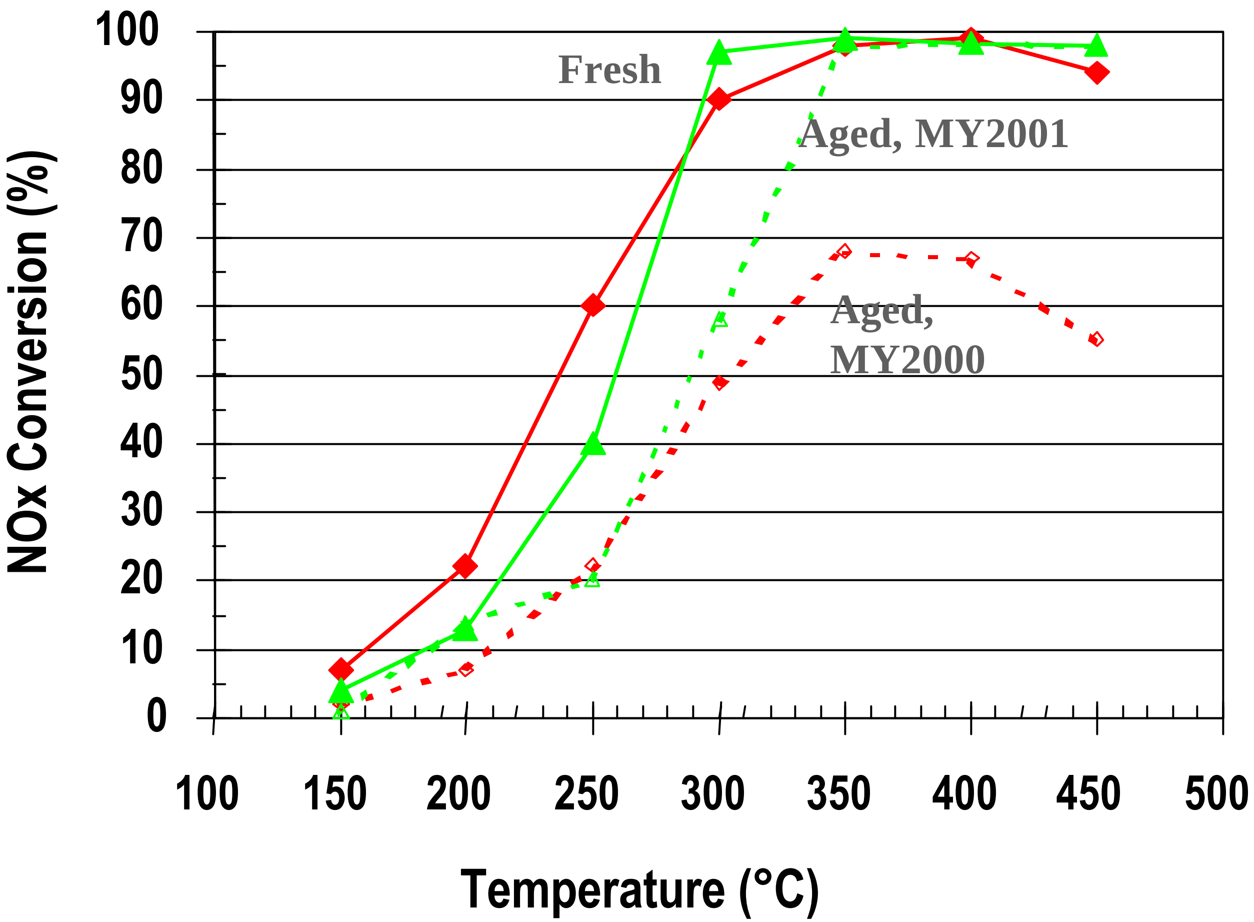
NOx Adsorber Rich/Lean Durability Showing Improvement; Improved from 70% to 95+% Efficiency after Aging



EPA CDIRP Technology Review, 6/02

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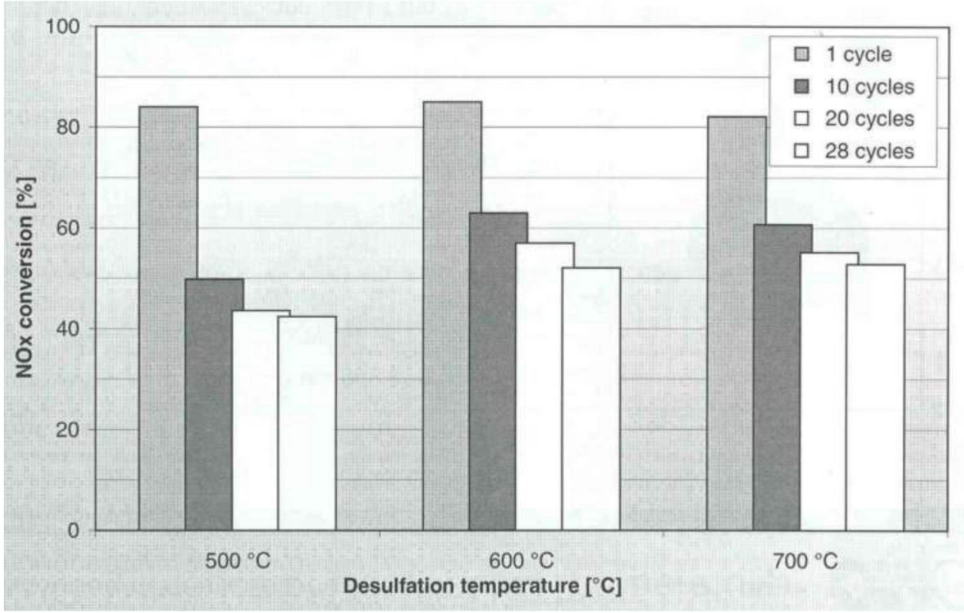
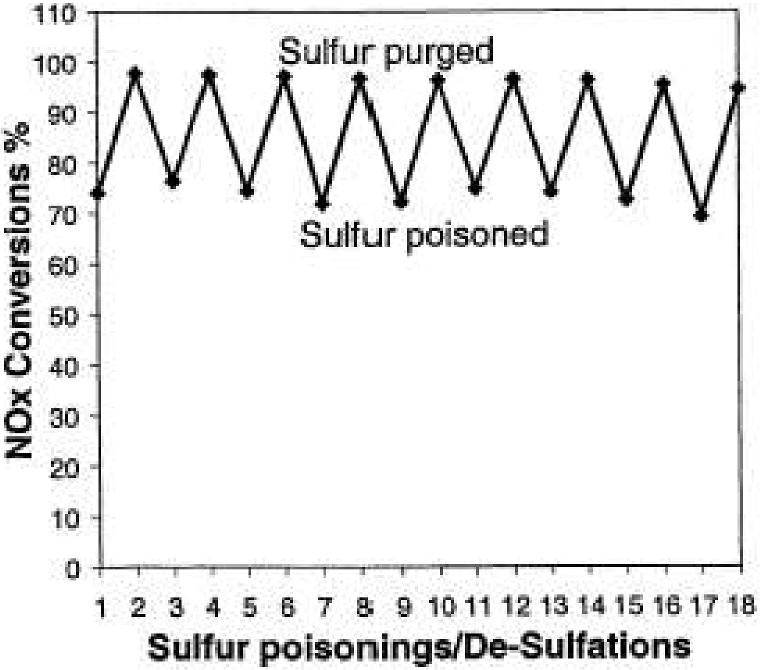
Repeated desulfations cause NOx trap deterioration but solutions are surfacing



NOx conversion deterioration from desulphation "stabilizes" after 10 to 20 cycles. (OMG, SAE TopTec 5/02)

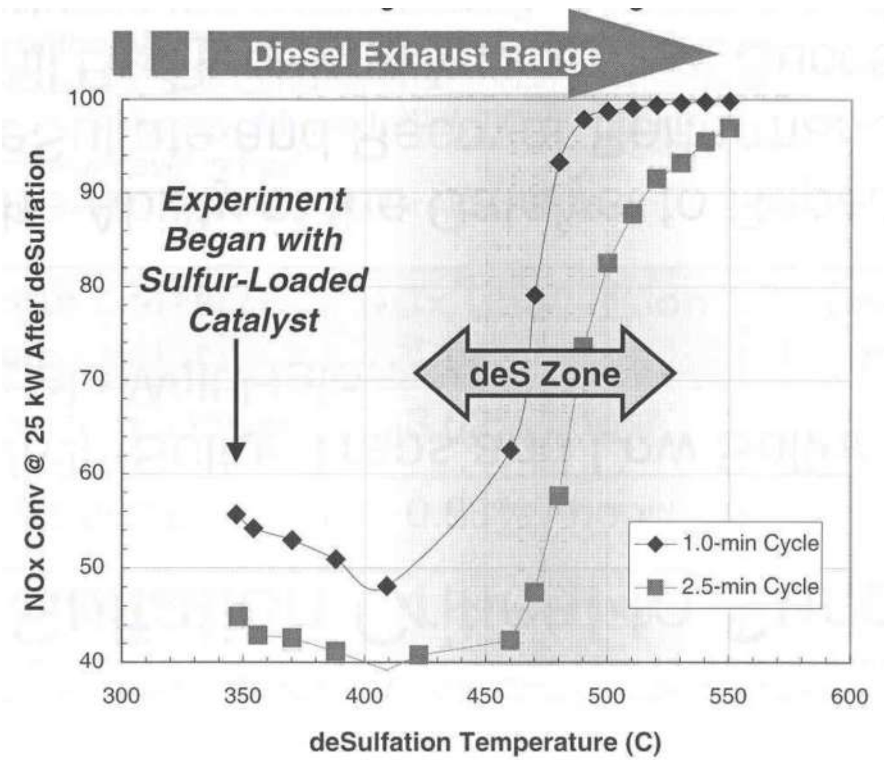


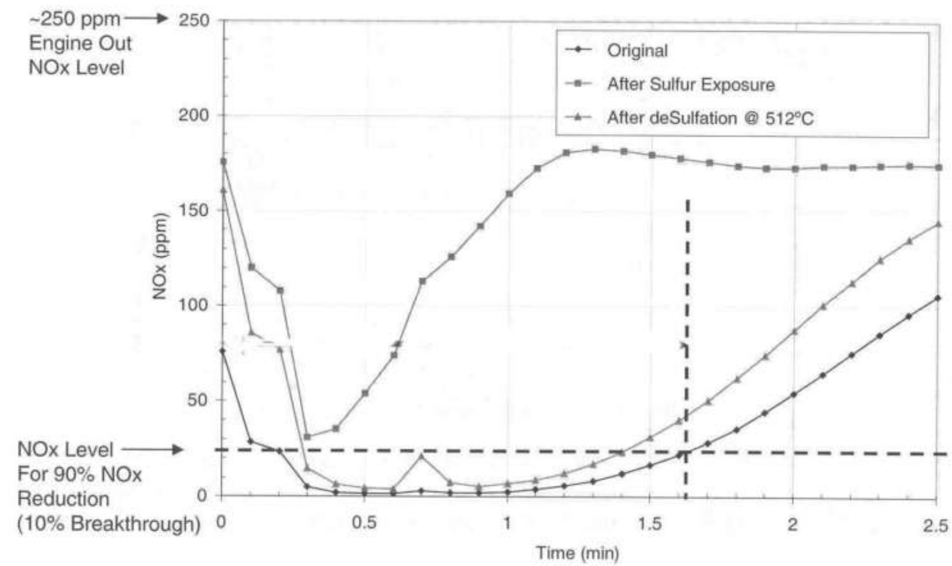
Sulfur tolerance of Ba-alkali LNT materials is improved. Ba materials oscillated between 30 and 70%. Tests at 350C. Sulfations at 700C for 10 min at A/F=13

Delphi SAE 2002-01-0734

Desulfation fuel penalties of 0.5 to 1.0%

Desulfation temperatures can be in the 450 to 550°C range





however, NOx recovery is not quite complete.

Emerachem SAE TopTec 5/02

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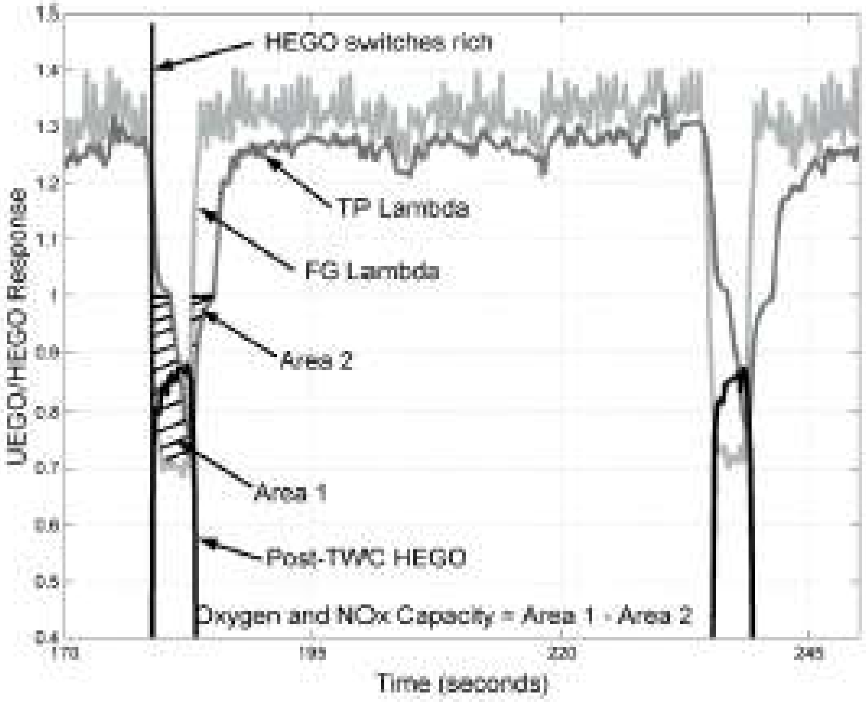
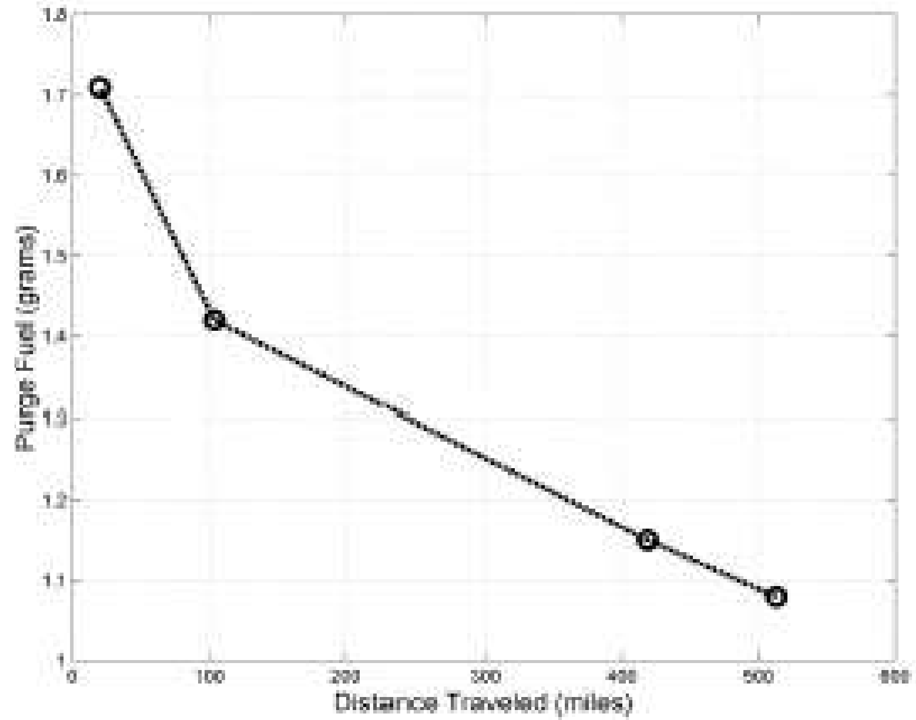
Methods of diagnosing sulfurization state of LNT are being developed



The oxygen sensor responses to rich are used to infer state of LNT.



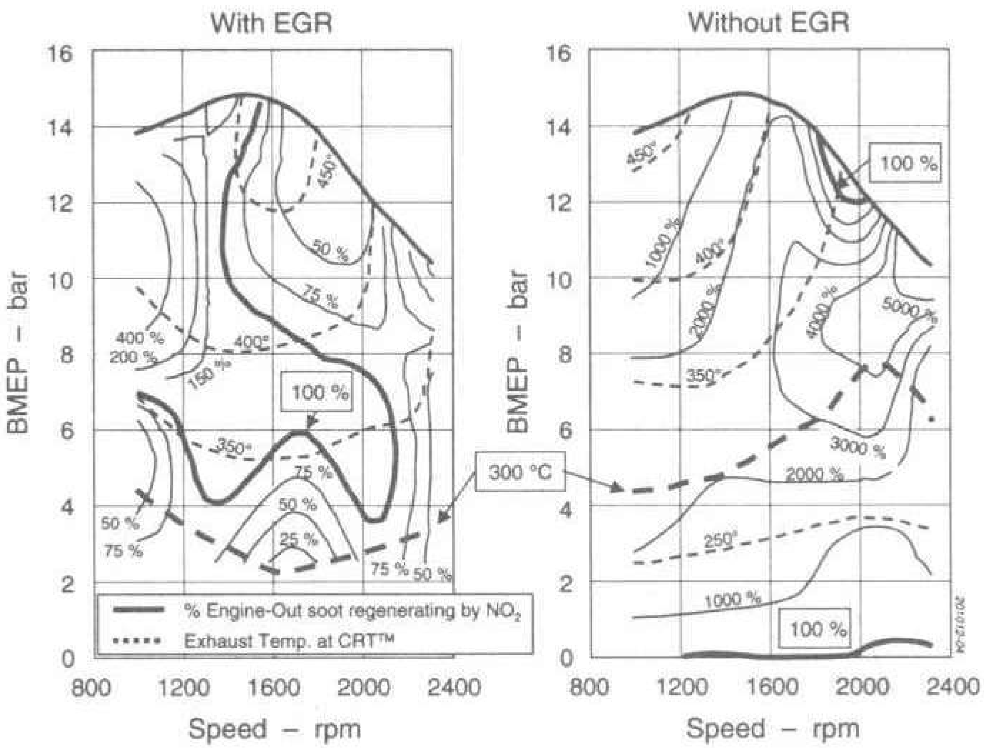
The amount of fuel to regenerate LNT is the key indicator

Ford SAE 2002-01-0731

Integrated systems

- EGR + DPF may be “NOx limited”, but this can be addressed
- SCR + DPF is proven and improving
- LNT + DPF is showing much synergy

Performance of the CRT with EGR is quantified



Without EGR the field of passive regeneration is temp. limited. With EGR it is NOx limited

6 cyl DI/TCI, 9 liter, 200kW engine with unit injections.

AVL JSAE 20015347

- Putting catalyst on the filter might enable NOx recirculating to open up the range of passive regeneration (JMI SAE 2002-01-0428)

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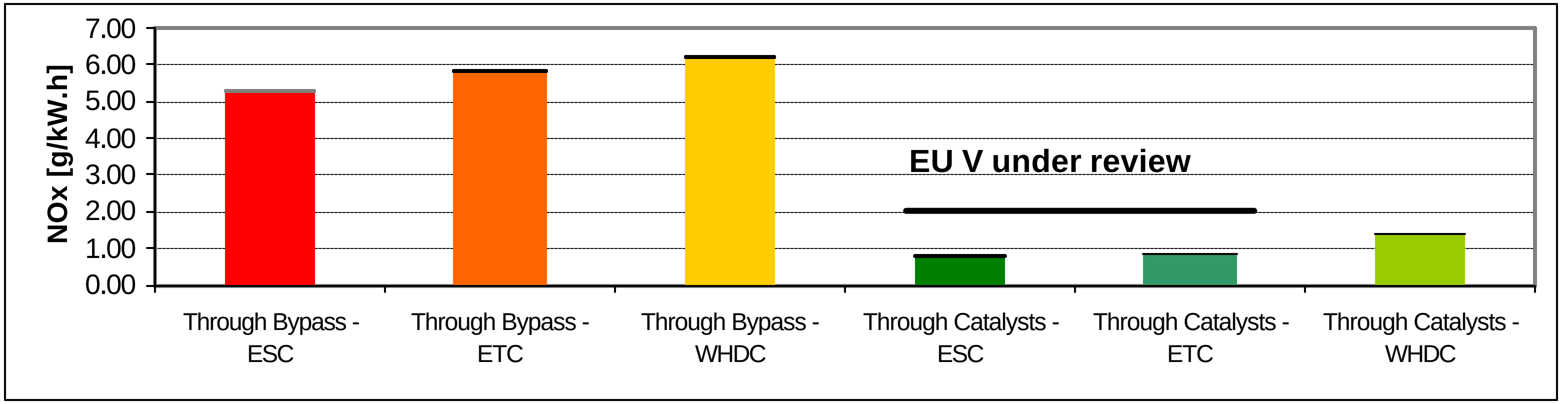
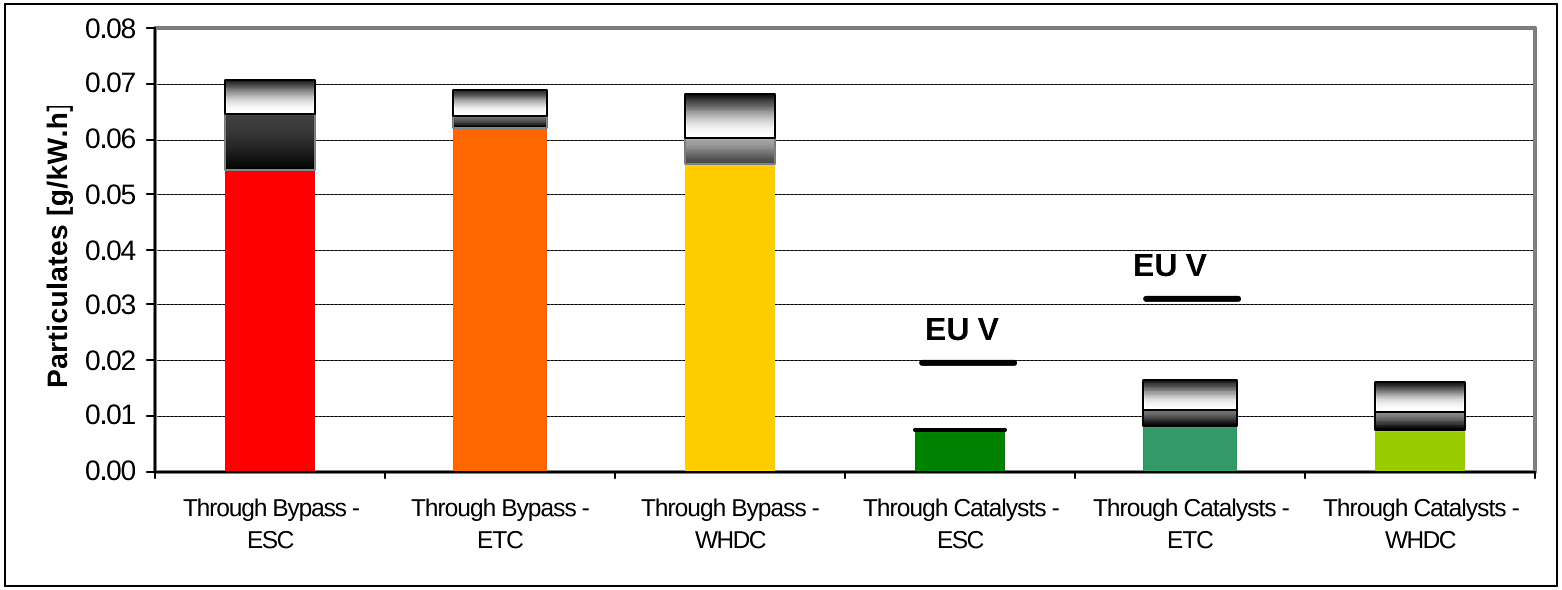
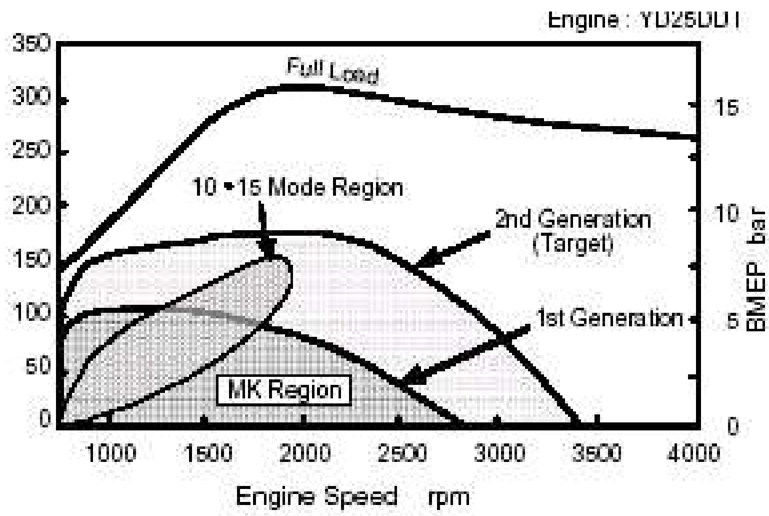
DPFs and SCR system comfortably hit Euro V standard after 1000 hours of aggressive aging

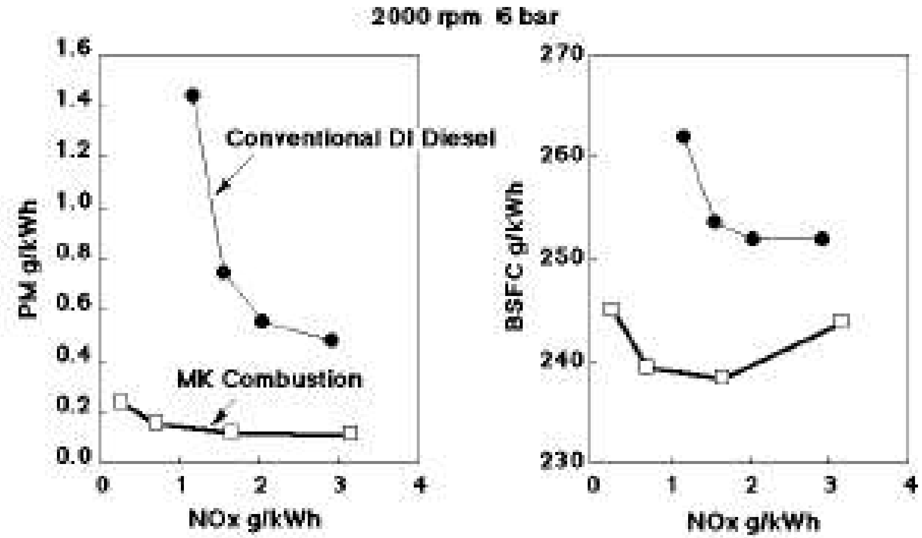




HCCI is improved for LDD, extending the pre-mixed combustion to medium load conditions



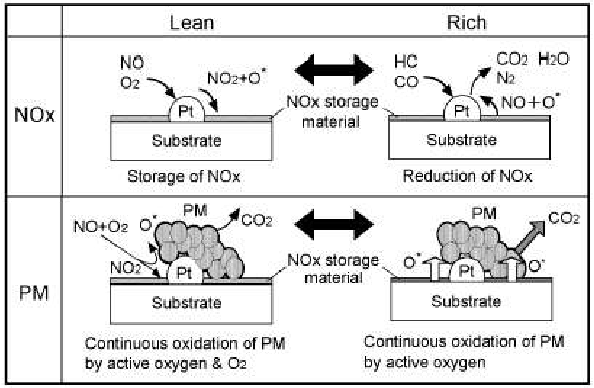
The range of HCCI operation is extended via ignition delay using improved cooled EGR and decreased compression ratio, and decreasing injection duration via HP injectors



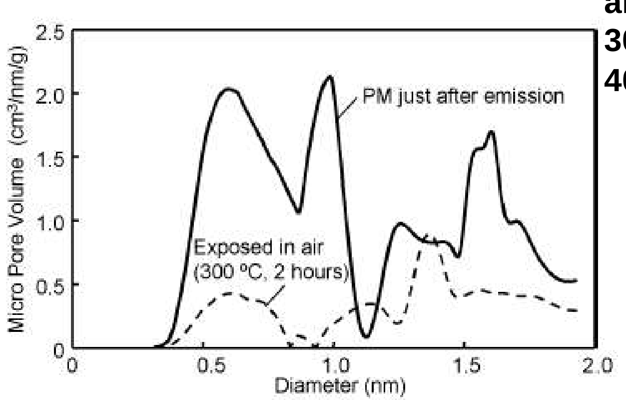
For a 5000# SUV to hit Bin 5, a DPF and 70% efficient LNT will be needed

Nissan SAE 2001-01-0200

New integrated DPF / NOx trap and integration with engine are described



The principle of combination diesel particulate/NOx reduction system. PM is oxidized in both lean and rich conditions.



Fresh soot has more micropores and higher activity than older soot

$NO + 1/2\ O_2 = NO_2$

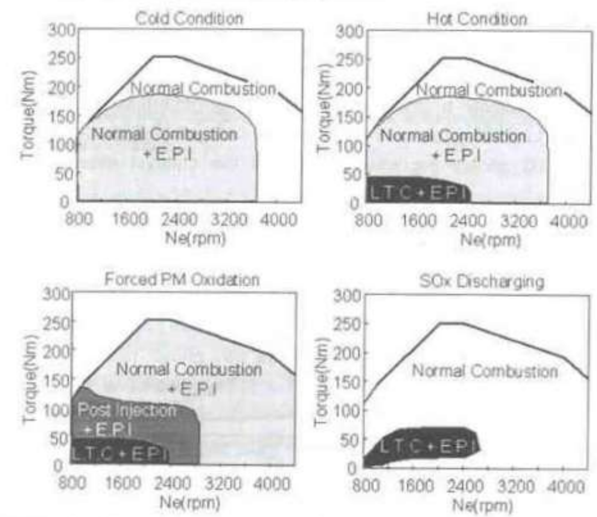
$BaO + 2NO_2 + 1/2\ O_2 = Ba(NO_3)_2$

"$1/2O_2$" is the "active oxygen", and is generated on the forward and reverse reactions

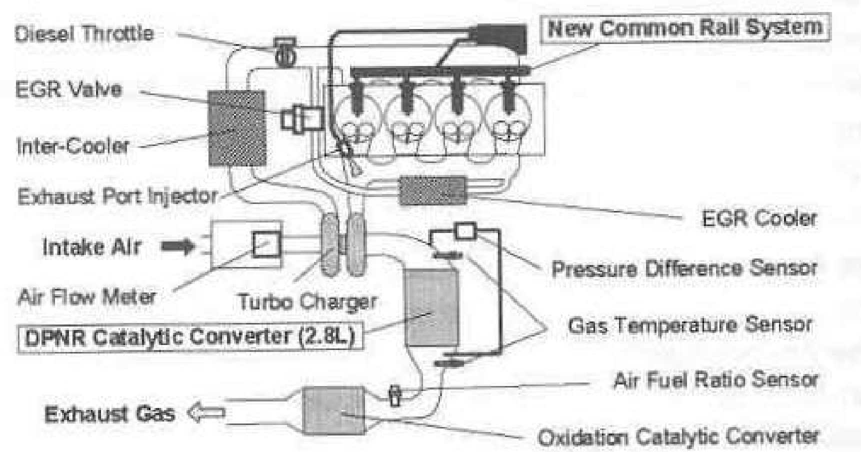
LTC: adv. EGR control, injection timing, and throttling are used to drop PM and NOx in increase HC and T (+50C°)

EPI: auxiliary fuel injection helps richness and drivability.

Aged DPNR hits 0.005 g/km PM and 0.12 g/km NOx on MVEG cycle 3000# car; close to hitting Bin 5; 40 mi/gal



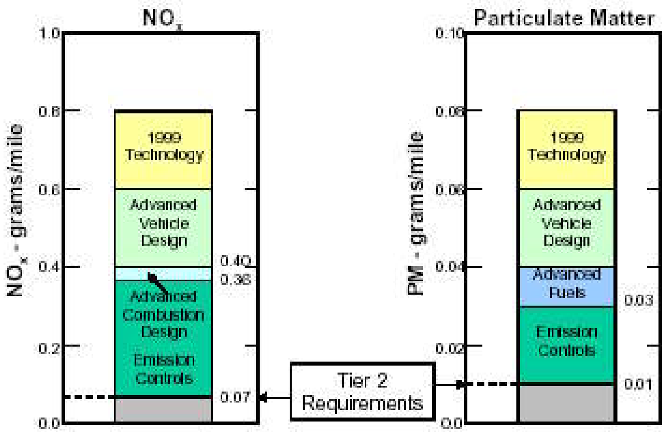
System Control under Different Operating Conditions
(LTC: Low Temperature Combustion. EPI: Exhaust Port Injection



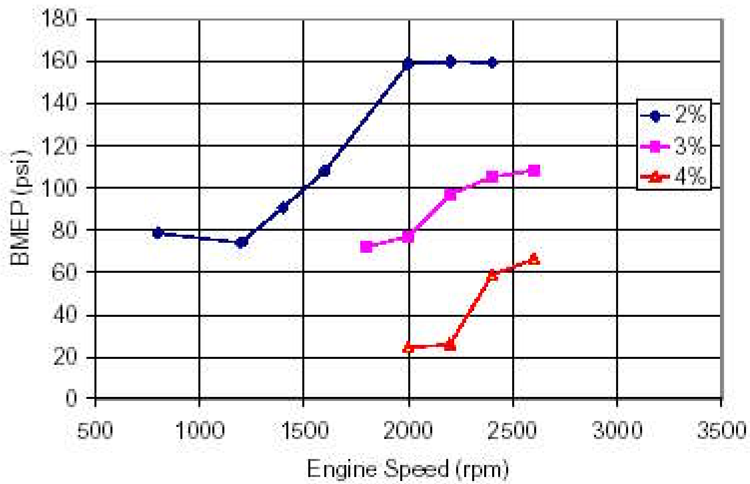
Toyota SAE 2002-01-0957

Toyota, Vienna Motorsymposium 4/02

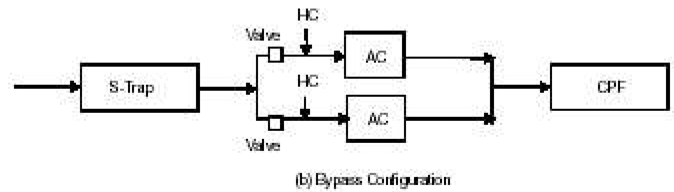
A comprehensive study on attaining Tier 2 Bin 5 using a 5.9 liter engine shows potential



Integrated approaches are needed to hit the Bin 5 regulation



20% bypass during LNT regeneration results in modest fuel penalties



System used to demonstrate Bin 5 compliance with Cummins ISB engine. 7 liters SOX trap, 14 liters of LNT, 12 liters of CDPF.

	NOx		PM	
	g/bhp-hr	% change	g/bhp-hr	% change
Engine Out	1.20		0.222	
EAS Out, cold	0.34	-72%	0.019	-91%
EAS Out, hot	0.15	-87%	0.011	-95%
EAS Out, hot	0.13	-89%	0.014	-94%
EAS Out, hot	0.17	-86%	0.017	-92%
EAS Out, hot	0.18	-85%	0.016	-93%

Simulated FTP results. 83% NOx efficiency is needed. 87% efficiency is obtained.

Comprehensive paper investigated:

- Non-thermal plasma, lean NOx catalyst alternatives
- System configuration
- Sulfur management
- LNT regeneration strategies
- DPF regeneration methods

Cummins, DOE SAE 2002-01-1867

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Summary and predictions

- **For Euro IV, Europe is headed towards SCR for the long haul vehicles, and DOCs for urban and medium-duty use; DPFs in limited applications**
  - Japan will be using filters and engine technology to hit 2005
  - Prediction: US2007 will need no more than 40% NOx and 70% PM average efficiency
  - Prediction: Euro V HDD will use same emission control technologies as Euro IV
- **Filter regeneration strategies and filters are evolving.**
  - Fine-tuning of regeneration approaches is increasing reliability and range
  - Filter materials are improving performance
- **NOx solutions are available to achieve 70%+ efficiency**
  - SCR systems are delivering high efficiency, but may have some in-use and secondary emissions issues
  - NOx adsorbers are making rapid progress, but still a long way to go
- **Integrated PM/NOx systems are being developed**
  - Synergies exist between SCR or LNT NOx control and DPFs
  - Prediction: synergies for LNT/DPF will be greater than for SCR/DPF, giving LNTs the edge to future emission control
  - Prediction: as with gasoline vehicles for over 25 years, integration of diesel emission control technologies with engine management will yield unexpected favorable results

Thank you for your kind attention!