"Update on Diesel Emission Control Technologies"

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A variety of diesel emission control technologies will be used to meet the upcoming tightening of tailpipe emission regulations. The author will review the state of the technology, focusing on the numerous developments since the beginning of the year. Topics will include a brief review of where the regulations stand, the effect of some engine technologies on ultrafines, diesel particulate filters, SCR, NOx adsorbers, the latest oxidation catalysts, and integrating these technologies into systems.

Review of Diesel Emission Control Technology (1 of 2)

Tim Johnson

August 2002

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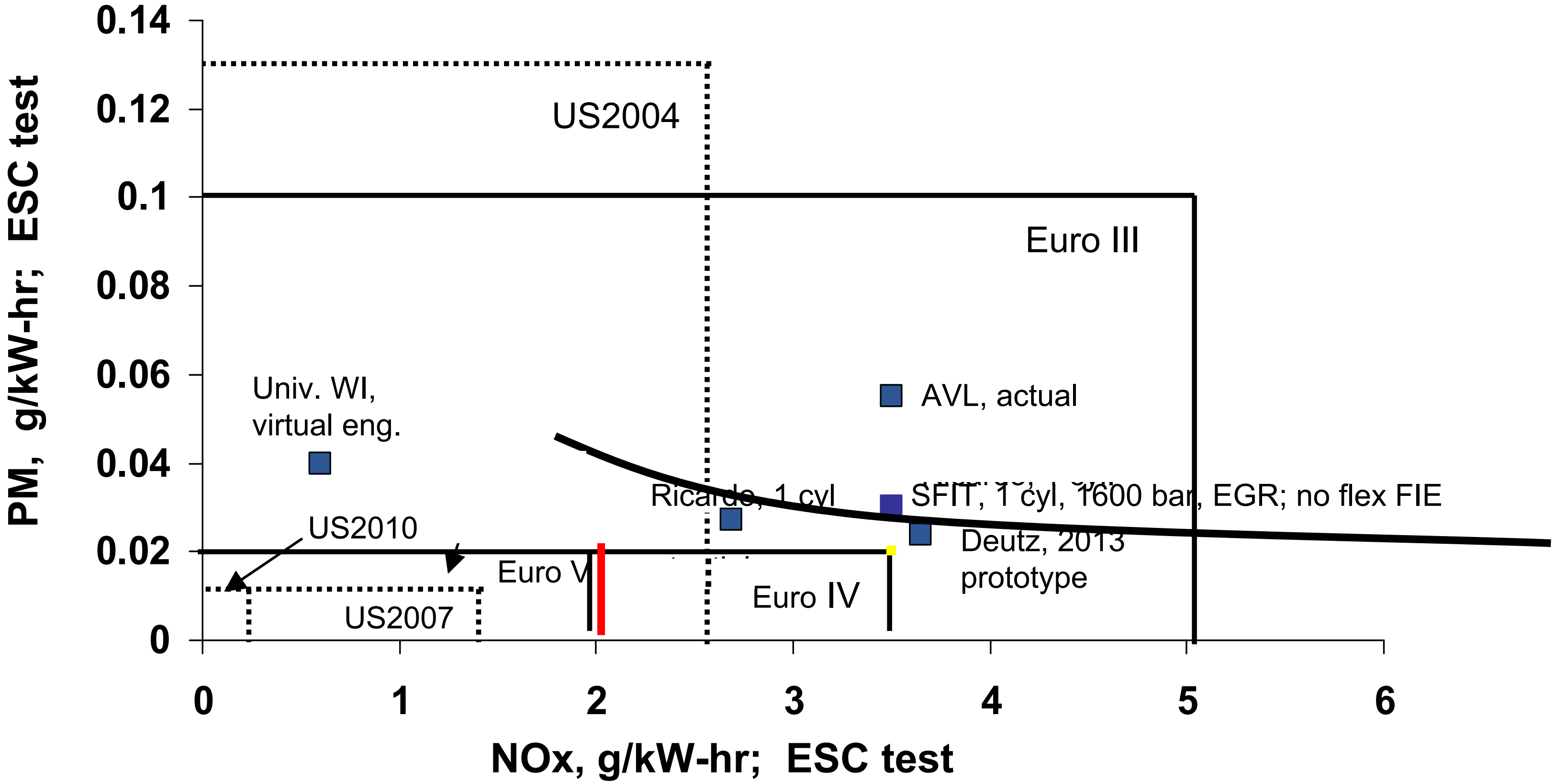
Discovering Beyond Imagination

Outline

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

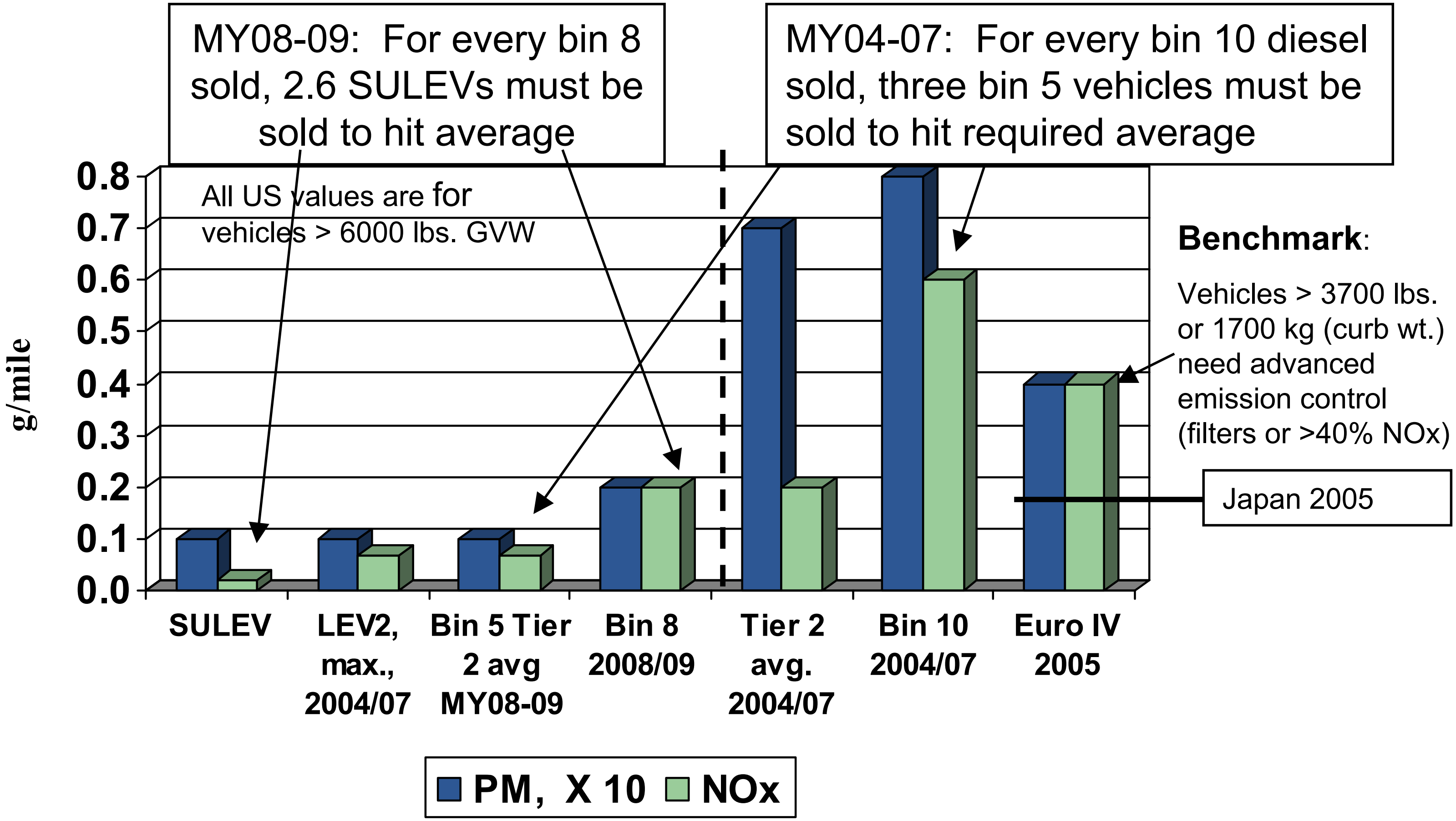
Where will HDD engines be in 0 to 2 years?



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

Japan 2005 = Euro V (2008)

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



MY08-09: For every bin 8 sold, 2.6 SULEVs must be sold to hit average

MY04-07: For every bin 10 diesel sold, three bin 5 vehicles must be sold to hit required average

All US values are for vehicles > 6000 lbs. GVW

Benchmark:

Vehicles > 3700 lbs. or 1700 kg (curb wt.) need advanced emission control (filters or >40% NOx)

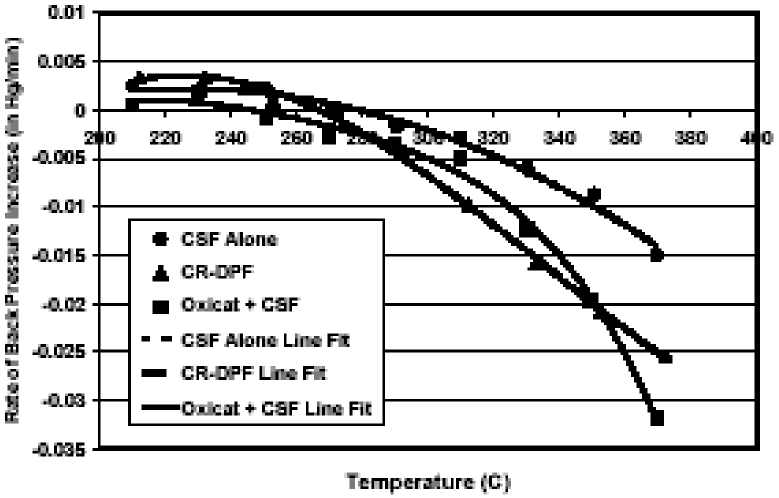
Japan 2005

- 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#

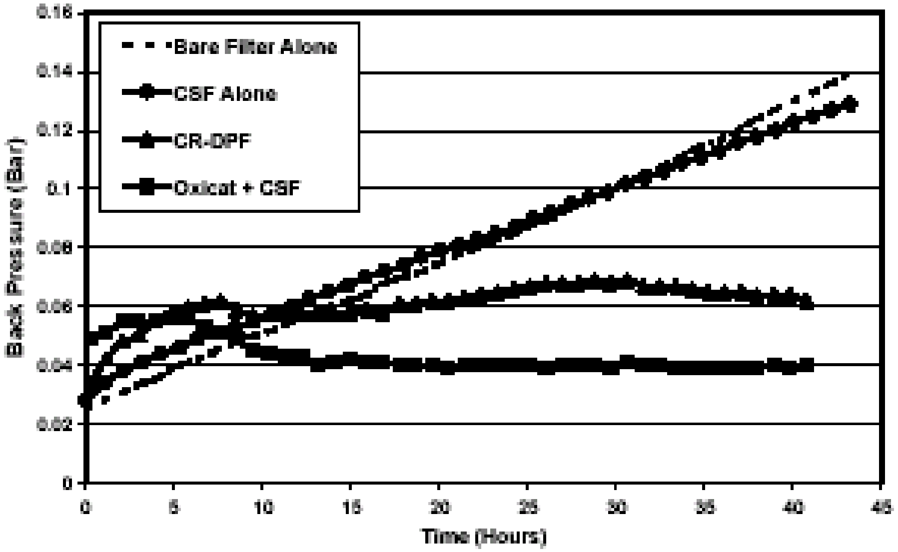
Recent developments in filters

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

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



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

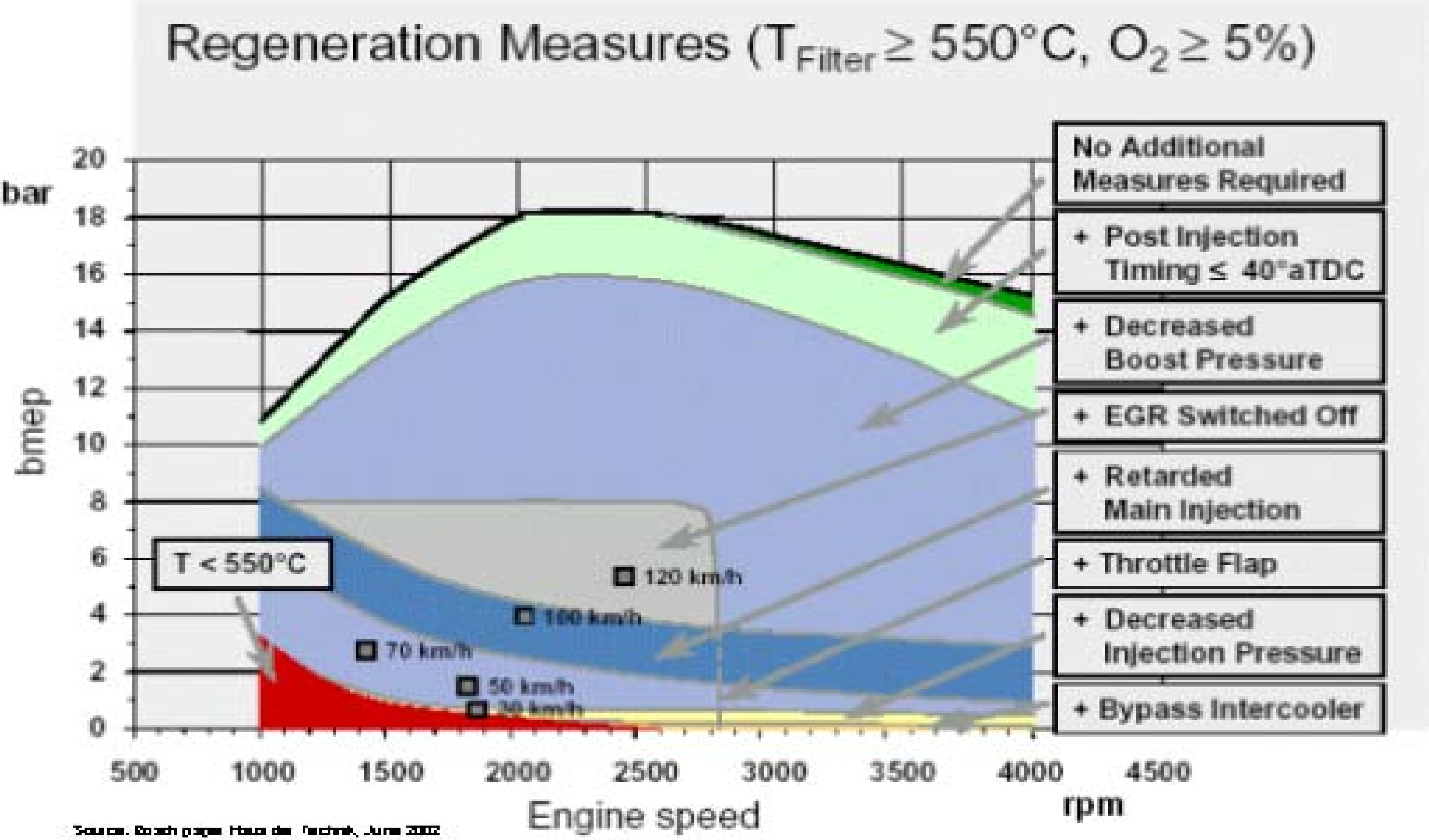


New DPF system gives lowest back pressure in low temperature testing. LT cycle gives 160C<T<265C; mix of steady state and transient; 10 liter 210 kW turbo bus

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

JMI SAE 2002-01-0428

Regeneration strategies are being refined for better reliability

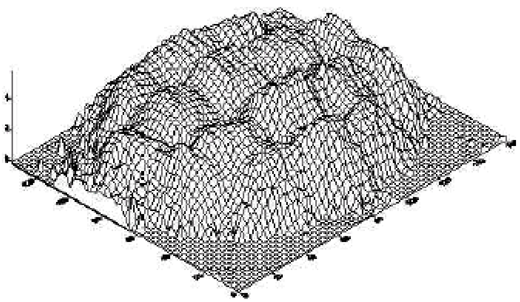


Source: Bosch paper Haus der Technik, June 2002

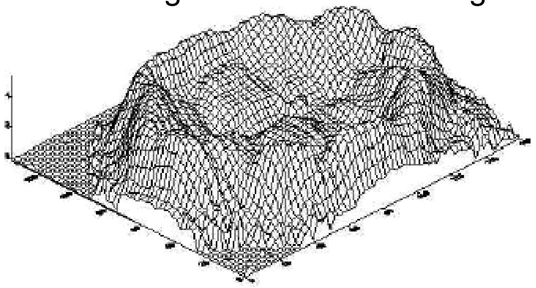
Bosch, Vienna Motorsymposium 4/02

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

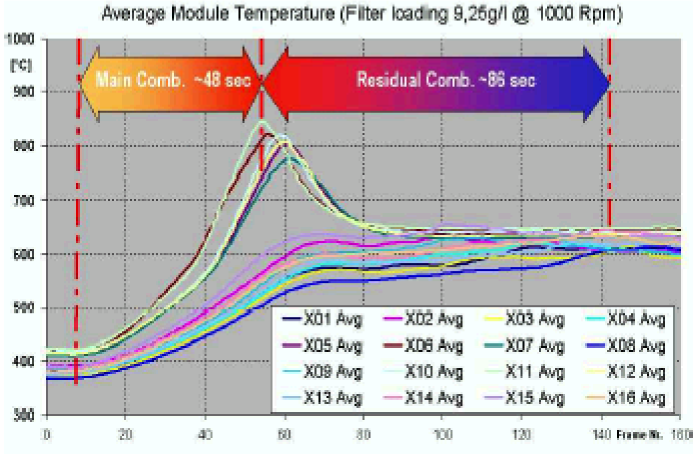
9.3 g/liter loaded at 60 kg/h

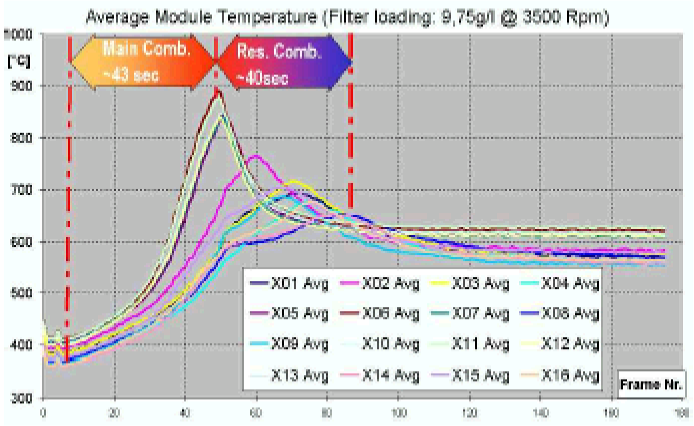


9.7 g/liter loaded at 320 kg/h



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.

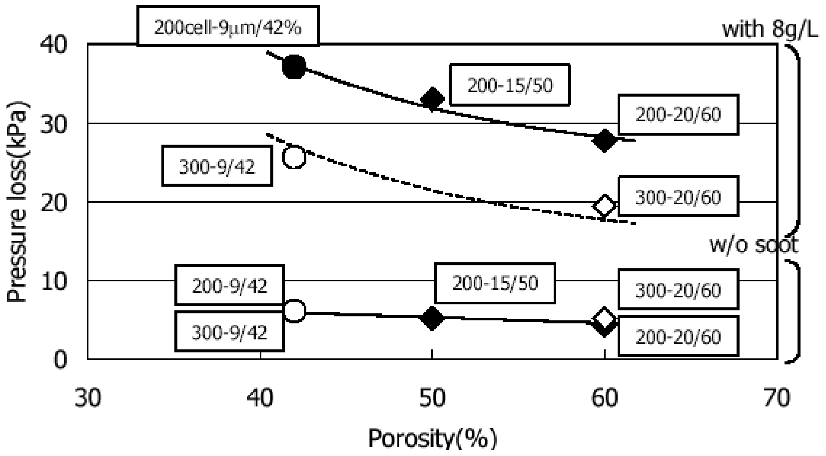




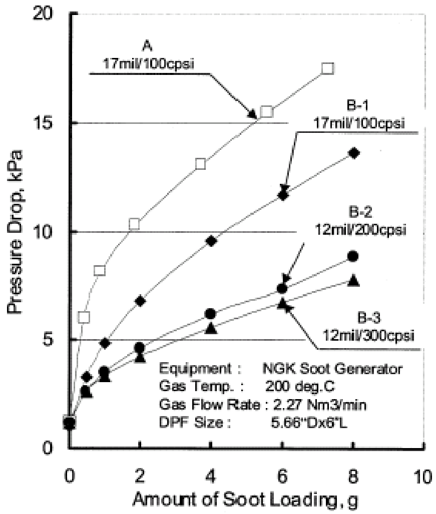
In both cases the regeneration begins in the central segments. However, the peak temperature is higher for the filter loaded under high flow rate (right). Perhaps this is due to lower flow rate (less heat removal) in the center sections. Regeneration with a burner and at 350 kg/h.

Zeuna Staerker SAE 2002-01-2158

DPF properties are being optimized to significantly reduce pressure drop

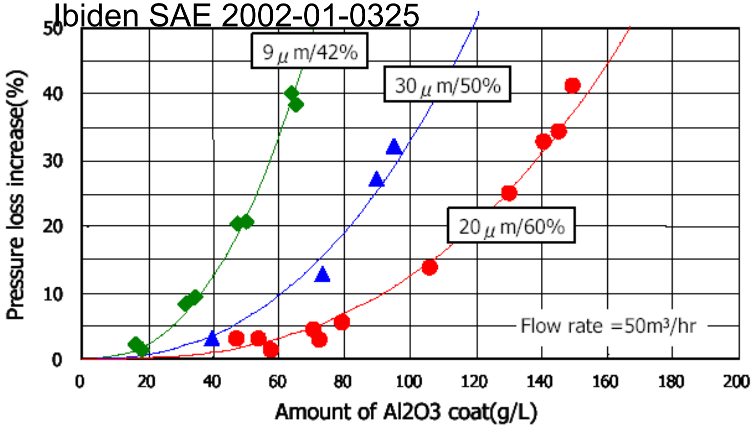


Pressure drop dependency on cell geometry and porosity is different for loaded and unloaded SiC filters.

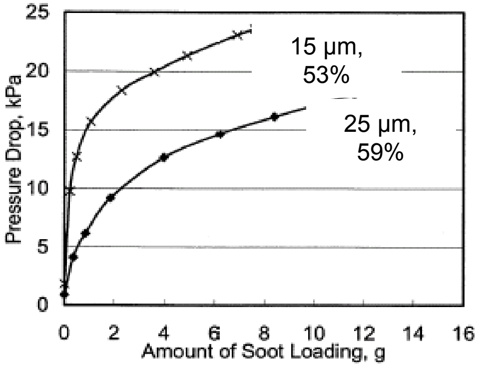


At higher cell densities, back pressure is strongly dependent on wall thickness. Porosity is 59% w/ 25 μm avg. (Type A is 53% and 15 μm)

Ibiden SAE 2002-01-0325



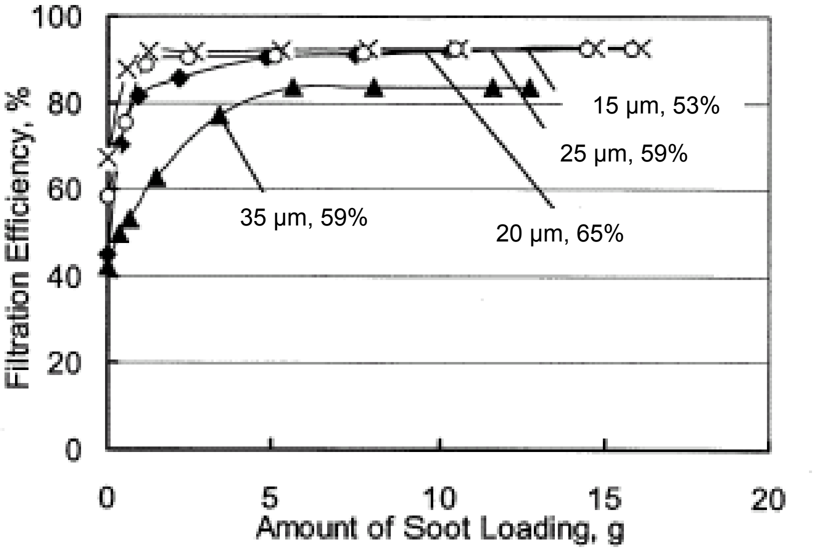
NGK 2002-01-0322



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.

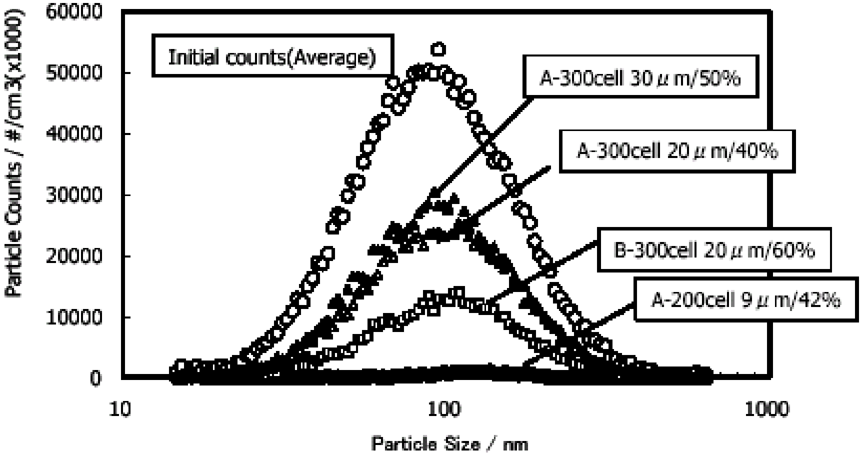
Pressure drop of washcoated filters can be dropped with pore engineering, 300/12, 100g/liter

Filter porosity can affect filtration efficiency by mass and number



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

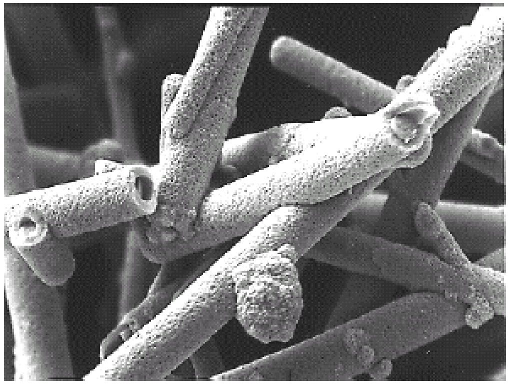
NGK 2002-01-0322



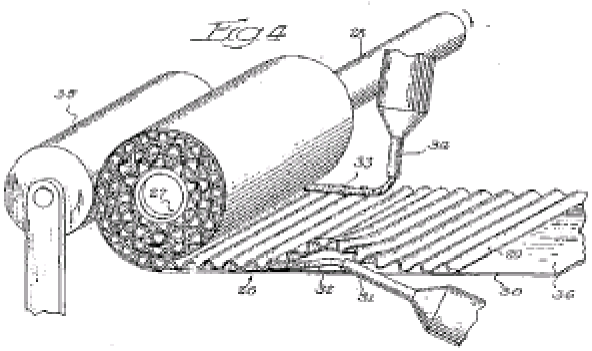
Initial filtration efficiency for filters. Ultrafine particulate efficiency will increase as filtration proceeds or if washcoat is added. Uncoated filters.

Ibiden SAE 2002-01-0325

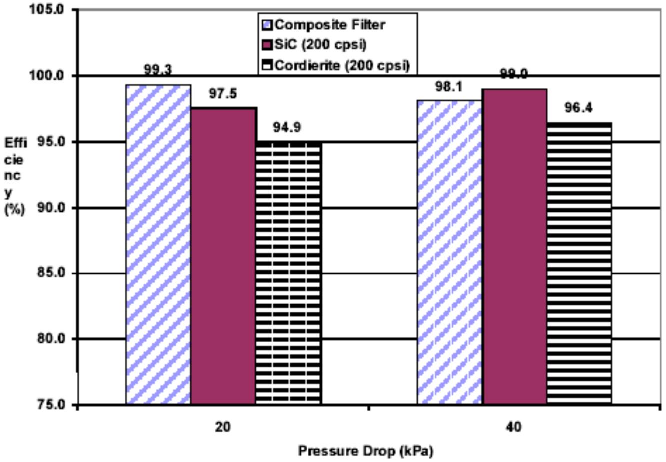
A new ceramic fiber filter is described



Alumina fibers are CVD coated with SiC. 3 µm diameter



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



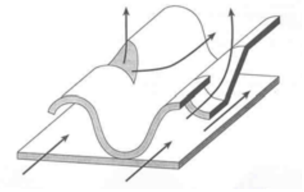
Filtration efficiency is marginally better than standard filters….

Fleetguard, 3M SAE 2002-01-0323

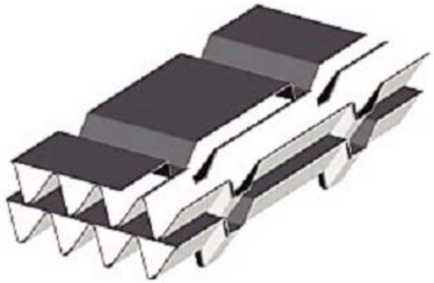
	Soot Holding (g)	
Filter	**20 kPa**	**40 kPa**
Composite	21.0	37.5
200 cpsi Extruded SiC	22.0	41.0
200 cpsi Extruded Cordierite	26.6	40.0

… but standard filters can hold more soot at given pressure drops.

Partial PM “separators” are described



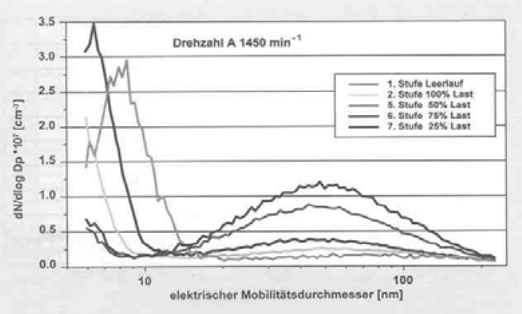
- Not suitable for dirty engine
- Ash goes through
- Soot trapping mechanism is via a metal screen or diffusion to catalyst via thermophoresis and the NO_2 oxidation



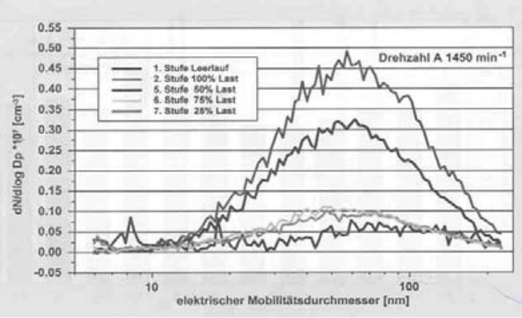
Another concept that does not use screens for filtration; performance not yet reported

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

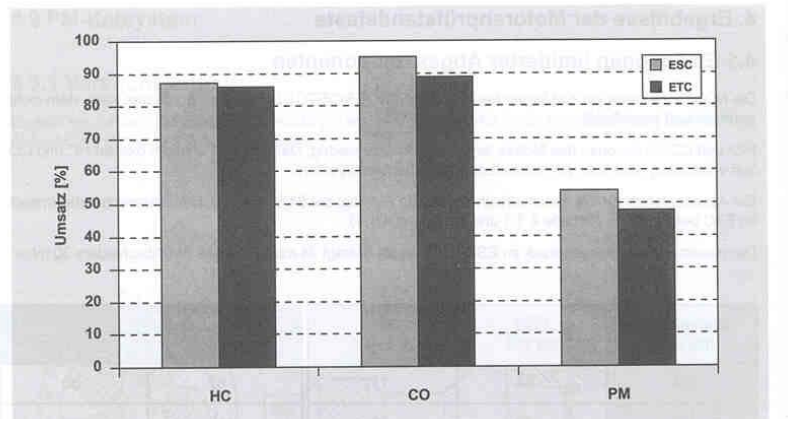
Before



After



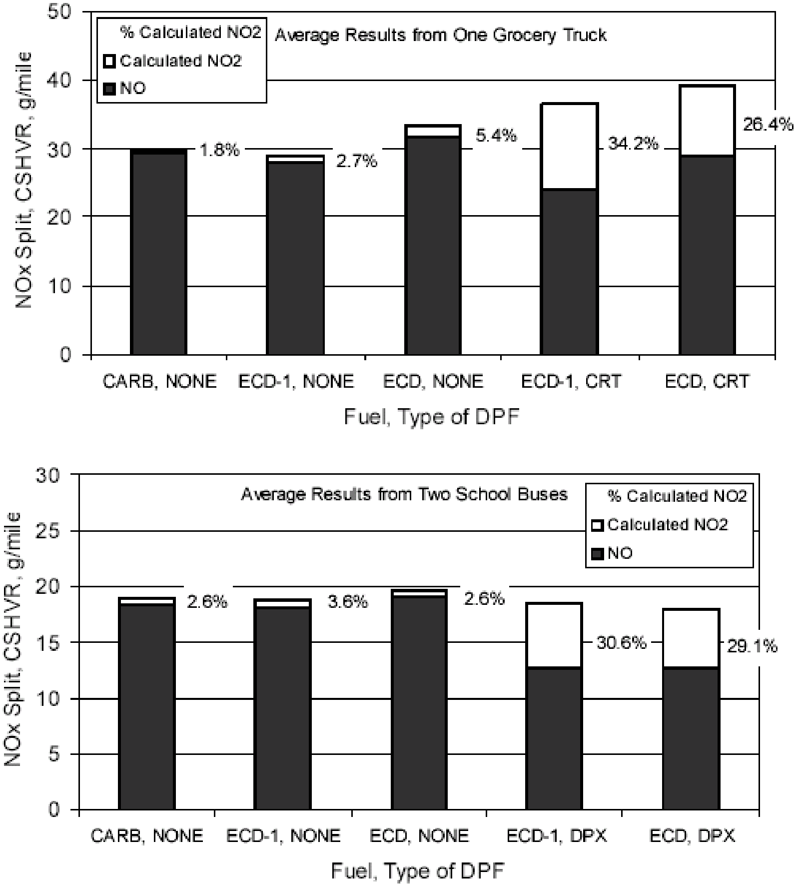
PM separator drops ultrafines by only about 50% on ESC.



50,000/hr space velocity; oxidation catalyst in system

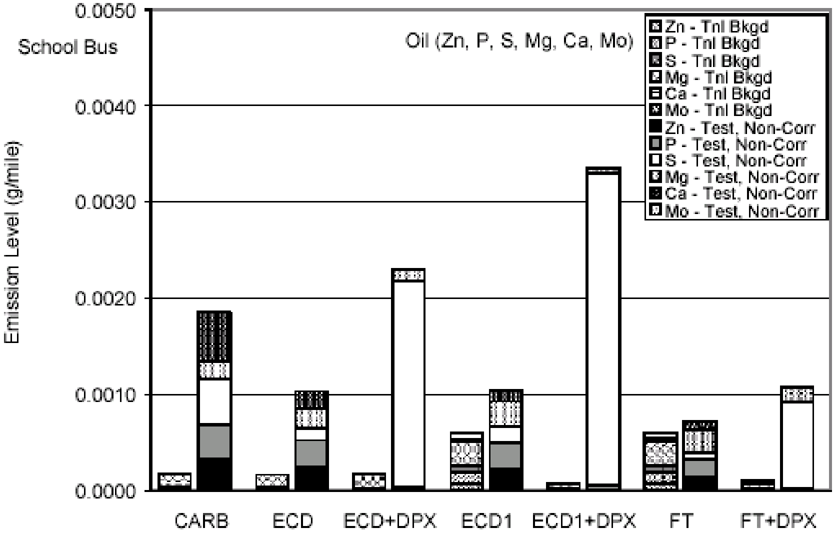
MAN, Emitec Vienna Motorsymposium 4/02

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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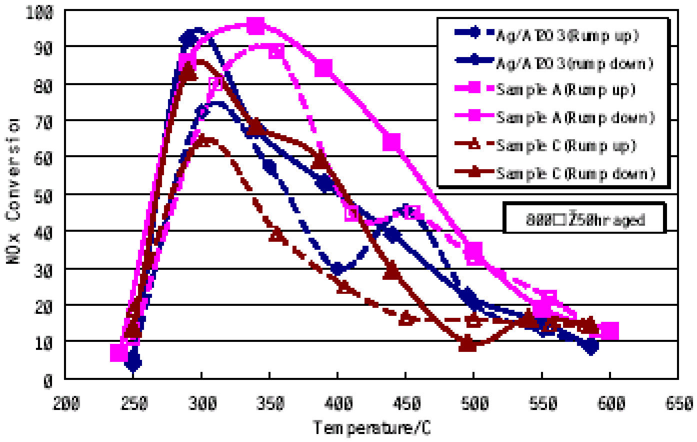
NOx Control

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 – 4% 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.

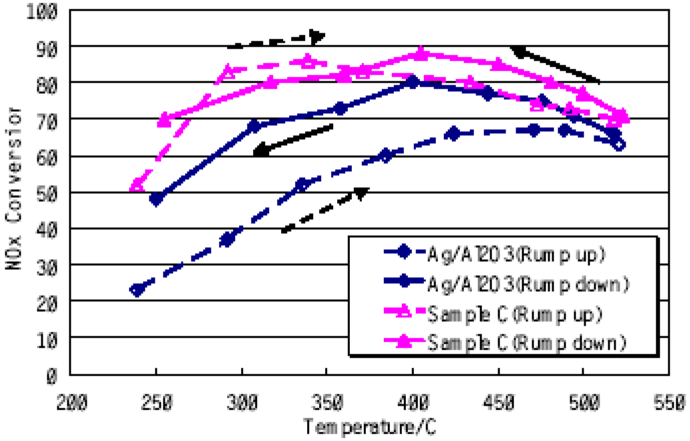
Additives to Ag/Al2O3 catalysts improve performance



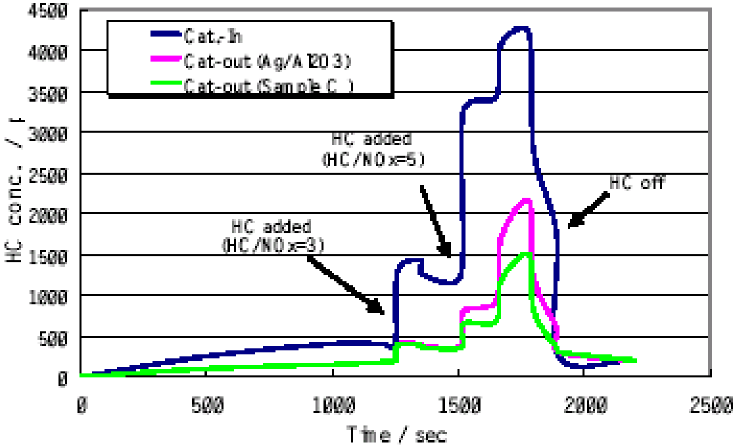
Improved catalyst has less ramp-up / ramp-down hysteresis due to better clean-up of adsorbed HCs. Aged at 800C for 50 hrs.Model gas: NO 500ppm, CO 300ppm, CO2 6%, O2 10%, HC 3,000ppmC1, H2O 6%, balanced N2, **SV=40,000h-1**. Symbol: filled; ramping down., open; ramping up.

- 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



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



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

SCR technology is summarized

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

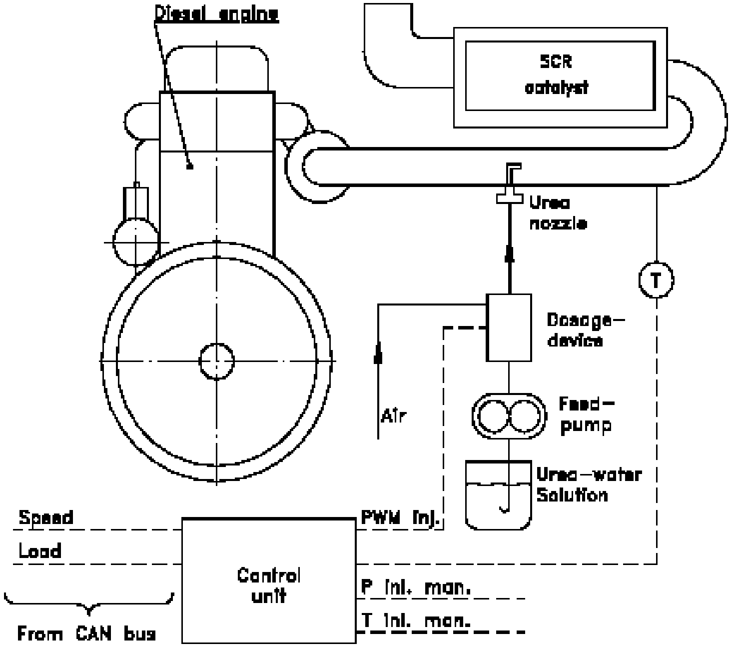
- Efficiency is up and size is down due to improved catalysts and substrates
  - 1995: 18% efficiency
    2000: 96% efficiency

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 at 250 to 300C
- 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 system is reported that uses engine parameters to calculate urea injection. Hits Euro IV&V on dyno, misses in real life.



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.

TNO, Engelhard SAE 2002-01-0286

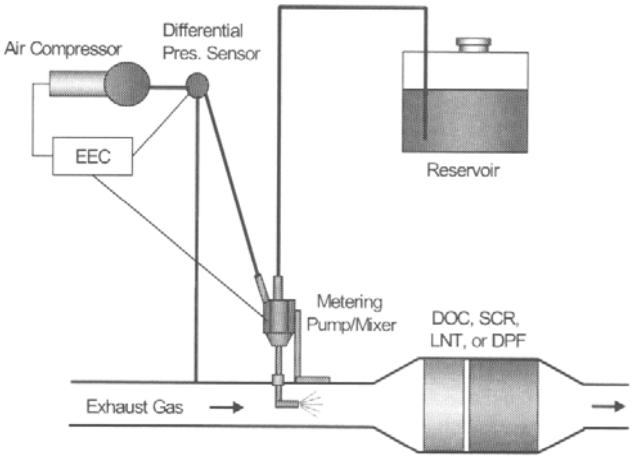
		CO [g/kWh]	HC [g/kWh]	PM [g/kWh]	NO_x [g/kWh]	NH_3 aver. [ppm]	NH_3 peaks [ppm]
ESC	upstream	0.26	0.11	0.035	7.13		
Renault V.I.	downstream	0.33	0.02	0.033	1.34	1	10
	change	(+27%)	(-82%)	(-6%)	(-81%)		
ESC	upstream	0.62	0.09	0.049	6.75		
DAF	downstream	0.71	0.01	0.042	1.05	6	20
	change	(+15%)	(-89%)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

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

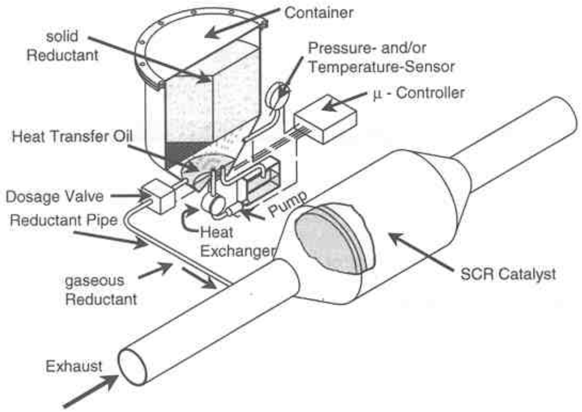
However, in real life, conversion efficiencies are too low due to low average load and temperatures. New catalysts and oxidation cats will help.

Improved urea dispensing devices for the exhaust and fueling stations are making SCR more attractive



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

Ford SAE 2001-01-3622

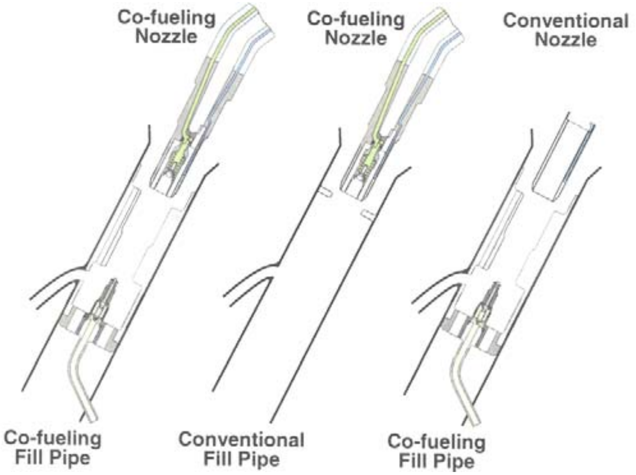


Solid urea is vaporized using hot oil. 6.1 liters of carbamate is good for 10,000 km for 2.0 g/kW-hr NOx drop.

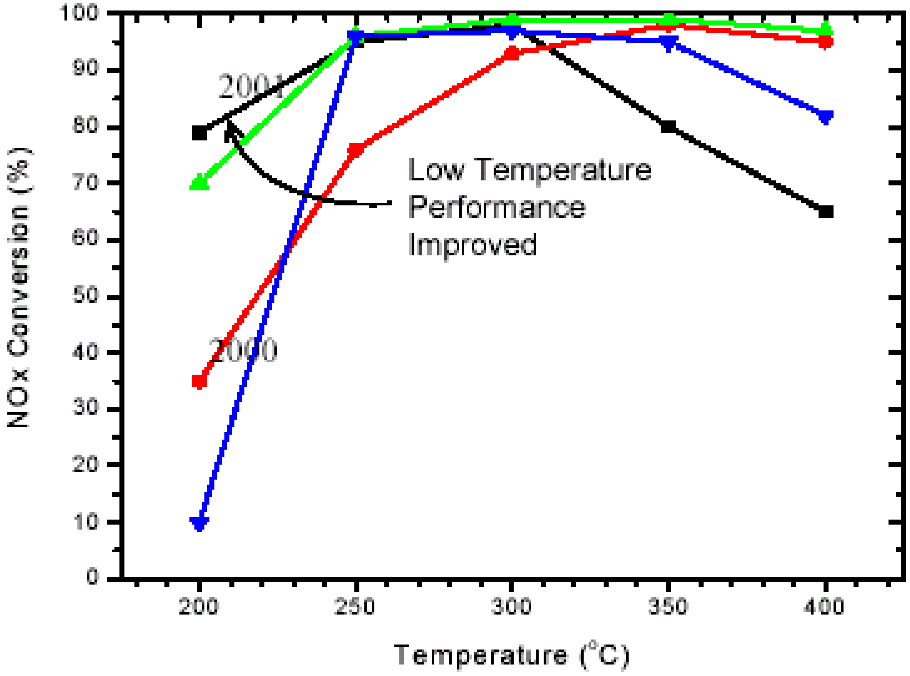
AVL Vienna Motorsymposium 4/02

New diesel fuel co-fueling nozzle and fill pipe enable SCR- and non-SCR vehicles to be fueled; disables SCR vehicles to be fueled by non-SCR nozzle

Ford SAE 2002-01-0290

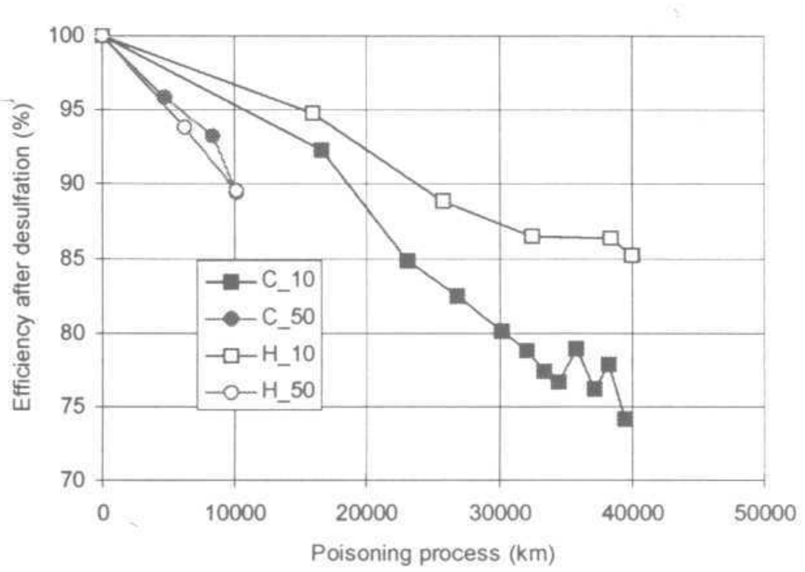


Continuous Improvements in Low Temperature Performance of NOx Adsorber Catalysts Are Realized while Maintaining HT Performance



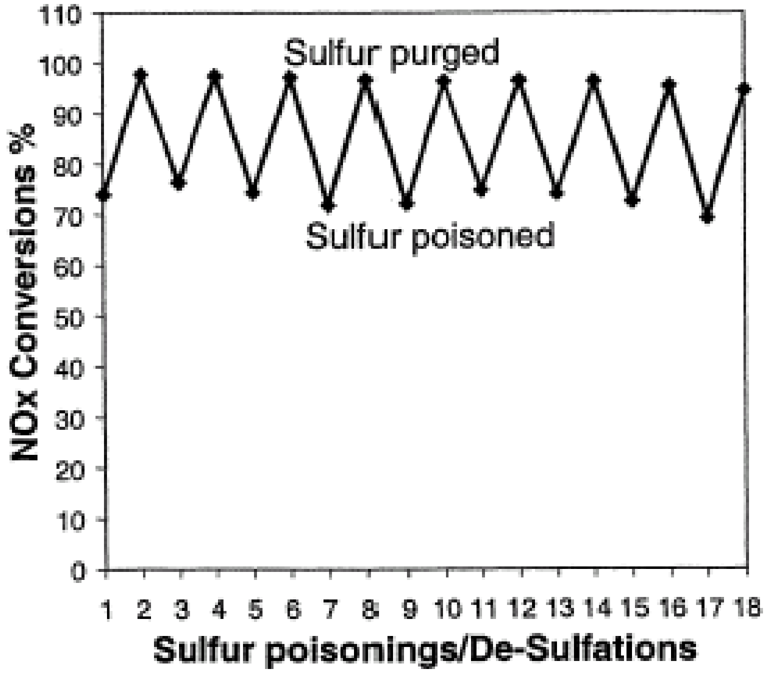
Source: MECA Company

Repeated desulfations cause NOx trap deterioration but solutions are surfacing



Hexagonal cell LNT stabilize at higher NOx efficiency levels and require fewer desulfations than square cell LNT; 682C, A/F=13.2, 12 min.

IFP SAE 2001-01-1934

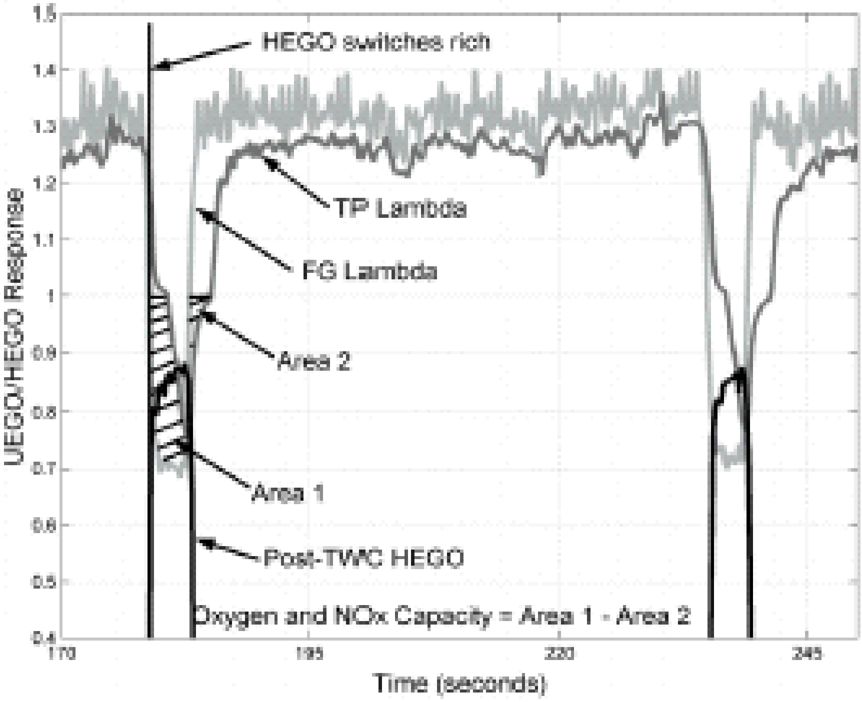


Sulfur tolerance of Ba-alkali LNT materials is improved. Ba materials oscillated between 30 and 70%. Tests at 350C. Sulfations at 700C for 10 min at A/F=13

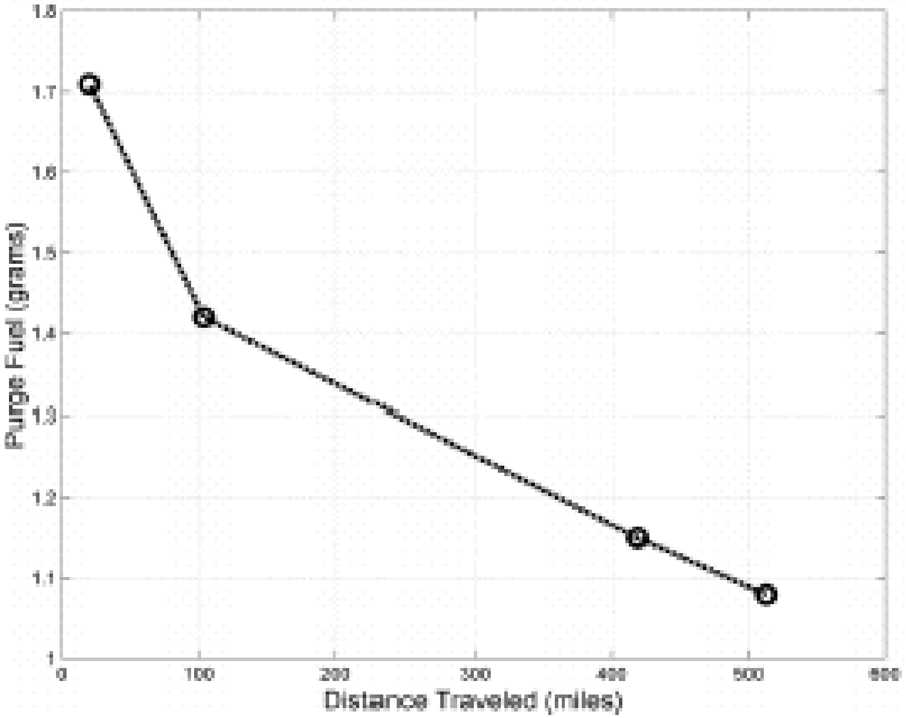
Delphi SAE 2002-01-0734

Desulfation fuel penalties of 0.5 to 1.0%

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

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Integrated systems

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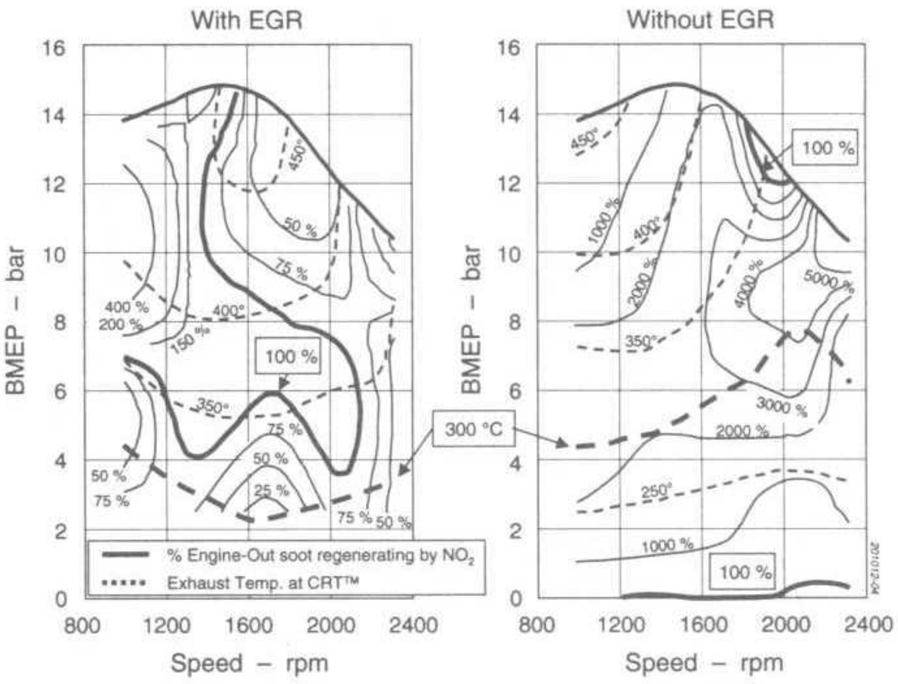
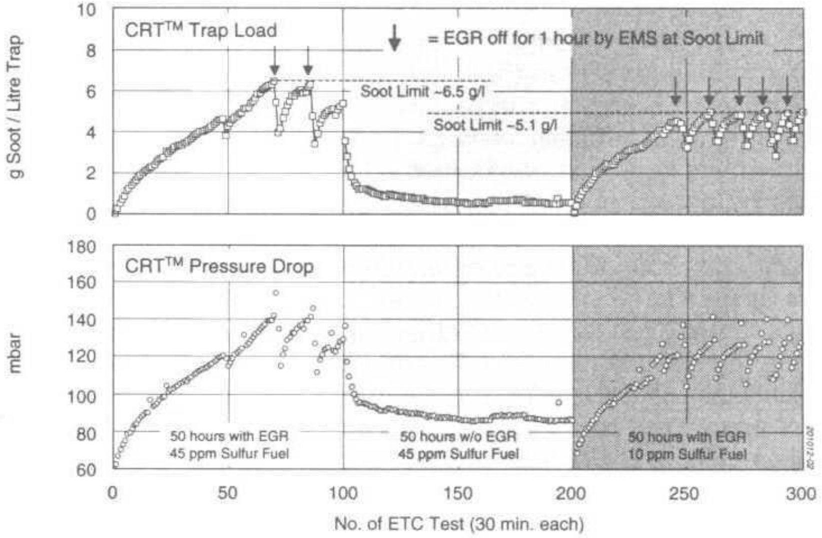
Performance of the CRT with EGR is quantified





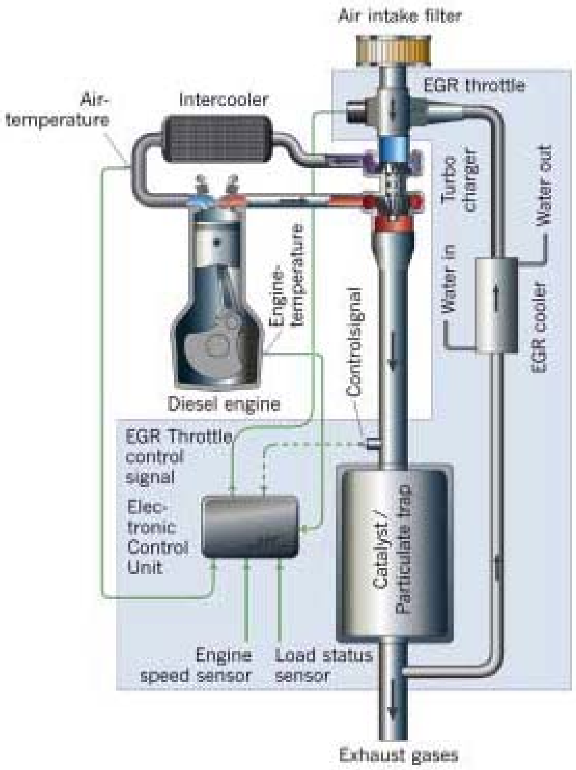
CRT™ Performance in Continuous ETC Testing. All Data taken at Check Point 1700 rpm / bmep 10.8 bar after every ETC Test.

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

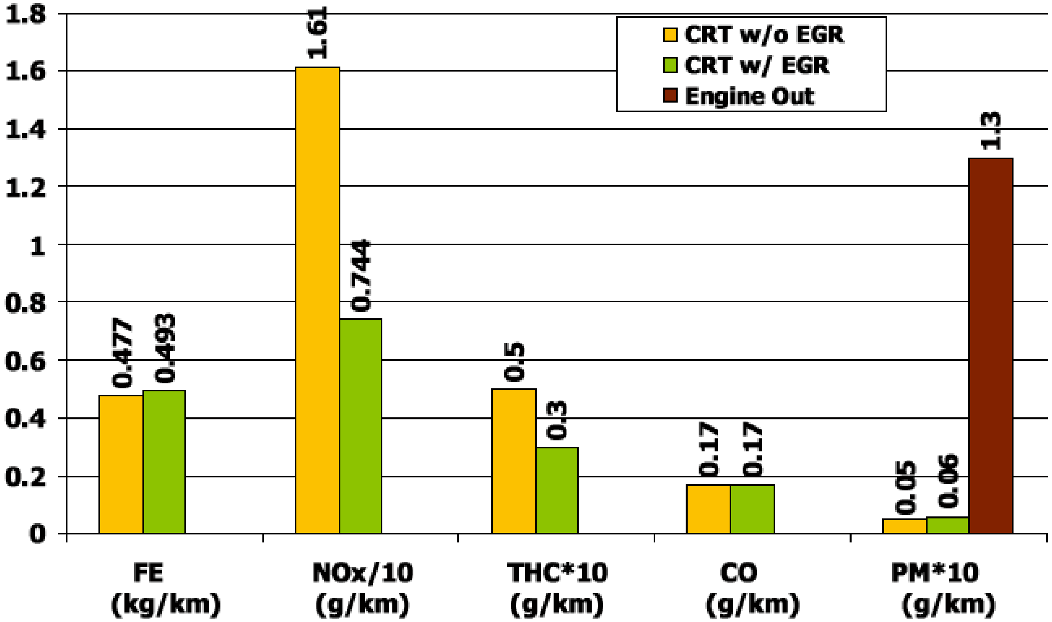
Integrated NOx and PM solutions are emerging for retrofit applications



Low pressure (long route) EGR is best suited for retrofit applications. Inputs to EGR control are load, back pressure, and RPM.

Emissions Results for EGR/CRT System

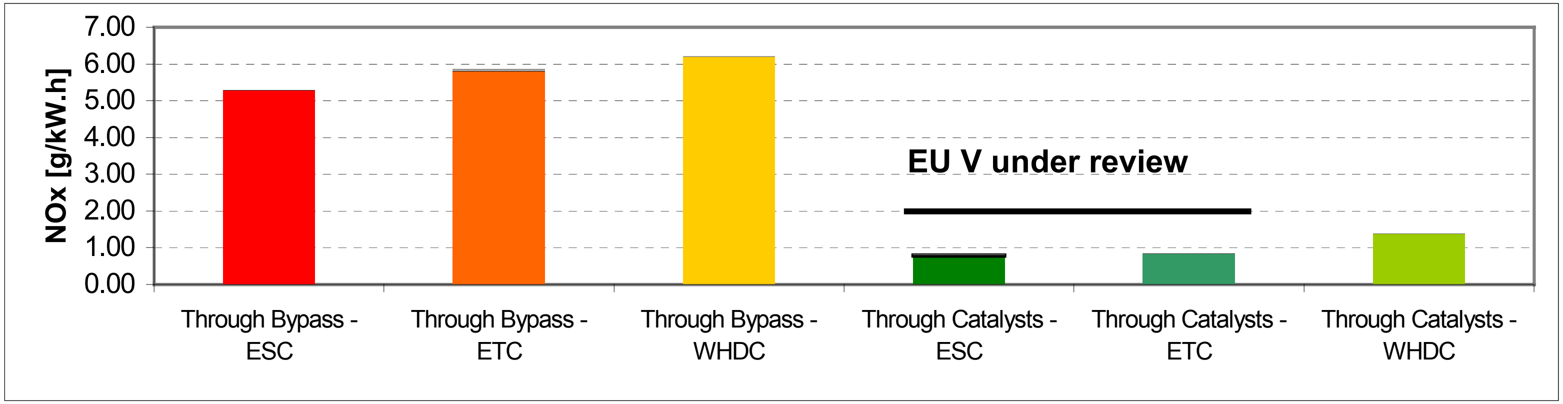
Volvo B10BLE Engine bus, Braunschweig Cycle on Chassis Dyno

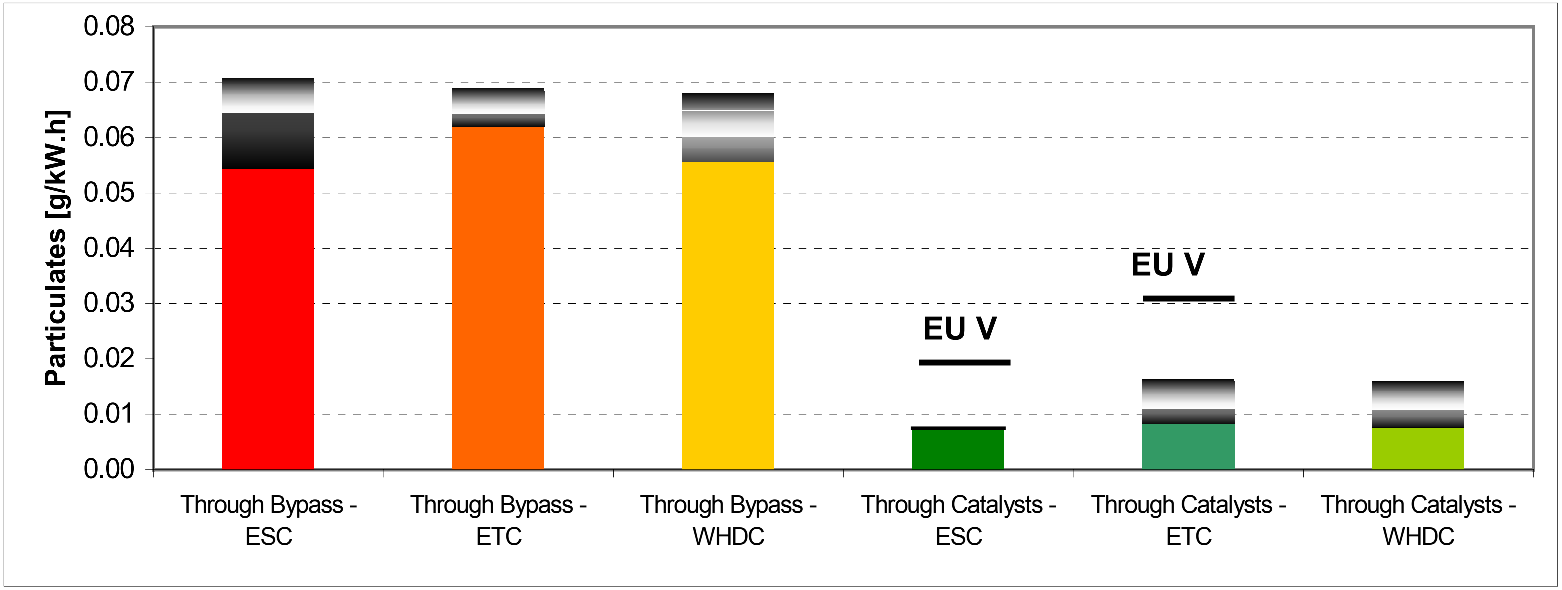


54% NOx reduction and 96% PM reductions were experienced on a chassis dyno running on the Braunschweig test cycle. 5% fuel penalty

Johnson Matthey, DOE DEER Conf, 8/02

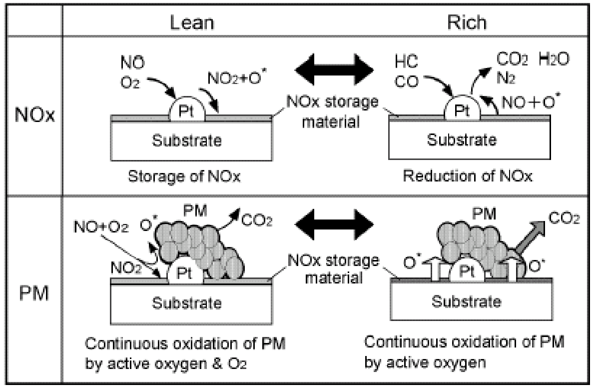
DPFs and SCR system comfortably hit Euro V standard after 1000 hours of aggressive aging





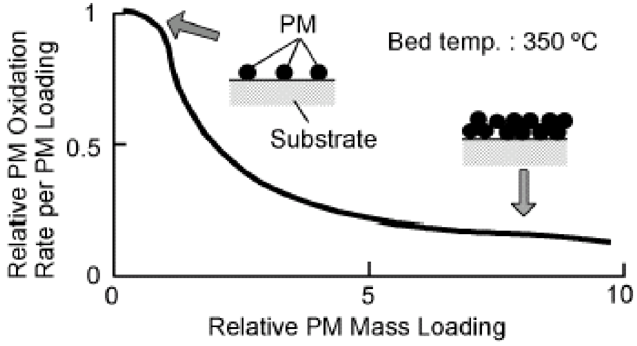
AECC FISITA 6/02

New integrated DPF / NOx trap is described; gets 80% reductions in PM and NOx



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

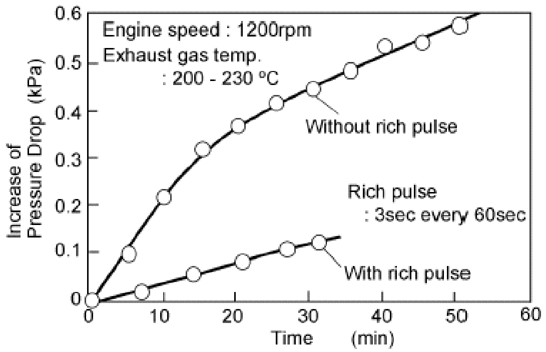
At a bed temperature of 350ºC, a maximum PM load rate of 3 g/l is tolerable before the catalyst blocks. Typical balance point temperature = 250ºC



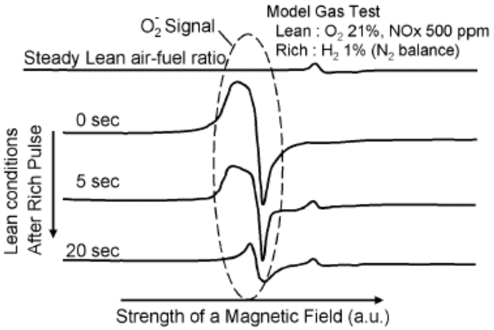
$$NO + 1/2\ O_2 = NO_2$$

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

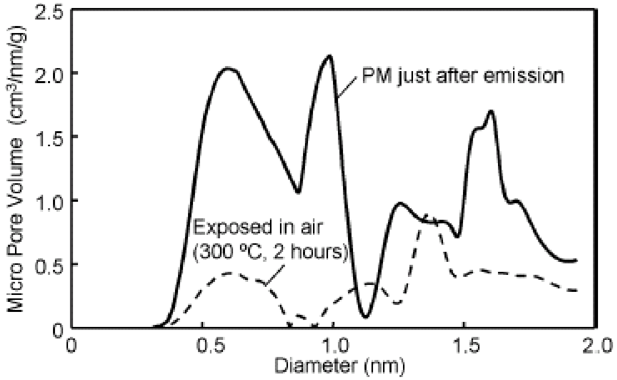
"$1/2O_2$" is the "active oxygen", and is generated on the forward and reverse reactions



Periodic rich pulse causes PM to oxidize



Active oxygen pulse is strongest right after rich pulse

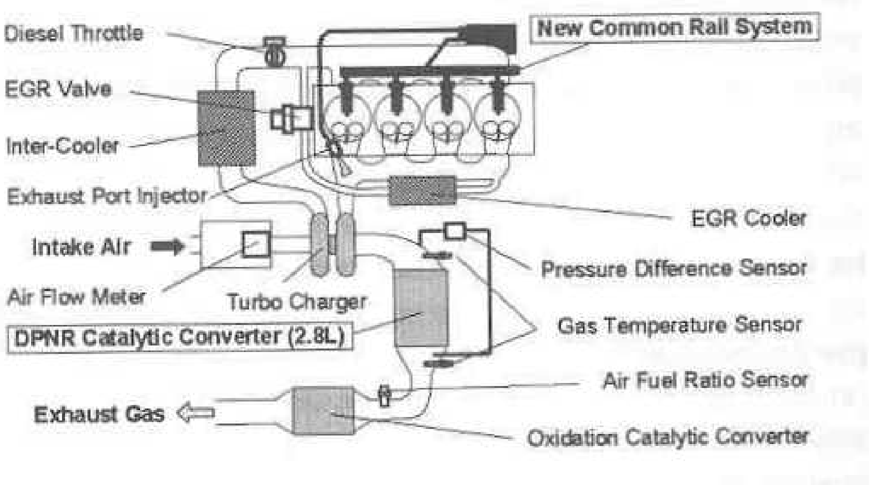


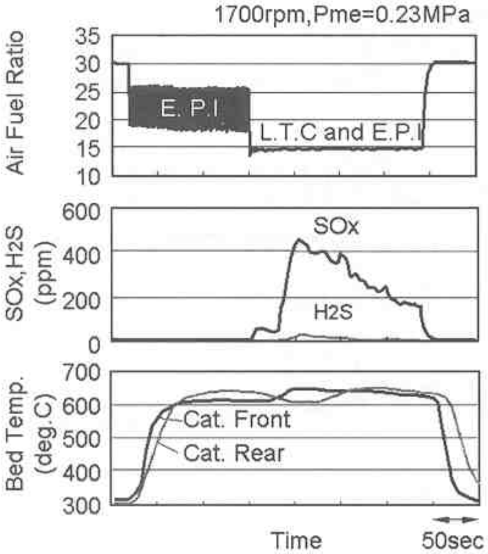
Fresh soot has more micropores and higher activity than older soot

Toyota SAE 2002-01-0957

Toyota integrates engine management in very closely with the DPNR

Toyota, Vienna Motorsymposium 4/02



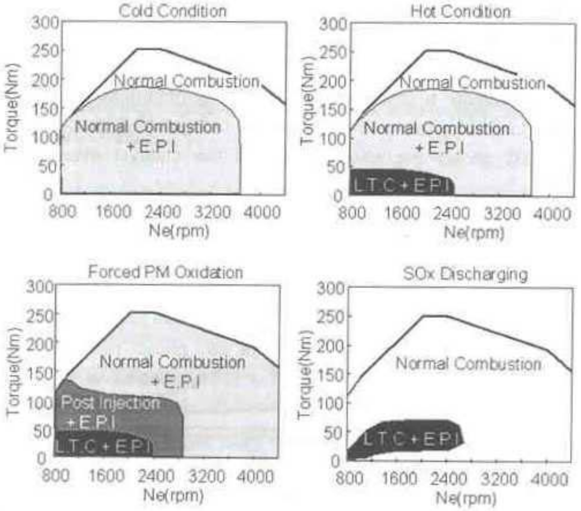


LTC: adv. EGR control, injection timing, and throttling are used to drop PM and NOx in increase HC and T (+50C°)

EPI: auxiliary fuel injection helps richness and drivability.

Aged DPNR hits 0.005 g/km PM and 1.2 g/km NOx on MVEG cycle 1400 kg car

Lean/rich switching is used to minimize H_2S during desulfurization



System Control under Different Operating Conditions

(LTC: Low Temperature Combustion. EPI: Exhaust Port Injection)

Summary

- The nature of nanoparticles is becoming understood. Exhaust plume analyses are the key.
  - Engine hardware and filter porosity can affect ultrafine particles
- 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
  - Europe is heading toward SCR for long haul and filters (maybe DOC) and EGR for urban in 2005
  - NOx adsorbers are making rapid progress
- Integrated PM/NOx systems are being developed
  - Synergies exist between SCR or LNT NOx control and DPFs

Thank you for your kind attention!

CORNING

Discovering Beyond Imagination