Update on Diesel Exhaust Emission Control Technology and Regulations

Tim Johnson

October 2004

MDEC 2004

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Discovering Beyond Imagination

Diesel emission control technology is making significant progress

- Diesel regulations are getting tighter in all sectors. Diesel will likely not be "done" until emissions are as low as permitted by technology.
- Filter technology
  - Regeneration methods are getting sophisticated. Future regeneration methods will be accommodated by advanced combustion methods.
  - Improvements continue on filter properties and ash management.
- NOx solutions
  - SCR interest in the US and Japan is increasing. LT performance is key.
    - HHDD and LDD
  - NOx adsorbers are still developing rapidly
  - LNC is showing "renewal"
- Integrated solutions
  - LNT+DPF has synergies, and are bringing LDD to Bin 5 and perhaps beyond
  - SCR+DPF is progressing

2

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Regulations and Approaches

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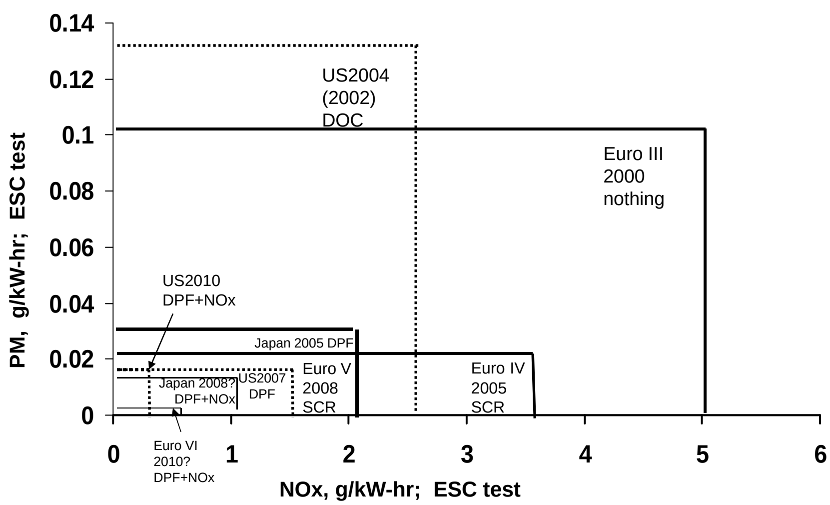
Heavy-Duty Diesel highway regulations will force PM or NOx control in October 2005 and both NOx and PM perhaps in 2008. Heading to very low numbers in major markets.



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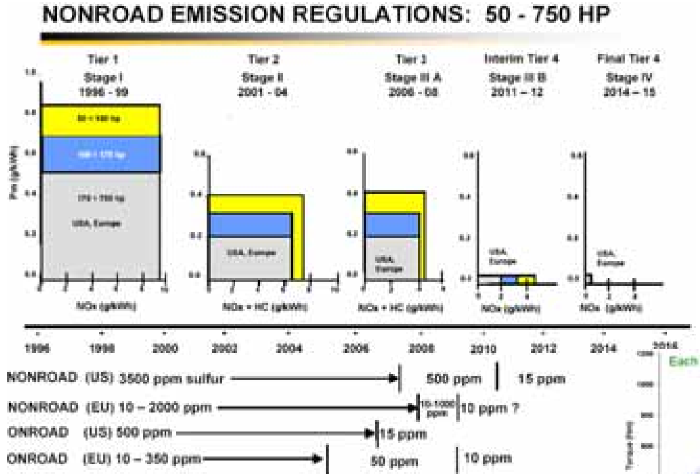
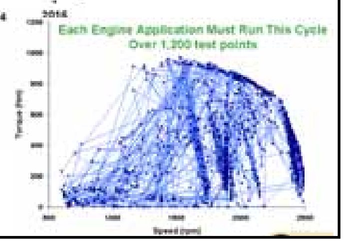
New non-road regulations in place. Roughly a 4-year lag with highway regulations.





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Courtesy of John Deere

Recent developments in PM control

- Filters can take diesel out of the PM inventory
- Technology is the state of optimization and cost reduction
  - –Regeneration
    - •LDD and MDD: engine management
    - •HDD: auxiliary exhaust injection
  - –Reduced back pressure and size
  - –Ash management

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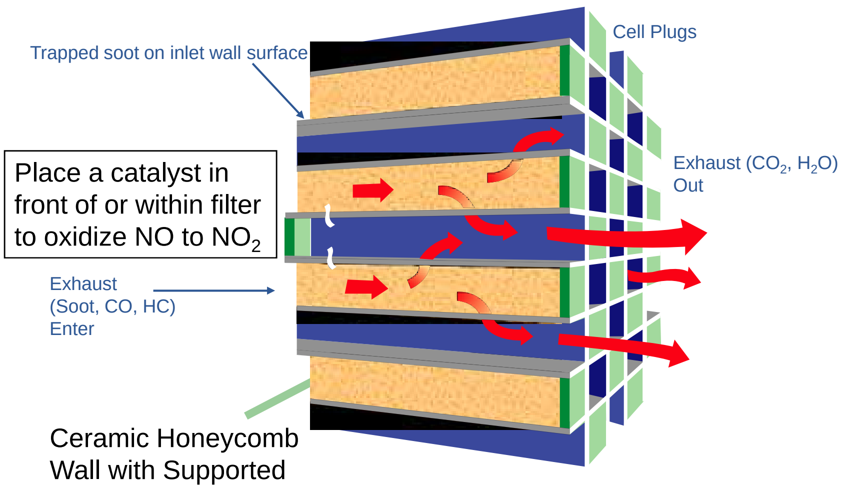
Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot



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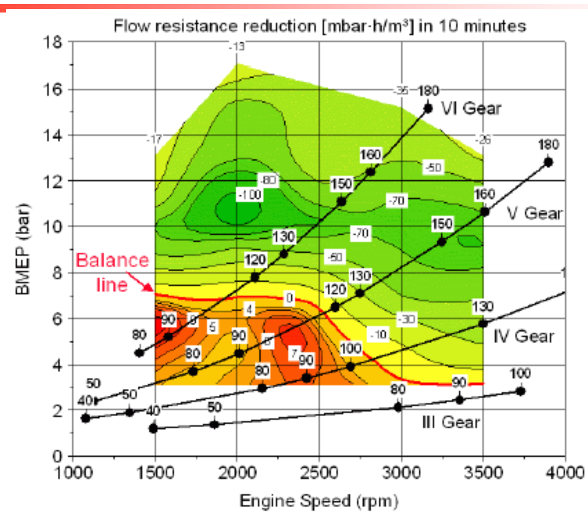
Regimes of passive and active regeneration are described for a LDD



Fiat FISITA 5/04.

Above the "balance line" is passive regeneration using DOC+CSF. 1.9 liter CR DI engine, D-Class vehicle, 10 minute backpressure changes at 10g/liter soot.

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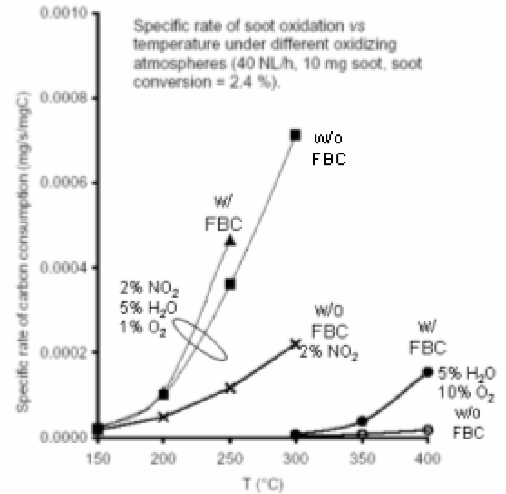
NO$_2$ has a big influence on soot oxidation, as does the presence of catalyst



Other Results:

- OSC materials enhanced the soot oxidation reaction, and showed strong synergies with NO$_2$
- LNT catalysts had little influence on oxidation rates
- Hypothesis: the presence of C (O) complexes are important in soot oxidation

9

Univ Haute, PSA SAE 2004-01-1943

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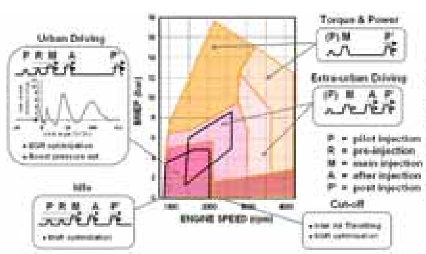
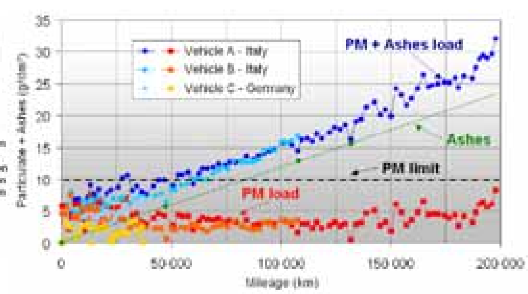
Fiat describes a comprehensive approach towards CSF regeneration





•Strategy maximizes passive regeneration and considers partial regenerations and aging.

•Complete regenerations occur only under efficient conditions

Fiat FISITA May 2004

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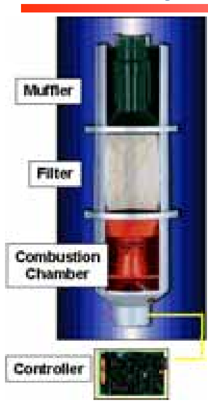
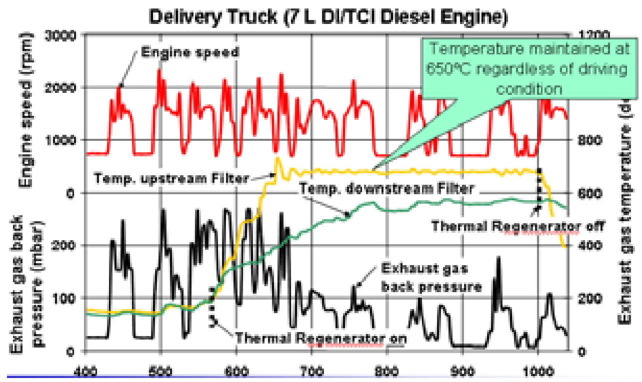
Burner system is described for regenerating filters





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ArvinMeritor AVECC 4-04

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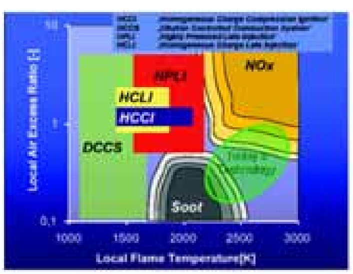
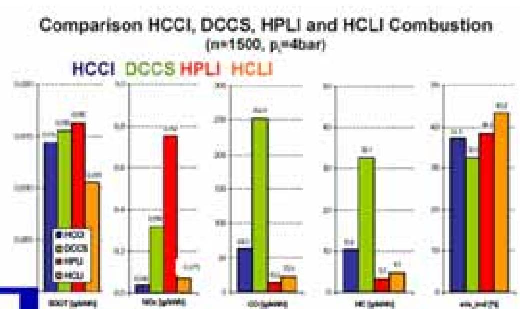
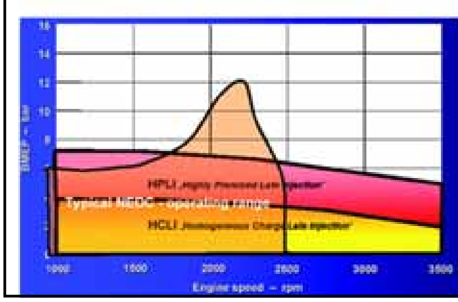
Alternative combustion strategies are moving forward and delivering T and HCs when needed

AVL DEER 9-03







- HC levels are rather high for alternative combustion strategies (3+ g/kW-hr)
- NOx is relatively low (<0.8 g/kW-hr)
- Temperatures are generally higher
- Gas is generally lean

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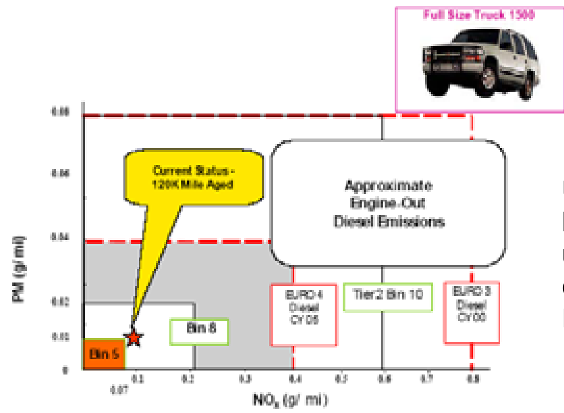
A prototype system is near Bin 5 at 120,000 miles for a LDT



US FTP Bin 5 can be hit, engine-out only, using advanced combustion strategies. Platform unknown.

GM Vienna Motorsymposium 4-04

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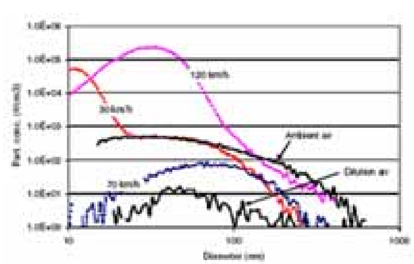
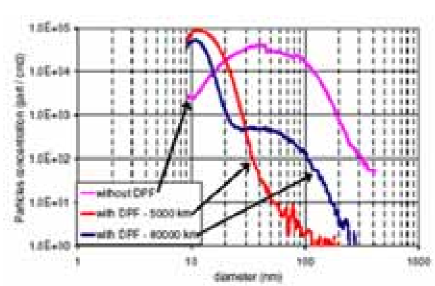
Results on PSA taxis with DPFs at 80,000 km are reported



Ultrafine particle emissions at 80,000 km are similar to ambient air, but nanoparticle emissions are higher at 30 km/hr (perhaps lube oil) and 120 km/hr (perhaps sulfate)



At 30 km/hr, accumulation mode emissions increase, but are still very low. Reason is unknown.

PSA, IPF, SAE 2004-01-0073

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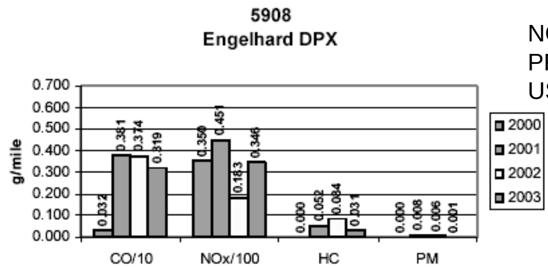
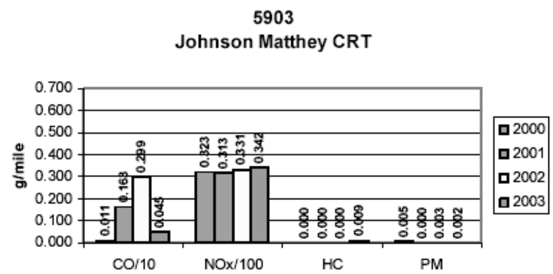
Cordierite DPFs retrofitted onto delivery trucks show good performance out to >360,000 miles



NO FUEL PENALTIES, NO BACK PRESSURE BUILD-UP OVER THE USE OF THE FILTERS



BP, SAE 2004-01-0077

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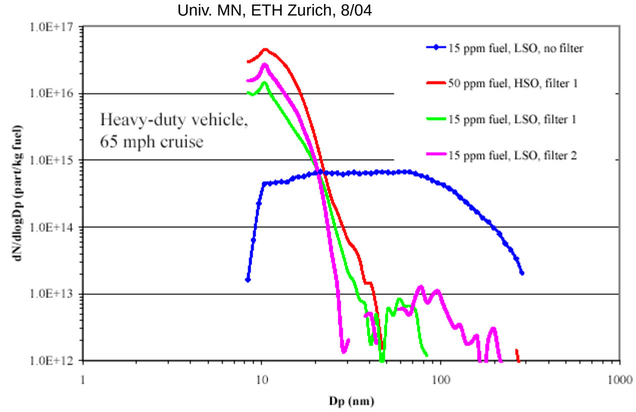
C-DPFs with ULSD and low-sulfur oil still generate aerosol nanoparticles under some conditions. Thought to be sulfuric acid, which is easily buffered in the lung.

Univ. MN, ETH Zurich, 8/04



Another secondary emission: NO_2
- •Issue mainly for retrofits
- •Quantification of issue being determined (CARB working group)
- •Solutions exist or are in the works

16

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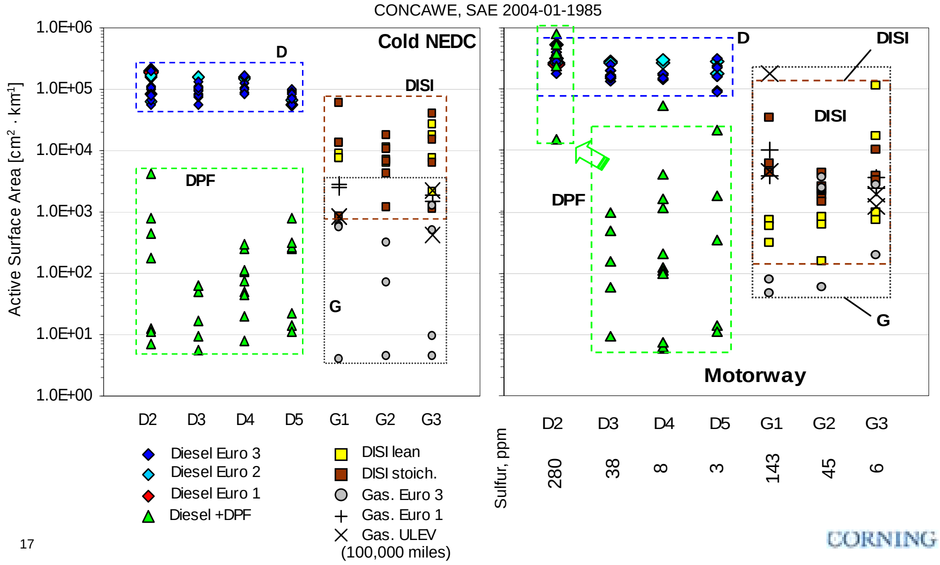
The active surface area of ultrafines from LDDs with DPF is generally lower than for aged ULEV gasoline

CONCAWE, SAE 2004-01-1985



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NOx Control

- In-cylinder and aftertreatment approaches are proposed for 2007; both needed in 2010
- SCR leads the NOx aftertreatment field, at least for Class 8 vehicles
- Lean NOx Traps are developing rapidly and are used in lighter applications

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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%	3-5% urea in Euro IV	1.0 emerging	Low temp. performance issues. US interest in LDD and HDD. OBD and infrastructure discussions.
LNT	80-95% Light aging	1.5 – 4% total regen. + desulf.	1.0 to 2	Desulfation strategy and durability issues being addressed. PGM cost issues
DeNOx catalyst	20-80%	2 to 6%	0.85 to 4	Generally not sensitive to sulfur. New concepts emerging.

SCR

State-of-the Art SCR system has NO_2 generation and oxidation catalyst to eliminate ammonia slip

SCR Catalyst (S)

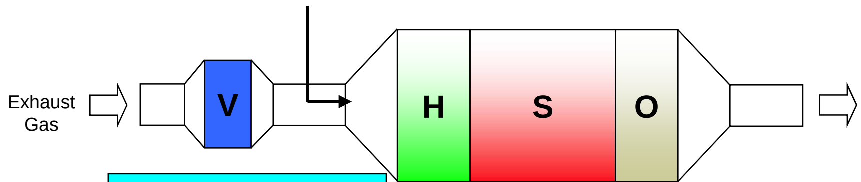
$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$

$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$

$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$

Urea

$(NH_2)_2CO$



Oxidation Catalyst (V)

$2NO + O_2 \rightarrow 2NO_2$

$4HC + 3O_2 \rightarrow 2CO_2 + 2H_2O$

$2CO + O_2 \rightarrow 2CO_2$

Oxidation Catalyst (O)

$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

Hydrolysis Catalyst (H)

$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$

Degussa, 9-99

21

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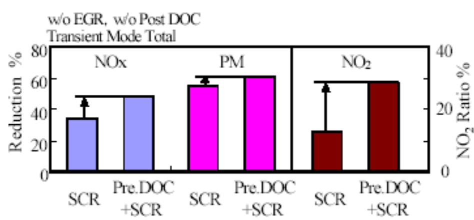
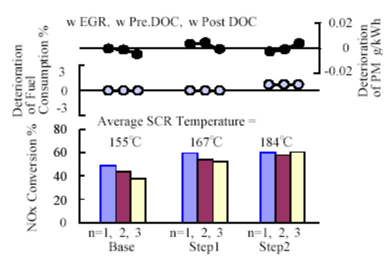
Low temperature SCR NOx conversion is obtained using DOC to generate NO_2 and exhaust brake for temperature control



W/ DOC, NOx eff. improves due to NO2 formation



The exhaust brake is used to increase T at no load (step 1) and during idle (step 2); decreased NOx efficiency with time likely due to ammonium nitrate blocking

Mitsubishi FUSO SAE 2003-01-3248

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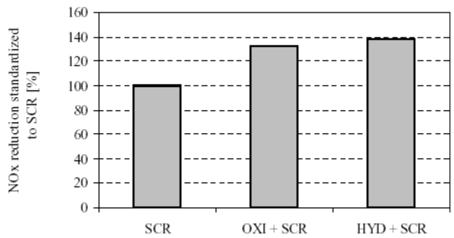
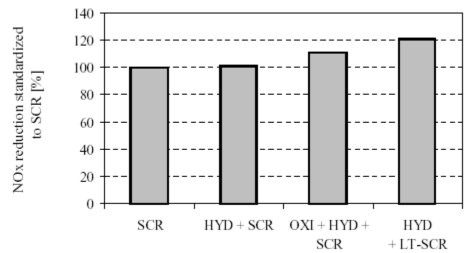
Oxidation catalysts and urea hydrolysis catalysts are used to increase SCR performance.

J05 Transient Test – Cold Start



J05 Transient Test – Hot Start



Under cold conditions, oxicats convert NO to NO2, which aids LT reduction, and urea hydrolysis catalysts aid urea decomposition at about 160C. 70% NOx efficiency is attained. At higher temperatures, performance is marginally improved.

Argillon, FISITA 6/04

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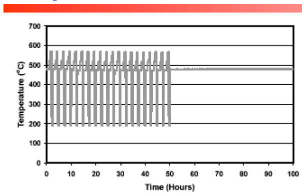
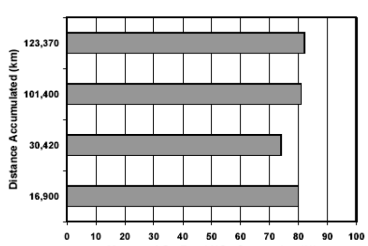
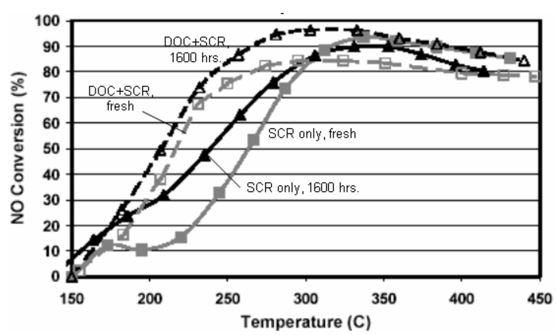
A new coated SCR system is reported that has impressive durability

JMI SAE 2004-01-1289



Lube oil age cycle goes to 550C. Lube oil consumption 0.075 l/hr. 350 ppm sulfur fuel. 11 liter engine 8.5 liter SCR





SVR=0.78; Aging to simulate 1.2 million km lube oil and 300,000 km driving up to 550C

24 High efficiencies obtained with NH3/NOx=0.85; 50% time >310C

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Lean NOx Traps

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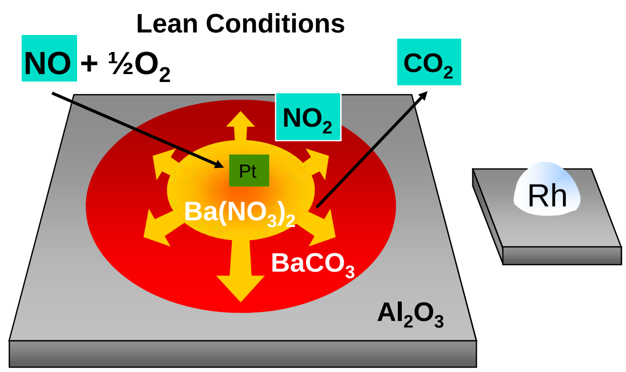
In lean operation, the LNT converts NOx to NO_2, and stores it as a nitrate



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

26

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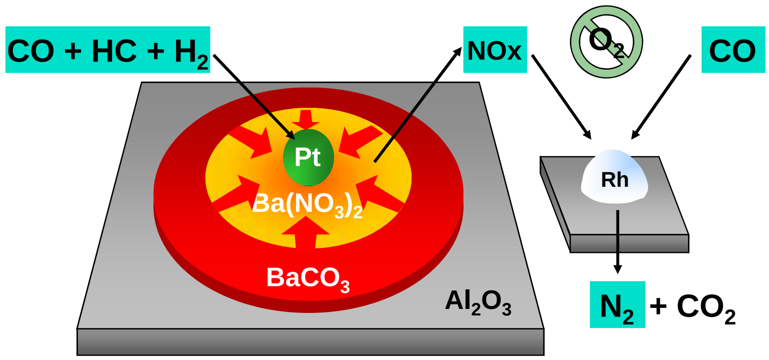
In rich mode, the nitrate dissociates to NO_2, which is converted to nitrogen using the HCs or CO

Rich Conditions



27

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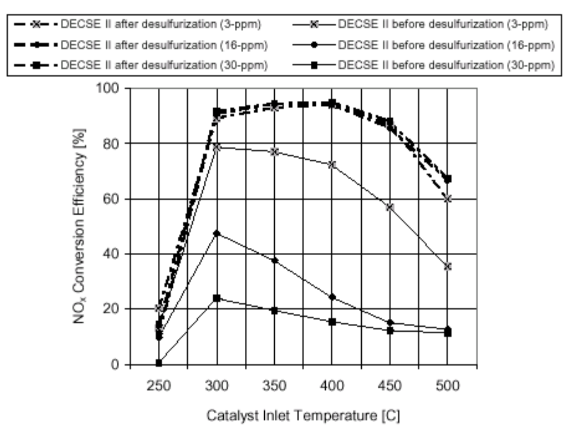
NOx traps can achieve 95% efficiency in steady state tests, but have sulfur sensitivity



NOx trap efficiency is high, but decreases with sulfur exposure; recovery is demonstrated

DOE DECSE report, Phase 2 NOx Adsorbers, 10/00

28

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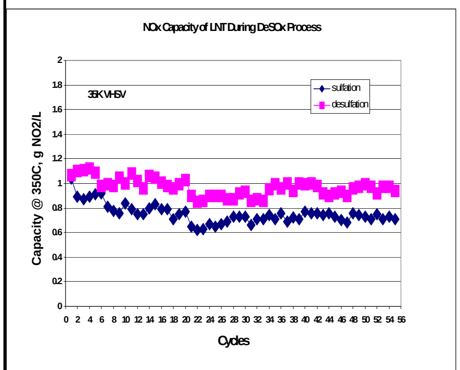
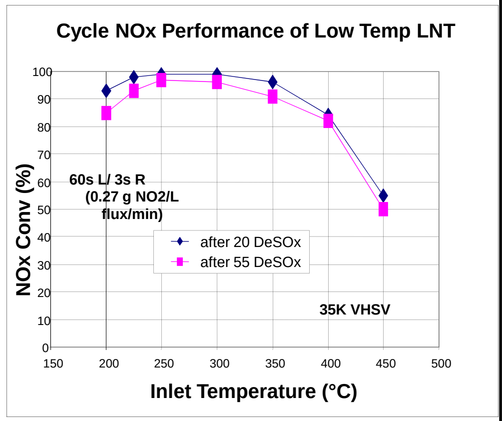
LNTs are becoming more tolerant to sulfur





29

Engelhard, AVECC 2004

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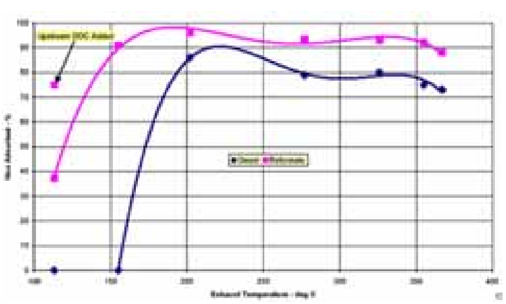
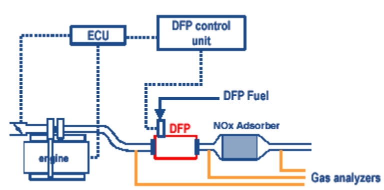
Hydrogen/CO reformate significantly improves LNT performance

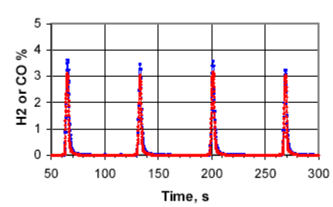
Plasma reformer uses 250W to form 9% H_2 and 14% CO from 35 kW of fuel; w/ DOC:20% H2



ArvinMeritor SAE 2004-01-0582

In-line diesel fuel processors (DFP) can also generate hydrogen and CO





Catalytica SAE 2004-01-1940

30

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Lean NOx Catalysts

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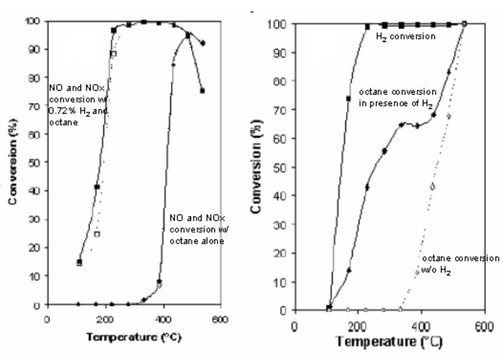
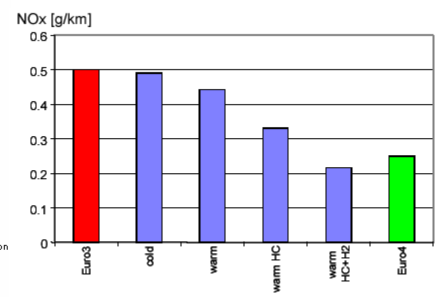
Small amounts of hydrogen significantly enhance Ag/Al_2O_3 LNC performance





ETC on HD diesel engine test shows hydrogen synergy. 27% hot efficiency w/o, 50% efficiency with 0.25% hydrogen. SVR = 3 to 4

- PAH in HC found to be detrimental on Ag catalysts
- Hypothesis is hydrogen either promotes reactive C=N species, or removes poisons
- Nominal 3-5% fuel penalties at high efficiencies

KNOWNOX Project FISITA 5/04

32

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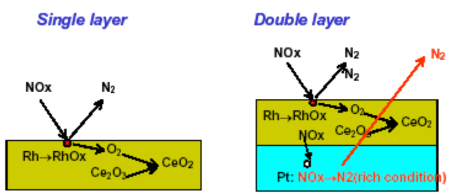
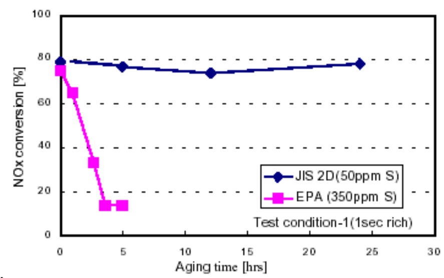
A new LNC with double layer is reported;

run like a LNT, uses oxygen storage mechanism to dissociate NOx





- In lean/rich cycling (20/2 sec), at 250C inlet, bed temperatures reach 420C
- Desulfation starts at lambda=0.95 and 380C (inlet); bed temperatures reach 600C; heavy desulfation takes 4 minutes
- SVR = 1.2

In steady-state engine testing, 80% NOx efficiency was observed at 250C inlet T; some sulfur sensitivity

33

Isuzu, SAE 2003-01-3241

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Integrated systems

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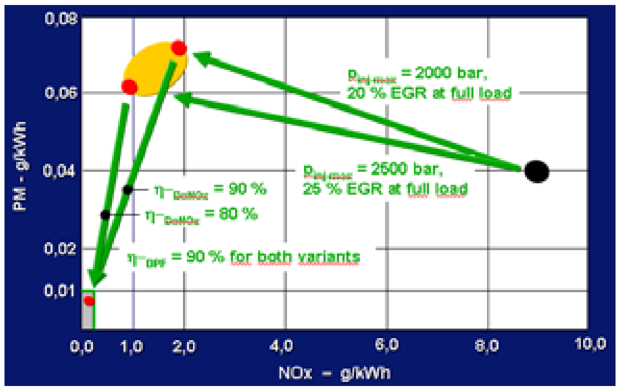
Engine and aftertreatment requirements are described to hit US2010 targets



To hit the US2010 target of 0.013 g/kW-hr PM and 0.27 g/kW-hr NOx, 2500 bar injection pressures, 25% EGR at full load, 80% deNOx, and 90% DPF will be needed.

AVL DEER 9/04

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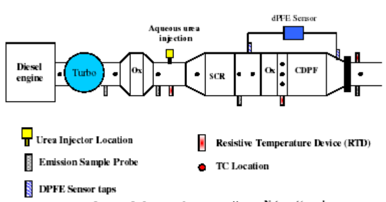
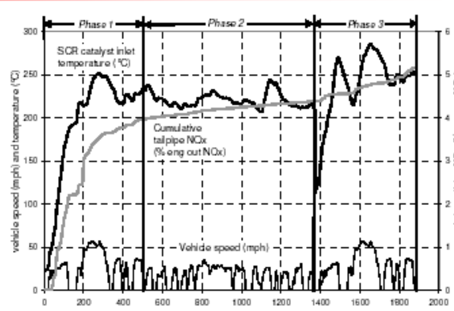
Refinements and further testing are reported on a LDD SCR system. Cold start and HC issues are addressed to hit Bin 5.



SVR SCR = 2.1 zeolite

Species	Engine -out [g/mi]	Tailpipe [g/mi]	ULEV II 50k mi PC Standard [g/mi]	Efficiency [%]
NMHC	0.45	0.012	0.04[a]	82%
CO	0.80	0.143	1.7	60%
NO_x	0.48	0.037	0.05	92%
Phase 1	*0.50*	*0.082*	---	*83%*
Phase 2	*0.47*	*0.017*	---	*96%*
Phase 3	*0.48*	*0.040*	---	*92%*
PM	---	0.001	0.01[b]	

[a] NMOG standard.
[b] PM standard at 120k mi.



In LDD with fast heat-up SCR, 80% of NOx is emitted in Bag 1.

ULEV2 (Bin 5) is easily hit using the SCR/DPF system. US06 levels also hit. Average of five vehicle tests. Ford Focus. FTP FE 38.5 MPG.

Ford SAE 2004-01-1291

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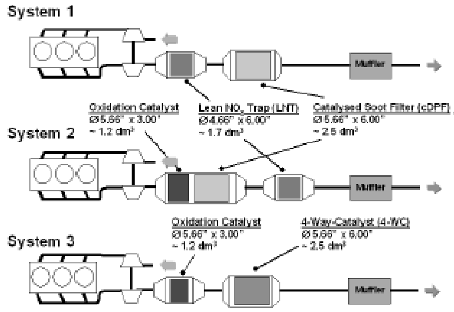
CSF/LNT system layout is analyzed. DPRN-type is judged best



	System 1	System 2	System 3
NO_x-Conversion Rate	comparable range for all systems		
HC breakthrough	moderate (still critical)	high	high
Suitability for low temperature application	high	low	high
Desulfurization capability	moderate	low	high
Soot regeneration capability	good	excellent	excellent
Risk of thermal damage of NO_x adsorber during PM Regeneration	low	high	high
Heat calibration effort (PM regeneration)	high	moderate	moderate
Continuous PM oxidation within DPF	low	high	moderate
PM regeneration interval	low	high	moderate

AVL SAE 2004-01-1425

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Progress is impressive. Competition is impressive. Future is “exciting”.

- Regulations will continue pushing diesel as low on emissions as technology will allow.
- Technology will be pushed by alternative combustion strategies and competitive forces.
- Filter regeneration is getting sophisticated. Advanced engine combustion strategies offer opportunity.
- NOx solutions are evolving rapidly.
  - SCR is being optimized for low temperature performance. And size.
  - LNT durability is being addressed and perform well at low temperatures. Reductant control is important.
- Integrated solutions are making HDD the environmental benchmark
  - Impressive integration and advancement.
  - Resources are being allocated to start in earnest towards 2008-10.

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Thank you for your attention!

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