Update on Diesel Exhaust Emission Control Technology and Regulations

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August 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 not be "done" until emissions are near zero.
- 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

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Regulations and Approaches

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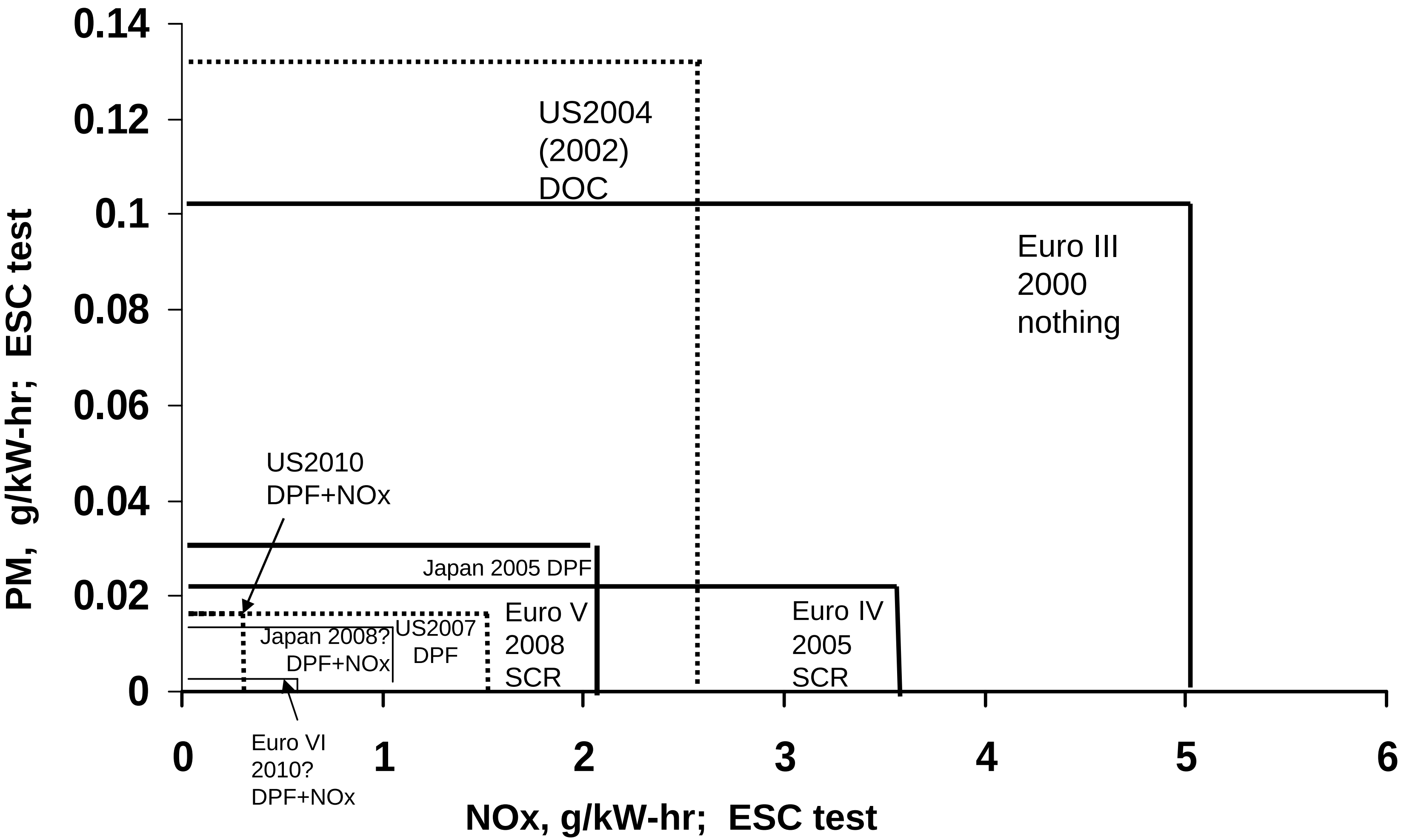
Heavy-duty diesel highway regulations will force PM or NOx control in October 2005 and both NOx and PM, perhaps in 2008



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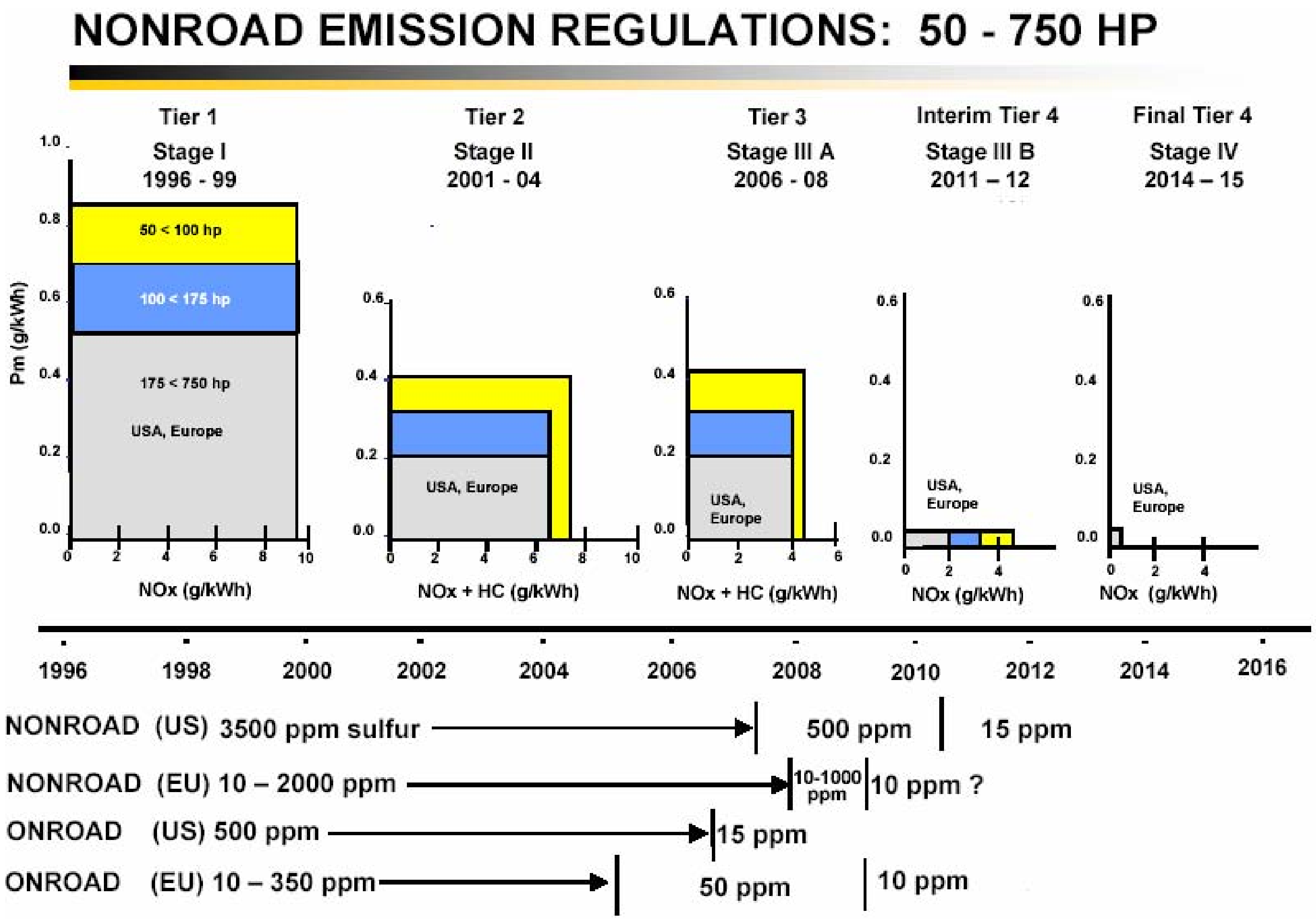
New non-road regulations in place



Courtesy of John Deere

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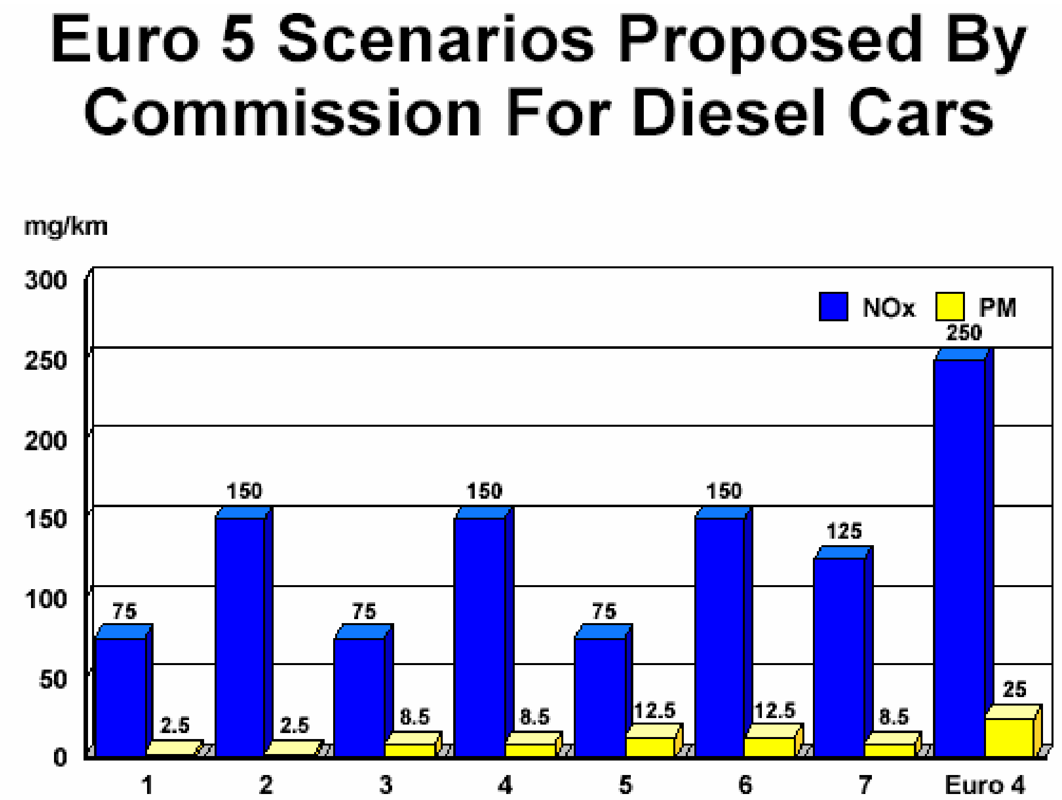
Light-duty diesel post-2005 regulation is being developed in Europe



Survey of stakeholders on potential seven Euro V levels was done. Results show diverse opinions of Greens and OEMs.

- Discussion is mainly on NOx; significant PM reductions are directionally agreed upon, absolute levels being negotiated.
- DPF tax incentives are likely in Europe before finalization of Euro V, perhaps as soon as next year
- Proposal "requested" by y.e. 2004; outlook is questioned
- Particulate number protocol is fixed and vehicles are being tested. "Draft regulation" is in the works for discussion purposes.
- Implications to US: Loose NOx standards in Europe would remove synergies, and make US stand on it's own in the diesel infancy

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DPF Incentives are of significant interest in Europe

Status of tax incentives for diesel cars with traps in european countries (07/2004)

Country	Incentive	Main requirement	Starting from	Remarks
France	Up to 800 €	Low fuel consumption plus "trap"	2005 ?	Plans withdrawn ?
Germany	[300/600 €] release of annual tax	[PM ≤ 8,5/2,5 mg/km], based on EURO 5 ?	2005/2008	Stages in parallel or in succession ?
Netherlands	400 – 500 € reduction of VAT	"With trap", or PM ≤ 5,0 mg/km ?	2005	Planned, compensation of trap system price
Sweden	Change in circulation tax suggested	t.b.d., based on EURO 5 ?	t.b.t.	Under discussion
Switzerland	Bonus of import tax of ca. 2 – 4 % related to car price	Stringent PM emission limit including PM number limit	2007 ?	Under discussion
UK	Up to 75% of retrofit trap system price (max. 3890 €) i.e. for taxis	Related to certain technologies, different requirements	since 2000	CleanUp-Programme for commercial vehicles

German UBA, July 2004

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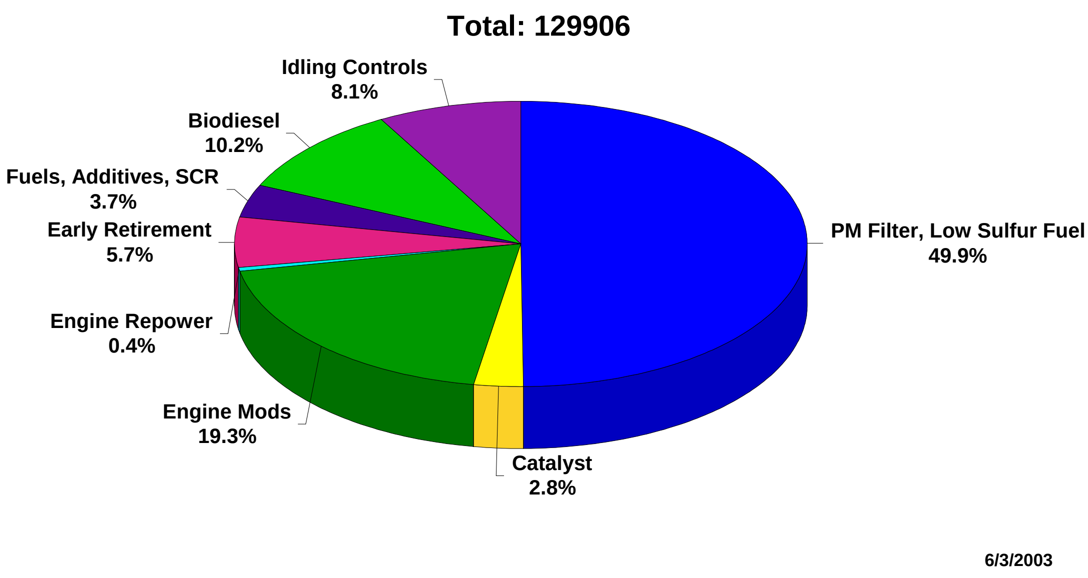
Diesel retrofits are taking off in a big way

Status of US EPA's Voluntary Diesel Retrofit Program



- Tokyo requires clean diesel
- Swiss have retrofit all construction equipment
- US school buses could have $30MM in funding over next two years
- NYC requiring all construction vehicles in government contracts to be retrofit
- Developing countries are starting model programs
- California mandating replacement or retrofit
- EPA wants to expand beyond school buses; filters across board in 2015
  - 11MM engines in US alone

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Diesel Oxidation Catalysts

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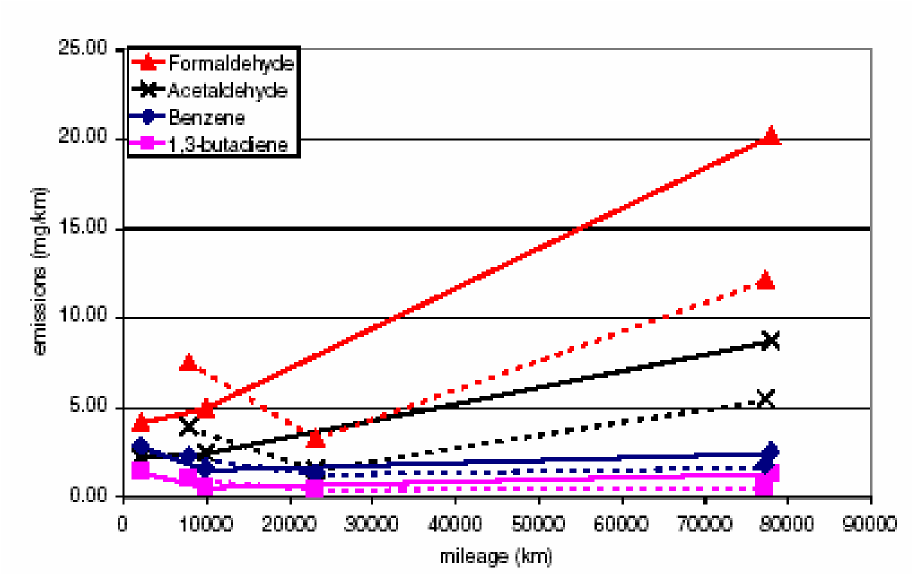
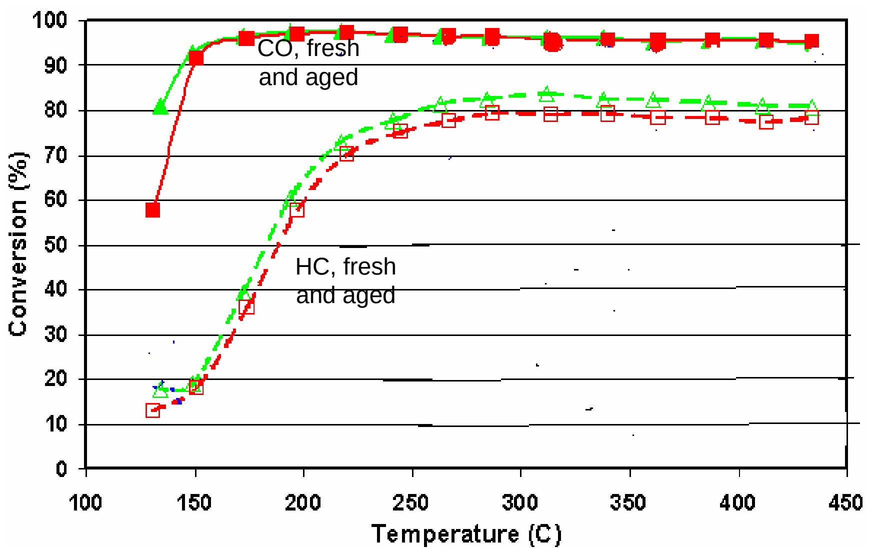
DOCs in DPF systems show some aging effects for HCs; New formulations improving



Some toxic air contaminants increase with DPF aging. PSA taxis. Lines represent two different vehicles.

PSA, IPF, SAE 2004-01-0073



Aged 80,000 km in 50 ppm sulfur fue. NO2 performance dropped only 10%, vs. 40% for previous formulations

JMI, SAE 2004-01-0072

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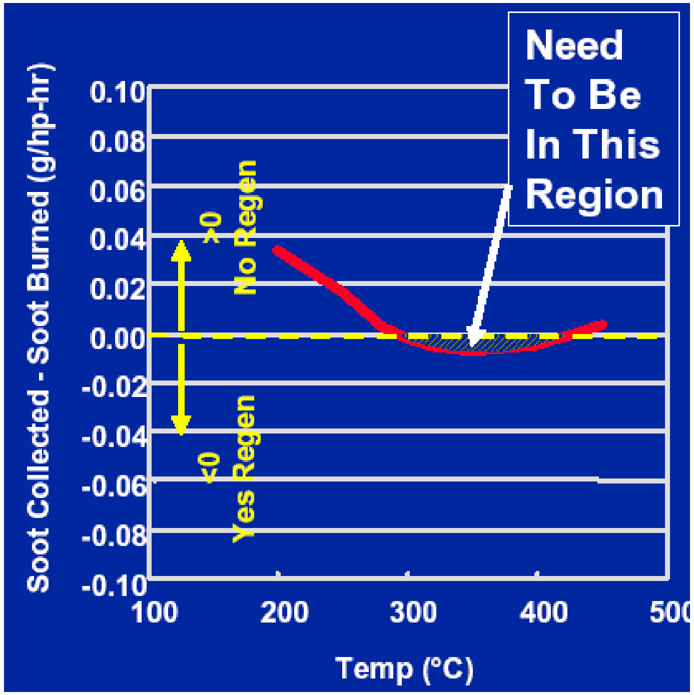
Recent developments in PM control

- 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

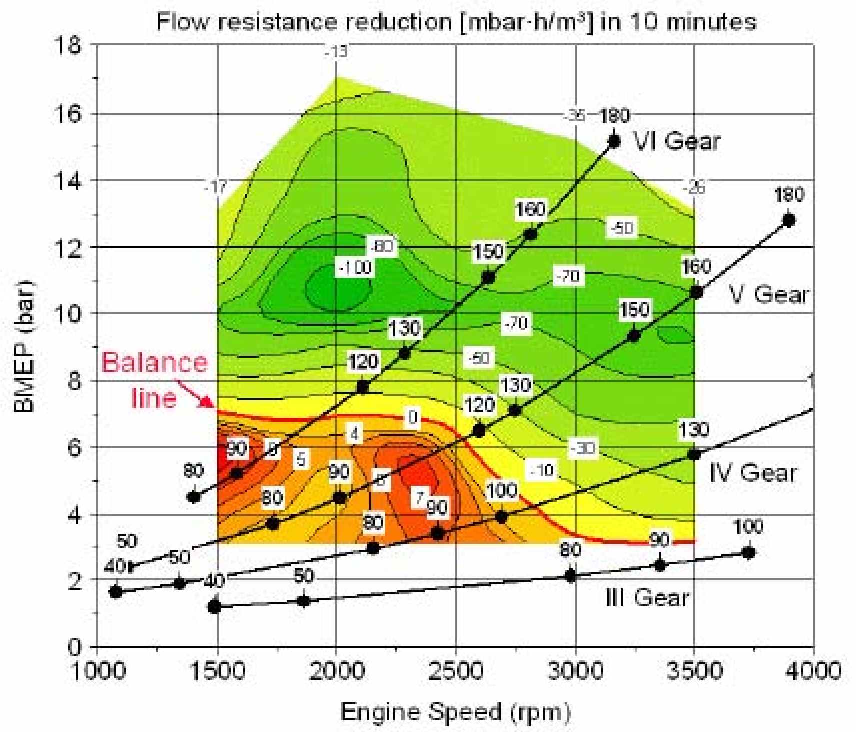
Passive regeneration uses NO_2 as the oxidant, formed by the oxidation of NO

NO + 1/2O2 = NO2

NO2 + C = NO + CO



Passive regeneration requires appropriate temperature. Too hot, and NO2 can not be formed. Too cold and kinetics of oxidation are too slow. Caterpillar ATA TMC 6/03



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. Fiat FISITA 5/04.

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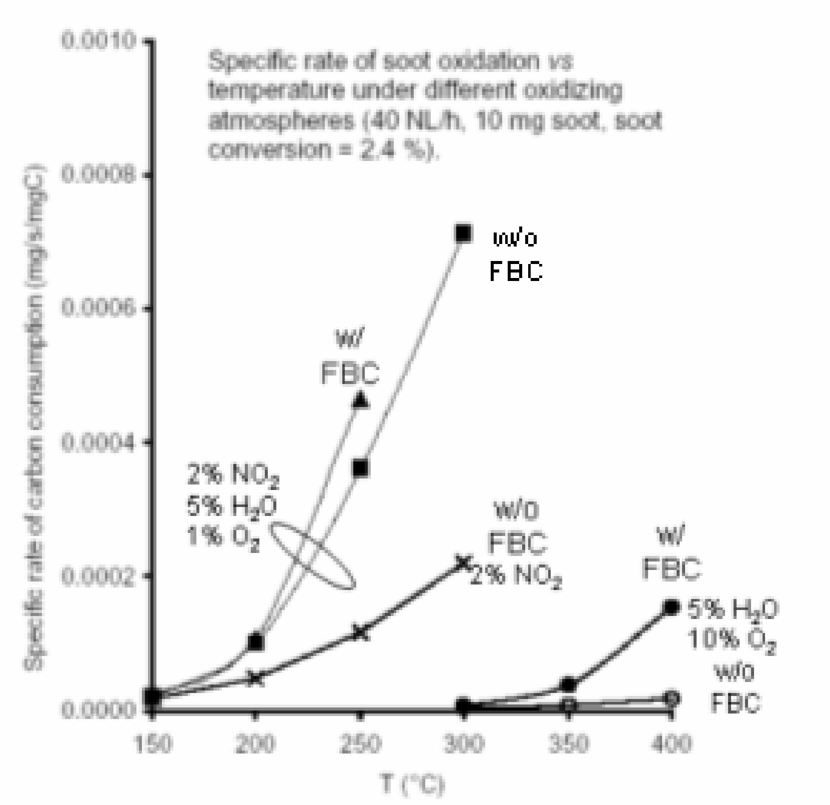
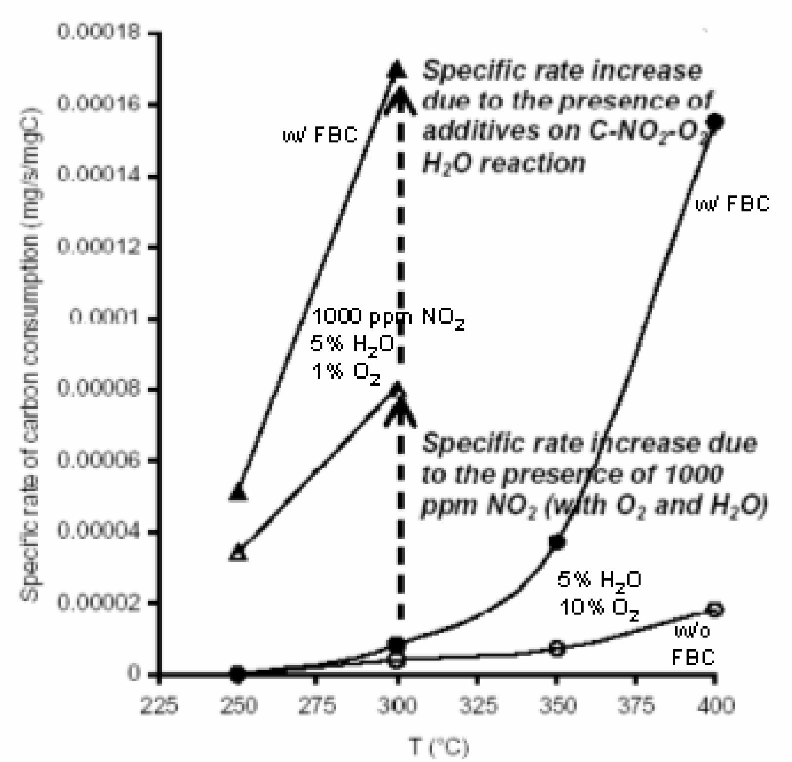
NO_2 has a big influence on soot oxidation, as does the presence of catalyst





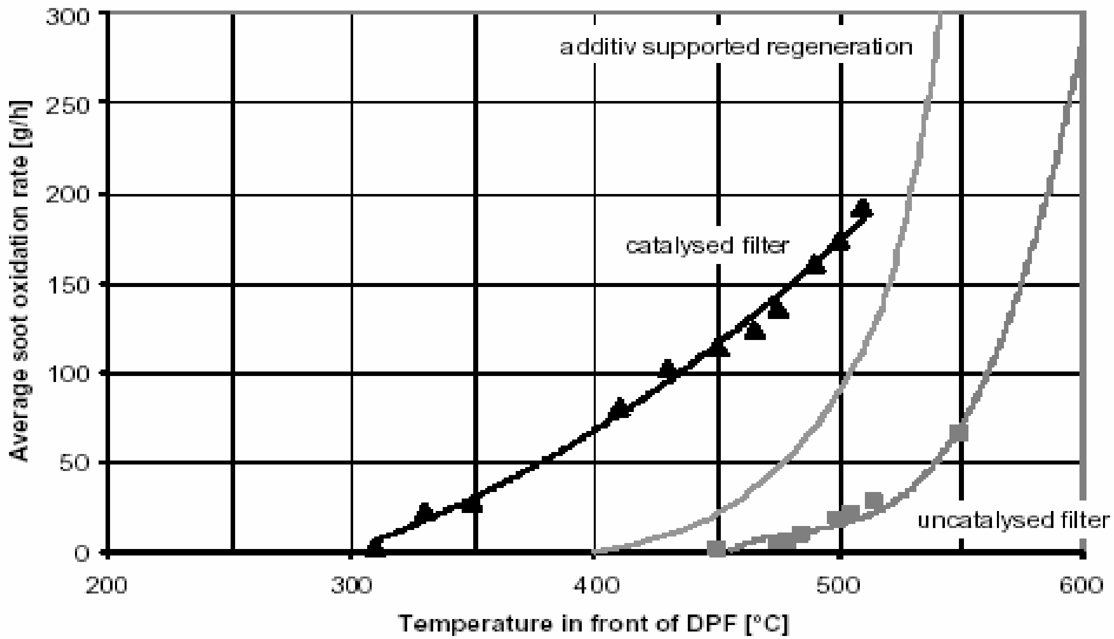
NO_2 and oxygen synergies exist (top set of lines vs. middle and bottom sets). Fuel borne catalyst helps in both conditions,

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

Univ Haute, PSA SAE 2004-01-1943

Active regeneration is needed if passive regeneration is not acceptable



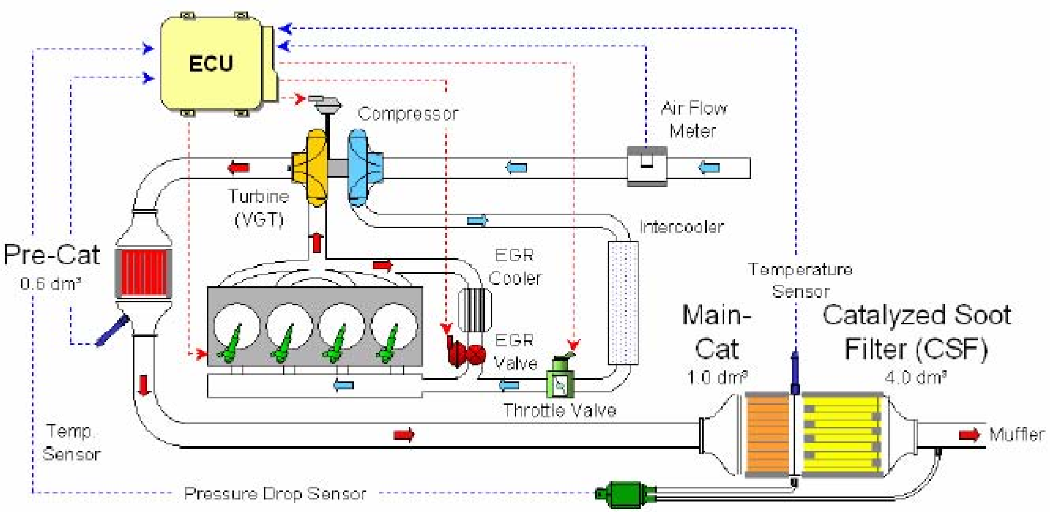
CSF oxidize soot at 50 - 100C less than FBC and 150C less than uncatalyzed systems; 75 g/ft^3 pt. Umicore, SAE 2003-01-3177

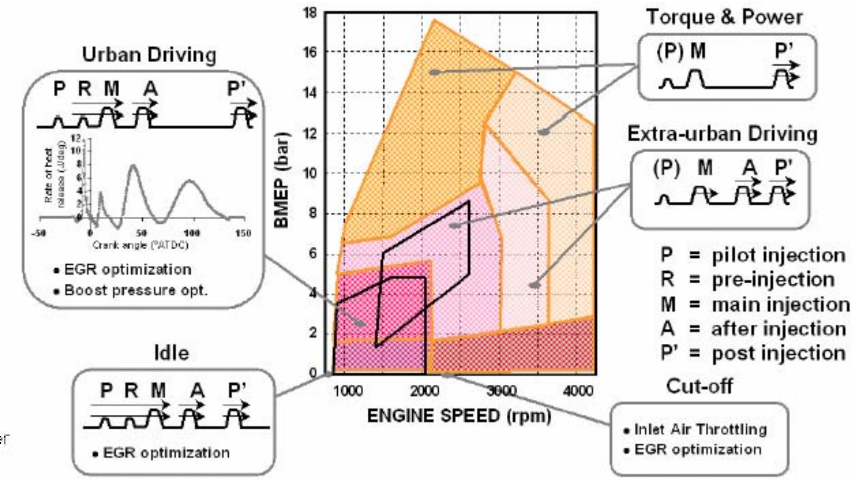
$C + O2 = CO2$

- Heat needs to be actively added to increase temperature to get fast oxidation.
- Uncatalyzed filters need T>600C
- Fuel borne catalyst systems need T>300–500C depending on formulation.
- Catalyzed soot filters need T>300-450C depending on formulation.

Fiat describes a comprehensive approach towards CSF regeneration

Fiat FISITA May 2004



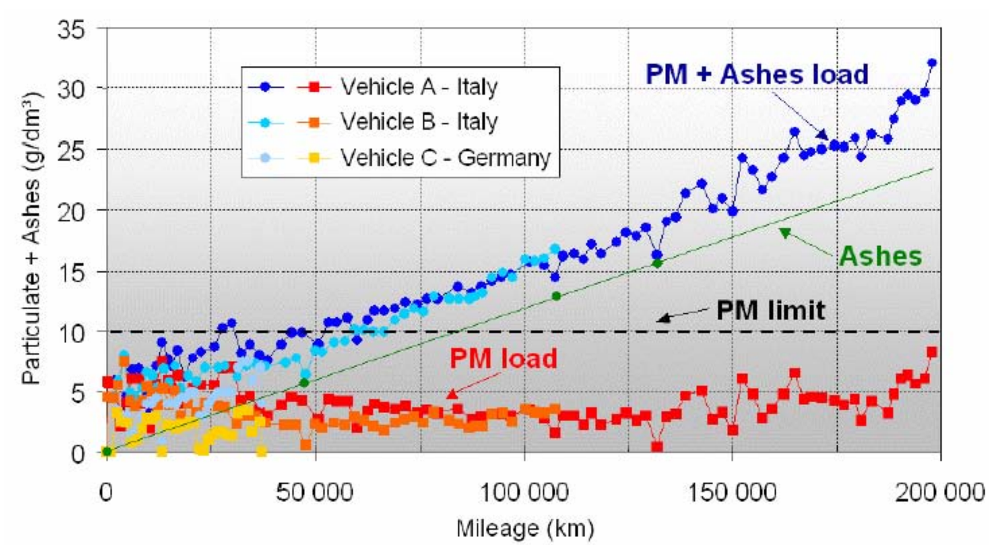


• Regeneration takes about 12 minutes at 130 kph and 10 g/liter soot

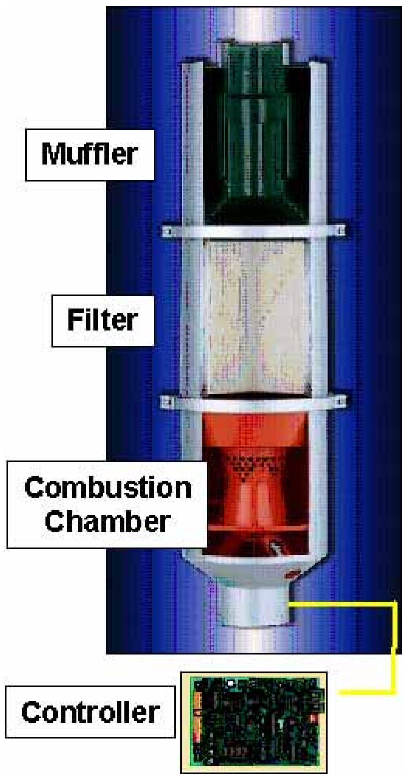
• Significant soot oxidation begins at 350C

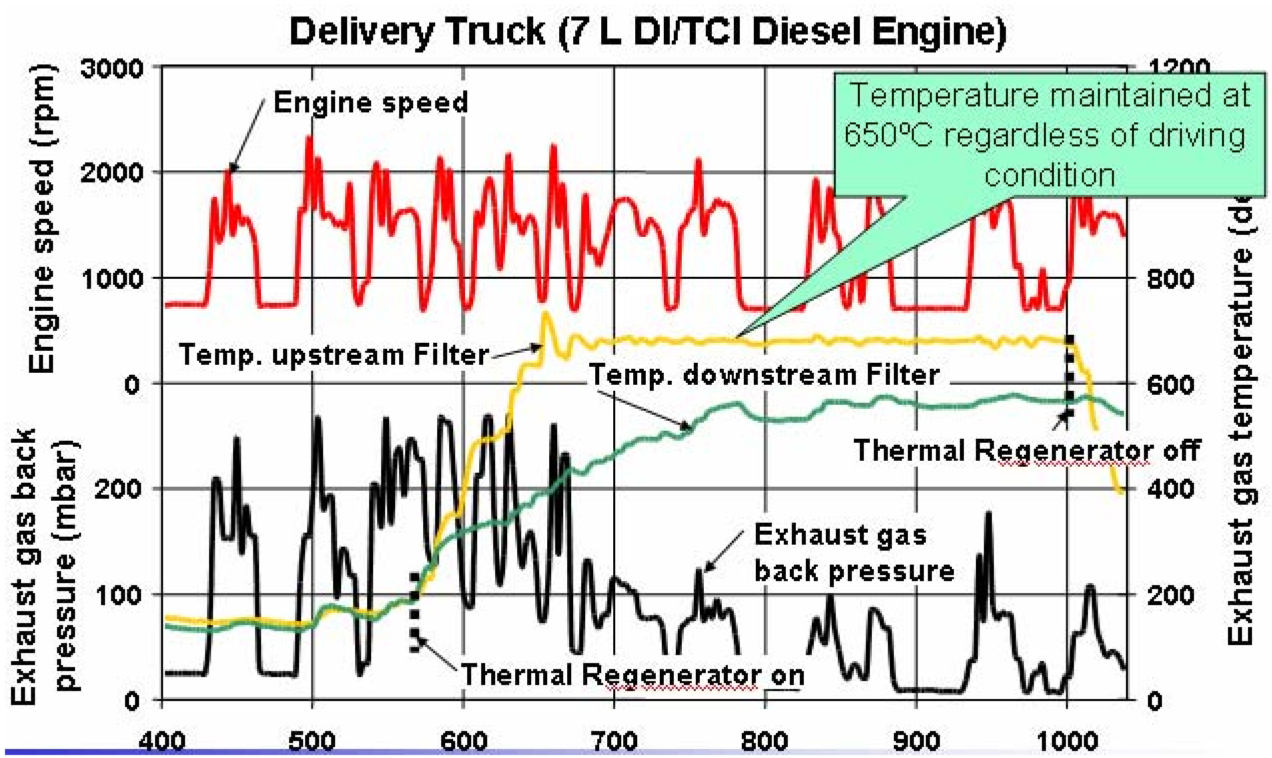
•Strategy maximizes passive regeneration and considers partial regenerations and aging.

•Complete regenerations occur only under efficient conditions



Burner system is described for regenerating filters





ArvinMeritor AVECC 4-04

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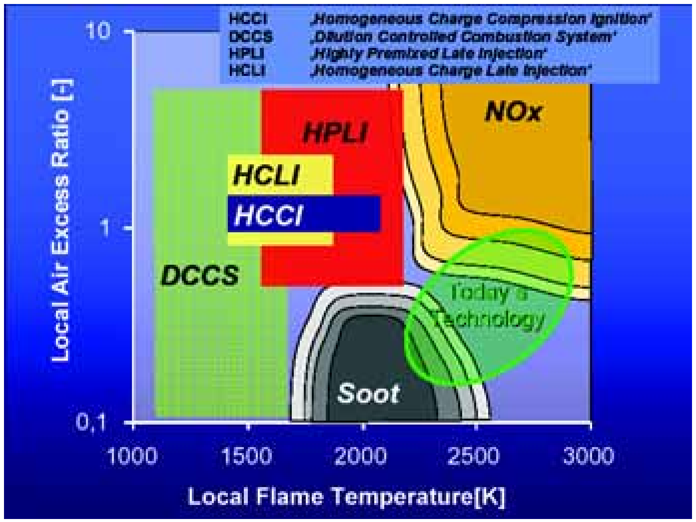
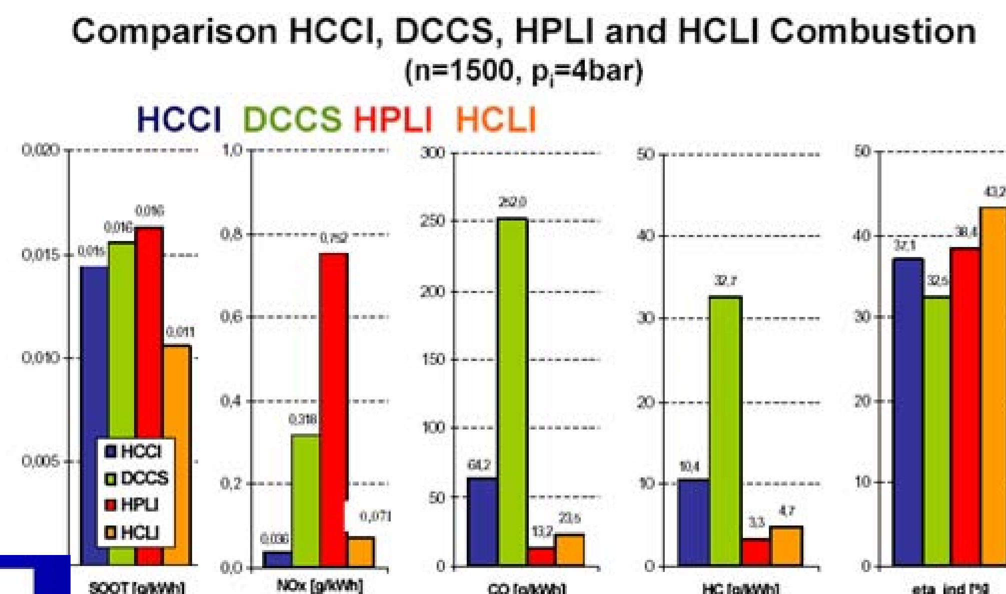
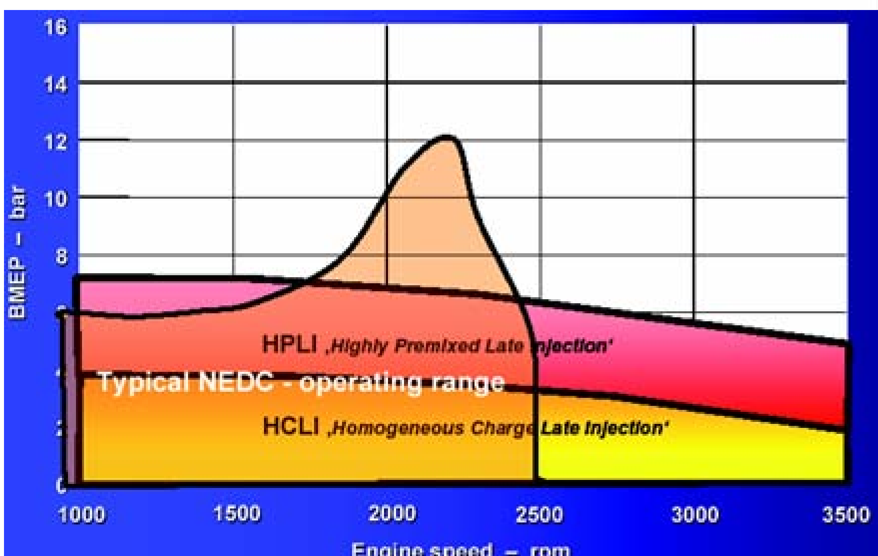
Alternative combustion strategies are moving forward and delivering T and HCs when needed

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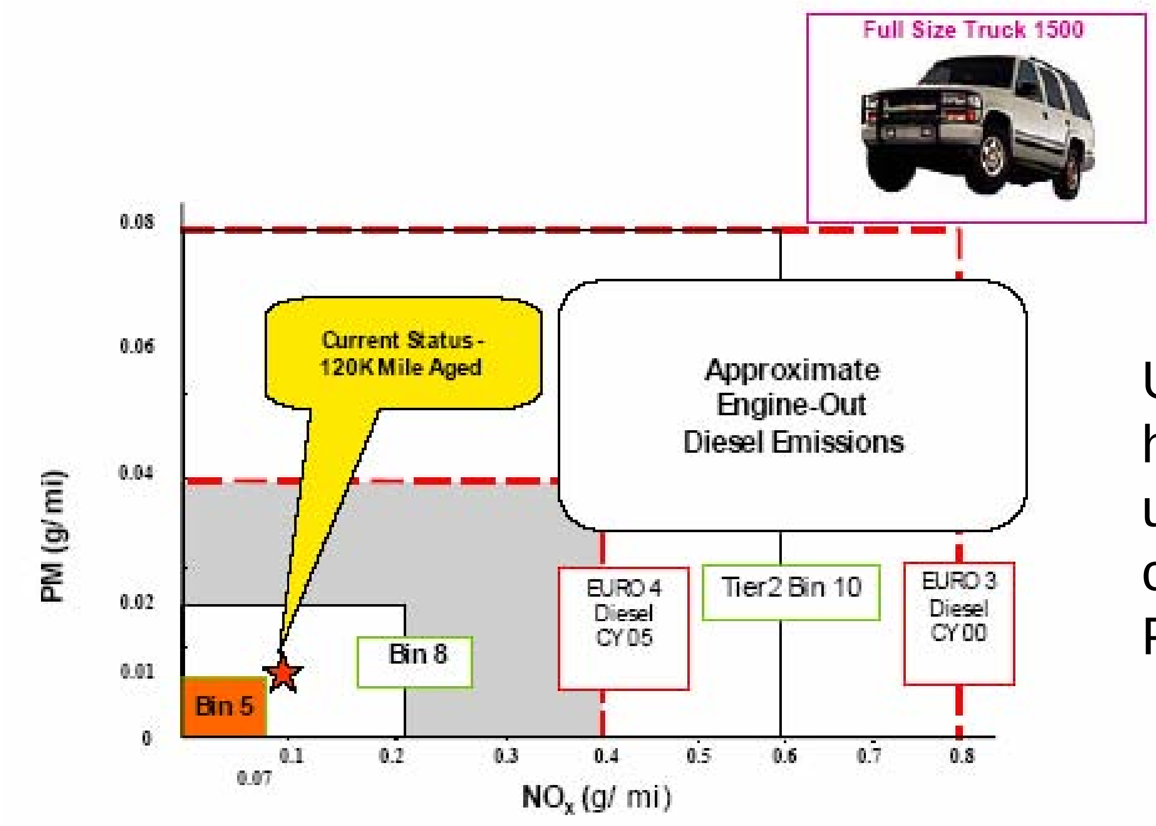
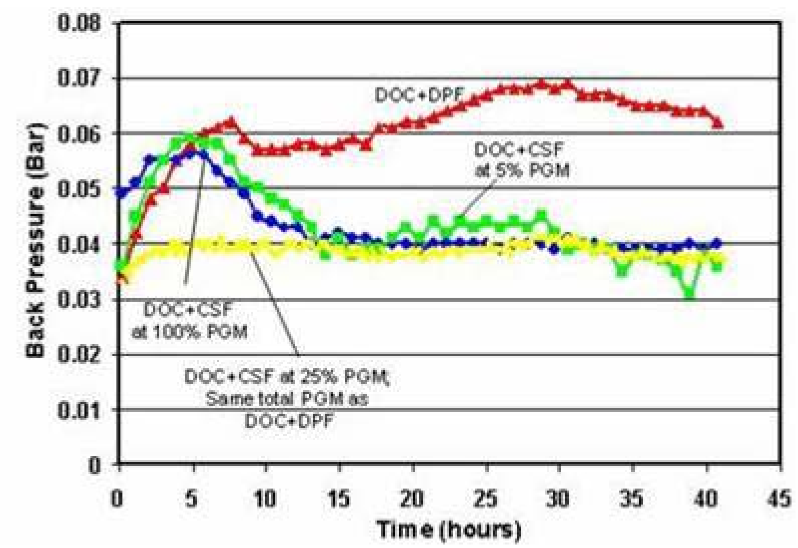
A prototype system is near Bin 5 at 120,000 miles for a LDT

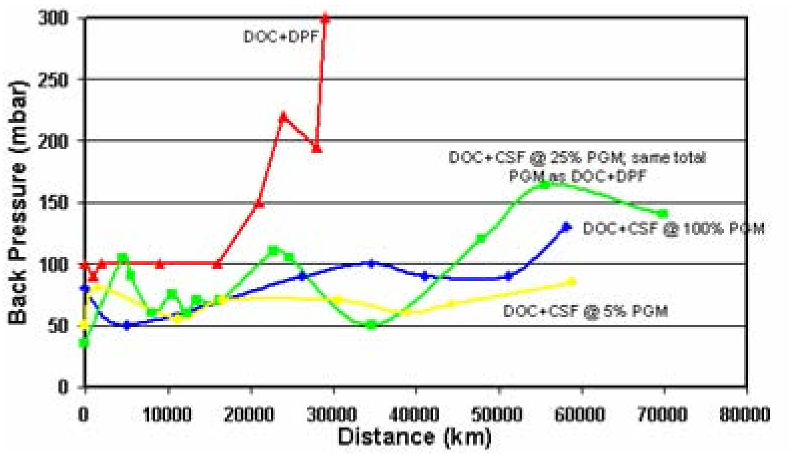


US FTP Bin 5 can be hit, engine-out only, using advanced combustion strategies. Platform unknown.

New DPF catalysts formulations are dropping PGM levels



JMI, SAE 2004-01-0072



On-road performance of low-PGM filter systems shows stable backpressure. 50% of time >220C; 30%>250C, 10%>270C;

System	Oxicat	Filter
CR-DPF	18.5 liters	17 liters
Oxicat + CSF @ 100%	4.25 liters	17 liters
Oxicat + CSF @ 25%	4.25 liters	17 liters
Oxicat + CSF @ 5%	4.25 liters	17 liters

10 liter bus engine

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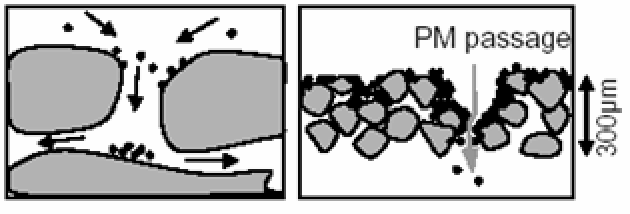
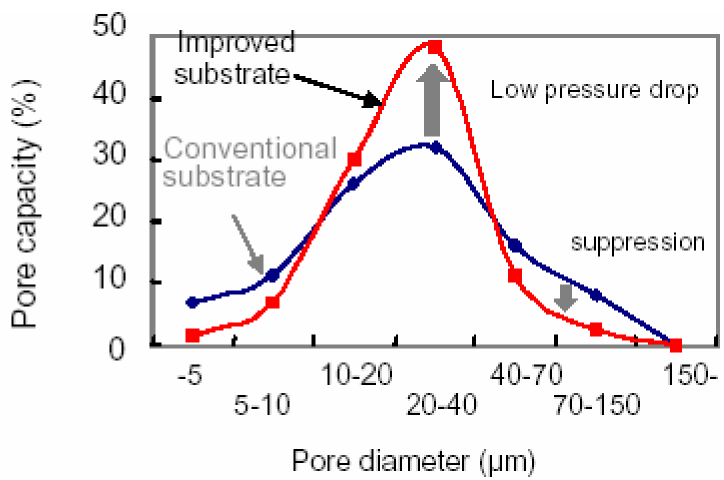
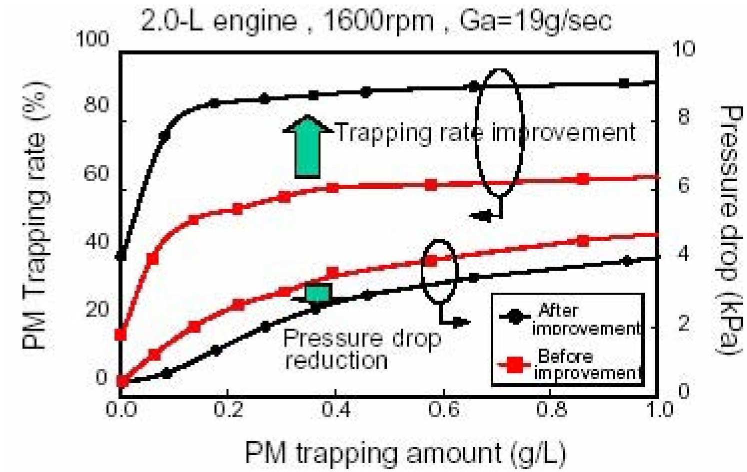
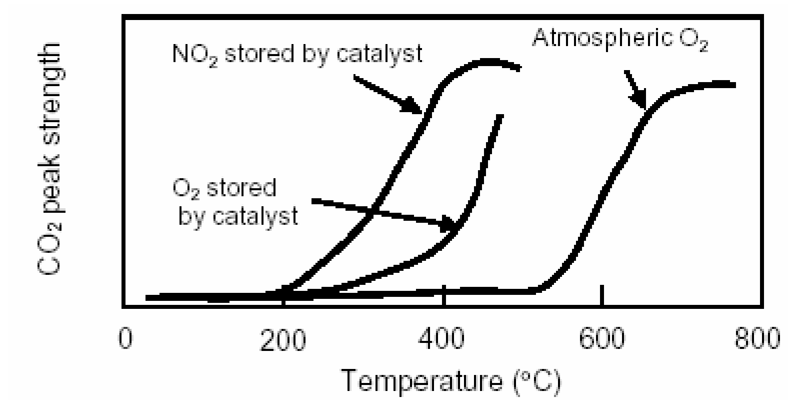
DPNR catalyst is improved



High PM emission can occur at large pores (right). Many small pores gives low pressure drop and high efficiency (left).







New catalyst coating method drops back pressure by 25%

Toyota, SAE 2004-01-0577

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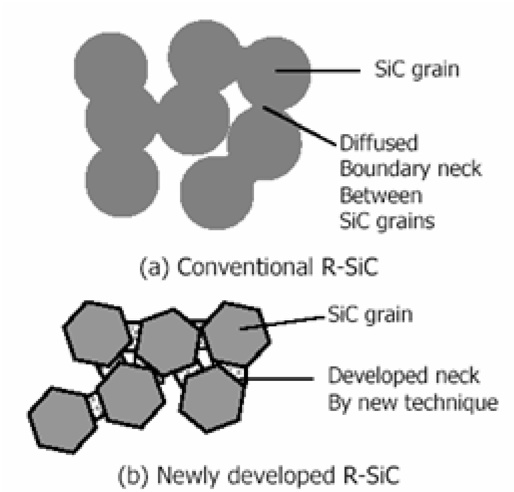
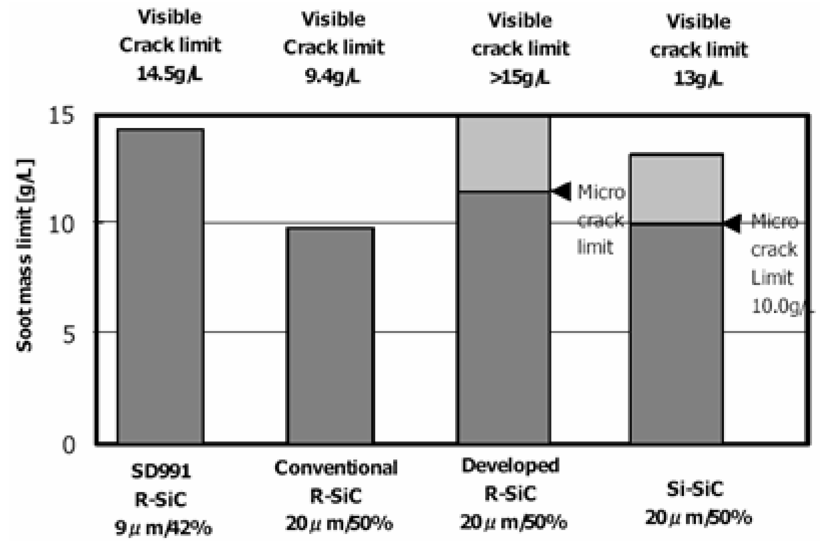
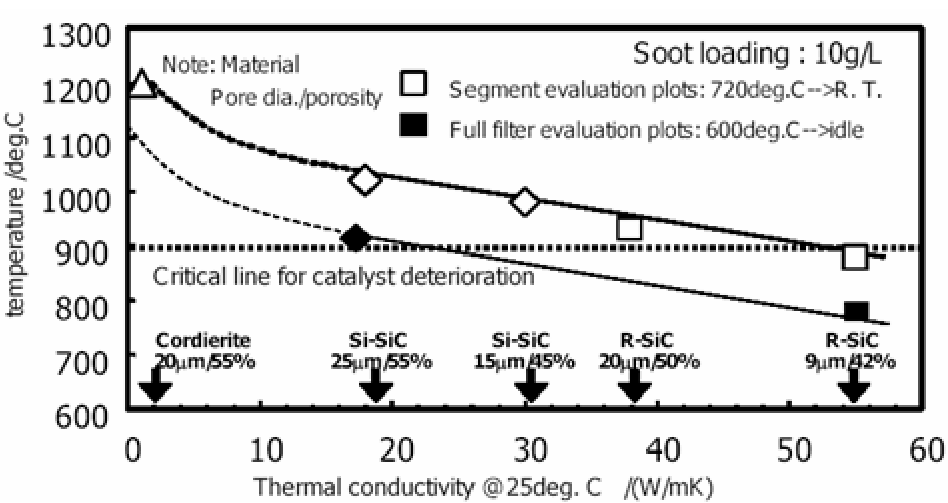
New SiC DPF composition has improved durability



SiC DPFs are improved by increasing bonding region of grains.



New material has same soot load capacity as original, while maintaining favorable porosity characteristics.



Ibiden SAE 2004-01-0954

Maximum temperature during regeneration is largely dependent on thermal conductivity for similar thermal masses. For reference, new Si-SiC at 10 micron/45% has conductivity of 40 W/mK (NGK 2004-01-0951)

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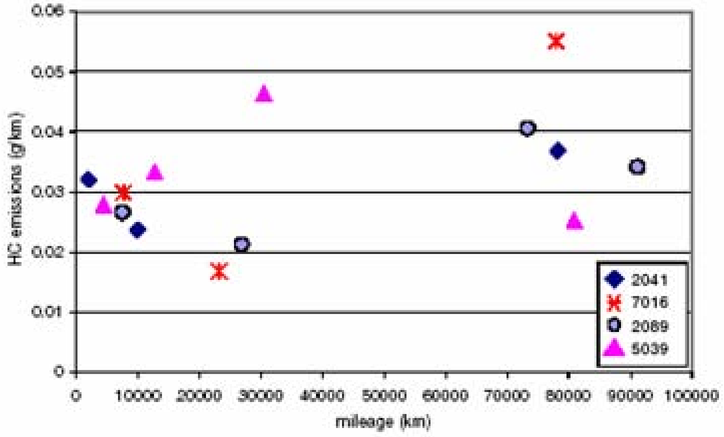
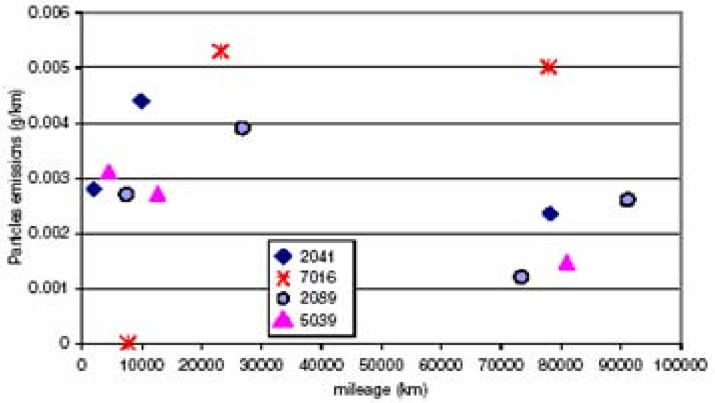
Results on PSA taxis with DPFs at 80,000 km are reported

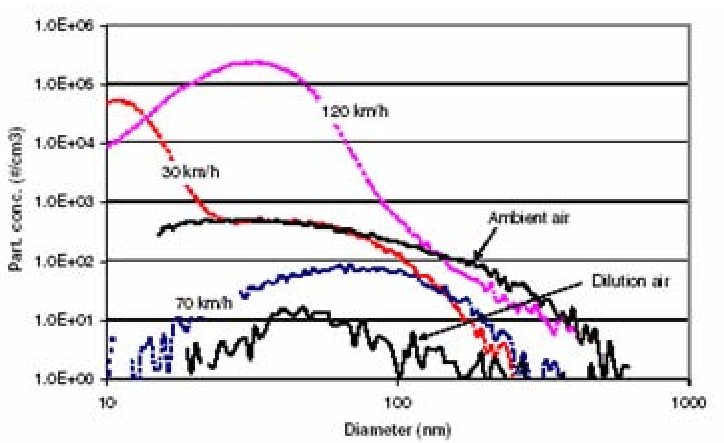
PSA, IPF, SAE 2004-01-0073



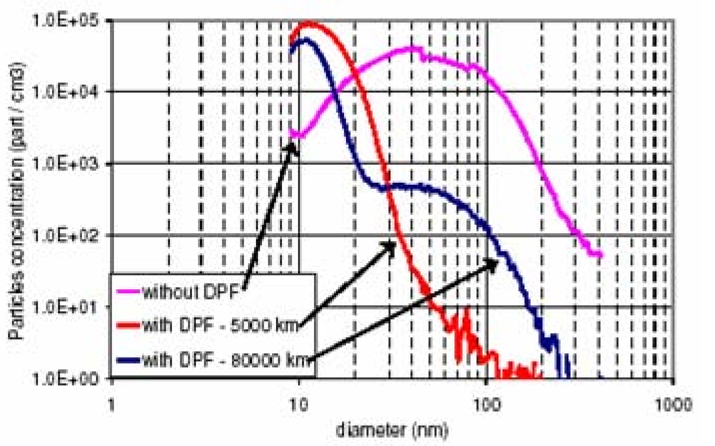
HC emissions go up marginally with aging



CO emissions are constant with aging



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.

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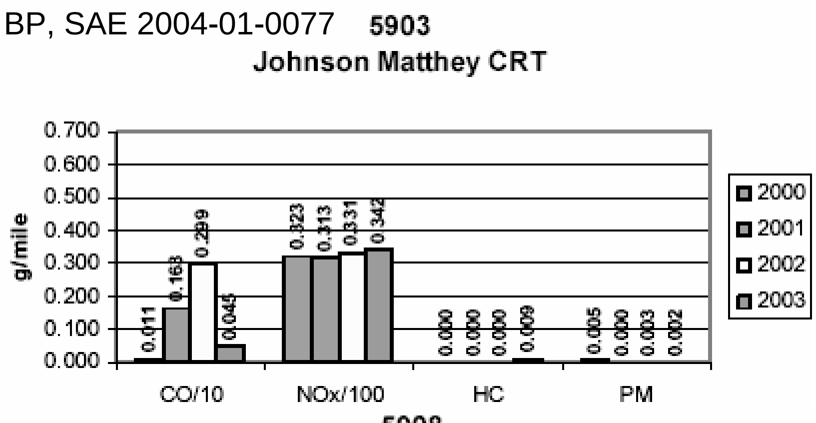
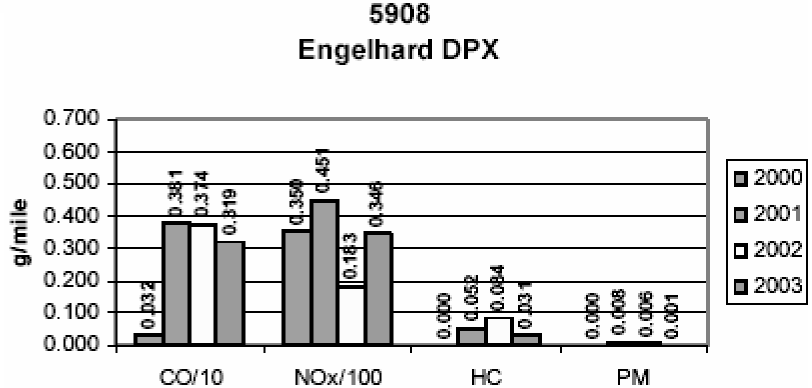
Cordierite DPFs retrofitted onto delivery trucks show good performance out to >360,000 miles

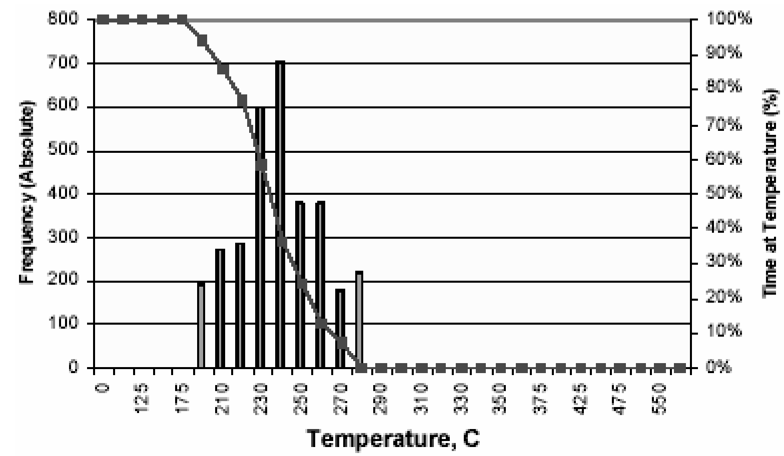
BP, SAE 2004-01-0077



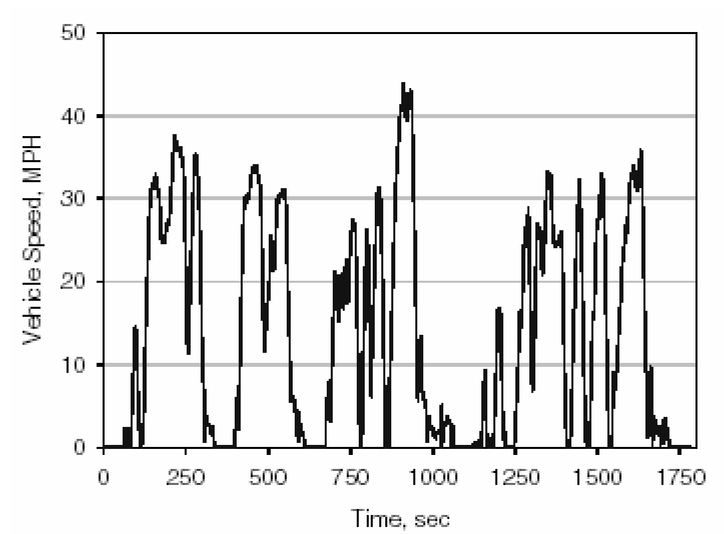


Two common filter systems still perform well after >360,000 miles of duty in a regional class 8 delivery truck

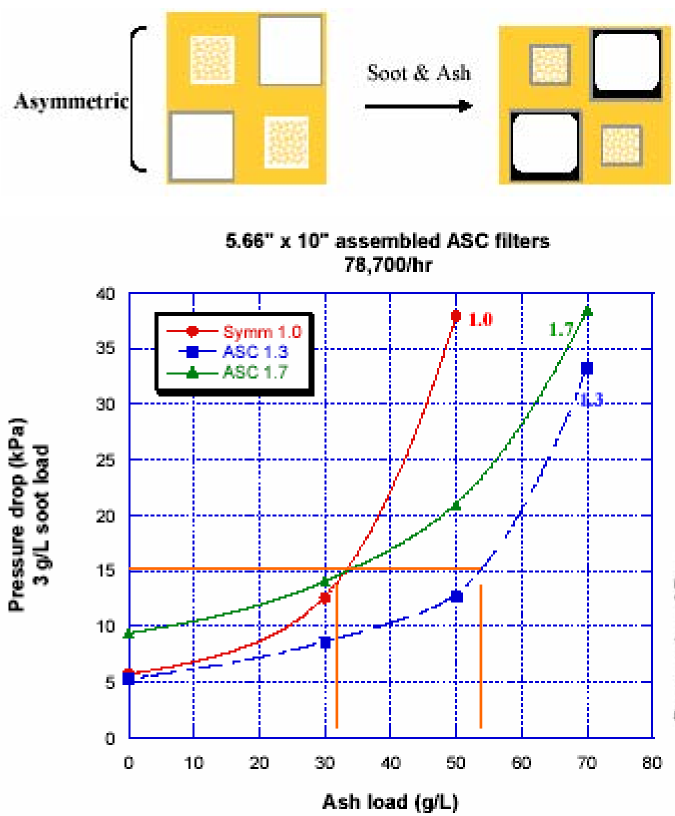
NO FUEL PENALTIES, NO BACK PRESSURE BUILD-UP OVER THE USE OF THE FILTERS



Exhaust temperature profile during emission testing for the truck on the cycle below.

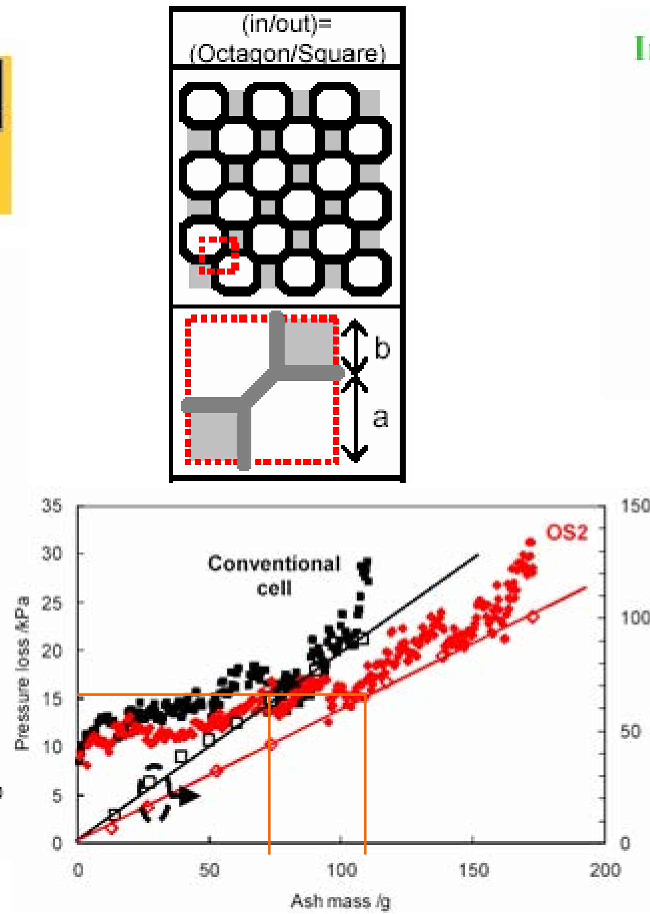


Three new filter cell geometries increase ash loading capacity by 50%. Pressure drop in exit cell limits improvement.



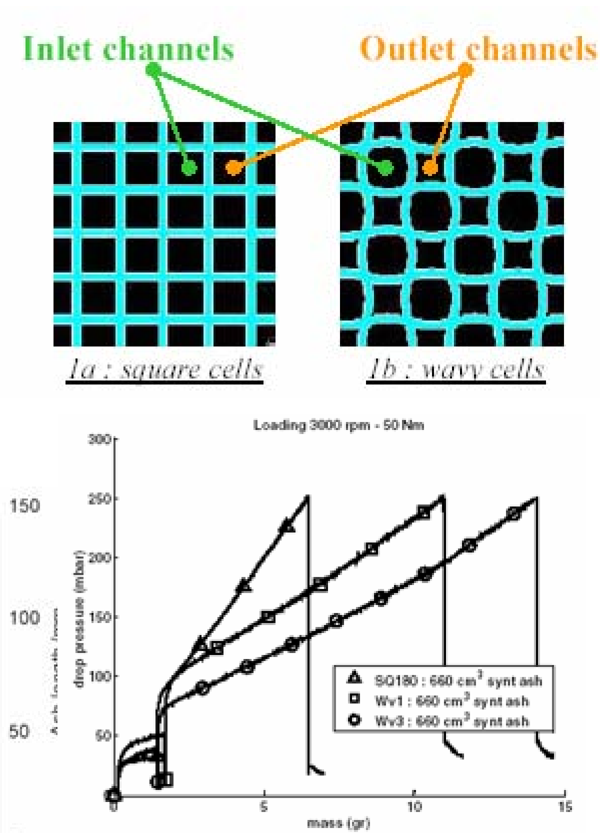
Ash capacity for asymetric square cells increases 50 to 60% relative to std. geometry.

Corning SAE 2004-01-0948



Octasquare geometry offers 50% improvement in capacity

Ibiden, SAE 2004-01-0949



At 7 g/l soot loading and constant ash loading, Wv3 has 50% lower back pressure (50% higher ash capacity).

St. Gobain SAE 2004-01-0950

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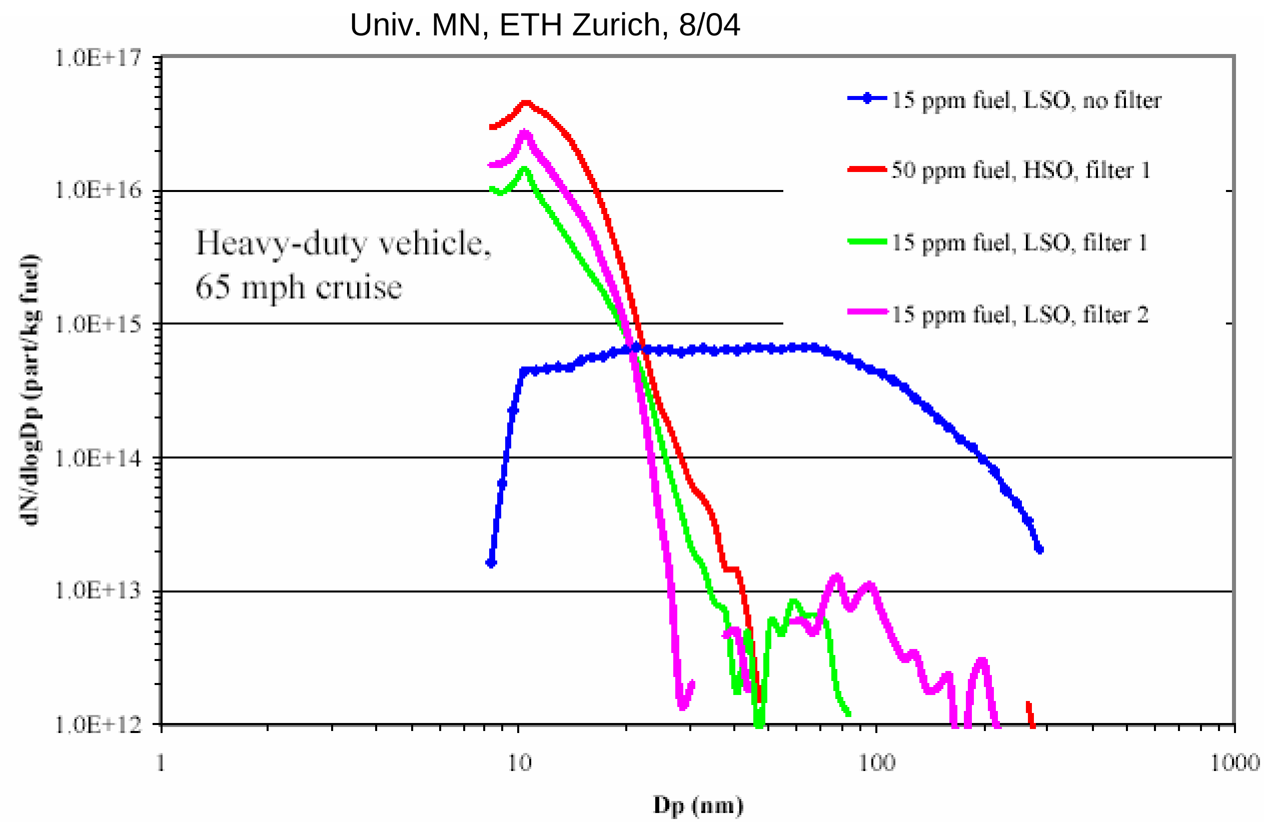
C-DPFs with ULSD and low-sulfur oil still generate aerosol nanoparticles under some conditions. Thought to be sulfuric acid, which is easily buffered in the lung.



Another secondary emission: NO_2

- Issue mainly for retrofits
- Quantification of issue being determined (CARB working group)
- Solutions exist or are in the works

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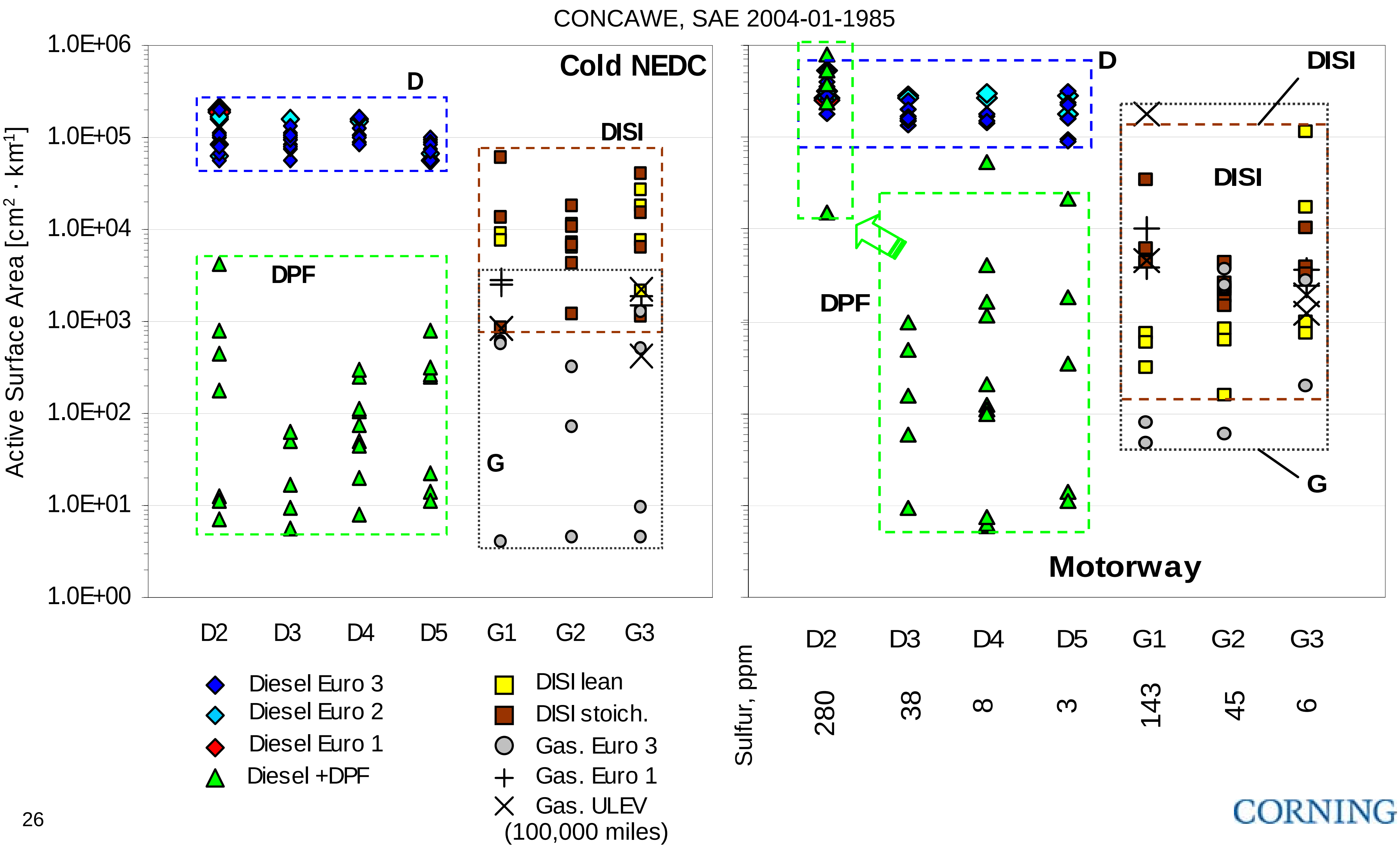
The active surface area of ultrafines from LDDs with DPF is generally lower than for aged ULEV gasoline



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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

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%	1-1.5% urea or about **0.6 to 1%** in US2010	1.5 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.

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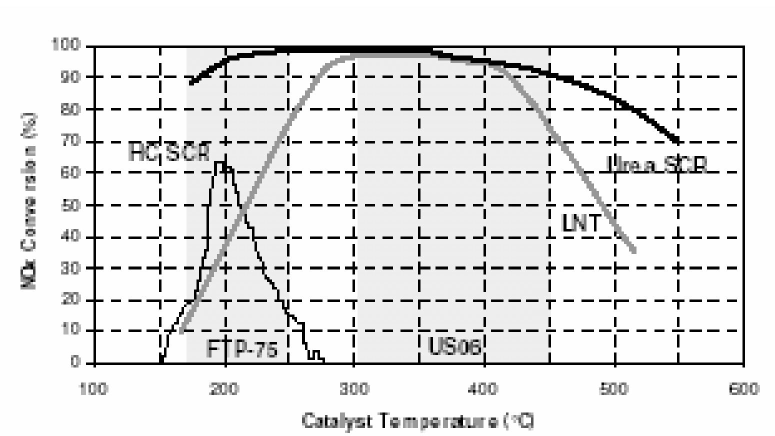
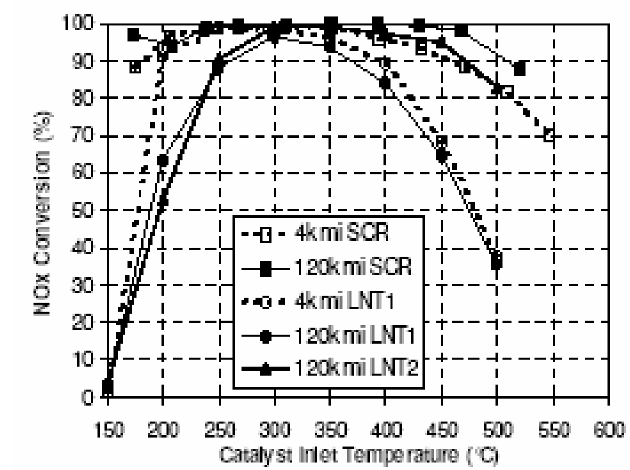
Technical merits of LDD SCR and LNT are compared. Cost issues are central.

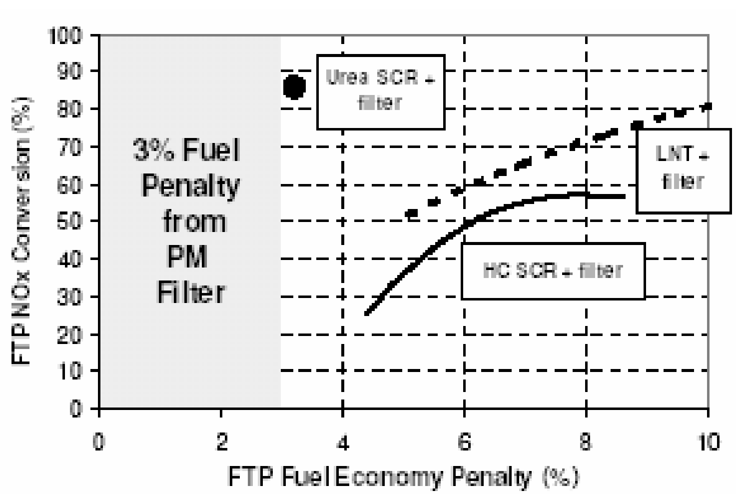


SCR has a wider temperature operating range than LNT. Model gas work on slightly aged samples. SCR NOx is NO+NO2. SVR for LNT and SCR = 1.

Ford SAE 2004-01-1292



SCR has better thermal durability than LNT. Hydrothermal aging of SCR. Desulfation aging of LNT.



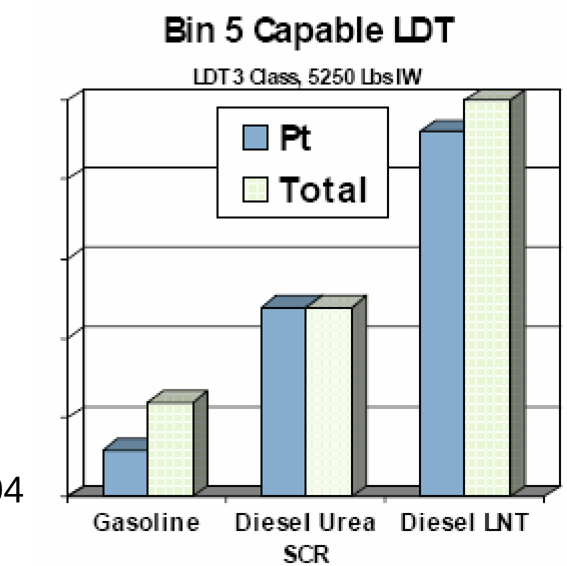
LNT fuel penalties are higher than SCR

Green house gases:

SCR: 2.2% CO_2 penalty

LNT: 7.8% CO_2 penalty

GM Vienna 4-04



SCR

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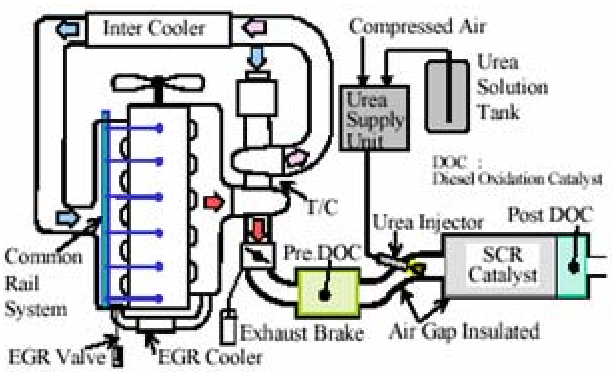
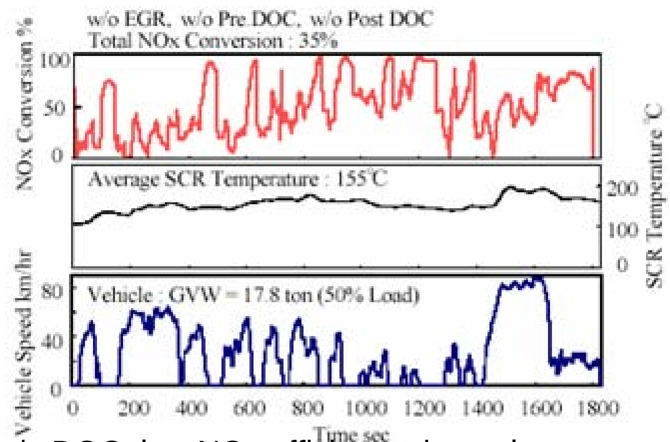
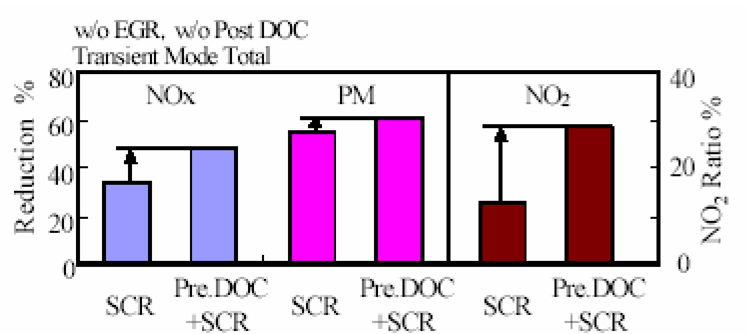
Low temperature SCR NOx conversion is obtained using DOC to generate NO2 and exhaust brake for temperature control



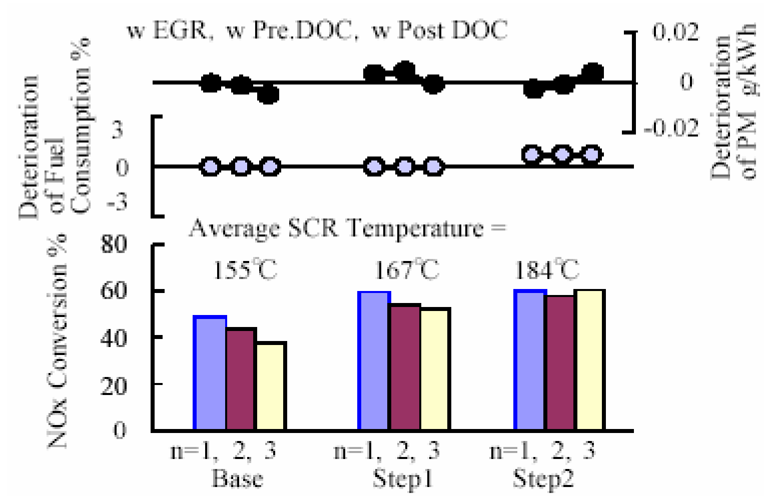
12.9 liter engine; SCR=53.4 l (SVR=4.1)



w/o DOC, low NOx efficiency due to low temperatures



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



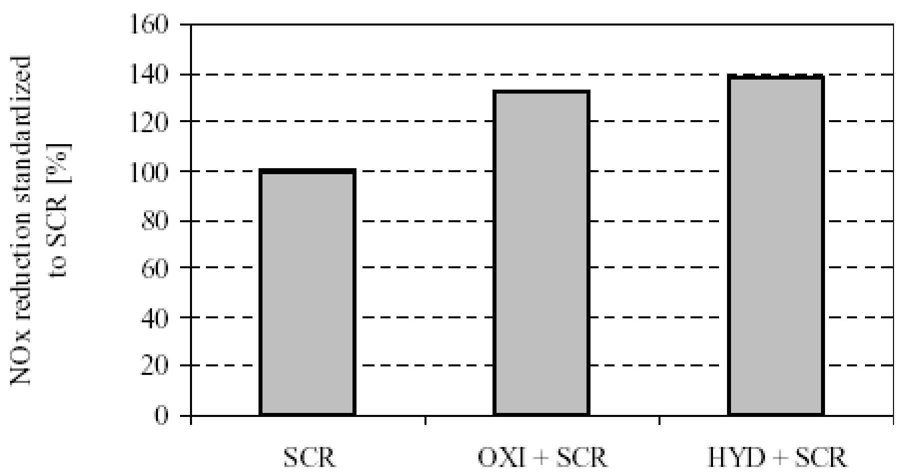
Mitsubishi FUSO SAE 2003-01-3248

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

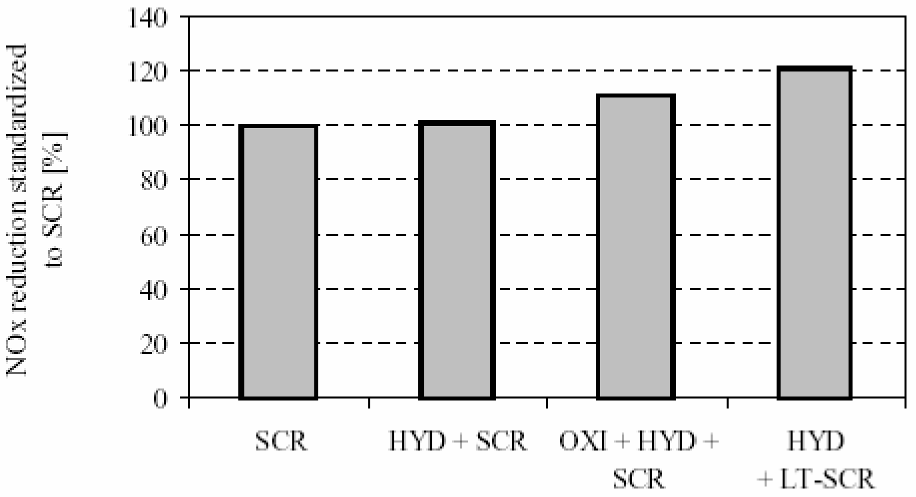
CORNING

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

J05 Transient Test – Cold Start



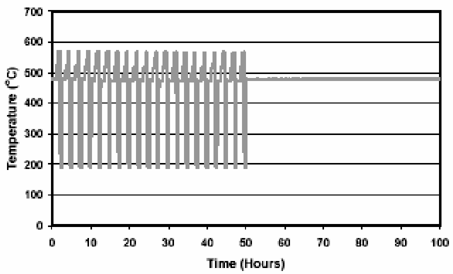
J05 Transient Test – Hot Start



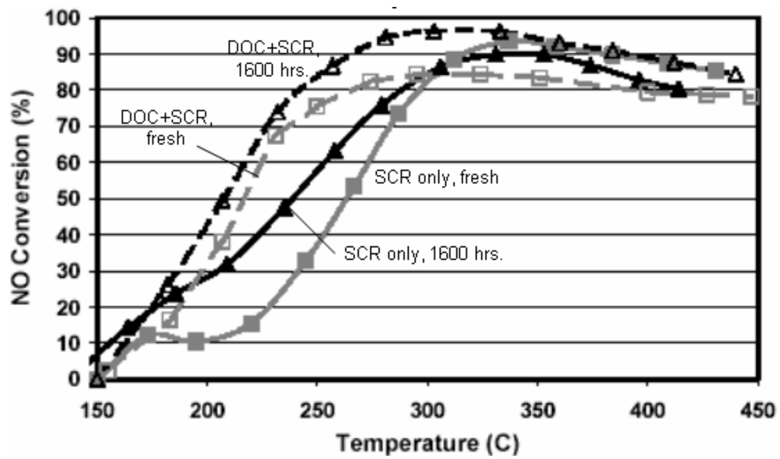
Under cold conditions, oxicats convert NO to NO2, which aids LT reduction, and urea hydrolysis catalysts aid urea decomposition at about 160C. 70% NOx efficiency is attained. At higher temperatures, performance is marginally improved.

Argillon, FISITA 6/04

A new coated SCR system is reported that has impressive durability



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=0.85; Aging to simulate 1.2 million km lube oil and 300,000 km driving up to 550C

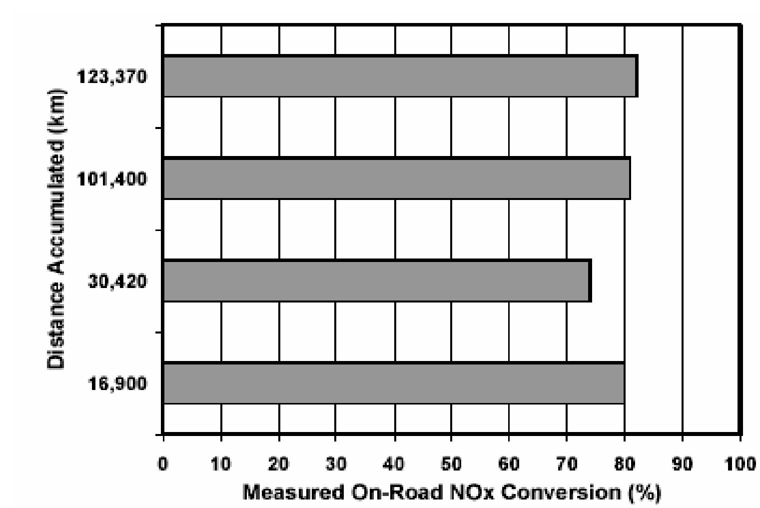
ECS test results on lube oil aged catalysts

System	NOx Emissions (g/kW-hr)	Conversion (%)
Engine-Out	7.682	---
SCR Only: Fresh	1.367	82.2%
SCR Only: Aged 400 Hours	1.483	80.7%
SCR Only: Aged 1,600 Hours	1.867	75.7%
Oxicat + SCR: Fresh	0.614	92.0%
Oxicat + SCR: Aged 1,600 Hours	1.144	85.1%

JMI SAE 2004-01-1289

Component	Dimensions	Volume
CR-DPF DOC	12" x 6"	11.0 litres
CR-DPF Filter	12" x 15"	27.5 litres
SCR	4 off 9.5" x 6"	27.8 litres
Clean-Up Catalyst	2 off 9.5" x 4"	9.2 litres

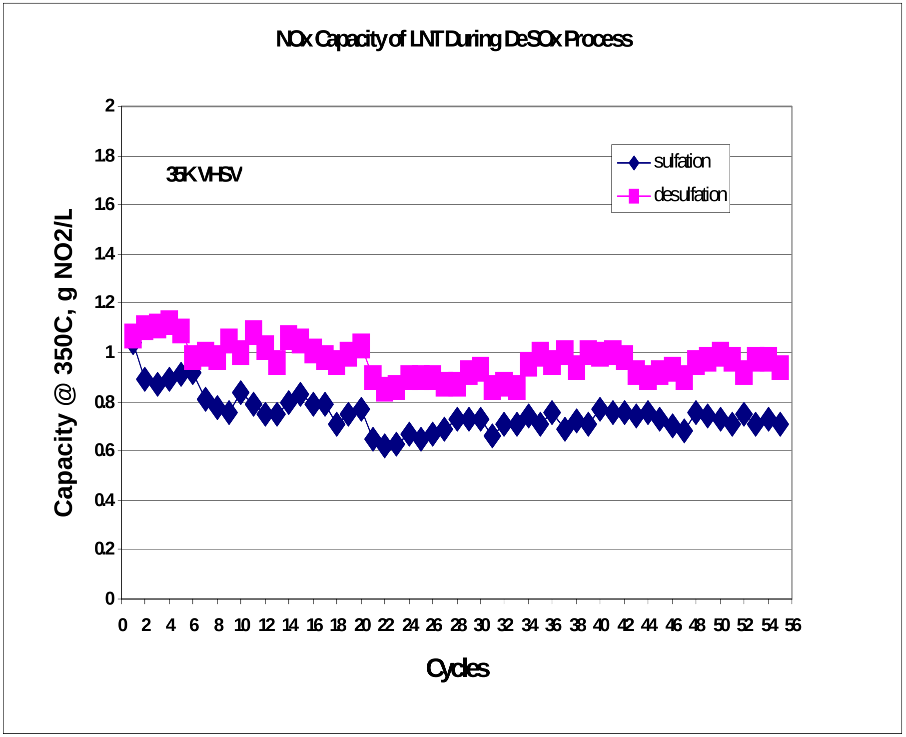
For road test: 15 liter Cummins ISX; SVR: DOC=0.73, DPF=1.83, SCR=1.85

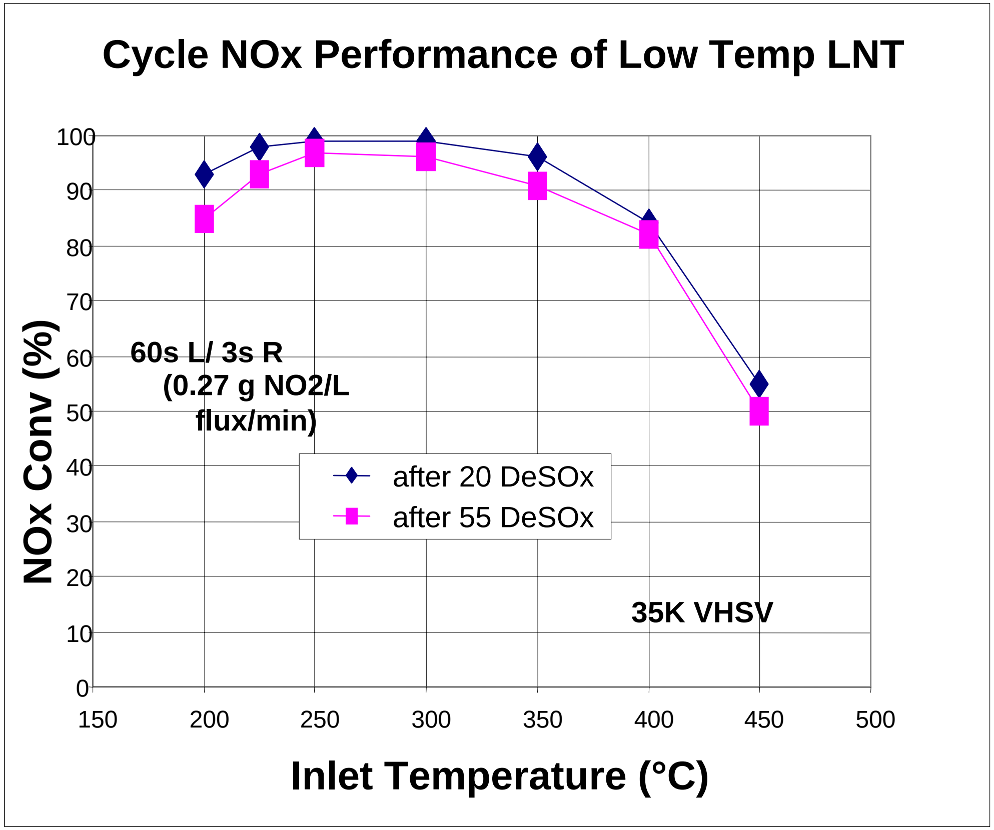


High efficiencies obtained with NH3/NOx=0.85; 50% time >310C

Lean NOx Traps

LNTs are becoming more tolerant to sulfur

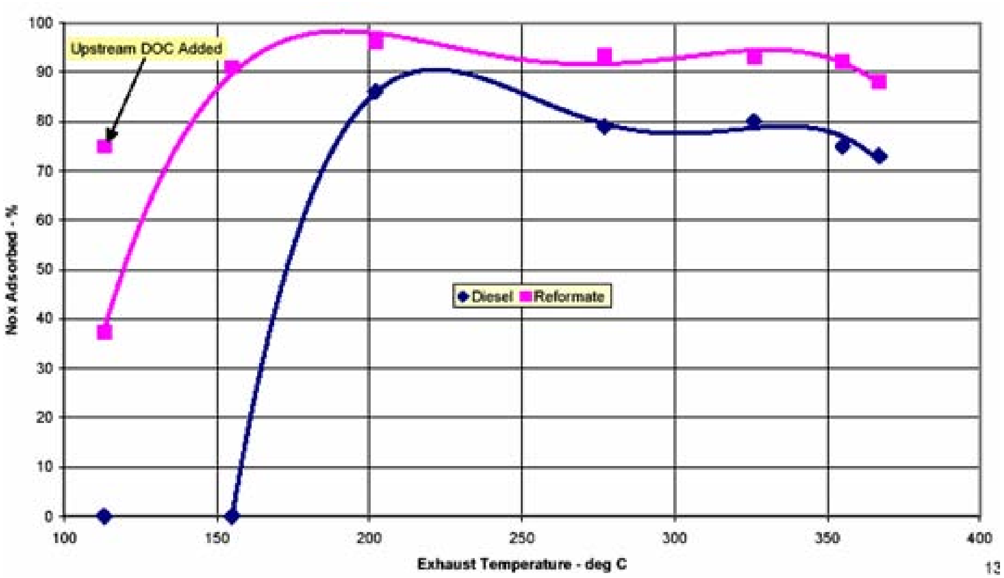




Engelhard, AVECC 2004

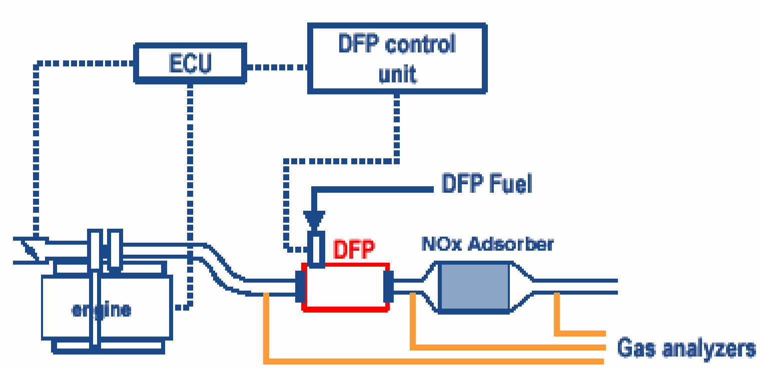
Hydrogen/CO reformate significantly improves LNT performance

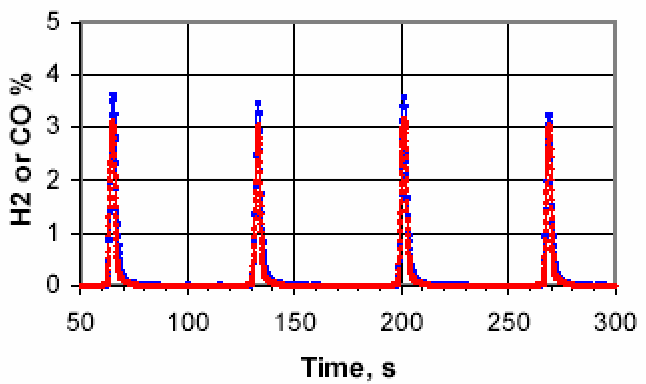
Plasma reformer uses 250W to form 9% H_2 and 14% CO from 35 kW of fuel; w/ DOC:20% H2



ArvinMeritor SAE 2004-01-0582

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





Catalytica SAE 2004-01-1940

Lean NOx Catalysts

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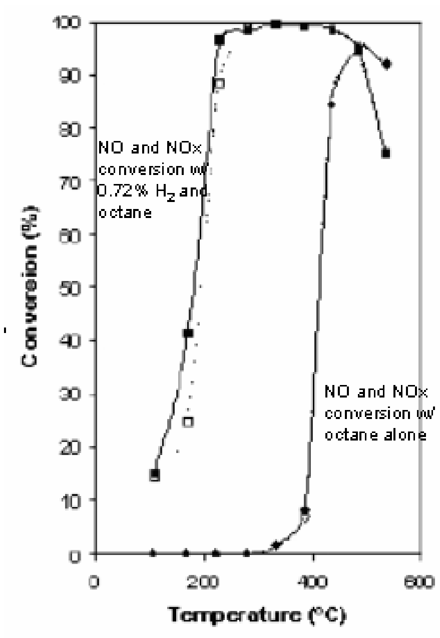
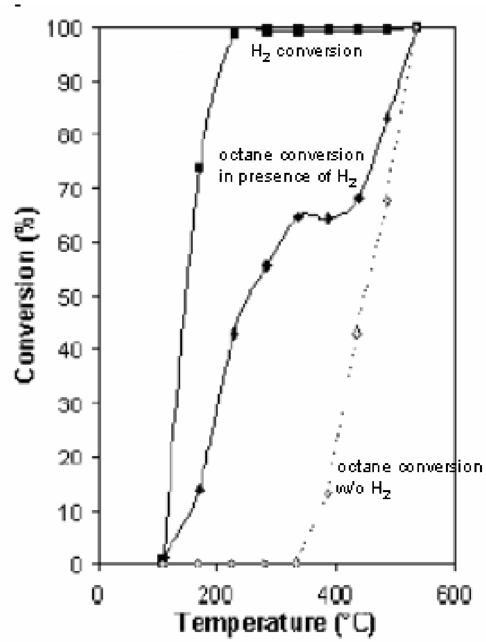
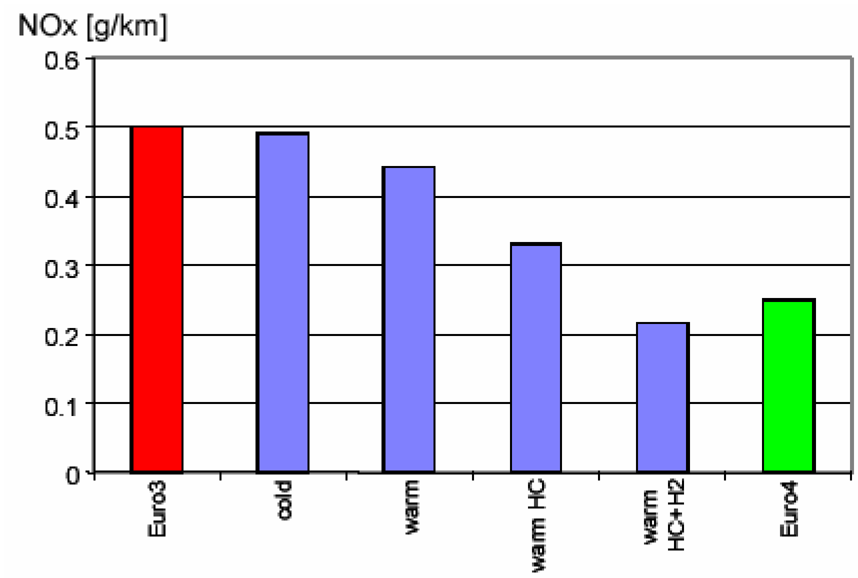
Discovering Beyond Imagination

Small amounts of hydrogen significantly enhance Ag/Al_2O_3 LNC performance







Small amounts (0.75%) of hydrogen significantly enhance HC utilization with Al/Al_2O_3 LNCs (right). NOx conversion efficiencies are hence enhanced.

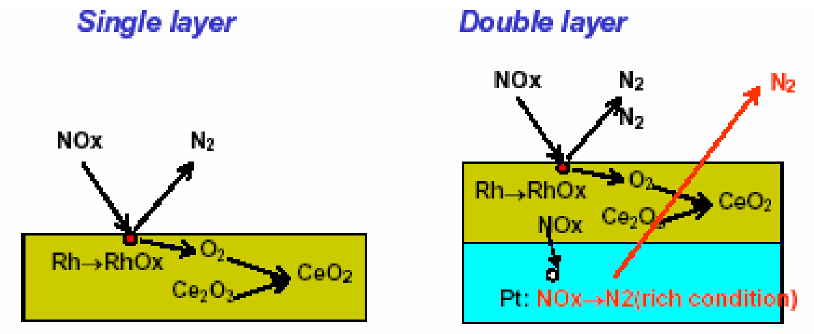
ETC on HD diesel engine test shows hydrogen synergy. 27% hot efficiency w/o, 50% efficiency with 0.25% hydrogen. SVR = 3 to 4

- 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

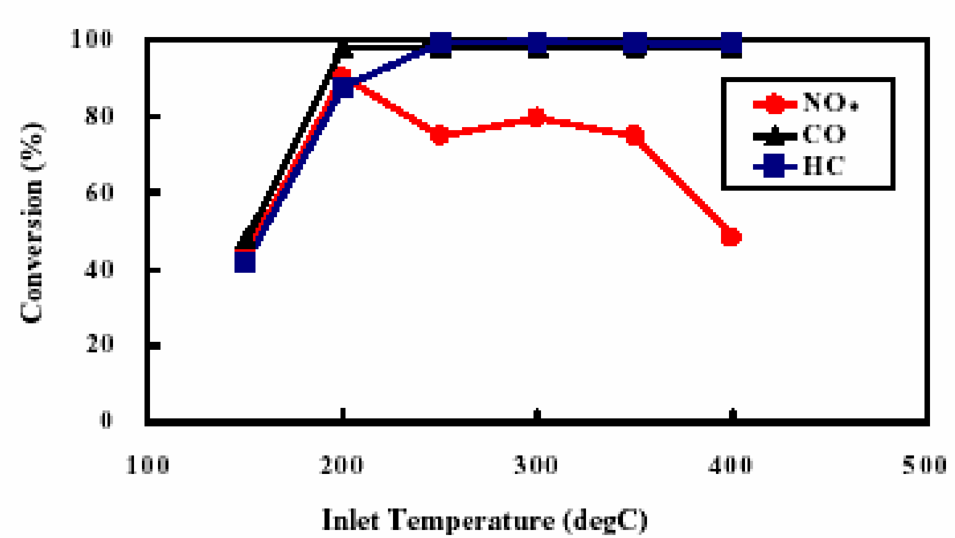
CORNING

A new LNC with double layer is reported; run like a LNT, uses oxygen storage mechanism to dissociate NOx

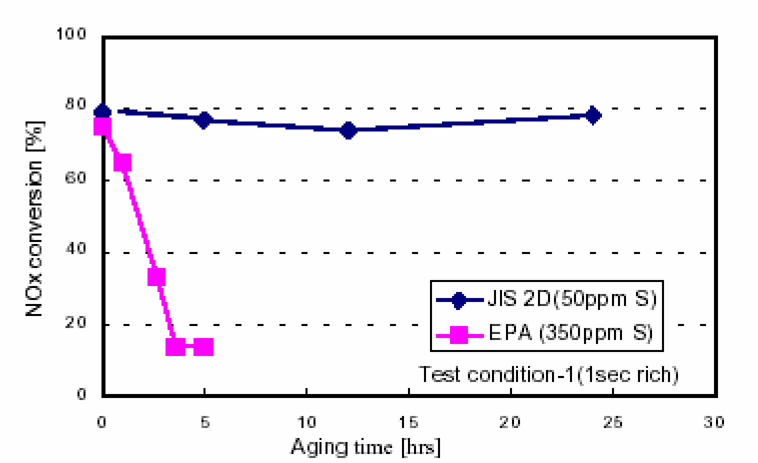


Single layer:
- oxygen from NOx is stored in oxygen storage medium
- some NOx is also stored; periodic rich to release oxygen, releases NOx

Double layer:
- underlying TWC react NOx during rich purge



In model gas work, double layer LNC performs respectfully at 200-350C



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

- 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

Isuzu, SAE 2003-01-3241

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Integrated systems

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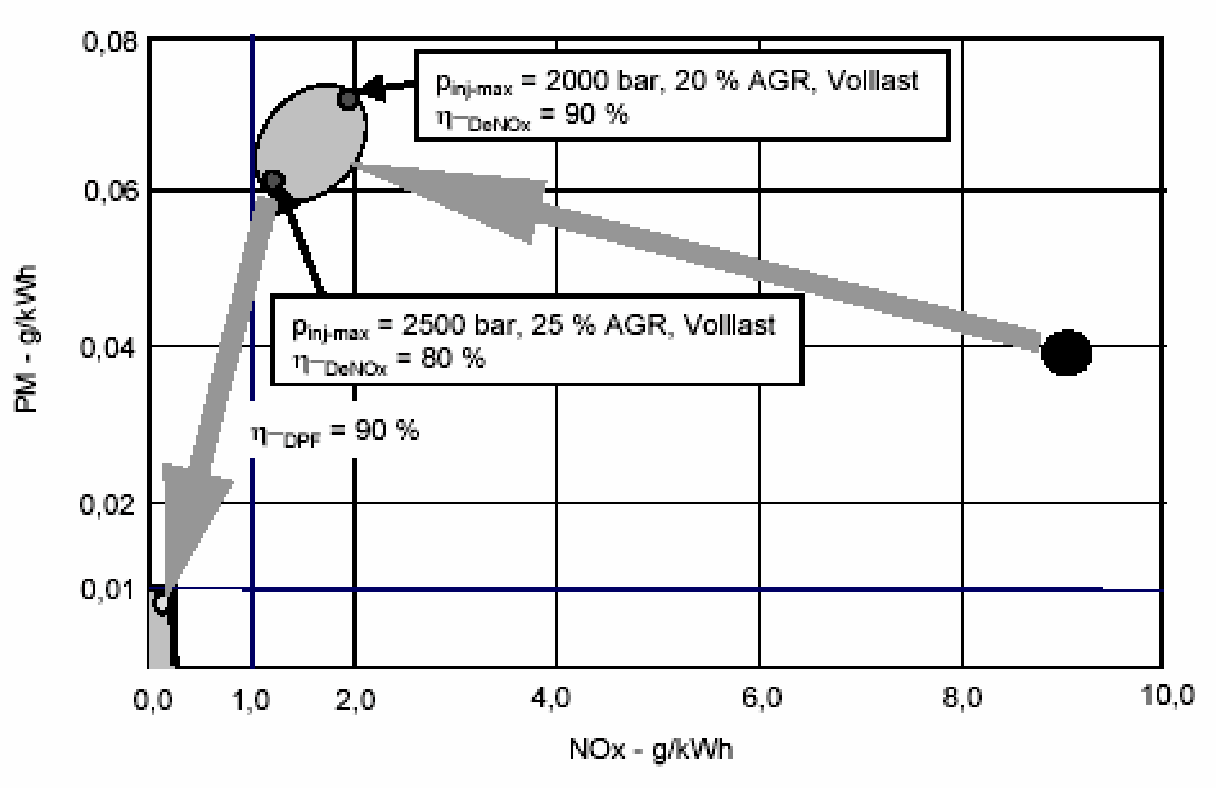
Discovering Beyond Imagination

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.

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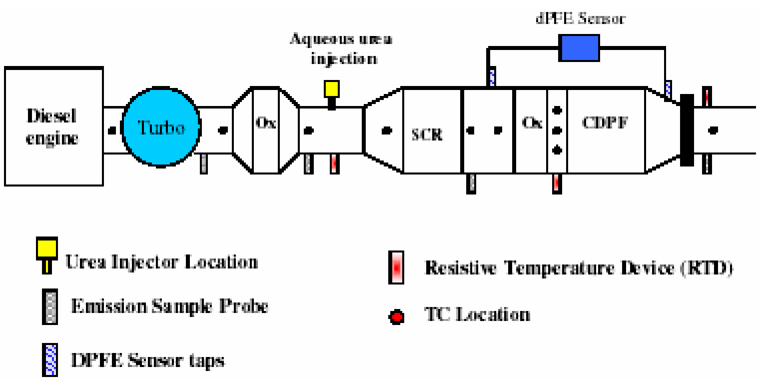
Refinements and further testing are reported on a LDD SCR system. Cold start and HC issues are addressed to hit Bin 5.

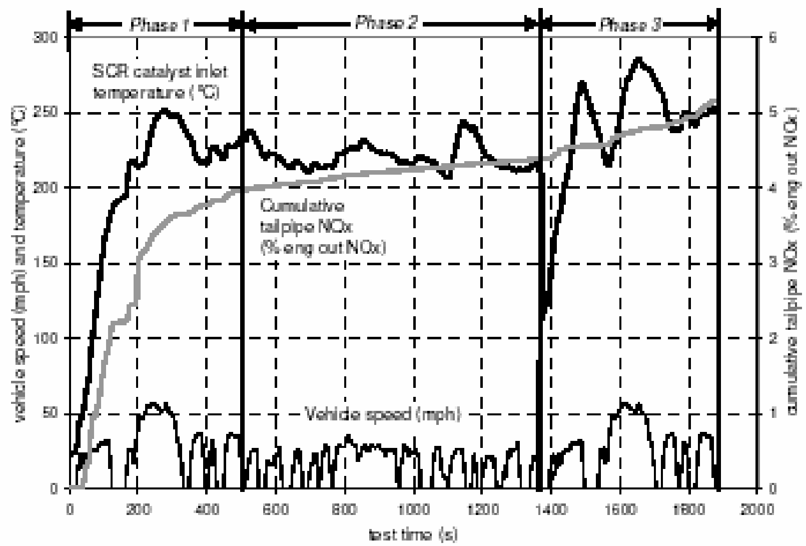


SVR SCR = 2.1 zeolite

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]	

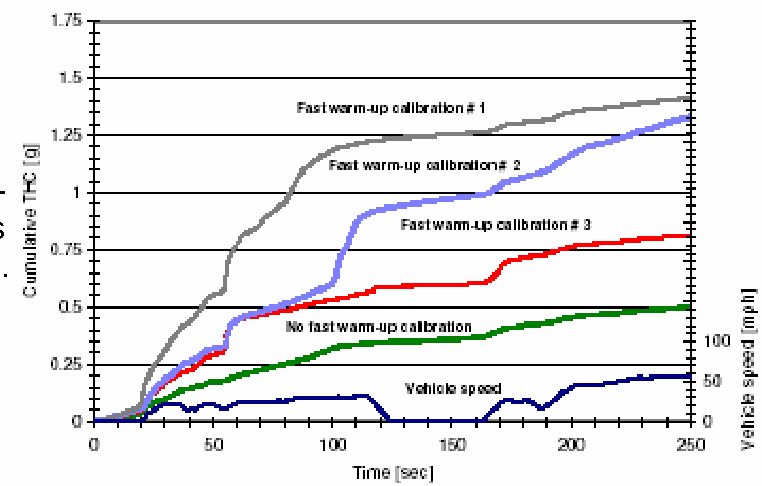
[a] NMOG standard.
[b] PM standard at 120k mi.

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.



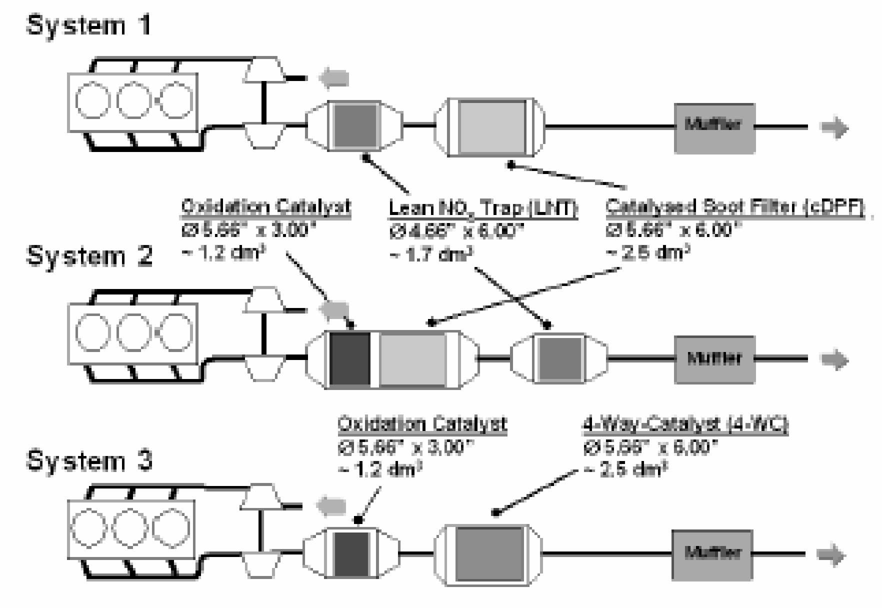
In LDD with fast heat-up SCR, 80% of NOx is emitted in Bag 1.

Zeolites store HCs. Fast light-off strategy puts HCs into zeolite. This can be minimized with calibration



Ford SAE 2004-01-1291

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



	Oxi-Cat	NO_x adsorber	CDPF	4-WC
Dimension	∅ 5,66" x 3"	∅ 4,66" x 6"	∅ 5,66" x 6"	∅ 5,66" x 6"
Volume	~ 1,2 dm^3	~ 1,7 dm^3	~ 2,5 dm^3	~ 2,5 dm^3
Cell Density	400 cpsi	400 cpsi	200 cpsi	300 cpsi
Wall Thickness	4 mil	4 mil	16 mil	12 mil
Substrate	Ceramic	Ceramic	SiC	Cordierite

	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

AVL ECO TARGET engine is used: 1.2 liter 3-cyl

Improved DPNR system has smaller catalyst, and improved desulfation and soot oxidation strategy for improved fuel economy.

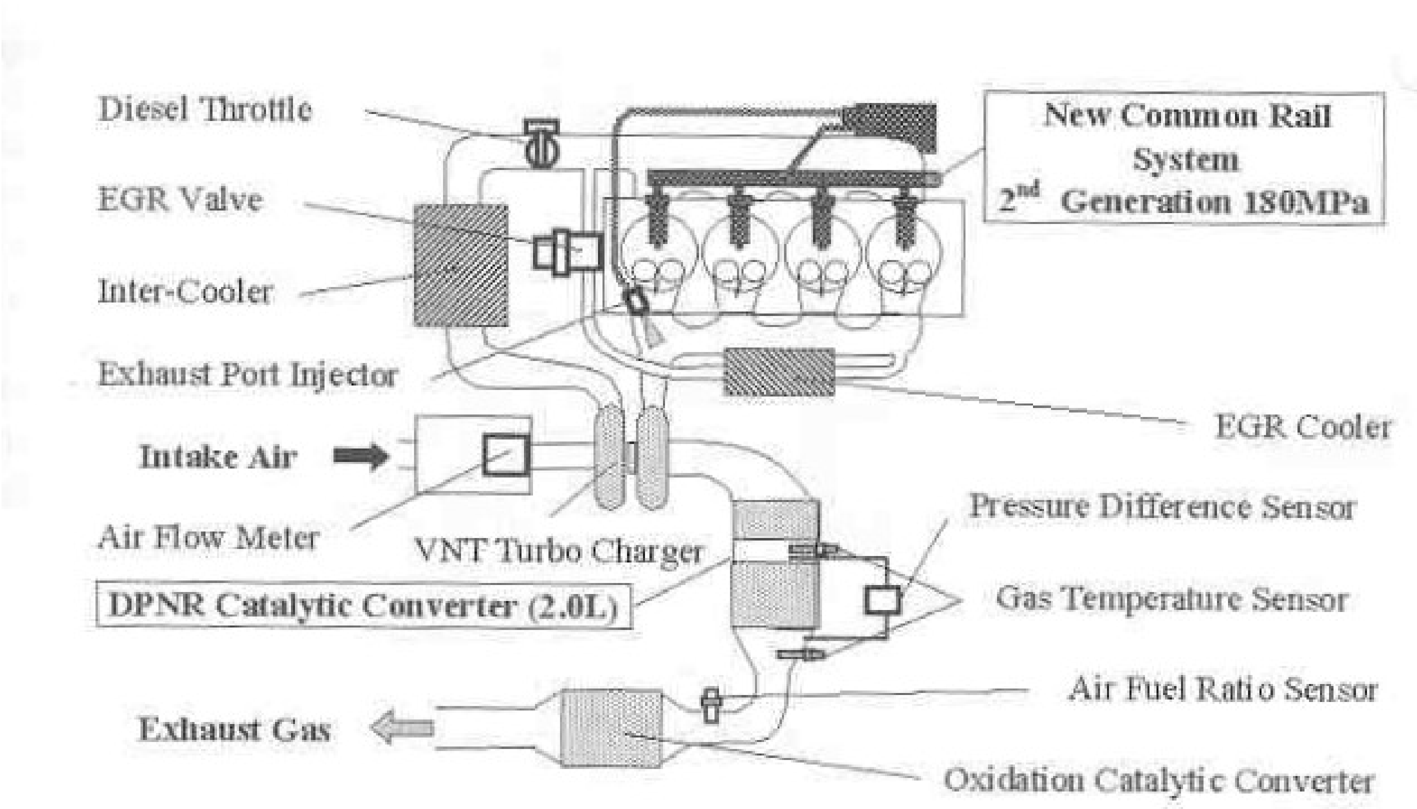
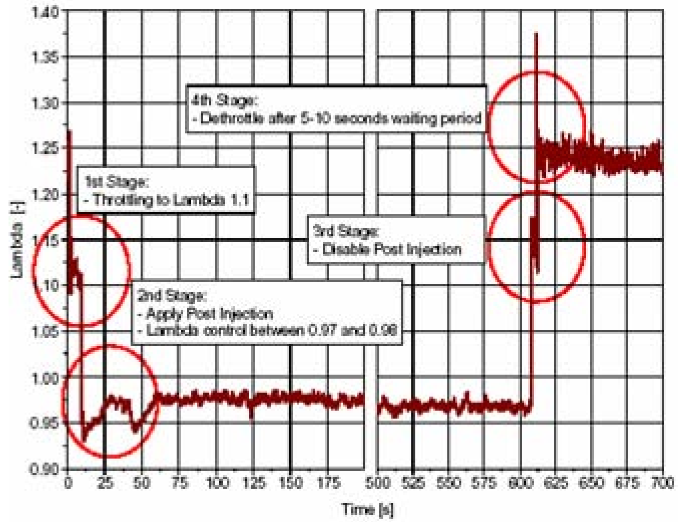


Figure 1: New DPNR system has smaller catalyst size 30% to 2.0 liters (SVR=1), a NOx adsorber up front to increase soot oxidation rate by 20%, improved EGR valve, higher CR pressure from 1350 to 1800 bar, and improved low-temperature combustion strategy (20 to 140 km/hr).

Toyota Aachen Colloquium 10-03

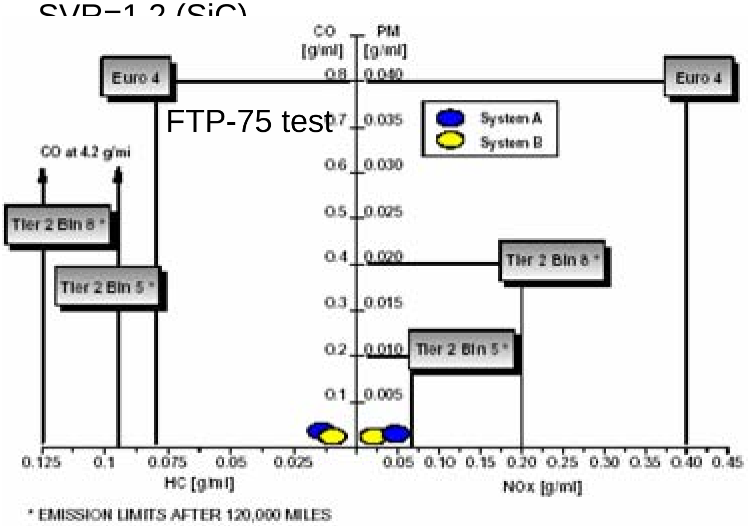
Development of Tier 2 Bin 5 LDD system is described in detail

1.9 liter, 1560 kg vehicle; Precat is 50/50 LNT/DOC in system A, and 100% LNT in B, SVR = 0.7; LNT SVR=1.2; DPF SVR=1.2 (SiC)



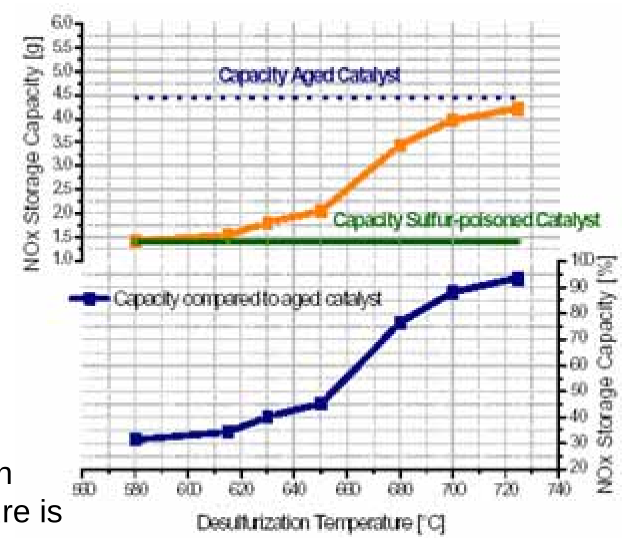
Stepped desulfation strategy minimizes HC slip; 700C for 10 minutes

- retarded injection and throttling used for fast heat-up; 25 sec
- faster idle
- lean/rich strategy development on 9 points of engine map
- Fuel penalty < 5%



FTP-75 test

FEV APBF SAE 2004-01-0581



Minimum desulfation temperature is 700C

Miscellaneous

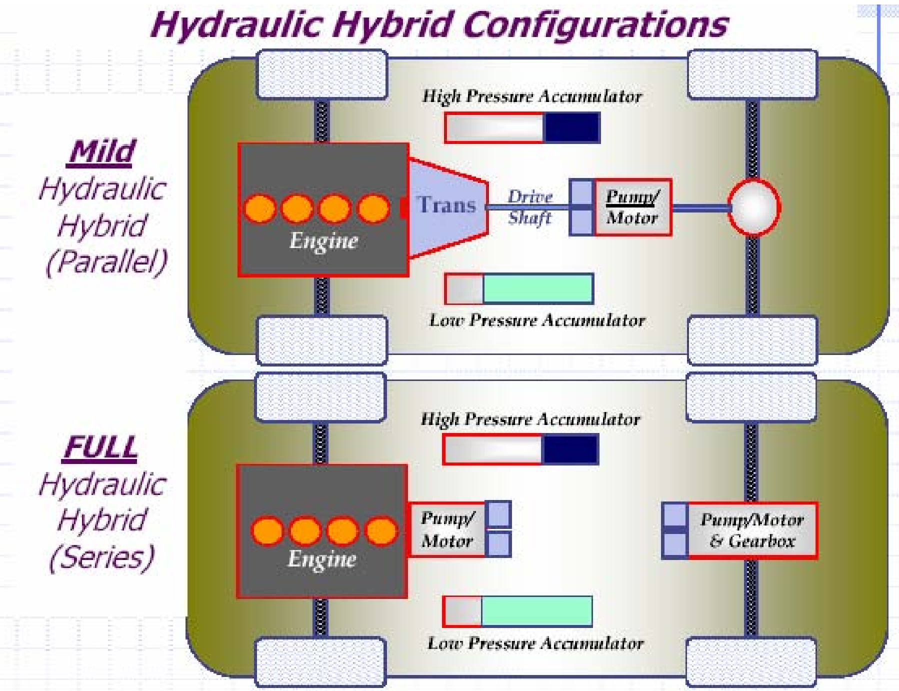
CORNING
Discovering Beyond Imagination

“Convoying” of trucks can save 10 to 15% of fuel

- Study looking at fuel consumption as a function of truck spacing.
- Both trucks benefit at the proper spacing.
- 10 to 15% fuel can readily be saved.

CE-CERT, Univ Calif., Riverside, 2004

A new hybrid technology based on hydraulic storage of energy, not batteries, is gaining interest



Urban Delivery Vehicle - *Full Hydraulic Hybrid*

- First-ever full integrated hydraulic hybrid delivery vehicle, targets 70% mpg improvement in city driving
- 2-year payback has attracted serious attention from fleets
- Partnership involving EPA, Eaton, UPS, OEM & Army
- Announcement later this year

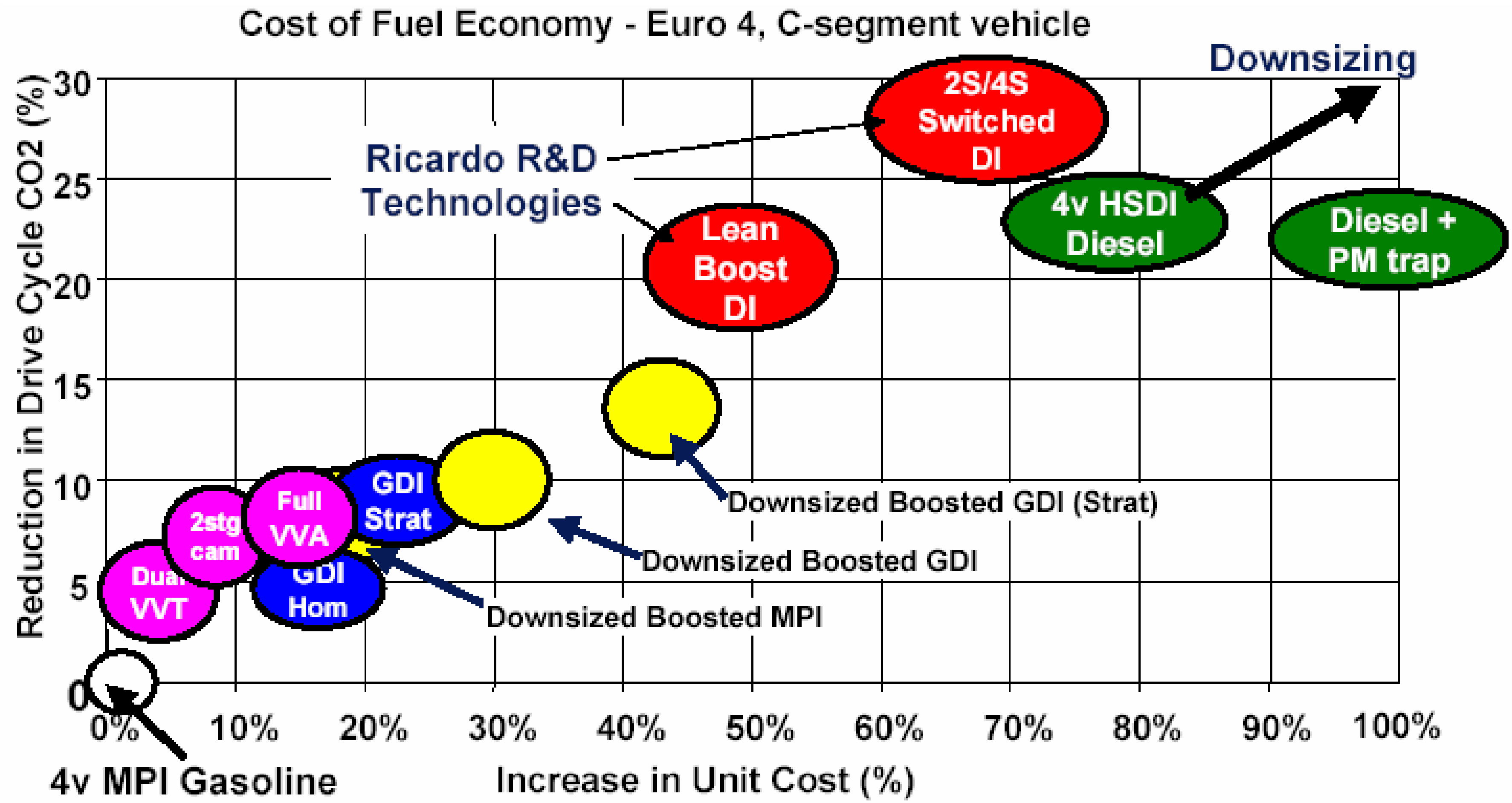
Showcasing full hydraulic hybrid systems in an Urban Delivery Vehicle.

Given that hybridization allows engine to operate at sweet spot and near steady-state conditions → HCCI

epa.gov/otaq/technology

CORNING

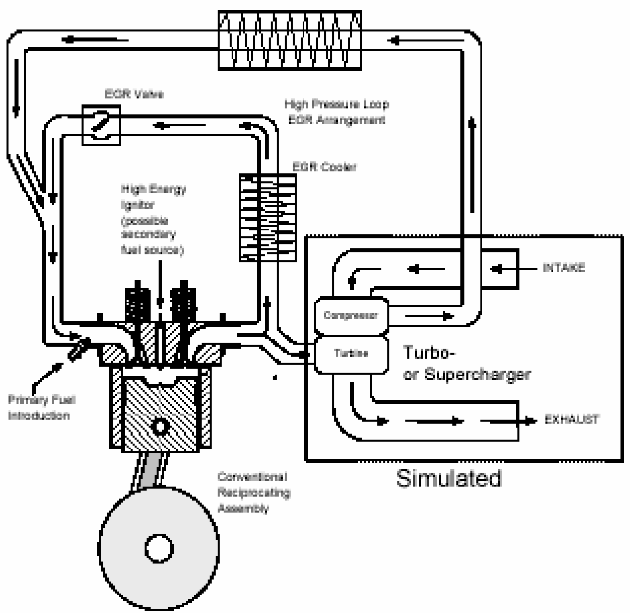
New gasoline technologies are becoming more cost competitive than diesel regarding CO_2

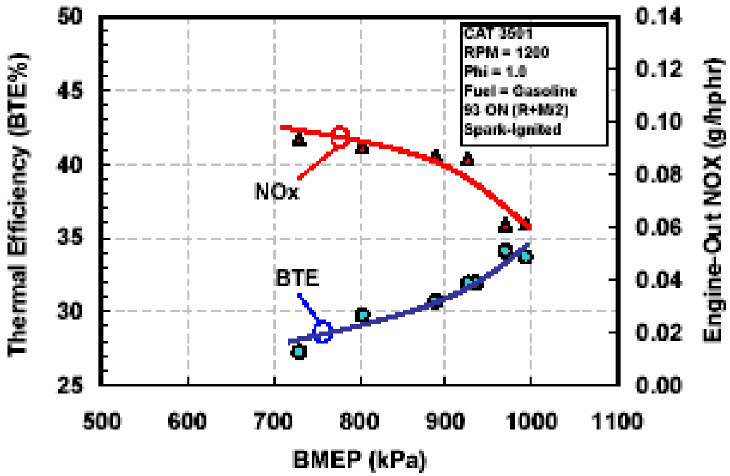


Ricardo SAE TopTec 9/03

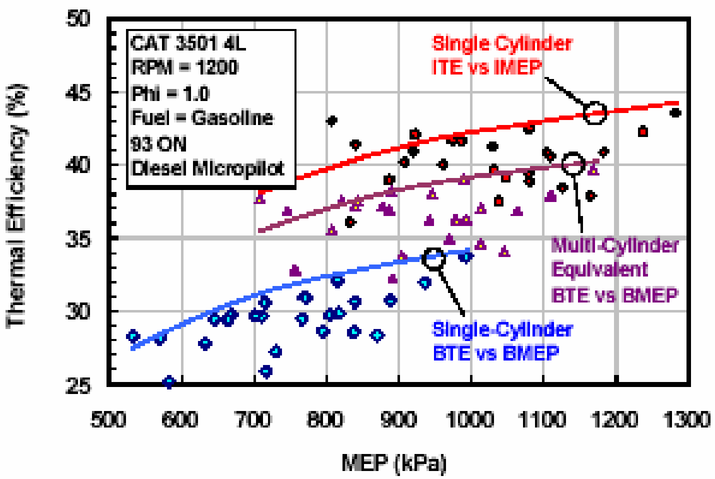
CORNING

Advanced gasoline engines are being developed that may enter HDE market





- Single-cylinder emission and efficiency results are favorable
- NOx levels a 30% of US2010
- Efficiencies within 15 relative percent of diesel



Models indicate potential for higher efficiency, bringing them to current diesel levels

- VVA gives throttless induction
- High EGR gives knock-resistant combustion
- High boost gives efficiency
- Needs: strong ignition source

SwRI consortium proposal 2/04

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.

CORNING

Thank you for your attention!