Advances in Emission Control Technology for Diesel-Powered On-Road and Off-Road Vehicles

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Manufacturers of Emission Controls Association

MDEC 2001

Presentation Outline

- Overview
- Challenges
- Technologies to Control Hydrocarbons and Particulate Matter
- Advanced Methods for NOx Control
- Systems Control
- Conclusion

Importance of Diesel Engines

- Fuel efficient [20% better than gasoline]
- Low CO_2 emissions
- Durability [Engines last 1 million miles]
- Low maintenance costs
- Low CO & HC
- High torque
- Low fuel cost

Diesel Engines: Challenges

- NO_x emissions
- PM emissions
- PM-NO_x trade-off
- Durability
- Fuels
- Range of applications

Can All Facets of the Diesel Emissions Issue Be Addressed?

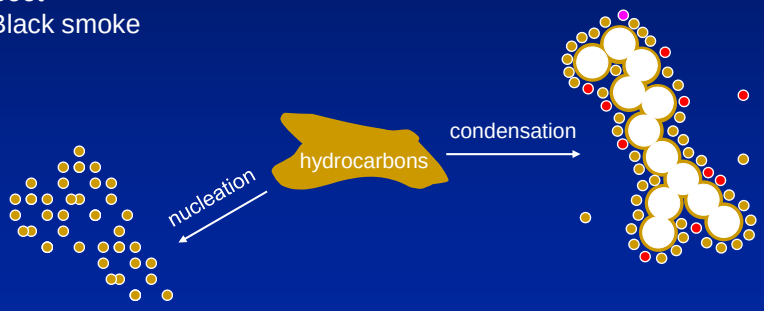
- Are Control Technologies Available to Remove Both Diesel PM (Mass and Number) and the Other HC-Based Toxic Emissions?
- Are These Control Strategies Compatible with Further Reductions in NOx Emissions?

Yes, If an Integrated Approach Is Used - **Advanced Engines, Integrated Emission Control Technologies, and Clean Fuels**

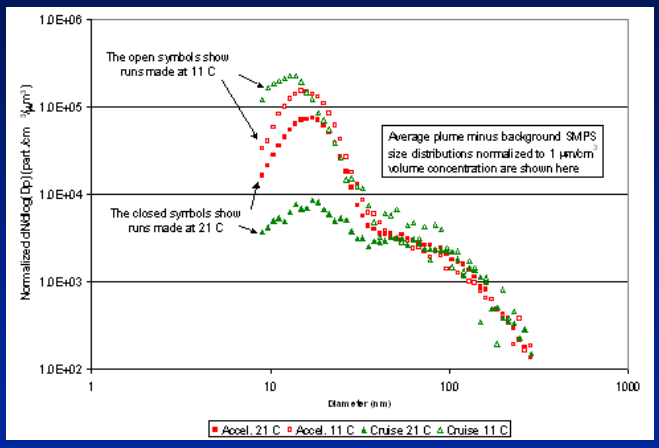
Particulate Matter

Terms
- Diesel particle
- Diesel particulate matter
- Diesel particulate
- Soot
- Black smoke

- Ash: Ca, Zn, Mg → oil additives
  Fe, Cu, Cr, Al → engine wear
  Fe, Cr, Ni, Al →exhaust pipe, manifold
- Organic sulfur→SO_2 →2% H_2SO_4 droplets



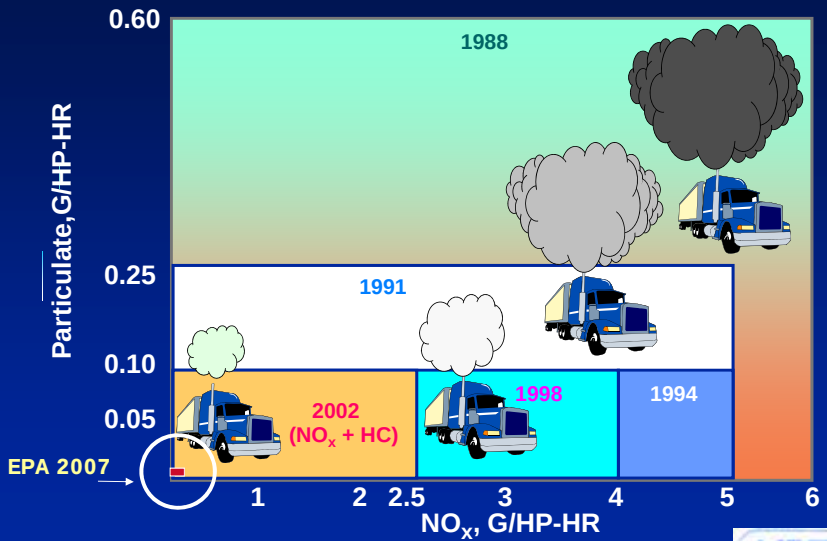
Nanoparticles Can Be Measured in Diesel Exhaust Plumes on the Road



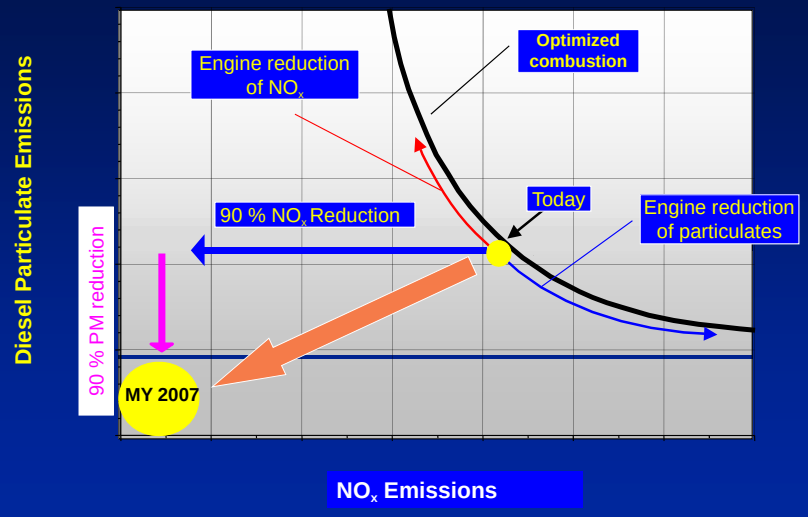
From a mobile PM laboratory following a heavy-duty diesel on the highway.
1999 Cummins engine, California fuel

Univ. of Minn. SAE 2000-01-2212

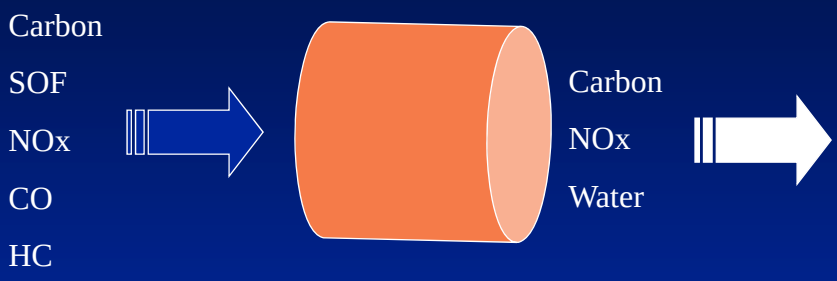
Legislative Environment - United States



2007 US HDD Regulations



Diesel Oxidation Catalysts (DOCs)

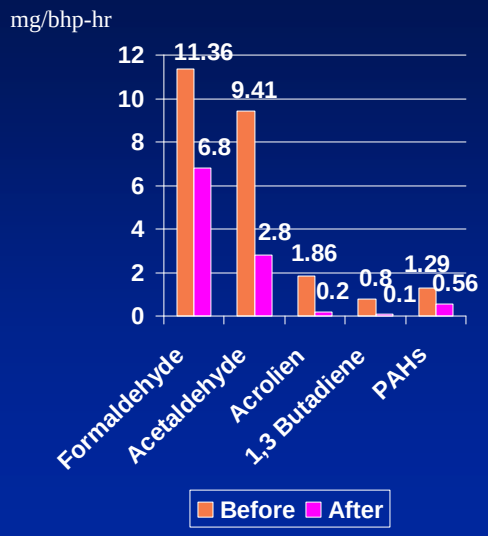


Diesel Oxidation Catalysts Are Efficient and Proven

- Oxidation Catalyst Control Capabilities
  - PM -- 20-50% Reduction
  - CO and HC -- >90% Reduction
  - Toxic HCs -- >70% Reduction

Reduction levels depend on fuel sulfur levels and subsequent catalyst loadings

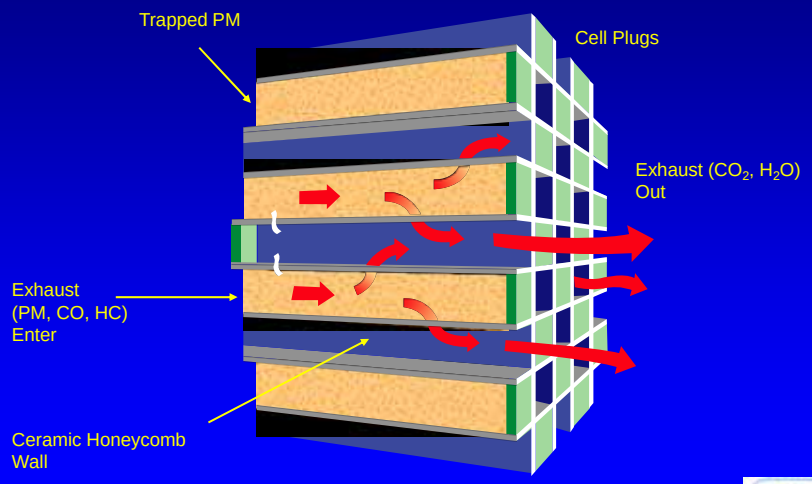
DOCs Destroy Large Fractions of Toxic Emissions



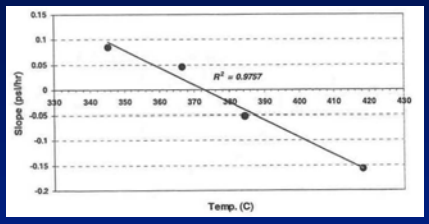
- Toxic Hydrocarbon Compounds Reduced by 68%
- PAH Emissions Reduced by 56%
- Greater Reductions Possible with Low Sulfur Fuel

Source: MECA 1999

Diesel Particulate Filters



For Catalyst-Assist Filter Systems, Balance Point Temperature Is a Key Filter Regeneration Parameter



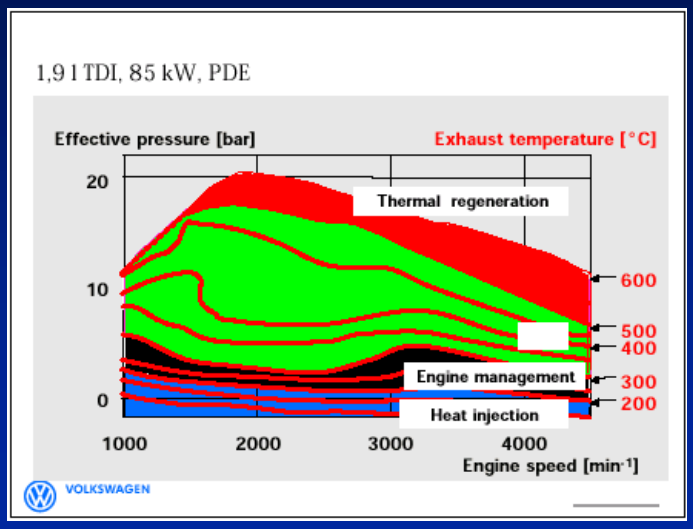
Determined by measuring back pressure as a function of temperature. BPT is temperature at which filter back pressure doesn't change.

MY 98 7.2L 300HP

Engelhard SAE TopTec 9/00

- Balance point temperature is not a perfect measure, but is okay to use for relative comparisons
- Depends strongly on PM composition, engine technology, RPM, fuel sulfur level, and filter technology
- Nominally, 300-350ºC is state-of-the-art

Active Filter Regeneration Is Needed Only After Extended Operation in Urban Driving



Peugeot Post Injection/DOC Filter Regeneration Strategy

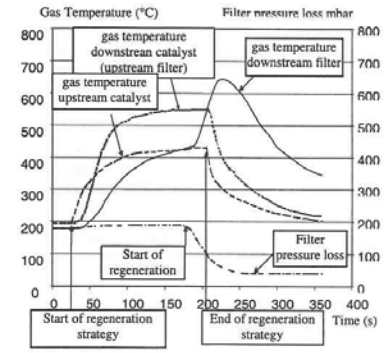


Figure 8. Example of exhaust gas temperature increase and particulate filter regeneration under steady state conditions

Late injection increases exhaust temperature, lighting off catalyst. Soot burns, and back pressure drops. Ce fuel catalyst used to decrease regeneration temperature

Peugeot SAE 2000-01-0473

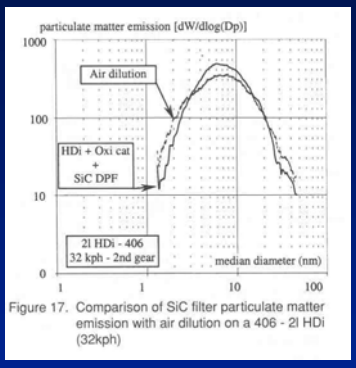
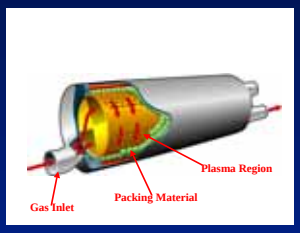


Figure 17. Comparison of SiC filter particulate matter emission with air dilution on a 406 - 2l HDi (32kph)

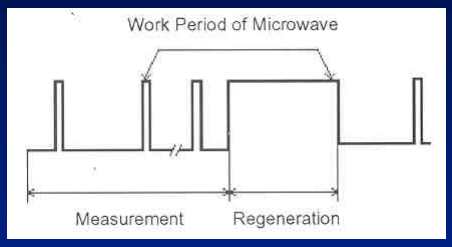
The filters clean the exhaust to ambient air levels.

- **State of DOC is important**
- **Torque is affected, but compensated for using injection strategy and turbocharging**
- **OBD on filter**
- **Minimized fuel penalty**
- **Fuel effects**

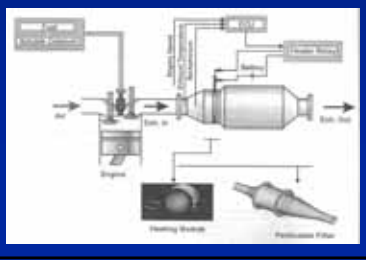
Non-Engine Active Regeneration Systems Are Emerging



NTP PM reactor has beads in the plasma; 50-75% efficiency by mass, >90% by number; PAHs greatly reduced; AEA SAE 2000-01-1926



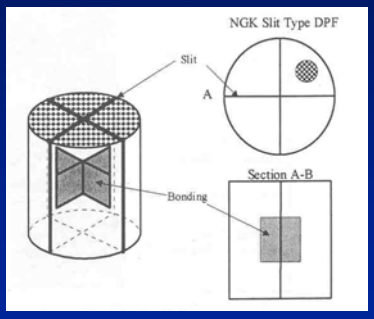
Microwave system periodically checks soot loading and regenerates when necessary. 800W, 50% eff.; Northern Jiaotong Univ SAE 2000-01-2445 & SAE 2000-01-2846



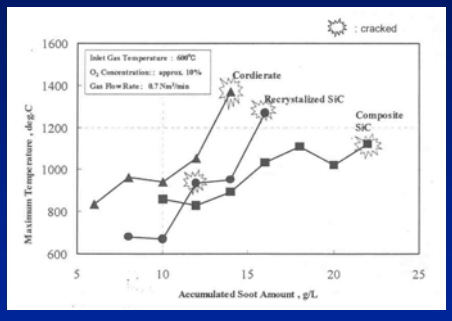
Electrical heating is being reported. 2.4 kW for LDD; Emitec SAE 2000-01-1924

New SiC Design and Materials Show Enhanced Filter Durability

Because of high thermal expansion, SiC needs to be segmented with flexible joints to survive



Four quadrants are cemented together only in the central region. The quadrants thus relieve thermal stress much more efficiently.



New composite SiC has more capacity for soot. Composite is SiC bonded by Si metal.

NGK SAE 2001-01-0192

Ash Removal

After 80,000km New

PSA 607 DPF

After 80,000 km, the DPF will be removed from the vehicle and needs to be cleaned. An engraving indicates the cleaned condition.

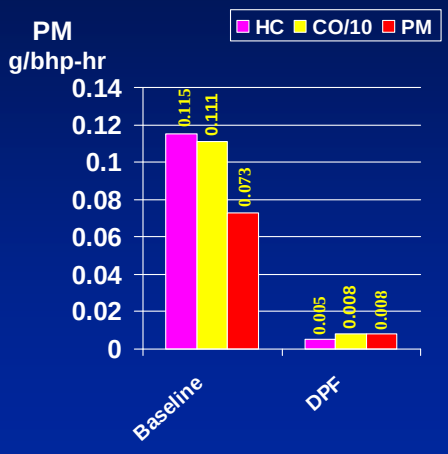
Cleaning process:

1. Burn-off of soot with hot air
2. Cleaning with water and air under "high" pressure.

Note: Water cleaning may adversely affect some canning mats.

Pictures as per ADAC website, Aug.28, 01

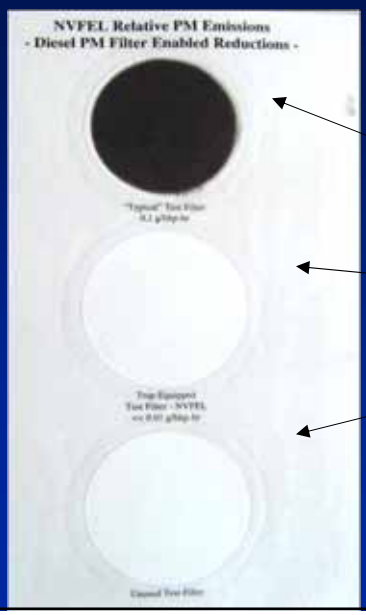
Diesel Particulate Filters Nearly Eliminate PM



- PM Emissions Below 0.01 g/bhp-hr Can Be Achieved
- Significant Reductions in CO and HC Emissions Can Also Be Achieved
- Filter Control Capabilities
  - PM -- 80%->90% Reduction
  - CO&HC -- >90% Reduction
  - Toxic HC-- >90% Reduction

Source: MECA 1999

PM Emissions with Trap



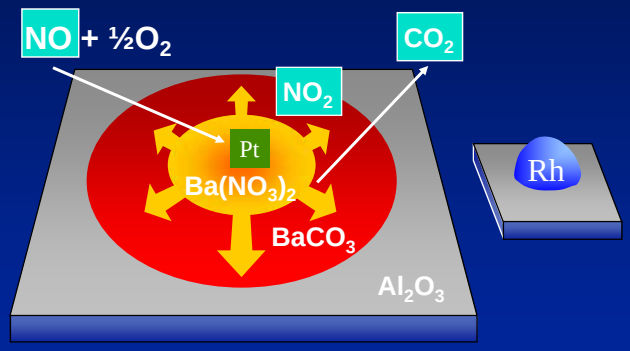
- Typical test filter – current standards
- Test filter – 2007 standards
- Unused test filter

NOx Reduction Technologies

- State of the Art Technologies for NOx Reduction
  - NOx Adsorbers
  - SCR
  - Lean-NOx Catalysts
  - Plasma Technology

The NOx Adsorber in Storage Mode During Lean Operation (NOx Stored as A Nitrate)

Lean Conditions

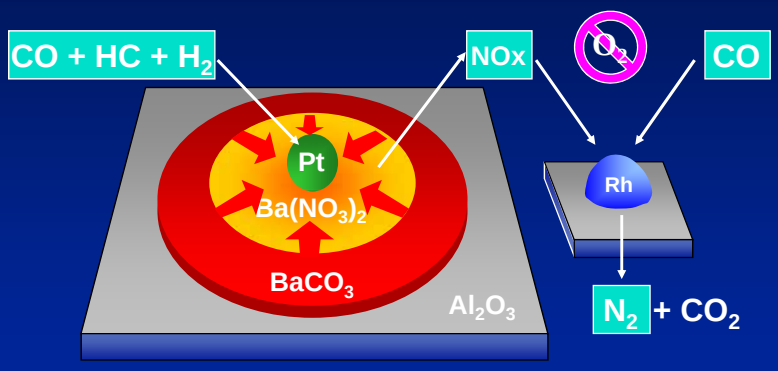


Reference: MECA

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

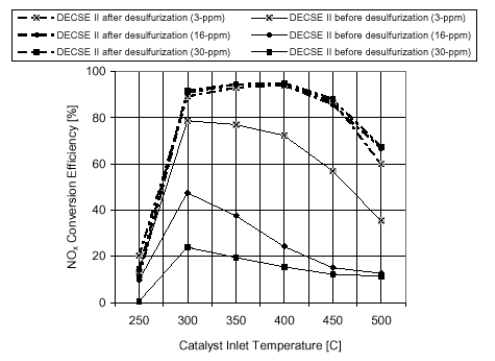
The NOx Adsorber in Release Mode During Rich Operation (NO_2 Converted to Nitrogen)

Rich Conditions

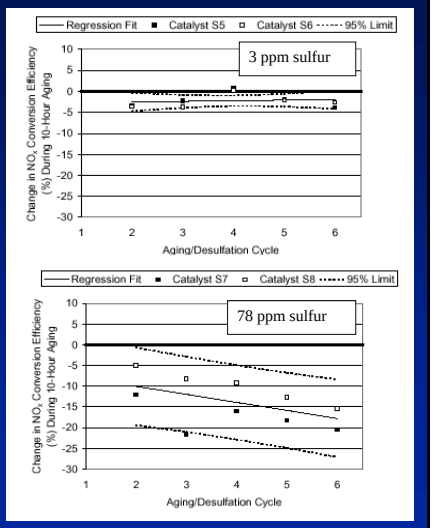


Reference: MECA

NOx Adsorbers Can Achieve 95% Efficiency in Steady State HDE 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

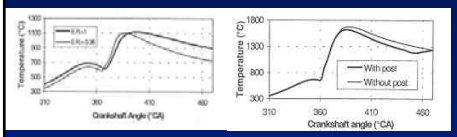
Exposure to 3 ppm sulfur does not degrade NOx trap after desulfation; 78 ppm sulfur does

NOx Adsorbers (3.8% Fuel Penalty to Achieve Euro 5, 2.6% to Achieve Euro 4)

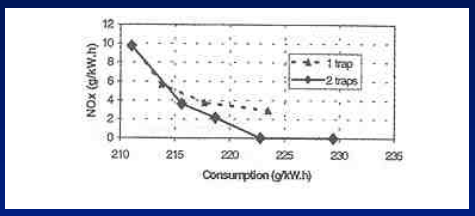
1.6 l single cylinder test engine

EGR effect

Post-injection effect

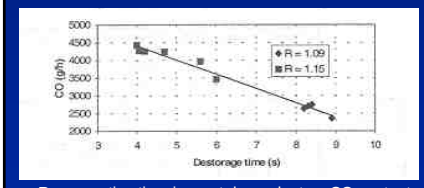


With EGR, rich post injection has minimal effects on peak cylinder temperatures. Engine durability expected to be unaffected.



Two parallel traps (SVR = 3.1) results in lower fuel consumption. Increased regeneration time is offset by higher NOx efficiency.

Influence of CO on regeneration



Regeneration time is most dependent on CO content. Derived under a variety of fuel injection timings and quantity.

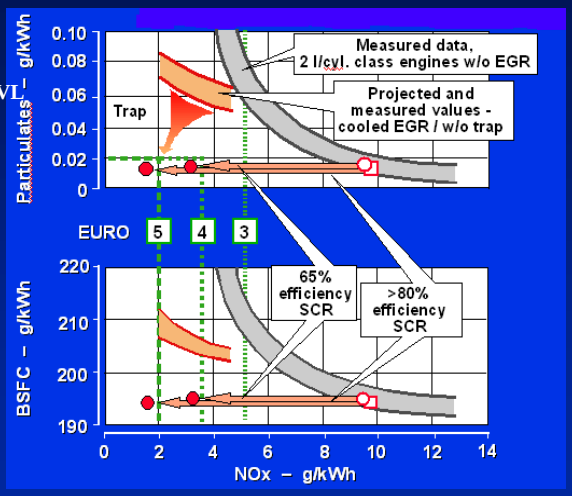
NOx emission vs. fuel penalty is optimized using regeneration time, gas composition, and frequency.

RVI and IFP Vienna Motor Symposium 4/01

Fuel Savings By Using SCR Can Be Achieved

65% efficient SCR enables operation at high NOx and low fuel consumption. AVL SAE TopTec 9/00

The SCR payback period in Europe is less than a year in 2008, but more than 3 years in the US; Open University - ImechE 12/01



HDDE SCR Field Demonstration - Durability Results Are Impressive

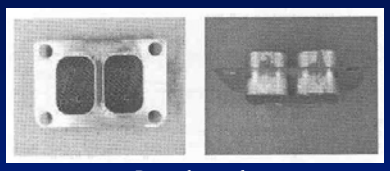
Progr.	Eng.	Description	ΔNOx	Mileage	Comment
1	MAN	road test	56 % 54 %	0 km 130.000 km	activity of catalyst constant within meas. accuracy
1	MAN	-	-	overall	Urea: 4.1 % (avg.) of Diesel
2	DC	test bench	65 % (ESC) 70 % (FIGE) 63 % (ESC) 71 % (ETC)	0 km 0 km 272.000 km 272.000 km	activity of catalyst constant within meas. accuracy
2 2	DC MAN	road test	74 % 66 %	212.000 km 200.000 km	NOx-red. comparable with test bench results
2	DC/MAN	-	-	overall	Urea: 5.5 % (avg.) of Diesel

All measurements were done and reported by TÜV Automotive, Germany

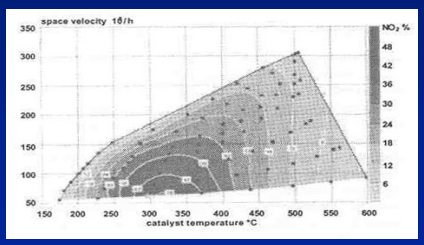
12 liter, 300 kW engines

Siemens SAE TopTec 9/00

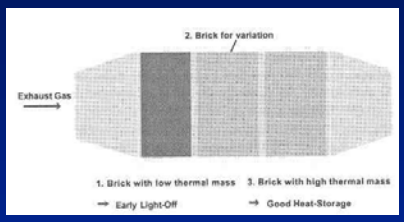
Systems Like Compact SCR Use NO_2 Generation to Enhance Conversion Performance



Pre-turbo catalyst



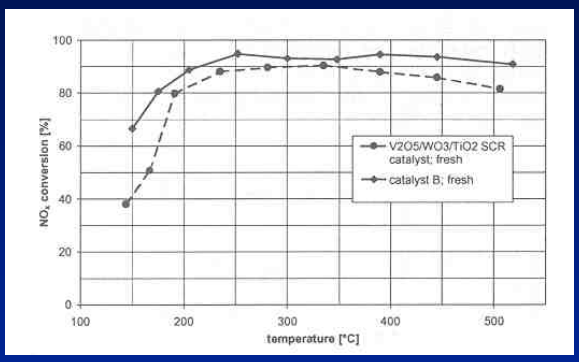
NO_2 production is high over much of the engine map for pre-turbo cat



Hybrid catalyst has low thermal mass at inlet and high thermal mass at exit

Emitec SAE 2001

Zeolite SCR Catalysts Are Being Developed and Being Evaluated for LDD.

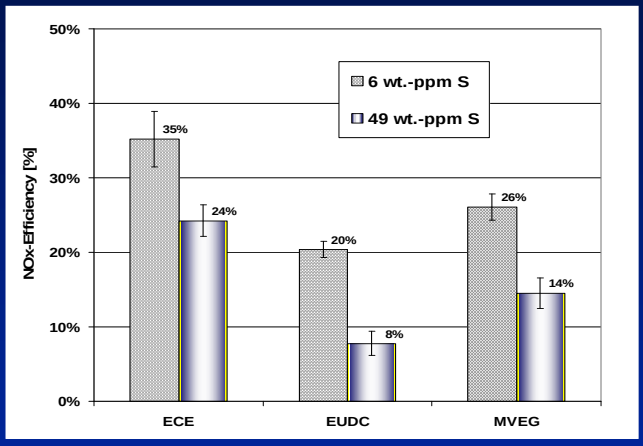


Ion-exchanged zeolite (B) has similar NOx performance as standard SCR catalyst. No deterioration after 200 hours was reported.

dmc² SAE 2001-01-0514

- 4 l TDI
- <50 ppm S
- 8.6 l catalyst on 400 csi substrate

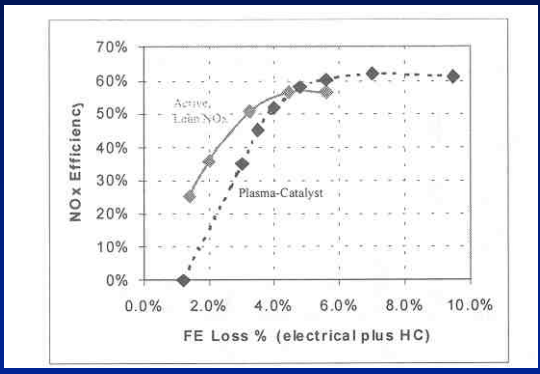
Passive Lean-NOx Catalyst Efficiency Decreases to 14% When Fuel Sulfur Increased from 6 to 49 ppm



1.9 liter, TDI, Euro 2 calibration; 5.8 liters of catalysts; baseline MVEG NOx of about 0.68 g/km; no added HCs

AECC, FEV SAE 2000-01-1877

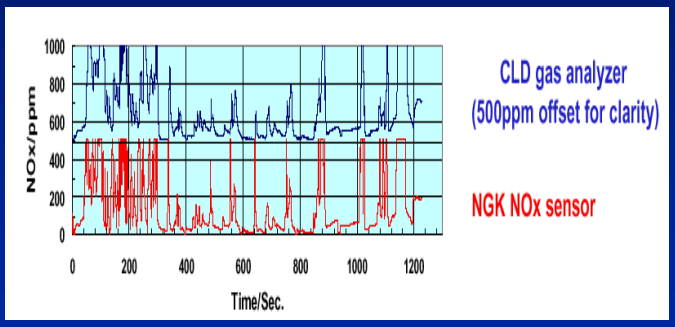
Plasma - Catalyst Systems Are Achieving 60-70% NOx Reductions at 6-8% Fuel Penalties



New systems are getting 85-90% efficiency
Plasma systems operate at 150-500°C
Plasma systems are insensitive to sulfur

Ford and PNNL (SAE 2000-01-2895)

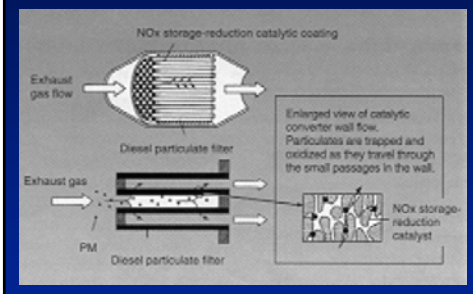
NOx Sensors Will Facilitate the Use of NOx Control Technologies

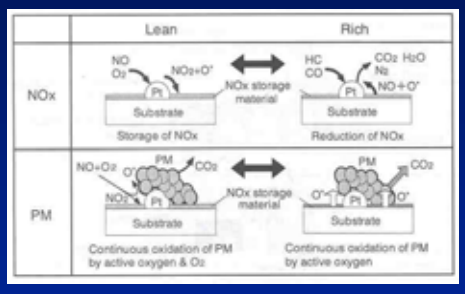


NGK and Siemens literature

Integrated NOx/PM Solutions

Catalyst Integration for NOx Adsorbers and Filters Is Being Developed



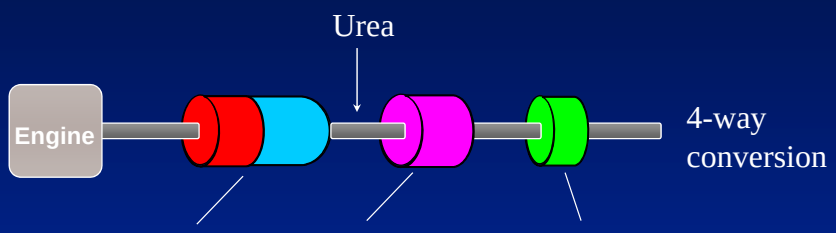


NOx trap material is coated into internal porosity

"Active oxygen" aids filter regeneration

Vienna Motor Symposium 4/01

Integrated System Using a DOC, DPF, and SCR



Catalyst/Filter

Removal of HC, CO, PM

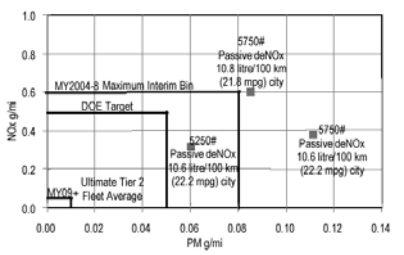
SCR

Removal of NOx

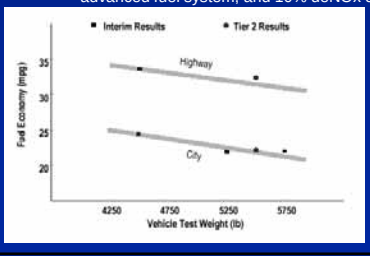
Oxidation Cat

Removal of NH_3 slip if required

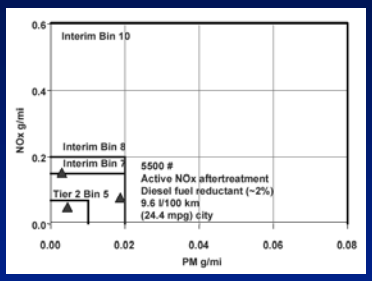
A 1997 4.2 liter SUV Engine Achieved EPA Tier 2 Bin 5-7



Stock 1997 Euro 4.2 liter engine was dropped from 1.8 gpm NOx and 0.3 gpm PM to hit Bin 10 by adding cooled EGR, VGT, advanced fuel system, and 10% deNOx cat.



59% better fuel economy observed vs. similar gasoline engine on SUV (within 2%). Bin 10 and Bin 5 configurations had similar results.



Bin 5 was hit (once out of three) by adding a DPF and NOx trap. Diesel fuel reductant. No FTP cold start. Engine dyno simulation using ULSD fuel. System size not disclosed.

Cummins SAE 2001-01-2065

Conclusions

- A Variety of Technologies Are Available for PM and NOx Emission Control of Both Light-Duty and Heavy-Duty Vehicles
- Technologies Are Advancing and Recent Developments Indicate that HDDE 2007 and EPA Tier 2 Emission Levels Are Very Likely Achievable Well in Advance of Regulatory Requirements
- Continued Progress Will Be Made to Simplify Systems

Conclusions (cont.)

- Low Sulfur Diesel Fuel Will Enhance the Performance of All Catalyst-Based Exhaust Emission Control Technologies
- The Ultimate Solution to Reducing Emissions from Diesel Engines Requires a Systems Approach Utilizing Advanced Engine Designs, Advanced Integrated Emission Control Technology, and Low Sulfur Diesel Fuel