Diesel Emission Control Technology Review

Tim Johnson

August 22, 2006

DEER 2006

Detroit

Summary

- Regulations
  - Europe is in middle of determining Euro 5 and Euro 6 (LD) levels
    - Implications to US approach
  - Europe will begin formal Euro VI proposals early next year
- Engine strategies are making impressive progress
  - Advanced strategies will save on aftertreatment; require significant combustion control
- NOx solutions are available for ultra-low emissions
  - SCR is addressing cold temperature and secondary emission issues
  - LNTs are performing well today at about 60-70% efficiency; economically attractive for smaller platforms
- DPF systems show continuous improvement
  - Very sophisticated regeneration control strategies; aluminum titanate durability described
- Some outlying issues yet to be addressed
  - NO_2 and ultrafine PM

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LD Regulatory Issues

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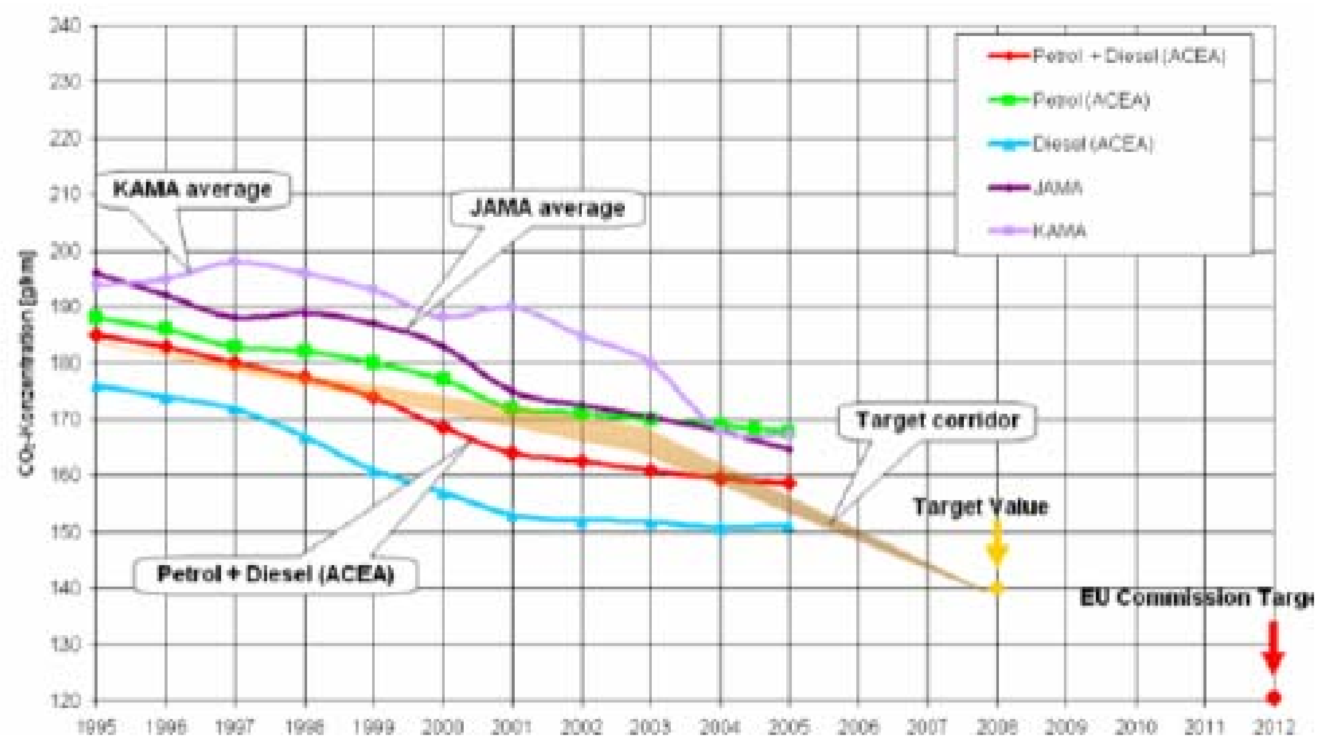
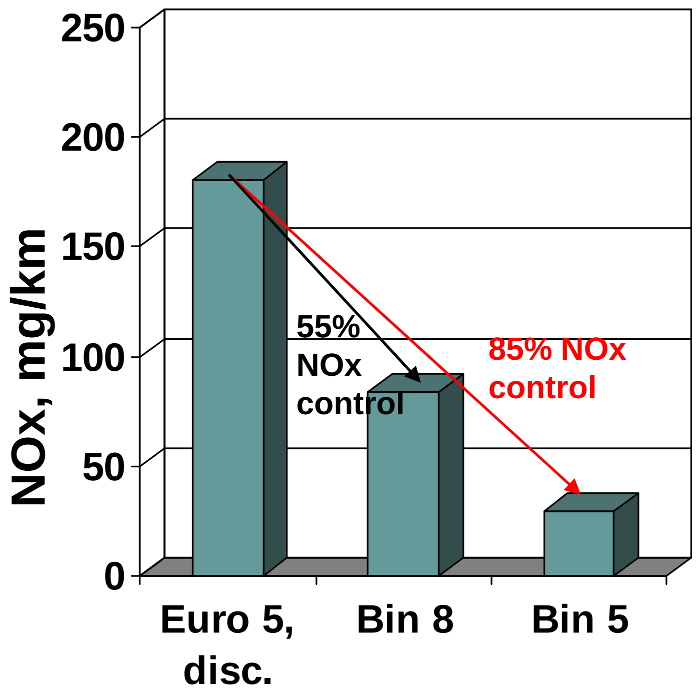
Although significant progress is being made on reducing European auto CO_2 emissions, the voluntary target was missed for the first time in 2005.



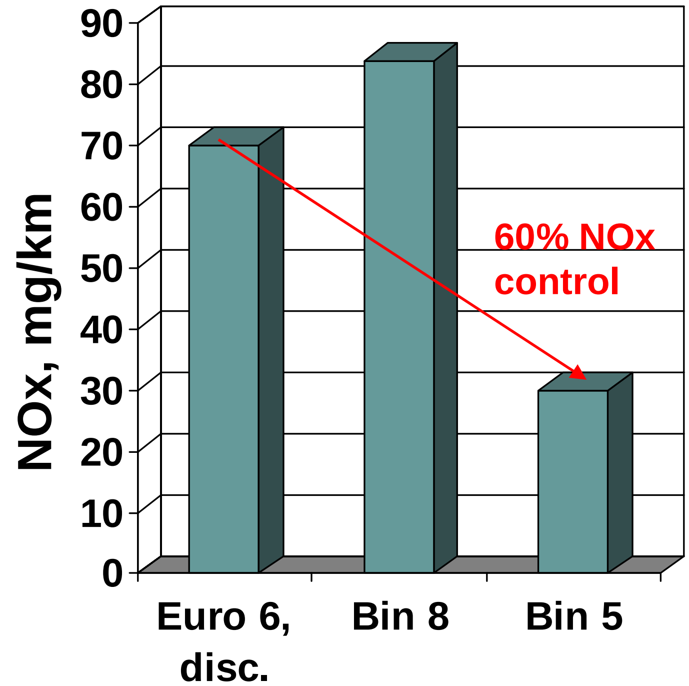
However, despite considerable increases in vehicle mass, power, and capacity, CO2 emissions have still dropped.

DaimlerChrysler, Dresden Conf. 5-06

To sell European cars into the US market, a minimum of 50-60%% NOx control is needed to today to hit a 42-state market (70% US). By 2013 (earlier with Euro 6 incentives) 60% NOx control could get the 50-state market.



Given EU discussion of Euro 5 at about 180 mg/km NOx, 55% NOx control on these cars is needed to hit Bin 8 (70% of US), and 85% NOx control is needed to hit Bin 5 (all US).



Given EU discussion of Euro 6 at about 70 mg/km NOx, 60% NOx control is needed to hit Bin 5 (all US).

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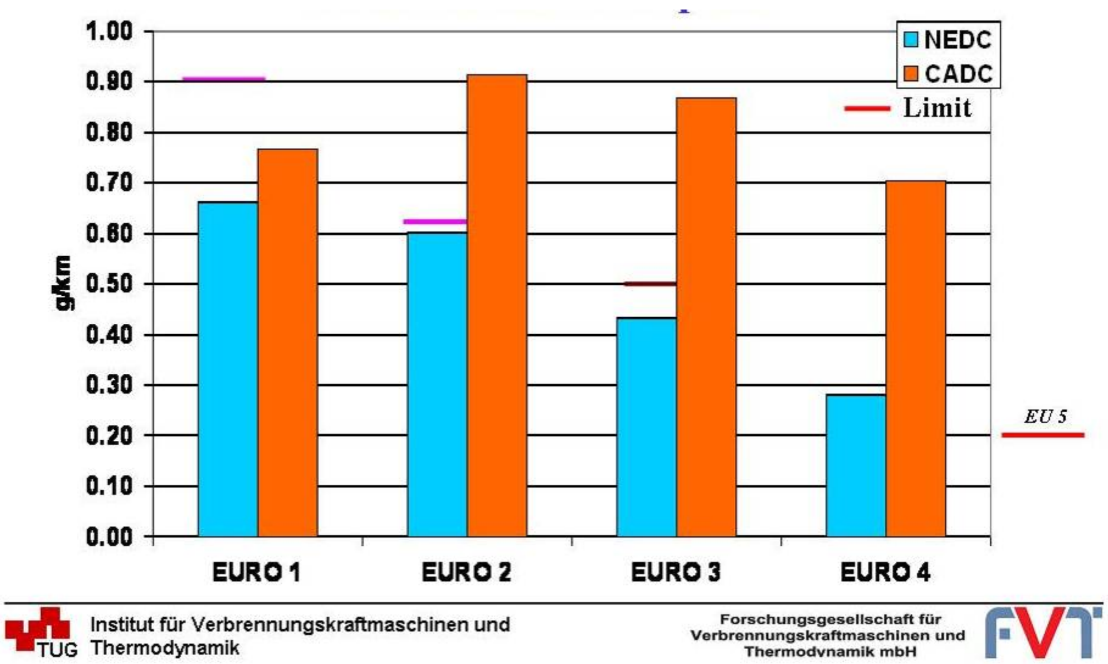
While NOx limit values have gone down by more than 50%, by some measures there is only minor improvement. EU is looking at auxiliary test cycles.



CADC is an example of a "real life" European drive cycle developed using 80 cars over 100,000 km is urban and autobahn driving.

HD Regulatory Trends

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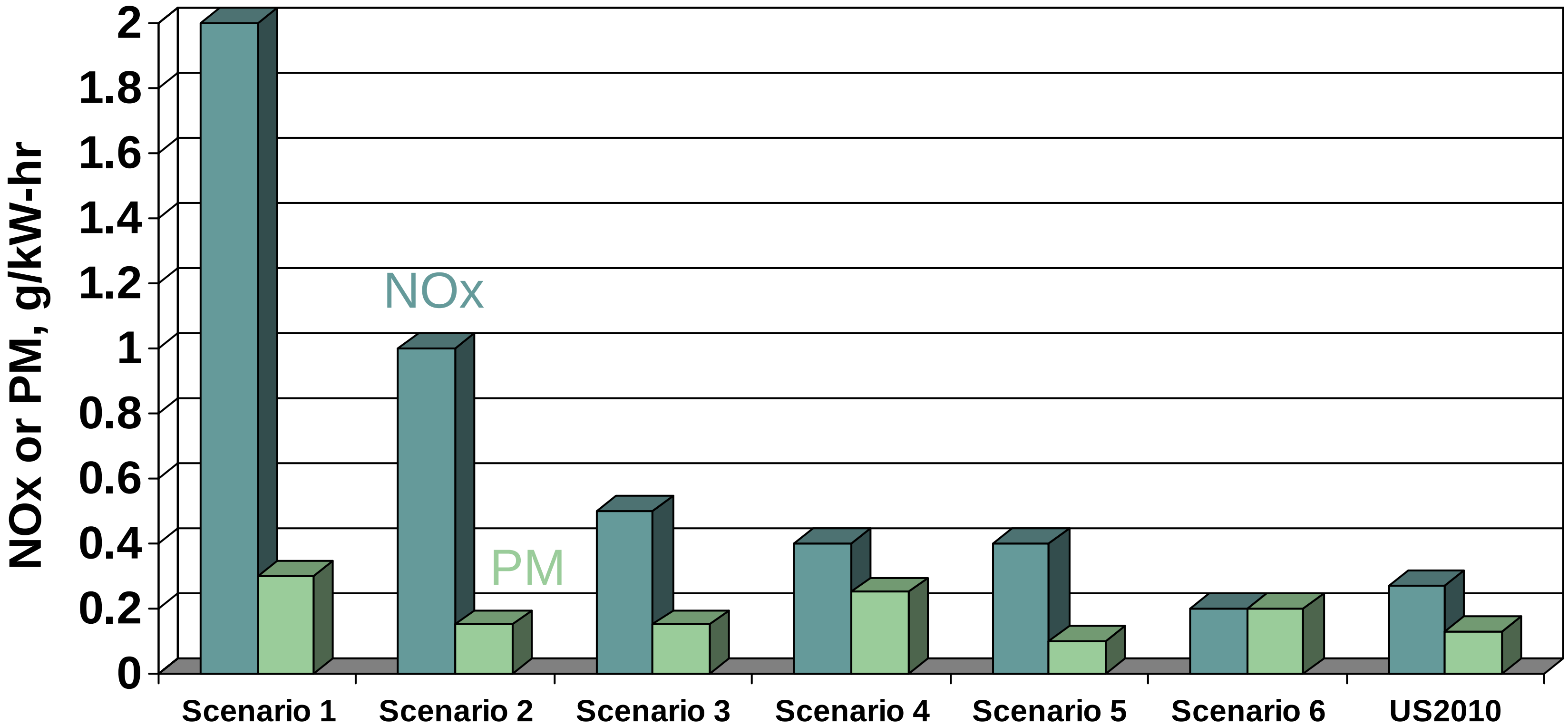
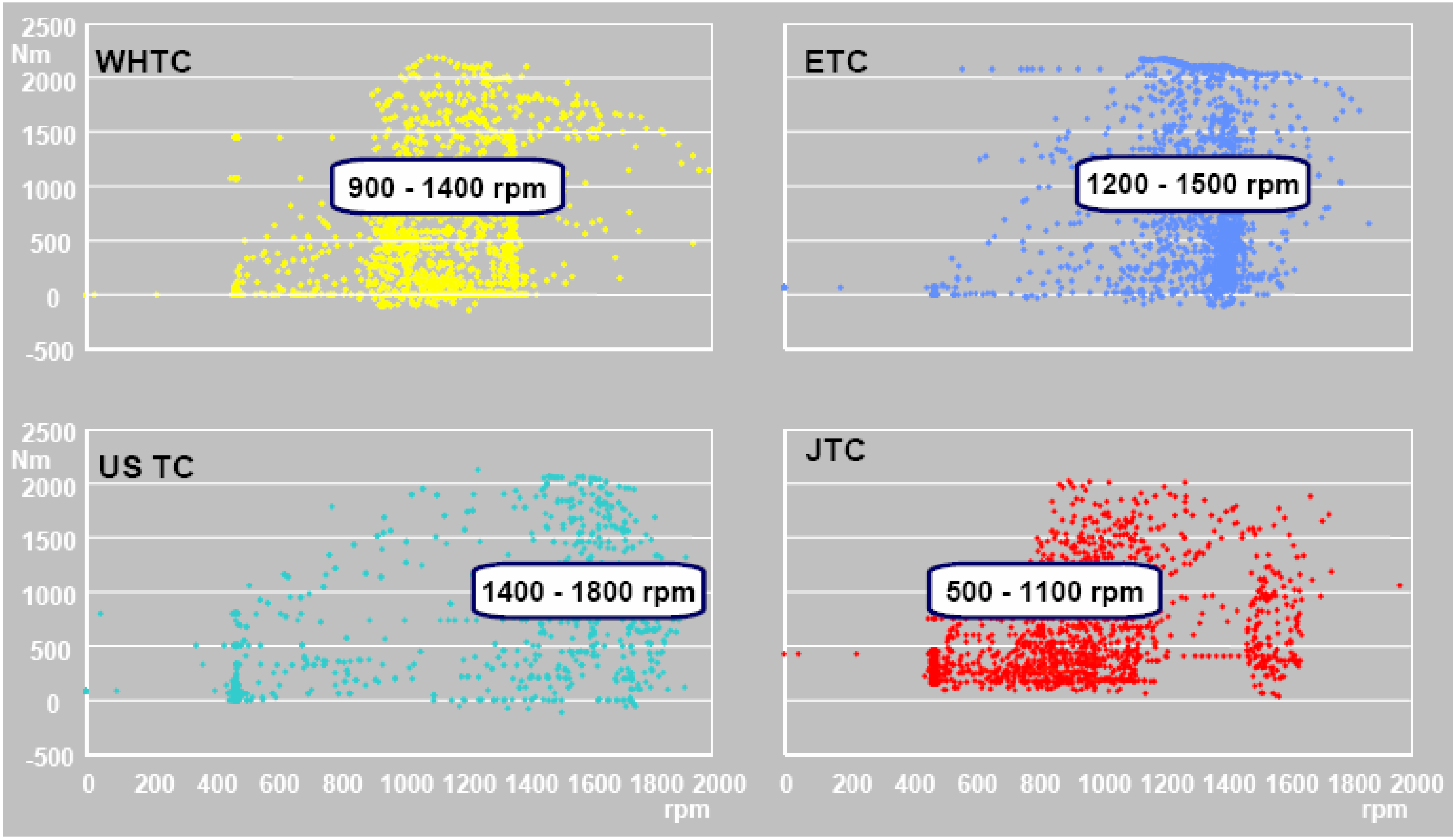
The EU is considering six different Euro VI scenarios.



- NTE and number-based PM standards also considered.
- Timing of 2012-14 discussed
- EC will make a proposal about May 2007

Four different transient test cycles are being evaluated.



Iveco, Euro V/VI Conf. 6-06

Engine Developments

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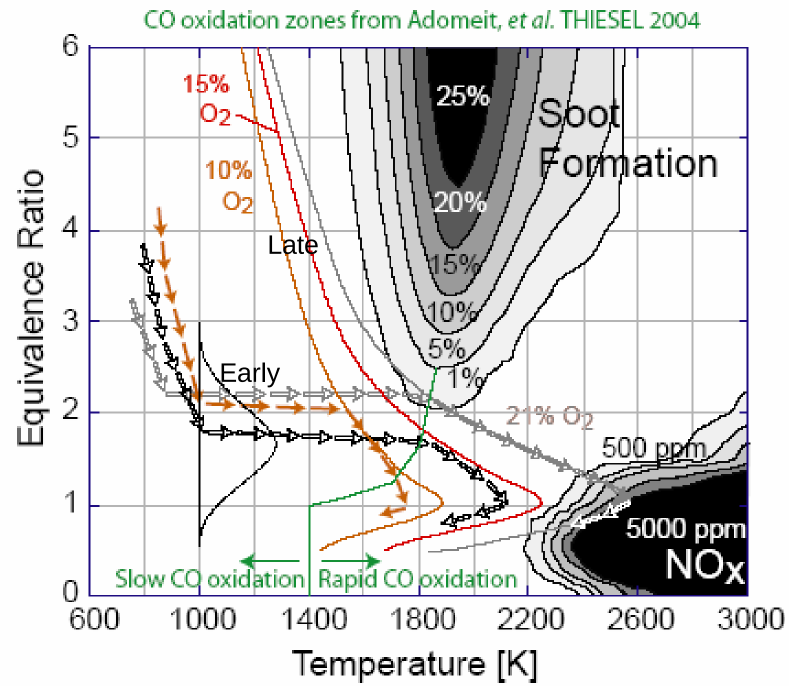
Late- and early-injection cool flame strategies likely follow different paths and have different propensities to form soot or NOx

Postulated low-temperature ϕ-T plane paths

Late-injection

- Cooled EGR, low compression , and cooling due to volume expansion give $\overline{\phi} < 2.0$ at ignition
- Range of ϕ at ignition influences soot and NO_x formation
- Mixing-controlled combustion occurs until ϕ=1. Volume expansion lowers T_{max}
- Late-mixing processes occur well away from CO oxidation boundary



Early-injection

- Mean ϕ at ignition higher (?)
- Soot and NO_x emissions are not as sensitive to the distribution of ϕ due to low T_{max}
- A very similar path is followed, but a greater time will be required to traverse the mixing-controlled segment (higher ϕ, turbulence decay, greater volume of fluid to mix)

For both strategies, a major challenge is to mix to ϕ = 1 before temperatures drop and CO oxidation slows

Sandia NL, 9th Int'l Engine Conference, 6/05

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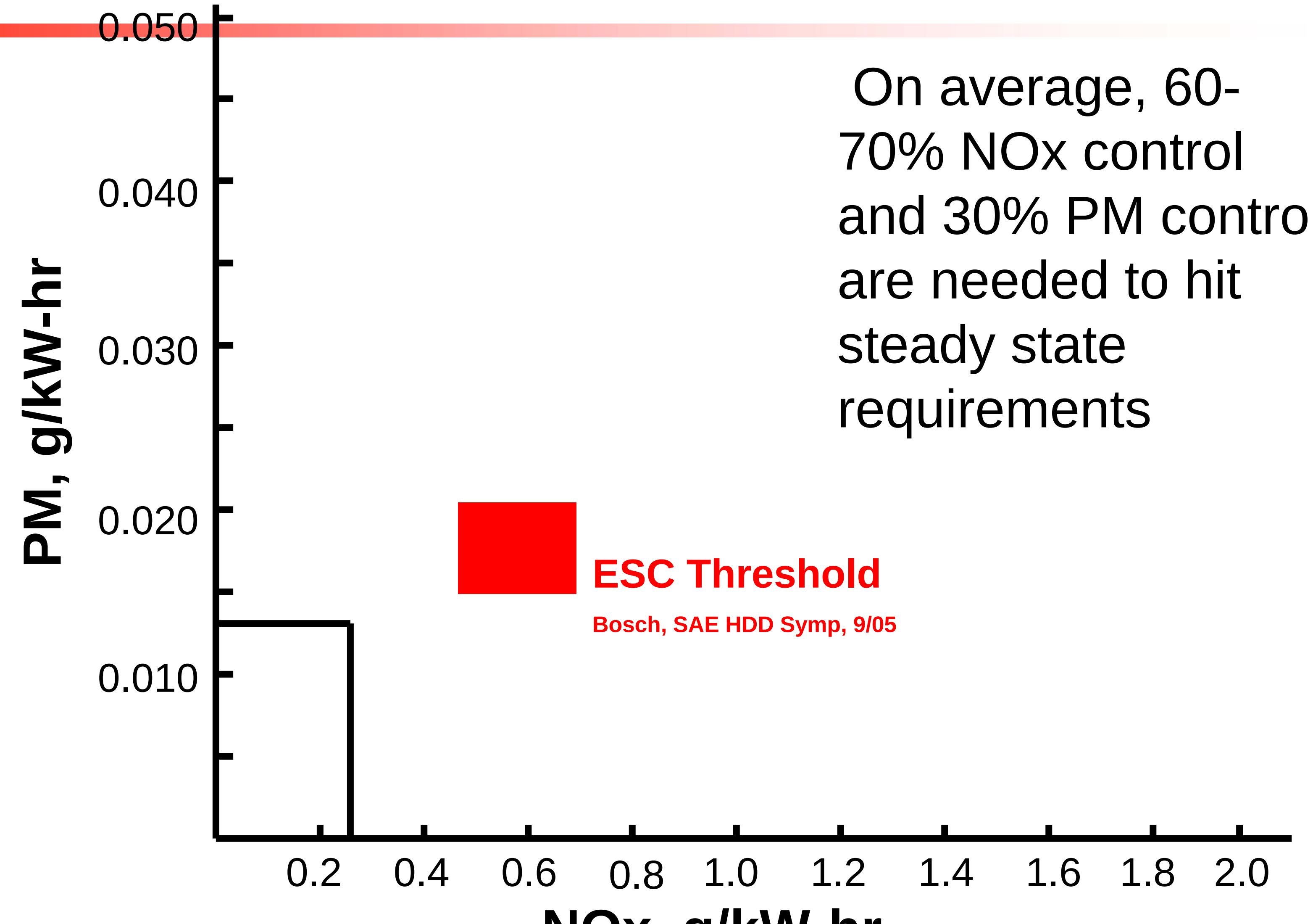
HDD RESEARCH ENGINES are hitting 0.6/0.015 NOx/PM on the ESC



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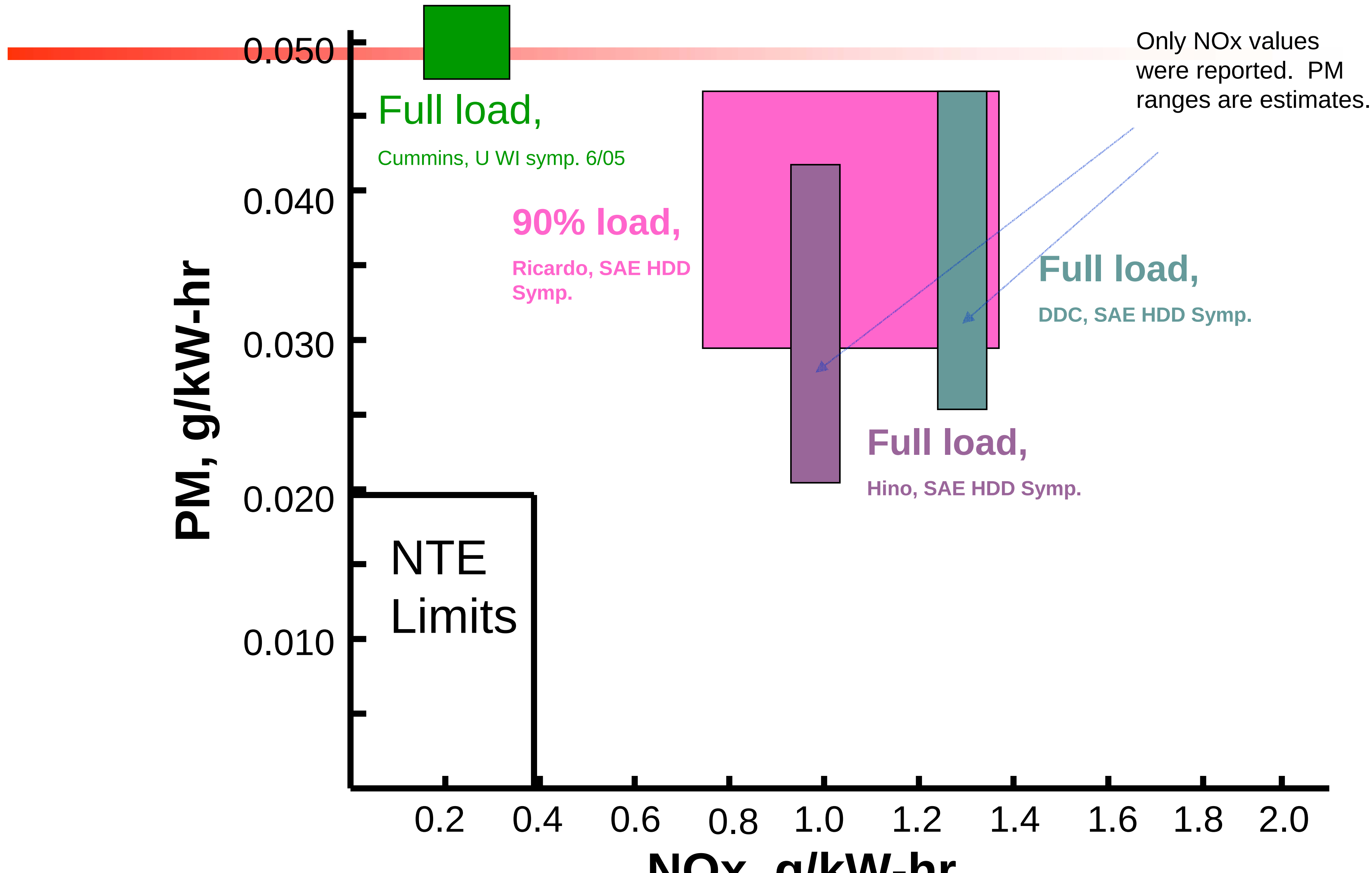
HDD RESEARCH ENGINES have full load NOx of 0.25-0.8 g/kW-hr; 0-50% NOx and 50-80% PM treatment for NTE;



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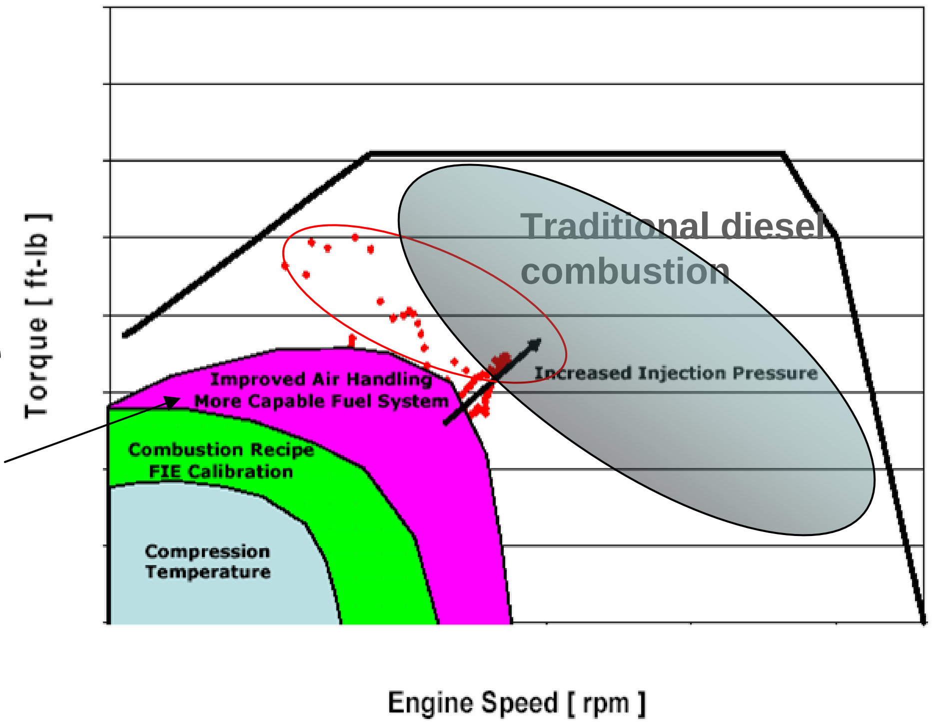
HD Engine/Regulatory Comments

- US2010 regulations can be achieved in a number of ways
  - Most likely approach is to use incremental engine technologies to US2007, and add appropriate NOx control
    - Incremental improvements will drop NOx from nominally 1.0 g/bhp-hr NOx to nominally 0.7 g/bhp-hr NOx
    - SCR will be used in fuel-sensitive sectors for 80-85% NOx efficiency; allows1.0-1.3 g/bhp-hr engine-out
    - 2010 could be fuel-consumption neutral vs. US2007
  - More advanced engine hardware might drive NOx down to 0.5 g/bhp-hr NOx
    - High EGR, FIE, boost, control
    - Requires 60% NOx control (LNT)
      - SCR will allow 1.0-1.3 g/bhp-hr engine-out for fuel economy gains
    - First cost vs. operating cost and marketing trade-offs

Research results show large coverage of US LD test cycle in advanced combustion mode

Cummins, Univ WI ERC symposium, 6/05

Clean advance low-NOx combustion

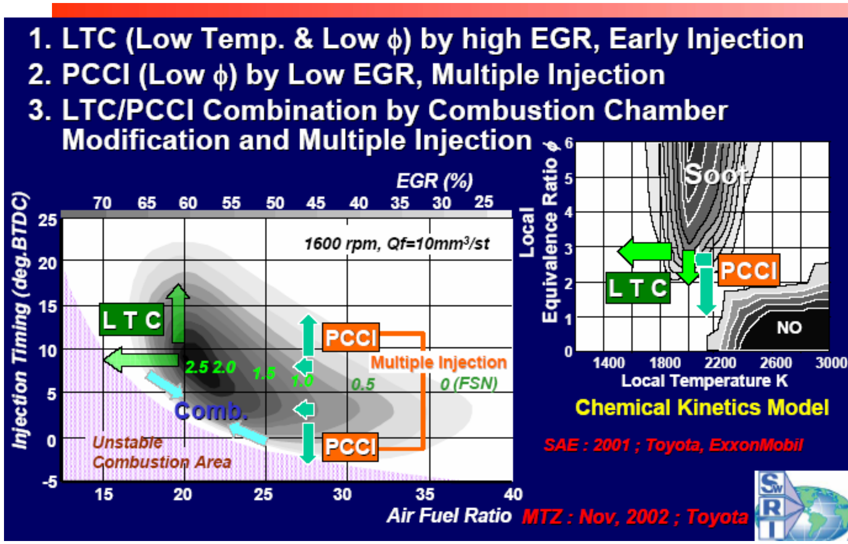


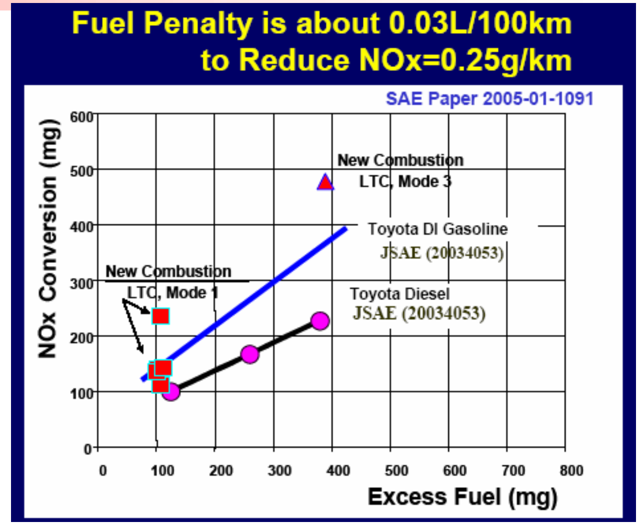
Only a small fraction of test cycle load points fall within traditional combustion mode

As much of the certification cycle is met using advanced combustion, NOx aftertreatment requirements are reduced or eliminated.

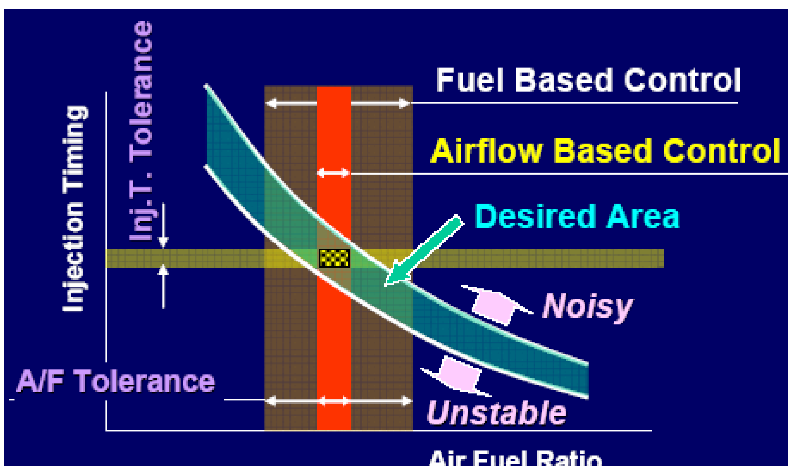
Wildcard: Off-cycle emissions might warrant aftertreatment.

Combined LTC/PCCI/traditional diesel combustion strategy provides low noise, maintained fuel efficiency, and manageable emissions.





Running rich LTC with an LNT gives very low fuel penalty .



Parts	Purpose	Note
Throttle Valve	Airflow based control	Common to Gasoline
EGR Cat for HPL	Low Load LTC	Small oxicat
EGR Valve for LPL	High load LTC	Size up
EGR Cooler for LPL	High load LTC	Size up
λ Sensor	Combustion Control & OBD	Common to DI Gasoline
NOx (O2) Sensor	OBD	Common to Gasoline
LNT	NOx conversion	Common to DI Gasoline

Additional engine hardware is modest

Model-based control of airflow and injection timing/quantity results in precise combustion

SwRI internal research 11/05

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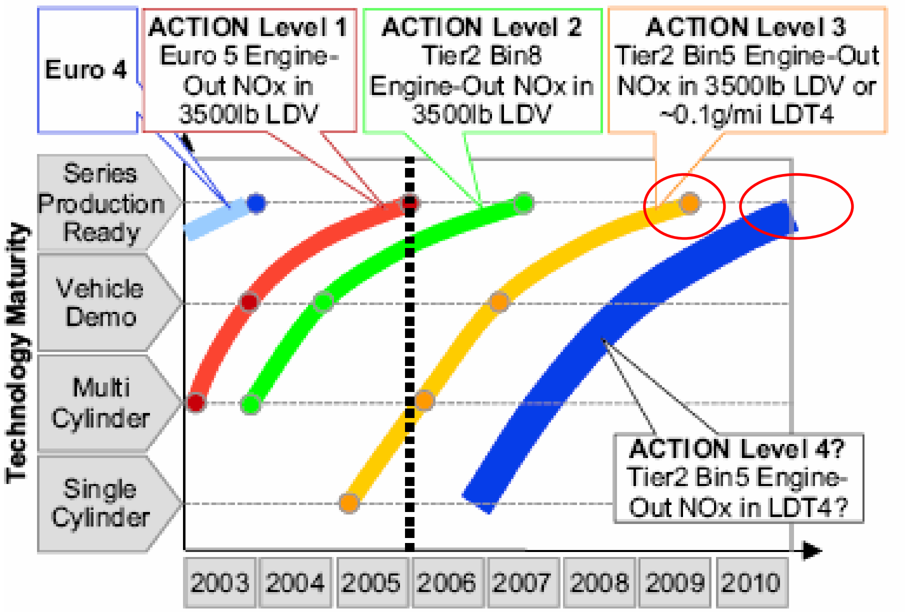
One LD engine roadmap shows minimal, if any, NOx control to hit T2B5 for 3500 pound vehicle MY09



Tier 2 Bin 5 cars without NOx aftertreatment could be available in 2009. LDT in 2010.

- Level 2 with SCR is projected to have the same cost increment as Level 3.

Comment: Timing of advanced combustion strategies varies from 2009 to 2012-14. Noise, transient, and low-end boost are among issues that generally need to be resolved for these type of technologies.

Ricardo, SAE 2006-01-1145

Engine results give aftertreatment requirements. LDD: Only US has small window for NOx aftertreatment

- Euro 5 appears attainable on all fronts with traditional diesel combustion and no NOx aftertreatment
- Japan 2009: Strong potential to hit w/o NOx treatment
  - PC at 80 mg/km NOx is at threshold
  - LDT and MDT 1700-3500 kg, NOx reg is 150 mg/km NOx; at threshold
- US T2B5, it is a matter of timing
  - 2007: 75-85% NOx aftertreatment to hit T2B5; traditional combustion
    - DC announcement: Bin 8 Fall 2006 (0.2 g/mi NOx)
  - 2009-11: Cutting edge PC might hit w/o aftertreatment, using mixed mode
    - Nominal (50%) aftertreatment applied for off-cycle emissions
    - LDT: perhaps 30-50% control at HL points will be needed
  - Wildcard: perception and addressing off-cycle NOx

SCR

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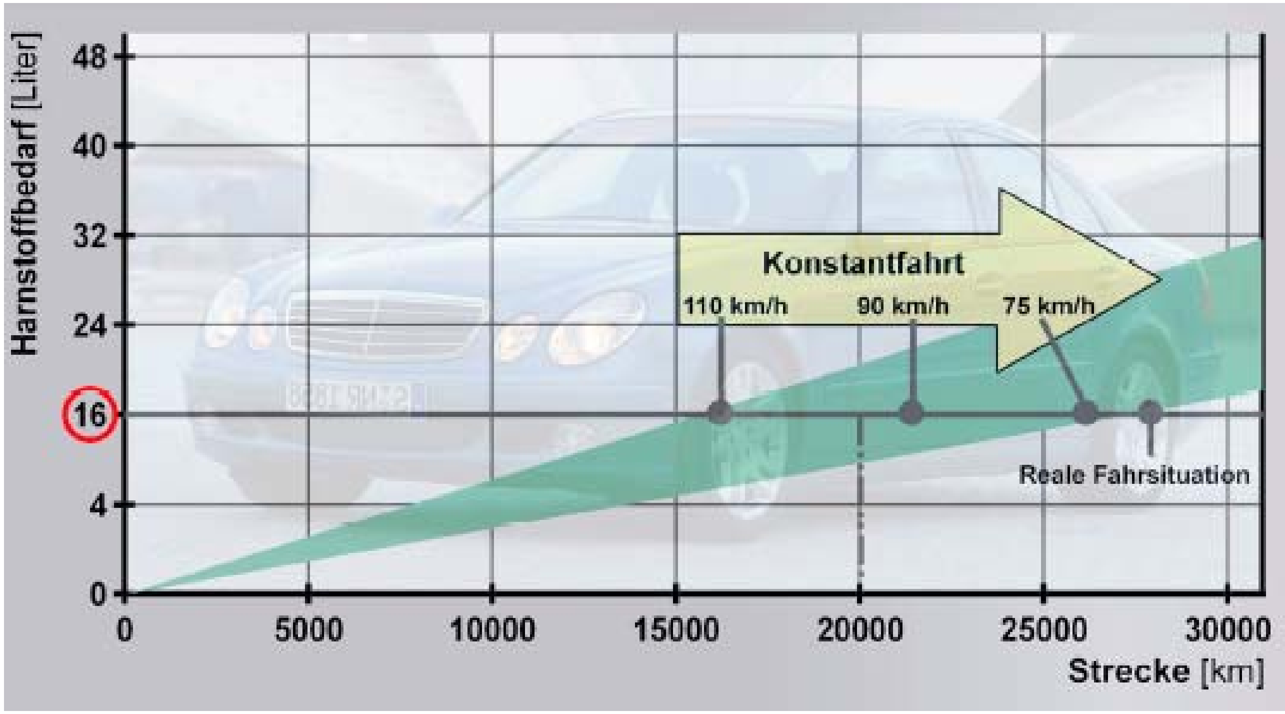
US SCR plan is making progress for US2010

- EPA:
- “No operation without urea!”
  - Unacceptable: Only warnings and long urea change interval
  - OK: Vehicle inter-locks at fueling station
  - OK: Recalibration to meet NOx limits
- Urea infrastructure has to be readily available
  - Convenient
  - Timely

Going Forward: Industry needs to make a proposal. We are close. EPA will publish guidance document, and open it to public comment.

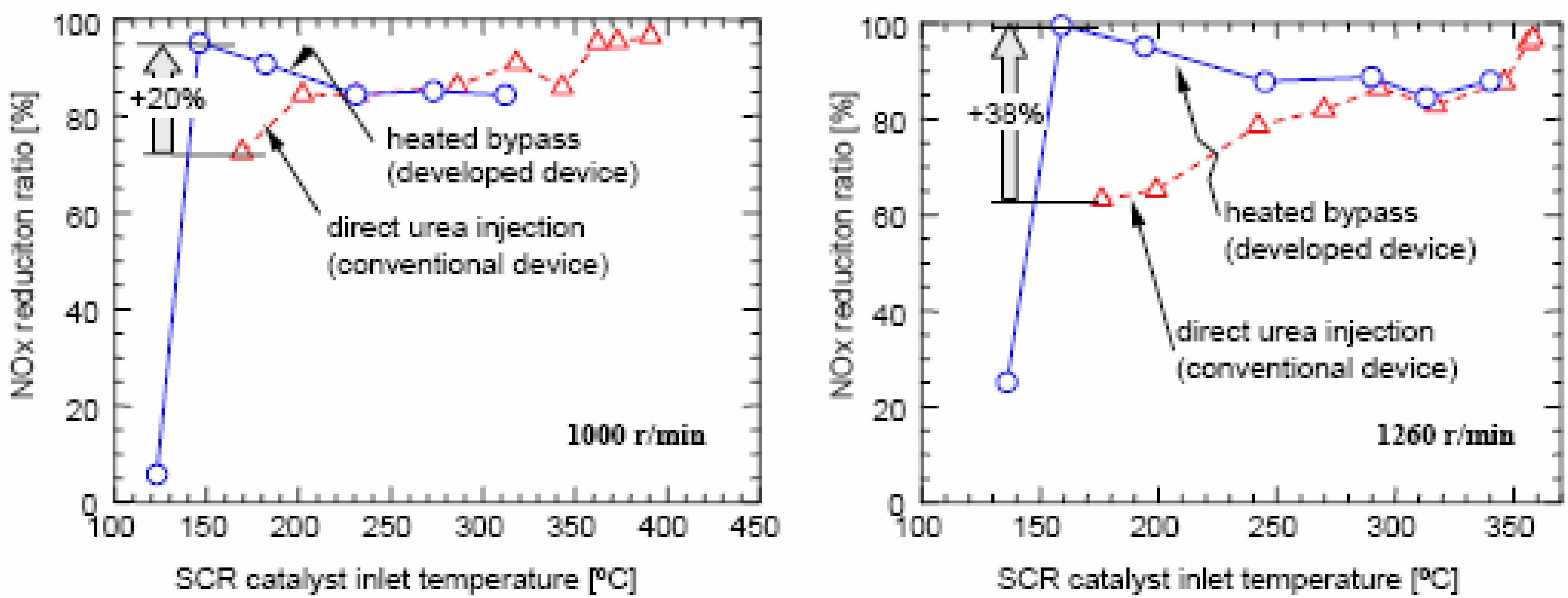
DaimlerChrysler (and auto industry) is proposing urea fills during lube oil change. Use bottles, if needed at the filling station.

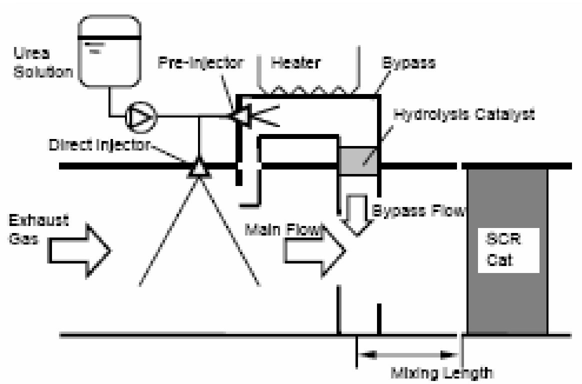


- **About a 1% urea consumption is anticipated. A 16 liter urea tank will be filled at oil drain intervals and can last 16,000 to 27,000 miles.**
    - **Empty urea tank? 600 ml bottle gets the vehicle 450 miles.**

DaimlerChrysler, Vienna Motorsymposium, 5/05

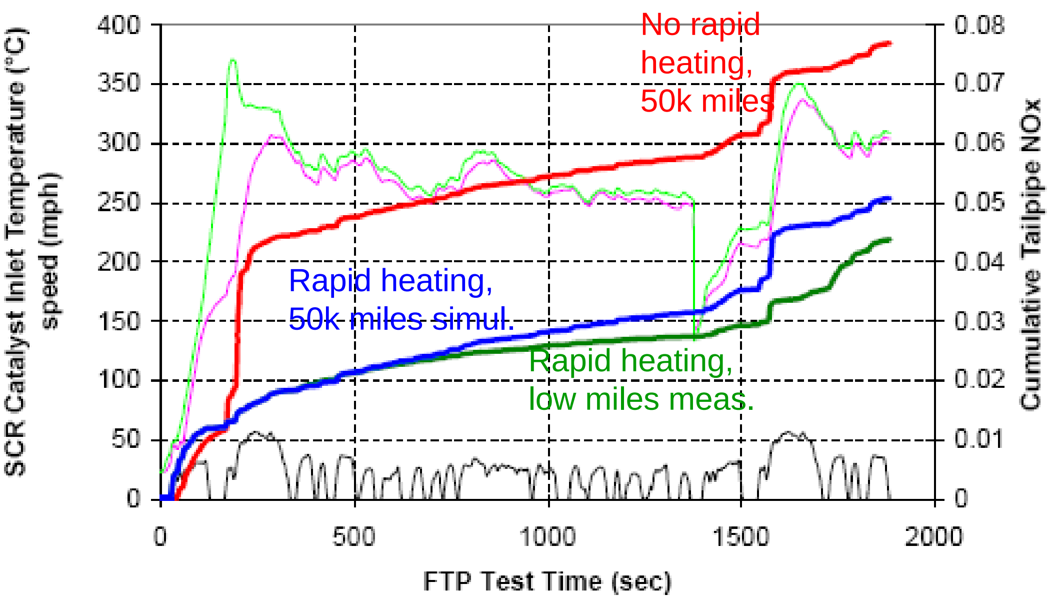
Urea decomposition is critical for good LT SCR operation. New device illustrates effect of LT urea decomposition.



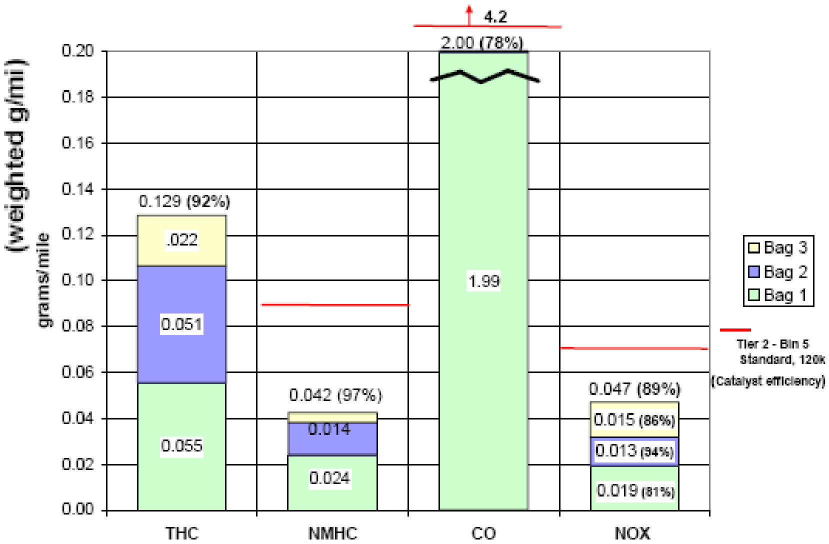


Hitachi, SAE 2006-01-0642

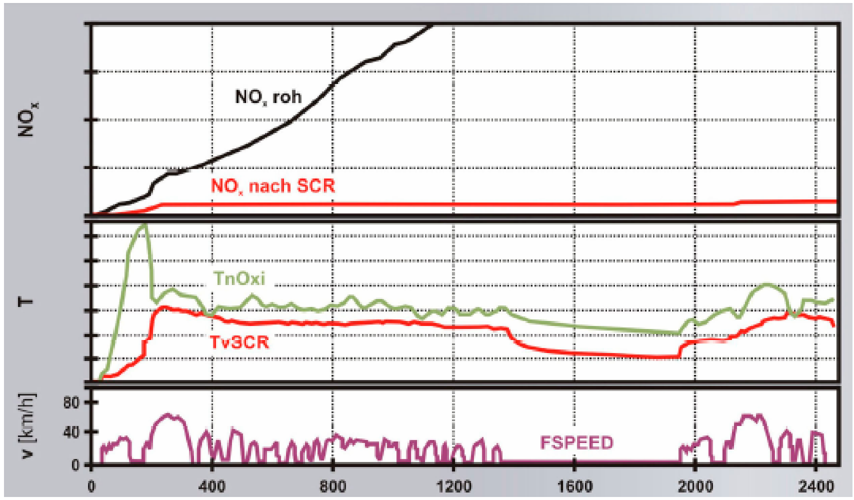
Rapid SCR heat-up strategies are making progress towards getting large vehicles to Bin 5



Ford, DEER conf. 8-05



Fast heat-up strategy approaching goal. 6000# vehicle, low mileage. Bag 1 includes cold start emissions.



HC injection is used to achieve fast light-off of the system.

DaimlerChrysler, Vienna Motorsymposium, 5/05

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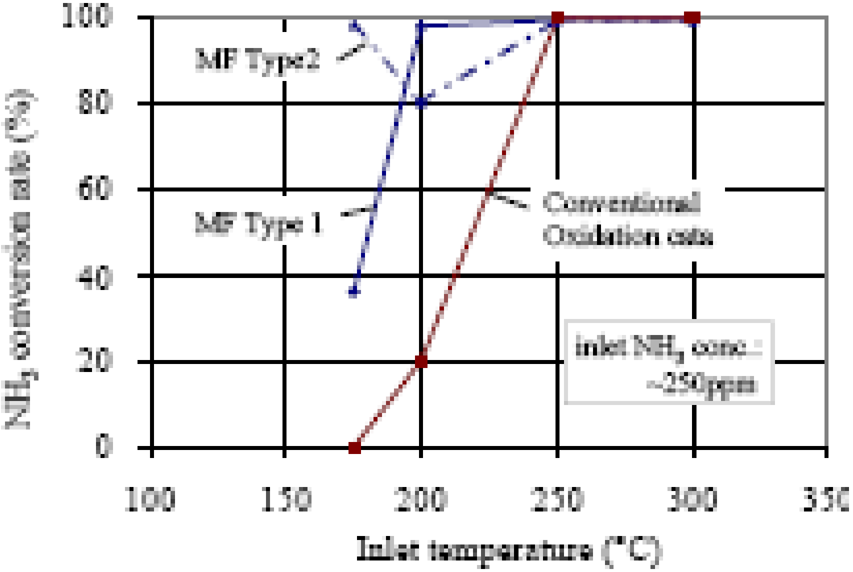
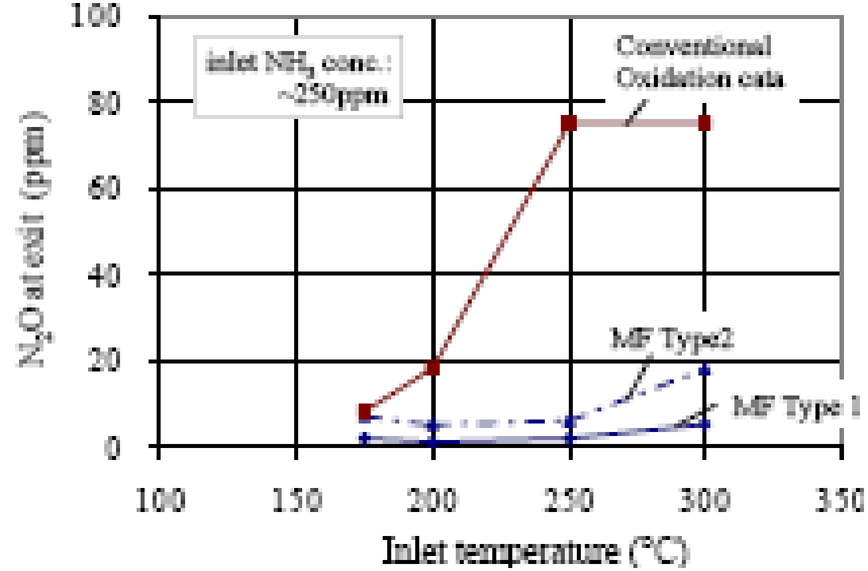
A new V-free, TiO_2-based SCR and slip catalyst is described.

Very high NH_3 conversion rate to N_2 is described. Good SCR capability.



The multifunction catalysts take out NH_3 at T>200C. MF2 stores NH3 at 175C (actual 50% conversion).
SV=100,000/hr, 250 ppm NH_3, 625 ppm NO, engine exhaust.



Much less N_2O is formed in slip catalyst vs. typical oxidation catalyst.

Two multifunction SCR catalysts (SCR+slip) were evaluated. All catalysts are V-free, TiO_2-based. Engine is 1.5 liter. Front 300-csi DOC SVR=0.6. Front CSF SVR=1.65. All SCR and MF catalysts are coated on 600-csi substrates.

Babcock Hitachi, SAE 2006-01-0641

Lean NOx Traps

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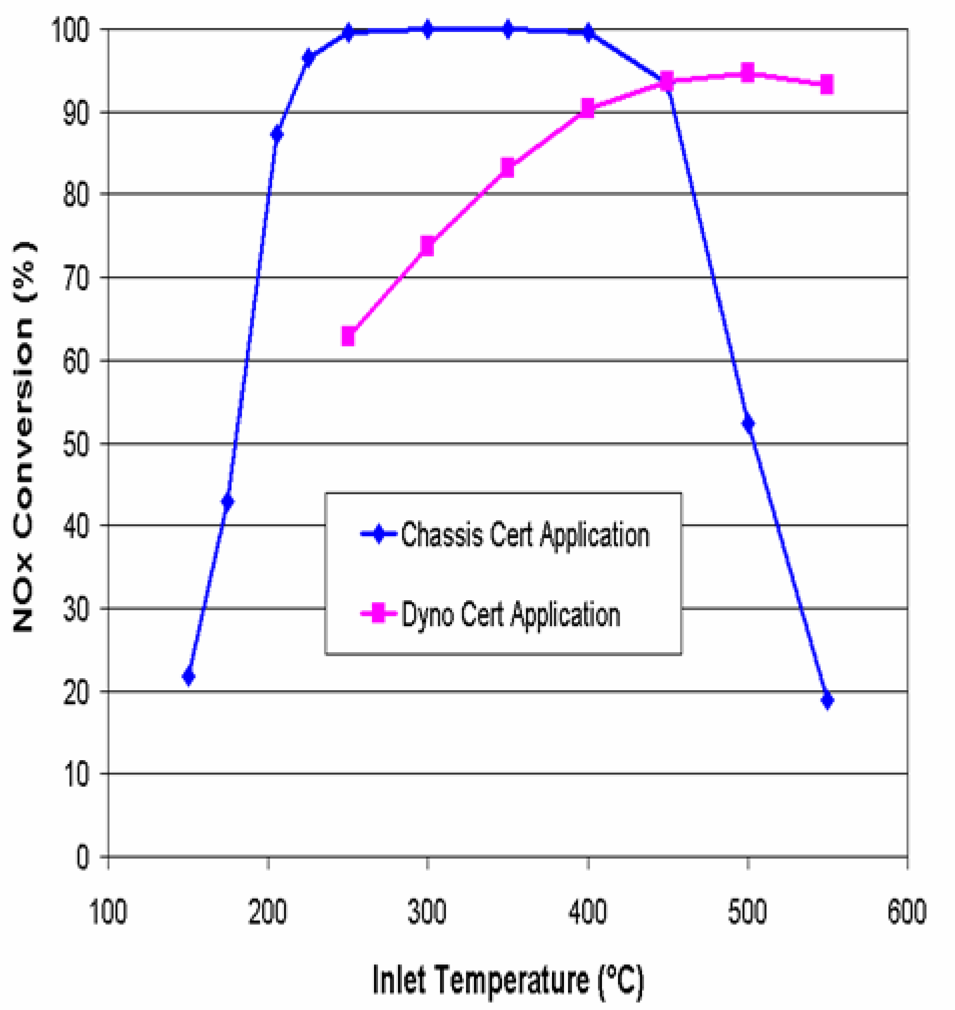
LNTs are being designed for LD and HD applications



For chassis cert, the issue is cold start and LT NOx efficiency.

For engine (dyno) cert, the issue is HT efficiency at 500C and under high flow rate and NOx flux.

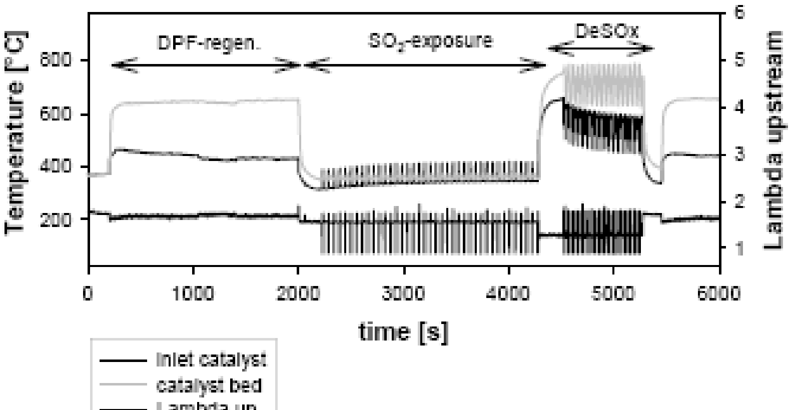
Catalysts Hydrothermally Aged 5h 800°C

- ➔ Chassis Cert Application
  - » SV=30K, NOx flux=0.2 g/L
- ➔ Dyno Cert Application
  - » SV=120K, NOx flux=0.8 g/L

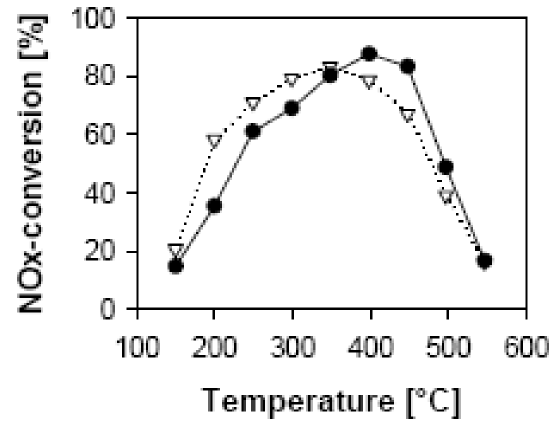
Engelhard, SAE Gothenburg 9-05

State-of-the-Art LNTs get 63% NOx efficiency at SVR=0.9

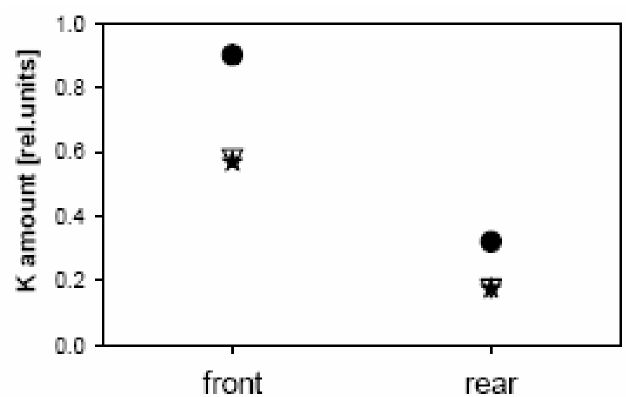
Umicore SAE 2006-01-1369



Aggressive SOx and HT aging uses LNT to heat up DPF using 100 ppm sulfur fuel. Full life simulation.



K and Ba formulations show similar performance after 108 aging cycles. 30,000/hr SV



K anchoring is improving. Graph shows relative amounts of K that was lost from LNT. K loss drops from 3.7% to 3.1%. K is captured on downstream SiO_2 substrate.

On vehicle:

- 3.2 liter V6 (Euro 4?)
- SVR=0.94, full useful life aging, 110 g/ft3 PGM
- US FTP: 63% NOx reduction

Comments:

- Need nominal 120 mg/km (Bin 8) engine out to hit T2B5. Efficiencies will be higher with cleaner engine.
- Compared to SCR: Assuming $200 urea system, this LNT cheaper for < 2 liter engine. Assumes washcoat, substrate, can, DOC at same cost. LNT much cheaper if also performs as DOC

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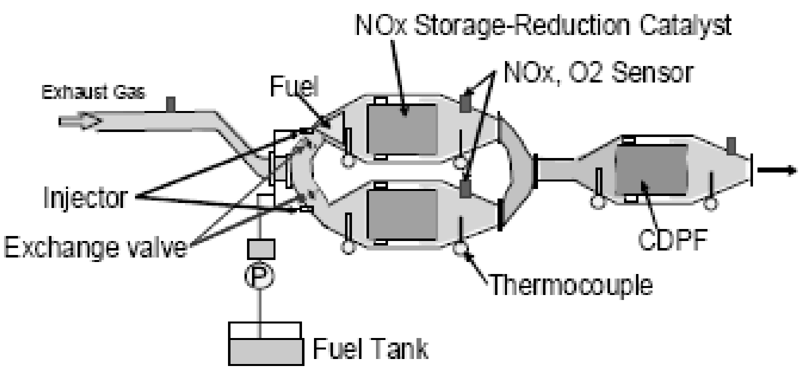
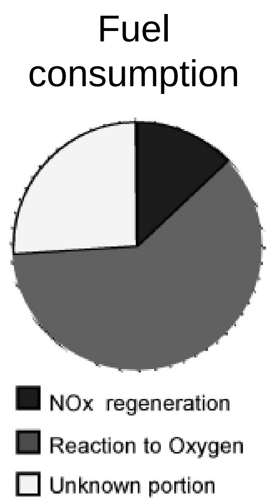
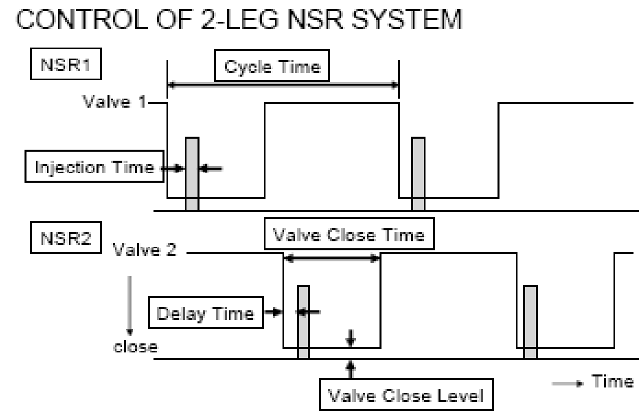
Dual-leg LNT system saves fuel and reduces size of the system. 80% efficiency at SVR=1.4 and fuel penalty of 1.4% at full load and speed.

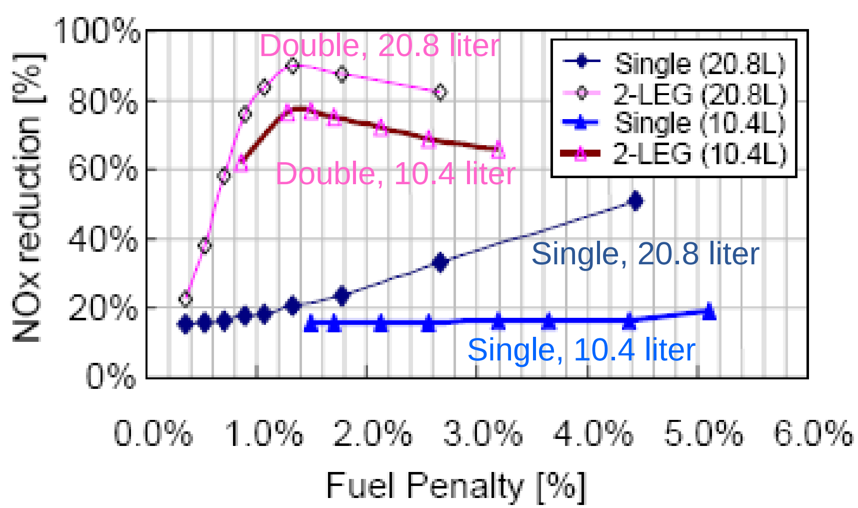


Dual leg LNT system architecture. 7.7 liter, CR, boosted engine; 2X10.4 liters LNT, 8.5 liter CDPF. 7 bar injectors, 18 holes





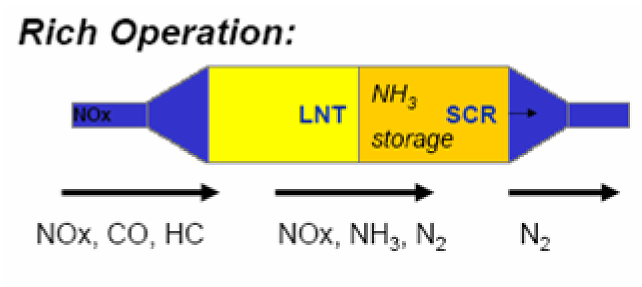
Control system is a function of operating point.



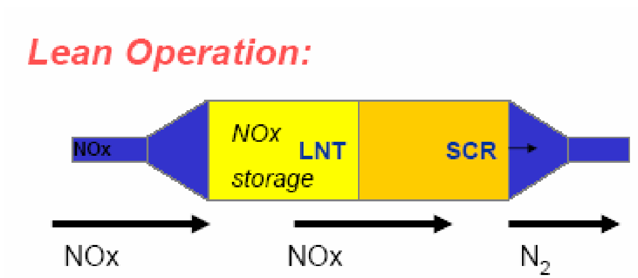
At 100% load and 100% speed, 10.4 liters of LNT (SVR=1.4) achieves 78% NOx reduction at 1.4% fuel penalty.

Hino, SAE 2006-01-0211

SCR catalyst is added after an LNT to increase system efficiency

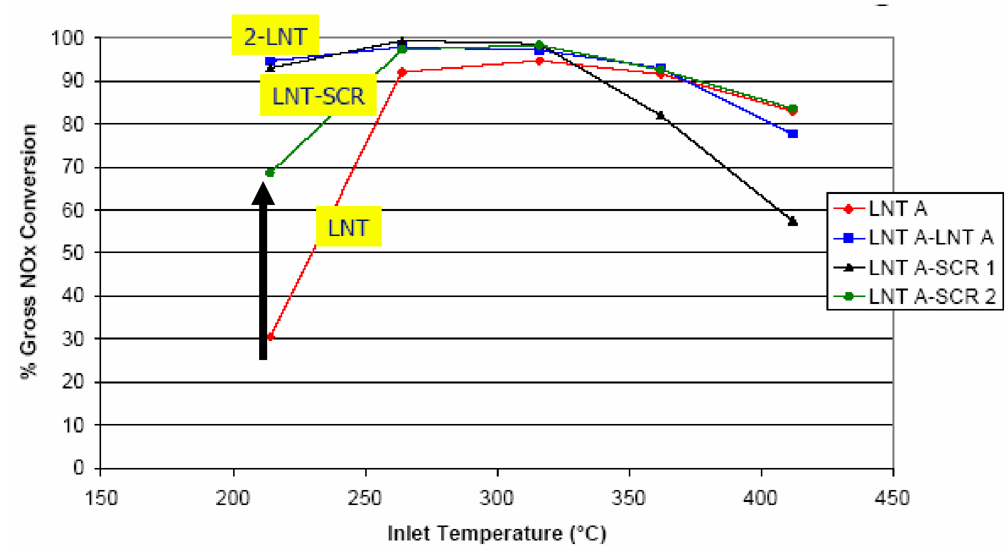


Rich operation: NH_3 is produced in the LNT, and converts NOx slip in SCR; some NH3 is stored

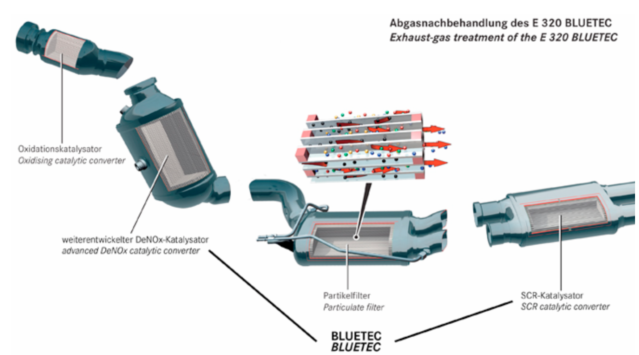


Lean operation: LNT does most of the NOx reduction

Ford, DEER 8/05

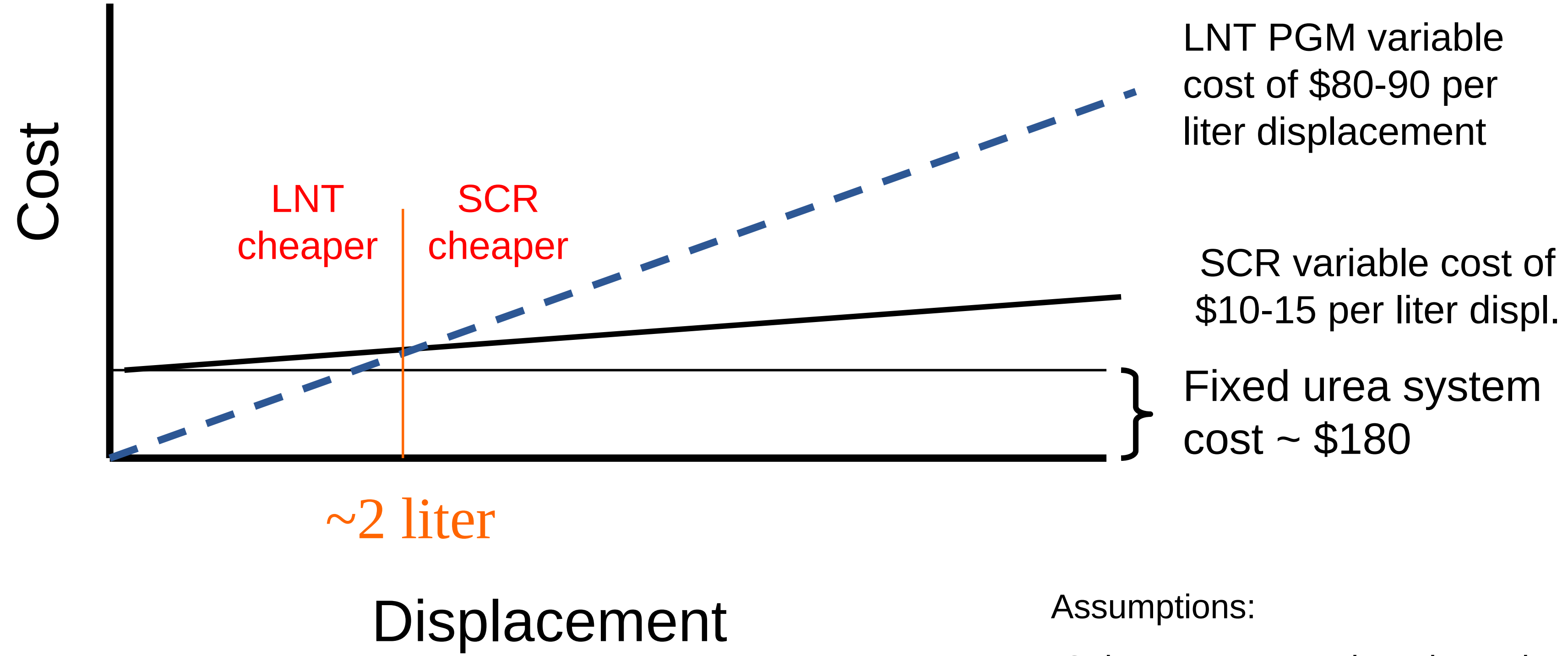


LNT+SCR performs better than LNT alone.



DCX going commercial with concept in Fall 2006.

First-cost economics favor SCR for engines larger than about 2 liters. Aggressive mixed mode and urea system (potential future systems) have breakeven at 5 liters displacement.



Assumptions:

•Substrate, can, and wash coating costs are the same for LNT and SCR

•SVR=0.8 assumed for LNT and SCR; NH_3 slip catalyst SVR=0.25, PGM 30 g/cu.ft.; PGM LNT = 80 g/ft^3;

•PGM at $40/g

PM Control

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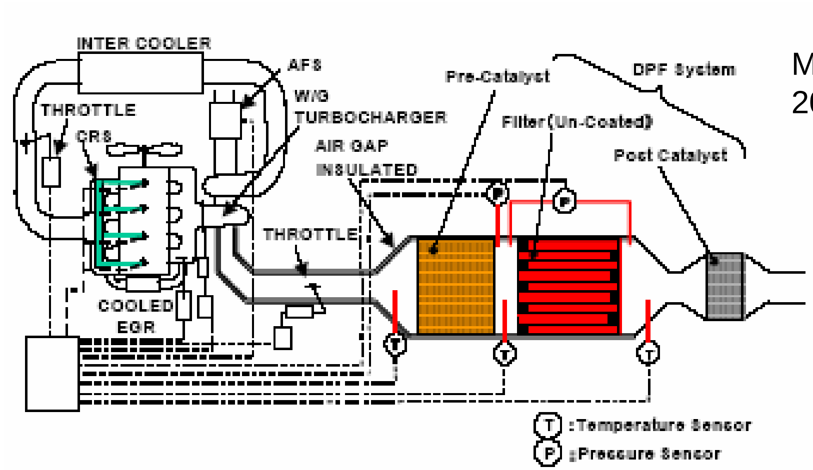
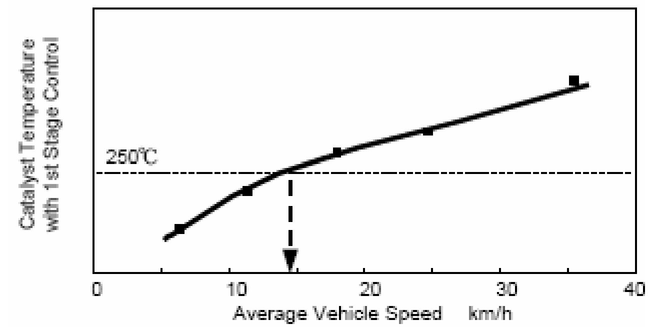
Mitsubishi FUSO describes their DPF management strategy. Intake and exhaust throttles, optimized DOC heat-up, and cumulative oxygen delivered to DPF to control regeneration duration.

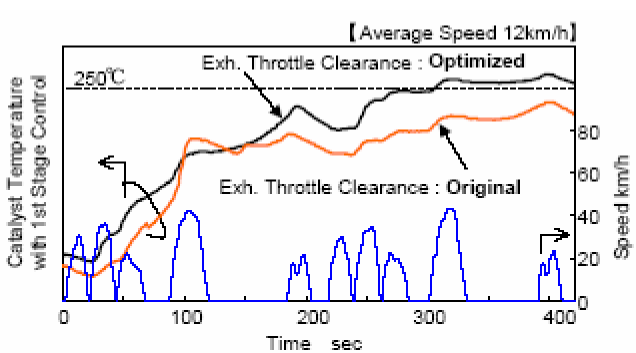


Mitsubishi FUSO, SAE 2005-01-3694



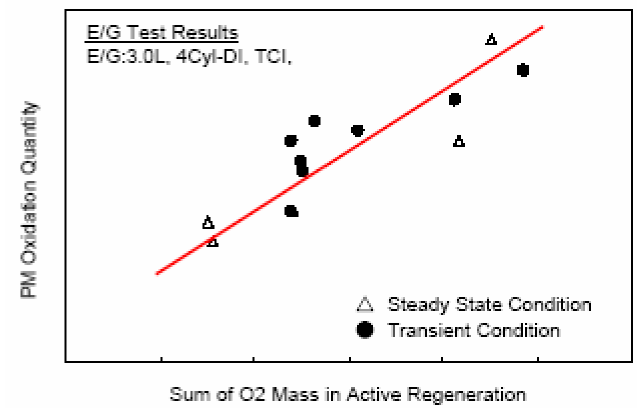
Avg. vehicle speed needs to be 14 km/hr to actively heat DOC to 250C. Not doable in stop and go traffic.

4.5 ton LCV, 3.0 liter engine; Intake and exhaust throttles, uncoated SiC DPF.



Optimized exhaust throttle control and fuel injection is used to heat DOC to 250C, even at ambient temperatures of -10C.

Method developed to maintain DPF temperatures during delivery truck cycles, during extended decelerations, and in -10C ambient conditions



Cumulative oxygen delivered to DPF during regeneration is used instead of time to control duration. Saves 20% of fuel at 44 km/hr. Minor savings at 18 km/hr.

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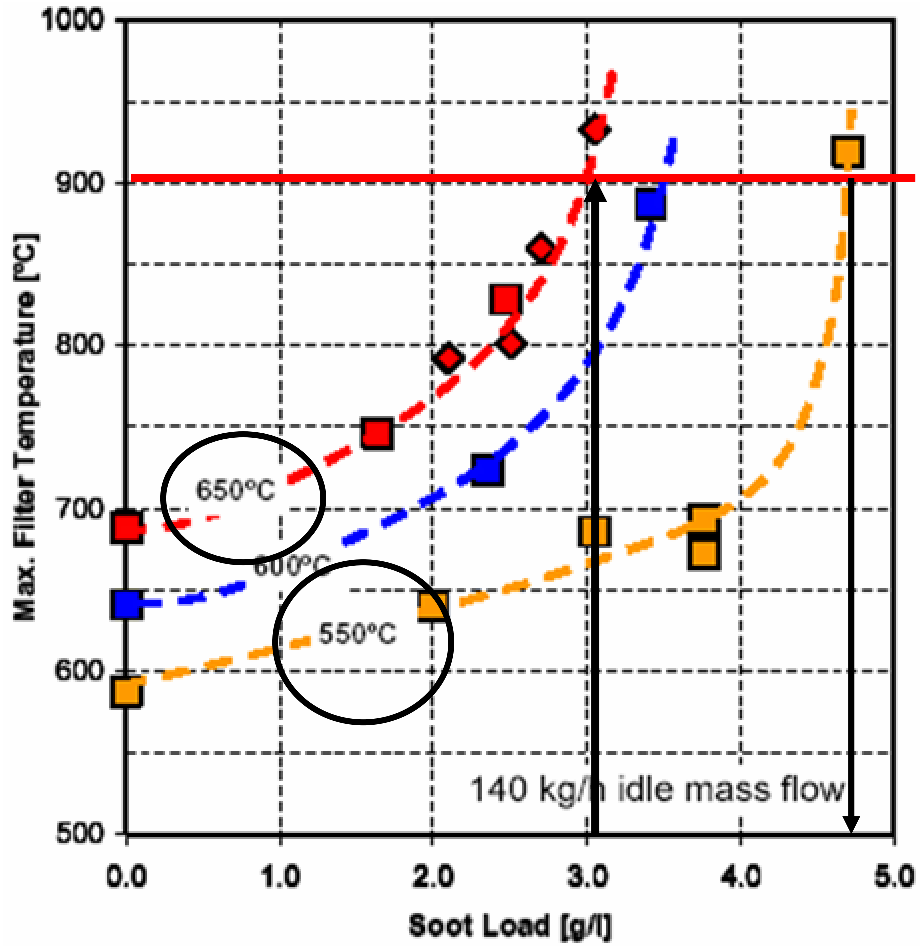
DPF regeneration response of cordierite is described. Suggests multiple regeneration steps: 550C inlet temperature at high loadings and increased temperature as soot is burned.

Increase inlet temperature: faster and more complete regeneration



Soot burns

In this case, max. DTI temperature is 900C

Other means of managing cordierite: EGR, geometry, catalyst, control models

Corning, SAE Commercial Vehicle Conf, 10/05

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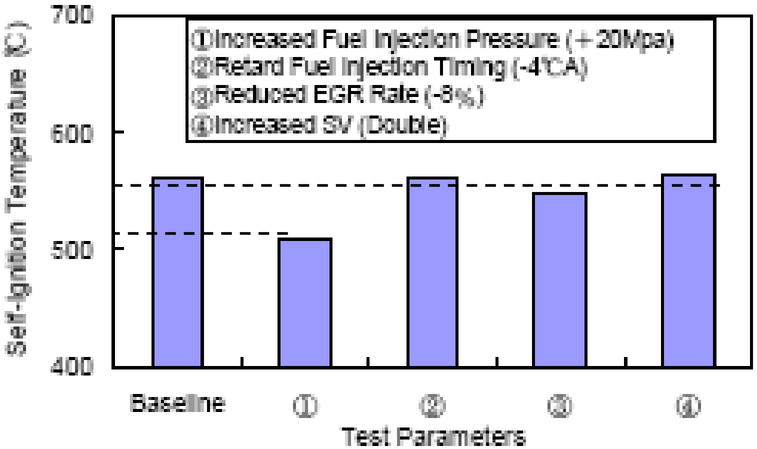
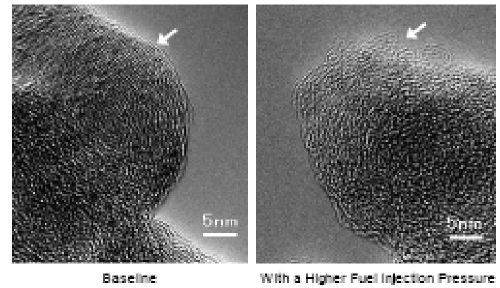
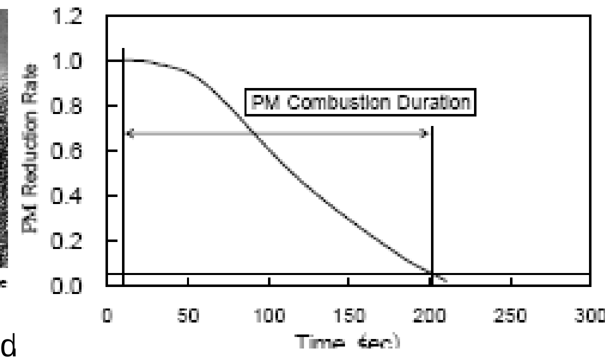
An algorithm is developed to safely control DPF regeneration.



Increased fuel injection pressure is the only evaluated parameter that affects soot oxidation temperature.



Soot morphology change observed for increased injection pressure.

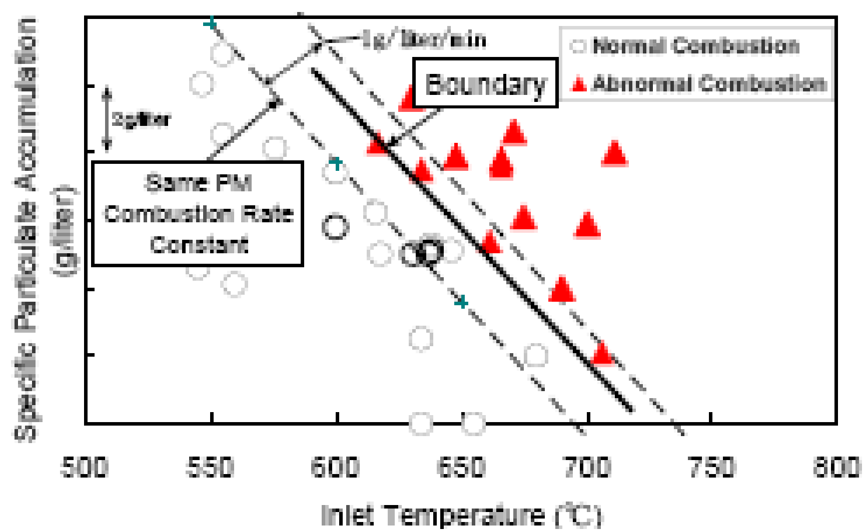


Method used to obtain oxidation rate constant (soot amount/combustion duration). Chart obtained from visual observation.

Coefficients for rate constant

n	Independent Variable (X_i)	Standard Regression Coefficient (β*)
1	Filter Temperature	0.90706
2	Specific Particulate Accumulation	0.48803
3	Oxygen Flow Rate	0.04632

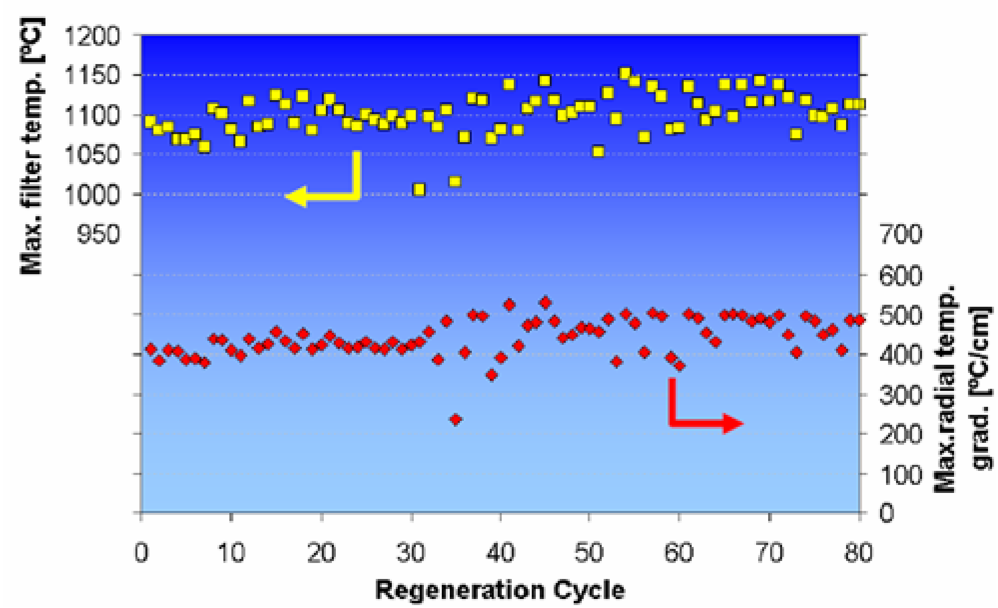
$$S = \exp(A_1 \cdot X_1 + A_2 \cdot X_2 + A_3 \cdot X_3 + B)$$



Combustion rate constant and inlet temperature are used to detect threshold between normal and abnormal regeneration.

Hino, SAE 2006-01-0878

Durability of aluminum titanate filters is described

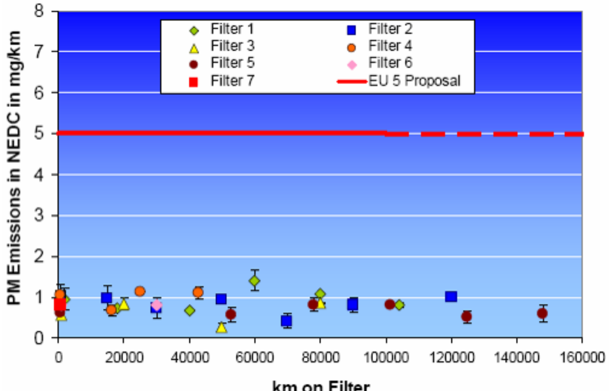


Temperatures and gradients for 80 severe uncontrolled regenerations. FSN was acceptable after every test. Gradient from TCs 10 mm apart in periphery 25 mm from back face.

Crack-free DPF after 55 severe uncontrolled regenerations and 90 standard regenerations.

VW, Dresden Conference, 5/06

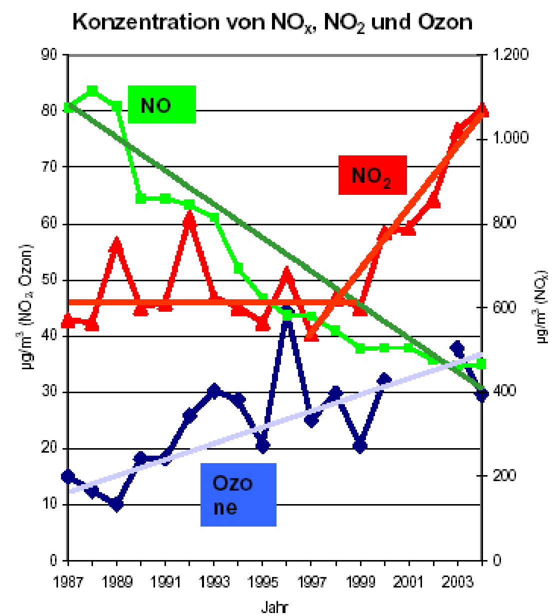
First single component DPF system to go commercial.



Some secondary issues to resolve

CORNING
Discovering Beyond Imagination

NO_2 is increasing on German autobahn due to DOCs on LDD

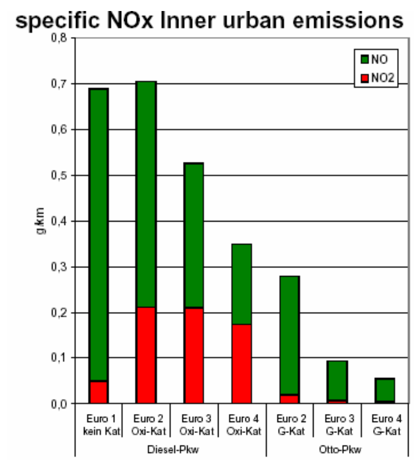


Source: IFEU 2005

Measurements at the Autobahn A 4

measurement values NO- and NO_2-immissions between the lanes (yearly average)

- NO- reduction about 60 %
- Ozone : increase by a factor of 2 - 3;
  from 1999 increase of about 20 %
- **NO_2** no change until 1998
- from 1998 to 2004 twofold increase



Quelle: IFEU im Auftrag des UVM 2004

Specific NOx and NO_2 emissions of PC

- Diesel-PC have much higher specific NOx emissions than Otto-PC….
- and have additionally higher NO_2 shares
- The specific NO_2 emissions of Diesel-PC in analysed investigation were between 6 until 50 fold higher than for Otto-PC

Cause:

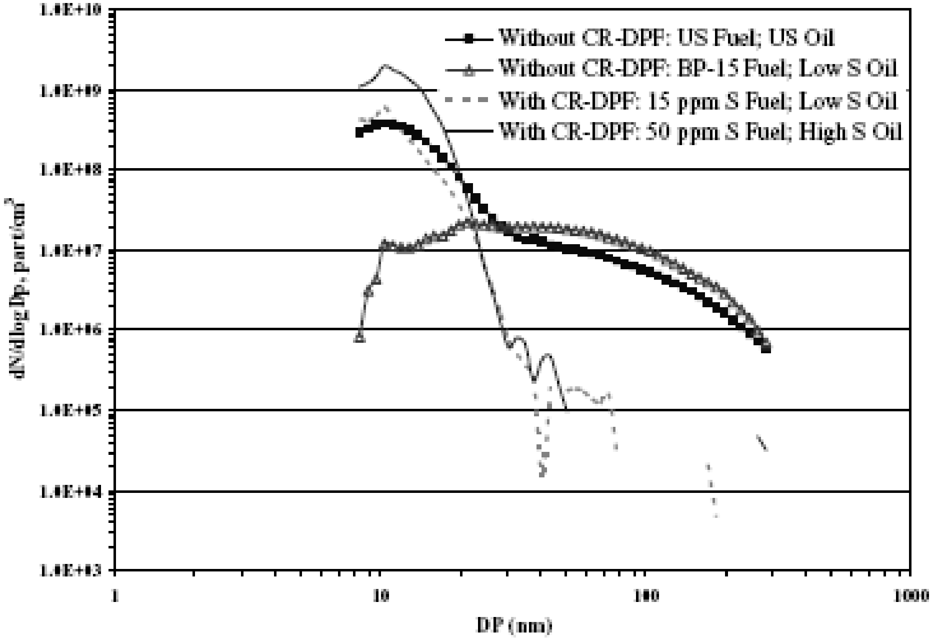
Use of Oxidation catalysts starting with Euro 1 (from 1993)

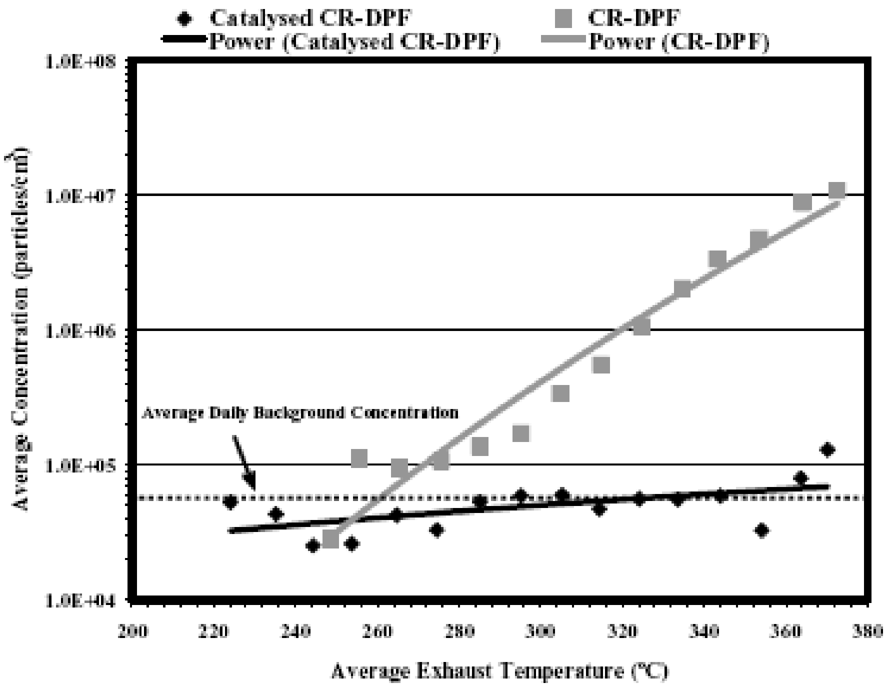
Conclusions of Analysis

- Direct emissions of PM and NOx need to be drastically reduced
- NOx emissions are relevant for secondary PM but also for many other environmental problems
- Road transport is major contributor to both, PM and NOx, and is therefore a key target for additional measures
- There is a urgent need to control NO_2
- Planned and adopted measures are insufficient

UBA, 9/05

Ultrafine emissions from filtered truck are described.





Filters take out 99+% of soot particles, but can increase sulfuric acid aerosol particles <30 nm, even with LS fuel and lube oil. Effect strongly depends on atmospheric conditions. 100 km/hr cruise for HDD truck.

New catalyst component (sulfur trap) added to filter drops sulfuric acid aerosols to below ambient concentrations.

Univ. MN SAE 2006-01-0916

CORNING

LDD future: potential for super ultra-low emissions;
minimizes risk of stranded investment should CARB tighten

"Combining advanced aftertreatment with engine optimization will allow demonstration of a system capable of meeting the requirements of U.S. SULEV / Tier II Bin 2…"

"These advanced diesel technologies will be integrated into a vehicle capable of meeting the lowest current worldwide exhaust emissions standard (SULEV, Tier II Bin 2) without compromising customer appeal…"

"…combining engine-out optimization with advanced aftertreatment, a highly cost effective solution is expected."

Ricardo press release August 2006.

Earlier Bin 3 demos: SwRI SAE 2005-01-1091; mixed mode engine, CSF+LNT

DDC DEER 2003; 4.0 liter LDT CSF+SCR

Summary

- Regulations
  - Europe is in middle of determining Euro 5 and Euro 6 (LD) levels
    - Implications to US approach
  - Europe will begin formal Euro VI proposals early next year
- Engine strategies are making impressive progress
  - Advanced strategies will save on aftertreatment; require significant combustion control
- NOx solutions are available for ultra-low emissions
  - SCR is addressing cold temperature and secondary emission issues
  - LNTs are performing well today at about 60-70% efficiency; economically attractive for smaller platforms
- DPF systems show continuous improvement
  - Very sophisticated regeneration control strategies; aluminum titanate durability described
- Some outlying issues yet to be addressed
  - NO_2 and ultrafine PM