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Diesel Emission Control in Review

Dept. of Energy DEER Conference

Tim Johnson
August 2007

Summary

- Regulations
  - European LDD regulations have implications to the US approach
  - Europe is formally proposing Euro VI (HD) this year
    - Wide range of scenarios considered – no industry consensus
  - CO_2 regulation appears to be the most dominating long term issue
- Engine strategies are making impressive progress
  - HD research engines show very low PM levels under steady state full-load conditions
  - Advanced combustion mixed mode engines are emerging for LD and HD
- NOx solutions are available for ultra-low emissions
  - SCR is addressing cold temperature and mixing issues
  - LNTs are performing well today at about 60-70% efficiency; hybrid LNC/SCR systems emerging
- DPF systems show continuous improvement
  - Very sophisticated regeneration control strategies.
  - New catalyst formulations add flexibility and improved performance
  - HC mix from advanced combustion engines might present challenges

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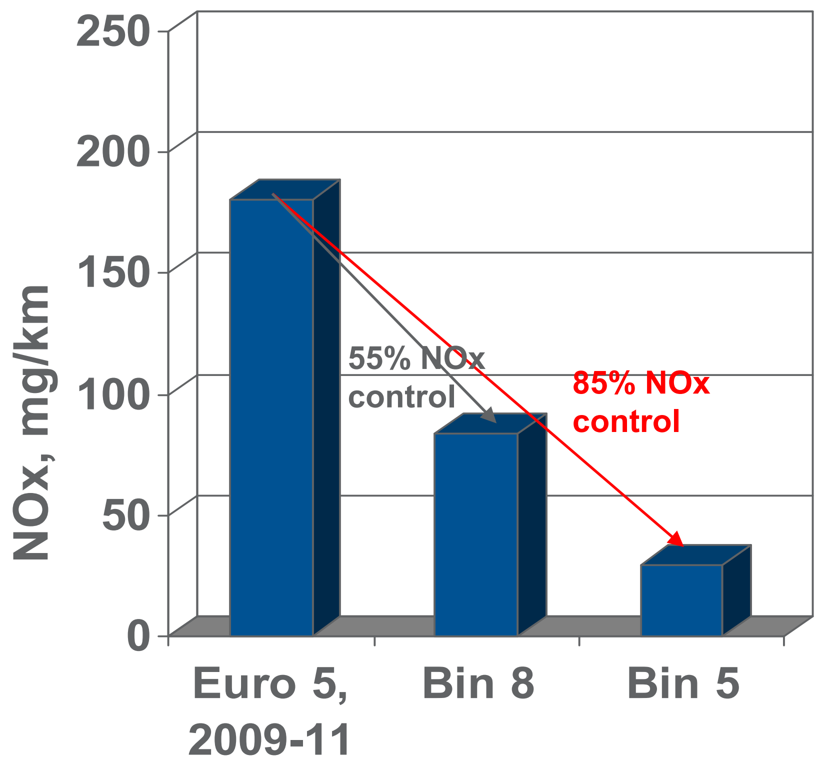
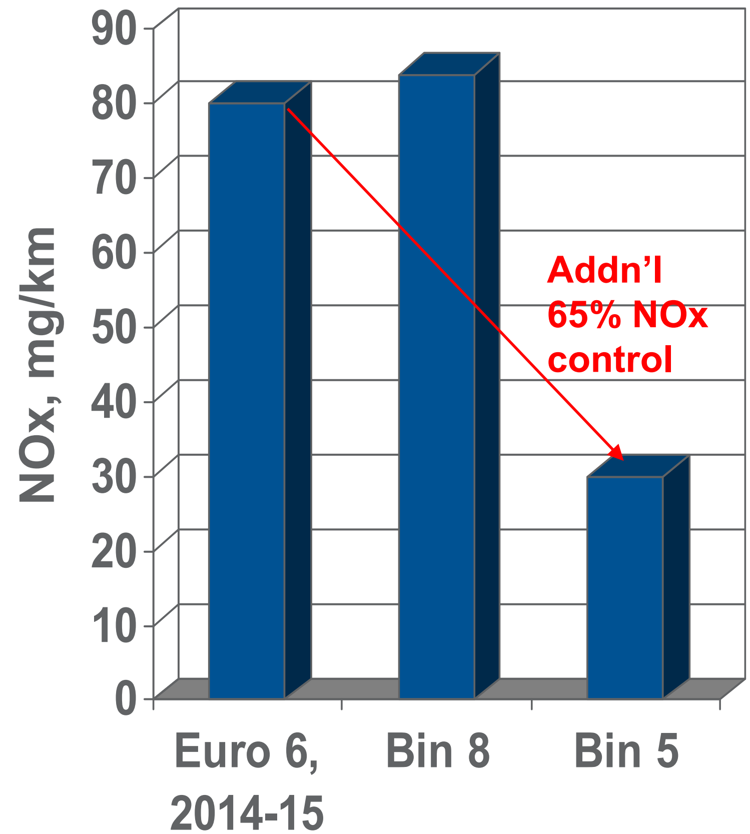
Regulatory Trends

To sell Euro 5 cars into the US market, a minimum of 50-60%% NOx control is needed to hit a 42-state market (70% US). For Euro 6 (2014), 65% additional NOx control would address the 50-state market.

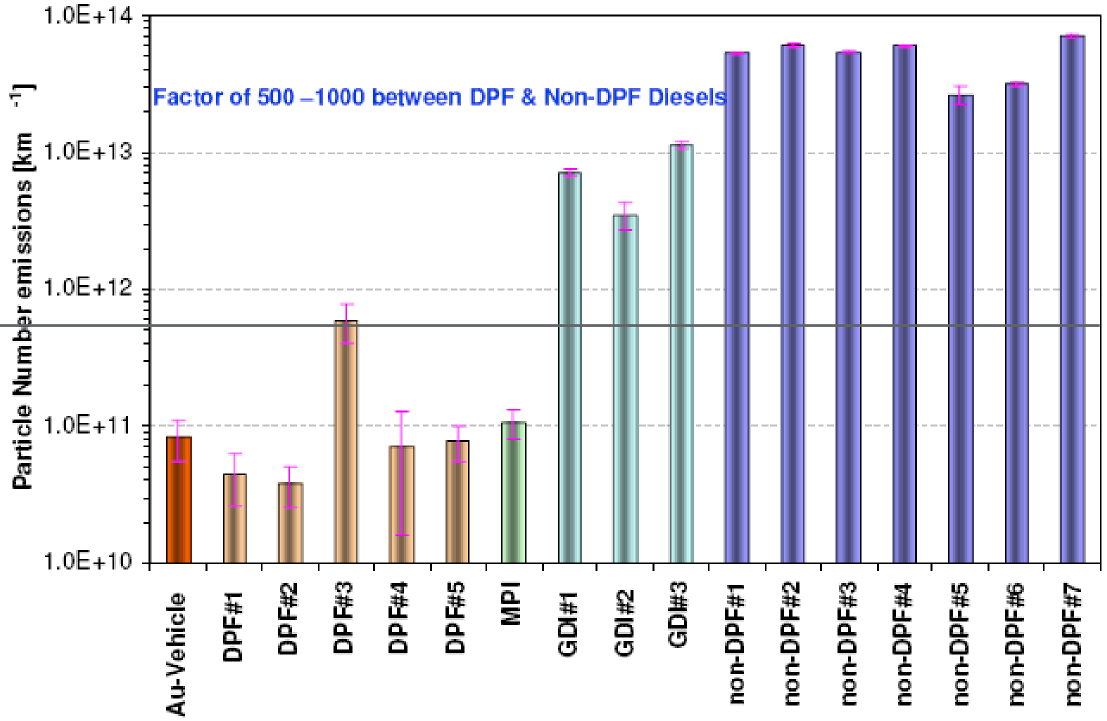




Ultrafine emissions regulation in Europe is moving forward

EC JRC, PMP ETH conf 8-06

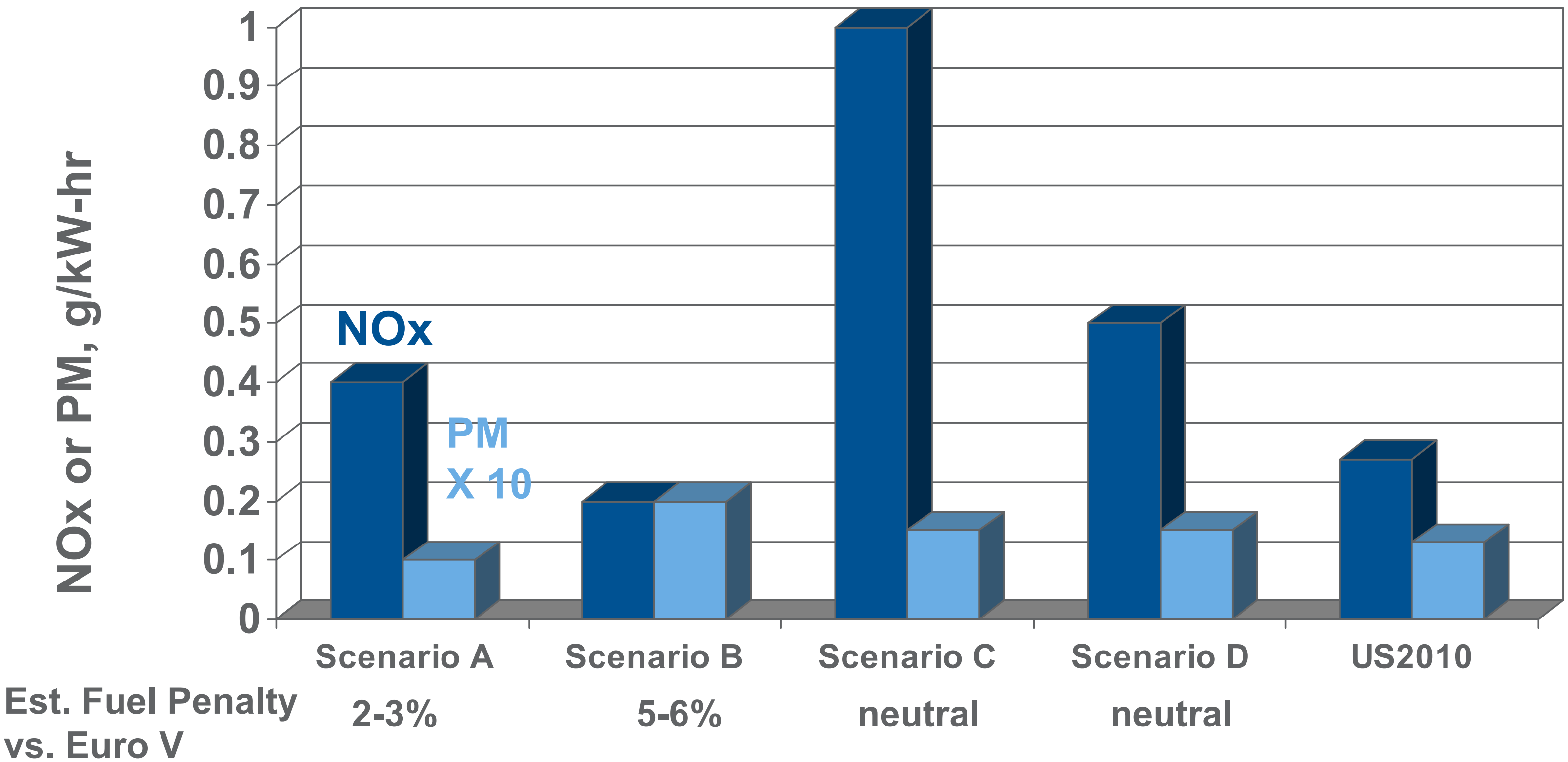
5X10[11]/km, diesel only



Euro 5.5 particle limit values of 3 mg/km; P# $5X10^{11}$/km for 2011-12

- Best unfiltered diesel at 10^{13}/km, so 95% number efficiency needed.

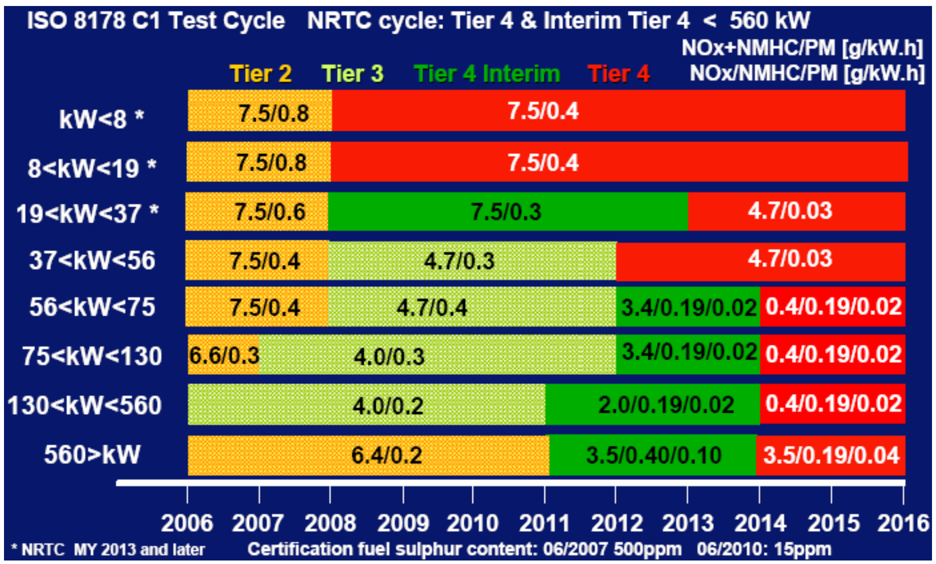
The EU is considering four different Euro VI scenarios.



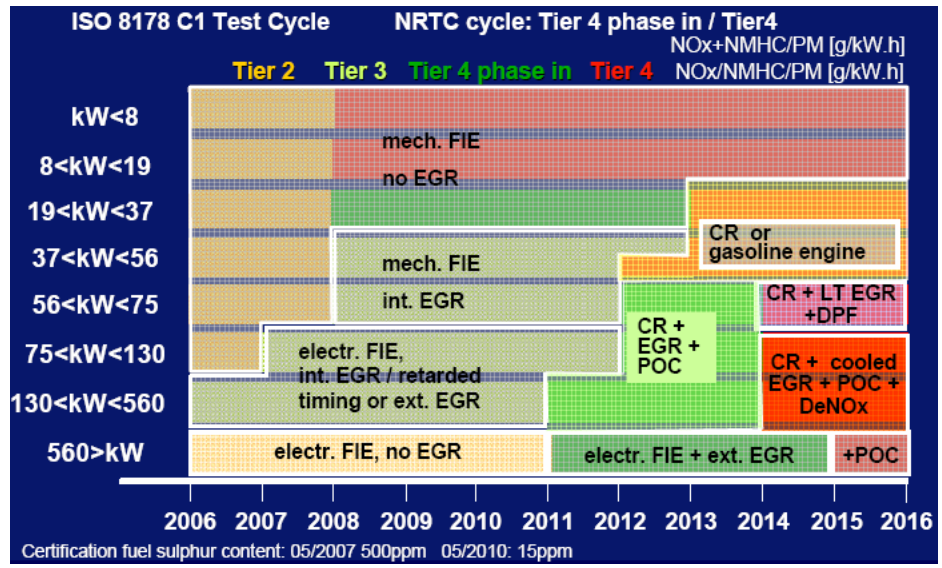
- Number-based PM standards considered.
- Considering also doing Euro VII, but will result in delay.
- Considering fuel consumption vs. criteria emission trade-off.

Non-road engine and emission control systems are described

Regulations



Technology



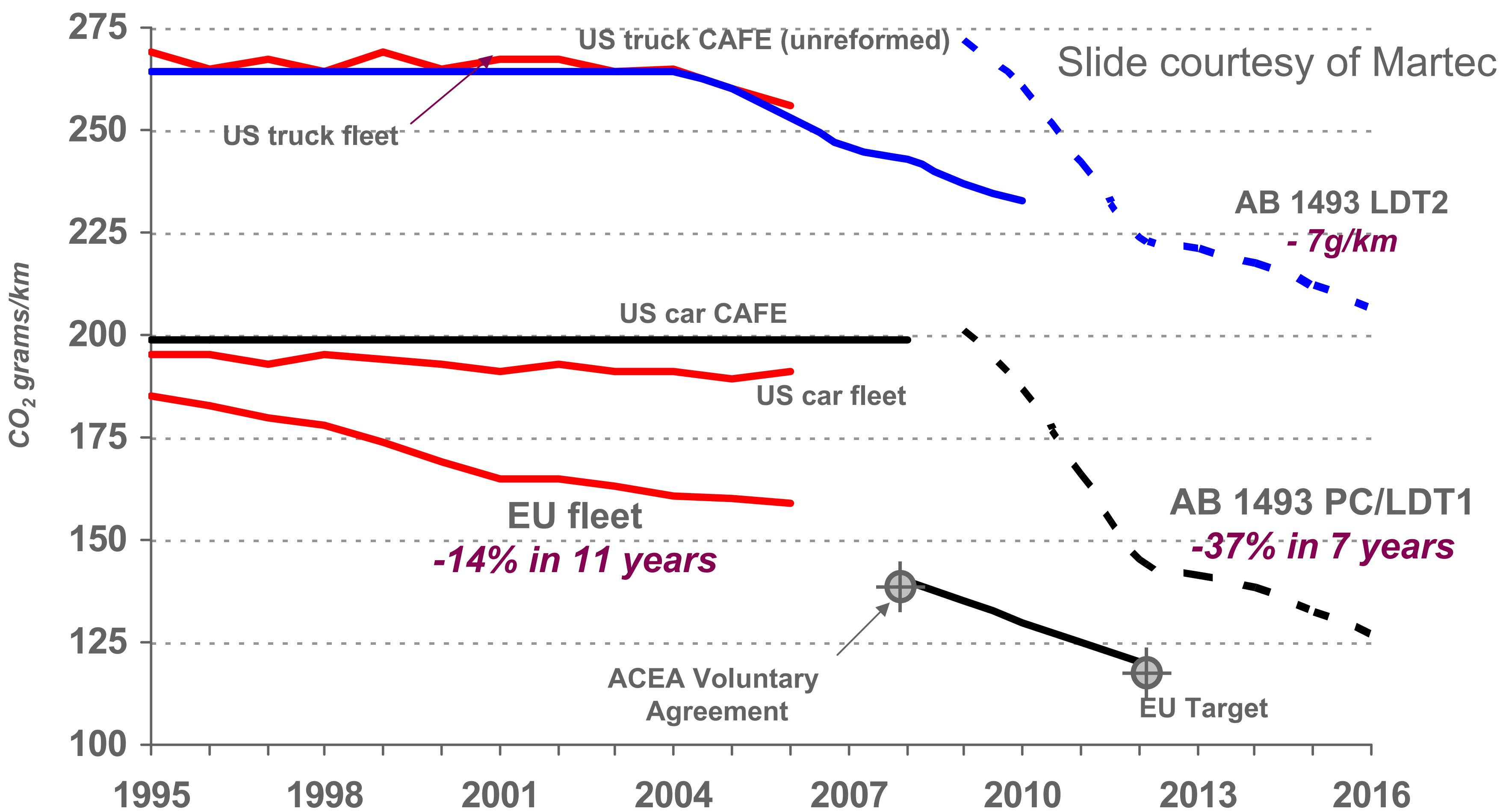
DPFs emerge only in 2014 in one small engine class.

AVL June 2007

Non-Road has significant challenges

- US2007-like regs in 2011
  - Europe and US, with Japan to be formalized
  - Cooled EGR limitations
  - DPFs leading concept, but some are looking a at Euro IV/V SCR approach
- US2010-like regs in 2014
  - EGR+SCR+DPF seems to be leading
  - Much resistance to urea-SCR
- Best solution seems to be mixed-mode with HC-deNOx (LNT or LNC) and DPF
  - Timing fits
- Huge watchout
  - NR moves into engineering in 2009. Conflicts with US2010, Euro VI, and US LDD
    - Industry resource crunch, especially in supply chain and for dynos
    - Medium sized NR companies appear behind, already

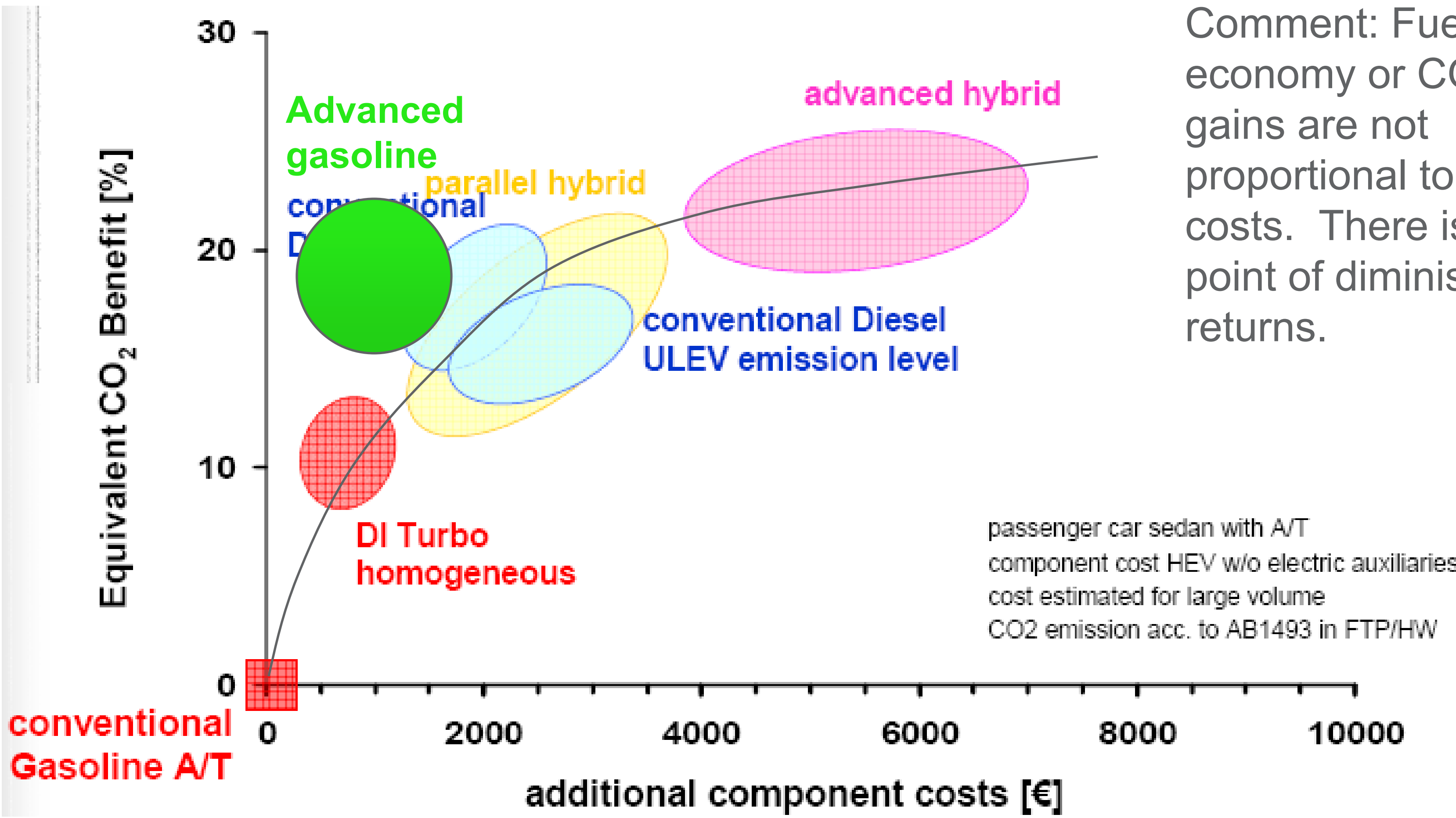
AB 1493 forces the fleet average 21% below the 2006 EU fleet actual. 37% cut in 7 years required



US and EU test cycles are not equivalent. ARB standard includes GHG losses from AC system. AB 1493 LDT2 definition includes 8,500-10,000 lb. gvw MDPVs. Fuel economy conversions at 19.55 lb CO_2/gallon gasoline and 22.43 lbs/gallon diesel. US fleet excludes flex fuel credits.

Various approaches can be used to achieve higher fuel economy. However, improvements get increasingly more expensive.

FEV, AVL Environ. and Motor Conf. 9/06



Comment: Fuel economy or CO_2 gains are not proportional to costs. There is a point of diminishing returns.

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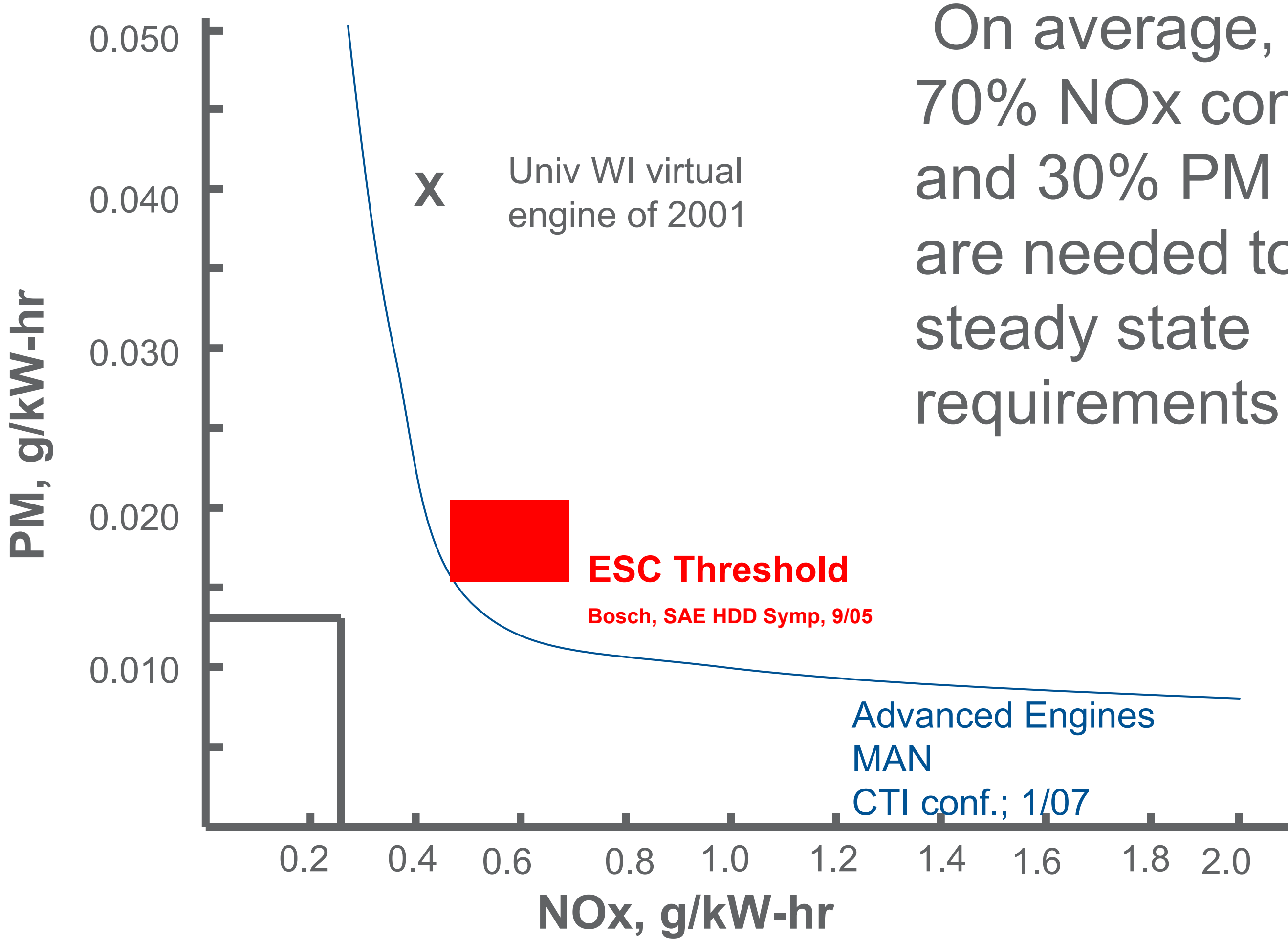
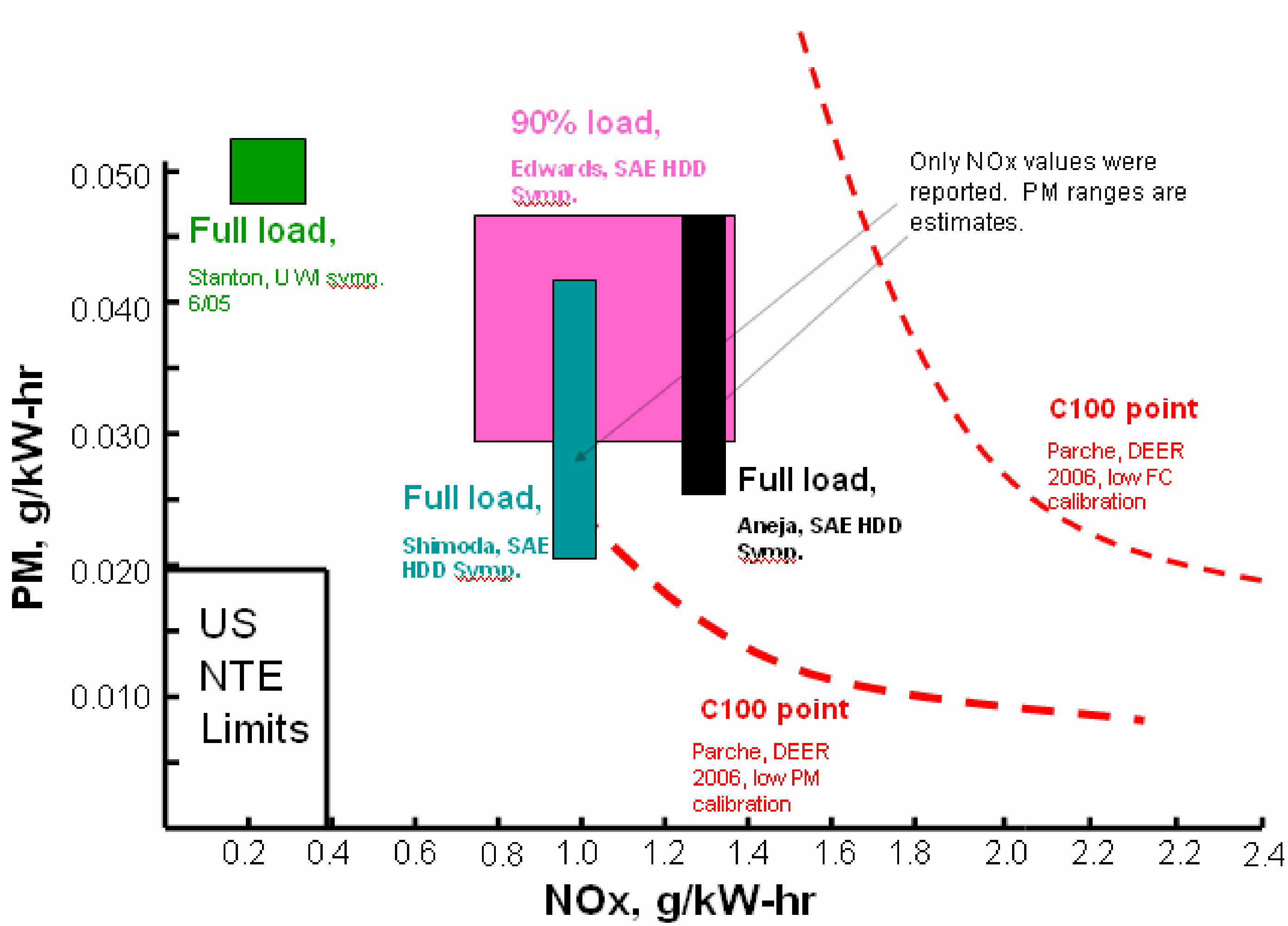
Engine Developments

HDD RESEARCH ENGINES are hitting 0.5/0.015 NOx/PM on the ESC

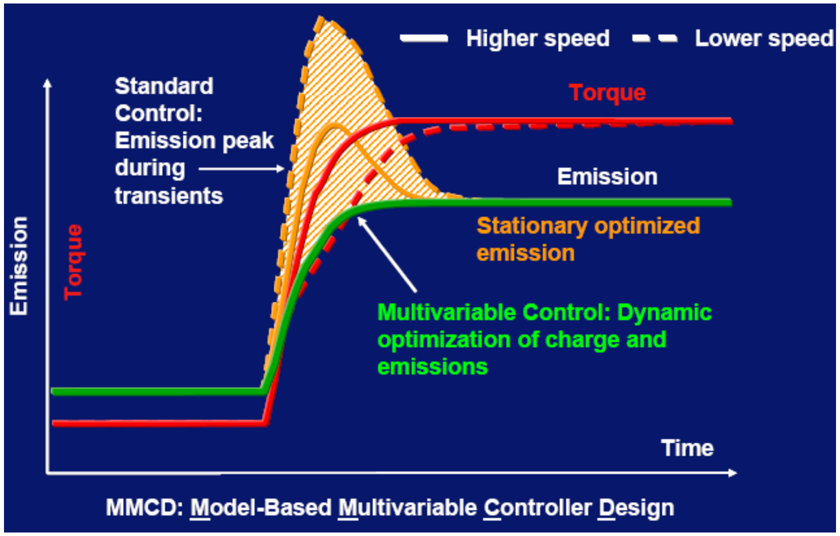


On average, 60-70% NOx control and 30% PM control are needed to hit steady state requirements

HD research engines are showing impressive performance under steady state conditions.



Both hardware (2-stage boost) and multivariable control algorithms help in transient control



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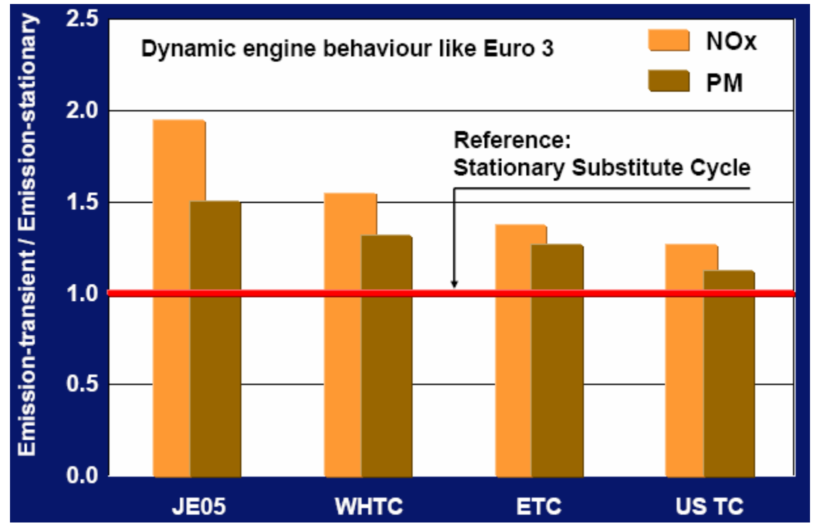
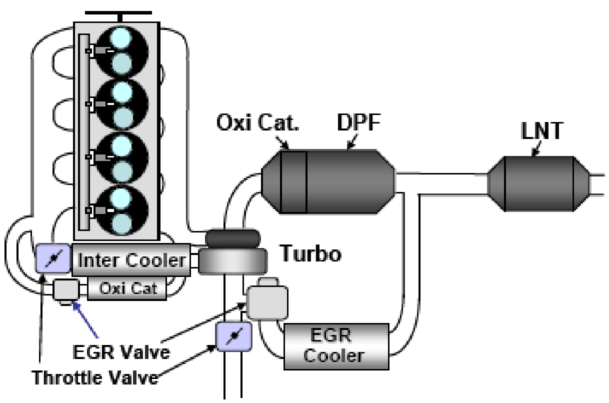


NOx levels are about 25% and PM about 10% higher on the US transient cycle with proper transient controls.

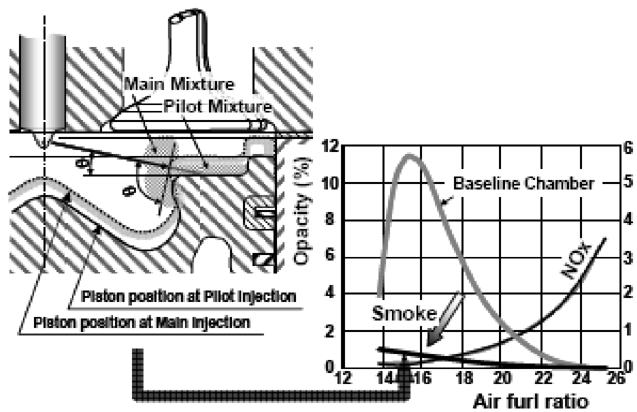
Other findings of interest:

- Transient operating modes are closely correlated to a series of steady state points.
- % EGR may be a better transient control parameter than Mass Air Flow or EGR valve opening. (Ford, Imperial College, SAE 2007-01-1938)

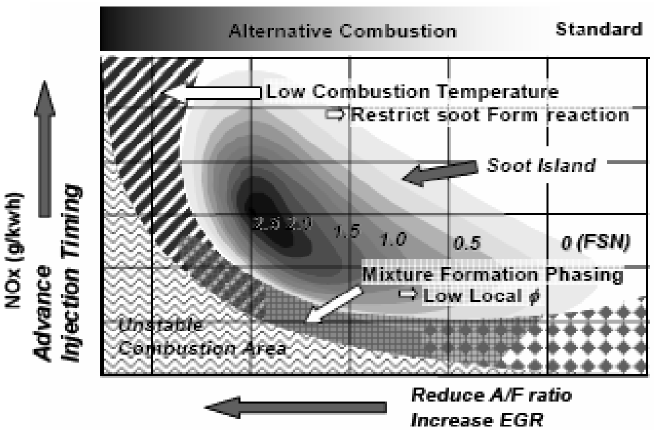
SwRI/Honda describe advanced combustion strategy for T2B5 LDD engine.



2.2 liter engine and system



High EGR and local equiv ratio control (here) are used to minimize soot formation under stoichiometric or rich conditions. Localized control of F/A is used for rich, medium load and for lean operation.



Low load: High EGR to prevent soot. Med load: EGR reduced and local equiv. ratio (physical method) is applied. High load: Standard combustion utilized.

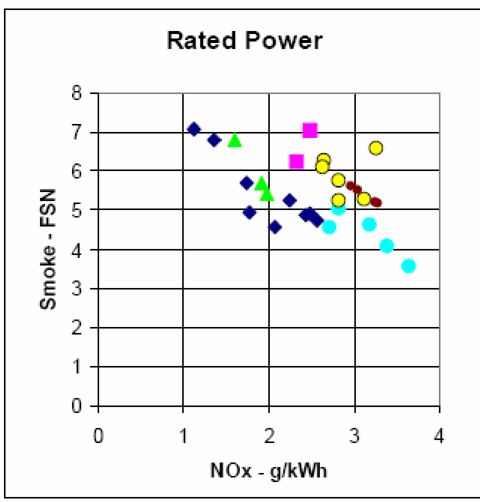
•Retarded inj. and intake throttle are used for fast heat-up.DPF at 250C w/i 30 sec. Low NOx due to adv. comb.
•Throttling is also used to maintain T under low load and idling conditions. Low idle speed used.
•LNT regen at high load uses rich comb + post inj, if necessary. Medium load is rich comb. Low NOx at light load: no regen. Much discussion on rich-lean mode switching.
•TWC to address cold start (Honda, SAE 2007-01-1933)

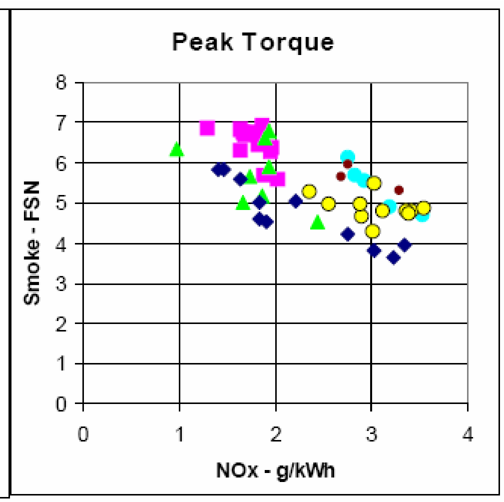
Stoichiometric diesel is being investigated as a non-road alternative

Deere, DEER 8-07

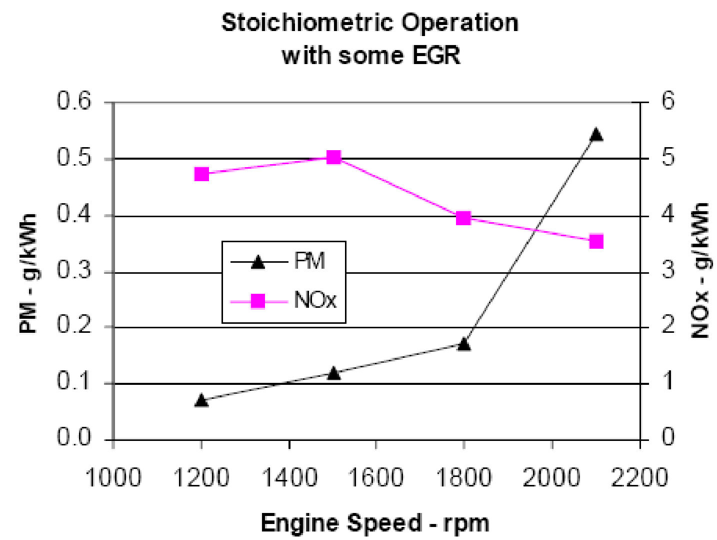
Stoichiometric diesel engine – goals and potential

- **Operate compression ignition engine at stoichiometric and use three-way catalyst for control of NOx, HC, and CO**
- **Use continuously-regenerating diesel particulate filter for PM control**
- **Obtain superior fuel efficiency because of rapid combustion near TDC and efficient air system with reduced exhaust aftertreatment losses**





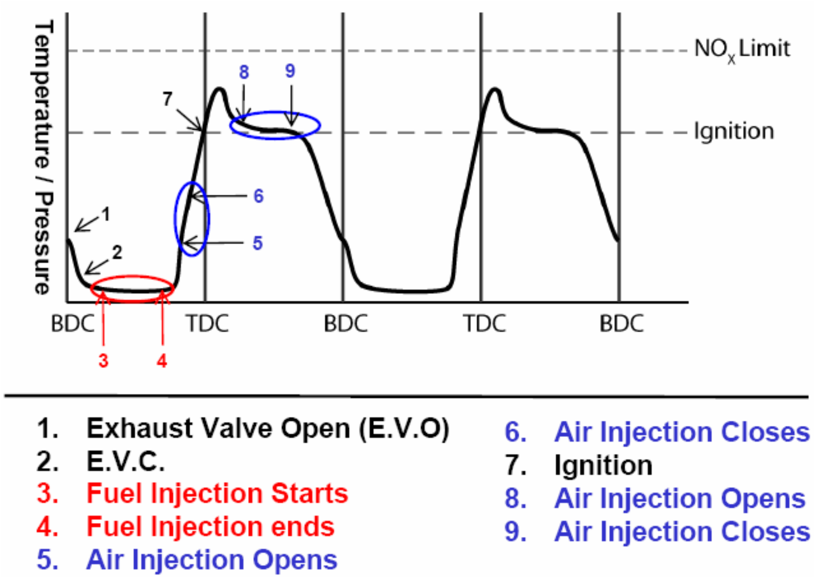
50% load operation



Issues

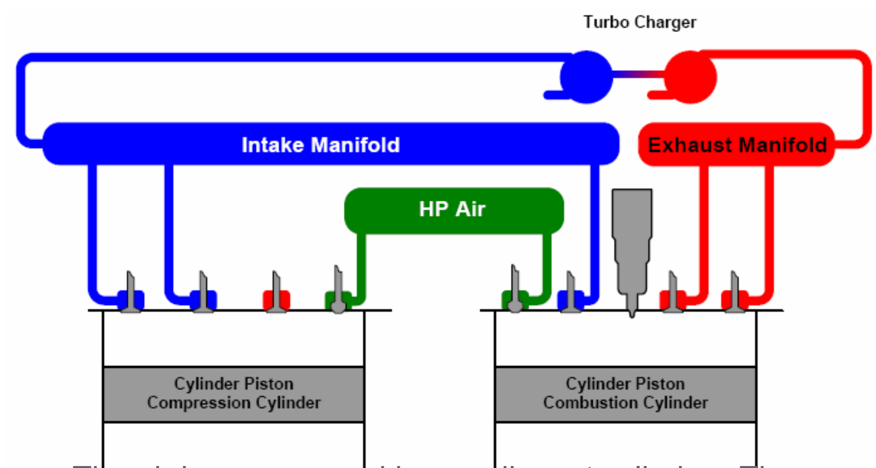
- **Smoke and PM at ϕ = 1.00**
- **NOx level and three-way catalyst efficiency**
- **High exhaust temperature**
- **Control to maintain stoichiometry, especially during rapid load changes**
- **Transient response**

New combustion cycle injects air at TDC in a 2-stroke cycle to improve efficiency and drop emissions

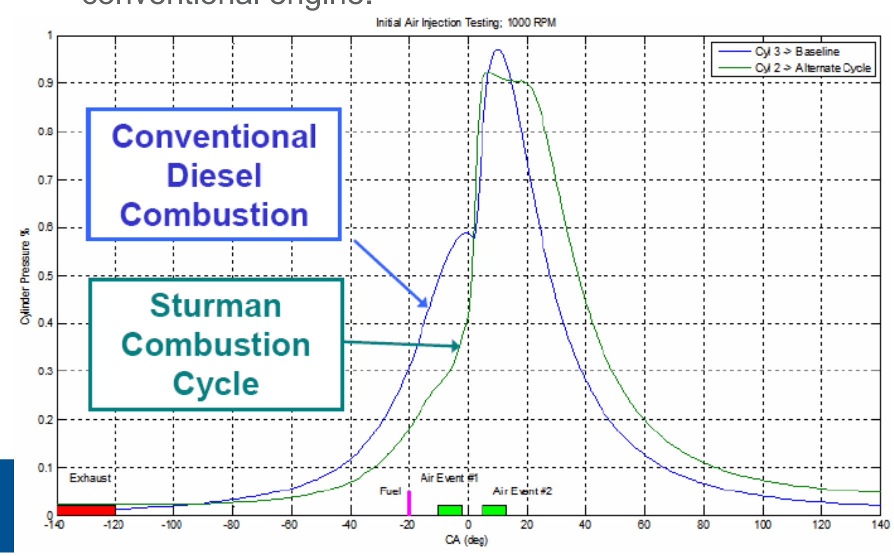


Fuel and internal EGR are compressed. Compressed air is injected near TDC and after to control combustion in the homogeneous fuel charge.

- Preliminary results show deNOx needs at 30-70% and PM needs at 50-80% efficiency for US2010.
- BTE is at 50%.
- Technology can be retrofit



The air is compressed in an adjacent cylinder. The combustion cylinder runs in 2-stroke operation so the number of combustion events is the same as for a conventional engine.



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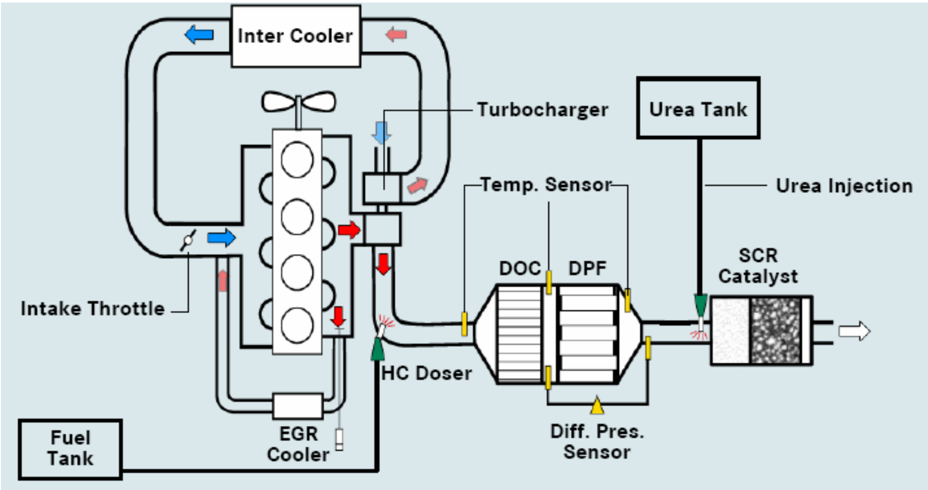
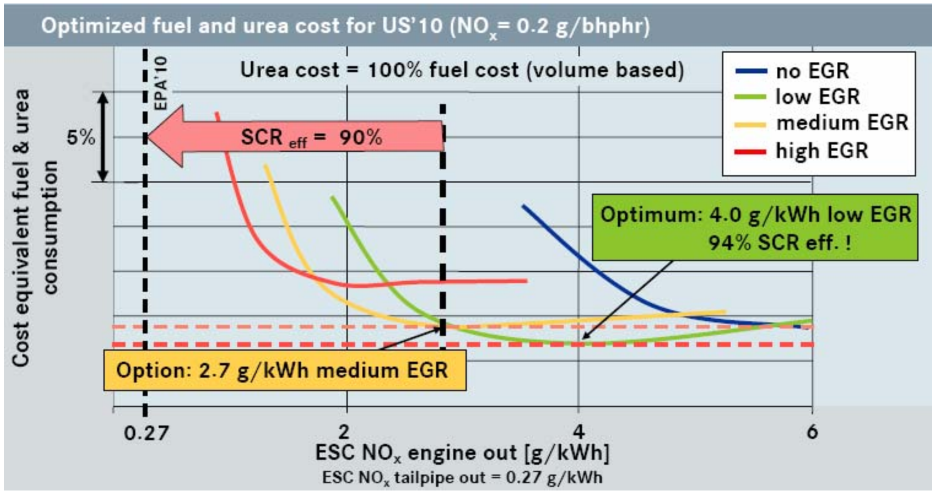
SCR

US2010 concepts involve SCR, but there are complex trade-offs with engine design, SCR efficiency and size, and relative urea costs.



Leading heavy-HDD US2010 system layout is DPF+SCR, with incremental changes in 2007 engine technology.



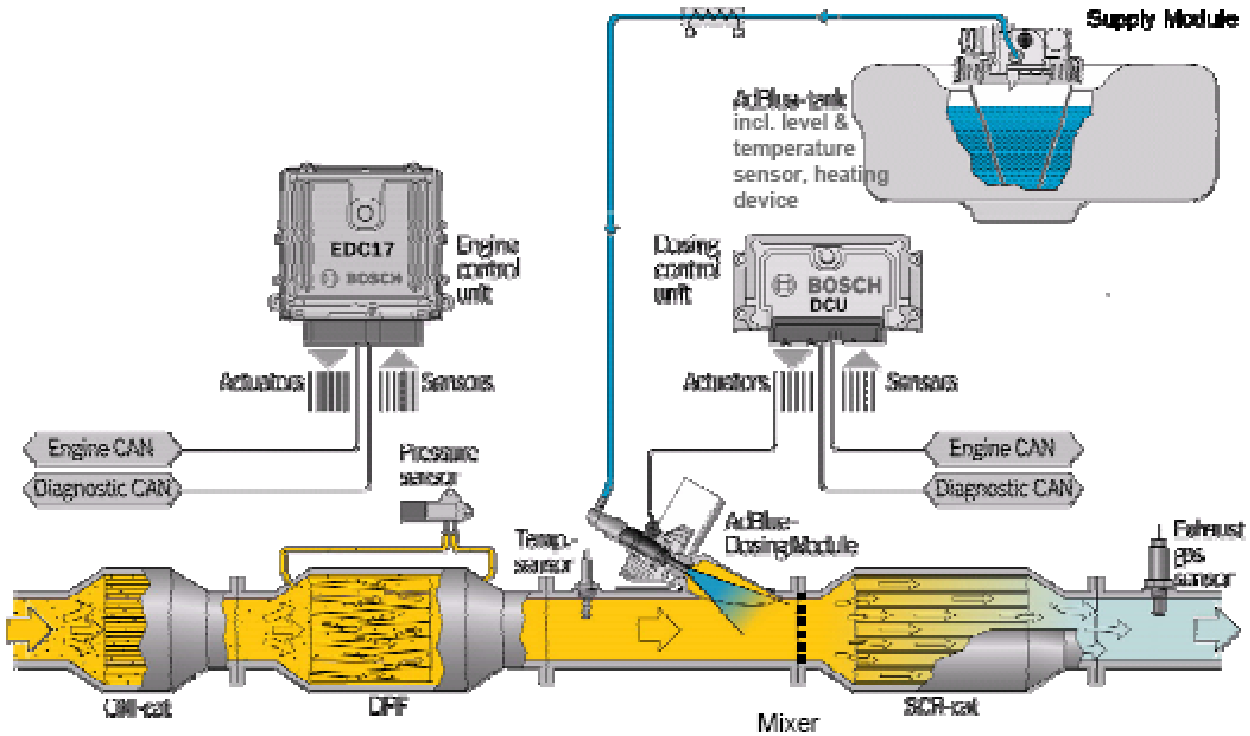
For any given engine architecture (BSFC vs. NOx), there is a minimum operating cost relationship with SCR efficiency based on urea consumption.

Daimler, CTI conference, 1-07

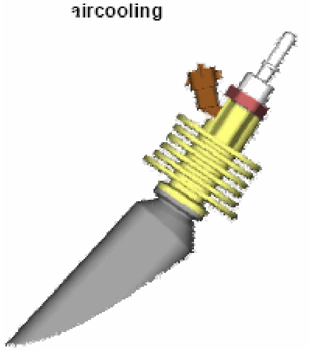
State-of-the-art LD urea delivery system described

Features:

- no return line for simplicity and cost savings
- self-draining lines to prevent freezing and urea deposits
- mixer to enhance urea decomposition

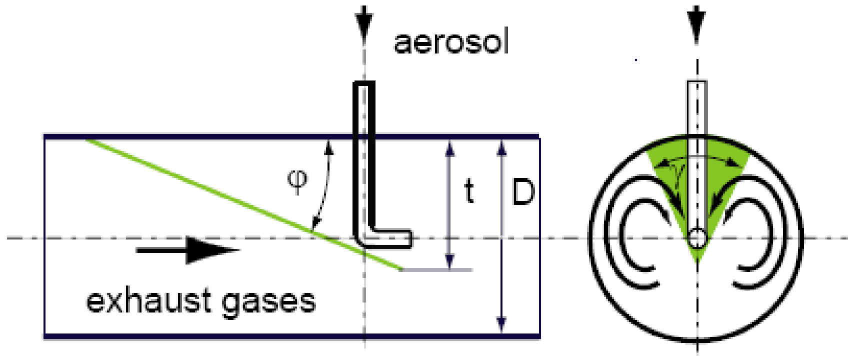


Dosing Module with aircooling



Bosch, MinNox conf. Berlin 2-07

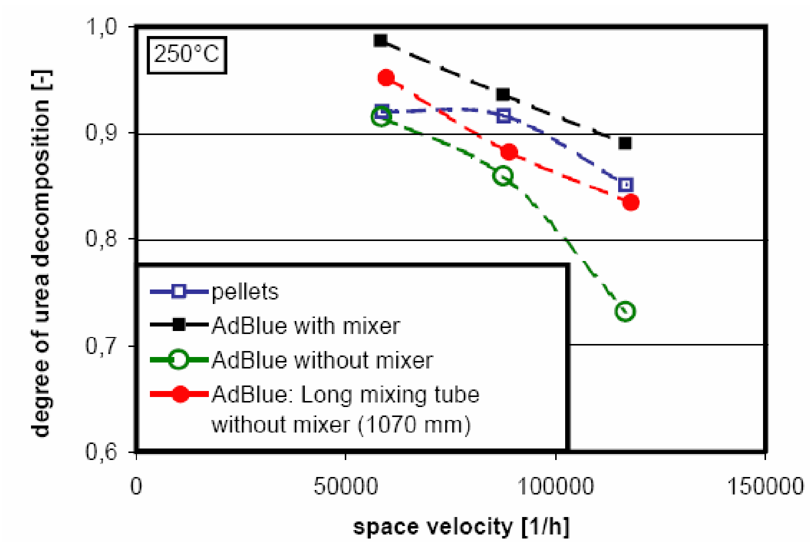
Urea mixing is especially critical



TU Munich, MinNox Conf. 1/07

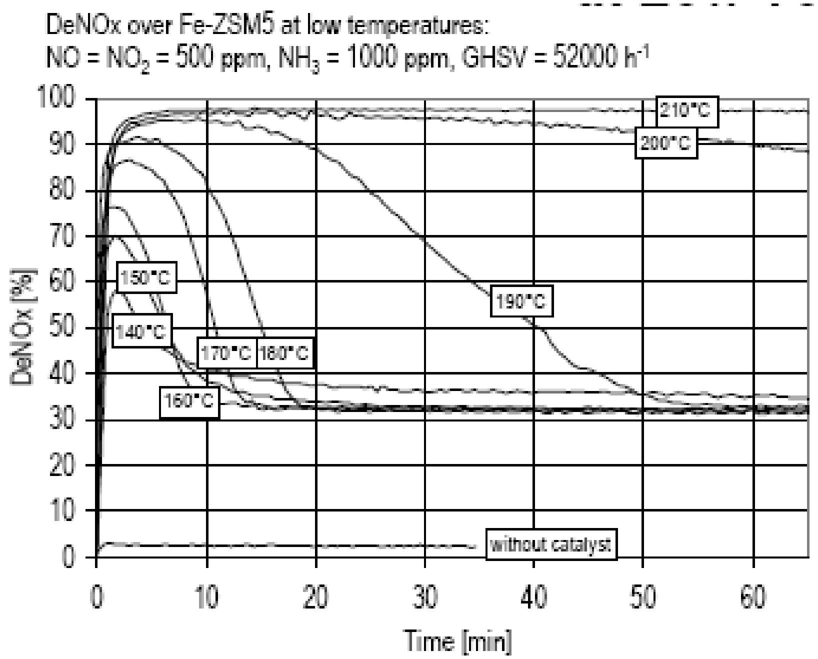
Poor urea mixing results in injector clogging, catalyst peeling, and poor distribution/hydrolysis of urea.

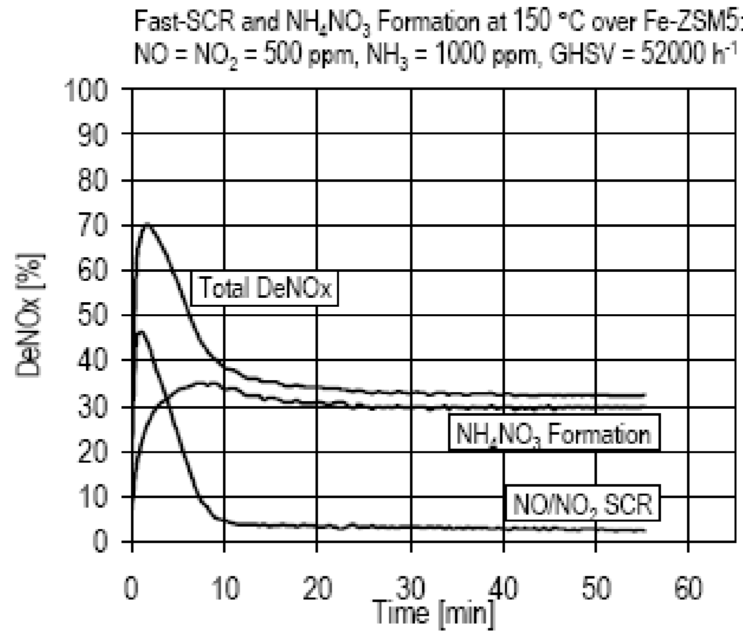
Vortex mixer is a thin shield in front of injector that creates strong localized mixing.



Urea is decomposed most effectively with vortex mixer at 250C.

Zeolite SCR catalysts perform well at LT for short periods of time. T<200C: NH_4NO_3 formation





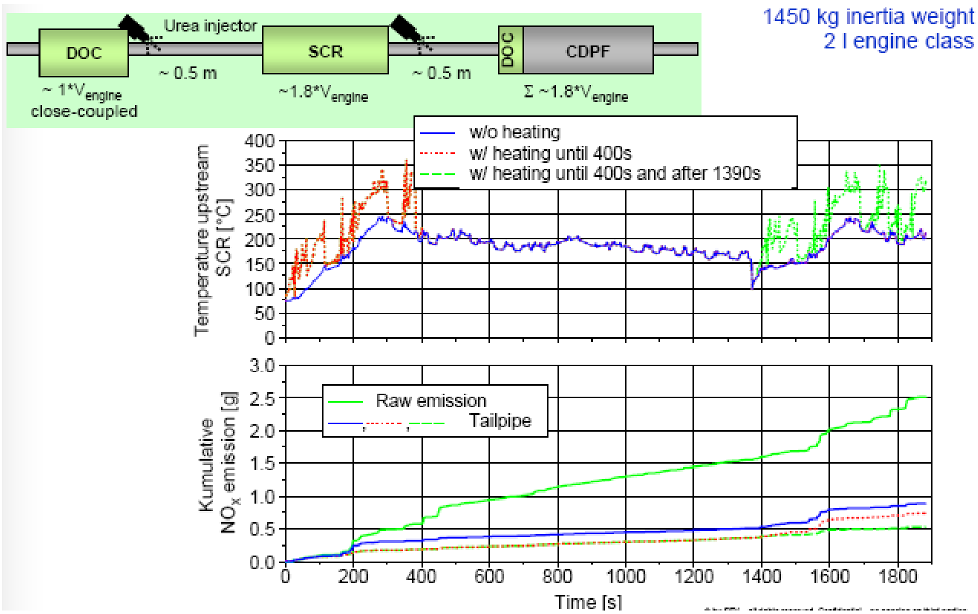
- Ammonium nitrate formation starts at 200 °C under NO/NO_2 SCR conditions
  - $\Rightarrow 4\ NH_3 + 4\ NO_2 \rightarrow 2\ NH_4NO_3\downarrow + 2\ N_2 + 2\ H_2O$
  - $\Rightarrow NH_4NO_3 \leftrightarrow NH_3 + HNO_3$
- At 150 °C almost no NO is consumed (no NO/NO_2 SCR)

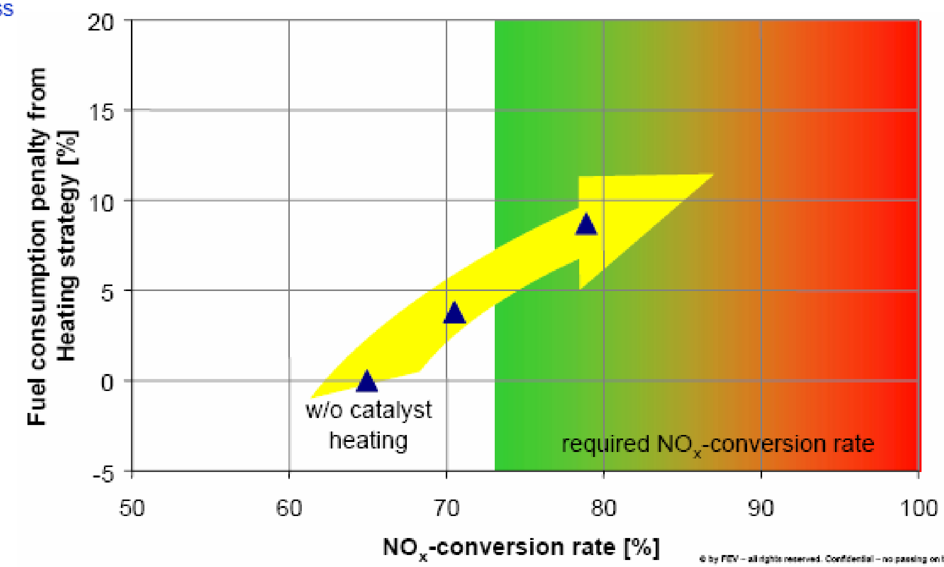
LT: Rate controlling step is $NO \rightarrow NO_2$ kinetics

PSI, MinNOx conf 2-07

Fast heat-up strategy is very effective, but costs fuel.

80% cycle deNOx costs 9% FP. Baseline at 65% efficiency

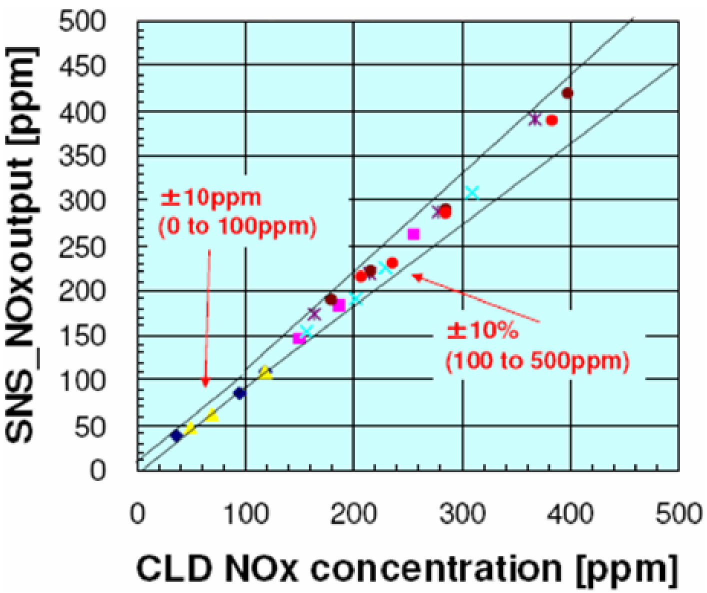


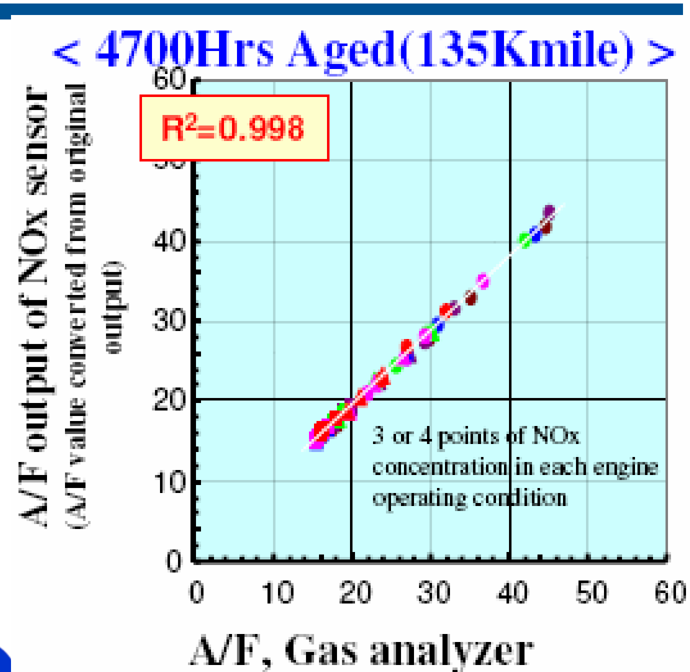


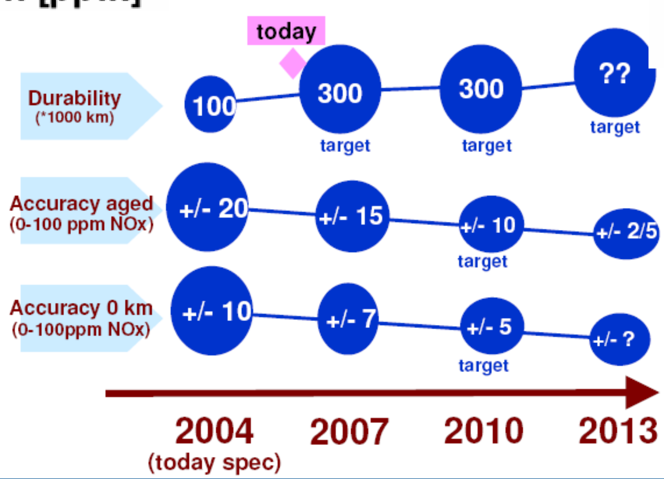
Fast heat-up strategy involves post-injection, only when needed.

FEV, MinNOx conf 2-07

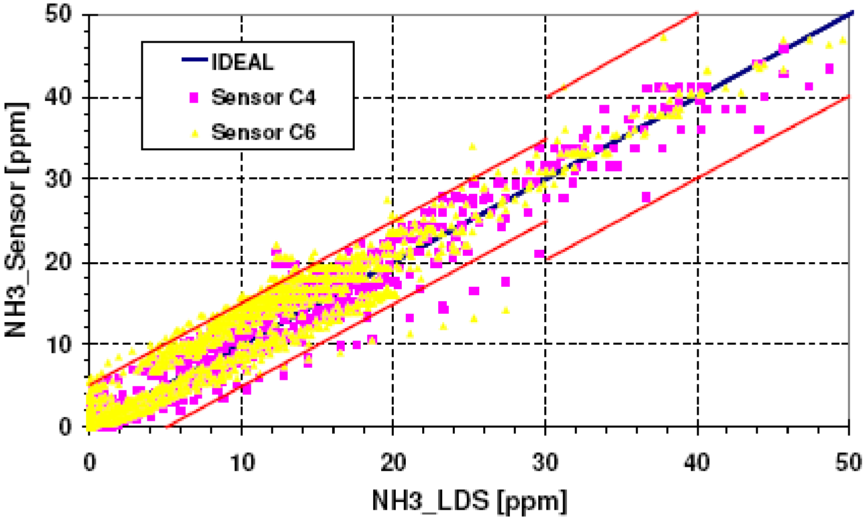
Update on NOx/O_2 sensor is provided





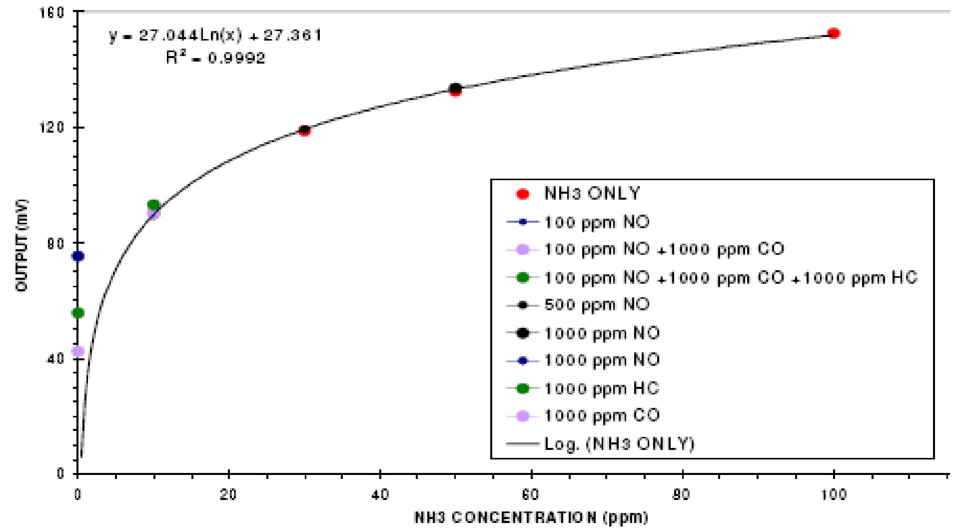


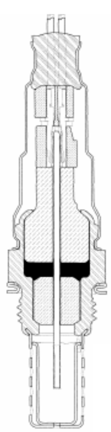
Ammonia sensor in development that will enable closed loop SCR control.



±5-10 ppm accuracy on ESC test after 700 hours.

Interference from NO, CO, and HC is negligent





- 3-5 second response time
- Closed loop NH3 control eliminates slip catalyst, and offers maximum SCR efficiency, as NOx sensors have ammonia sensitivity.

Delphi, CTI conference 1-07

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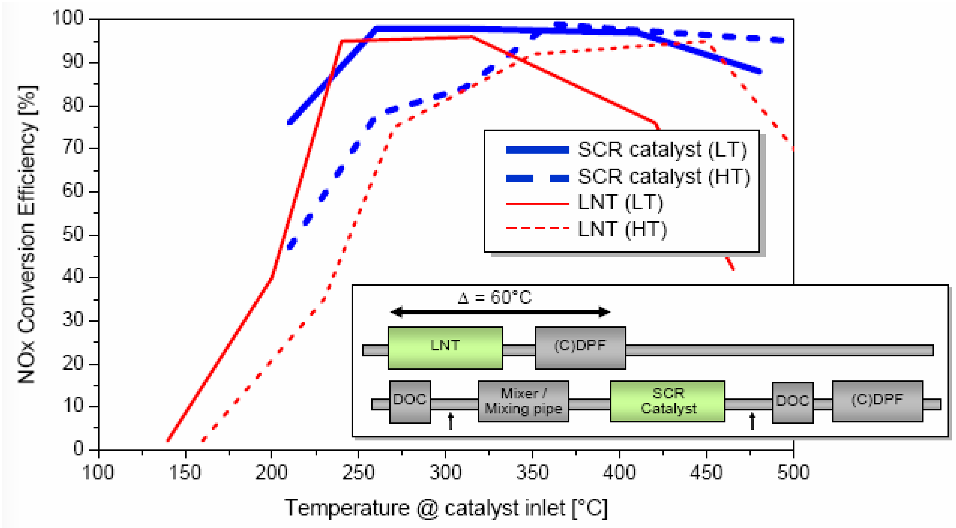
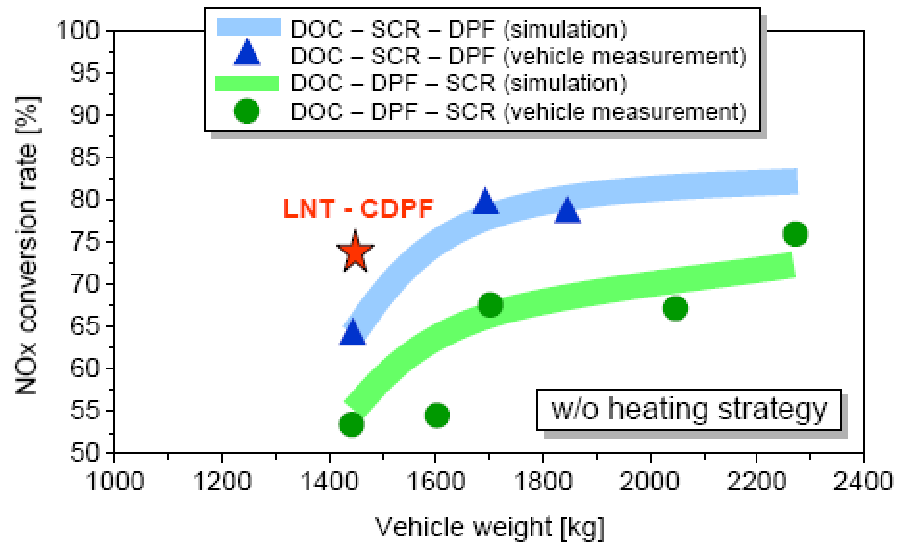
Lean NOx Traps

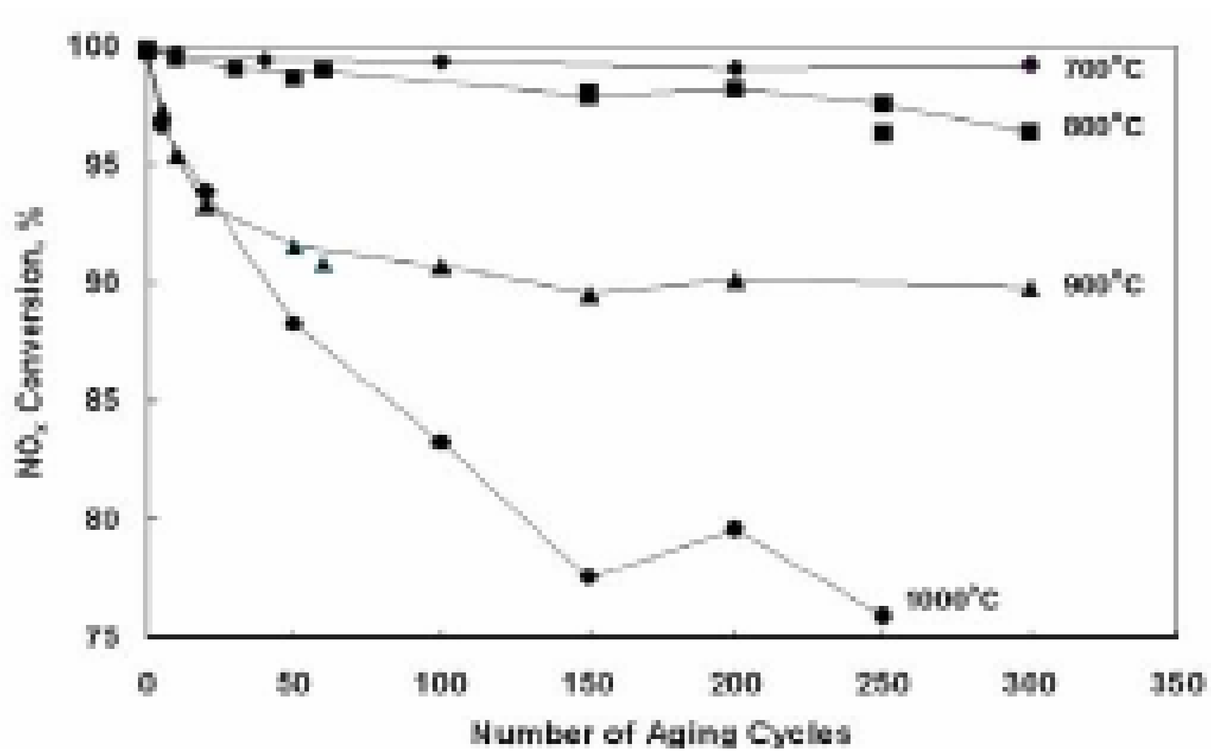
LNT can give higher efficiencies for smaller LDD. LNT can go closer to engine due to urea mixing length requirements.





FEV, MinNOx conf, 2-07

LNT deterioration is quantified. Main cause appears to be loss of potassium at T>825C.

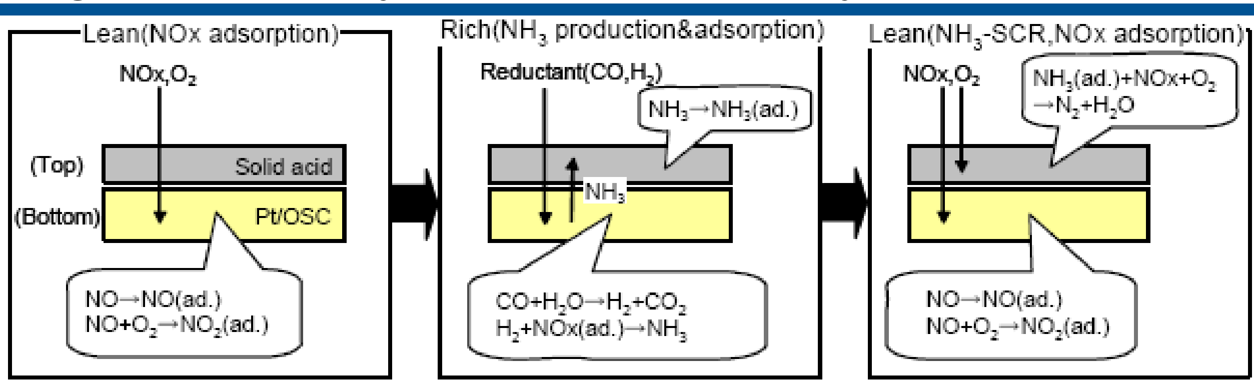


Univ TN, ORNL, Hannam Univ, SAE 2007-01-0470

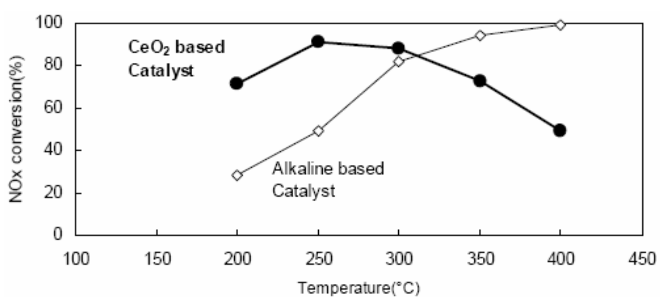
- T<~830C minimal loss of NOx eff due to PGM and adsorber sintering.
- severe loss of NOx eff at T>830C, mainly K migration and alumina phase change, up to 150 cycles. >150 cycles stable.
- T>1000C Ba-aluminate

NOx conversion at 400C is most significantly impacted by increases in T from 800 to 900C. PGM grain size increases only 15%, but K migration is main effect.

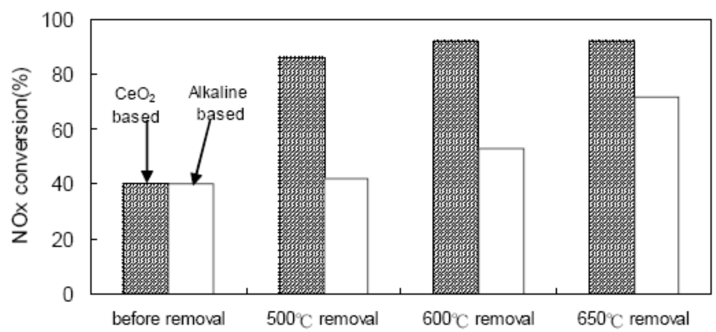
A new double layer LNT/SCR approach is described. CeO_2 LNT material has good LT activity and low sulfur affinity.



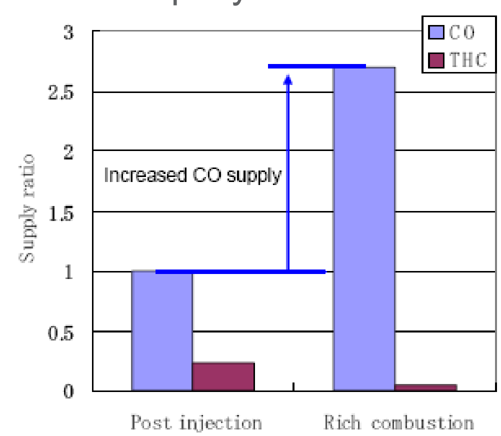
The bottom layer acts as an LNT in lean operation, and converts NOx to NH_3 via the water gas shift reaction during rich operation via the water gas shift reaction. The NH_3 is adsorbed by the zeolite top layer for use as an SCR reductant.



The CeO_2 LNT material performed well at low temperatures. System is placed in under-body position to reduce temp.



The CeO_2 LNT material has a low sulfur affinity, and thus can be desulfated at 500C.



Rich combustion is used to generate CO and H_2 for NH_3 generation.

Honda, Aachen Colloquium, 10/06

2007-01-0239

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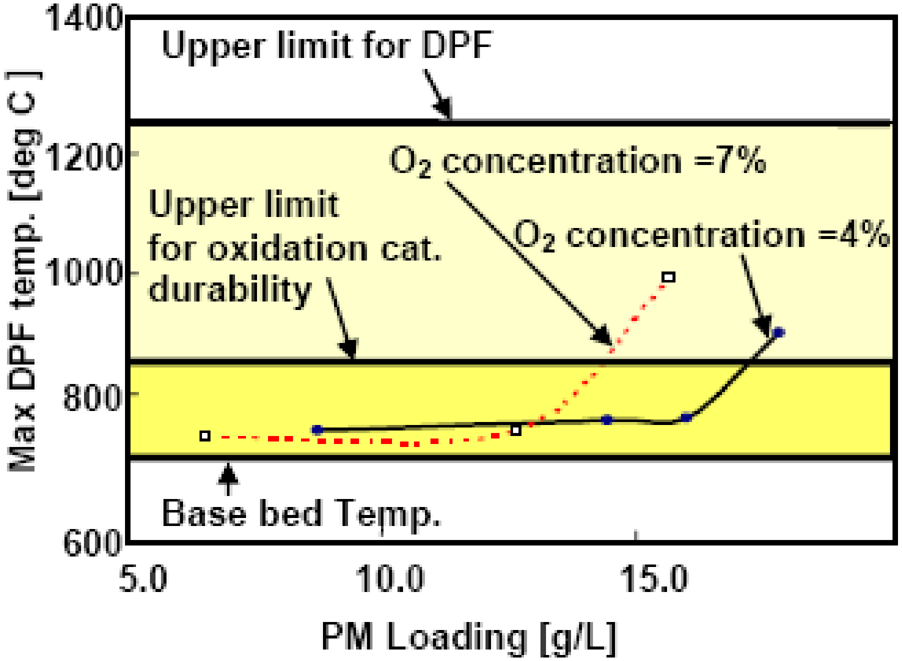
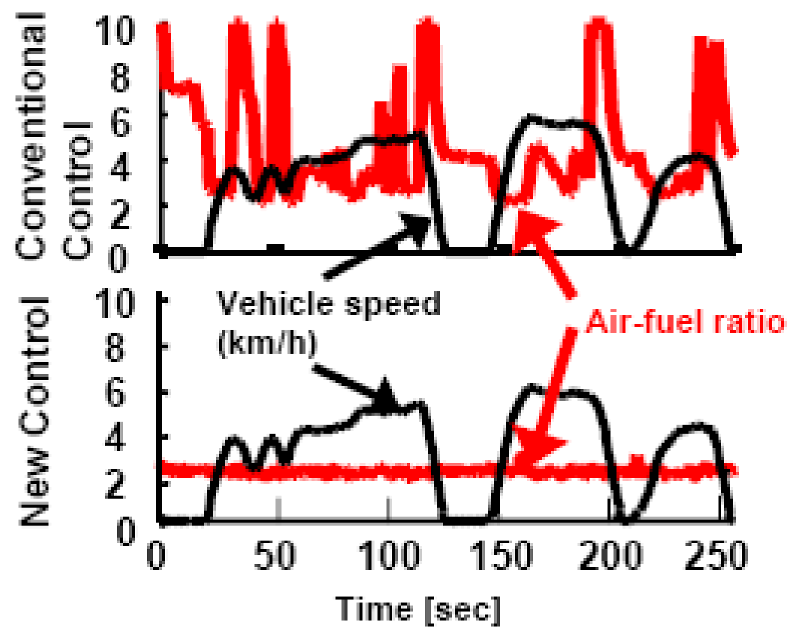
PM Control

A lambda sensor after DPF is used to control the regeneration.



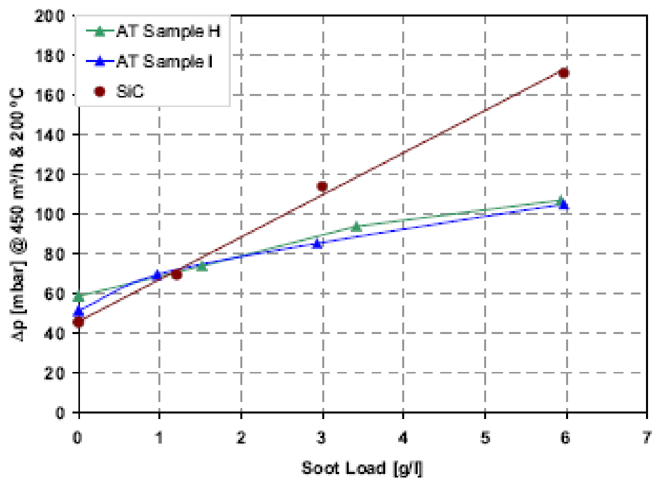
DPF bed temperature is controlled by oxygen level.



Oxygen control is very good in transient conditions.

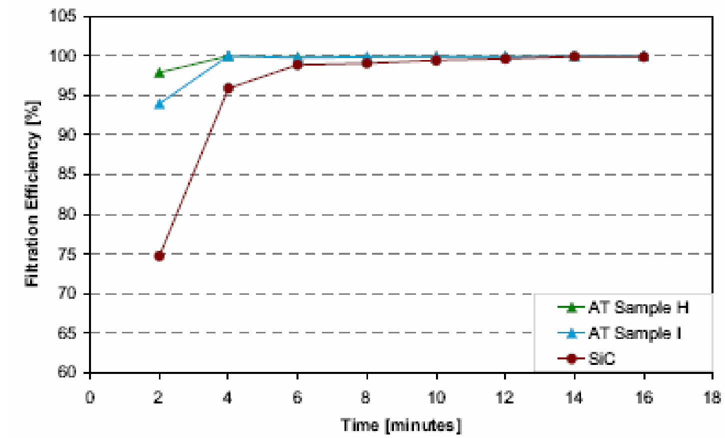
Adaptive learning tightens A/F control and allows better soot estimation.

Aluminum titanate filter are characterized



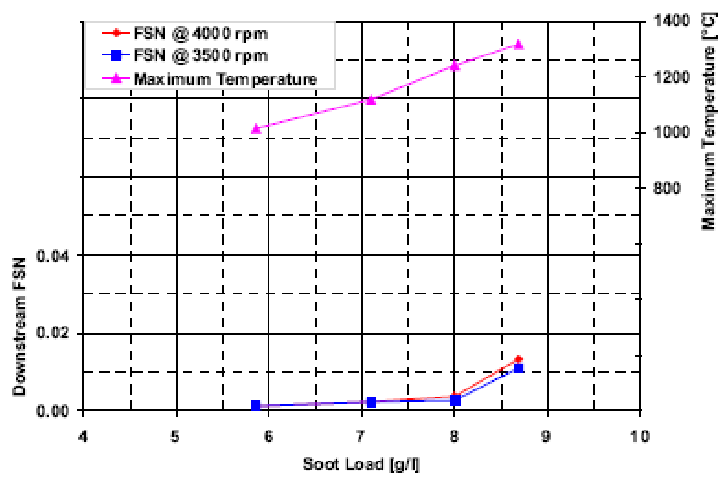
AT back pressure is very low upon soot loading.

Nominal 300/13 cell geometry.



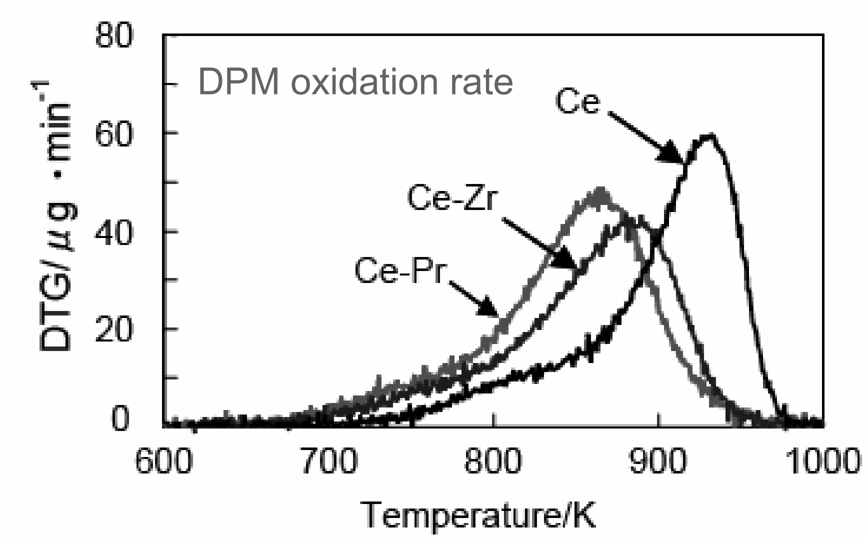
Filtration efficiency is very high, even for filters with low soot loading.

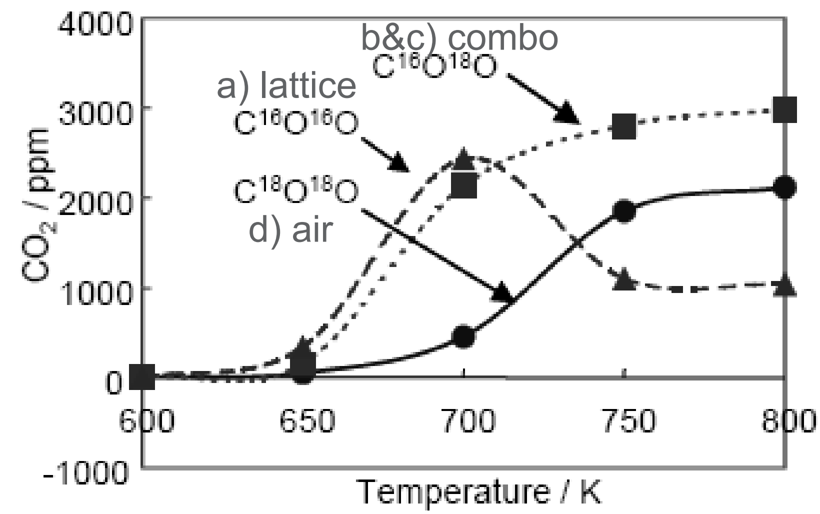
Soot mass limit of 8 g/liter is determined using severe conditions. 640C inlet temperature prior to DTI.



Soot oxidation reaction mechanisms of OSC is determined.

At T<470C reaction with lattice oxygen is key. Mazda, SAE 2007-01-1919



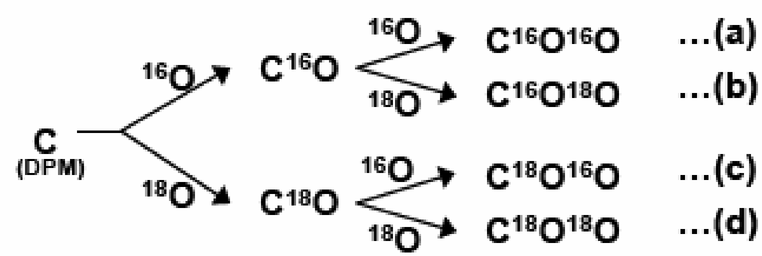


Reaction mechanisms with Ce-Pr OSC material:

• T< 700K (427C): C reacts with lattice oxygen

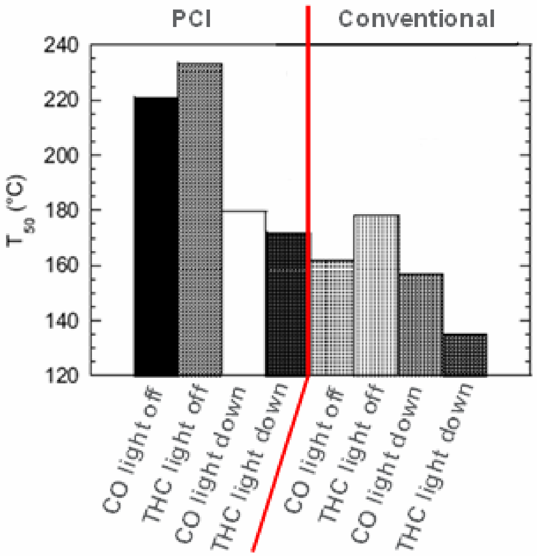
• 650K(377C)<T<750K (477C) C reacts with both air and lattice oxygen

• T> 750K: C also reacts with air oxygen, catalyzed by OSC

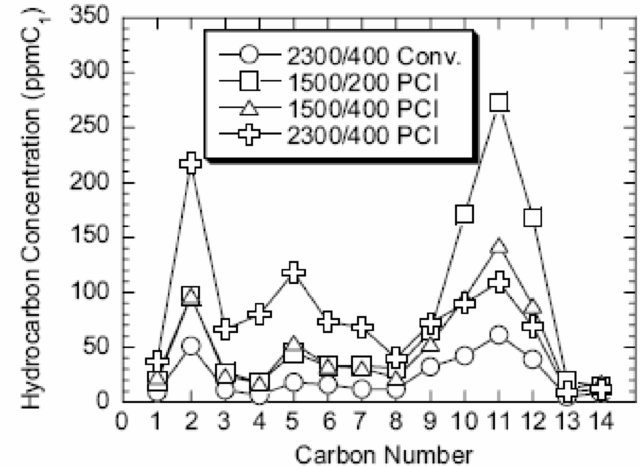


$^{18}O_2$ is only oxygen in air. $^{16}O_2$ is only oxygen in lattice.

Premixed combustion results in HC species that are more difficult to oxidize. Indications point to unsaturated HCs.

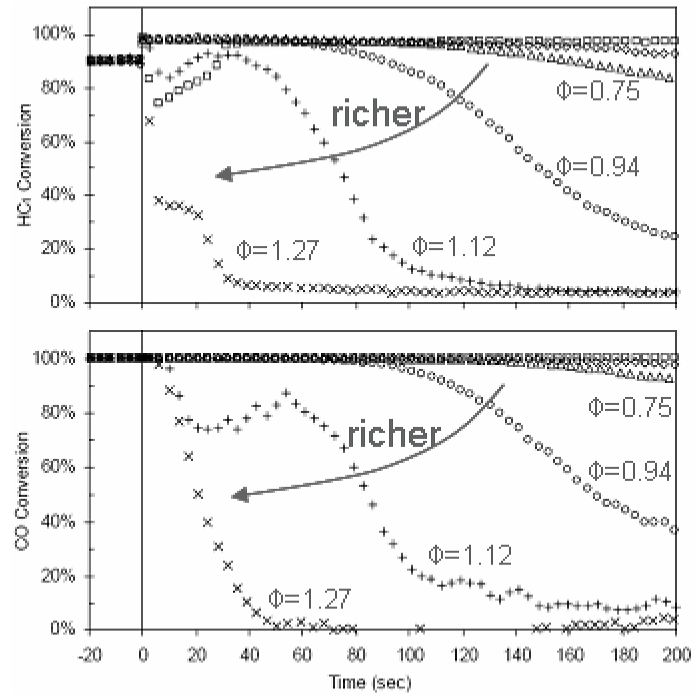


Premixed combustion CO and THC light off at temperatures 60 and 50Cº higher than for conventional combustion.



PCI gives much more HCs than conventional combustion, especially the C2 (ethene) and C11 (n-undecane).

Univ. MI & GM, SAE 2007-01-0231



Propylene adversely affects DOC performance.

Univ. MI, IJER to be published

Pt:Pd=3:1, 4.0 g/liter PGM loading, SVR=0.73.

Summary

- Regulations
  - European LDD regulations have implications to the US approach
  - Europe is formally proposing Euro VI (HD) this year
    - Wide range of scenarios considered – no industry consensus
  - CO_2 regulation appears to be the most dominating long term issue
- Engine strategies are making impressive progress
  - HD research engines show very low PM levels under steady state full-load conditions
  - Advanced combustion mixed mode engines are emerging for LD and HD
- NOx solutions are available for ultra-low emissions
  - SCR is addressing cold temperature and mixing issues
  - LNTs are performing well today at about 60-70% efficiency; hybrid LNC/SCR systems emerging
- DPF systems show continuous improvement
  - Very sophisticated regeneration control strategies.
  - New catalyst formulations add flexibility and improved performance
  - HC mix from advanced combustion engines might present challenges