Light Duty Diesels in the United States – Some Perspectives

Tim Johnson
August 10, 2005

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Discovering Beyond Imagination

US LDD issues are significant, but appear surmountable

- Regulatory environment
  - New era of low emissions and low fuel consumption
    - LDD potential to hit SULEV (Bin 1) if needed?
- Cost
  - Diesel engines are inherently more expensive, as is emission control
  - Other efficiency options also cost money
  - Diesel emission cost control is coming down
- Market
  - Will the US pay more for fuel economy?
- Fuel quality and availability
  - Refinery diesel:gasoline mix will be upset
- Competition
  - “King of the Road” gasoline is not standing still

The Pinch

Tight Emission Standards and Better Fuel Economy

Diesel has as good a chance as other options to satisfy these requirements

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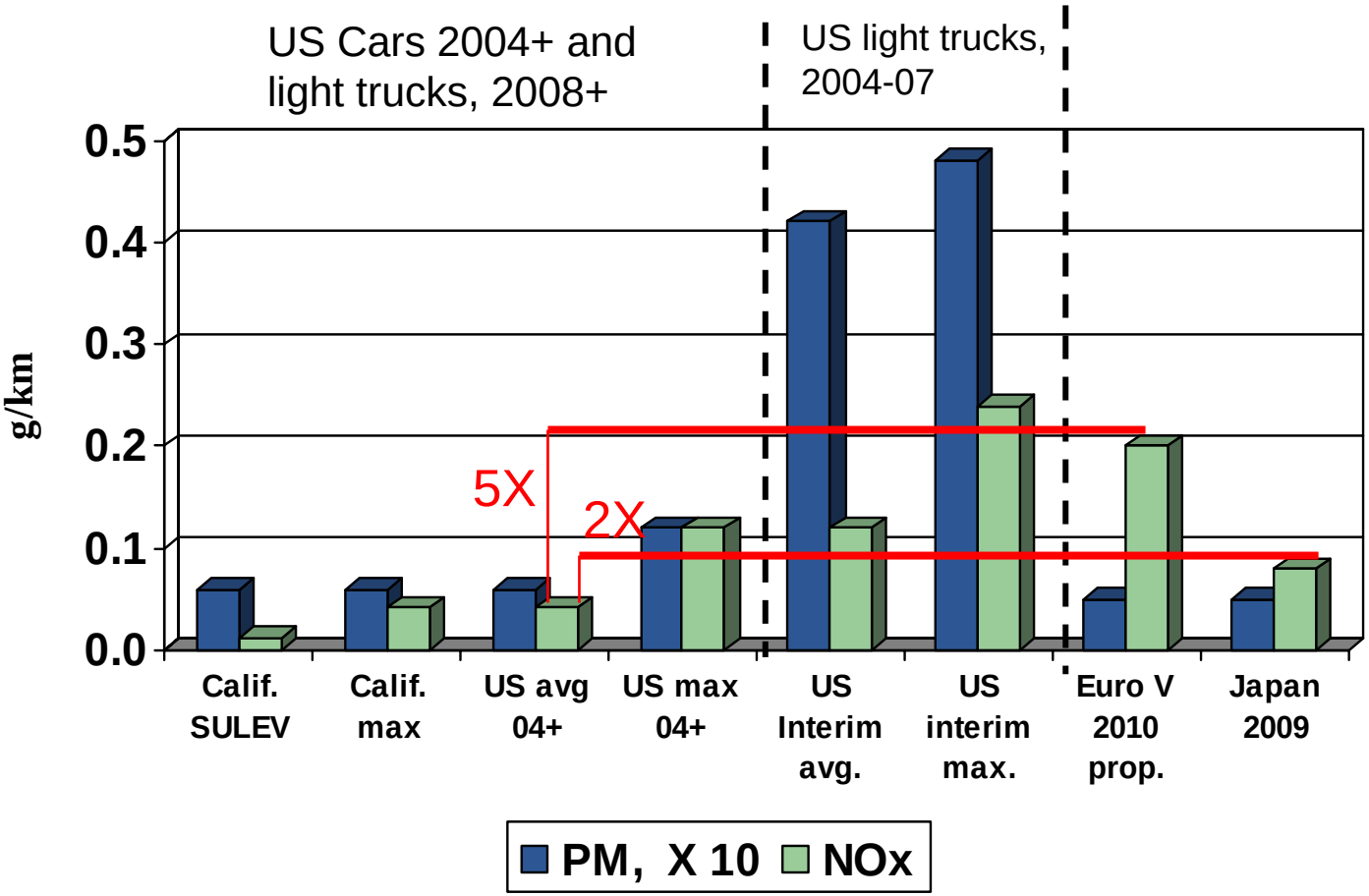
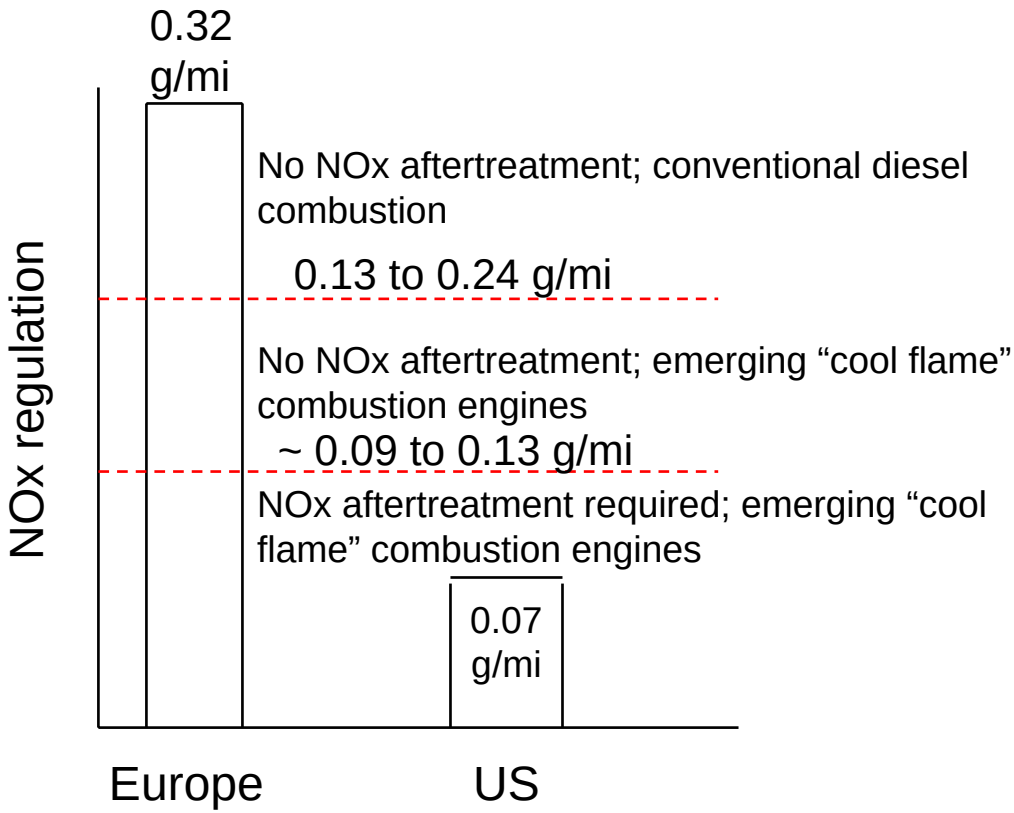
NOx for US Tier 2 Bin 5 (Calif max.) NOx is 20% of Euro V (prop.) and 50% of Japan 2005.



US diesels will have fundamentally a different combustion and emission control system than European diesels



• The tighter US regulations will force new, special technologies to be developed for this market.

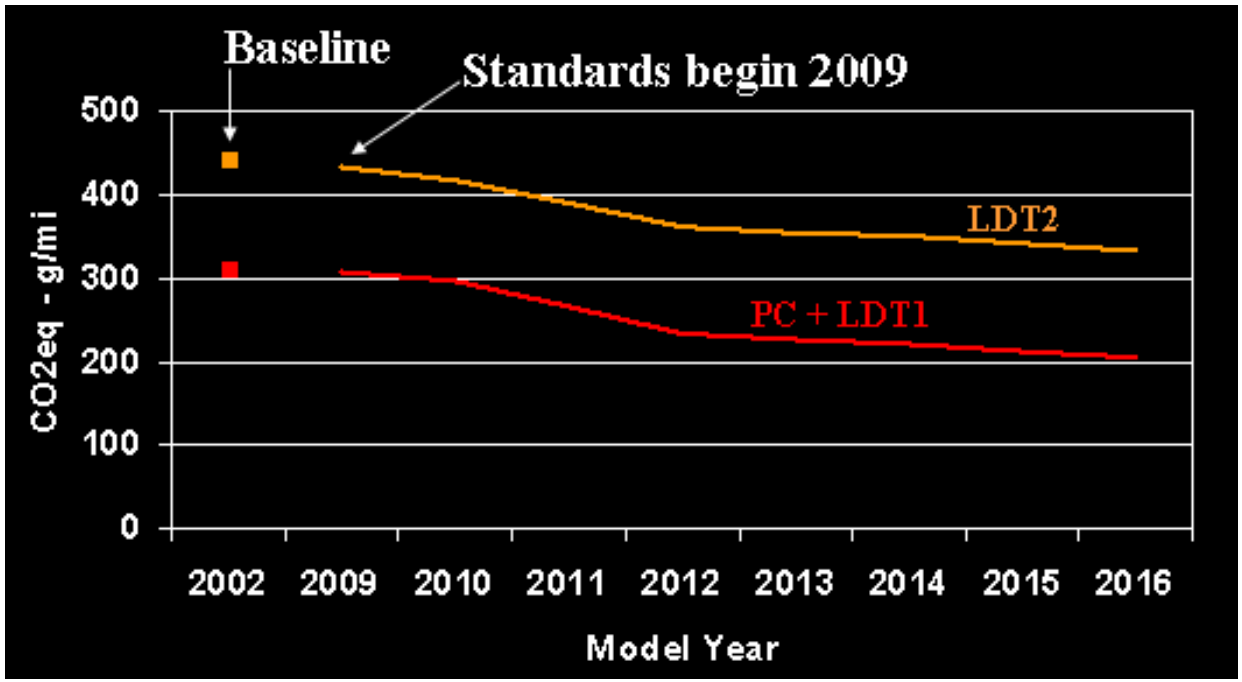
CARB GHG reduction plan has been approved by Board

Goals:

- Begin MY09
- Reduce GHG by 20% in 2010, 30% by 2016

  Roughly 4 yrs behind 1st stage European CO_2 commitment

- Drop petroleum consumption by 15%



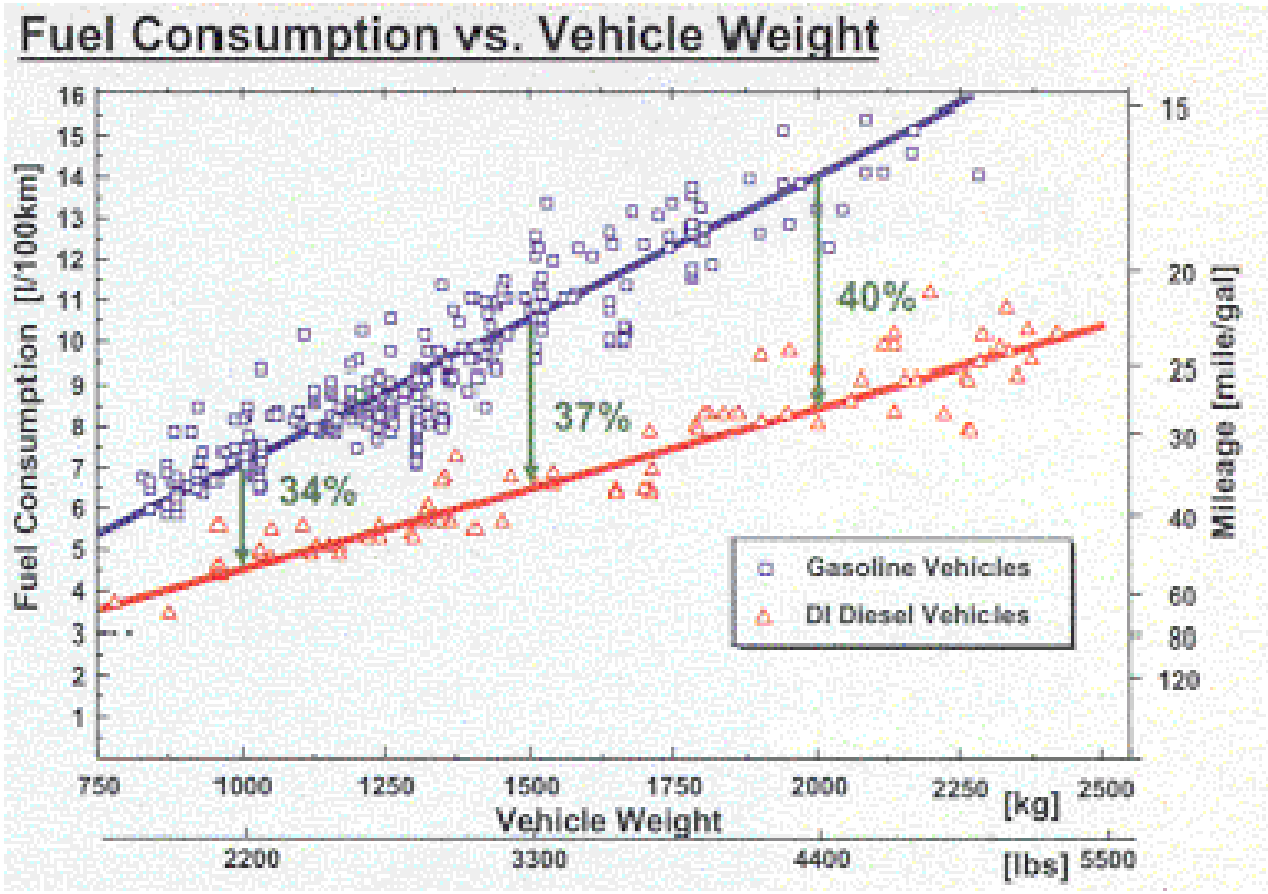
CARB, DEER 8-04

NESCAUM states and others, including Canada will likely follow

US conservative political pressures are surfacing on increasing fuel economy

- Energy Future Coalition and Set America Free (Bauer), both business or neo-con organizations, are strongly advocating movement towards higher fuel efficiency in the transportation sector
  - Incentive-based
- Former directors of the National Security Council jointly issued nonpartisan statement with similar recommendations
- DoD has claimed GHG is a “National Security” issue.

On average, diesels consume 34 to 40% less fuel per mile than comparable gasoline cars. (50 to 70% more mpg)



Fuel savings, going from gasoline to diesel

wt, lbs.	liter/100 km	mpg	CO2/mi
2200	-34%	+53%	-27%
3300	-37%	+60%	-29%
4400	-40%	+70%	-32%

CO_2 savings: Diesel has 37% more CO_2 per gallon, but takes 8% less energy to refine. Net: +27% more CO_2 per gallon of diesel.

FEV, Automotive Engineering May 2005

Costs

Fuel Economy and Low Emissions are Expensive

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Base diesel engine and aftertreatment cost appears to be $1200 more for a 2.0 liter-class engine

Gasoline

GASOLINE ENGINE MANUFACTURING COST BREAKDOWN		
	VOLUME P.A	300K
SUB SYSTEM	COMPONENT/ENG	GENERIC 1.8G I4
BLOCK	CYLINDER BLOCK	110.9
CRANK	CRANKSHAFT	99.3
PISTON	PISTONS	47.6
CONROD	CON-RODS	36.6
CYL HEAD	CYLINDER HEAD	86.7
VALVETRAIN	VALVETRAIN	133.8
CAM	CAMSHAFT	55.2
FUEL	FUEL SYSTEM	252.5
FLYWHEEL	FLYWHEEL	47.1
TC	TURBOCHARGER	0.0
TCI	INTERCOOLER	0.0
EXHAUST	EXHAUST MANIFOLD	39.8
EGR	EGR VALVE	0.0
EGR	COOLED EGR	0.0
EMISSIONS	DPF	0.0
EMISSIONS	CATALYST	83.5
FEAD	PULLEY-DAMPER	21.0
FEAD	BALANCER SHAFT	9.8
OTHER	OTHER	309.1
ASS/TEST	ASSEMBLY/TESTING	154.1
TOT	TOTAL	1487.0

Diesel

DIESEL ENGINE MANUFACTURING COST BREAKDOWN			
	VOLUME P.A	300K	
SUB SYSTEM	COMPONENT/ENG	GENERIC 2.0D I4	
BLOCK	CYLINDER BLOCK	127.6	
CRANK	CRANKSHAFT	121.4	
PISTON	PISTONS	88.0	
CONROD	CON-RODS	38.2	
CYL HEAD	CYLINDER HEAD	78.9	
VALVETRAIN	VALVETRAIN	130.5	
CAM	CAMSHAFT	49.8	
FUEL	FUEL SYSTEM	593.8	
FLYWHEEL	FLYWHEEL	55.4	
TC	TUBOCHARGER	143.5	
TCI	CHARGE AIR COOL	25.7	
EXHAUST	EXAUST MANIFOLD	43.3	
EGR	EGR VALVE	38.1	
EGR	COOLED EGR	12.5	
EMISSIONS	DPF	250.0	
EMISSIONS	CATALYST	59.2	$400*
FEAD	PULLEY-DAMPER	20.1	
FEAD	BALANCER SHAFT	5.0	
OTHER	OTHER	322.7	
ASS/TEST	ASSEMBLY/TESTING	174.8	
TOT	TOTAL	2378.5	

*author's estimate

DRI, Global Insights, 2002

ORNL: Fuel economy is expensive, but diesel is cheaper than HEV

ORNL, DEER 8-04

Diesel

	Small Vehicle (2.0-2.5L I4)	Midsize Vehicle (3.0-3.5L V6)	Large Vehicle (4.5-5.0L V6)
2005	$1,750	$2,300	$2,500
2008	$2,280	$2,925	$3,200
2012	$2,300	$2,950	$3,250

	Torque	MPG
2005	25%	35%
2008	25%	30%
2012	25%	33%

Hybrid

	Small Cars	Mid-Large Cars	Small Trucks	Large Trucks
Stop/Start	$600	$640	$640	--
ISAD	$1,250	$1,385	$1,450	$1,625
IMA	$1,620	$1,790	--	--
Full Hybrid	$3,320	$3,920	$3,700	$4,100

	Torque	MPG
S/S	0%	7.5%
ISAD	10%	12.5%
IMA	15%	20%
Full Lg. Trk.	15%	35%
Full Car & Sm. Trk.	20%	40%

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Emission system improvements

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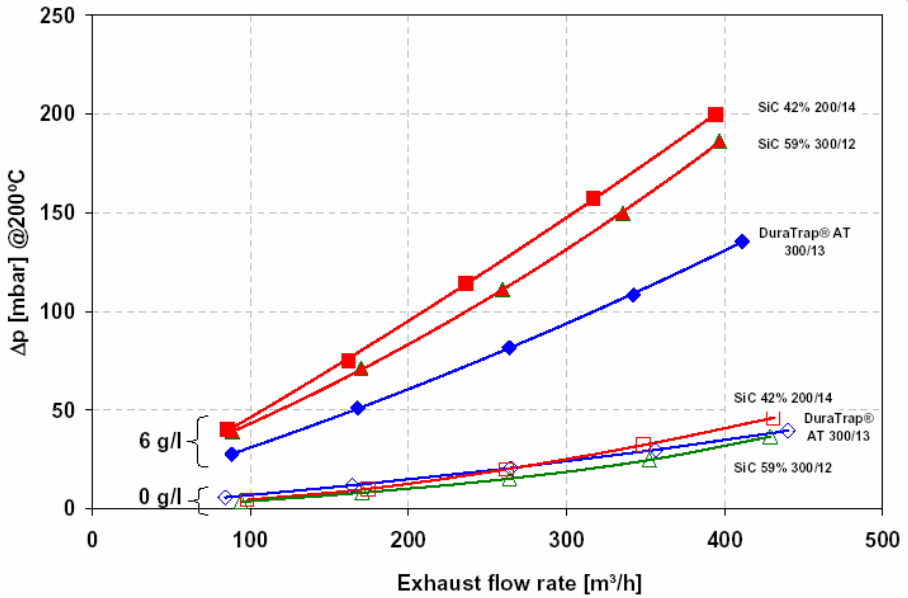
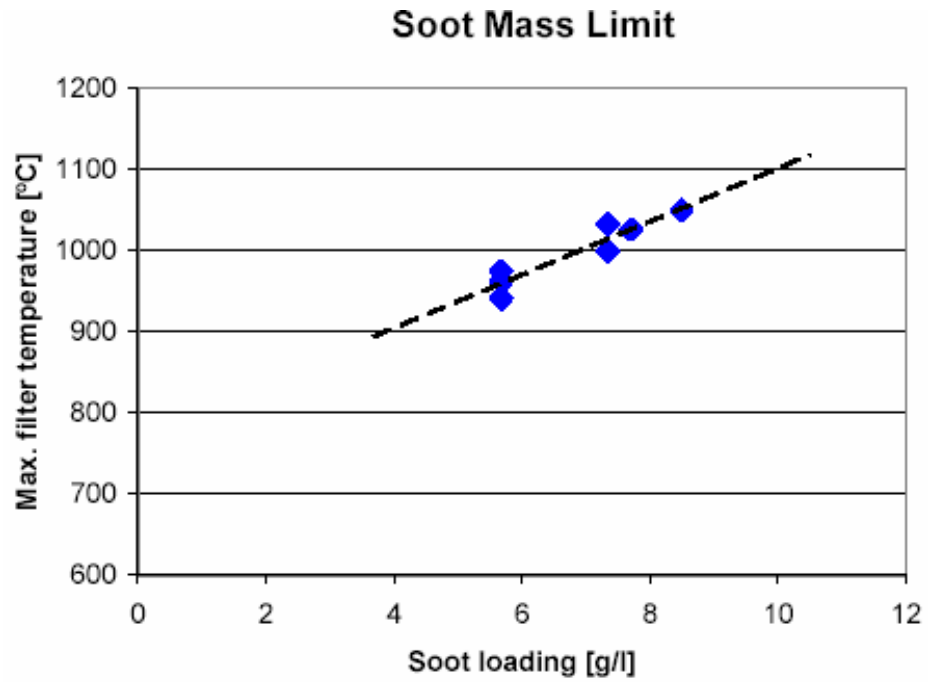
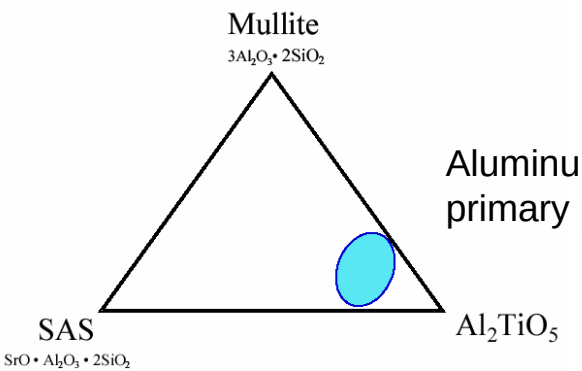
A new DPF high temperature material is reported



Catalyzed backpressure is 30% lower than SiC due to adverse segmentation effects and soot-porosity interactions. (Corning)



In worst-case soot regeneration modes, filter can take about 8 g/liter while being kept under 1100C.



Aluminum titanate is primary phase.

Material is being scaled up for series production this fall.

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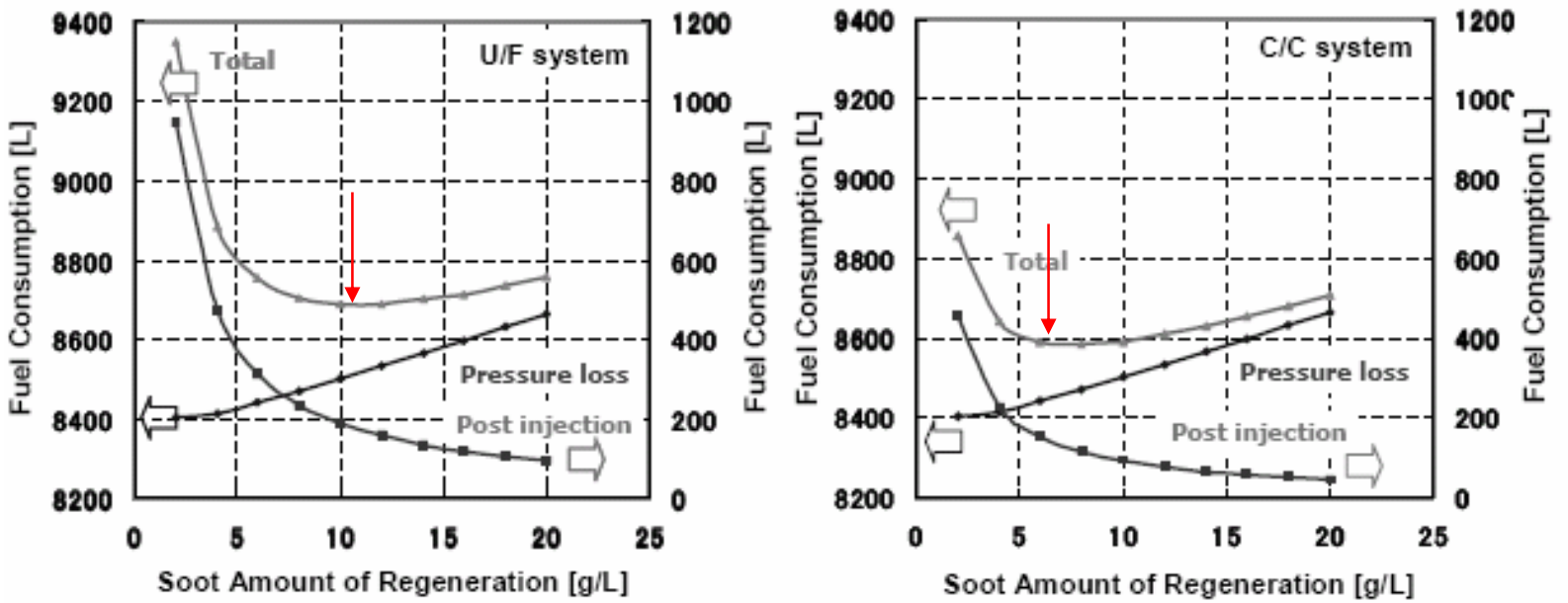
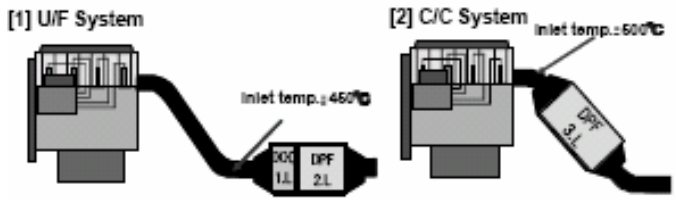
In close-coupled position, more frequent regenerations are allowed to minimize fuel penalty



In CC position, min. fuel penalty is at 6-8 g/l soot loading. In U/F it is at 10-11 g/l

- Because CC is hotter than UF position, less fuel is needed to regenerate
- CC CSF is also larger, so absolute PM loading is roughly the same as for U/F at min. fuel penalty

Ibiden SAE 2005-01-0579



System	Inlet temp.	PM combustion temp.	Temp. gap to 600℃	DPF Porosity
[1] U/F	450°C	600°C	150°C	42%
[2] C/C	500°C	600°C	100 °C	60%

50 C hotter in CC position

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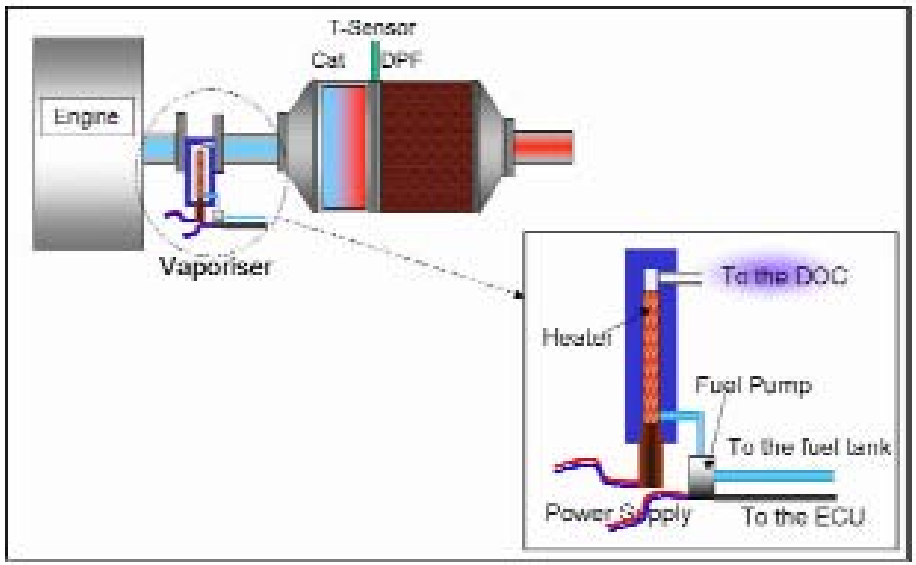
A new fuel vaporizer for DPF regeneration uses 50% of fuel vs. engines means ArvinMeritor SAE 2005-01-0671

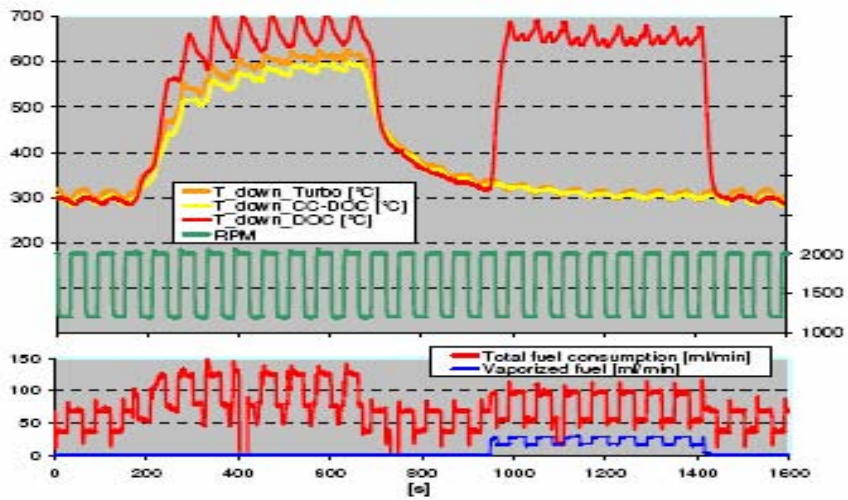
LDD fuel vaporizer

- System requires modeling to get good fuel and heat distribution
- DOC PGM loadings of 140g/cm. ft. were used (75g/cu. ft. too low)

HDD fuel vaporizer



Preferred System layout



Engine based regeneration (200-650s) takes 150 sec to heat-up DPF and 2x the fuel of a vaporizer (1000 to 1500sec). This will allow more freg. regenerations and lower soot loadings. Configuration for comparison: vaporizer after first CCC DOC.

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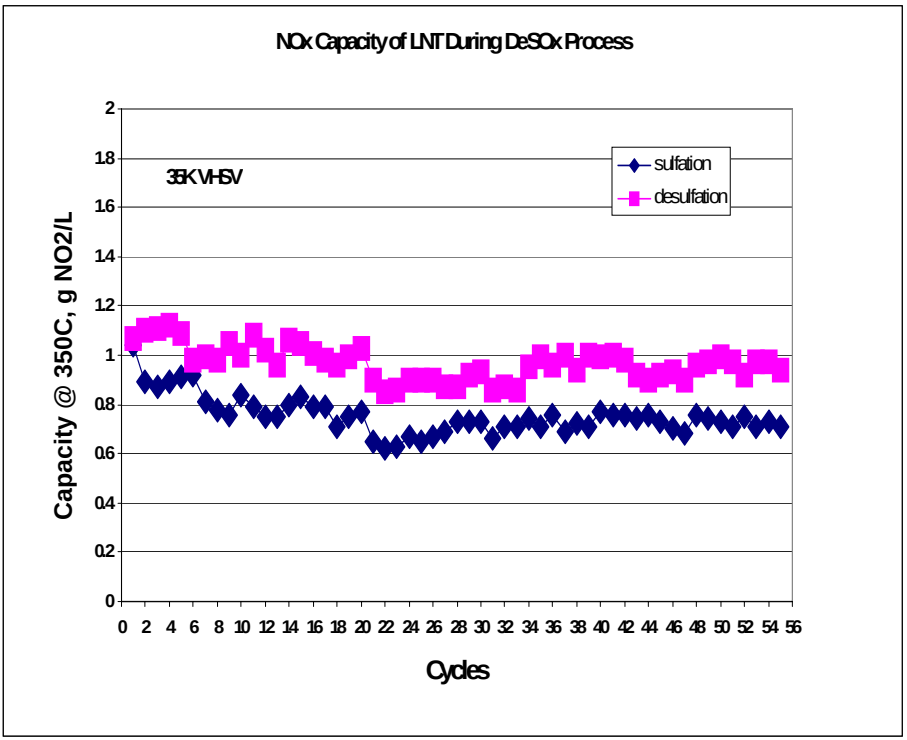
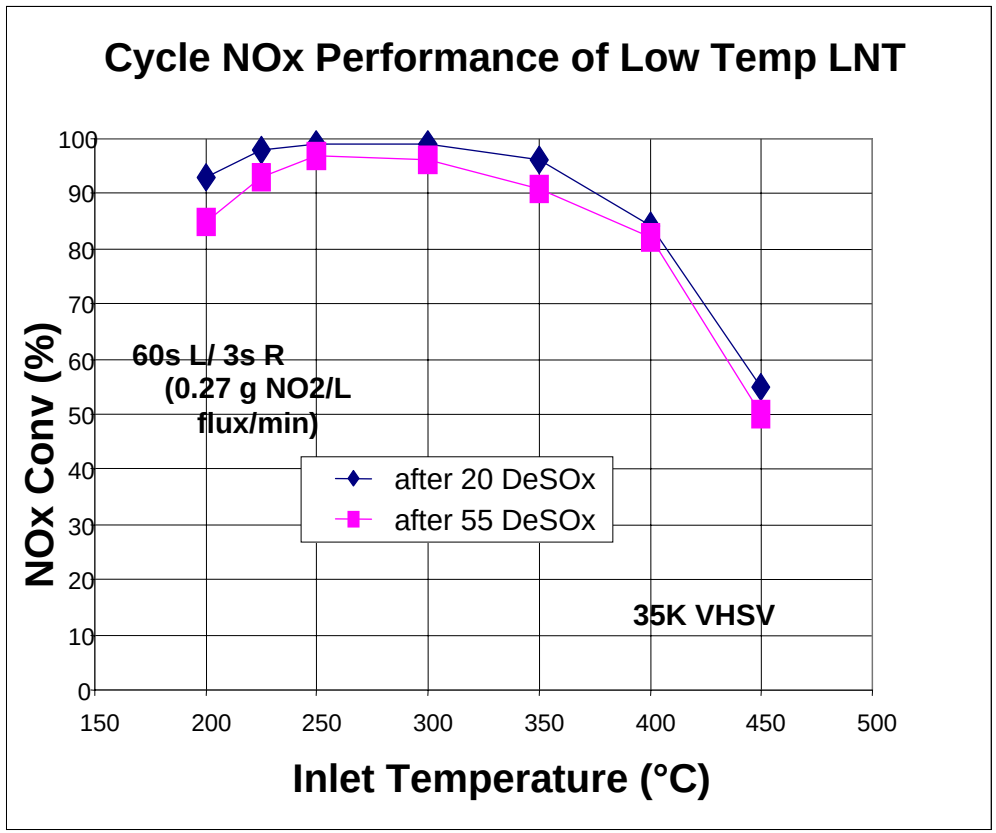
LNTs are becoming more tolerant to sulfur





Engelhard, AVECC 2004

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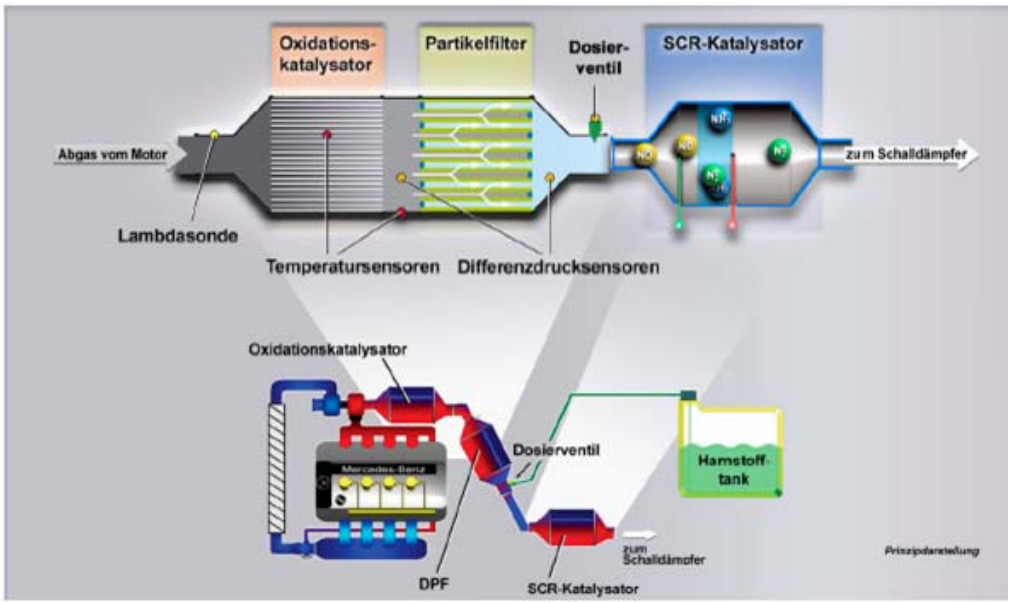
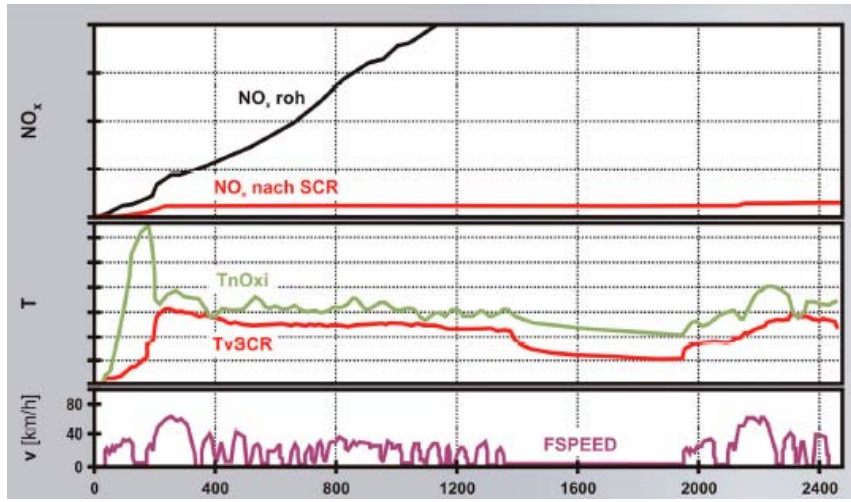
DaimlerChrysler generally describes their DPF+SCR system

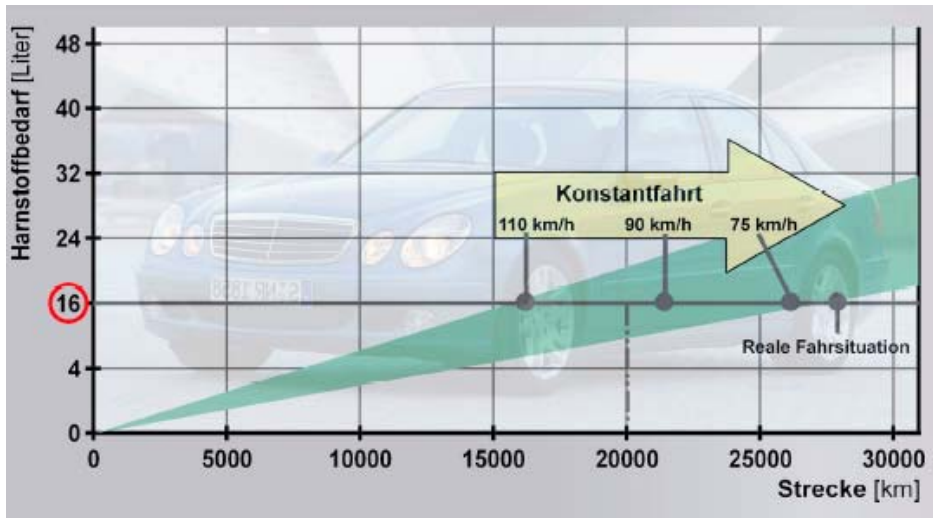




HC injection is used to achieve fast light-off of the system.

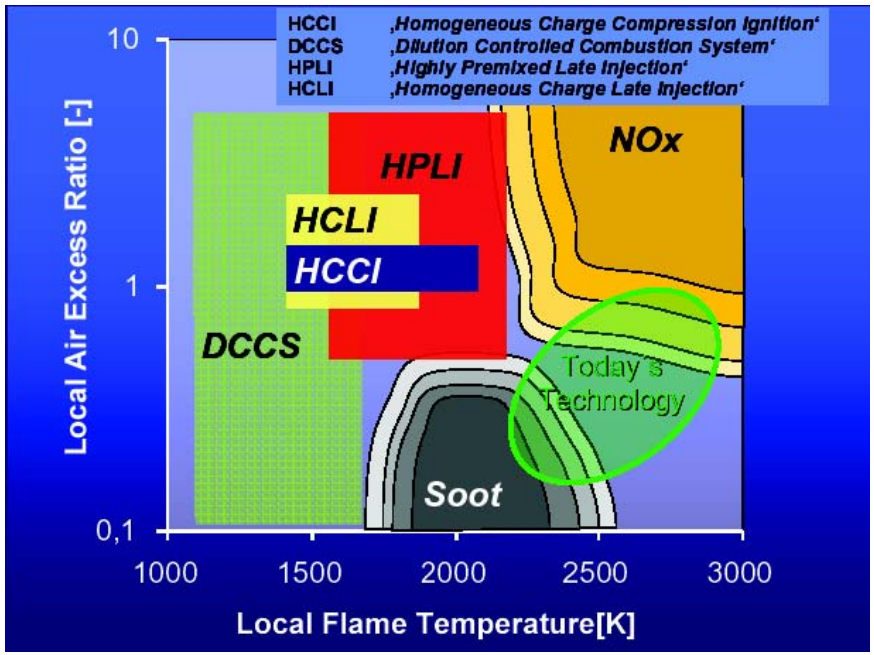
The SCR system follows the DOC+DPF. Urea comes from a remote tank, and is injected right after the DPF.

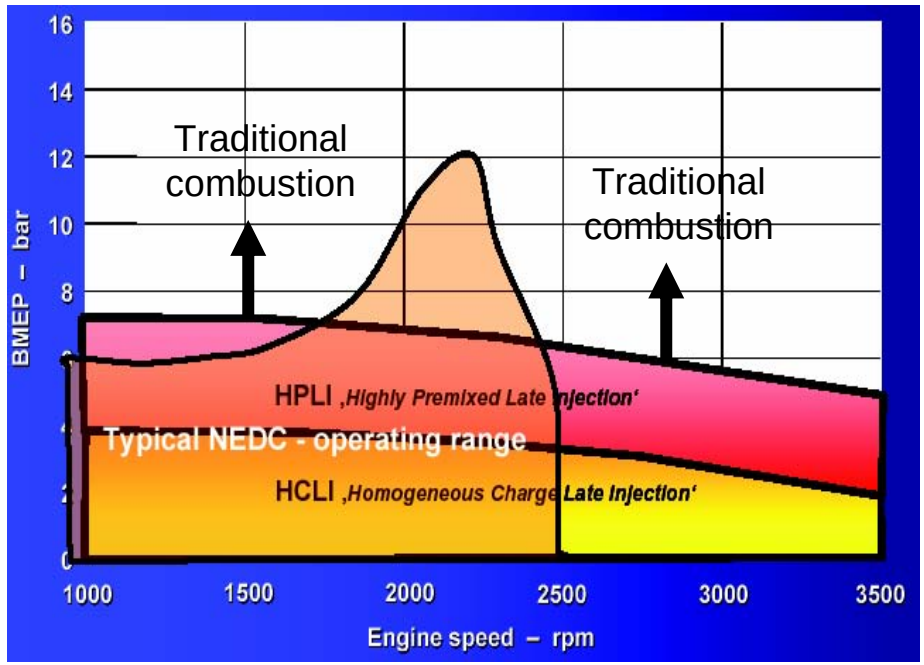
- About a 1% urea consumption is anticipated. A 16 liter tank will be filled at oil drain intervals and can last 16,000 to 27,000 miles.
- A fleet is going to US EPA for evaluation. Could be commercialized before MY09.



Alternative combustion strategies are moving forward in many varieties.

AVL DEER 9-03

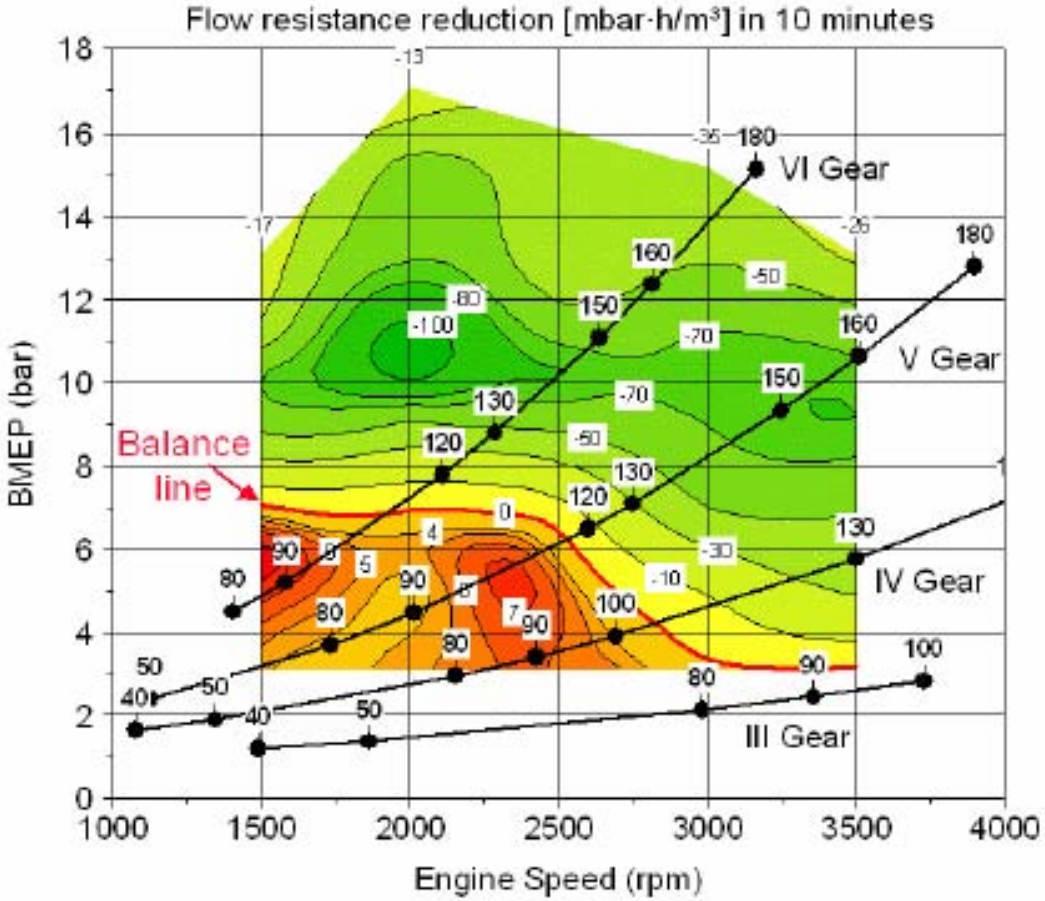




- Application of pre-mixed combustion at low load minimizes low temperature PM and NOx, but delivers higher HC and CO
- Everything changes: LT HC and CO control, minimal DPF management at LT, and little of no LT NOx treatment needed
- Driven by low NOx regulation – US LD, and maybe US2010 and Japan 2009 HD

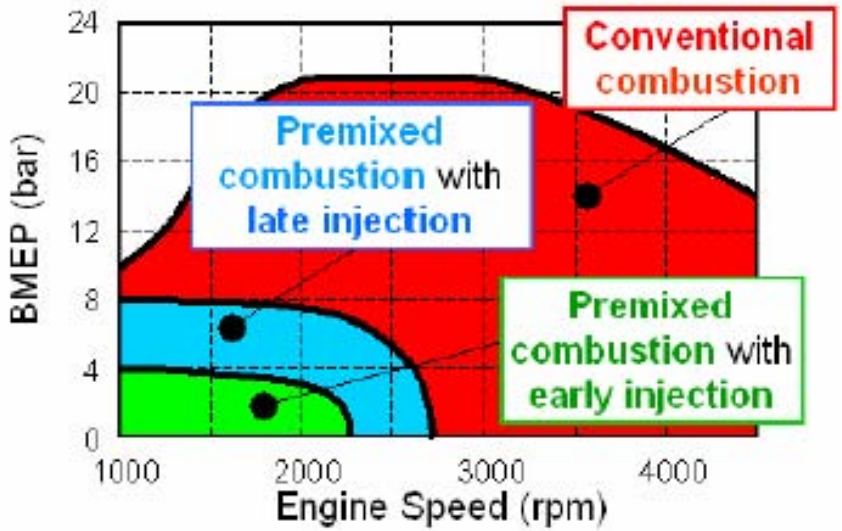
Advanced combustion will make active regeneration easier, or even unnecessary

Traditional Diesel Combustion



Above the "balance line" is passive regeneration using DOC+CSF. Below the line is active regeneration. 1.9 liter CR DI engine, D-Class vehicle, 10 minute backpressure changes at 10g/liter soot. Fiat FISITA 5/04.

High HC levels from advanced combustion facilitate DPF regeneration.



Advanced combustion overlaps active regeneration regime.

GM Powertrain-Fiat, ATA Conf, 10-04

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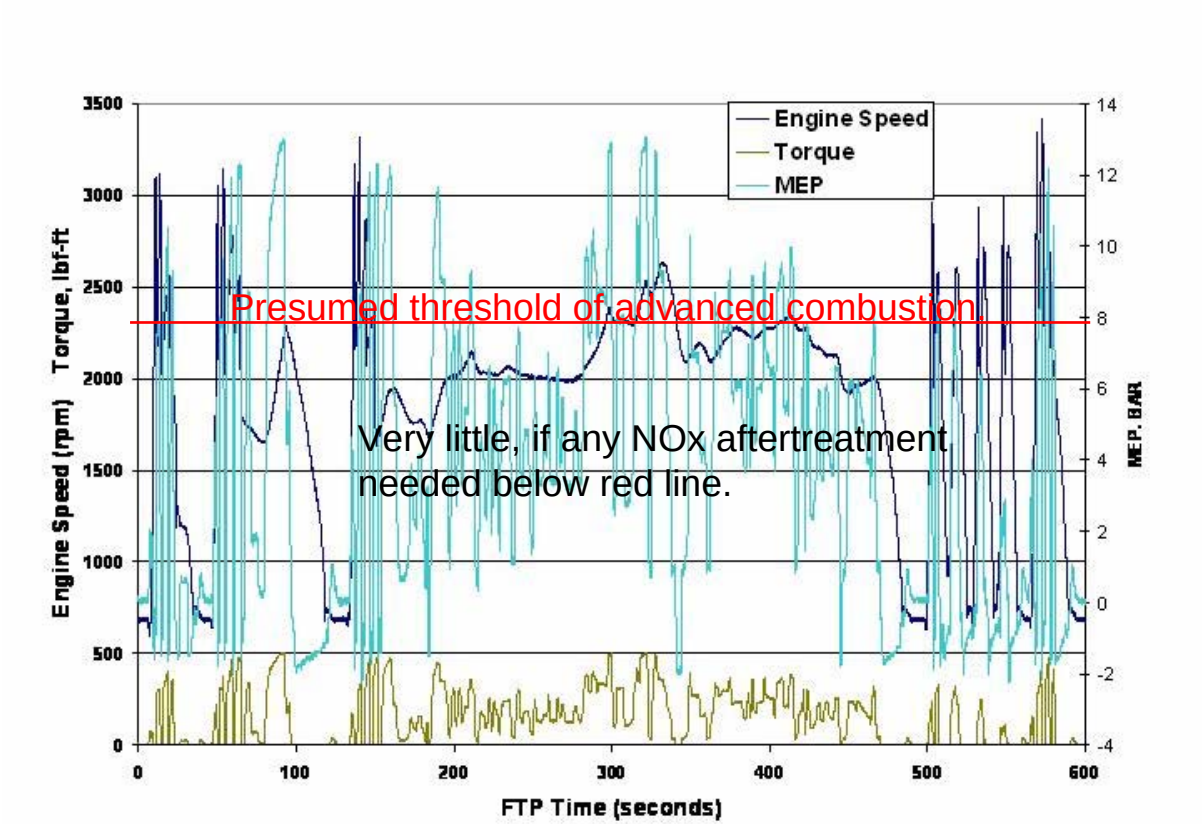
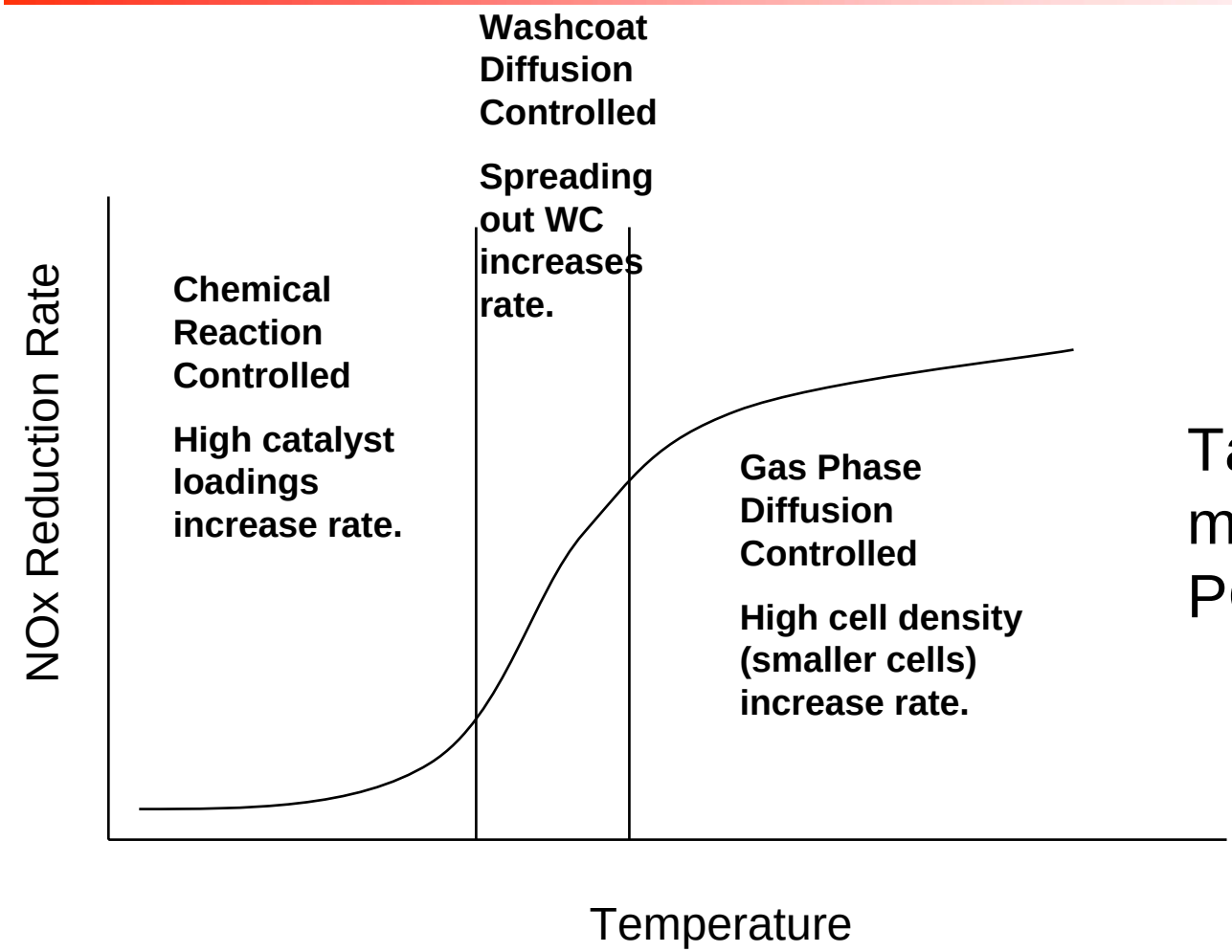
US06 cycle is highest load LD test cycle. Diesel LDTs will hit most of it with little NOx aftertreatment.



With mixed mode engines, NOx control is generally only needed at the high-load spikes; and then at only 30-50% efficiency.

Measured speed and torque values over the US06 cycle for a diesel PU. MEP values are calculated. 6.6 liter, GM Yukon

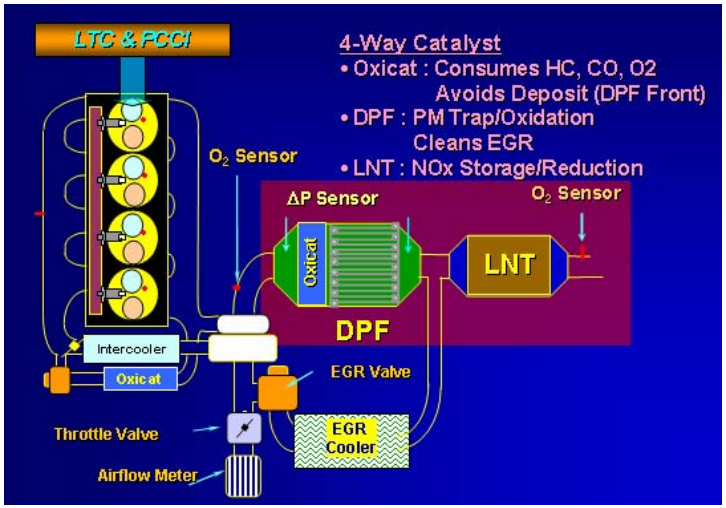
If LT NOx control needs are reduced, catalyst loadings can be significantly reduced



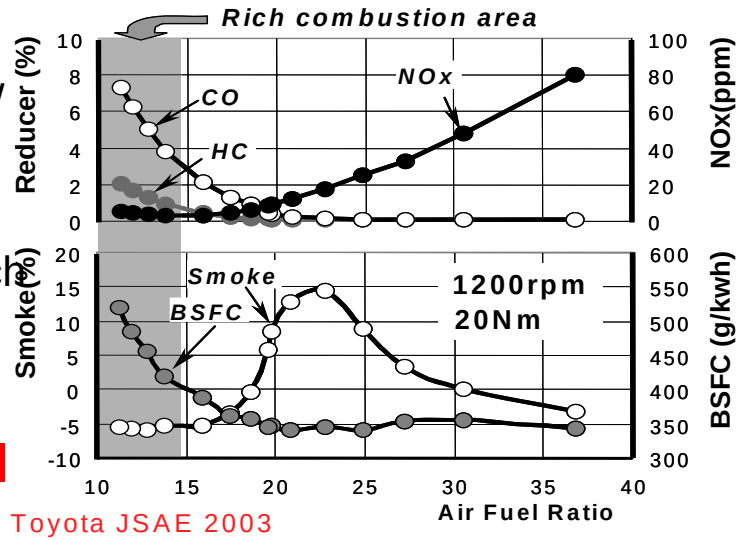
Taking out LT NOx might drop LNT PGM loading 70%.

Dual-loop EGR system gives allows stable operation with LNT system, and achieves 90% NOx efficiency and est. 0.035 g/mi NOx FTP

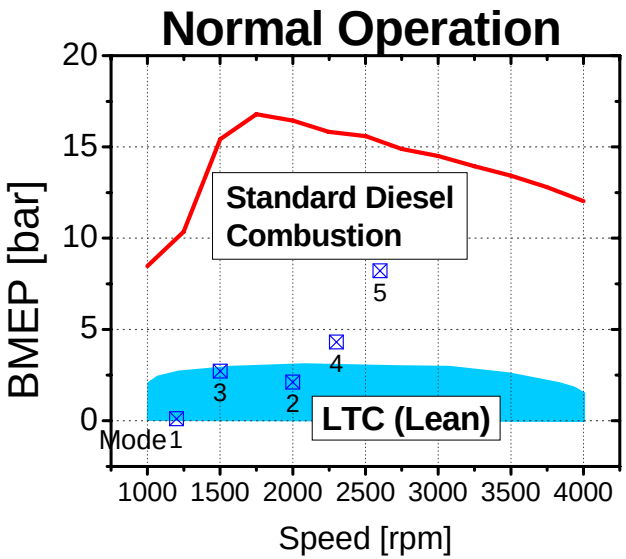
SwRI SAE 2005-01-1091

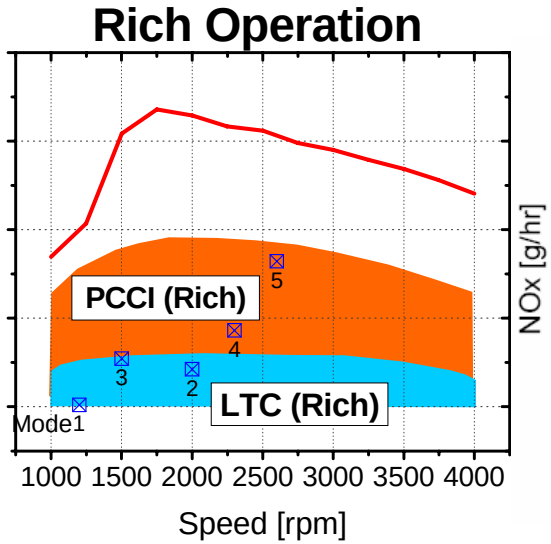


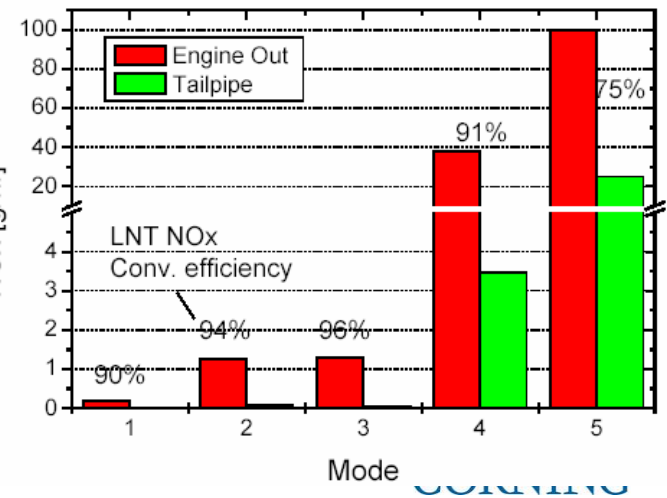
- Dual loop EGR is used to stabilize low load lean combustion.
- Highly-premixed rich combustion is used for LNT regen.
- **Bin 3 potential**



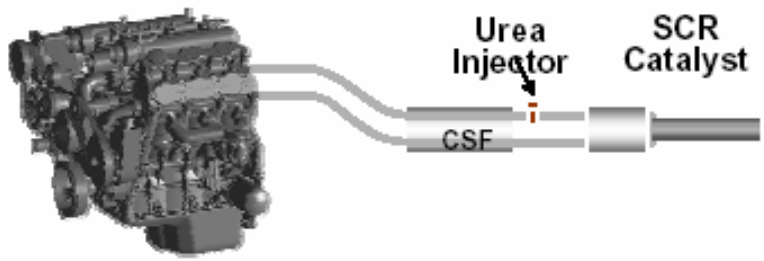
Toyota JSAE 2003



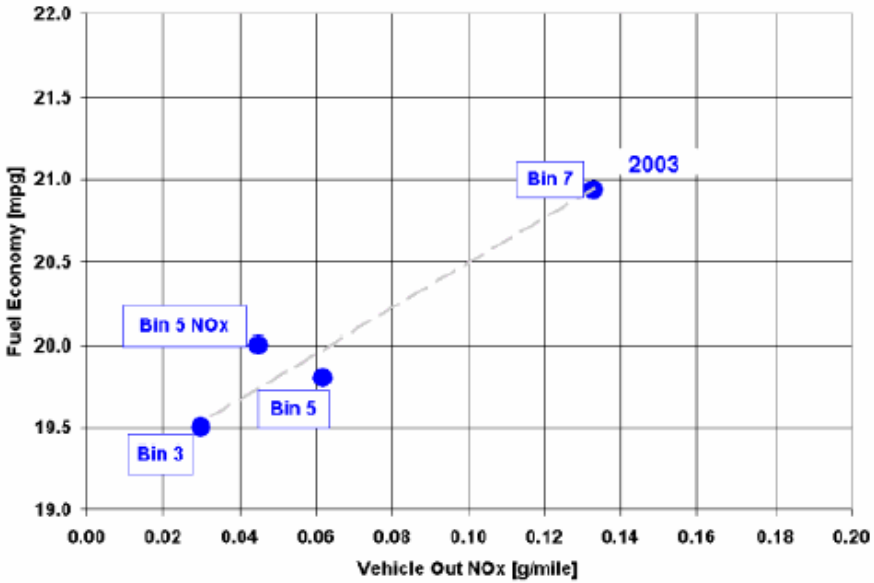




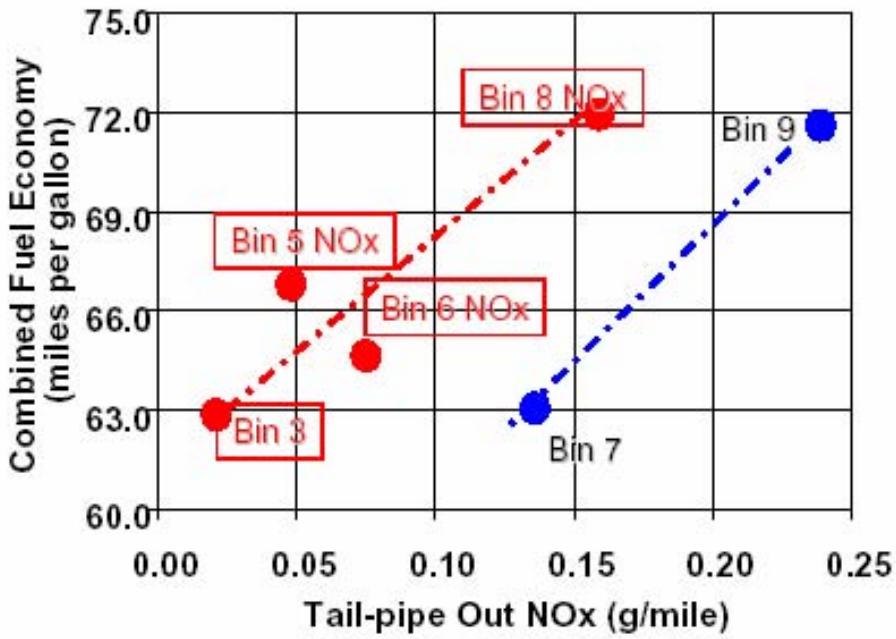
CSF+SCR system was demonstrated 2 years ago for LDD; Bin 3 was hit



4.0 liter LDT hits Bin 3 with CSF/SCR combination. Controlled NO2/NO ratio to SCR.



Passenger car platform also shows significant NOx reductions



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Is the US LDD Market there?

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Current results are encouraging

- Upwards of 2/3 of heavy light-duty trucks are diesel
- Other diesel options, like the E-Class Mercedes, Jeep Liberty, and VW Passat are selling well
- Interpretation of market forecasts (3-25%): expect about 10-15% penetration by 2015

Fuel Issues

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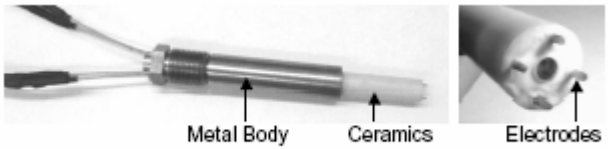
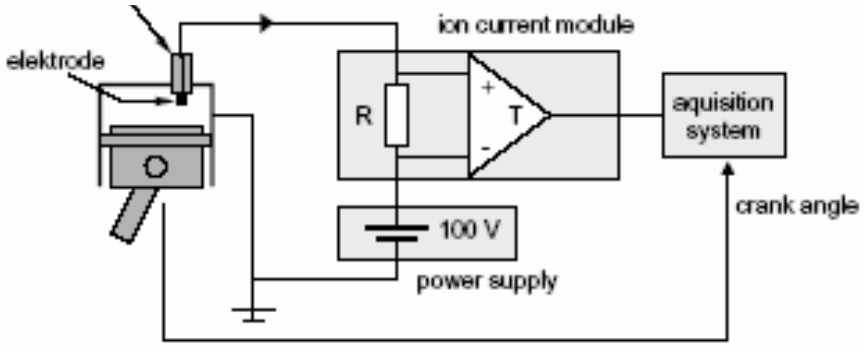
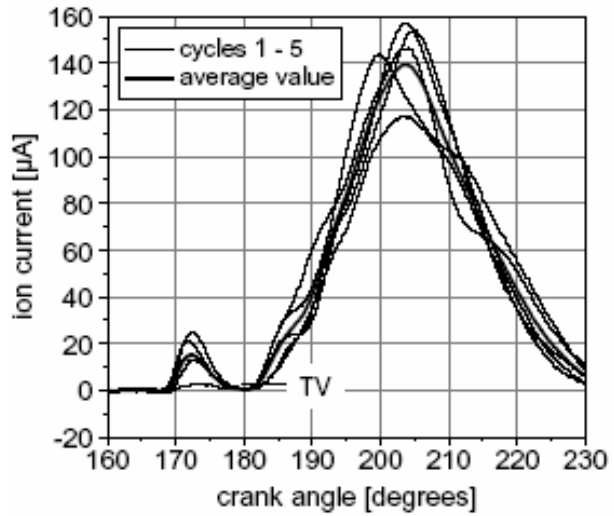
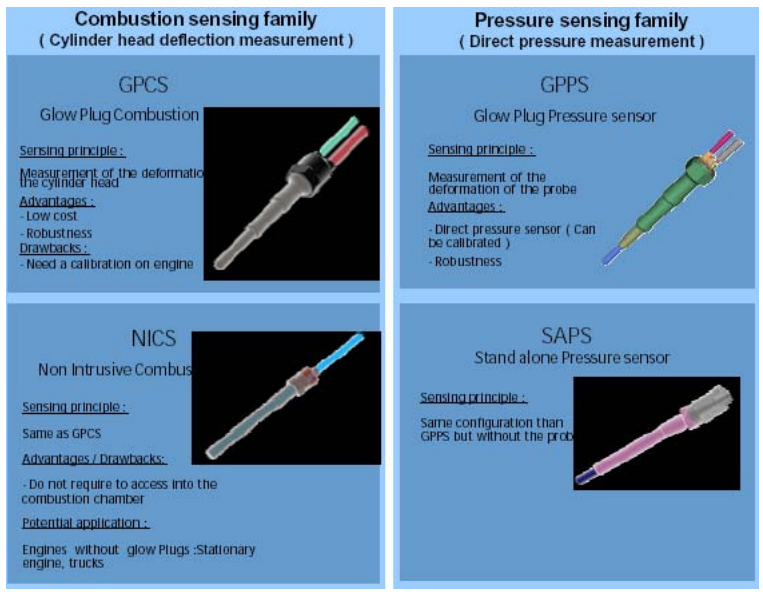
In-cylinder combustion sensors are coming to market that will allow control despite fuel variability





Univ Karlsruhe, SAE 2004-01-2922





Combustion pressure sensors are also going commercial. Absolute and head deflection sensors are available. Siemen, Federal Mogul 12/04.

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Gasoline options

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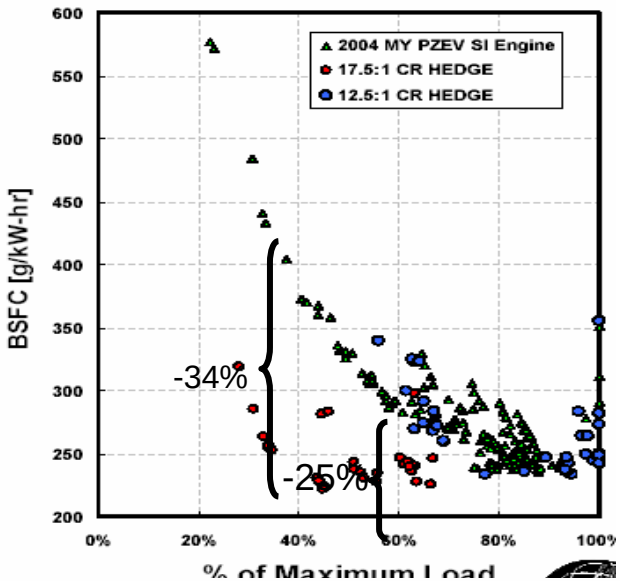
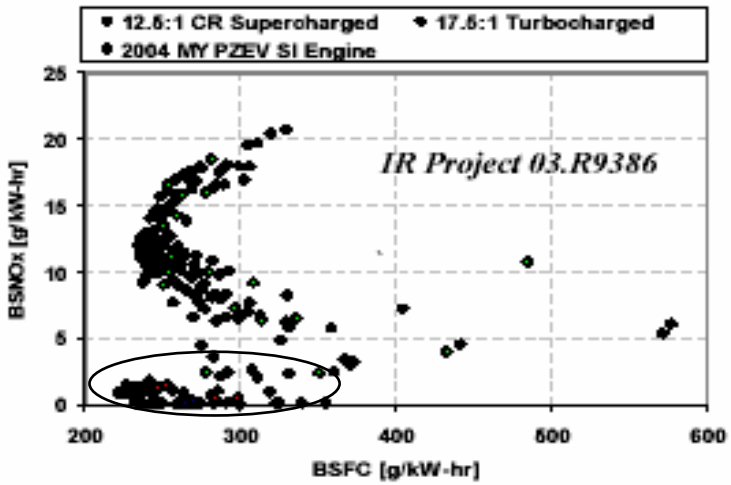
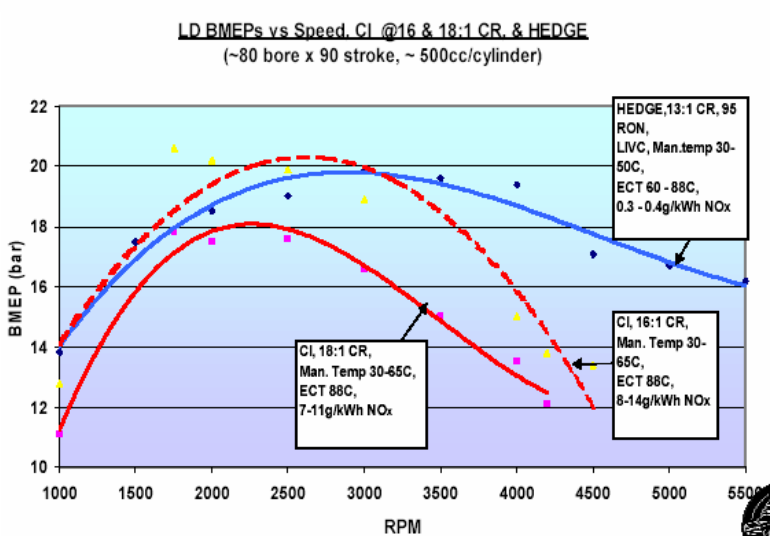
Research on gasoline is yielding same FE as diesel, PZEV engine-out NOx, and prospect for diesel low-end torque. Incremental costs to diesel: no FIE and less aftertreatment.





HEDGE <u>engine-out</u> NOx emissions are equal to PZEV <u>tailpipe</u> levels



SwRI SAE 2005 (2 papers)

CORNING

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- Market
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- Fuel quality and availability
  - Variability is addressed with hardware
  - Refinery diesel:gasoline mix will be upset
- Competition
  - “King of the Road” gasoline is not standing still
  - Diesel community needs to move fast