Next Generation DPFs for Light- and Heavy-Duty Diesel Applications

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Corning Incorporated

Light Duty DPFs

Many mid- and large-sized European light-duty diesel cars will have deNOx added to them for NOx and CO_2 reductions. This increases system back pressure. Smaller platforms desire more efficient regeneration behavior to reduce CO_2. Corning's next generation aluminum-titanate (AT) light-duty filters are designed to address these lower back pressure and higher soot mass limit requirements.

As shown in Table 1, the new, stronger AT material has slightly lower porosity as a result of an optimized pore-size distribution. This can be used to full advantage in one of two ways. The wall thickness of the honeycomb can be reduced, decreasing back pressure without compromising soot mass limit; or the wall thickness can be maintained at previous levels, but soot mass limit is increased 2-3 grams/liter while maintaining the same back pressure as the previous version.

Table 1. Summary of the new AT DPF for LDD applications, and resulting attributes.

	Approach	Porosity	Pore Size Distribution	Cell design	SML	Pressure Drop
DuraTrap® AT	Base	~50%	Base	300/13 ACT	Base	Base
DEV AT LP	Increased bulk density	~44-45%	Improved	300/13 ACT	+ 2-3 g/l	~ Base
DEV AT TW	Reduced wall thickness			300/10 ACT	~ Base	- 20-25%

The PN test results on the NEDC are not compromised with the new material, wherein the emissions are still generally 2-3 orders of magnitude below the limit value using fresh filters. The soot mass limit of the thinwall version of the filter is roughly the same as for a current silicon carbon filter of the same cell geometry, even though the AT filter retains more heat and thus higher peak temperatures. It is this property that allows the filter to regenerate more efficiently, burning 20% more soot in a hot, drop-to-idle test, and 10% more soot under a controlled regeneration (both cases at 4-5 g/liter soot loading). Long term durability is also good, wherein after more than 60 extreme drop-to-idle regenerations, PN emissions are still will below the regulatory limit value.

The material development efforts on the new AT filter now provide attractive options for the Euro 6 diesels – increased soot mass limit and improved regeneration efficiency to reduce CO2 emissions from regenerations for the engine strategies calibrated to higher PM levels; and lower back pressure with no compromise in soot mass limit for those strategies employing NOx emission control.

Heavy Duty DPFs

Heavy-duty diesel calibrations are emerging that take advantage of high-efficiency SCR (selective catalytic reduction) deNOx systems. These calibrations are characterized by high NOx/soot ratios that promote passive regeneration, wherein under most operating conditions, plentiful NO_2 continuously oxidizes the low amount of soot emitted from the engine and captured on the filter. Such calibrations greatly reduce the need to actively regenerate the DPF, thus reducing the need for high thermal mass in the filter to absorb the exothermic heat when large amounts of soot are burned at once. The new cordierite filter being developed complements this passive regeneration strategy by offering greatly reduced pressure drop, faster downstream SCR light-off, high ash capacity, and manageable soot mass limit for those cases requiring active regeneration.

The filter has improved pore size distribution and thinner walls than the US2010 version (0.008 inches vs. 0.012 inches in a 200 cell/sq. inch cell density), resulting in nominally 40% lower back pressure, as shown in Figure 1. The opportunity is available to downsize the filter up to 35% while maintaining equivalent or reduced pressure drop relative to the 2010 filter. Particle number emissions are 1-2 orders of magnitude below Euro VI limit values.

The reduced mass results in better thermal response for the overall exhaust emission control system. For example, Figure 1 shows that in the US HD FTP certification cycle, the outlet temperature of the filter is at temperatures of 180°C or hotter, the minimum threshold temperature for urea injection, for 10-15% more of the time, resulting in more heat going into a downstream SCR system.

Regarding compromises in soot mass limit, the maximum DPF temperatures during controlled regenerations is similar to that of the 2010 filter at soot loadings of about 4 g/liter, but the thermal stresses are less due to higher skin temperatures and lower radial thermal gradients. As a result, regeneration efficiency is improved during active regenerations upwards of 5 to 10%.

Improved SCR catalyst efficiency is resulting in engine calibrations that open the opportunity for improvements in HD filters. Reduced need for thermal mass in the filter results in 40% lower DPF back pressure, better system thermal response, and improved filter regeneration efficiency at manageable soot levels.

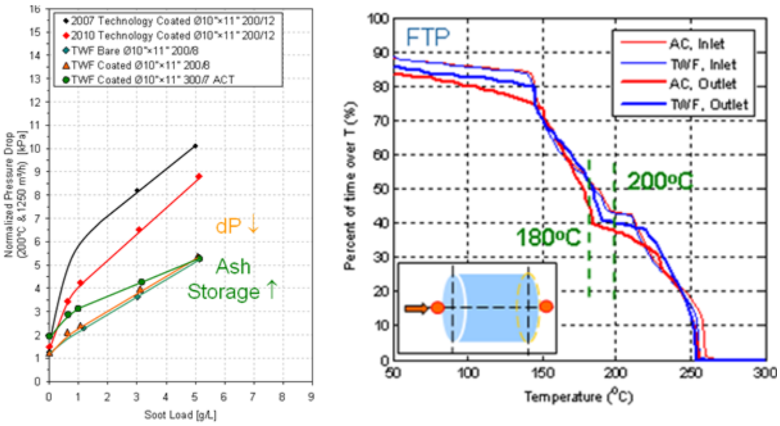

Figure 1. The new thinwall cordierite HD filter has 40% lower back pressure and lower thermal mass than the 2010 filter ("AC"), resulting in better thermal response for improved SCR catalyst management.

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Emerging Diesel and Gasoline Emission Trends

June 22, 2010

Tim Johnson

Summary

- Further tightening of criteria regs expected. California is beginning LEV3 proposal stage. EPA considering Tier 3.
  - Japan looking to 2016. Universal interest on urban NOx emissions. US focused on CO2.
- CO_2 mandates are proposed for LD and HD will follow
  - Onset of another major regulatory-driven technology evolution
- LDD focusing on downsizing, deNOx for FC reductions. Gasoline using downsizing, EGR, going lean.
- HDD engine technologies are addressing engine-out NOx and FC
- SCR is addressing “secondary” issues:
  - LT issues: ammonia sources and urea inj; NH3 storage formation, mechanisms.
  - Catalyst HT and sulfur durability addressed
- New LNT compositions and designs are shown.
  - Better performance, lower cost
  - LNT+SCR systems advancing
- DPF regen, catalysts, substrate properties, and material advancing.
- Gasoline emission control is focused now on PM&PN, and systems needed to meet LEV3

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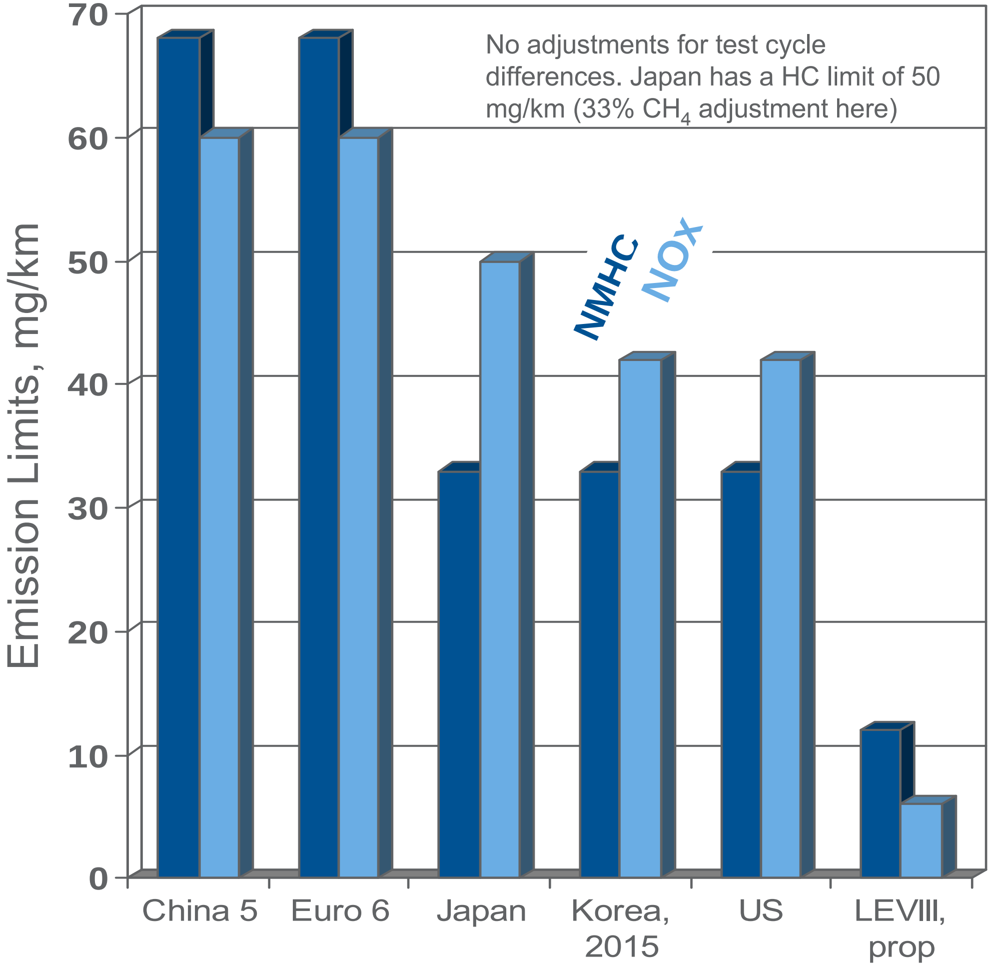
Regulations and Market

Current Gasoline emissions limits require similar technologies.

We could see another round of tightening around the world as LEVIII is implemented.

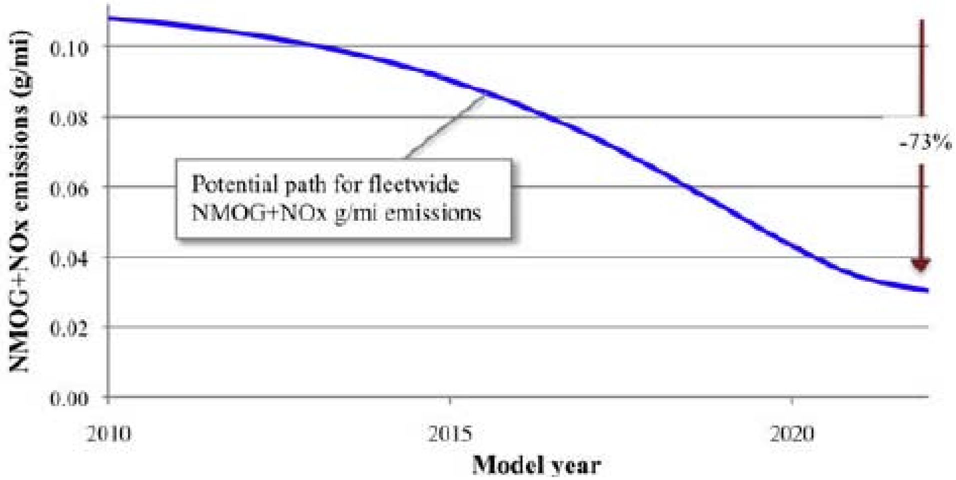


- Durability Requirements:
  - China 5 160,000 km
  - Euro 6: 160,000 km
  - Japan: 80,000 km
  - Korea: 192,000 km
  - US: 192,000 km
  - LEVIII: 240,000 km

Test cycle differences are not considered.

CARB-Proposing LEVIII Standards for 2014-2022

SULEV Fleet Average NMOG+NOx.



Possible scenario for fleet average NMOG+NOx standards.

•PM reduced 70% to 3 mg/mi in 2017, and then to 1 mg/mi in 2025, subject to 2020 review. Optional PN standard being considered for 2025.

•Composite SFTP option using FTP, SC03 and US06 cycles. SULEV fleet limit values at full phase in.

• OBD postponed

•Will be finalized as part of CO_2 regulation in November.

•EPA to follow CARB with a Tier 3 LD regulation.

NMOG+NOx Tailpipe Standards on the FTP

- 30 mg/mi average – Bin 2
  - 74% reduction
- Individual vehicles choose from 7 bins
  - 160 mg to zero (new bins at 70, 50, 20 mg)
- Phase-in 2015-2025
- Credits for Direct Ozone Reduction radiators and extended 150K mile warranty
  - 5 mg/mile each
- Useful life 150K miles (durability requirement)
- 8500-10K GVWR chassis tested vehicles included
  - Class 2b: 178 mg/mi – 51% reduction
  - Class 3: 247 mg/mi – 61% “
  - Phase-in 2016-22
  - Bin structure allows averaging

CARB, CTI Forum, 5/11

NMOG+NOx Tailpipe Standards – Supplemental Testing (SFTP)

- Option 1: Stand-alone US06 and SC03 Standards tied to FTP Bins
  - Separate standards for LEV, ULEV, and SULEV
- Option 2: Composite of US06, SC03 and FTP
  - 50 mg/mile NMHC + NOx average
  - Helps with diesel compliance
- Phased-in 2015-2025
- 8500-10K GVWR chassis tested vehicles included
  - Composite standard
  - Phase in 2016-25
  - Special test for low power density trucks (US06 Bag 2) and trucks > 10K GVWR (LA92)

CARB, CTI Forum, 5/11

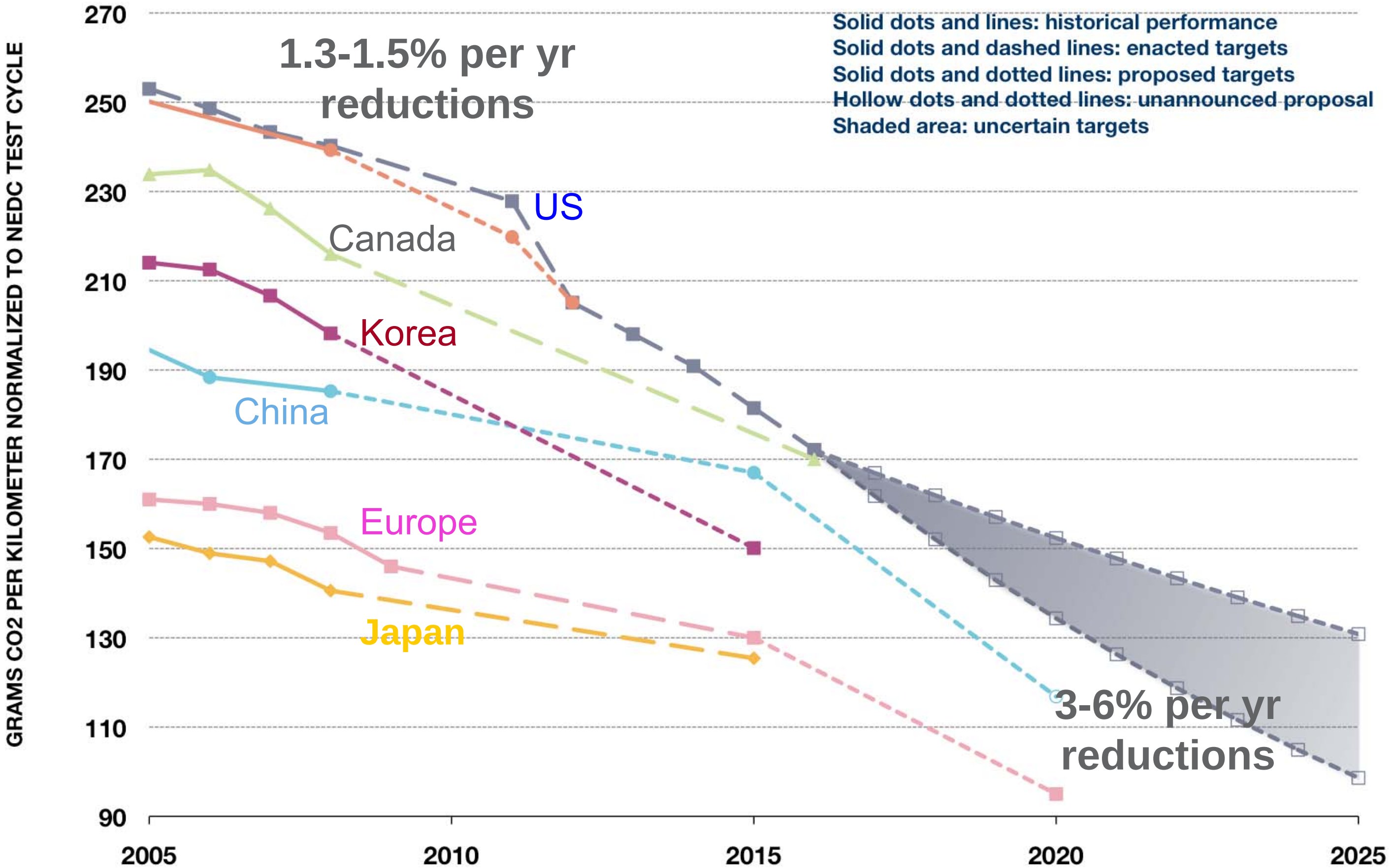
PM Standards

- Objectives
  - Limit GDI emissions to PFI levels
    - Current GDI up to 8X PFI PM levels
  - Reduce oil consumption-generated PM as vehicle ages
    - New data shows 5X increase in PM in some vehicles
- FTP
  - 3 mg/mile phase-in 2017-2020, 1 mg/mi 2025
  - Test procedure changes needed for lower standards
- SFTP
  - 10 mg/mile cars; 20 mg/mile trucks (LDT3/4)
  - 20 mg/mile MDVs (2B and 3)
- No particle number standard at this time

CARB, CTI Forum, 5/11

The US EPA (and CARB) are considering 3 to 6%/yr reduction in LD CO_2 emissions.

By 2025, 6%/yr brings near-parity with Europe of 2020.



[1] Based on 3% annual fleet GHG emissions reduction between 2017 and 2025 in the September 30th NOI .
[2] Based on 6% annual fleet GHG emissions reduction between 2017 and 2025 in the September 30th NOI .
[3] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.

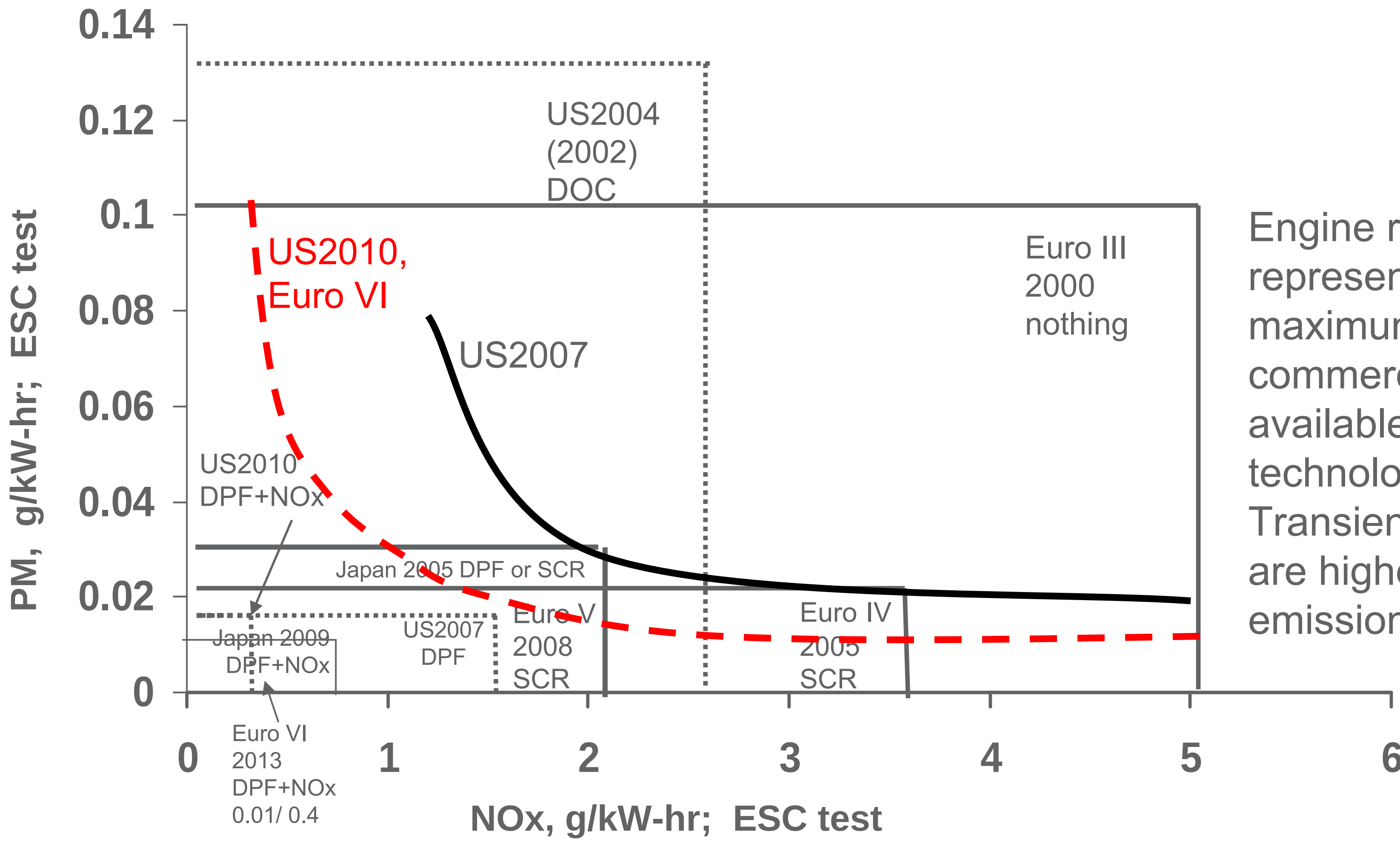
Technology Needed for Compliance - 2025 Models

Stringency, % GHG change/yr	Mass Reduction* lbs	%	Advanced engine, %	HEVs, %	Plug EV, %
3%	658	18	52	3	0
4%	733	20	63	18	0
5%	733	20	49	43	1
6%	712	19	44	47	9

* Limited to a maximum 20% in this Scenario B

CARB, CTI Forum, 5/11

HD regulatory and engine technology framework



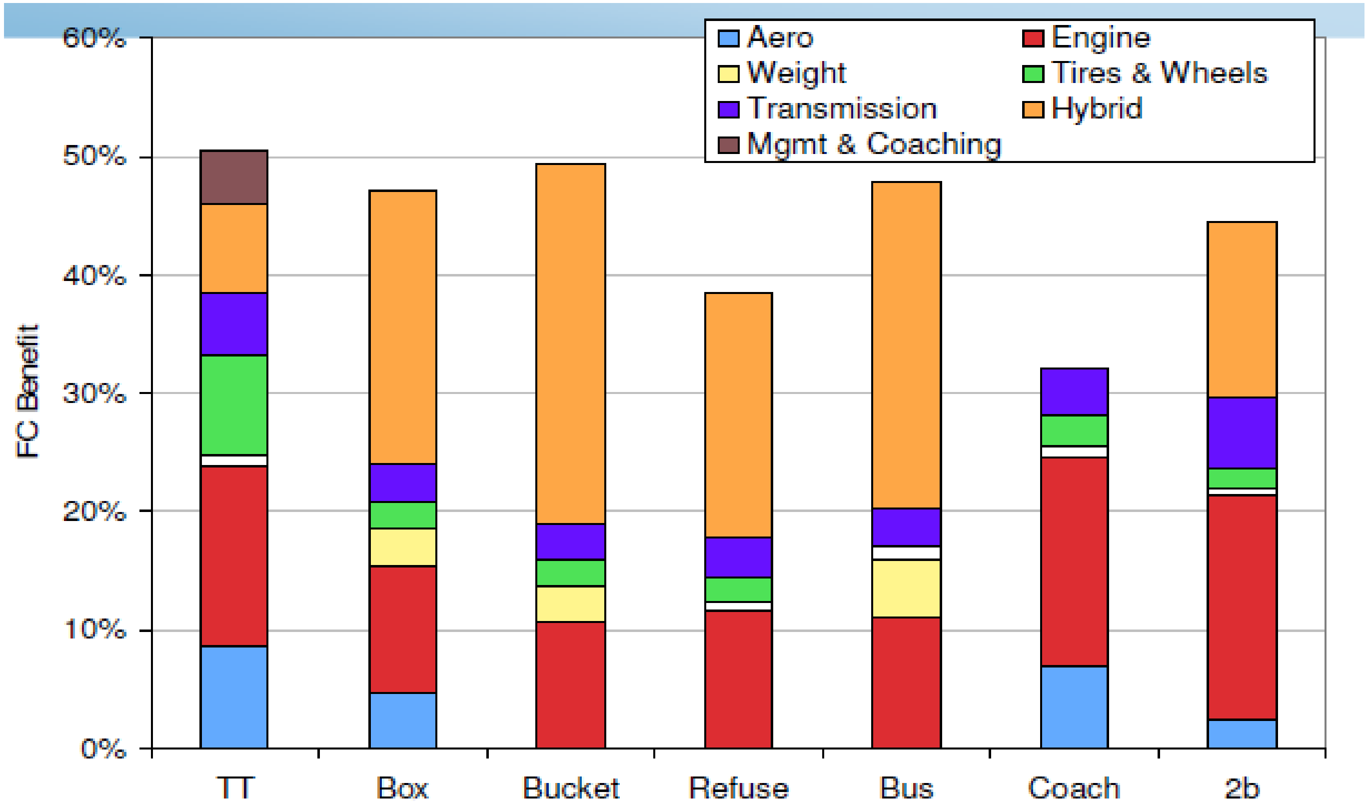
Engine results represent maximum commercially available technologies. Transient results are higher emission.

Other HD regulatory developments on criteria pollutants

- The US EPA is interested in off-cycle emissions
  - Urban or low-load NOx are potential sources
  - Changes in the NTE region may accommodate
- Japan is considering the next round of tightening for 2016
  - Need to complete its FC regulation in 2015
  - Looking at Euro VI duplication, except perhaps PN
- China may delay implementation of Euro IV July 2010
  - Delayed 1 yr. Concerns about partial filters
- India is implementing Euro IV – few engines sold due to registration outside of controlled cities

There are numerous opportunities for fuel savings on commercial trucks.

Engine improvements dominate line haul, coaches, and small delivery trucks. HEV dominates larger utility trucks and tansit buses.



Fuel savings of 30-50% can be achieved on representative truck applications. Engine benefits dominate, and then comes HEV. Note: Non-TT (tractor trailer) applications represent ~60% of new HD vehicles.

TIAX NAS Report 2009

HD engine CO_2 proposal calls for 3% reductions in both 2014 and 2017 for line haul (SET).

3-5% reductions for vocational (FTP) in 2014; 2-4% in 2017.

GVWR CLASS	FUEL	MODEL YEARS	CO_2 REDUCTION FROM REFERENCE CASE
HHD (8a-8b)	Diesel	2014-2016	3%
		2017+	6%
MHD (6-7) and LHD 4-5	Diesel	2014-2016	5%
		2017+	9%
	Gasoline	2016+	5%
LHD 2b-3	Gasoline	2016+	5%
	Diesel	2016+	9%

Total Vehicle Reductions

Line Haul:	20%
Vocational	7-10%
Small trucks	12-17%

General: Proposed engine CO_2 standards relative to the 2010 industry average. HHD: 3% drop in 2014 then additional 3% in 2017. MHD and LHD: 5% drop 2014, then additional 4% in 2017.

Table II-2: Proposed Heavy-duty Diesel Engine Standards for Engines Installed in Tractors

Effective 2014 Model Year		
	MHD Diesel Engine	HHD Diesel Engine
CO_2 Standard (g/bhp-hr)	502	475
Voluntary Fuel Consumption Standard (gallon/100 bhp-hr)	4.93	4.67
Effective 2017 Model Year		
	MHD Diesel Engine	HHD Diesel Engine
CO_2 Standard (g/bhp-hr)	487	460
Fuel Consumption (gallon/100 bhp-hr)	4.78	4.52

N_2O: 0.050 g/bhp-hr on FTP; 3% of carbon footprint; 2X 2010 capability

CH_4: 0.050 g/bhp-hr; at 2007 capability

Line Haul Engine SET 2010 industry baseline is 490 g CO_2/bhp-hr for HHD and 518 g/bhp-hr MHD. MHD and HHD: -3% 2014, -3% 2017. Optional for special cases: 2014: -5% CO2 from company's own 2011 engine.

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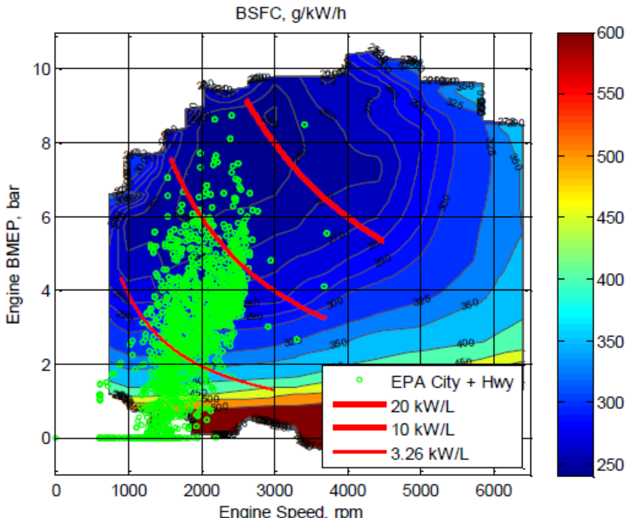
Engines

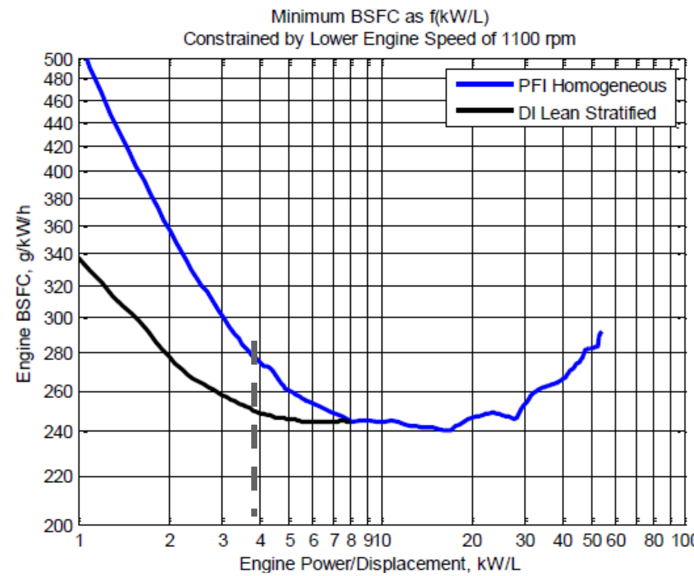
Options for reducing FC are evaluated using a specific power metric.

Lean DI, boosted downsizing, and cylinder cut-off help in the low-load regimes. cEGR and diesel expand benefits to higher loads.

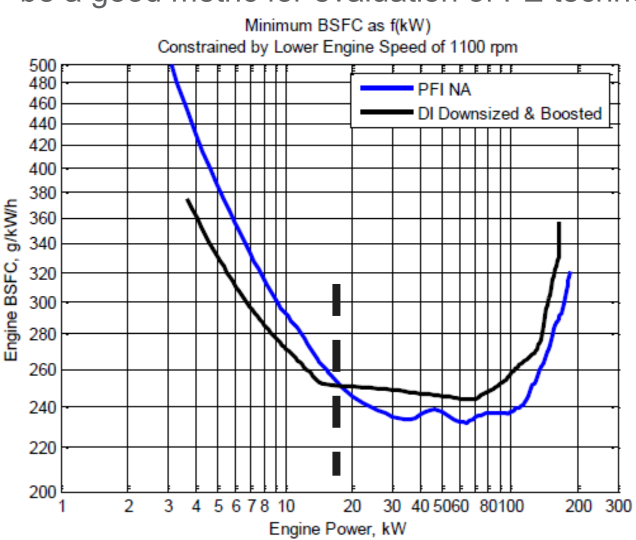


US CAFE points are focused on a small portion of the engine map. FC at 3 to 10 kW/liter specific power may be a good metric for evaluation of FE technologies.

FC as a function of kW is also a valid metric. Vehicle demand also needs to be considered. No simple metric.



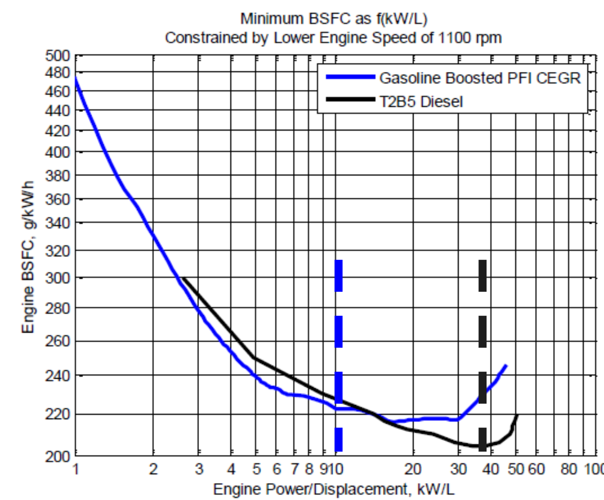
Lean DI is a low-load FC strategy.



Downsizing via DI and boost is a low-load FC strategy. High BSFC at high power levels. Downspeeding similar.

Chrysler, SAE FE Panel 4/10

cEGR extends FC benefit to somewhat higher loads. Diesel is a high load FC reduction strategy.

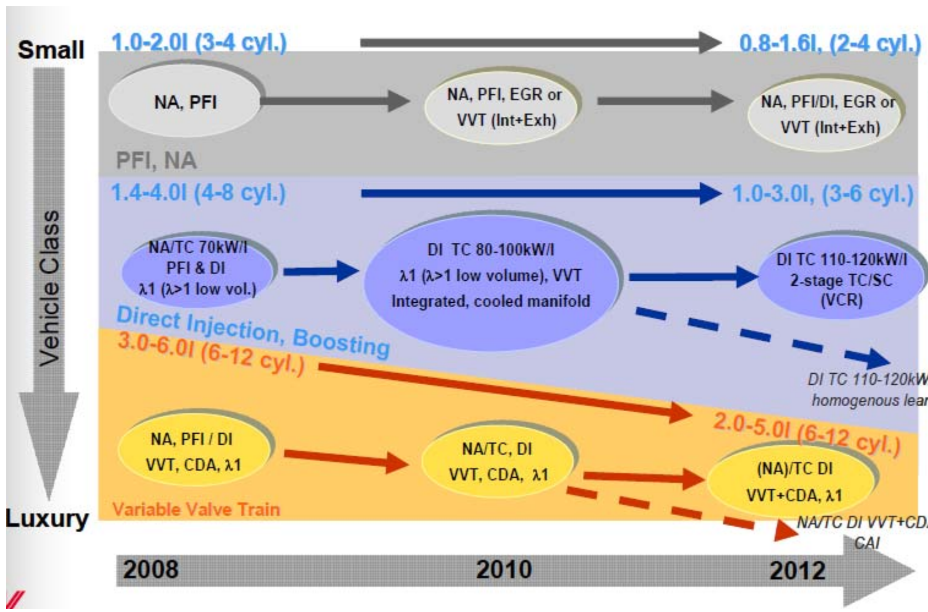


Different levels of technology will be applied to the weight classes of vehicles.

Technology Scope for T2B5 LDDs

					
		Segment / Technology	Small	Medium	Large
Diesel	Engine	Downsizing	Not feasible? (1.3l)→(1l)?	(2l) → (1,6l) -20%	(3lV6) → (2,2l I6/I4) -30%
		Boosting	Optimized VNT	1/2-stage	2-stage
		FIE	1450..1800 bar	1800-2000 bar (Piezo)	>2000 bar Piezo
		EGR-System	HP/HP&LP-EGR	HP&LP-EGR	HP&LP-EGR
		Optimized Combustion	Lowered Compr.	Lowered Compr.	Lowered Compr.
		Aftertreatment	DPF / LNT	DPF / SCR or DPF / LNT	DPF / SCR
	Transmission	Manual / Automated	AMT, DCT	AMT, DCT, AT	AT, DCT
		Gears	5-6	6-8	6-8
		Clutches Dry / Wet	Dry	Wet, Dry	Wet
		Electric / Hydraulic	Electrical	Electr., Hydr.	Hydr.
	Hybrid	Start/Stop	BISG	BISG & ISG	ISG
		Rekuperation	Restricted, 3KW	Enhanced	Full
		Optimized Operation	Limited	Limited	Yes
		Electric Drive (<20mi)	-	-	Yes

Technology Scope for Gasoline



FEV, DEER Conf, 9/10

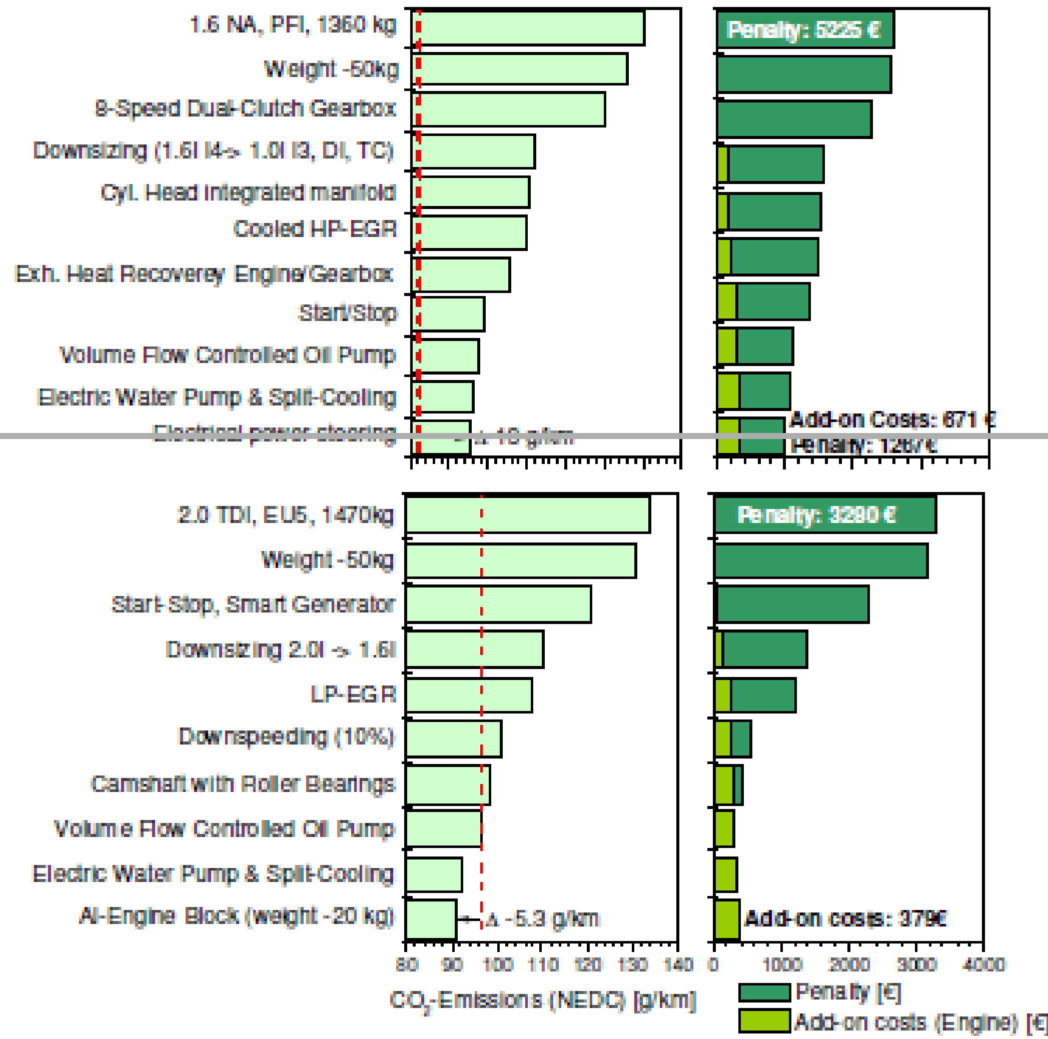
For Euro 2020, it is more cost effective to put the money into diesel than gasoline.

€25/g CO2

Gasoline

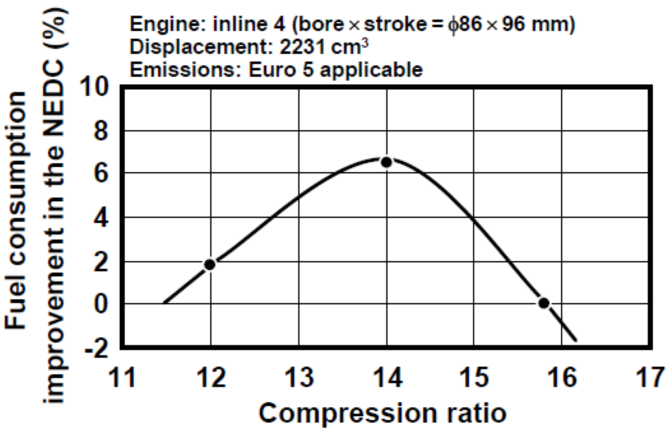
Diesel

€8.40/g CO2

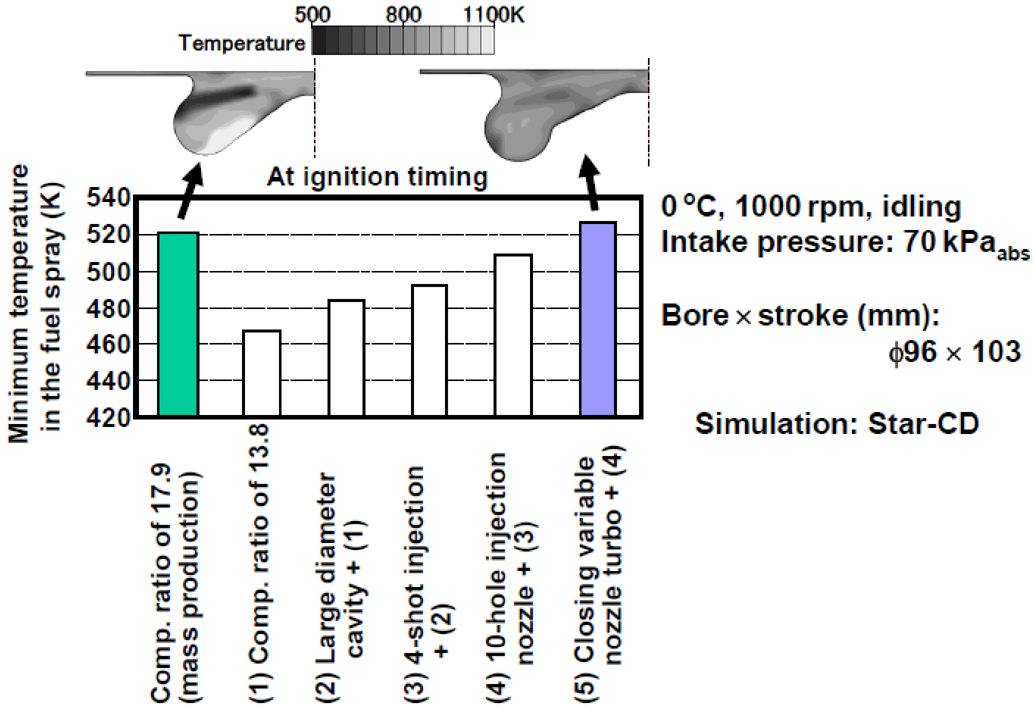


Lower compression ratios are desirable to reduce friction and NOx. CR 14 is optimum.

Cold start is issue, and addressed with more injection holes, better bowl design, and more pilot injections.



Friction goes down with CR, but thermodynamic efficiency is compromised. Best CR is ~14.

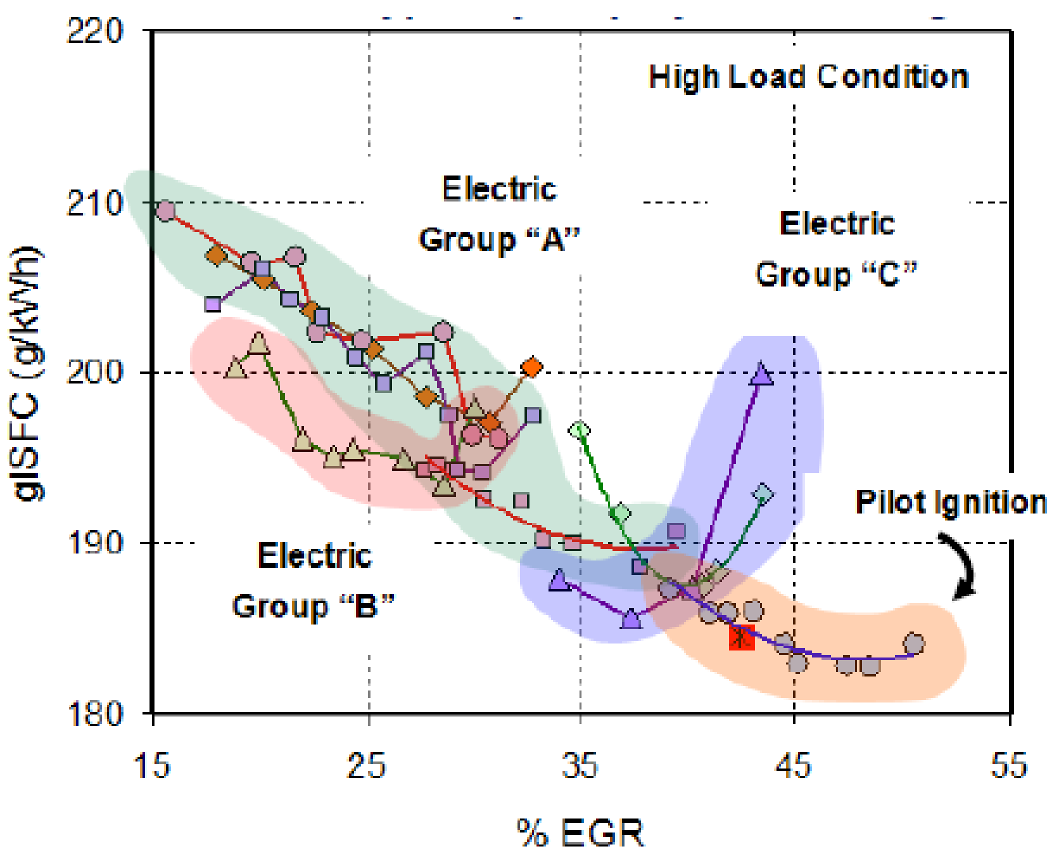


Vehicle testing:

At 100 sec after cold stat at -25C, THC was 100 ppm less than for a prod engine with CR=15.7.

Toyota, Aachen Colloquium 10/10, SAE 2011-01-1393

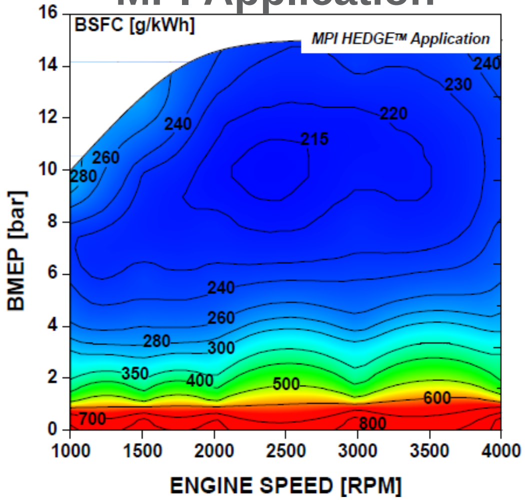
At high EGR levels strong ignition systems are needed to get stable and efficient combustion.



SwRI, SAE panel 4-10

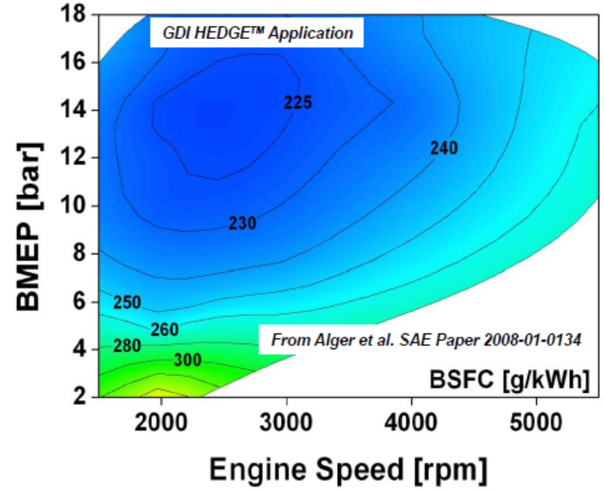
The HEDGE gasoline concept (stoich, cEGR, boosted) has bee evaluated in a variety of applications with good results.

MPI Application



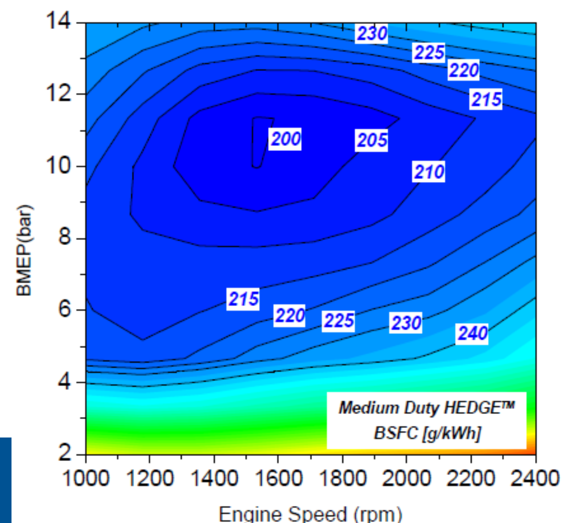
In an MPI application: -10% FC at low and med load, -10 to -30% at high load (good for downsizing). 4 cyl, CR>11

GDI Application



In a GDI application: -5 to -30% FC. Recent: <220 g/kW-hr at 20 bar BMEP; GDI might not be needed to get good results.

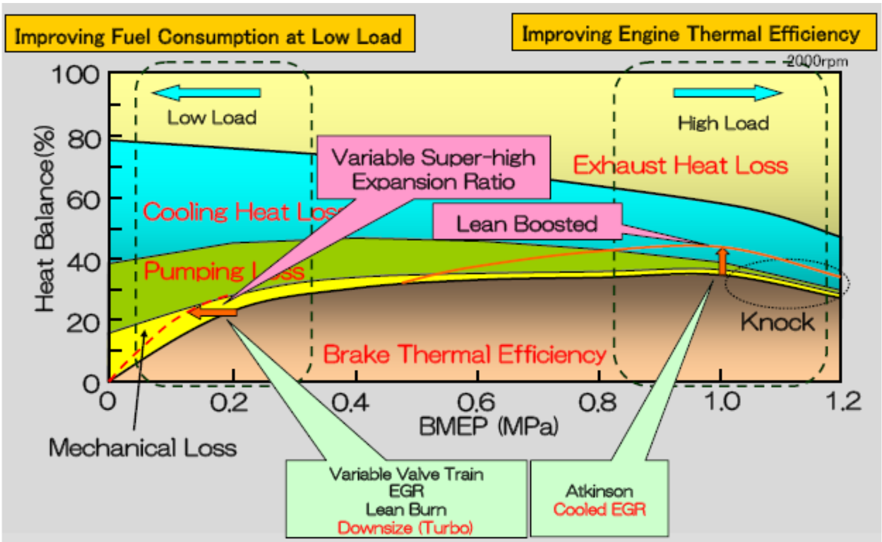
SwRI, SAE panel 4-10



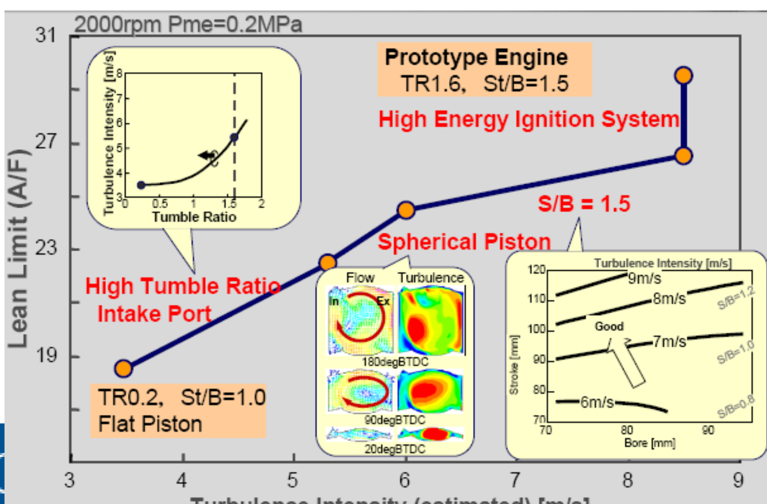
MD Dual Fuel Application

In a MD application: diesel-like torque and FC, CR>14; PCP limited. 5-20% diesel pilot injection

Toyota shows lean+EGR gasoline engine concept for 2020. Long stroke, low surface/volume, ~T2B5 engine NOx



At low load, long stroke, VVT, EGR+lean, boosted downsized. High-load: more EGR+lean.

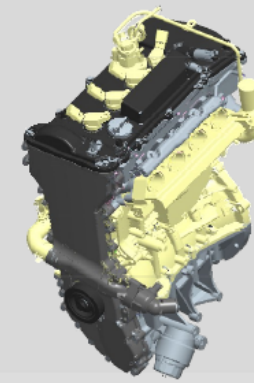


Next generation Prius engine concepts.

Cooled EGR Stoichimetric Concept

B=75mm
S=113mm
V=1996cc

- S.I. Direct Injection
- Long Stroke Design (Prototype Engine)
  Stroke / Bore = 1.5
- Cooled EGR (EGR Ratio ＞30%)
  High Tumble Ratio Intake Port TTR=3.0
  High Energy Ignition System 100mJ
- Lower Friction
  Lower Viscosity Oil
  Rolling Bearing

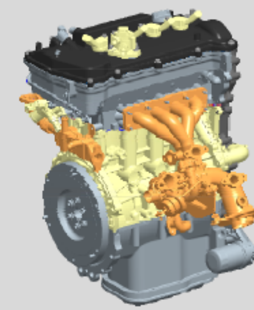


Later Prius engine concepts.

Turbo Lean Burn Concept

B=75mm
S=113mm
V=1996cc

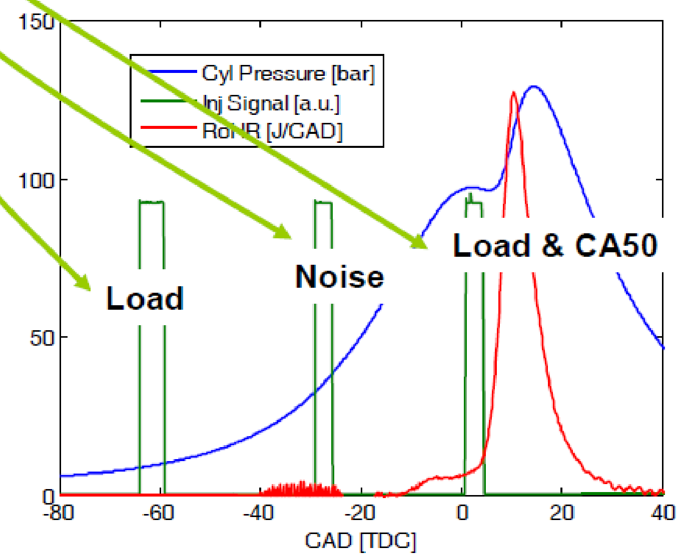
- S.I. Direct Injection
- Long Stroke Design (Prototype Engine)
  Stroke / Bore = 1.5
- Turbo Charged Air Lean with Cooled EGR
  High Tumble Ratio Intake Port TTR=3.0
  High Energy Ignition System 150mJ
  Lower NOx Emission



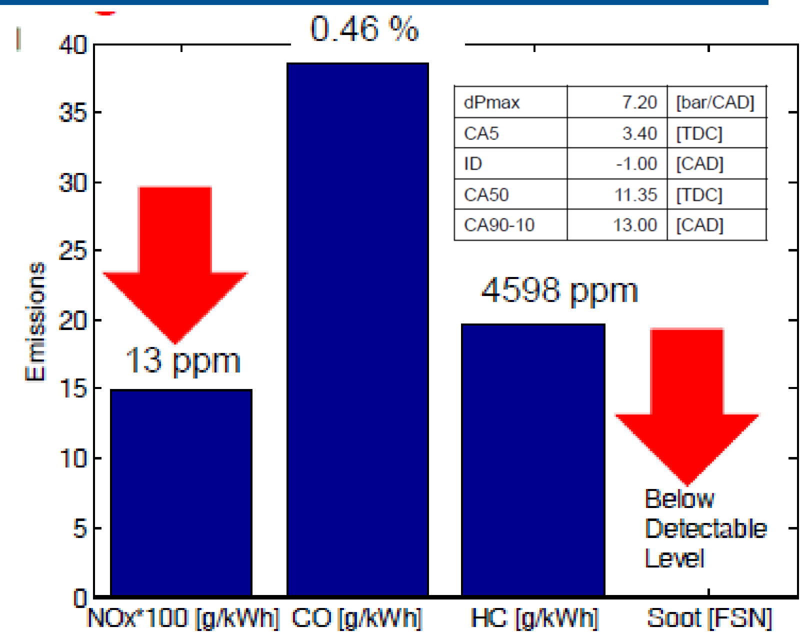
Partially Pre-Mix Combustion (PPC) gasoline is being applied to LD applications.

51% ITE (13.4 bar IMEP) and very low NOx and FSN

Injection	SOI [TDC]	Fuel MEP [bar]	Percentage [%]
1	-64.00	10.88	41.28
2	-29.20	7.74	29.36
3	0.80	7.74	29.36



N	2000	[rpm]
IMEPg	13.38	[bar]
Pin	2.57	[bar]
Tin	354	[K]
EGR	39	[%]
lambda	1.75	[-]



NOx emissions are 0.15 g/kW-hr, and FSN is minimal. **51% ITE** (need to account for friction and pumping losses).

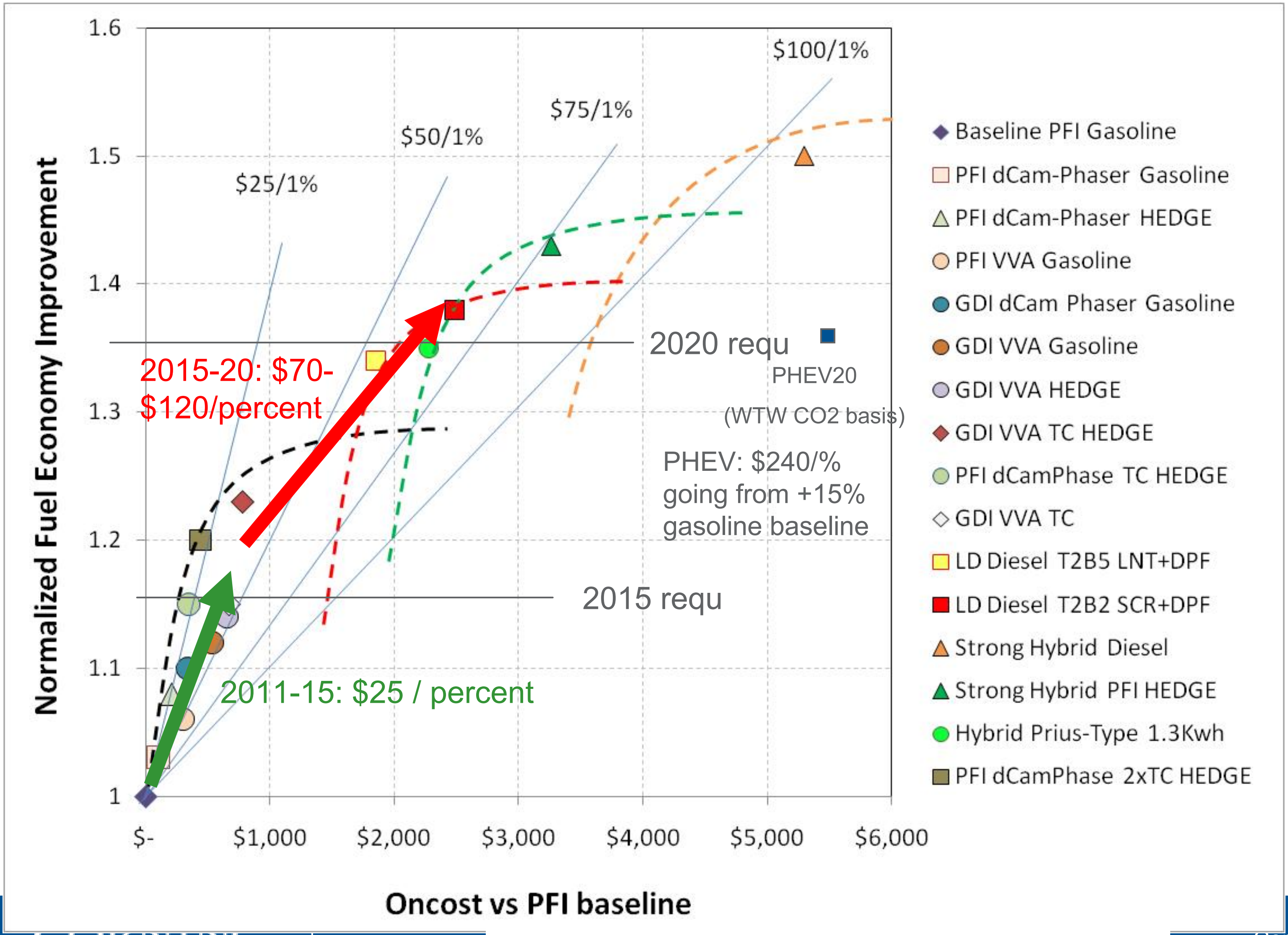
Three injections are used in LD applications. Volvo D5 LD engine running on gasoline at 13.4 bar IMEP.

Issue: Quite low octane fuel is used ("one of the refinery streams")

Lund Univ, DEER Conf, 9/10

2016-20 technology choice cost depend on 2016 starting point.

For most effective starting point (HEDGE) either LDD or HEV look attractive. For the most popular starting point (sGDI), LDD looks better than HEV.

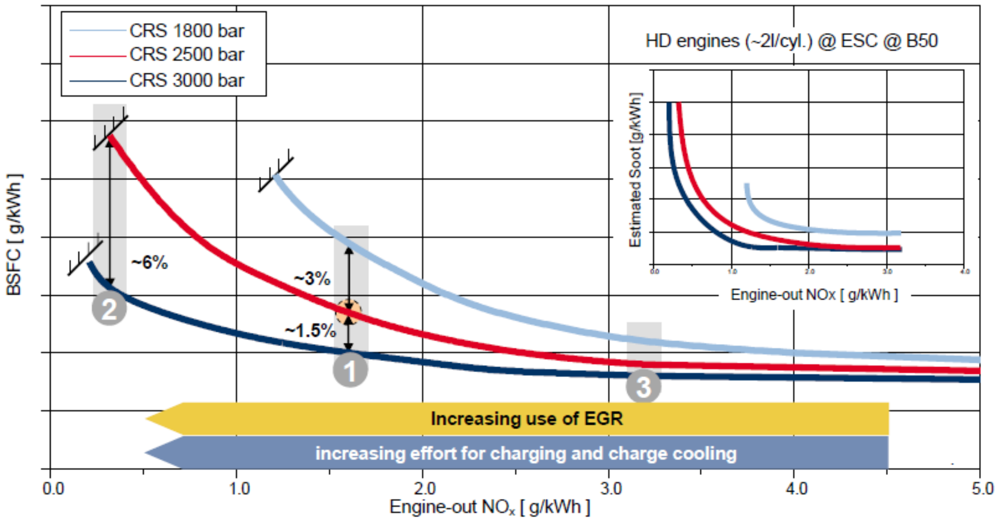


As efficiency improves, incremental costs go up, but fuel savings decrease.

- First step: $500 OEM cost saves $120/yr
- 2020 step, OEM cost of $1400 to $2900 saves $120 to $220/yr.

SwRI Powertrain Consulting Service 8/10

Low NOx engine calibrations require much technology. Engine hardware, fuel consumption and aftertreatment trade-offs.



① Combined Selective Catalytic Reduction (SCR) / Exhaust Gas Recirculation (EGR) strategy
② Non SCR strategy, ③ High SCR (low/non EGR) strategy

Engine-out NOx levels	Euro VI 0.4 g/kW-hr	~US2007 1.6 g/kW-hr	Euro VI - 90% deNOx ~US2010 - 94% deNOx 3.2 g/kW-hr
Fuel injection pressure, bar	3000 bar	2200 bar	1800 bar
Peak cylinder pressure	230 bar	180 bar	150 bar
EGR at full load	45%	27%	15%
Charge cooling relative to rated engine power	90%	50%	30%

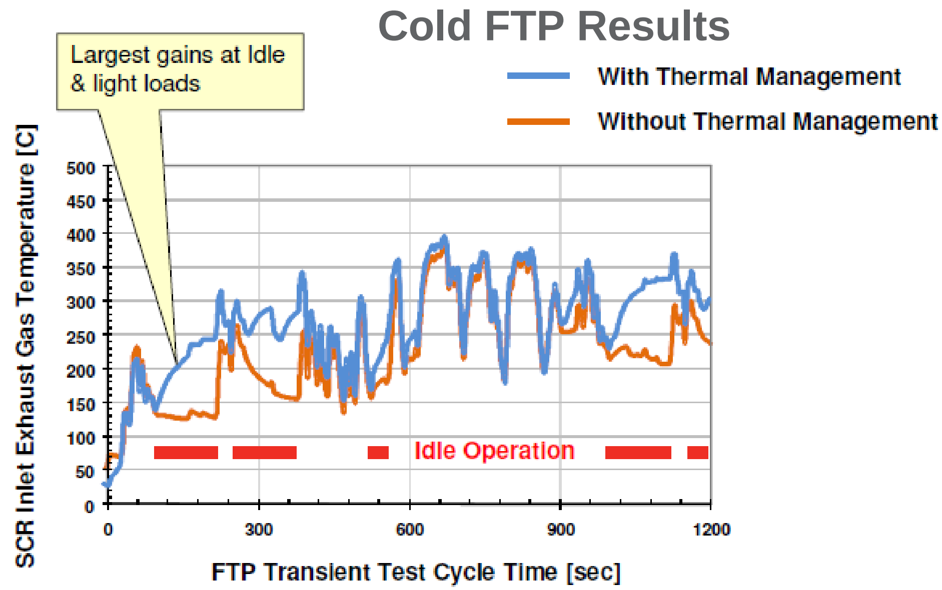
HP CR has less of an impact on BSFC at the higher NOx levels. 4% FC difference between low- and high-NOx calibrations with 3000 bar FIE. ~3% urea increase.

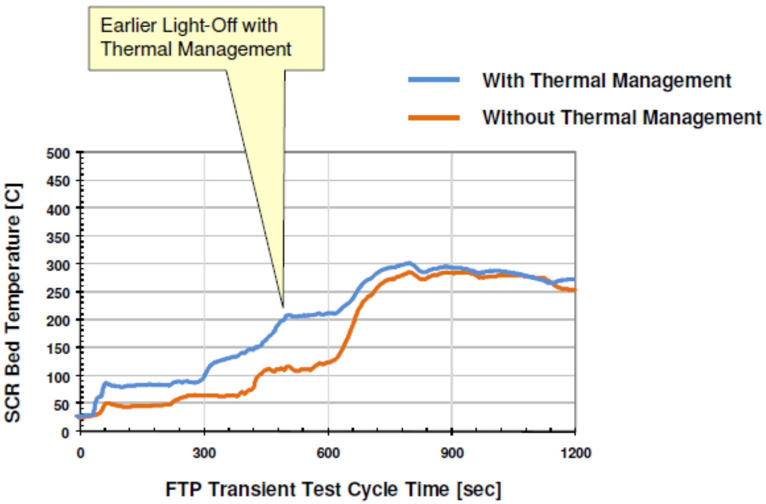
Bosch, Vienna Motorsymposium, 4/10 and
SAE Gothenburg HDDEC Conf, 9/10

Thermal management is used to reduce cold or low-load NOx. Minimal fuel penalty possible.

Thermal Management

- Control of fuel injection and air handling parameters
- Utilizes the flexibility of the XPI common rail and variable geometry turbocharger
- Allows faster warm-up and SCR light-off
- Minimizes cooling effects of idle and light load operations





FTP Phase	Without Thermal Mgt	With Thermal Mgt
Cold Cycle	0.364 g/HP-hr	0.301 g/HP-hr
Hot Cycle	0.357 g/HP-hr	0.031 g/HP-hr
Composite	**0.358 g/HP-hr**	**0.069 g/HP-hr**

Cummins, MinNOx Conf, 6-10

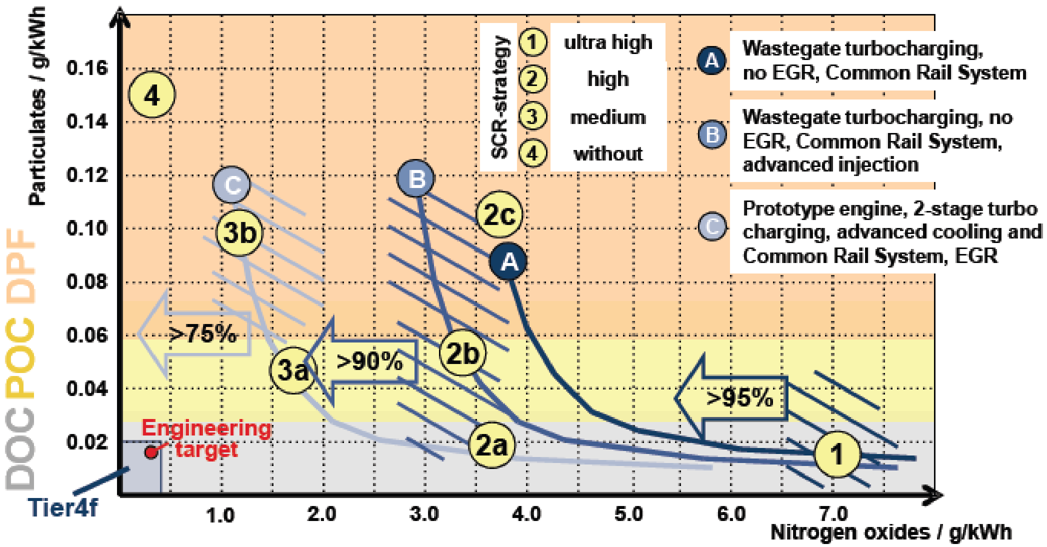
HD HEVs are seeing about 20-30% FC savings, use Li-ion batteries, and have a parallel architecture

Truck Manufacturer	GVW / Usage	HEV Type	Energy Storage	System Configuration	Claimed FC Improvement
Daimler (Atego BlueTec)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4 cylinder 44kW electrical machines +60kg weight increase (total vehicle)	20%
MAN (TGL 12.220)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.6L 4 cylinder 2 and 6kWh battery options 60kW electrical machine (425Nm) +100kg weight (reduced payload)	15%
DAF (LF 45)	7.5 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.5L 4 cylinder 44kW electrical machine (420Nm) 2km full EV range (fully charged)	30%
Kenworth (T270 / T370)	11.5/15.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries	Paccar PX-6 engine with ISG Eaton 6-spd ultrashift transmission 340volt Li-ion battery pack 44kW electrical macine +200kg weight (50kg battery)	20%
Peterbilt (330)	12.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries		30%
Hino (Ranger)	13.0 Tonne (Distribution)	Parallel (P1)	NiMH Batteries	Hino J05D engine 4.7L 36kW electrical machine (350Nm) 288volt NiMH battery pack	20%

Source: OEM websites and public information

T4f approaches depend on EGR rates, SCR efficiency, and high or low-load application

Emission EGT Strategies for Tier4f & Stage4 (56-560 kW)



- **Off-Highway applications with high load profiles (e. g. agricultural machines)**
  - → filter (open / closed) passive regeneration via CRT® effect
  - → SCR System (high efficiency)

- **Off-Highway applications with low load profiles (e. g. construction machines, fork lift)**
  - → filter (closed) active regeneration e.g. via burner
  - → SCR System (medium efficiency)

High-load applications are trending towards passive DPF and high-efficiency SCR. Low load: Active DPF and lower efficiency SCR.

Tier 4f strategy balances EGR, SCR efficiency, and PM strategy.
Note that the regs can be met using 93% deNOx, no EGR, and DOC.

Bosch CTI NR Conf, 10/10

Off-Road Engines Meeting Tier 4 PM Mass Limits Without Filters

- Advanced combustion controls allow newer diesel engines to meet PM mass limits without filters

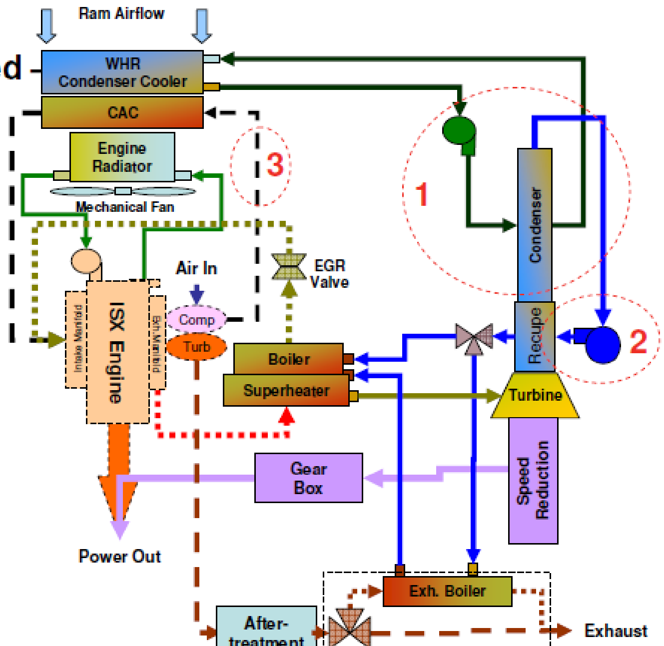
- Manufacturers announcing diverse Tier 4 final solutions, some without DPFs:
    - Cummins 9 liter and smaller Tier 4 final engines will utilize DOC+SCR
    - Cummins 12 & 15 liter Tier 4 final engines will utilize DPF+SCR

Source: Cummins ConExpo Press Releases

Second generation waste heat recovery system shown.

Improvements gain 1.4% FC impact, on top of 6.2% for generation 1.

1. **Replaced water-cooled condenser for air-cooled** – gained 0.2%
2. **Replaced 2-stage, centrifugal pumps with single-stage positive-displacement pump** – gained 0.6%
3. **Added Charge Air heat recovery** – gained 0.6%
4. **5% reduction in power transfer parasitics with MORC**

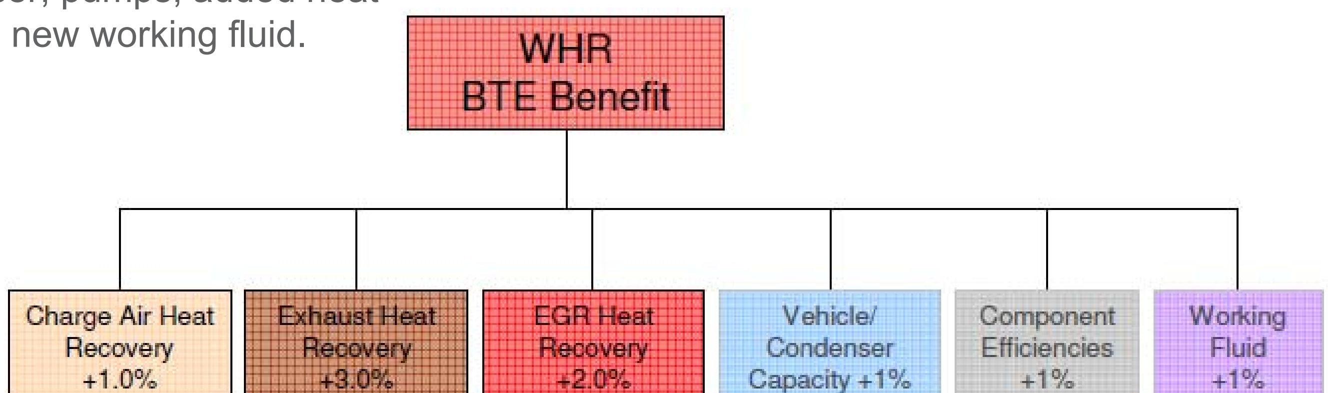


Second generation Organic Rankine Cycle (ORC) improvements include the condenser, pumps, added heat source, lower parasitic losses, and new working fluid.

Future Directions

- System Architecture and Controls
- Turbine Expander
- Expander to Engine Geartrain
- Heat Exchangers – on and off engine
- Feedpump and instrumentation
- Fluid Development (low GWP alternatives)
- Vehicle Packaging
- Cost Focus

Cummins, Emissions 2010 Conf, 6/10

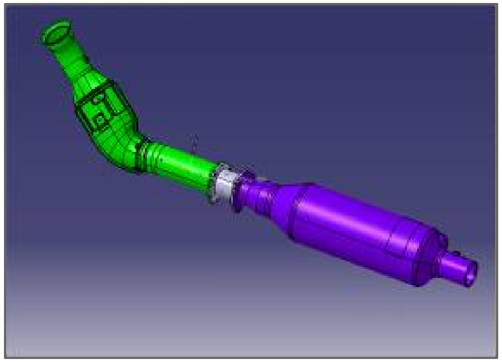


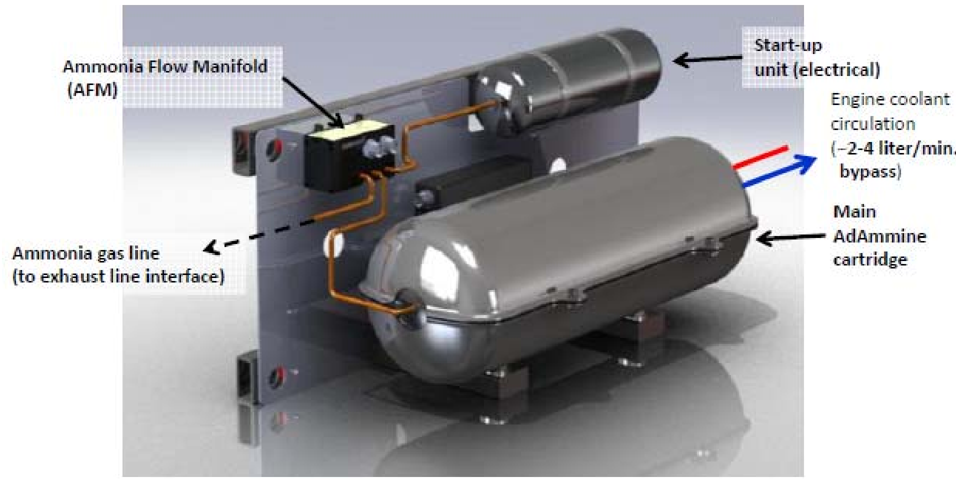
Potential benefit of 9% energy from WHR. 6.2% realized in generation 1.

CORNING

SCR

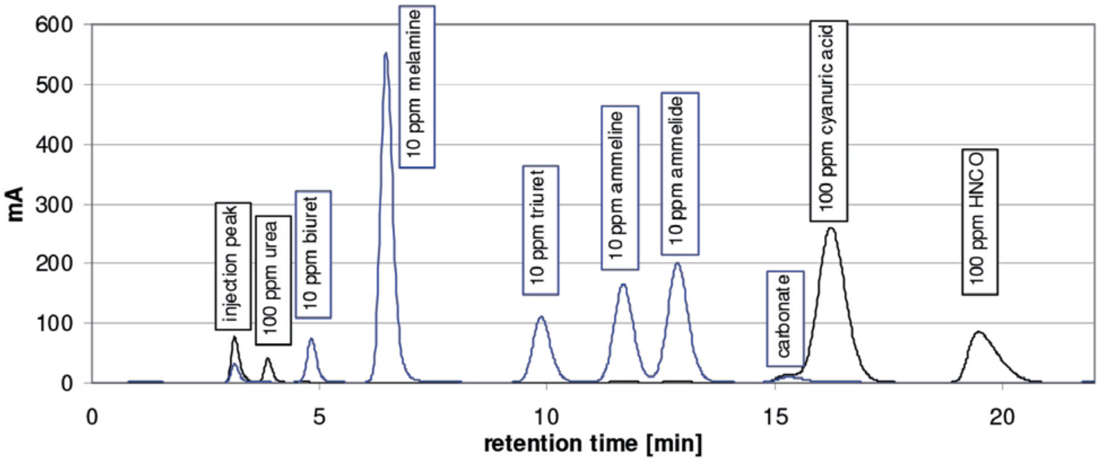
Solid Ammonia Facilitates Low Temperature Operability



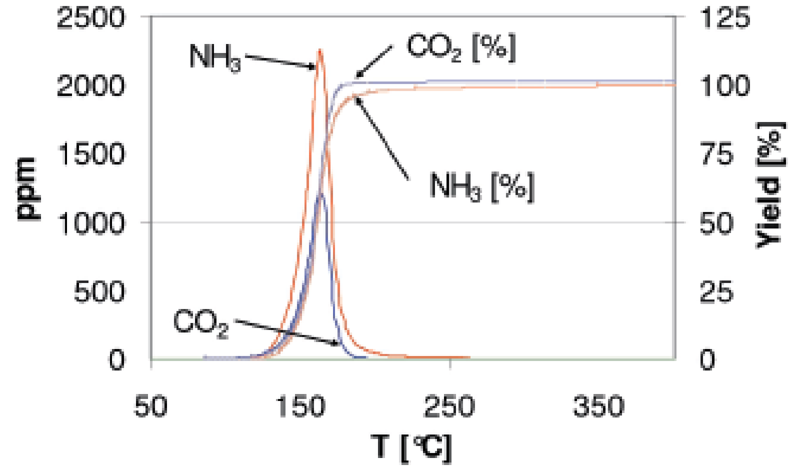


- Several systems being evaluated as alternatives to DEF
- Both offer higher ammonia concentrations
- Absence of hydrolysis enables lower temperature operability

Urea decomposition products are measured using a new thermal/gas analysis procedure. TiO2 is an effective urea decomposition catalyst.



Urea decomposition products released into a flowing model gas stream. Heat rate 10Cº/min, 40-550ºC.

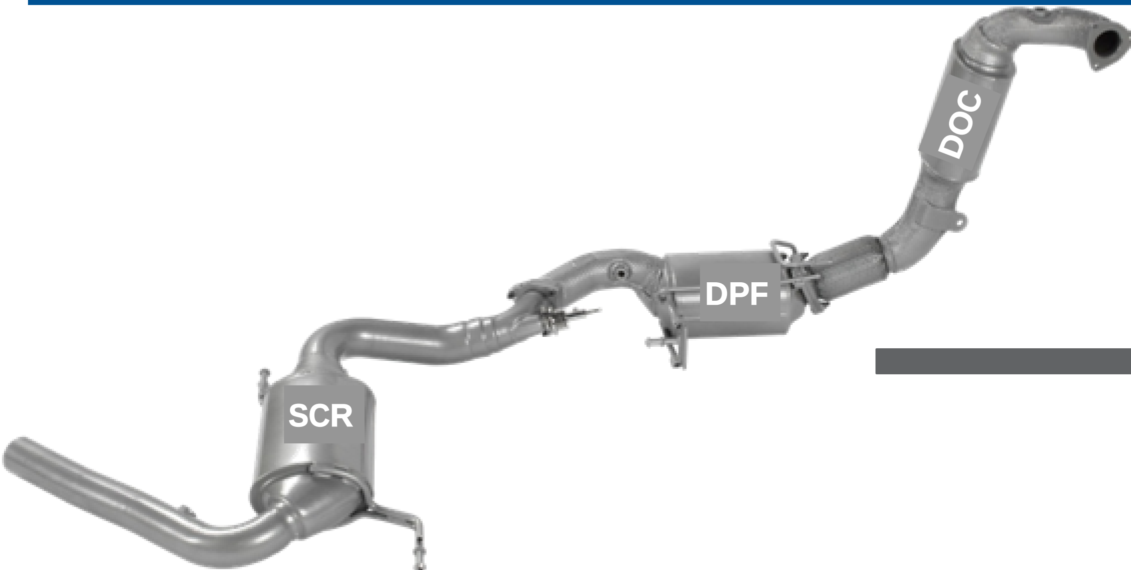


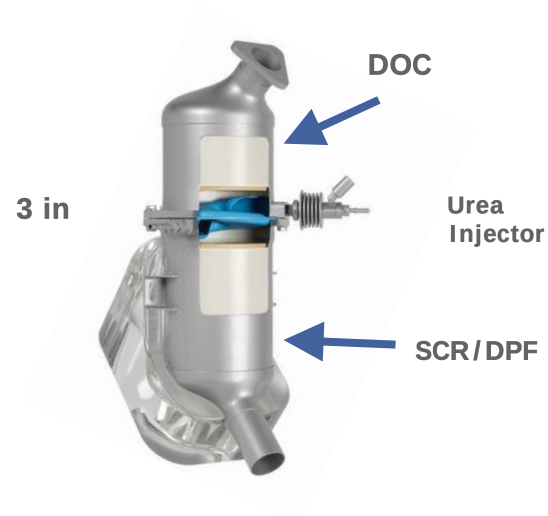
Urea decomposition on a TiO2 catalyst. No by-products were formed. Urea decomposition is not purely a thermal process.

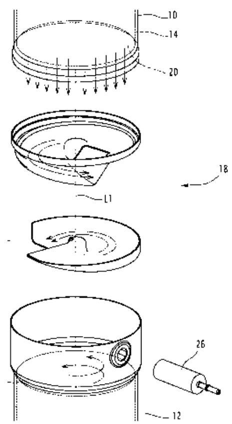
- Biuret decomposition NH3 peak is at 160C.
- Cyanuric acid and melamine NH3 peaks are at 250C.

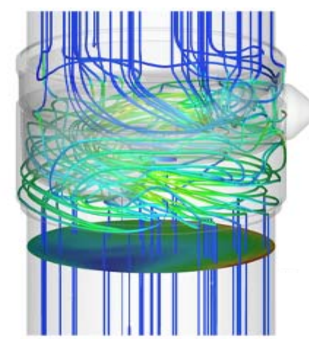
PSI, AVL PM Forum, 3/10

New Packaging Designs Reduce Cold-Start Emissions





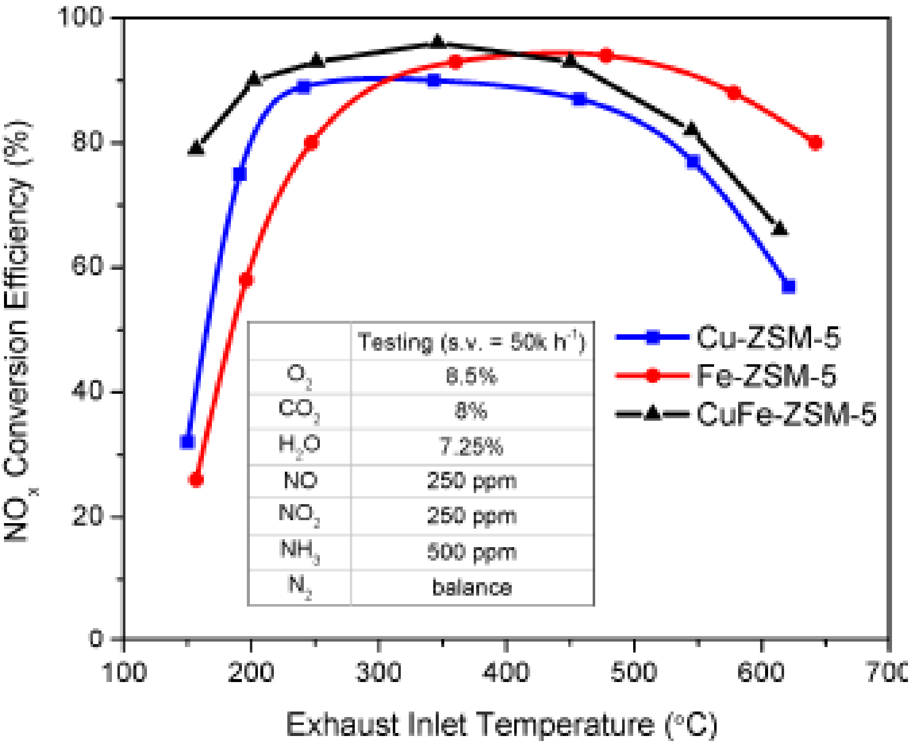




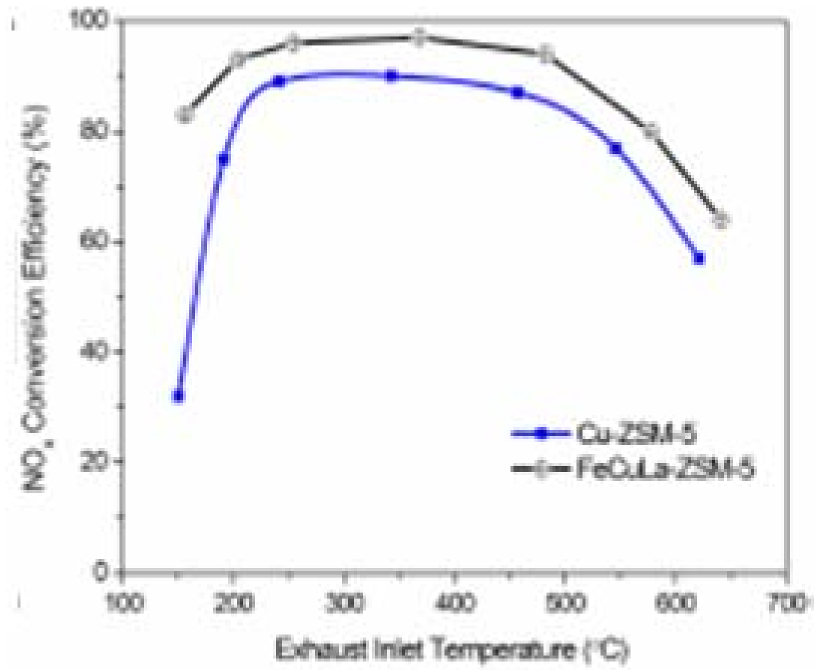
Reference: SAE 2011-01-1318

New zeolite formulations are being investigated.

CuFe chemical mixtures give excellent LT performance. CuFeLa also shows promise.



Unlike for physical mixtures that provide intermediate performance, the chemically mixed zeolite has better performance from 150-400C.



Other multi-metal formulations are being investigated. CuSc2 and CuFeLa show promise, among others

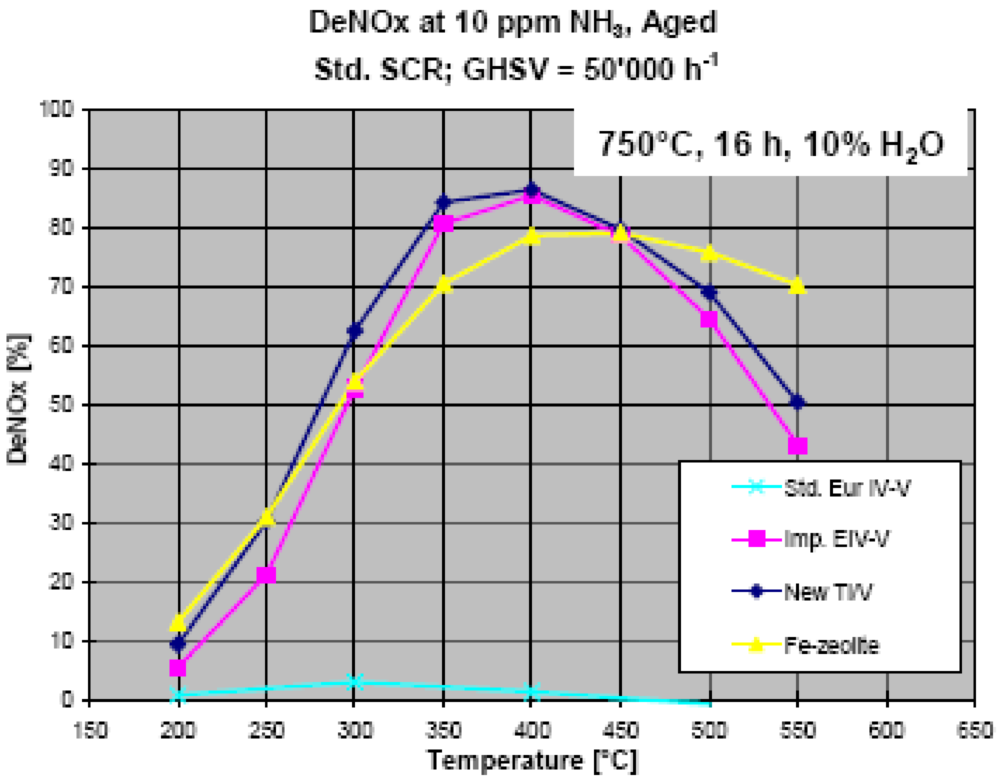
ORNL, DEER Conf poster, 9/10

Improved vanadia SCR catalyst has durability to 750C. Volatility below detection limits. Efficiency maintained.

Vanadia Volatility, 750C, 4 hr

Catalyst	µg V/g cat.
CA	83
CB	42
DA	N/M
DB	< 2.5
DC	< 2.5
DD	< 2.5

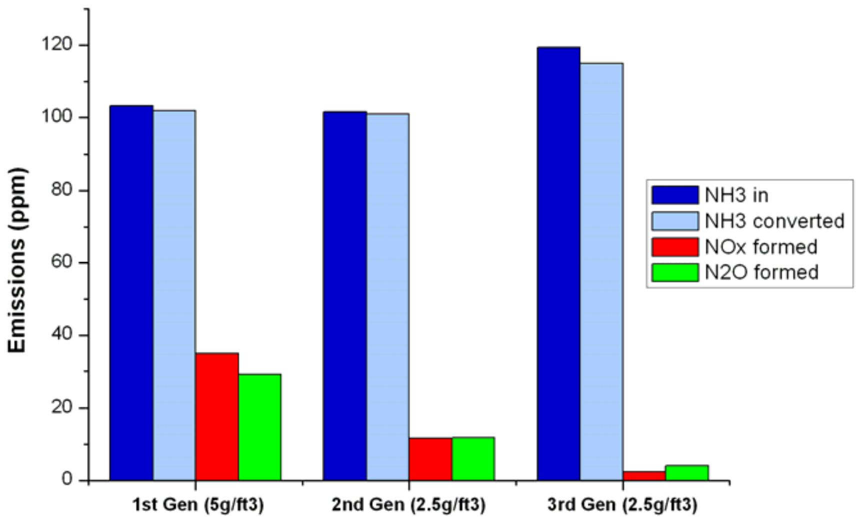
Development catalyst is below the detection limit on vanadia volatility at 750C. 5% H_2O, 5% O_2, 500 ppm NO, 500 ppm NH_3



The new formulation performs favorably to Fe-zeolite in the std SCR reaction after aging.

Improvements in ammonia slip catalyst are reported.

PGM cut in half, WHTC selectivity to N2 93% with 97.5% of ammonia converted.



Results on the WHTC show significant improvement in performance and cost. 97.5% NH3 converted with 93% selectivity to N2. ASC SVR=1. V-SCR catalyst

	Engine out	System out		
	NOx [g/kWh]	NOx [g/kWh]	NH_3 [ppm]	N_2O [ppm]
WHTC (34L VSCR+12L ASC)	12.0	0.3	2.5	6.0
WHTC (34L VSCR only)	*12.0*	*0.2*	*117.0*	*0*
WHTC (24L ZSCR+12L ASC)	11.5	0.4	1.0	10.0
NRTC (34L VSCR+12L ASC)	13.8	0.8	3.5	5.6
ETC (22L VSCR+3L ASC)	9.8	0.8	8.5	4.5

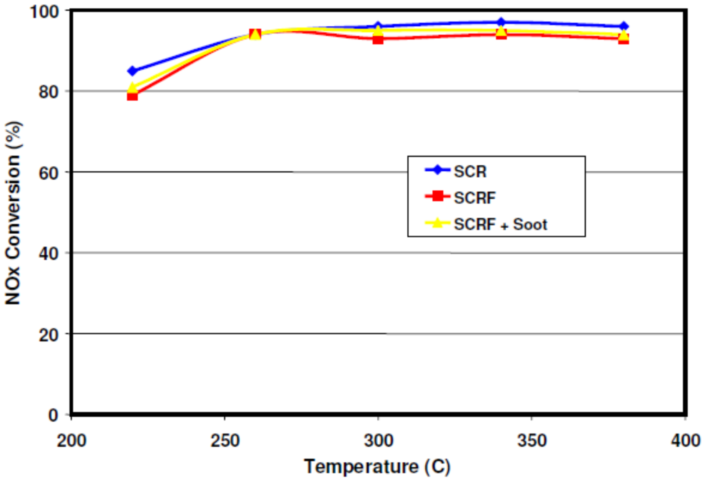
Fe-zeolites can form N_2O if excess NO_2 is used to promote LT deNOx. At NO_2~40%, ASC N_2O in was 5 ppm, out was 10 ppm at very high NH_3 levels.

Haldor Topsoe, DEER 9-10

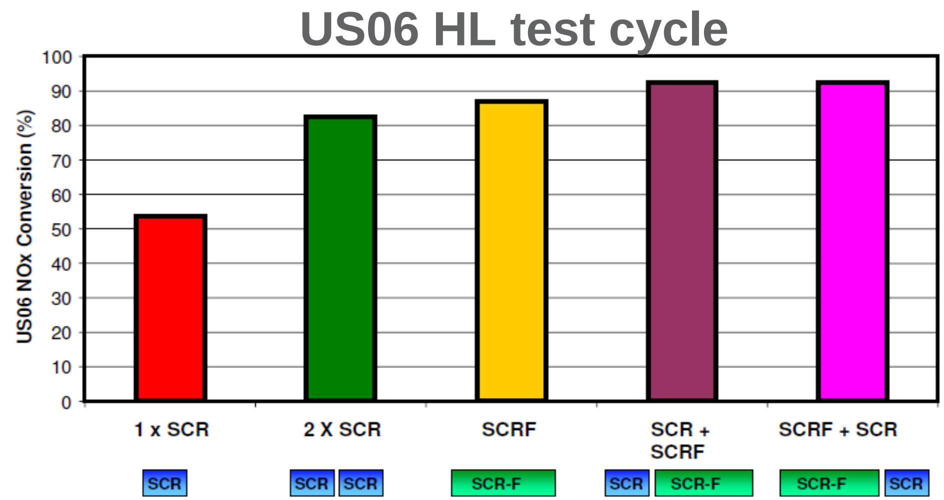
JM, SAE 2011-01-1312

SCR+DPF adds options to improve deNOx performance.

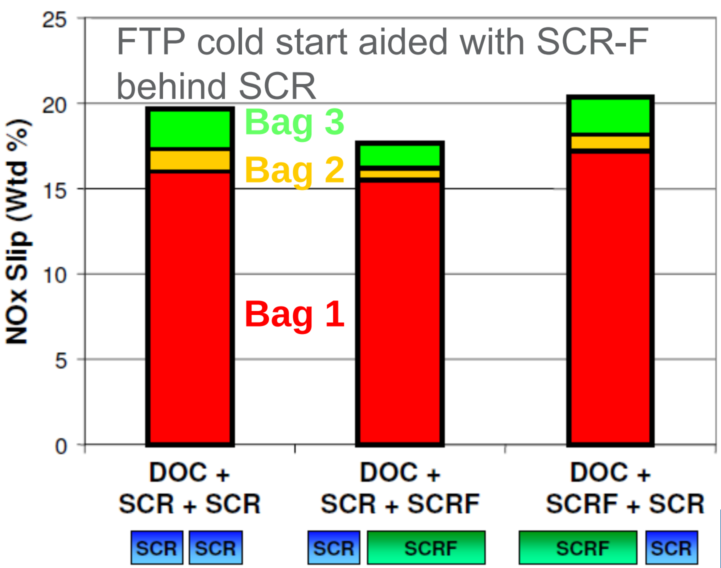
Increased volume is as effective as for flow-through catalysts. Adding catalyst to the DPF can drop emissions 60-65% at low deNOx points.

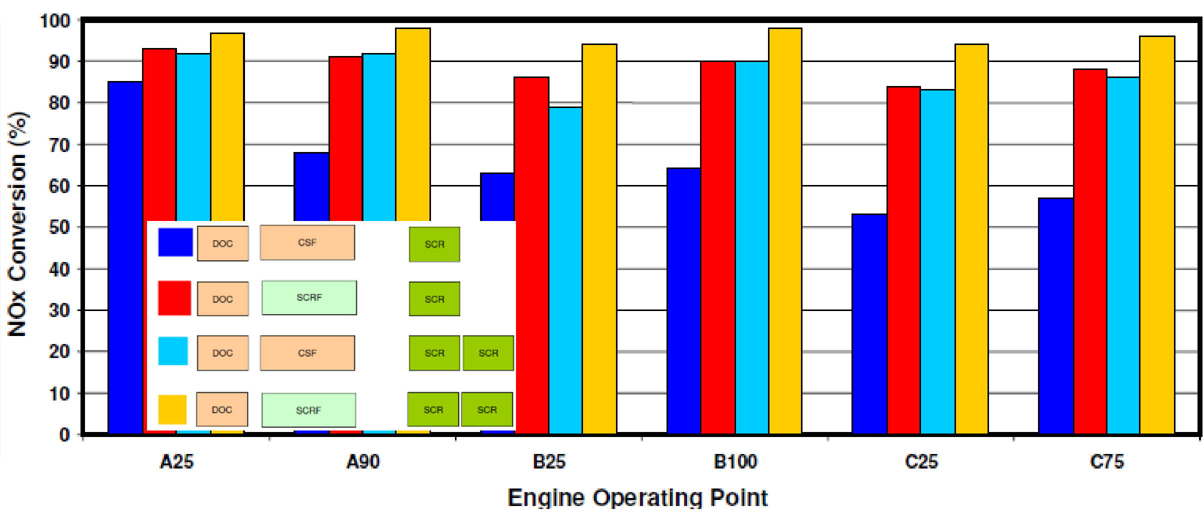


SCR+DPF with or without soot performs similarly to SCR. 1.2 g/liter soot



It matters little if the SCR volume is obtained using flow-through substrates or SCR+DPF (SCR-F)

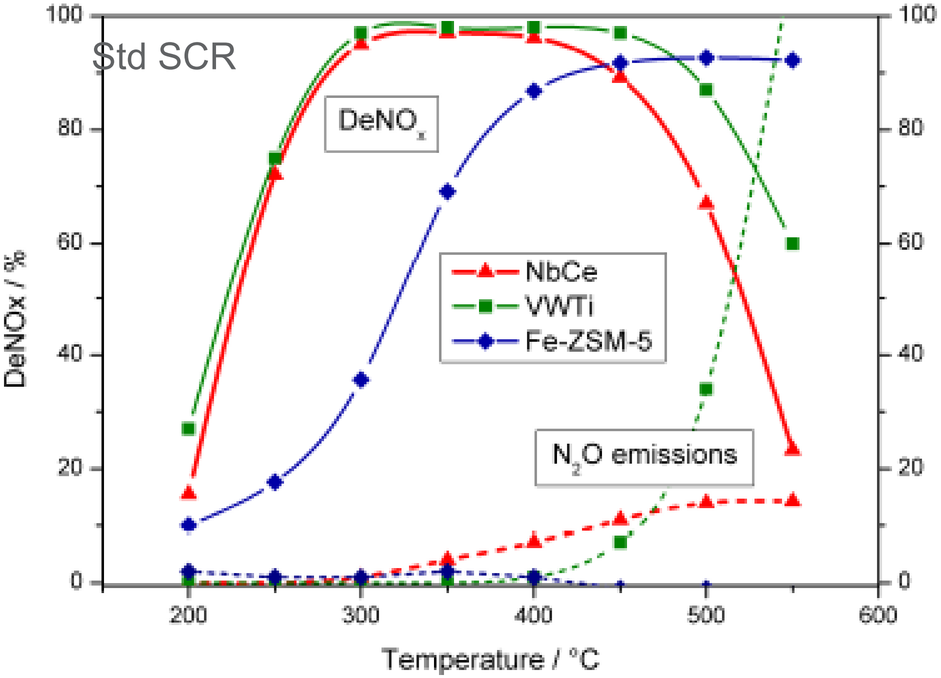




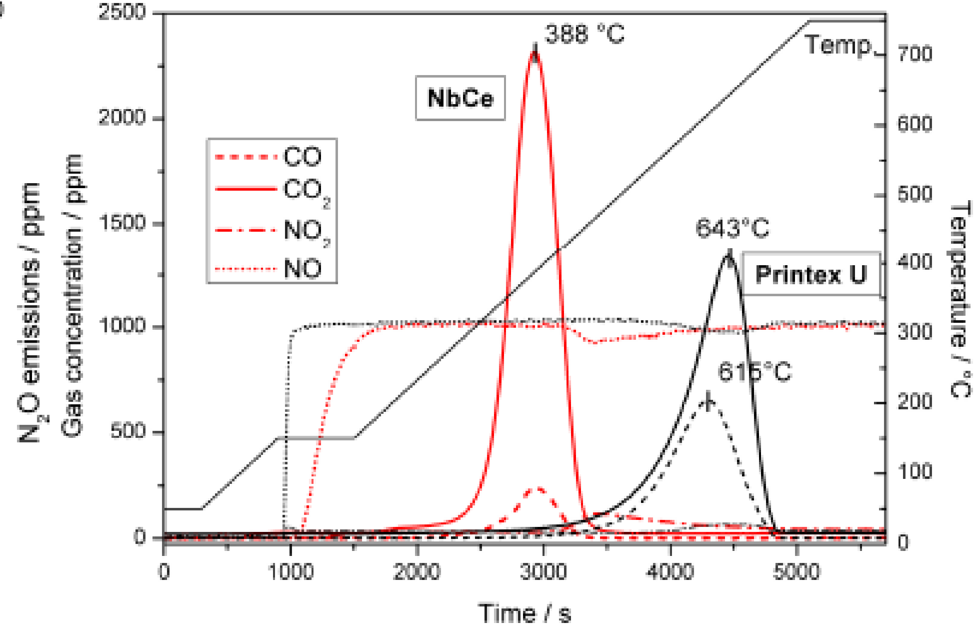
SCR on the DPF cuts emissions about 60-65% at the C25 load point.

A new Nb-Ce oxide catalyst has good SCR functionality and oxidizes carbon.

Comparable LT deNOx to CuZ (even better with NO2), urea hydrolysis similar to TiO2, and carbon oxidation at 380C.



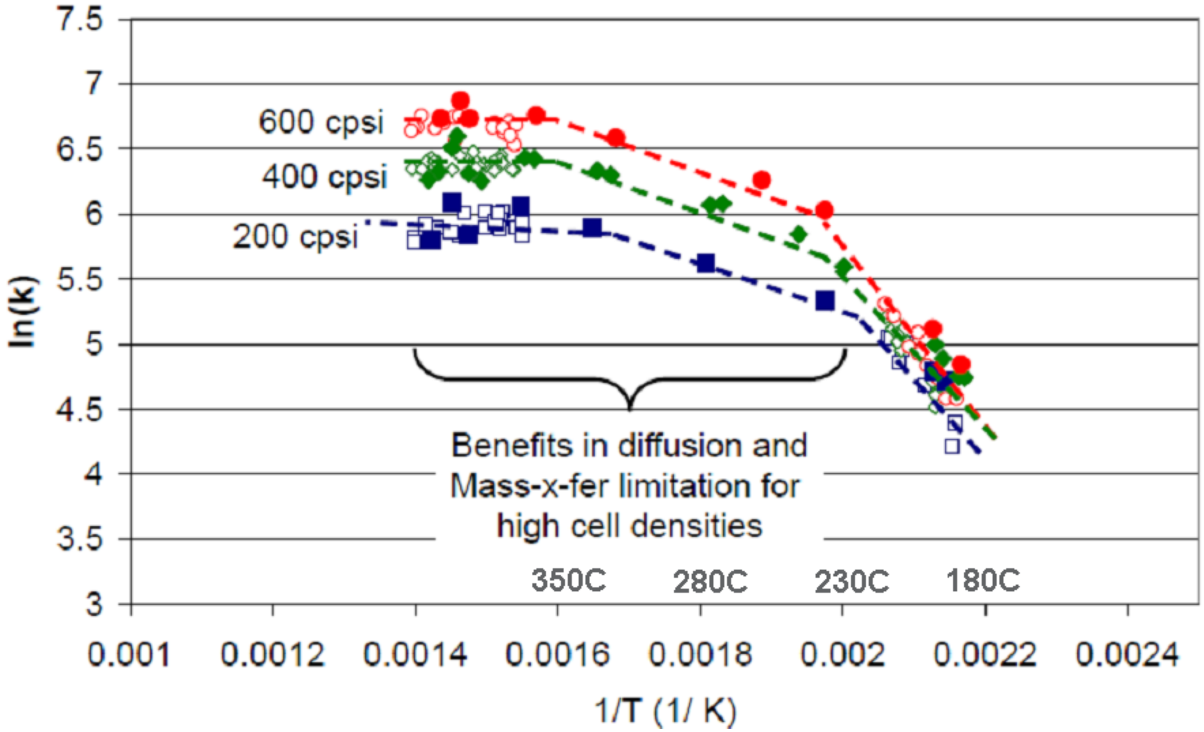
NbCe oxide SCR catalyst has impressive deNOx performance



Carbon oxidation occurs at ~380C via the direct oxidation mechanism.

SCR substrate properties are improving.

The continuous improvement is shown for higher cell density and thinner walls.



In the mass transfer controlled regime (230-350C)
600-csi substrates react 35% faster than 400-csi.

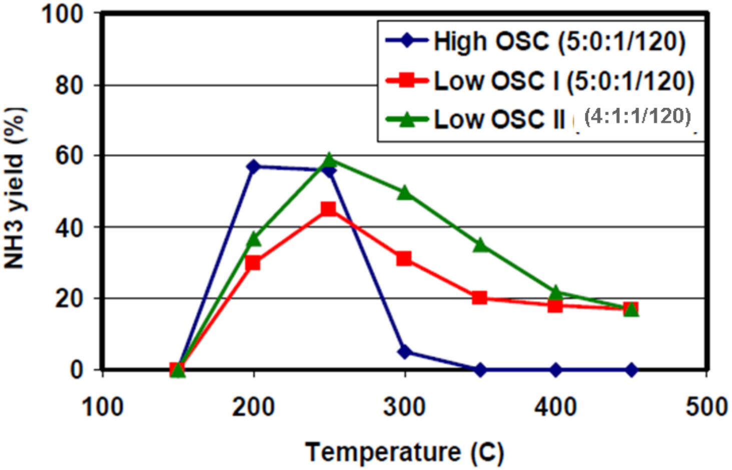
Corning, SAE Gothenburg, 9-10

CORNING

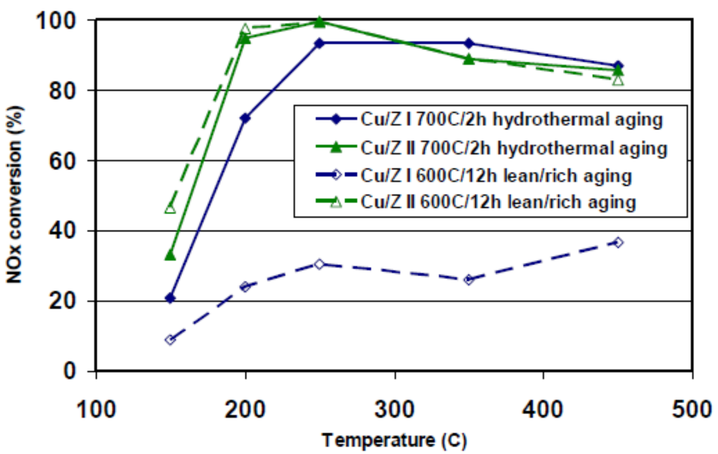
HC-deNOx

Performance of an NAC+SCR system is improved.

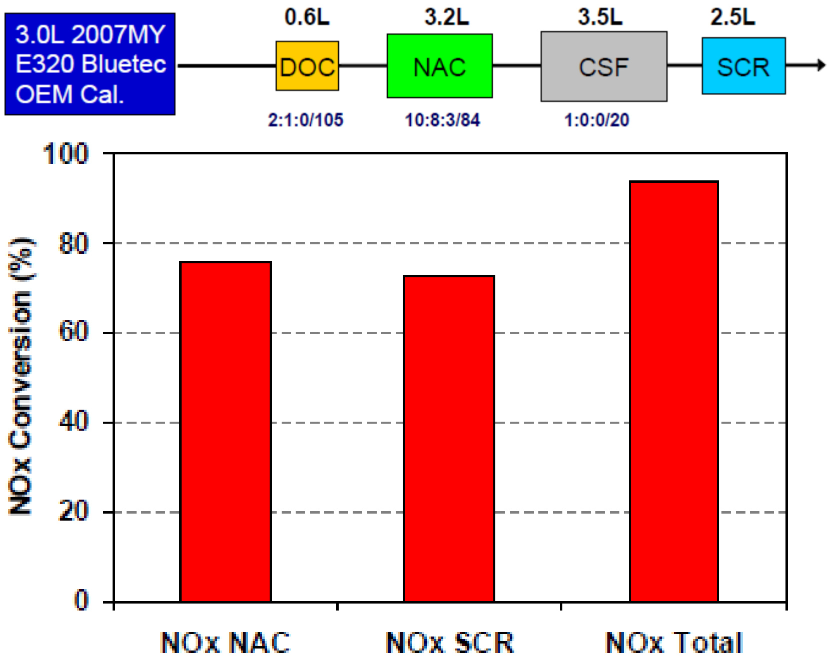
NAC NH3 formation enhanced with Pd and low-OSC. SCR durability improved.



Reducing the OSC and replacing 20% of the Pt with Pd improves the NAC ammonia generation.



Improvements are made to the lean-rich HC cycle durability of the Cu-zeolite catalyst.



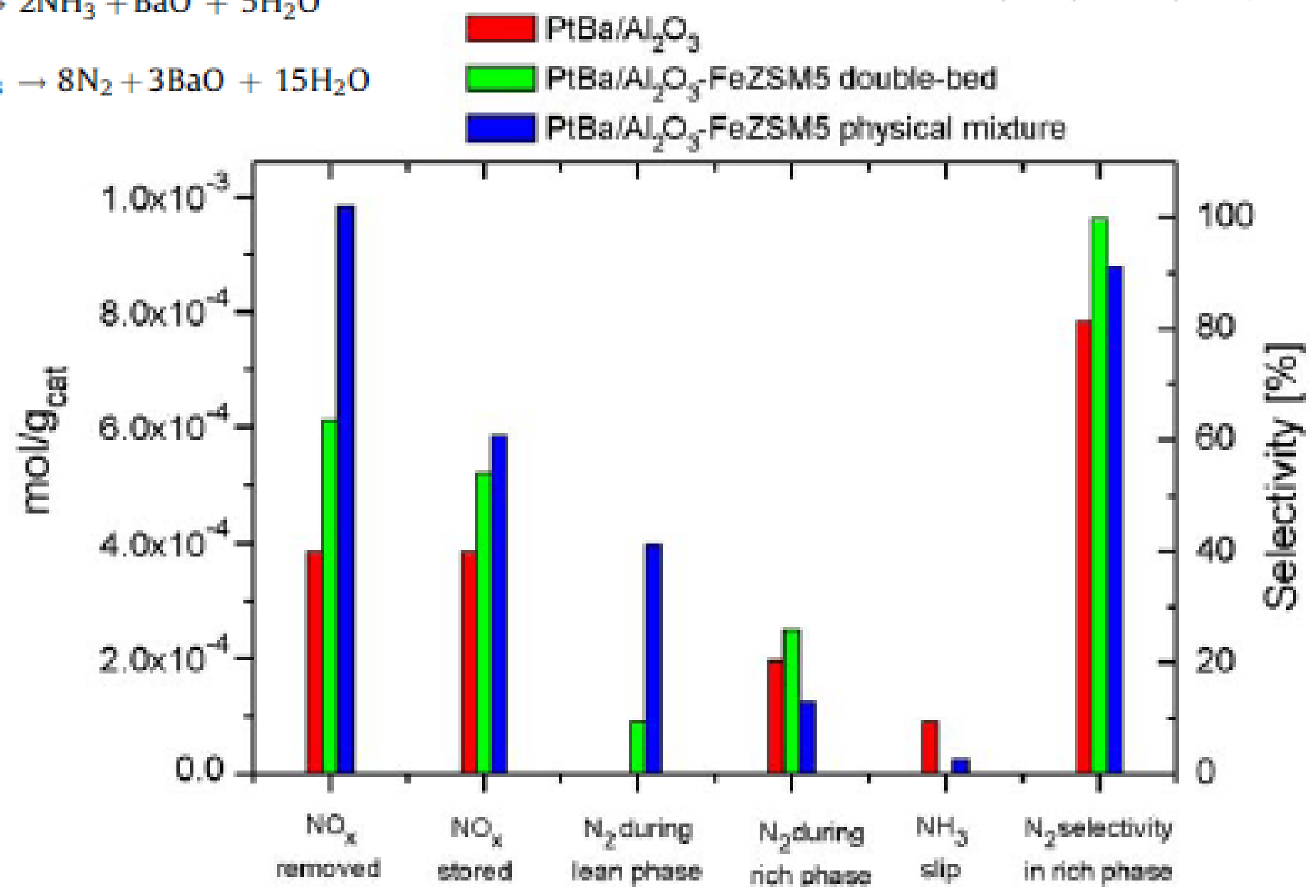
The improved combination system delivers 93% using the OEM calibration. The SCR increased overall performance of the low-PGM NAC by 17%.

Physical mixtures of LNT+SCR on one bed performs better in fundamental experiments than two-bed system.

$$3Ba(NO_3)_2 + 8H_2 \rightarrow 2NH_3 + BaO + 5H_2O$$

$$3Ba(NO_3)_2 + 10NH_3 \rightarrow 8N_2 + 3BaO + 15H_2O$$

R. Bonzi et al. / Catalysis Today 151 (2010) 376–385



Polytech. Milano, Catalyst Today, 2010

Physical mixture of LNT+SCR catalyst (blue) has higher NOx reduction performance in hydrogen than double-bed system (green). NH3 formed during rich regeneration is captured within the LNT by the SCR, promoting more deNOx during lean operation.

CORNING

DPF

Ford demonstrates characteristics of active and passive DPF regen. Active: No O_2 impact (>2%), soot load important, little PGM influence; Passive: NO_2 2.5X than w/ 15% NO_2, Pt is key, zeolite had no impact.

Active Regenerations

a. Little impact between 2 and 5% O_2; 1% needs 50C higher inlet.
b. Soot mass more dominant
c. Pt and Pd are similar and convert to CO_2. Cu-Z similar to uncoated ($CO:CO_2$=60:40). PGM had no impact on rate.

Passive Regenerations

a. 50% NO_2 gives 2.5X faster rate than 15% NO_2
b. NO_2 is more effective at 370C than at 485C
c. Pt samples at 370C and 50% NO_2 are 15% faster than those w/o Pt; at 485C: 25% faster
d. Cu-Z similar to uncoated.

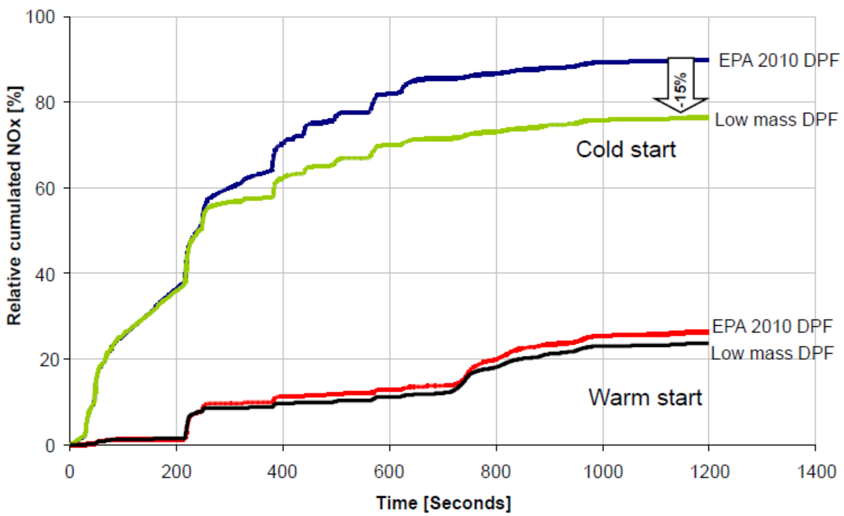
Other:

- Active regen costs 0.5 MPG
- Passive extends regen freq from 400 to 467 miles, saves 0.1 MPG
- HNCO needs to be counted for regen of uncoated filters

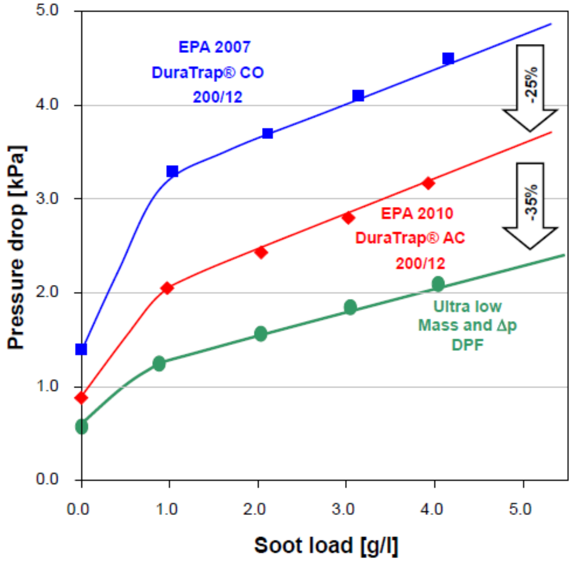
Ford, SAE 2010-01-0533

New low-mass DPF designs are being explored.

Passive regeneration architecture enables new DPF.



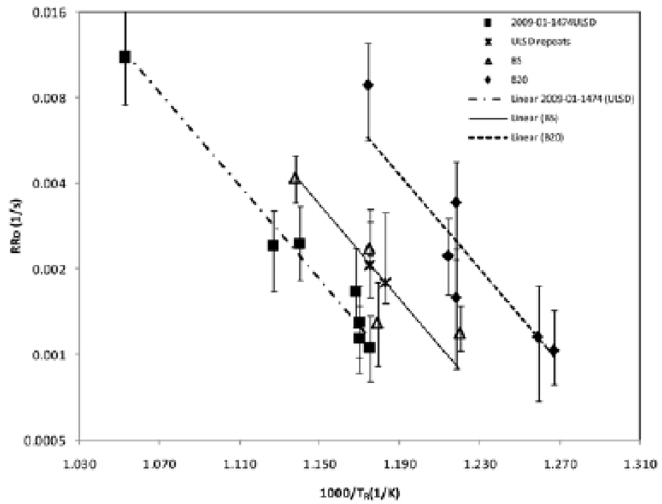
The DPF mass ahead of the SCR catalyst can have a big effect on cold start NOx emissions.



The drive towards low ΔP DPFs is continuing. New prototype has -45% ΔP of the US2007 version, and -35% ΔP of the US2010 model.

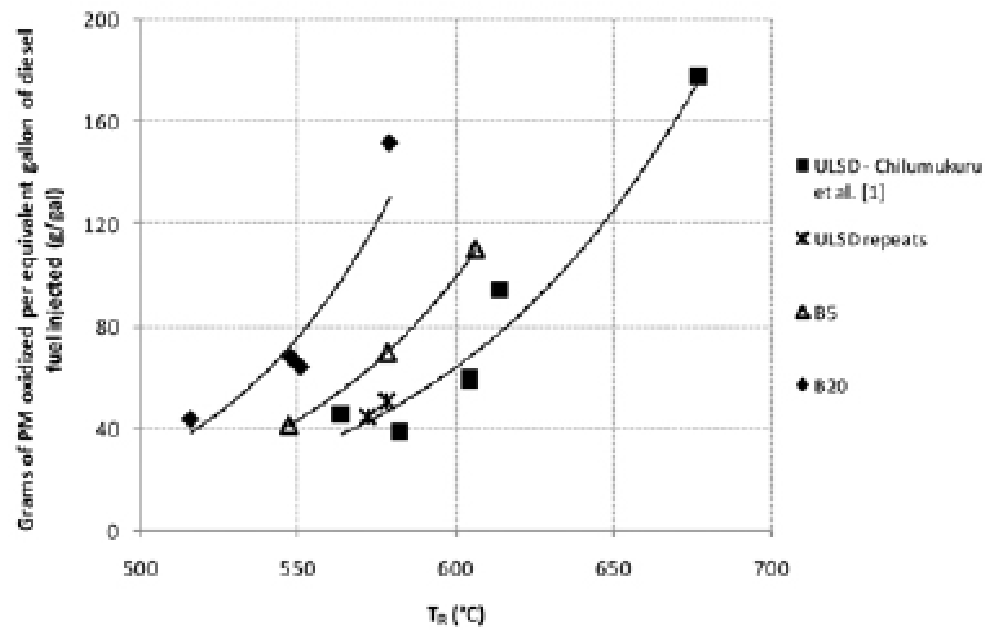
Corning, SAE Gothenburg, 9-10

Biodiesel blends burn faster and consume less fuel for regeneration.

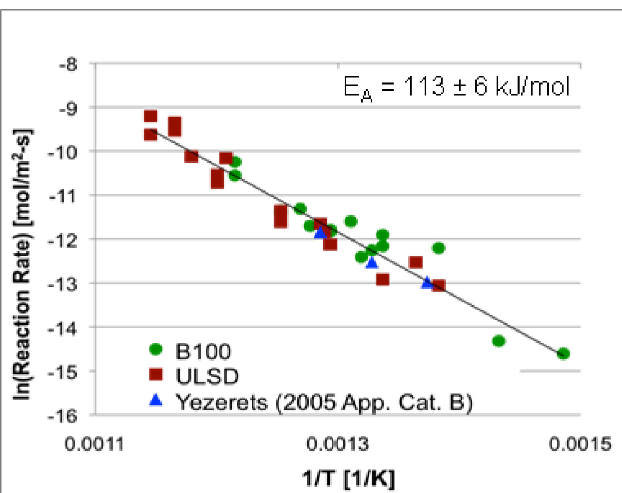


Soot from 20% biodiesel burns 3X faster than regular soot.

MTU, SAE 2010-01-0557



3X more soot is burned per unit of fuel when 20% biodiesel is used.



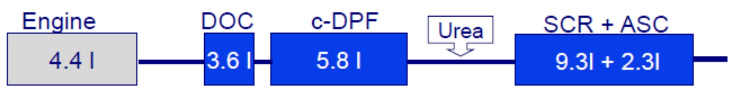
Biodiesel soot has more initial surface area. When this is normalized, reaction rates converge. (ORNL, CLEERS, 2010)

Particle Number emissions are quantified on a 4.4 liter non-road engine with DPF.

4 cylinder, 4.4 litre industrial prototype engine developed for NRMM Stage IIIB, provided by OE manufacturer.

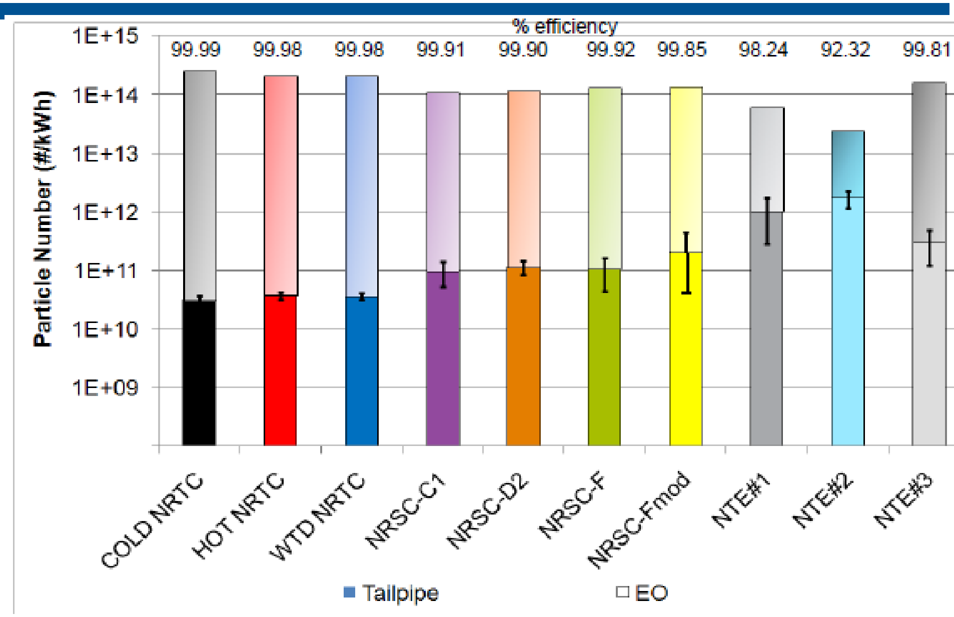
- High Pressure Common Rail (set at 160 MPa), Variable Geometry Turbocharger and cooled, electronically controlled EGR.
- Modified Stage IIIB engine calibration to be compatible with AECC-supplied Emissions Control System on the NRTC.
- PM ~ 35 mg/kWh, NOx ~ 3.0 g/kWh

System hydrothermally aged for 200hours at 600°C.

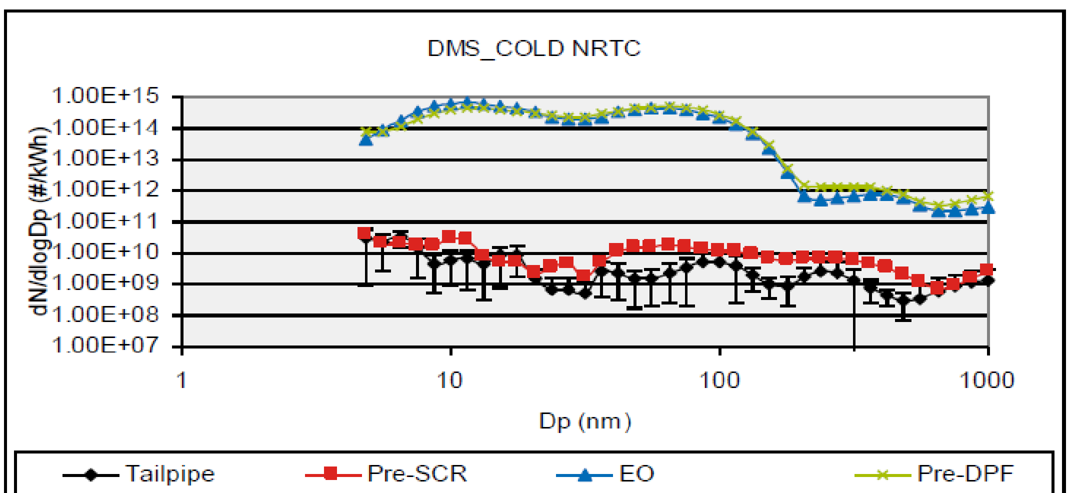


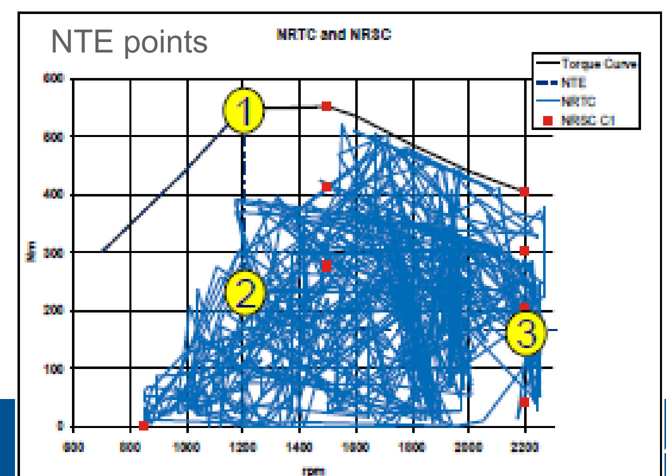
95% deNOx and 96% PM efficiency on the NRTC.
84-94% deNOx and 96% PM efficiency on NRSC.

AECC, ETH Nanoparticle Conf, 8/10

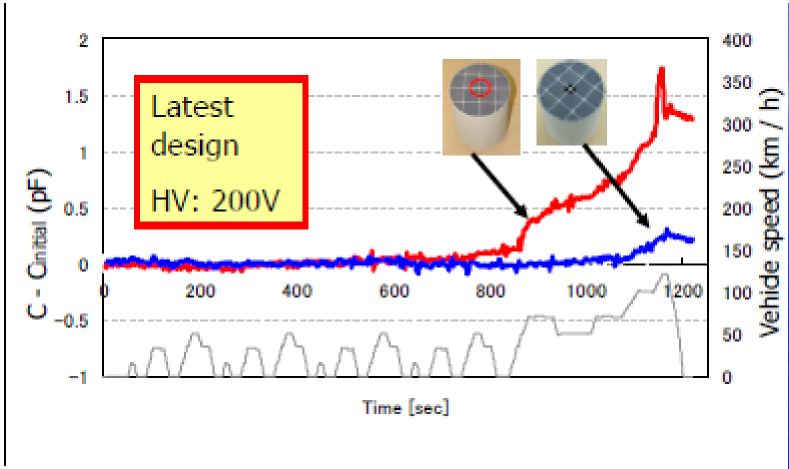


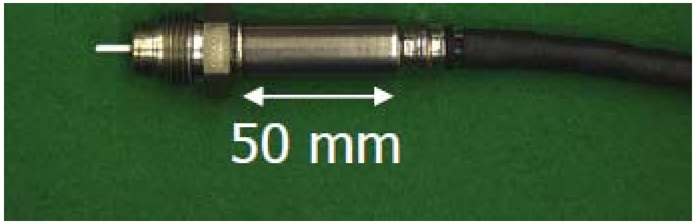
PN removal efficiencies >99.9% in all cycles. $<10^{11}$ / kW-hr





Advances Being Made in PM OBD

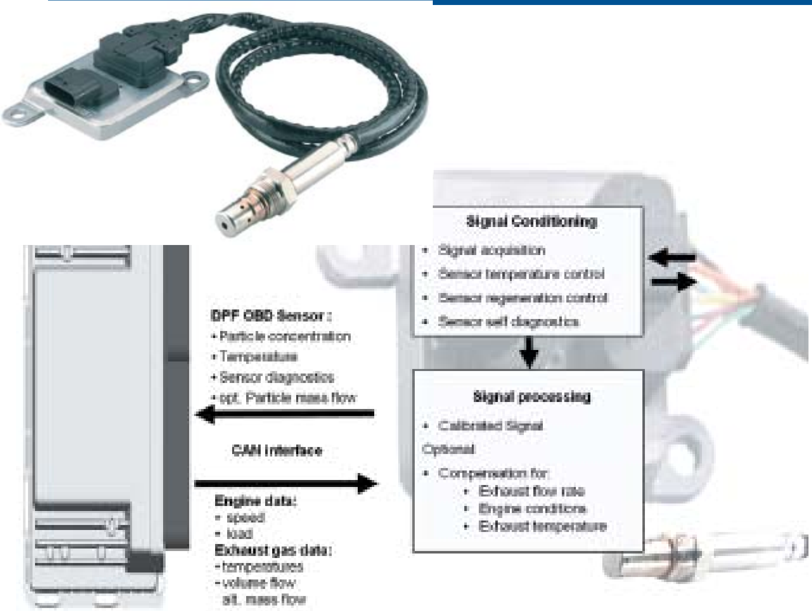


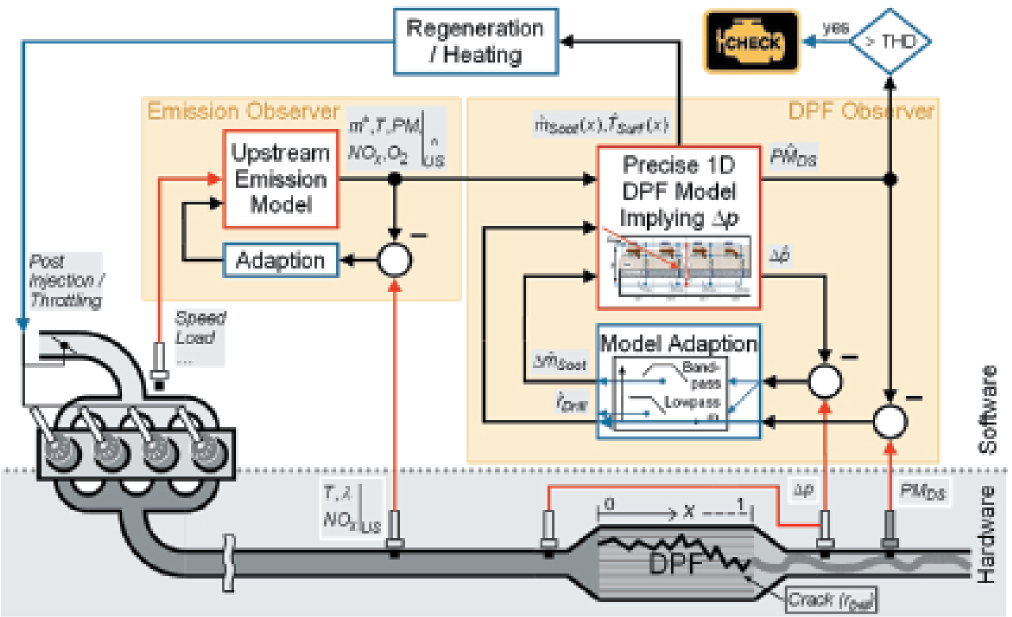


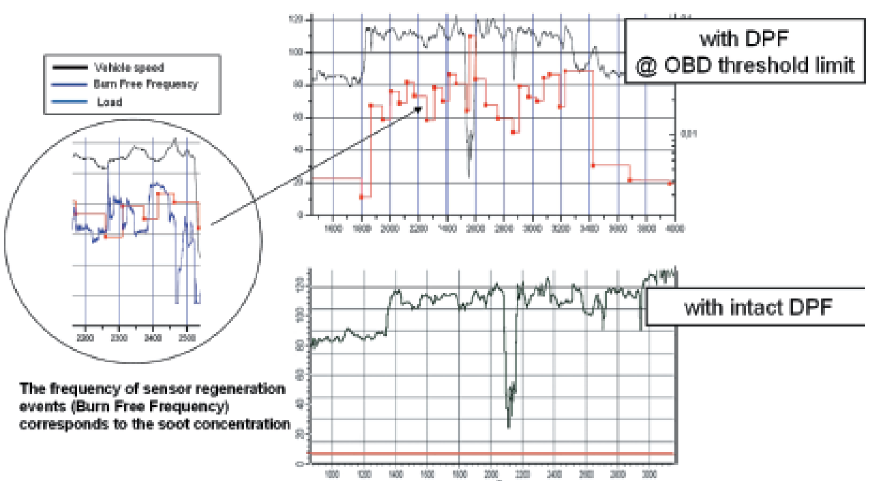
- Several in-line sensors are being developed to detect DPF failure
- DPF failure detection has been demonstrated
- Detection down to 1 mg/m^3 for OBD appears to be possible

Reference: SAE 2011-01-0302 & 0627

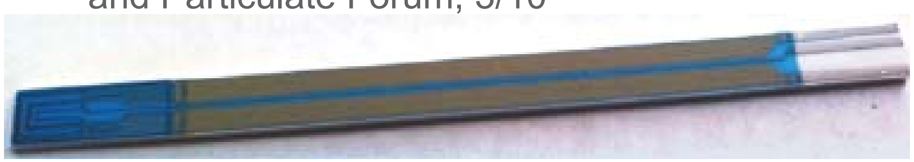
PM sensor for OBD is reported.





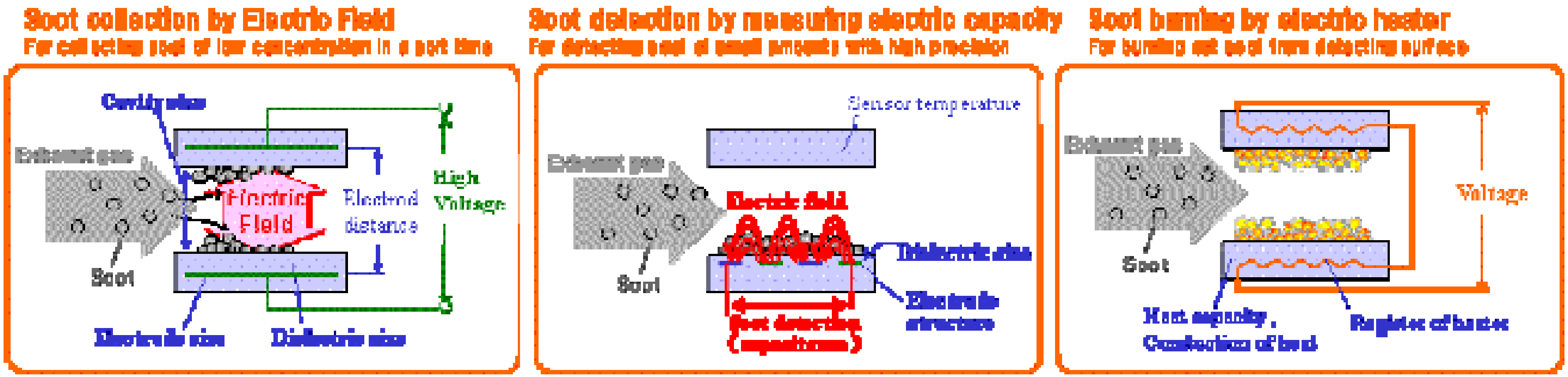


Continental, AVL Exhaust Gas and Particulate Forum, 3/10

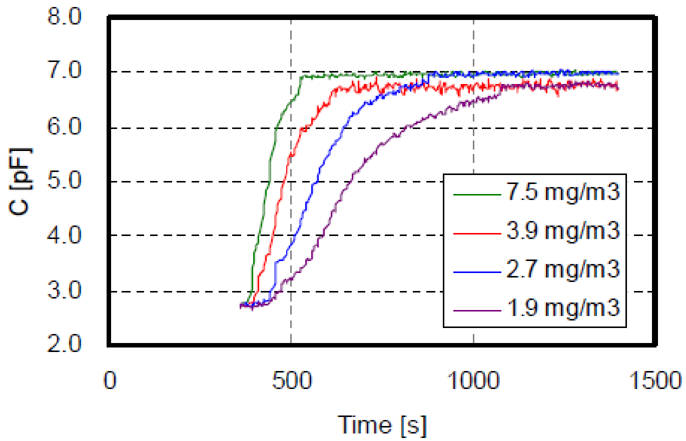


Sensor element collects soot and monitors current, then periodically regenerates to give an average soot level for the period. Signal here is with DPF at OBD threshold compared to good DPF.

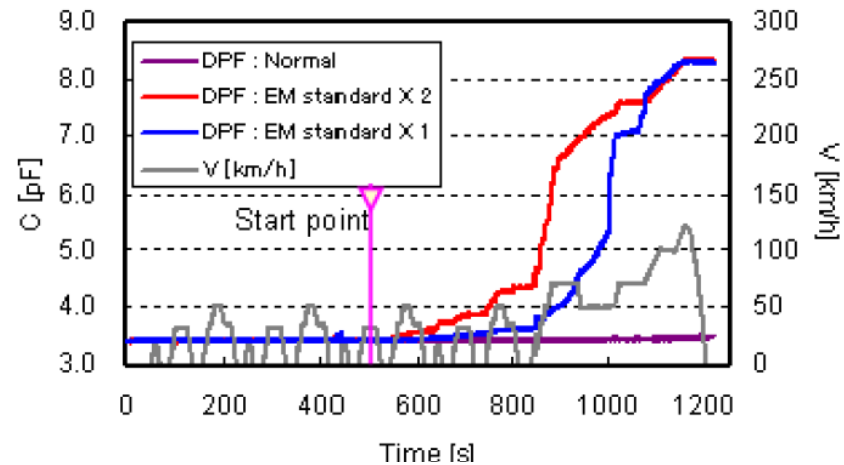
A sensor based on collection and changes in capacitance is introduced.



Three stage sensing: 1) Charged soot particles are collected under an electric field. 2) Capacitance changes are detected from accumulated soot. 3) Soot is burned off to repeat the process.



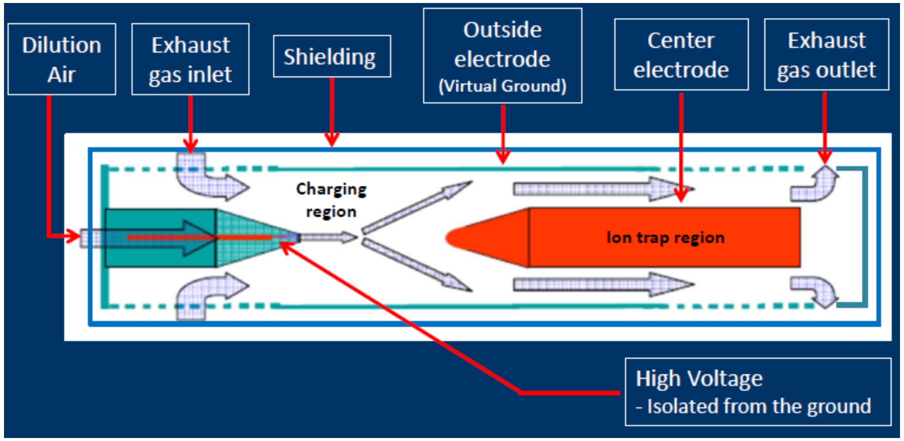
Capacitance change is sensitive to PM levels. 50 µg increase capacitance from 3 to 6 pF.

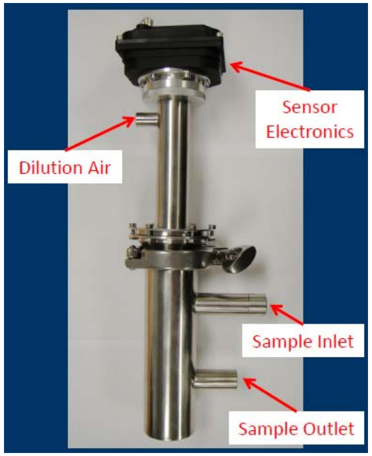


The sensor detects DPF leakage at 1X and 2X the standard.

NGK Insulators, Aachen, 10/10

New Non-Accumulating PM sensor shows excellent tracking to PEMS and potential to do PN

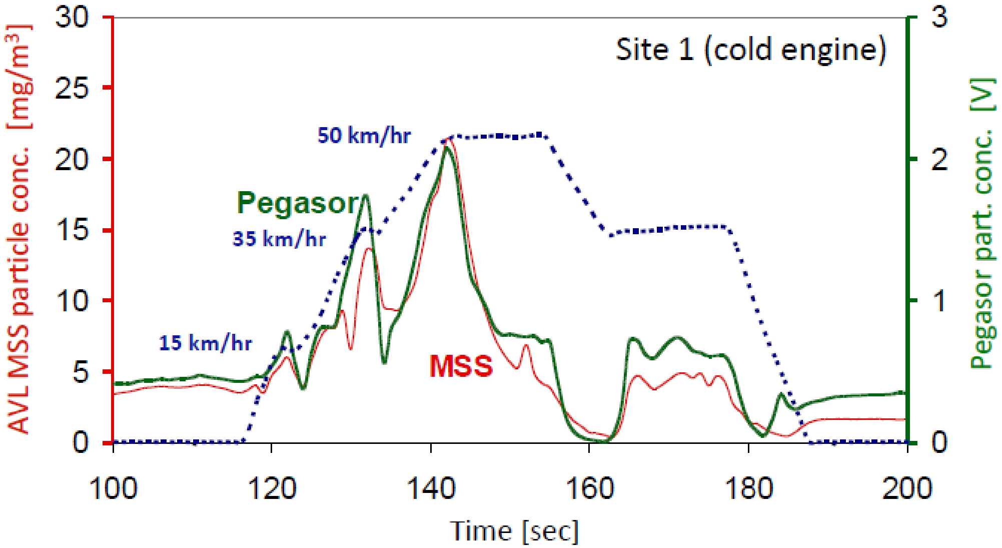




Supplier claims PN concentration measurement.

Non-accumulating PM sensor measures charged particles continually.

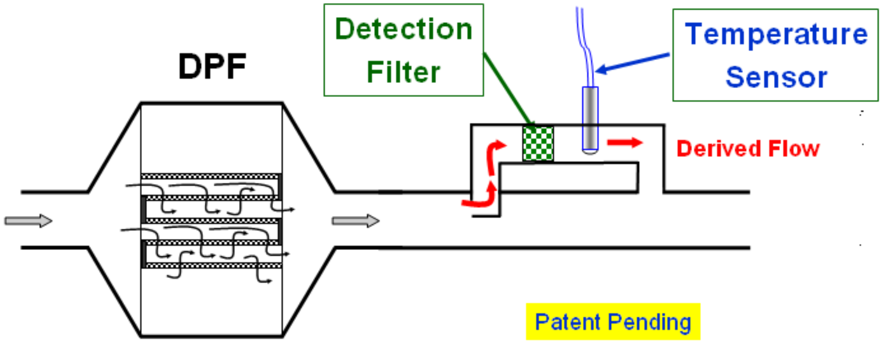
Sensor measure ~400X100 mm



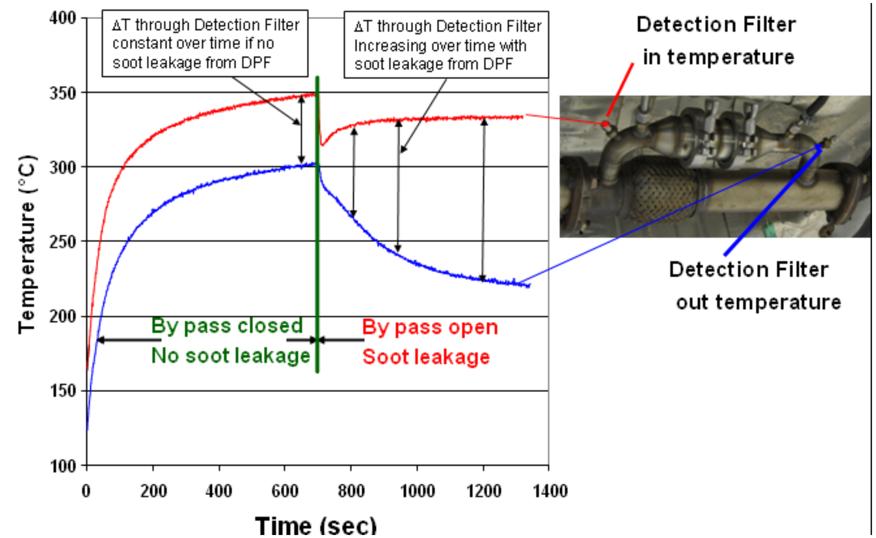
Pegasor, CRC Conf 3/10

Sensor shows excellent transient tracking to PM PEMS output. Claimed sensitivities down to 0.01 mg/m3

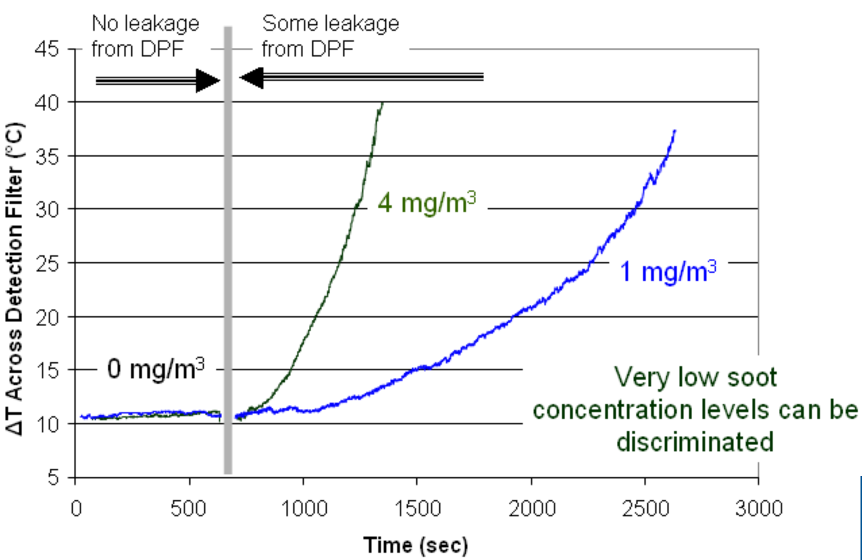
New, simple PM OBD device is shown.



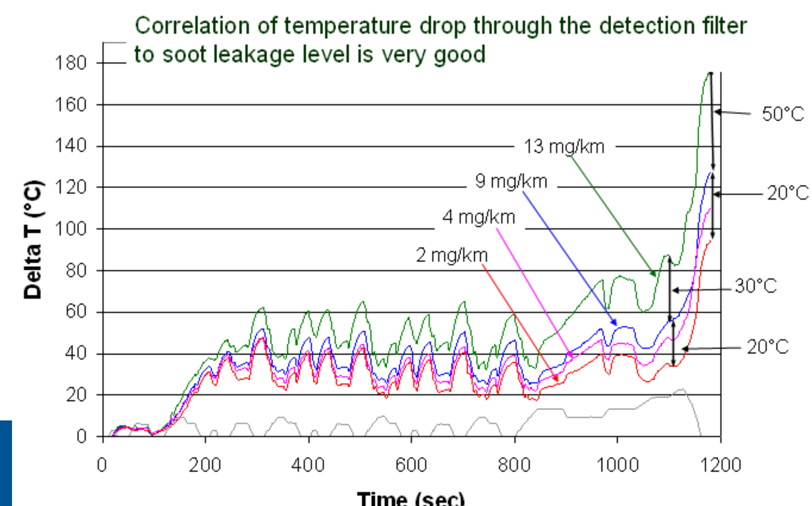
Simple DPF OBD system detects flow reduction in downstream miniature DPF as a way of detecting main DPF leakage.



When main DPF by-pass is opened, “soot leakage” results in ΔT shift across the detection filter.



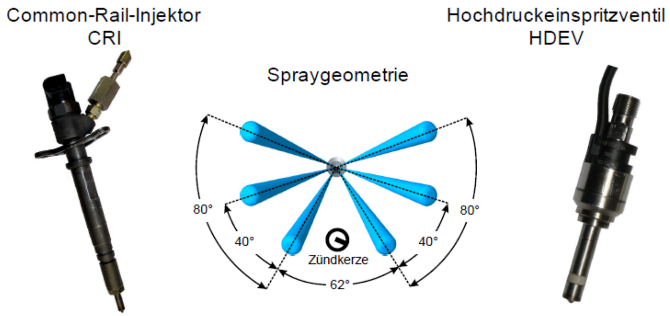
Preliminary steady- state (left) and transient testing shows promise. .



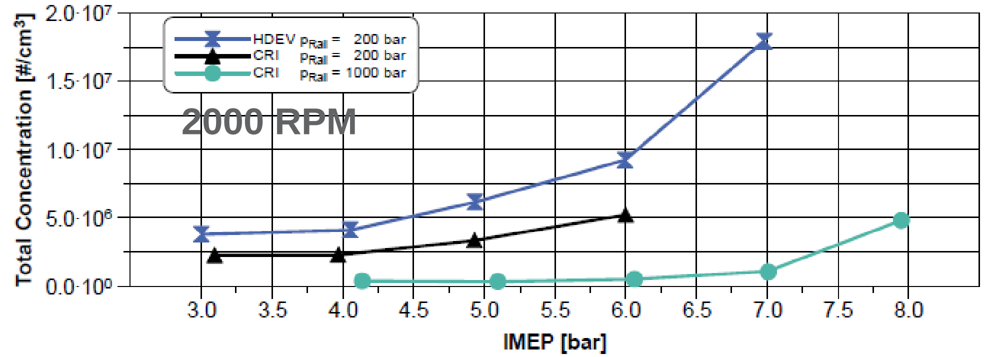
CORNING

Gasoline Emission Control

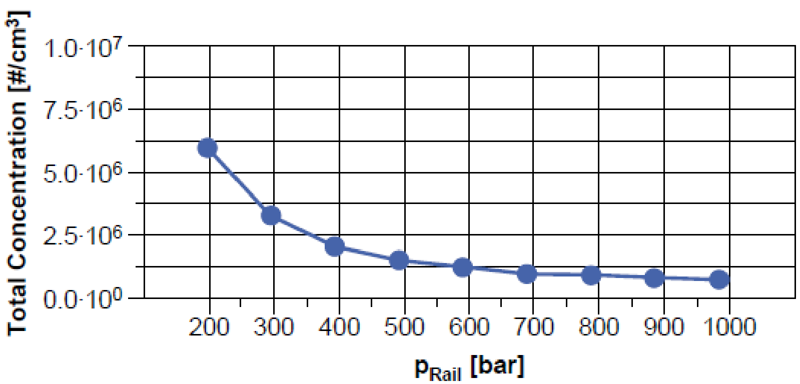
Increasing injection pressure can drop PN emissions ~95%.



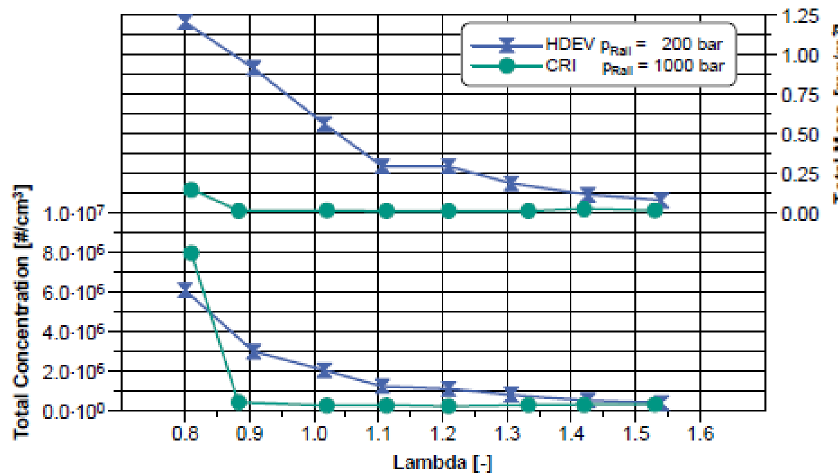
Experimental (left) and stock injectors.
Spray guided configuration.



PN will increase as load increases, but are reduced 95% at 1000 bar injection pressure.

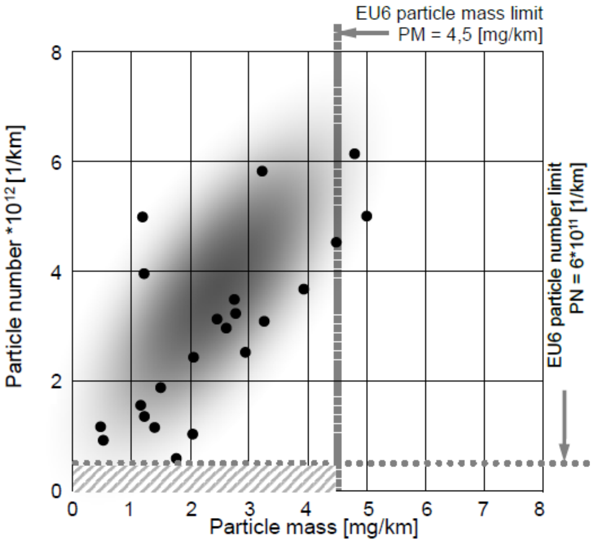


PN emissions are reduced substantially (-70%) when increasing injection pressure from 200 to 500 bar. 2000 RPM, 6 bar IMEP. stratified mode.

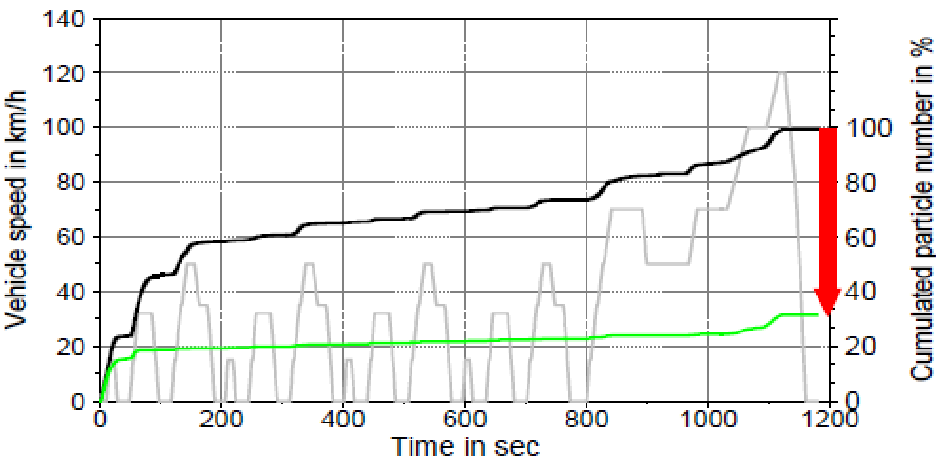


PN from a stratified injection goes down with increasing air/fuel ratio, but much less so with an already-low PN from HP injection.

Engine calibration can drop GDI PN emissions by 65% on the NEDC.



At low PM levels, gasoline PN can vary by 10X



+	**Start of injection**	Start of 1st injection was adjusted (~35 °CA later)
+	**Injection split**	Was matched with regard to particle number and rough running
+	**End of injection**	The end of 2nd injection was adjusted to the split
+	**Fuel pressure**	Was set near the maximum fuel pressure after engine start and to maximum at the start of 2nd hill
+	**Air fuel ratio**	Better air/fuel ratio pilot control up to start of engine, reaching ideal Lambda as fast as possible
+	**Ignition angle**	Subsequent adjustment at 7°CA on 1st hill and at 12°CA on 2nd hill
-	**Valve timing**	Changed valve timing results in efficiency reduction and increased fuel consumption

cold

+	**Fuel pressure**	Was set to maximum fuel pressure in complete range except idle and at low loads (near to minimum injection quantities)
+	**Start of injection**	Start of 1st injection was adjusted (~20 °CA later)
+	**Injection split**	Was matched with regard to particle number
-	**Ignition angle**	Later ignition angle results in particle reduction - but comes with rising fuel consumption
-	**Valve timing**	Changed valve timing results in efficiency reduction and increased fuel consumption
-	**Air/fuel ratio**	Operating at lambda = 1 ensures particle optimum regarding the other emission components

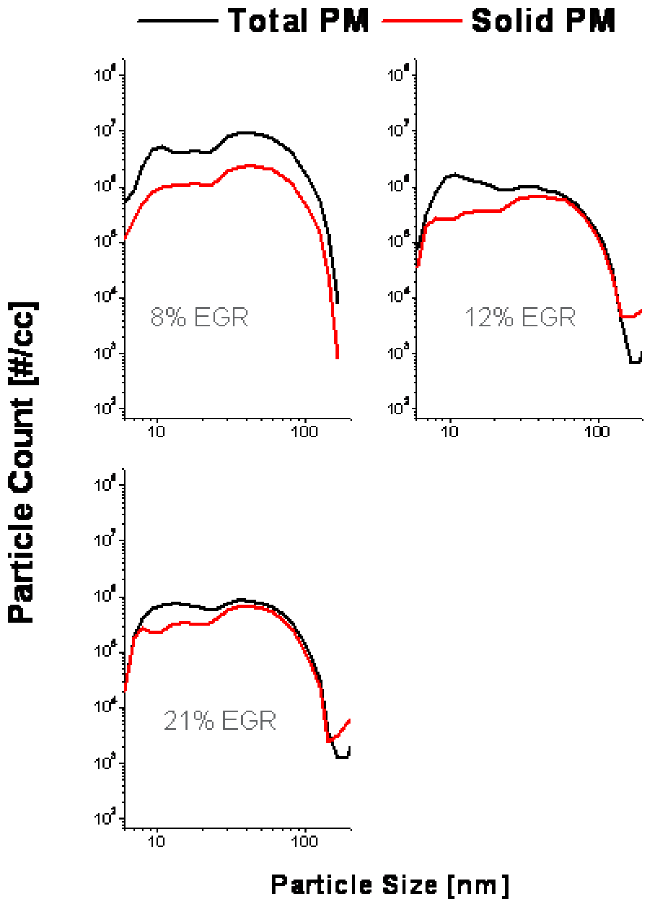
warm

65% PN reduction with new engine calibration measures

IAV, DEER Conf 9/10

Cooled EGR up to 12-20% can reduced GDI PN quite significantly.

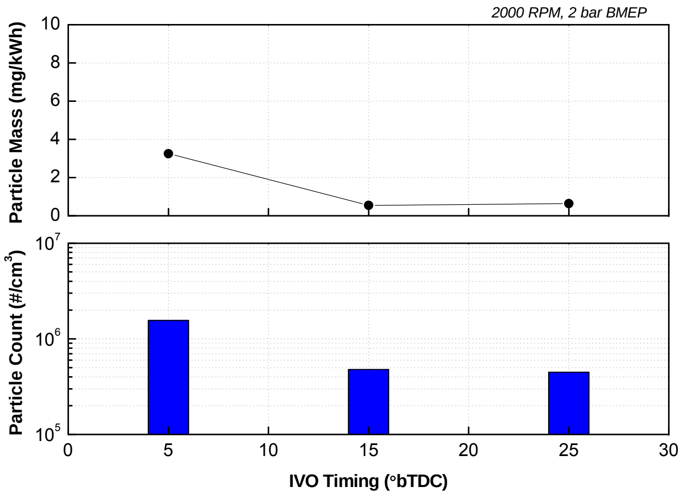
2000/2 bar



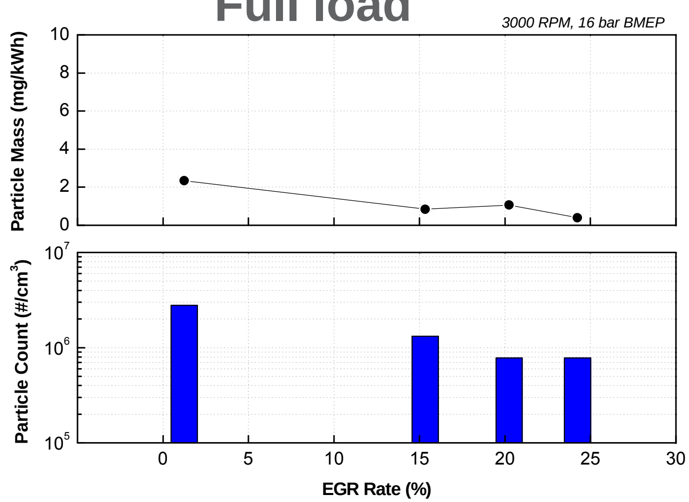
SwRI PCS 8-10

25% EGR dropped PN about 80% with with 20% enrichment. Higher levels of either: no impact.

2000/2 bar

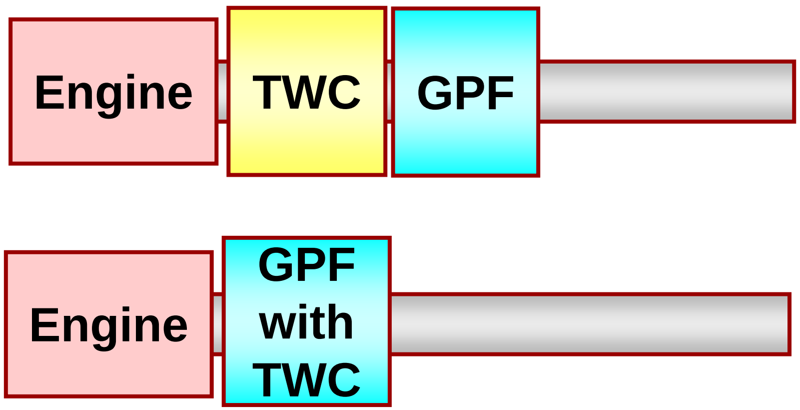


Full load

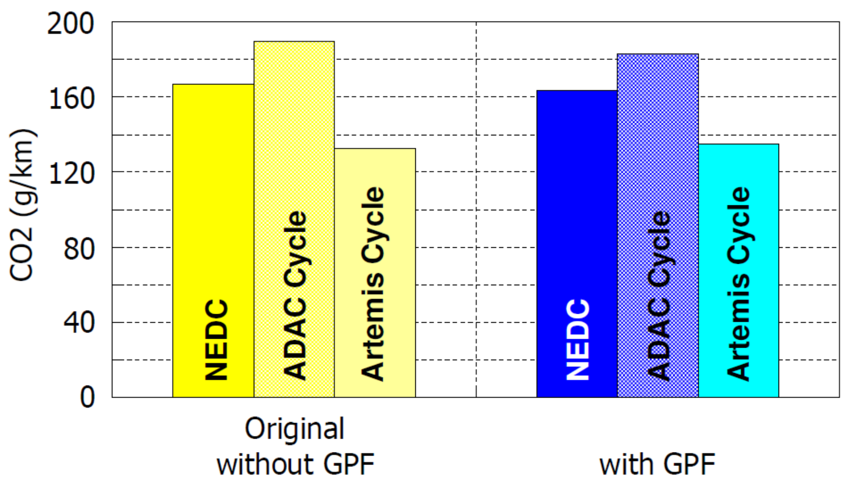


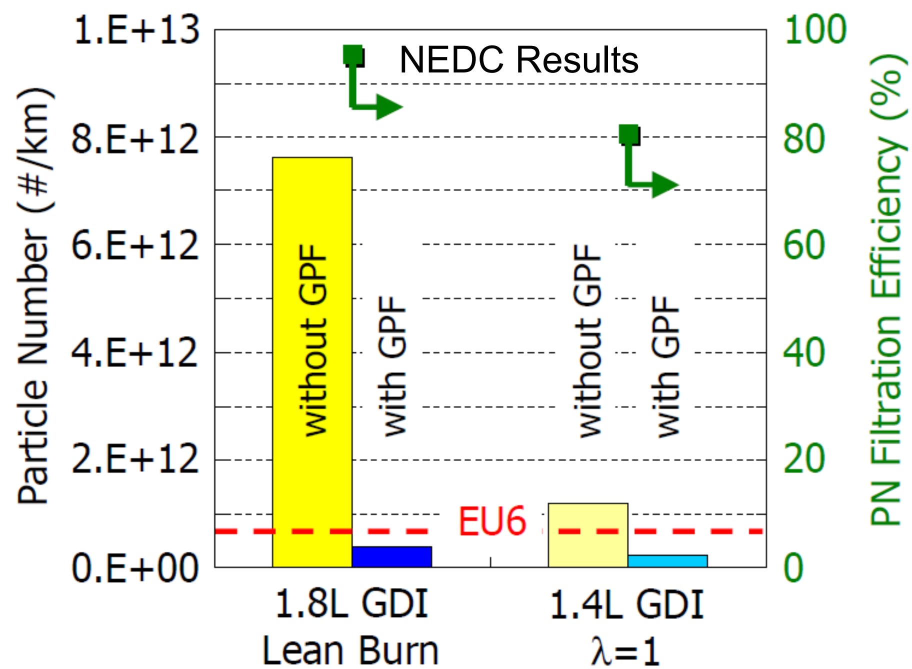
At 2000 RPM and 2 bar load, 12% EGR helps reduce PN. More EGR has little impact.

Benefits of Filters Being Demonstrated on GDI Engines



- GDI engines exhibit high PM emissions under high speeds and loads
- Wall-flow filters offer same benefits of PM number and mass reductions as with diesel engines

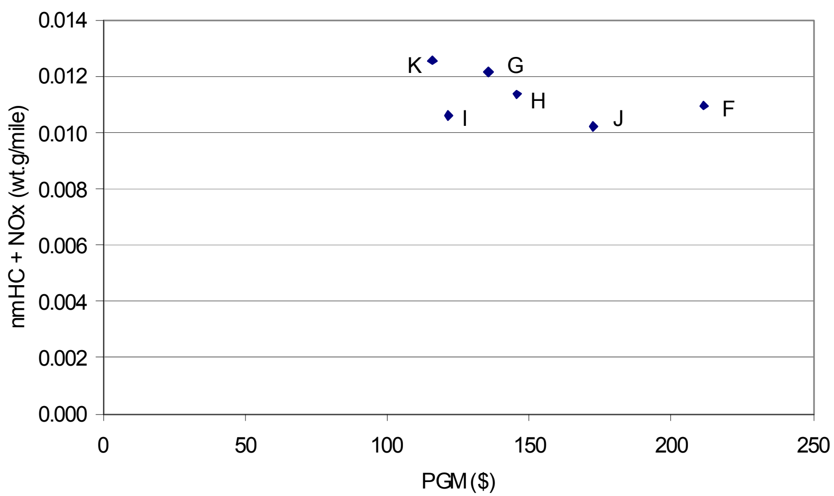




Ref. SAE 2011-01-0814

TWC System Architectures being Optimized For LEV III: 4 Cylinder Application with Secondary Air

SULEV20 Performance Achievable with Efficient Precious Metal Placement in a Close-Coupled, Multi-Substrate Converter



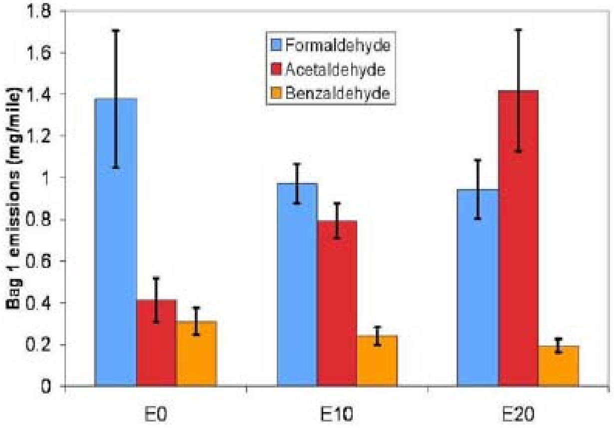
Ref: SAE 2011-01-0301

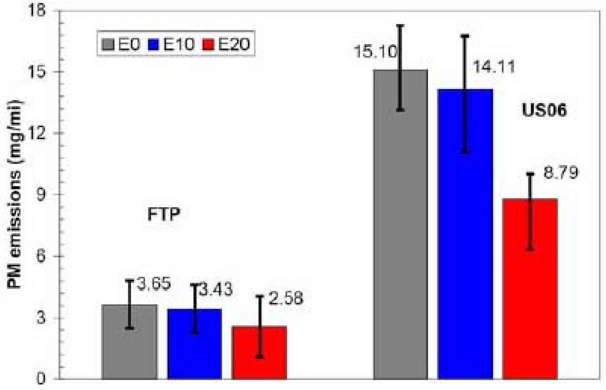
Catalyst	Pd (g/l)	Rh (g/l)
Front	3	0.3
Mid	2	0.1
Rear 1 or	2	0.1
Rear 2	1	0.3

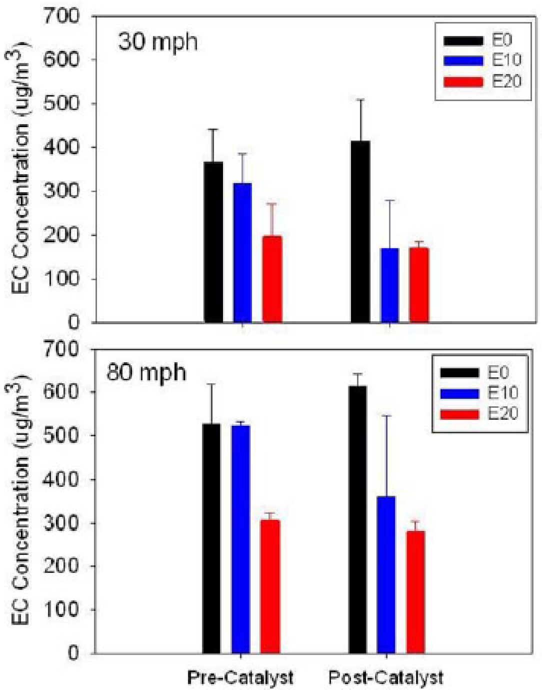
EtOH impact on criterion pollutants is quantified.

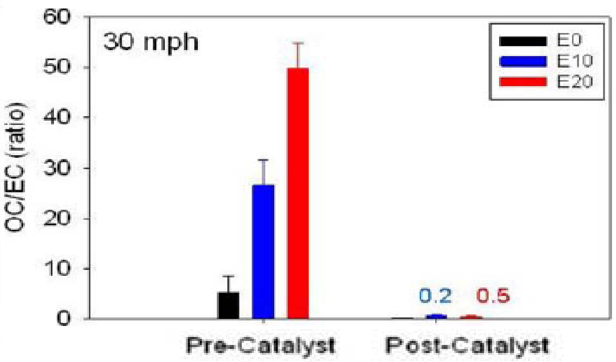
NOx but NMHC can go up. PM drops with the EC decreasing but OC increasing. Acetaldehyde increases.

	E0	E10	E20
FTP FE (MPG)	25.1	24.1	23.9
US06 FE (MPG)	26.6	25.4	24.9
NMHC (g/mile)	0.055	0.044	0.091
NOx (g/mile)	0.031	0.018	0.009
CO (g/mile)	0.35	0.36	0.30









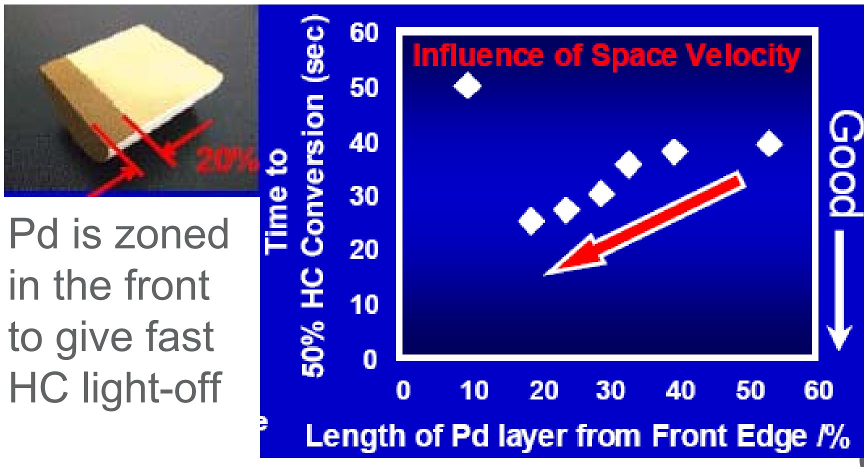
2007 GM 2.0 liter DISI

E20 drops EC about 40% pre-cat and 50% post-cat. At 30 mph, E20 increases OC 5.7X pre-cat and but is similar post-cat.

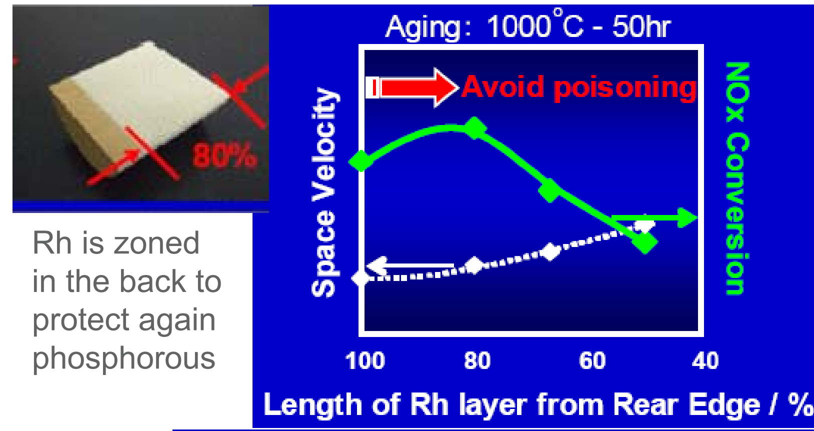
ORNL, SAE 2010-01-2129

Gasoline catalysts show multiple zone coatings and PGM stabilization methods.

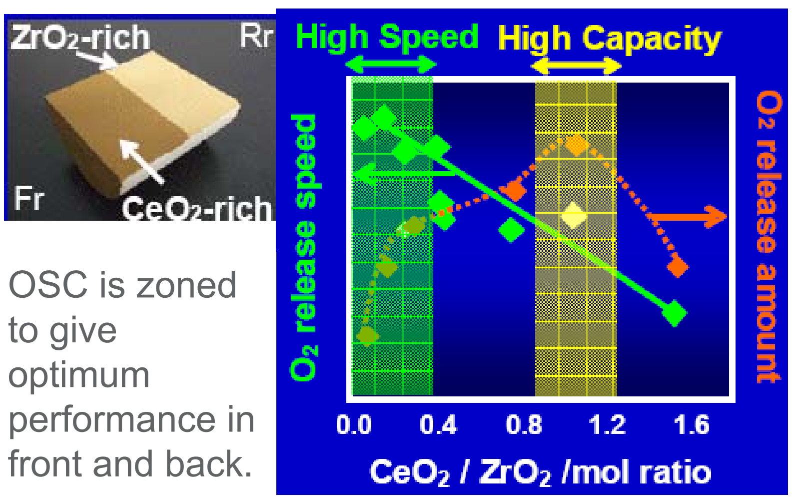
Pd in front, Rh behind, different OSC in front and back.



Pd is zoned in the front to give fast HC light-off



Rh is zoned in the back to protect again phosphorous

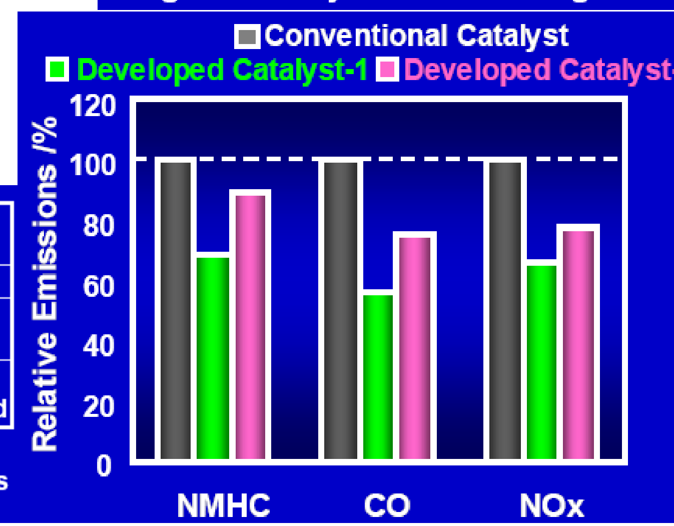


OSC is zoned to give optimum performance in front and back.

Catalyst w/ -45% Rh has -20% emissions

	Conventional	Developed Catalyst 1	Developed Catalyst 2
Coat	Double Layer	Zone-Coat	
Noble Metal	Pd/Rh	Pd/Rh	Rh45% reduced

Substrate Volume: 0.9[L]
Aging: Equivalent of 120K miles
Vehicle: '05MY ULEV/CAMRY



Toyota, SAE 2011-01-0296

Other: Rh is better-dispersed with Al2O3 barrier to prevent ZrO2 sintering; Nd2O3 pins Rh grains

Summary

- Further tightening of criteria regs expected. California is beginning LEV3 proposal stage. EPA considering Tier 3.
  - Japan looking to 2016. Universal interest on urban NOx emissions. US focused on CO2.
- CO_2 mandates are proposed for LD and HD will follow
  - Onset of another major regulatory-driven technology evolution
- LDD focusing on downsizing, deNOx for FC reductions. Gasoline using downsizing, EGR, going lean.
- HDD engine technologies are addressing engine-out NOx and FC
- SCR is addressing "secondary" issues:
  - LT issues: ammonia sources and urea inj; NH3 storage formation, mechanisms.
  - Catalyst HT and sulfur durability addressed
- New LNT compositions and designs are shown.
  - Better performance, lower cost
  - LNT+SCR systems advancing
- DPF regen, catalysts, substrate properties, and material advancing.
- Gasoline emission control is focused now on PM&PN, and systems needed to meet LEV3