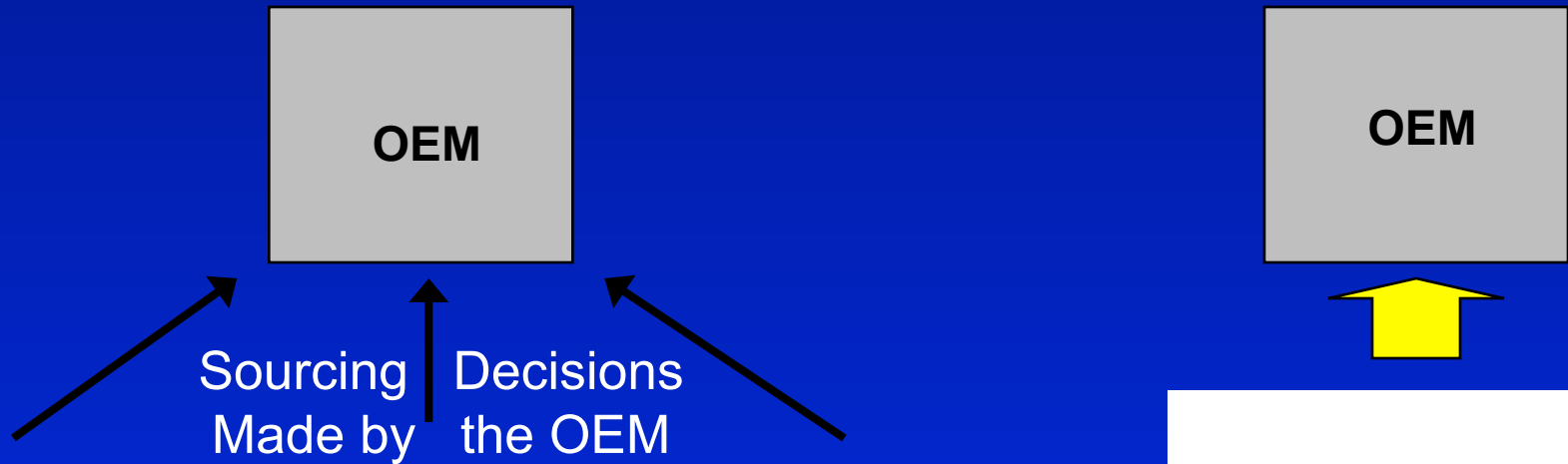

Light-Duty Vehicle Emission Control Technologies

*Mexico City Workshop
July 2014*

Dr. Joe Kubsh
Manufacturers of Emission Controls Association
www.meca.org



MECA - Industry Technology Voice with ARB, EPA, Environment Canada other Stakeholders; 41 Member Companies Cover Major OEM & Aftermarket Emission Control Manufacturers



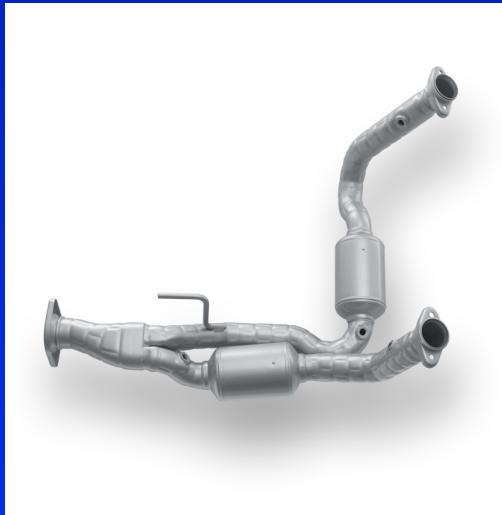
SUBSTRATES & MATS



CATALYSTS



EXHAUST SYSTEMS
(sensors, canning, air pumps, urea delivery)



Manufacturing Flow

Emission Control Industry supports > 65,000 jobs in the U.S.; manufacturing facilities also in Mexico

EVAP. SYSTEMS
(carbon canisters; purge valves; low permeation materials)



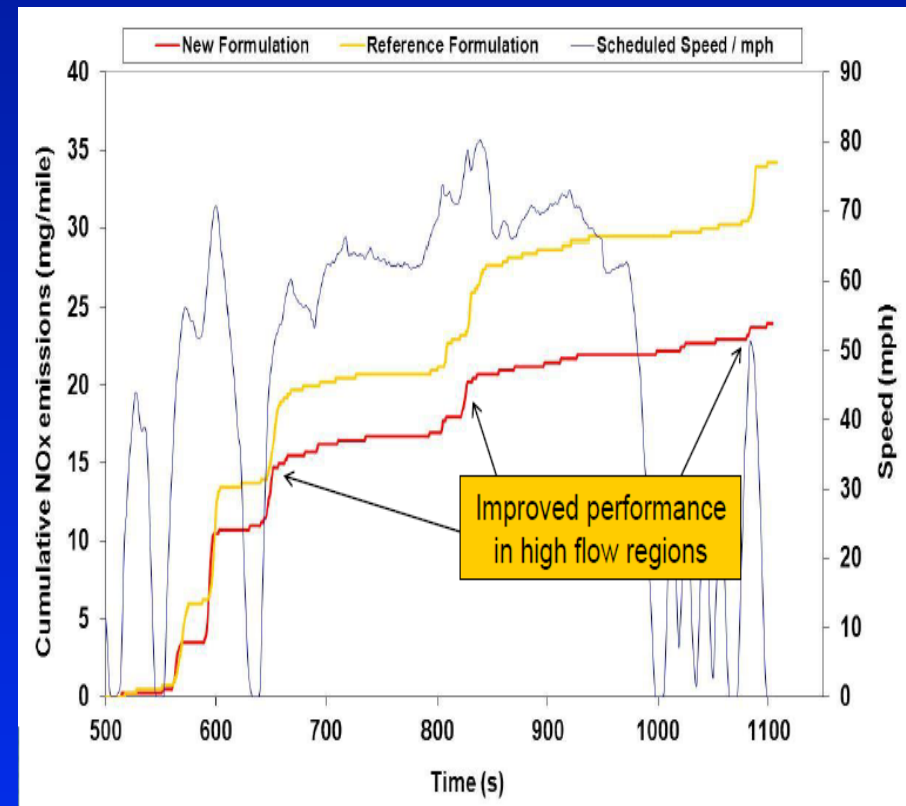
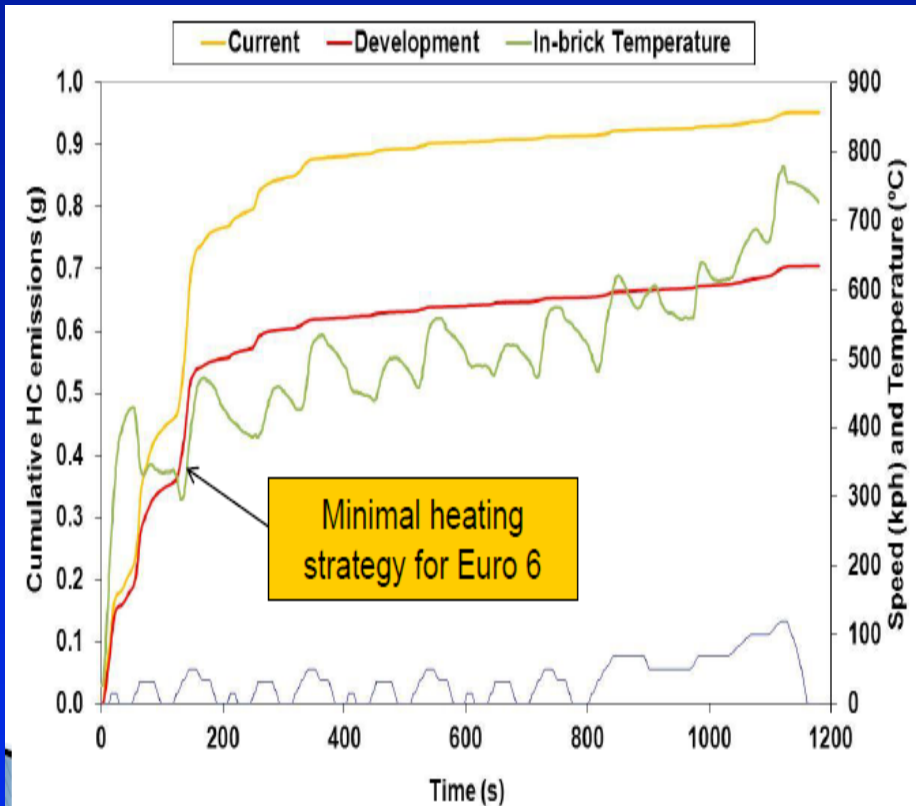
Light-duty Vehicle Emission Control Technologies

- Gasoline Vehicle Technologies for Tier 2/Tier 3 & LEV II/LEV III
- Light-duty Diesel Emission Control Technologies

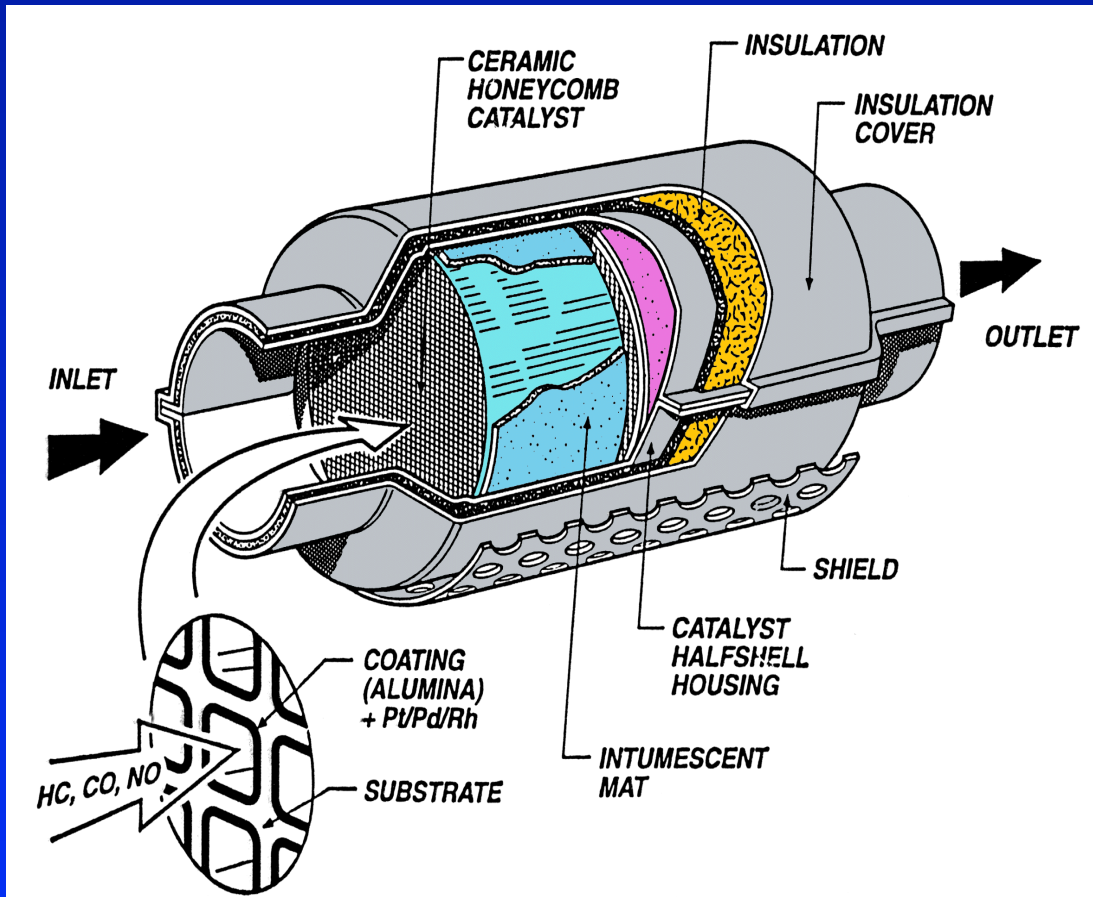
Mobile Source Emissions Regulations Drive Technology Innovation

- Light-duty: U.S. Tier 2/LEV II moving to Tier 3/LEV III
 - Near Zero gasoline exhaust emissions: advanced TWCs, HC adsorber cats, high cell density substrates, direct ozone reduction catalysts
 - Near Zero gasoline evap. emissions: advanced carbon canisters, low permeation materials, air intake adsorbents
 - Near Zero diesel exhaust emissions: EGR, DPFs, lean NOx catalysts, SCR
- U.S. 2007-2010 Heavy-Duty Highway Diesel
 - DPFs, SCR, EGR
- U.S. Tier 4 Off-Road Diesel
 - DPFs, SCR, EGR

LEV III/Tier 3 Applications Continue to Emphasize Cold-Start & High Speed NOx Performance

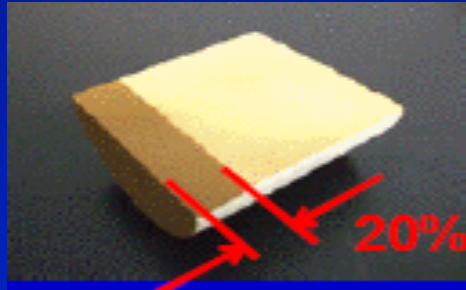


The Three-way Catalytic Converter: A Familiar Technology Re-Engineered for High Performance

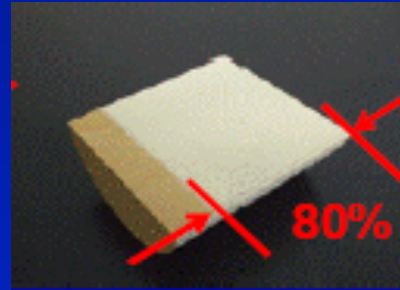


- Provides high efficiency “three-way (HC, CO, NO_x)” performance
- Layered catalytic architectures to maximize noble metal (Pt, Pd, Rh) effectiveness
- Advanced materials with high thermal stability
- High cell density ceramic or metallic substrates

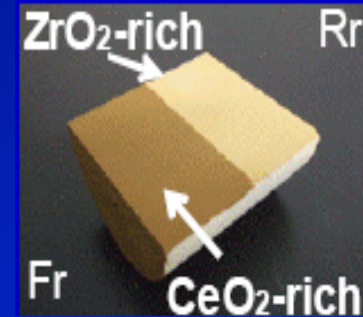
Gasoline Three-way Catalysts Utilize Advanced Design Strategies to Maximize Performance



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



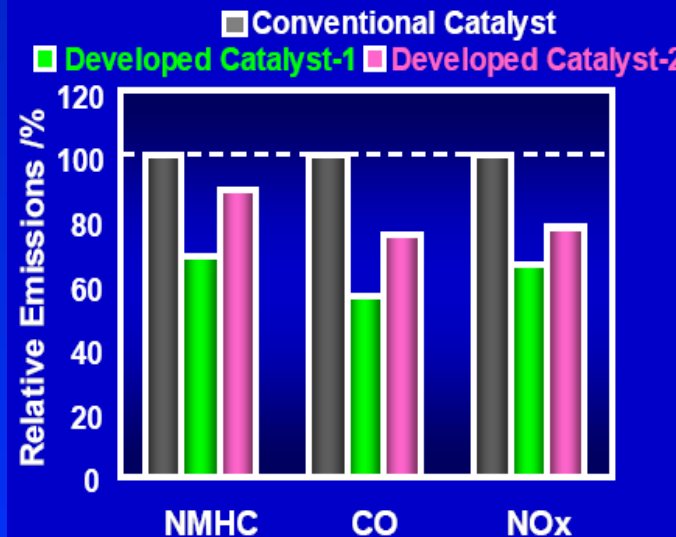
Rh is zoned in the back to protect against catalyst poisons



Zoned OSC to give optimum performance

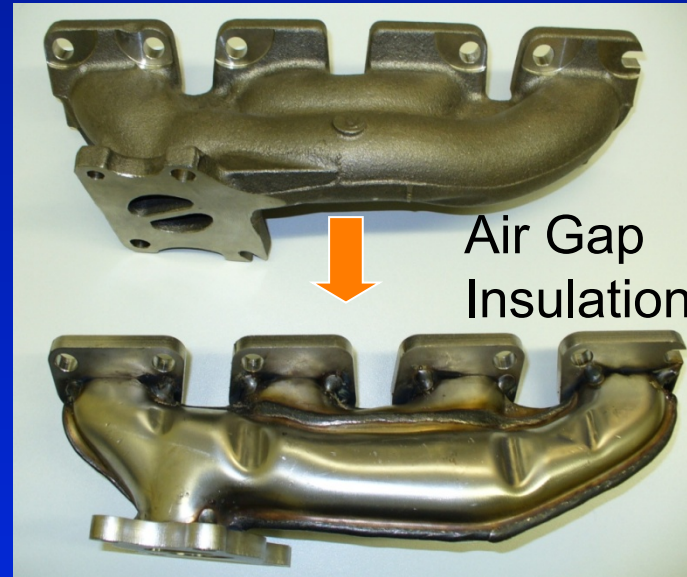
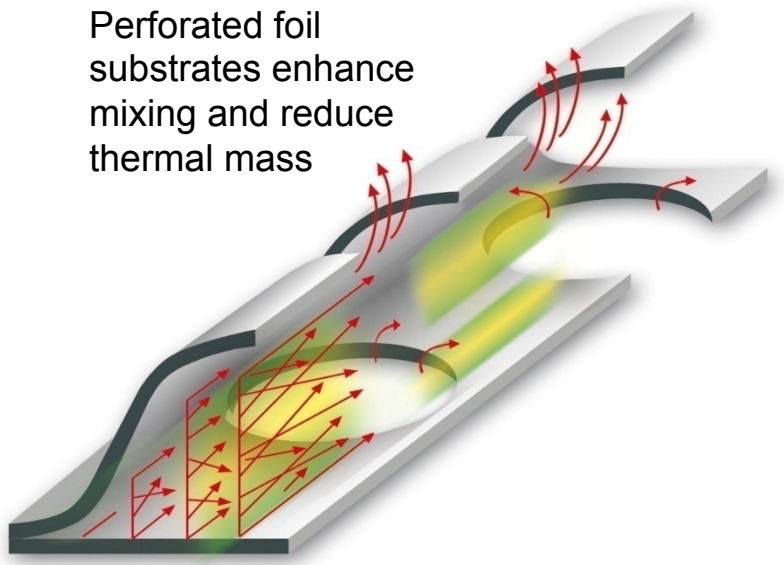
	Conventional	Developed Catalyst	
		1	2
Coat	Double Layer	Zone-Coat	
Noble Metal	Pd/Rh	Pd/Rh	Rh45% reduced

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

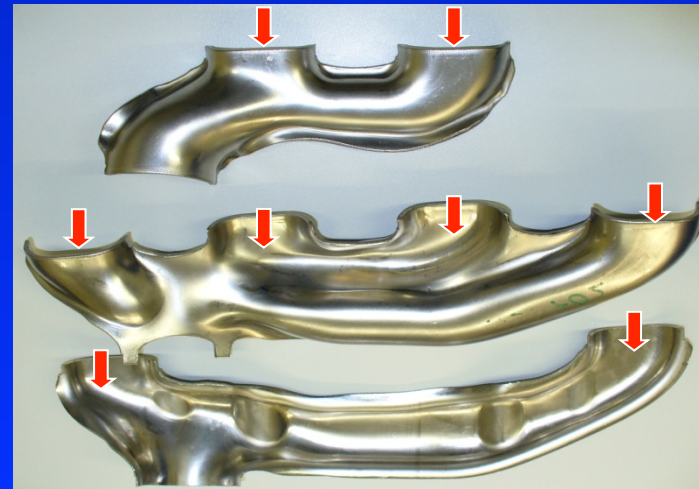
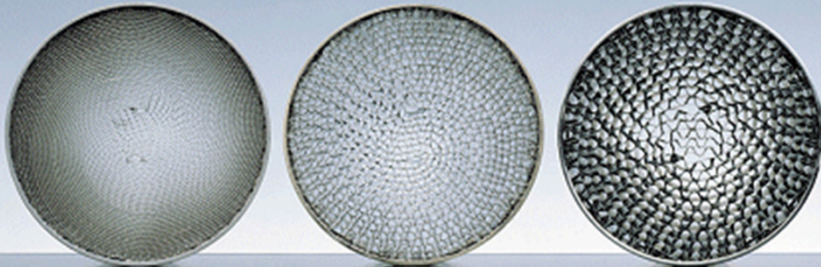


Thermal Management Focused on Cold-Start Emission Reductions

Perforated foil substrates enhance mixing and reduce thermal mass

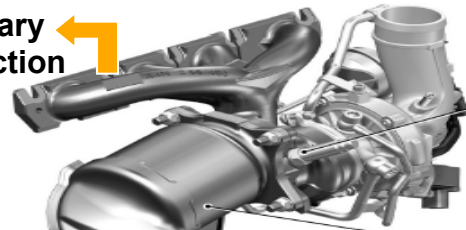


High Cell Density, Thin Wall Substrates



PZEV Experience With Turbo-GDI Application

Secondary Air Injection



stetige Lambda-Sonde (LSU 4.9 mit TP1-Schutzrohr) im Turbinen-Gehäuse

Motornaher Keramik-Kat: 4,16" x 3,8", 900 cpsi

ULEV2	PZEV
600 cpsi	900 cpsi
2.3 liter	2.5 liter
60 g/ft3	150 g/ft3

Entkoppelungs-element

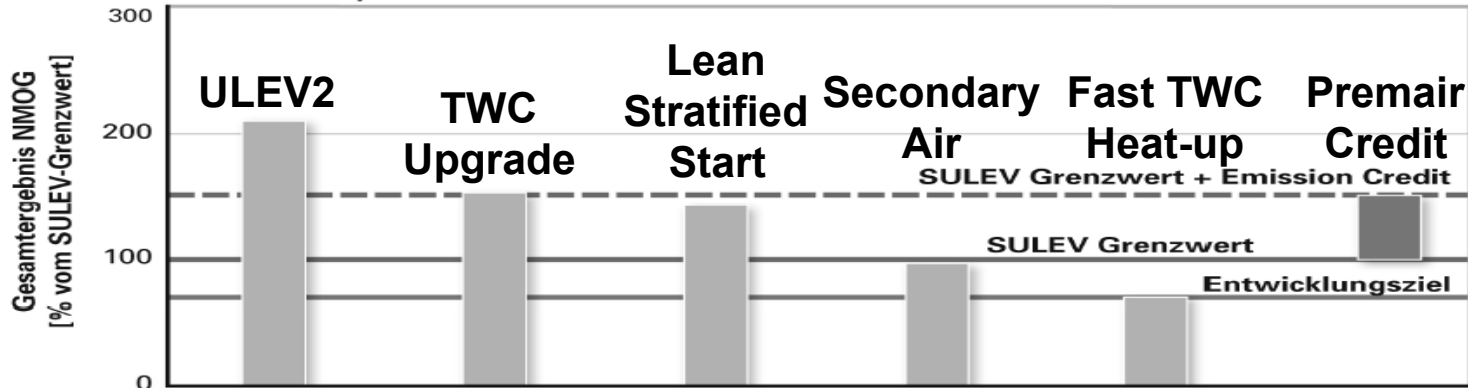
Lambda-Sprung-Sonde (LSF 4.2) vor Unterboden-Katalysator

ULEV2	PZEV
40 g/ft3	100 g/ft3

Unterboden-Keramik-Kat:

Lambda-Sprung-Sonde (LSF 4.2) nach Unterboden-Katalysator

Basis: Neukatsystem



Source: 2007 Aachen Colloquium



Variety of PZEV Strategies in the U.S. Market

Vehicle	A	B	C	D	E
Engine Displacement	2.0	2.4	2.0	2.4	2.4
PFI or DI	DI	PFI	PFI	DI	PFI
NA or Turbo	Turbo	NA	NA	NA	NA
AIR or non-AIR	AIR	AIR	non-AIR	non-AIR	AIR
Average Ignition Setting (°btc)	-20	0	-7	-12	-5
Engine Speed (rpm)	1150	1200	1500-1700	1200-1500	900-1200
Lambda	1.05 (AIR)	>>1 (AIR)	.95-1	.95-1	>>1 (AIR)
Max Cat Temp (°C)	670	1000	500	700	950

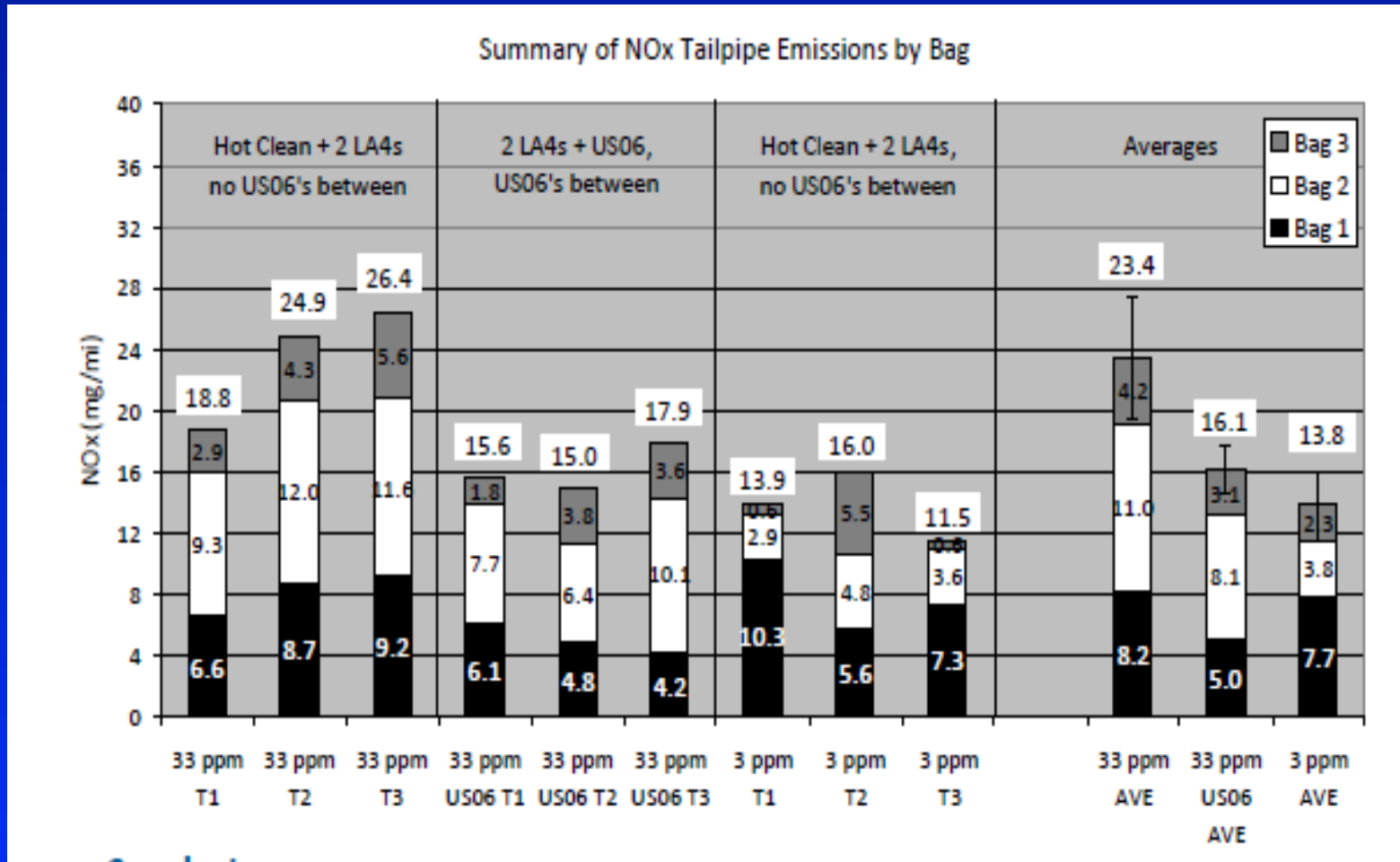
Vehicle	Positives	Negatives
A	PZEV turbo, low startup engine speed, more accurate fuel control	High system cost/complexity
B	Extremely fast catalyst light-off, low startup engine speed, less calibration time	Cost of AIR, excess fuel used in start-up
C	Lowest system cost	High engine speed in first idle
D	Split injections enable fast lightoff w/o AIR	Additional calibration effort
E	Extremely fast catalyst light-off, low startup engine speed, less calibration time	Cost of AIR, excess fuel used in start-up

Ref. : SAE 2012-01-1245



Gasoline Sulfur Degrades Catalyst Performance: Example Chevy Malibu PZEV Application

2.4 liter,
4 cyl.:
CC+UF
TWCs
Ref.: SAE
2011-01-0300



UF never above 600 C with FTP; NOx "creep"

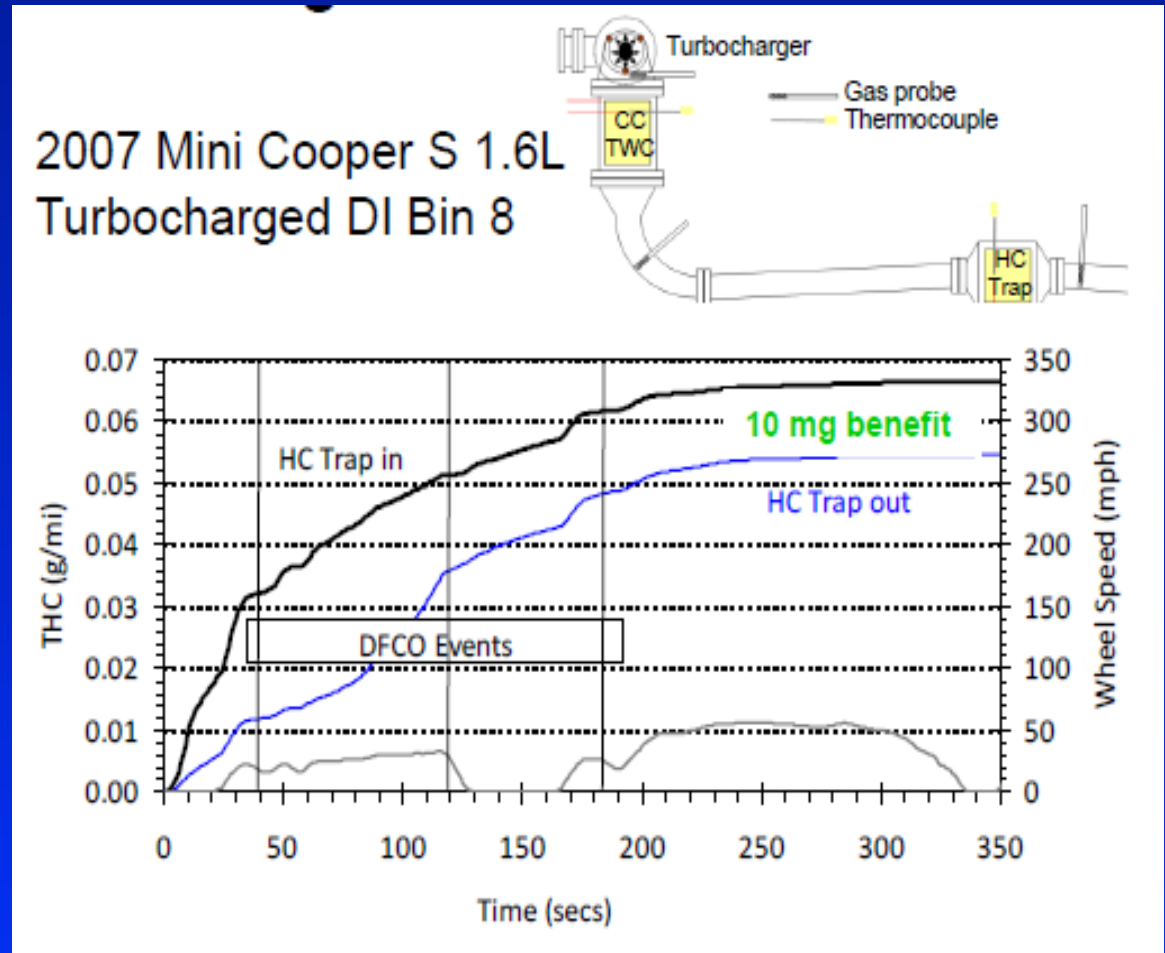
UF at 700-750 C during US06; NO NOx "creep"

NO NOx "creep" with 3 ppm S



Additional Cold-Start HC Control Available From Hydrocarbon Traps

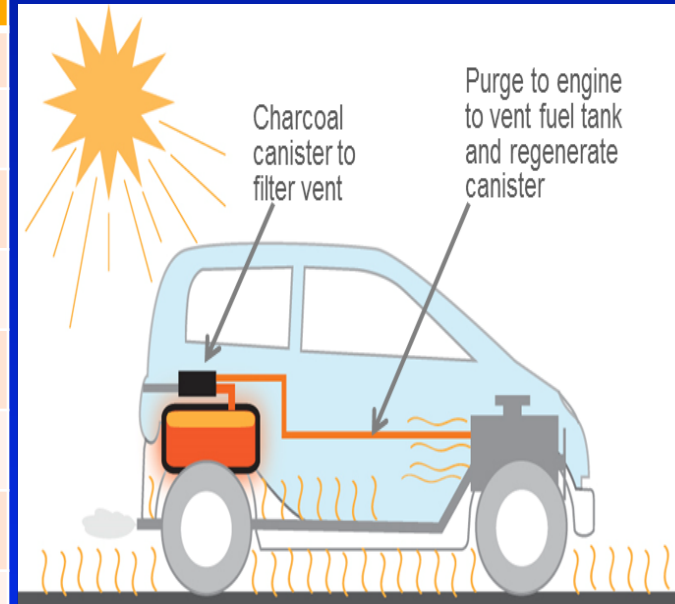
- Limited SULEV/PZEV HC trap applications to date
- Development work continuing with focus on durability/cost
- Example: HC trap PGM loading of only 26 g/ft³
- Calibration support needed for O₂ during HC desorption – decel. fuel cut-off



Reference: SAE 2013-01-1297

U.S. Evaporative Emission Standards Provide Comprehensive VOC Controls for Gasoline Vehicles

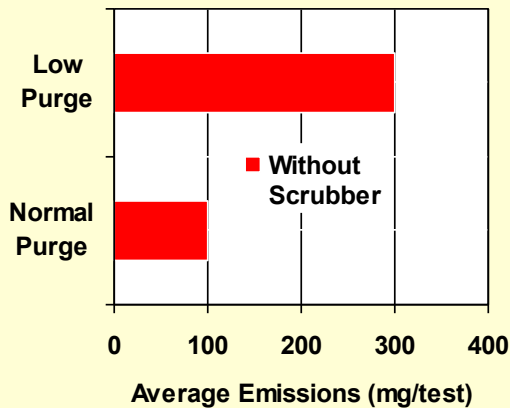
Standard	US ≤ 1995 and Euro Evap. Stds.	US ≥ 1996-2004
ORVR		✓
24-hr Diurnal	✓	
48-hr Diurnal		✓
72-hr Diurnal		✓
Evap Standard = 2 g/day	✓	
Evap Standard < 0.5-1.2 g/day		✓
Hot Soak	✓	✓
Running Loss		✓
In-use standards and monitoring		✓
OBD		✓



Since 1996, the US progressively added ORVR, extended diurnals, short drive cycles, running loss, low certification and in-use emissions standards, and OBD to improve air quality.

CARBON TECHNOLOGIES TO ACHIEVE PZEV/LEV III EVAPORATIVE REQUIREMENTS

CANISTER EMISSIONS

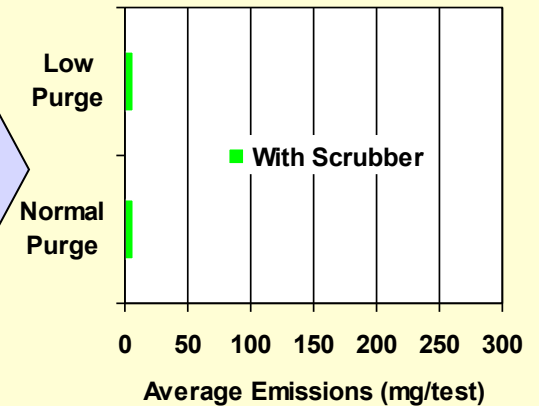


Addition of Canister Scrubbers

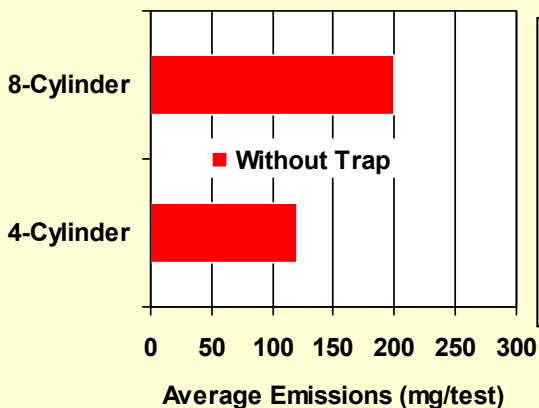


- Honeycombs
- Low Bleed Carbon

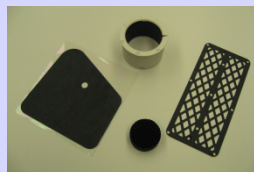
Reduction of 95-295 mg/test



AIS EMISSIONS

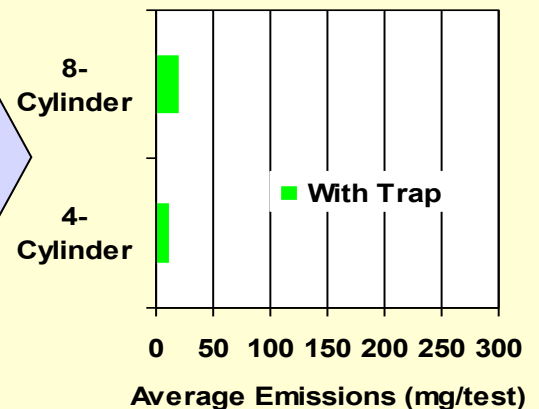


Addition of AIS Traps



- Honeycombs
- Carbon Sheet
- Low dP Elements
- Carbon Cylinders

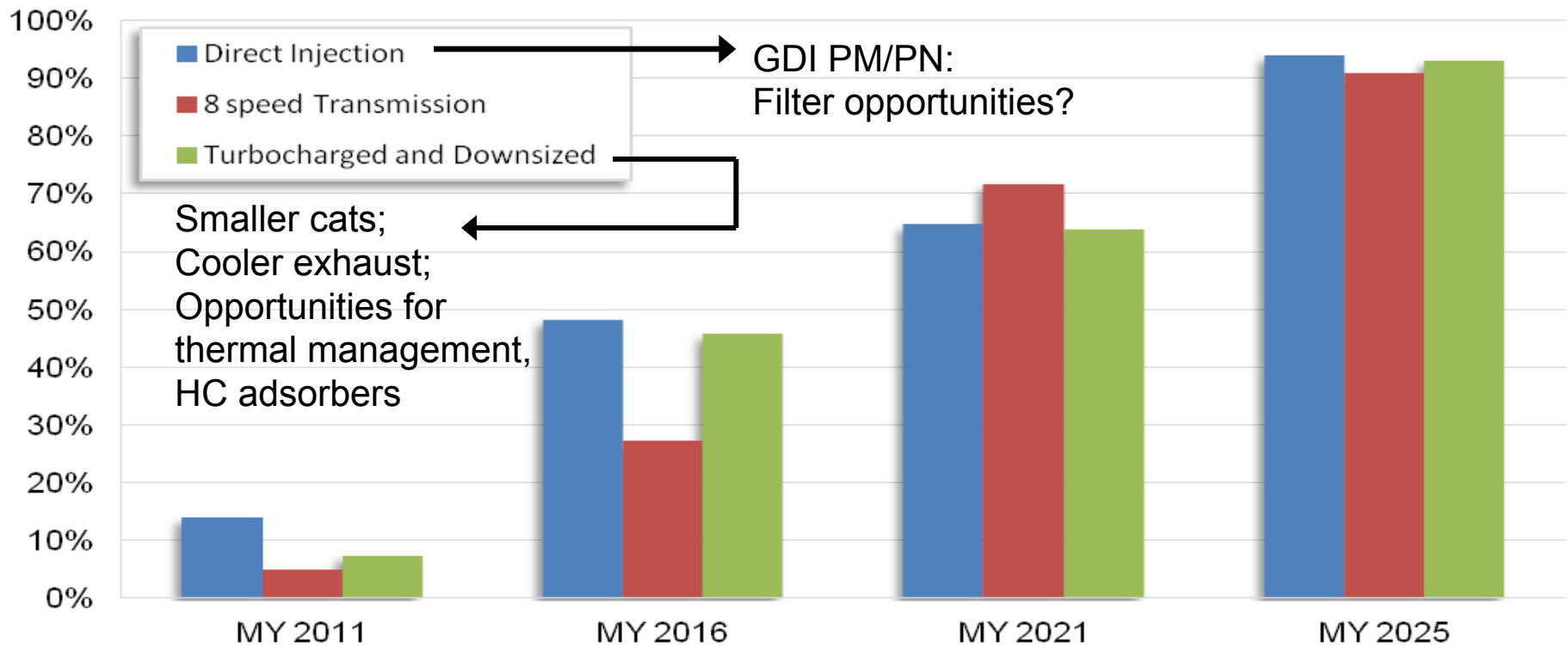
Reduction of 100-200 mg/test



Gasoline Particulate Filters

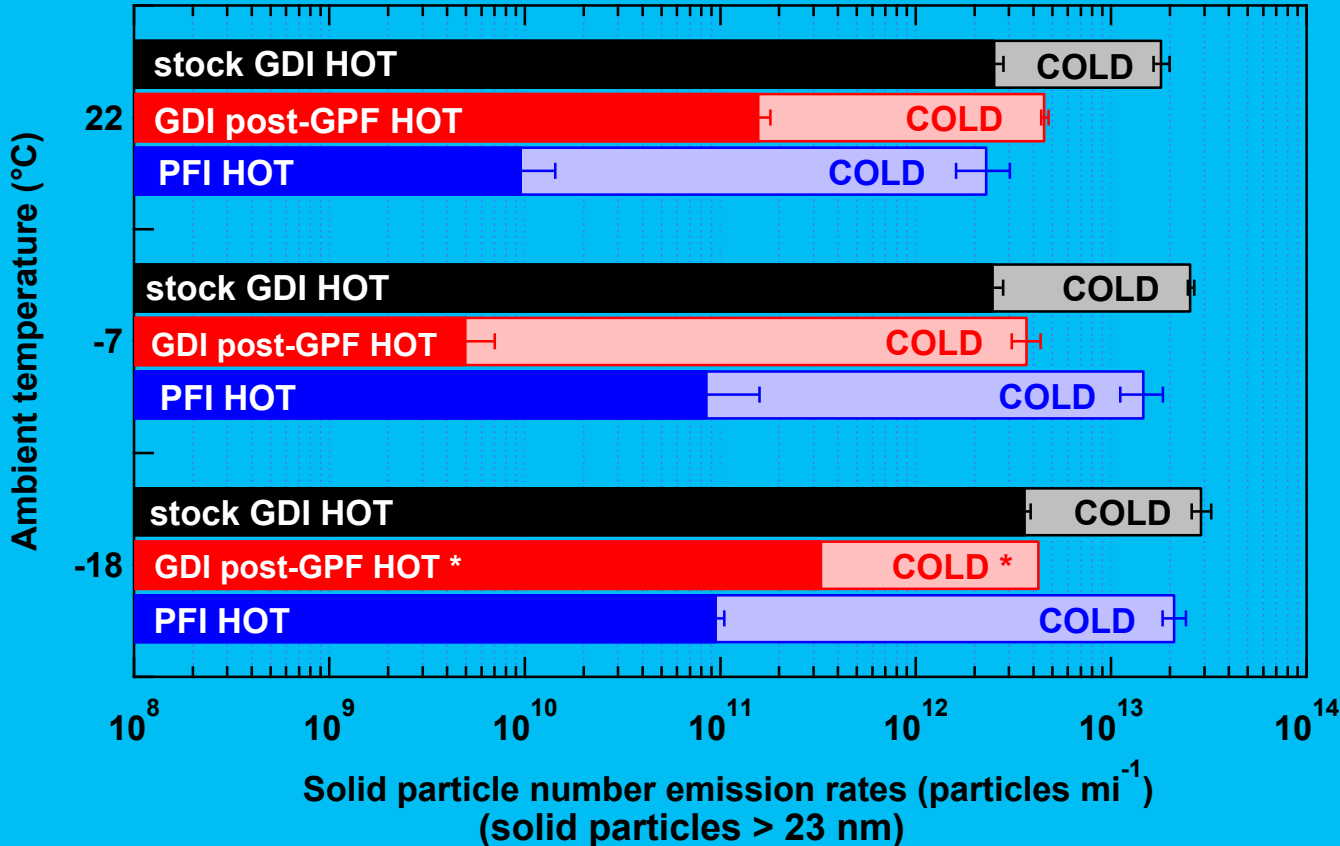
GHG Compliance Creates Emission Control Opportunities

Engines and Transmissions



GPF Effective at Reducing Particle Emissions even at Cold Ambient Temperatures

FTP Particle Emissions
in Bag 1 (Cold-start) and Bag 3 (Hot-start)



GPF Vehicle Durability Run Completed

2.0 L Audi TFSI
CC TWC (stock) + UF TWC GPF

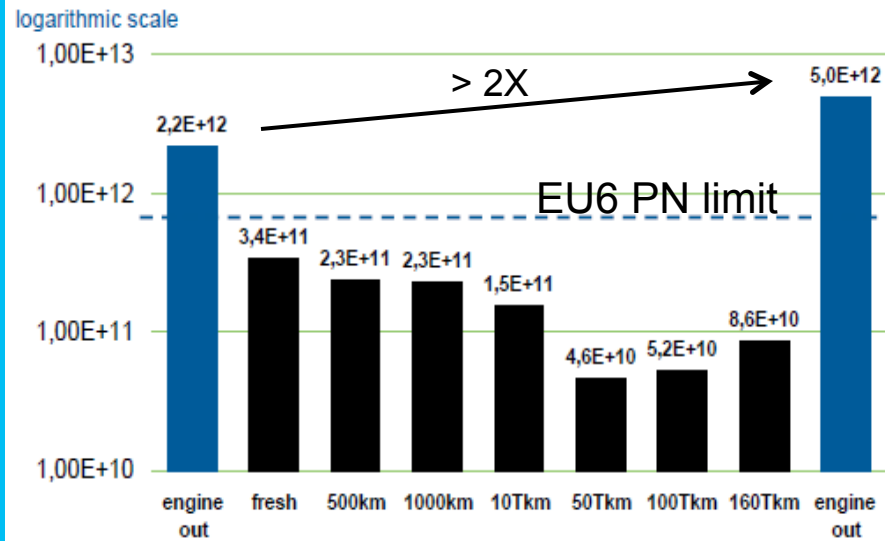
Stock Catalyst
CC: TWC 1.24L 80g/ft³



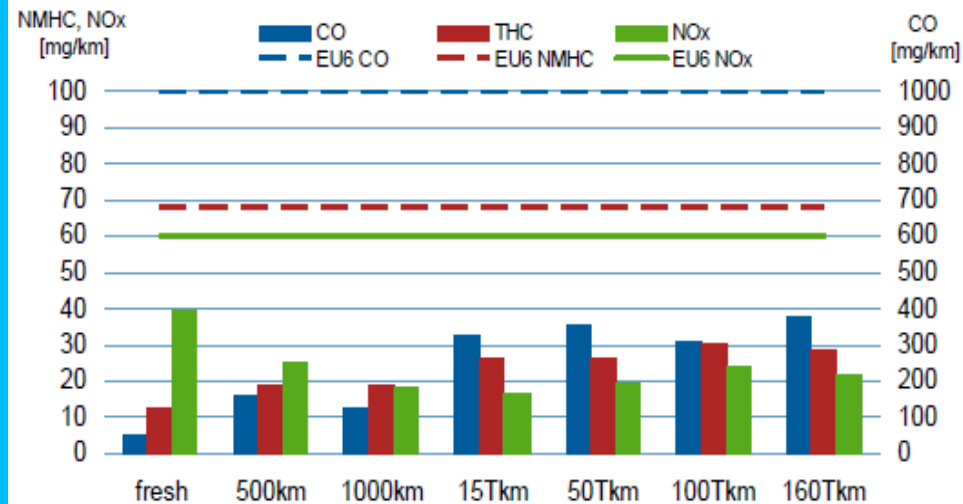
Test Converter Layout

CC TWC + UF converter
CC: TWC 1.24L 64g/ft³
UF: GPF 1.68L 10g/ft³

Averaged Particulate Number in NEDC test [# / km]



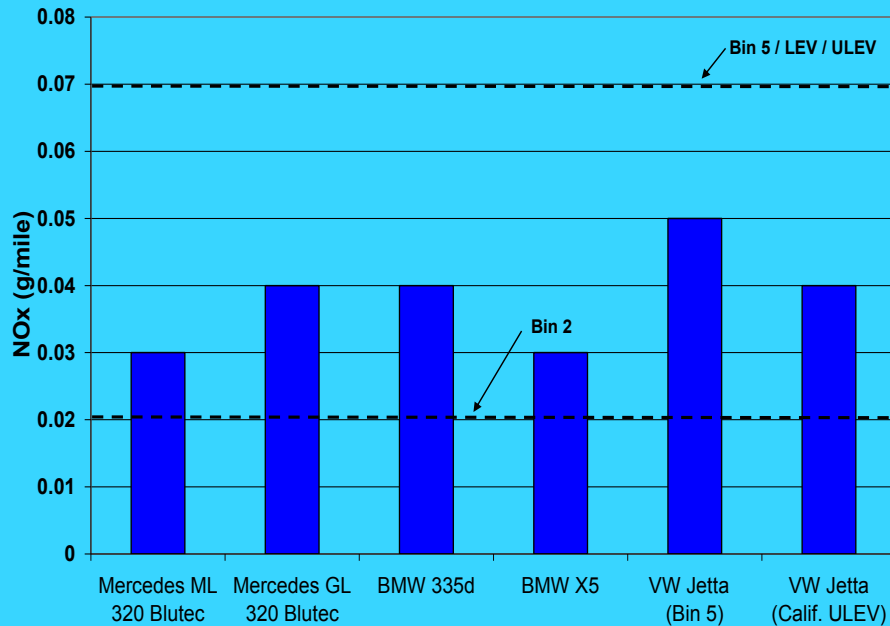
Tailpipe emissions for NEDC phases



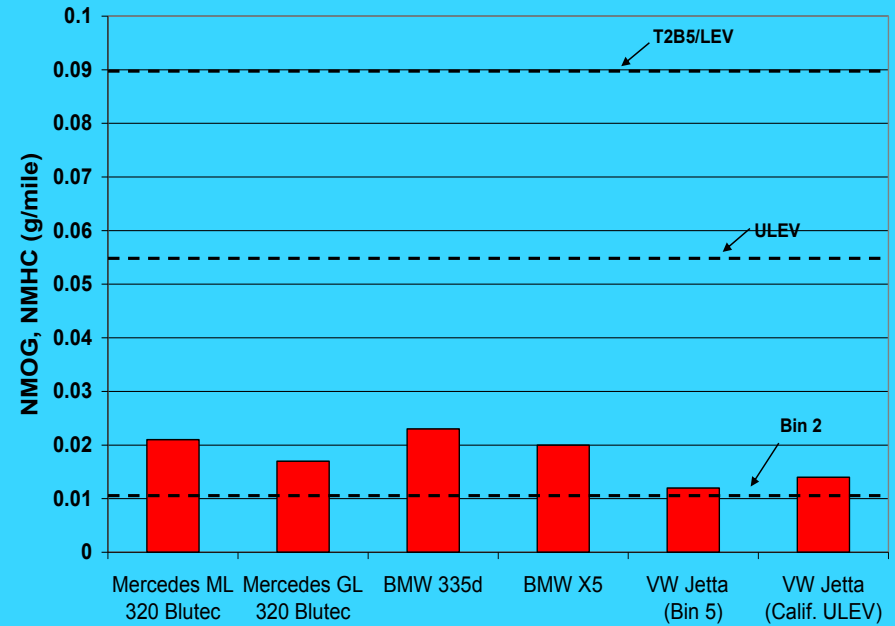
Light-duty Diesel Emission Control Technologies

First Wave LEV II/Tier 2 Light-Duty Clean Diesels FTP Emissions: 30 to 50 mg/mi NOx; 12 to 23 mg/mi NMHC

FTP-75 NOx at Full Usefull Life



FTP-75 NMOG and NMHC at Full Usefull Life



DPF+SCR

DPF+LNT

DPF+SCR

DPF+LNT

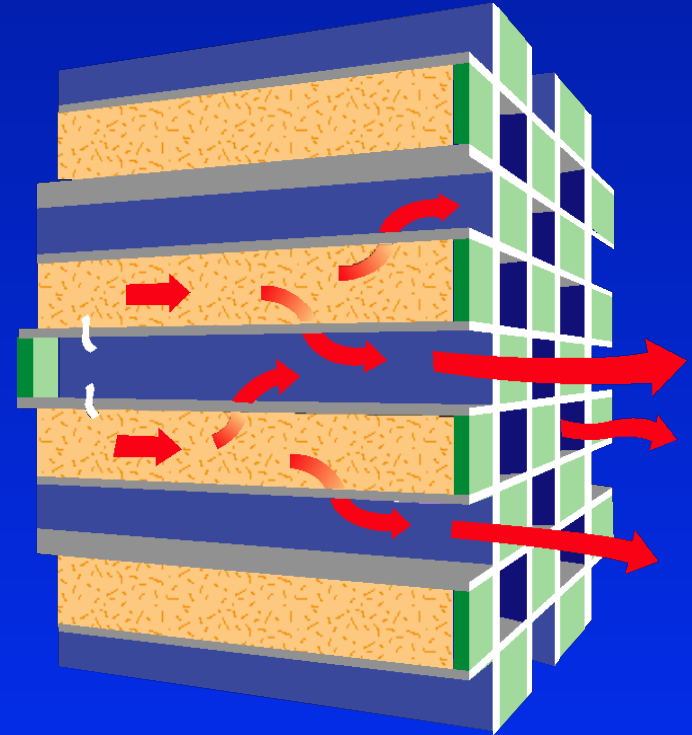
Current best in class: 50 mg/mi NMHC+NOx
(compare to 30 mg/mi NMHC+NOx for Bin 2 or SULEV)

CARB certification data



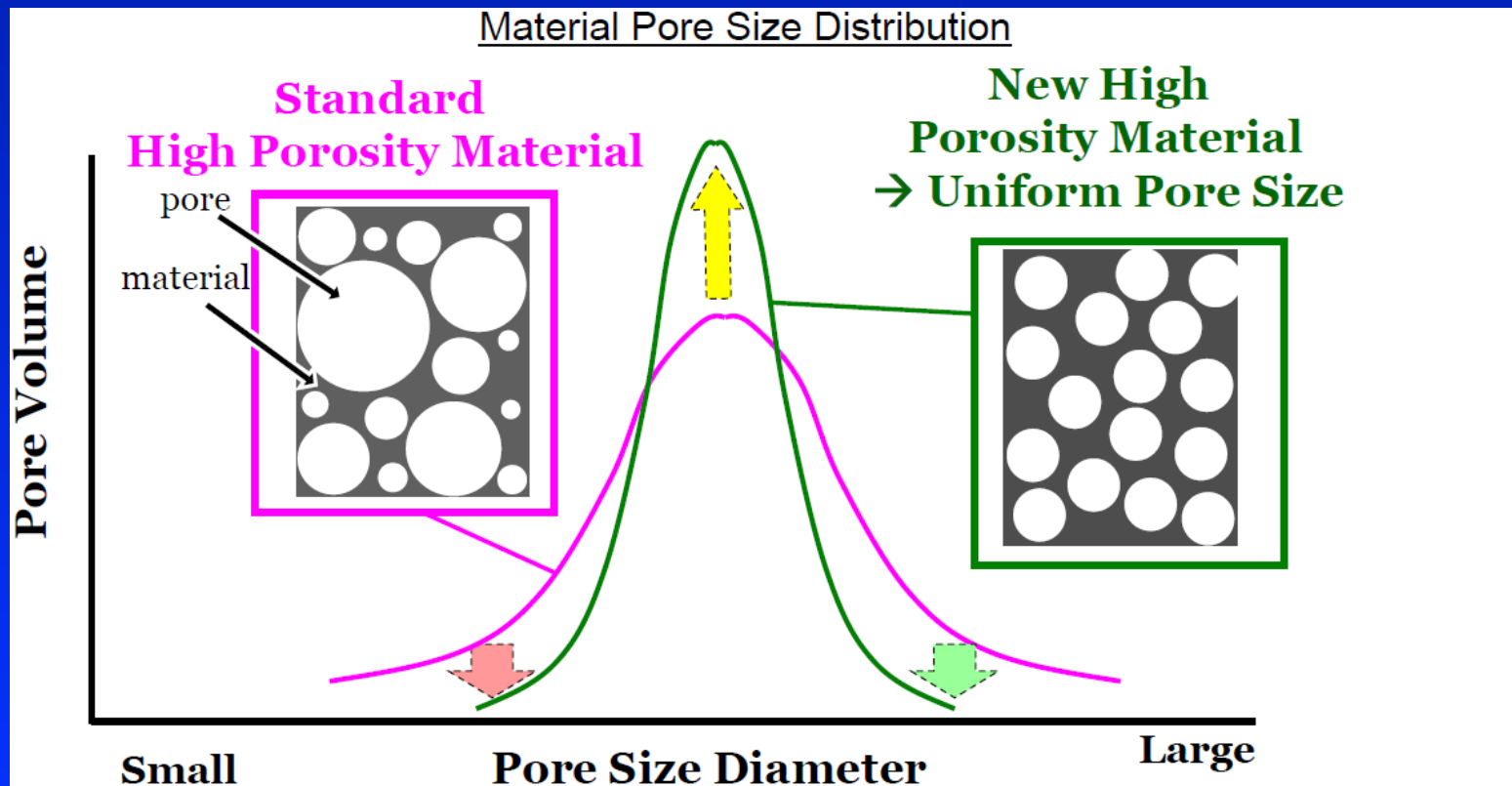
Diesel Particulate Filters (DPFs) Provide High PM/PN Removal Efficiency

- Wall flow ceramic filter element with high capture efficiency for particulates over a broad size range (cordierite or SiC filter elements)
- Captured soot needs to be burned off (regenerated) at regular intervals to manage backpressure on engine
- Commercialized on light-duty diesels in Europe in 2000, on US LDD starting in 2006; standard on US 2007+ trucks/buses, on 2013+ Euro VI trucks/buses – 10s of millions in-use worldwide
- Capture soot and inorganic-based particles associated with engine wear, lubricant consumption: regular maintenance required (filter cleaning)



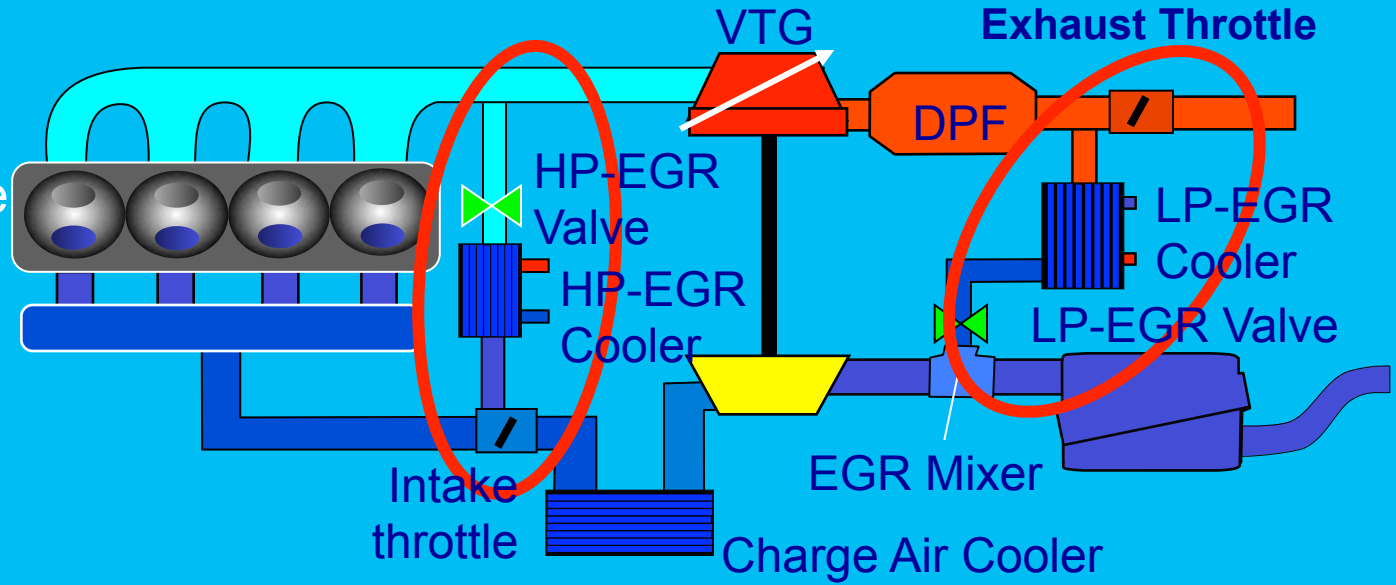
DPF Optimization Focused on Backpressure and Cold Start

- DPF designs with higher porosity, smaller, uniform sized pores
- Reduces backpressure
- Facilitates SCR catalyst coating on DPF
- Earlier ammonia injection and light-off

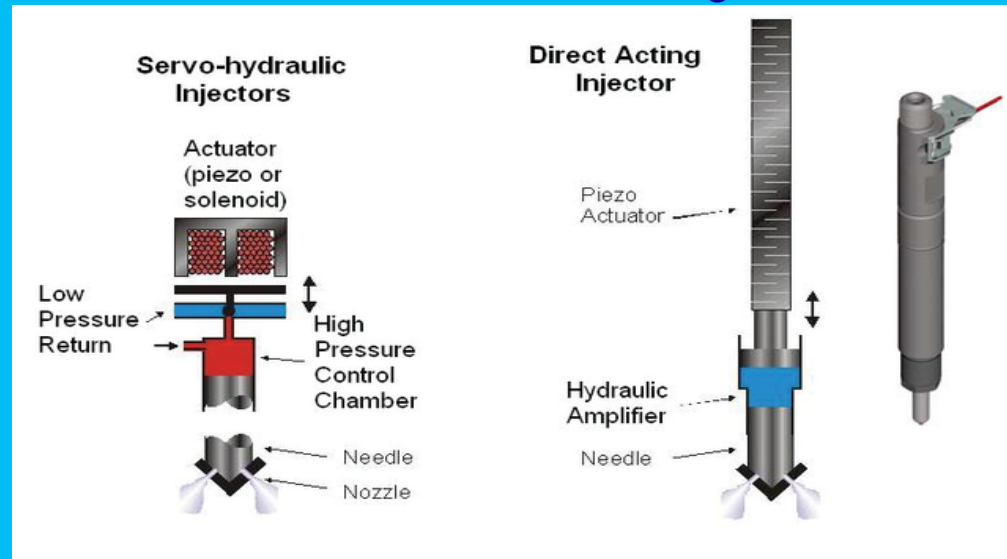


Diesel Engines Continue to Evolve Systems that Contribute to Lower Engine-out Emissions and Improved Efficiency

“Hybrid” EGR Systems Combine High Pressure & Low Pressure EGR Loops



Advanced Fuel Injection Systems Provide Enhanced Combustion Control and Lower Emissions



SCR Applications Moving from Stationary to Mobile Sources: Urea Infrastructure Expanding



**Tier 4
Off-Road
Engines**



**2010+
Heavy Duty
Vehicles**



Power Plants



Gas Turbines



**Tier 4
Locomotive
Engines**



Waste Incineration

**SCR
Products**



**Marine
Engines**



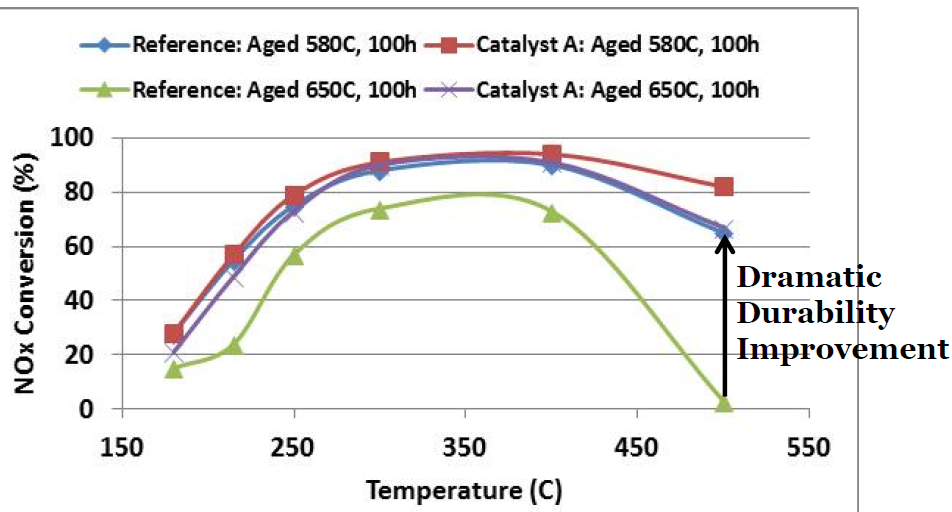
Diesel Passenger Cars



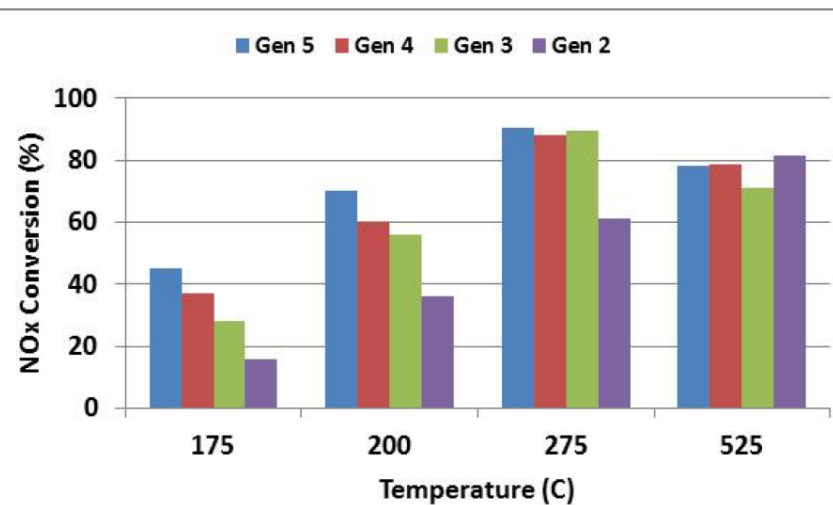
**Stationary
Engines**



SCR Catalysts Continue to Improve



Aged 650°C, 100 Hours; Tested at 100k SV

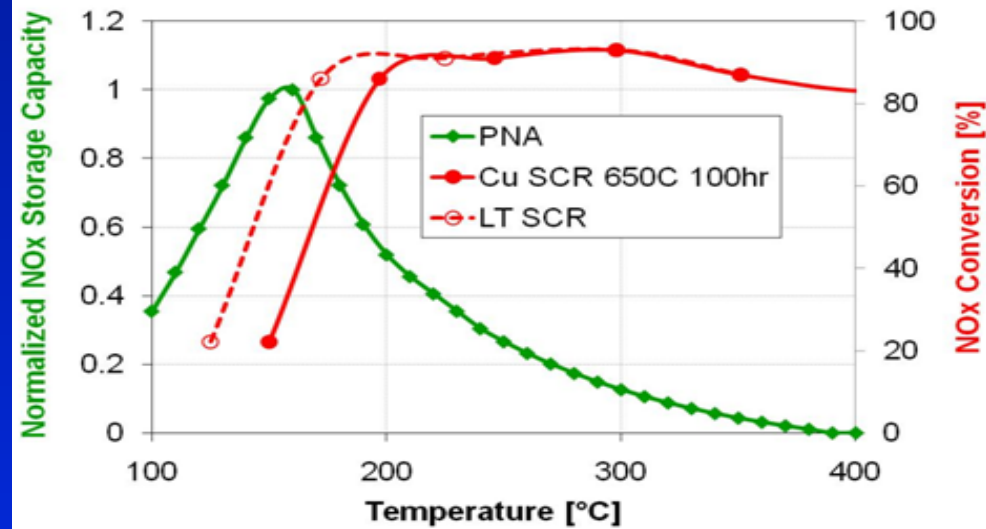
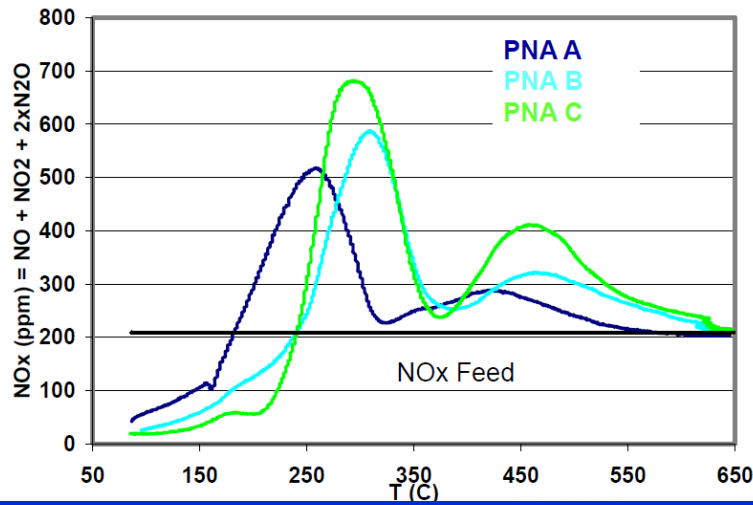


V-SCR with Excellent Durability

Cu-SCR Demonstrate Better Low Temperature Conversion

Combined NOx Adsorber/SCR for Low Temperature NOx

750°C/5%H₂O/16h aged, SV=30K, NO, CO=200ppm, C₁₀=500 ppm C₁, 10% O₂

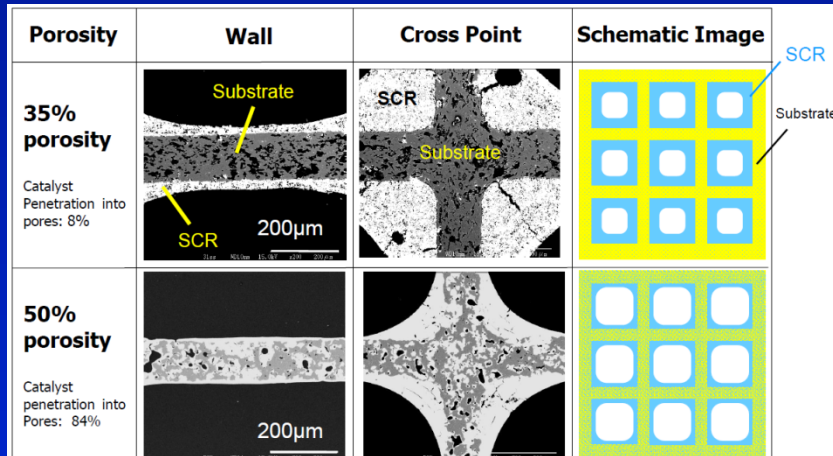


JM SAE HDD Symp. 9/12

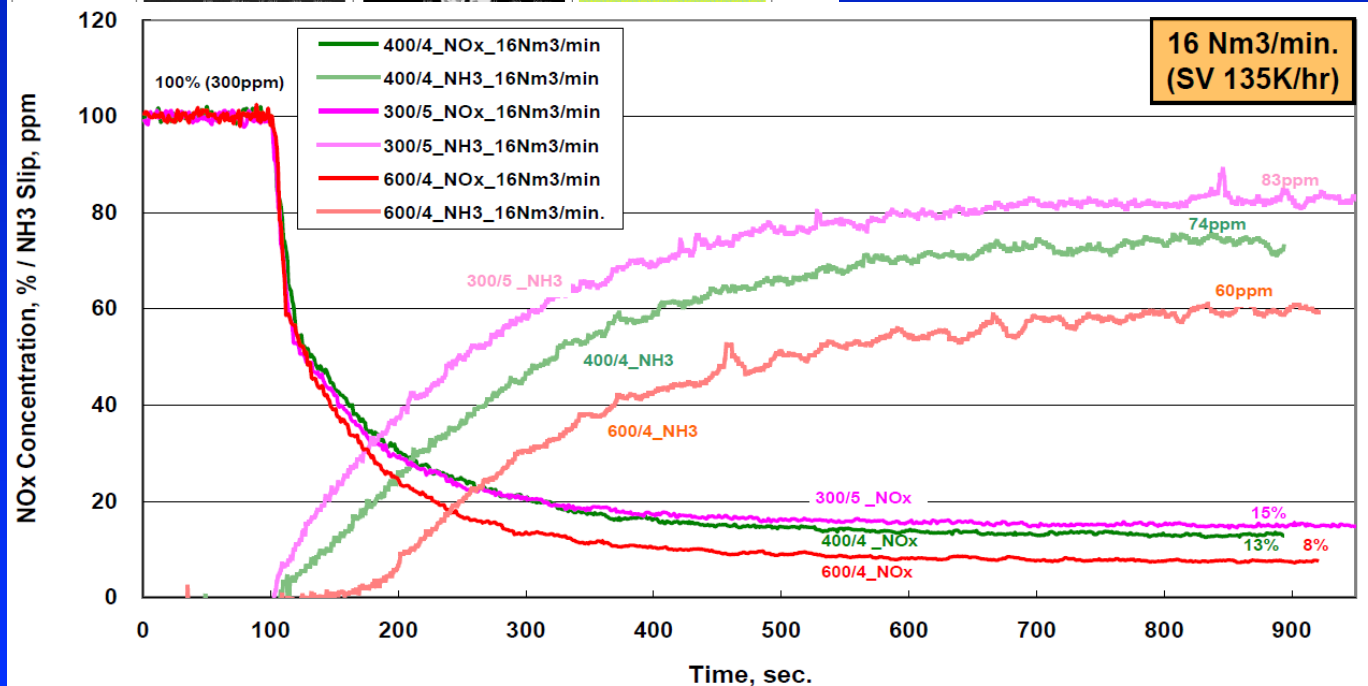
Cummins, DEER Conf. 10/11

- Passive NOx adsorber (PNA) begins to capture NOx below 150°C
- NOx release can be matched to SCR NOx conversion profile

Substrates Optimized for SCR



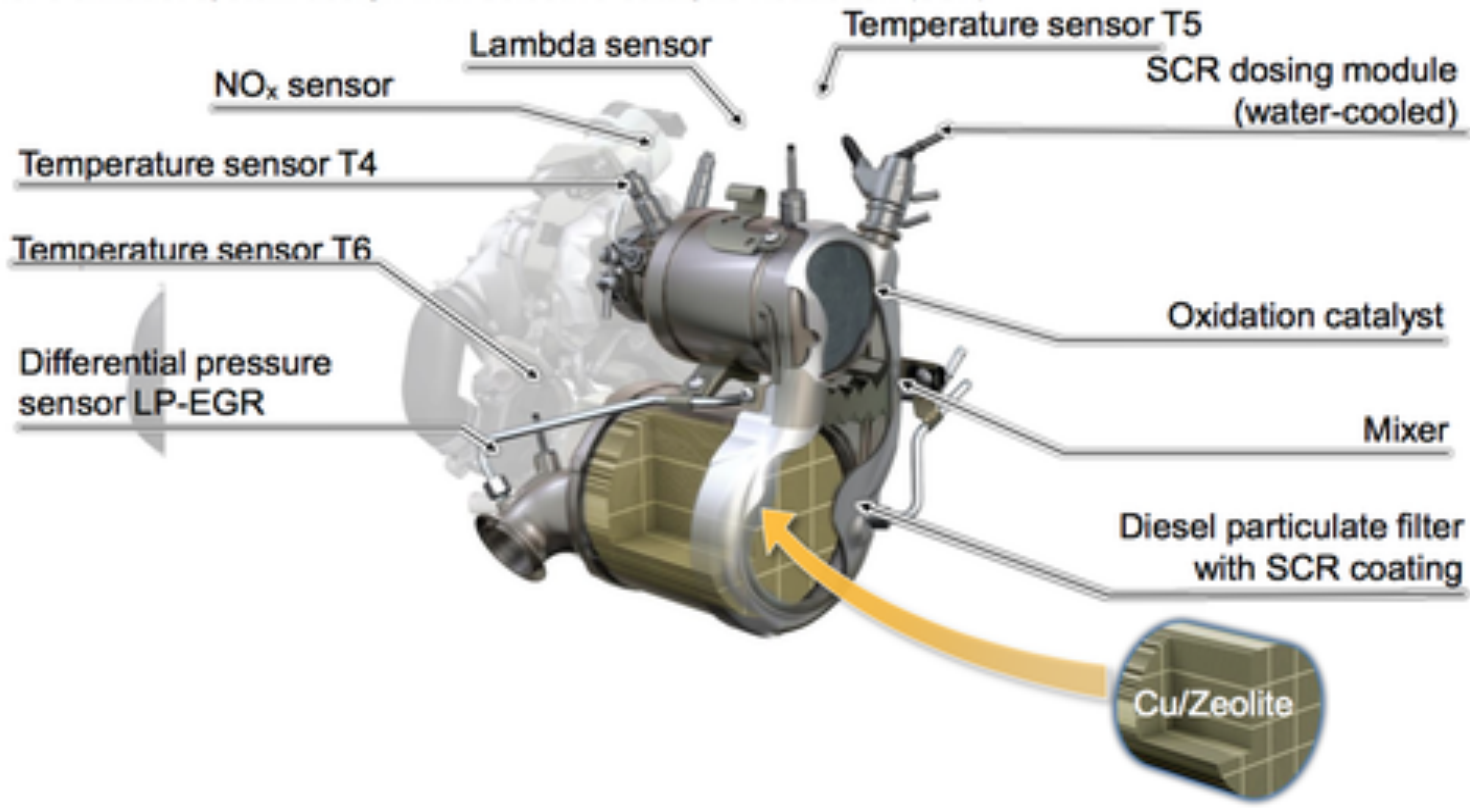
- High porosity incorporates catalyst
- High cell density, thin wall designs improve conversion
- Fast heat-up and earlier urea injection



SCR Catalysts Are Being Integrated with DPFs to Improve Cold-start NOx Performance: VW New 2.0 liter TDI

CLOSE COUPLED EXHAUST GAS AFTERTREATMENT

Tier 3 exhaust system design with Selective Catalytic Reduction (SCR)



Clean Diesel Vehicles Include Sophisticated Sensors and Diagnostics



Combined O₂/NO_x Sensor



Ammonia Sensor



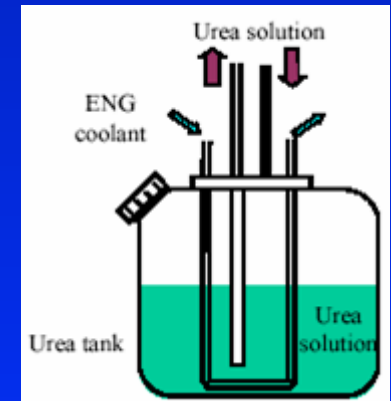
Soot Sensor



Urea Quality Sensor



Diagnostic Systems



Heated Urea Tanks

Summary

- U.S. Light-duty Emission Standards Are the World's Benchmark – Drive Emission Control Technology Innovation
- Developing World Quickly Moving to Catch-up on Clean Vehicle Technologies but Introduction of Clean Fuels Will Dictate the Pace of Change
- Future Powertrains Will Need to Compete on Both Emissions and Climate Change Performance
- Health Impacts of Ozone, PM, Climate Change Will Continue to Drive Regulatory Groups to Revisit the Need to Achieve Even More Emission Reductions from Mobile Sources

www.meca.org – Newly redesigned Your emission control technology resources on the web

The screenshot displays the MECA website homepage. At the top, there is a navigation bar with links for 'about us', 'contact us', 'sitemap', 'Intranet', and 'You are logged in'. Below this is a secondary navigation bar with 'MECA' logo and links for 'technology', 'regulation', 'diesel retrofit', 'resources', and 'newsroom'. A search bar is also present. The main content area features a large hero banner with the text 'Technology for Clean Air' over a background of a bright sun and clouds. Below the banner, there is a paragraph of text: 'The member companies of the Manufacturers of Emission Controls Association (MECA) include leading manufacturers of emission control technology for a variety of sources, including:'. To the right of this text is a 'Recently Posted' section with a 'News' tab selected and 'Other Updates' as an option. Below the text and 'Recently Posted' section is a grid of six technology categories, each with a representative image and a caption: 'Passenger Cars, SUVs, and Light-Duty Trucks', 'Heavy-Duty Trucks and Buses', 'Off-Road Diesel Equipment', 'Off-Road Spark-Ignited Equipment', and 'Alternative Fuel / Advanced Tech. Vehicles'. A 'View All Technologies' link with a right-pointing arrow is located at the bottom right of the grid. The 'Recently Posted' section lists three news items with dates: 'August 1, 2013: Retrofit Sales for Trucks and Buses in California Remain Lower Than Projected', 'July 18, 2013: MECA Releases New Report on Health Impacts of Ultrafine Particulates, Importance of Advanced Emission Control Technology', and 'July 17, 2013: MECA's Statement on the U.S. EPA's Direct Final Rule on Heavy-Duty Engine and Vehicle, and Nonroad Technical Amendments'. A fourth item is partially visible: 'July 15, 2013: MECA's Written Statement on the OTC's Model Rule for the Sale of Aftermarket Catalytic'.

- Emission control technology white papers and fact sheets
- Public testimony
- Regulatory information

- Retrofit technology descriptions
- Contacts for retrofit suppliers
- Case study reports



Back-up Slides

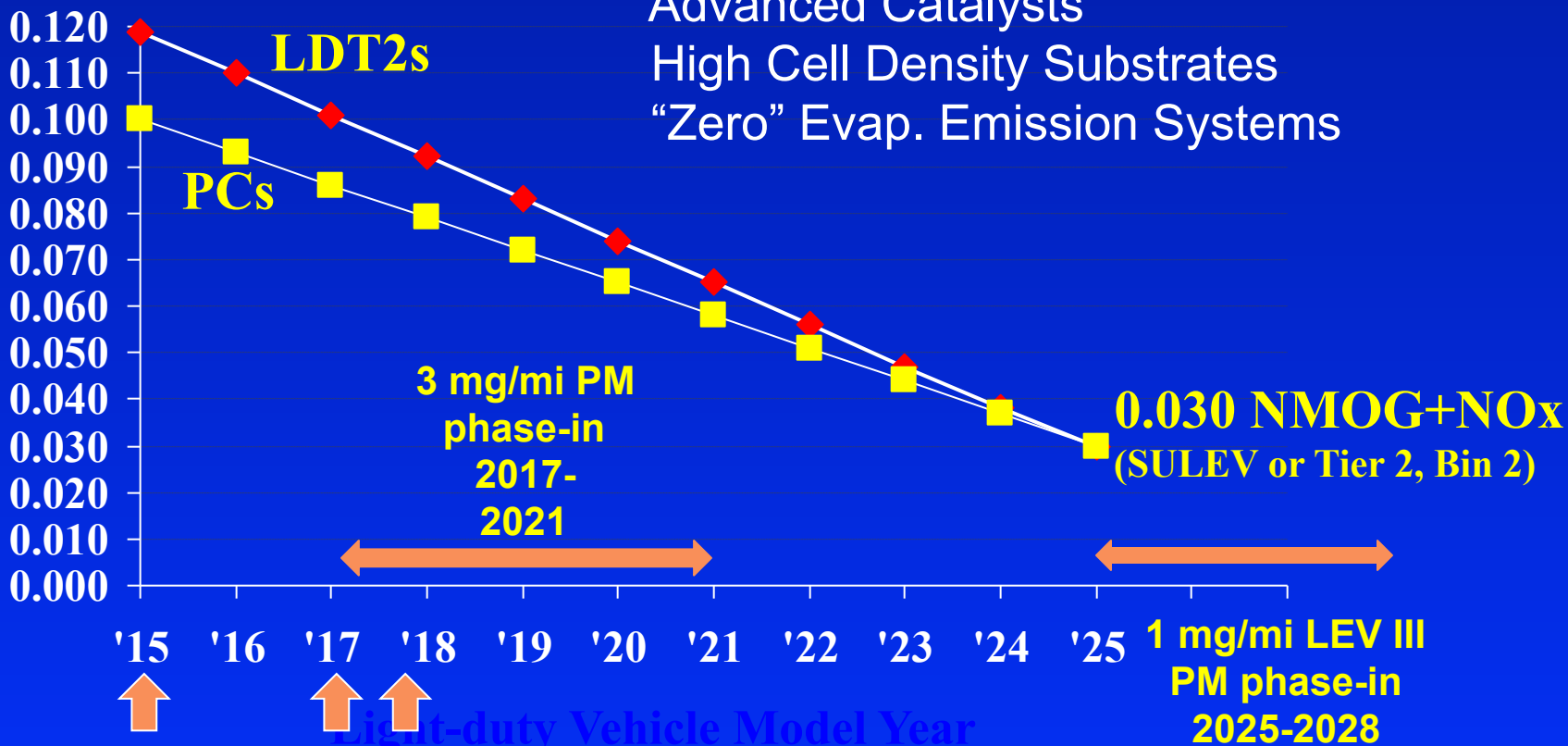
LEV III/Tier 3 Resets the Emissions Performance Bar for Light-duty Vehicles – Drives Innovation

FTP NMOG+NO_x

LEV III Emissions, g/mi

>2 Million PZEVs Already on the Streets:

Advanced Catalysts
High Cell Density Substrates
“Zero” Evap. Emission Systems



PM review

Tier 3 Start

Euro 6

GDI PN limit ($6 \times 10^{11}/\text{km}$)

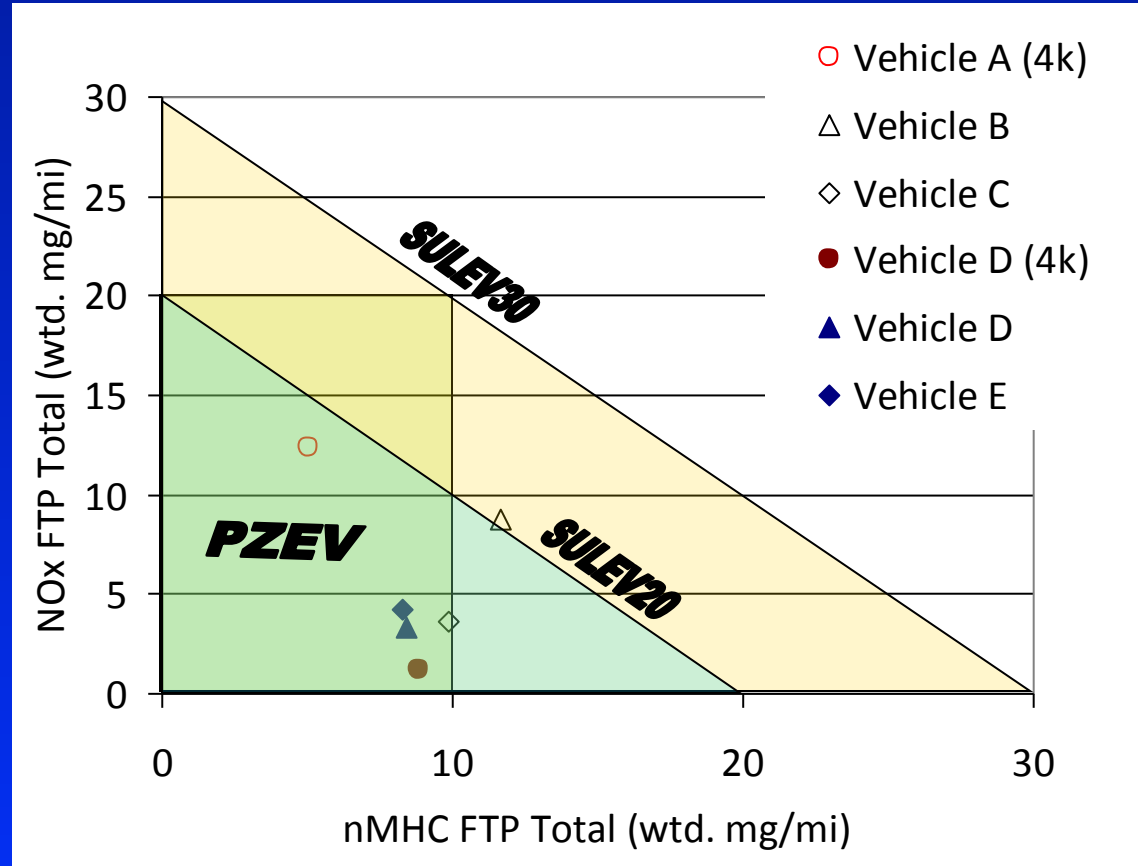
Note: California has a gasoline sulfur cap of 20 ppm;

Tier 3 includes 10 ppm gasoline sulfur average



Combined NMOG+NOx Standard Provides Additional Flexibility

- PZEV Vehicle Evaluations
 - 4/5 vehicles struggle with the 10 mg NMOG standard
 - Vehicle A(4K) is most comfortable
- SULEV20
 - 3 of the 5 vehicles get relief from the 10 mg NMOG standard
- SULEV30
 - No problem with current 4 cylinder PZEV vehicles
 - Opportunities to thrift catalysts

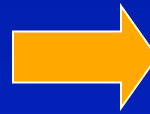


Ref. : SAE 2012-01-1245 1245



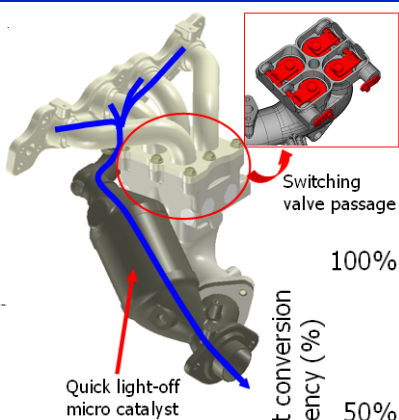
1/10 SULEV Achieved on Gasoline Vehicle with Advanced Engine and Emission Controls

Outline of the Measures	
(1) Reduction of Engine-out Emissions	<ul style="list-style-type: none"> Keep lean A/F at engine startup Promote in-cylinder oxidation
(2) High Exhaust Gas Temperature	<ul style="list-style-type: none"> Retarded ignition combustion at engine startup
(3) Quick Light-off Close-coupled Catalyst	<ul style="list-style-type: none"> Minimize the heat loss of exhaust gas Suppression of thermal degradation
(4) High Conversion Efficiency Underfloor Catalyst	<ul style="list-style-type: none"> Control the temperature of underfloor catalysts

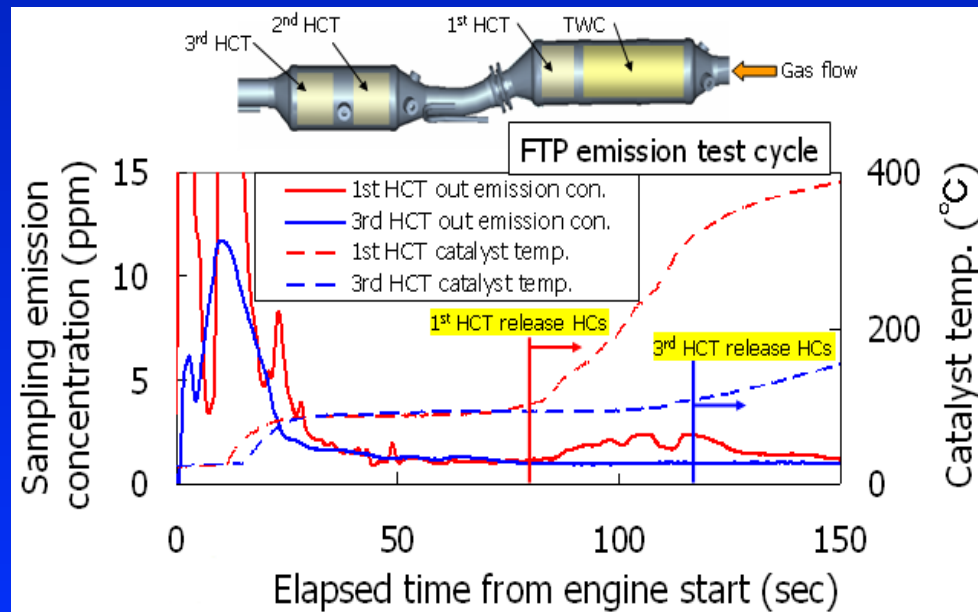
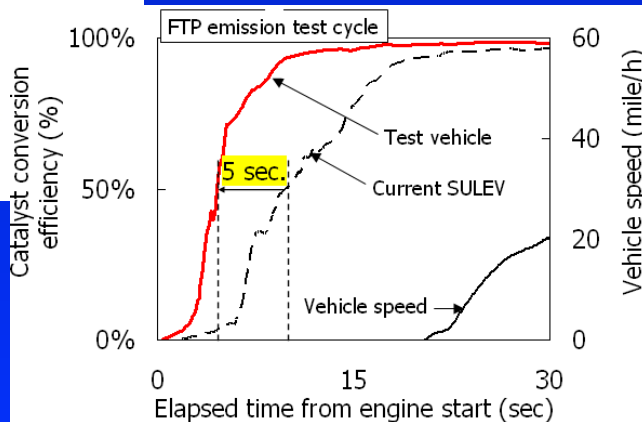


(With aged catalysts)

	NMOG (g / mile)	CO (g / mile)	NOx (g / mile)
SULEV standard	0.010	1.0	0.02
Attained value	0.00038	0.00727	0.00152

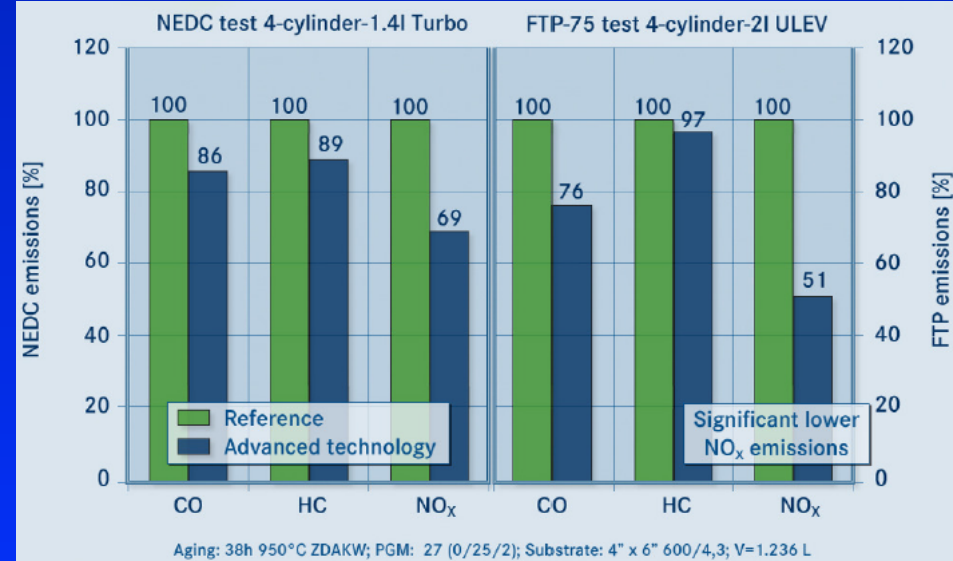
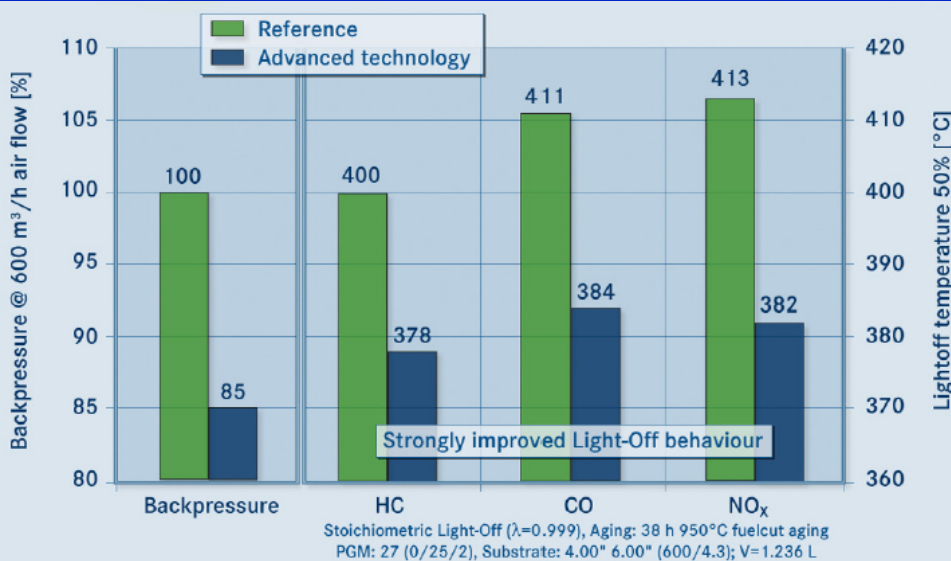


Exhaust manifold bypass quick catalyst lights-off 5 sec sooner



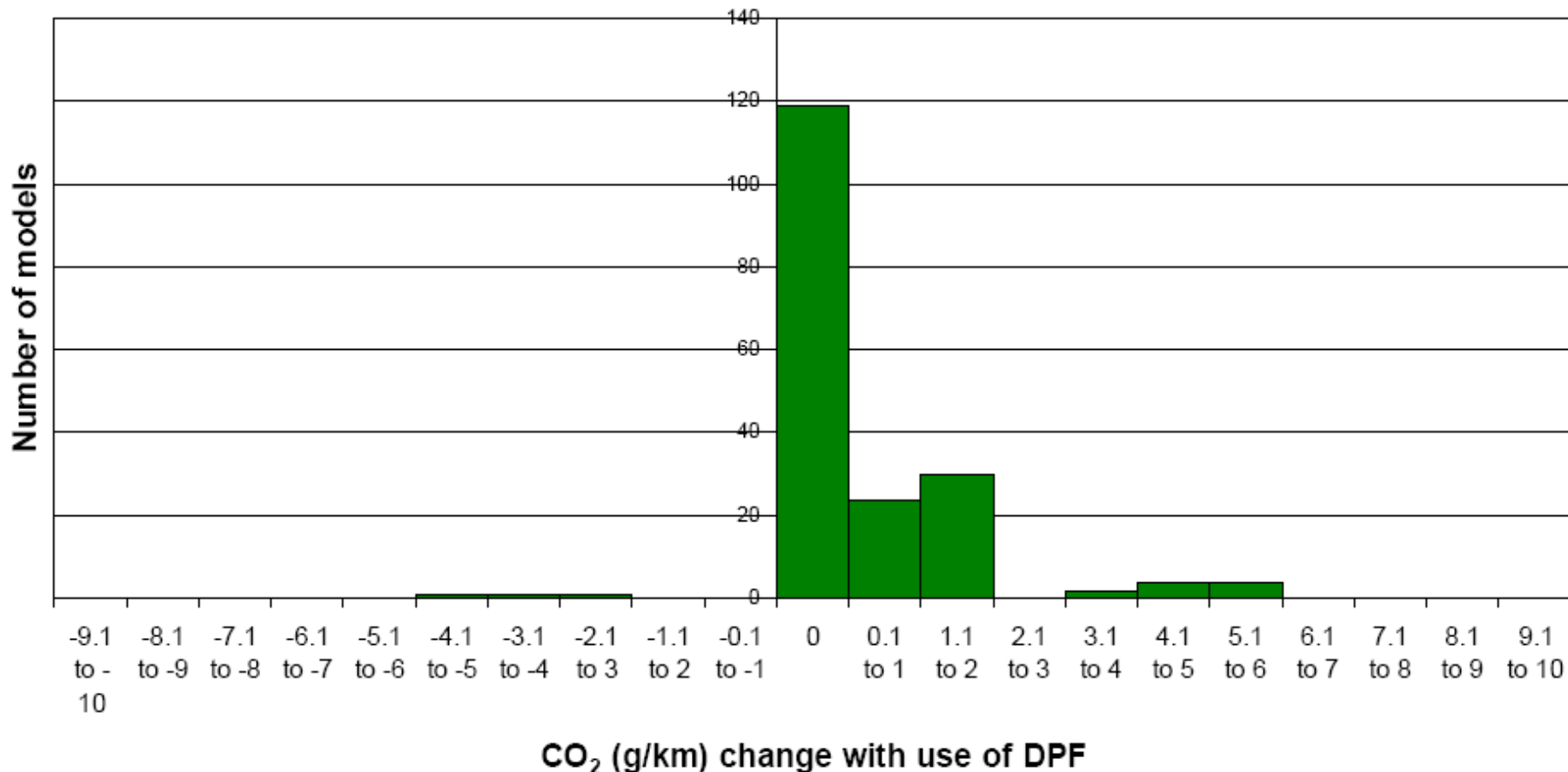
HEV and PHEV Vehicles Require Unique Catalyst Systems

- Emission peaks during engine restart
- Cool-down of exhaust system during pure electric drive
- Battery SOC (45-60%) impacts engine operation and temperature
- Catalysts must demonstrate rapid, low temperature light-off and low back-pressure.



DPFs Generally Have Small Impact on Fuel Consumption (0.6% ave. increase in CO₂ for 184 recent Euro models available with or without DPF)

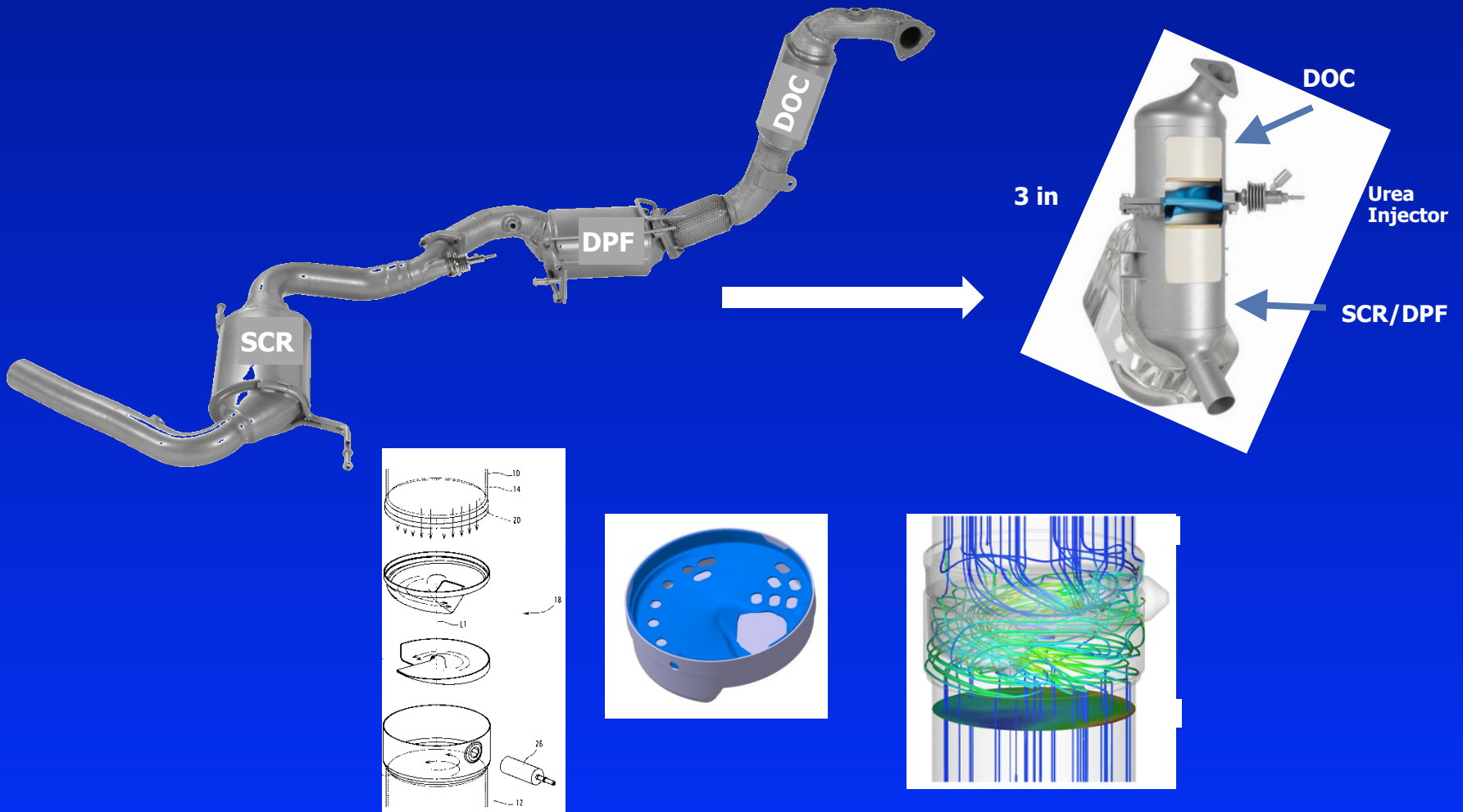
Comparison of vehicles with and without DPF



Reference: AECC analysis of 2007 model European vehicles



Advanced Diesel Systems Packaging Reduce Cold-Start Emissions



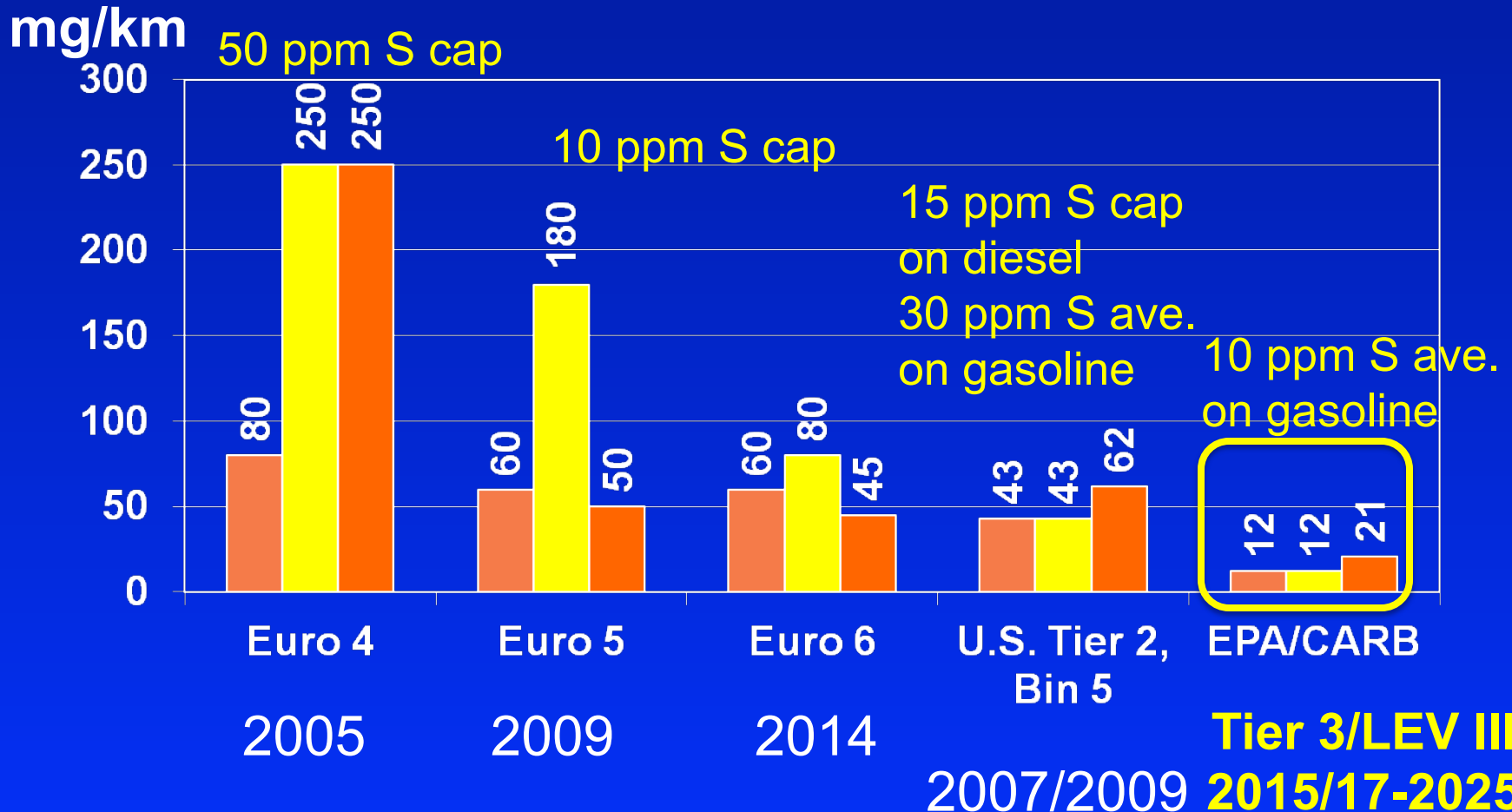
SAE Paper No. 2011-01-1318



U.S. vs. Euro Light-Duty Vehicle Emission Standards

Note: U.S. Tier 2, Bin 5 is equivalent to CARB LEV II - LEV

■ Gasoline NOx ■ Diesel NOx ■ Diesel PM X 10



Euro 5+ (2011) and 6 include $6 \times 10^{11}/\text{km}$ diesel particle number limit;
Euro 6c includes PN limit for GDI

