# U.S. Emission Controls Technical Roadmap for Heavy-duty Diesel Engines

*China MEP/US EPA Clean Diesel Workshop*

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Manufacturers of Emission Controls Association

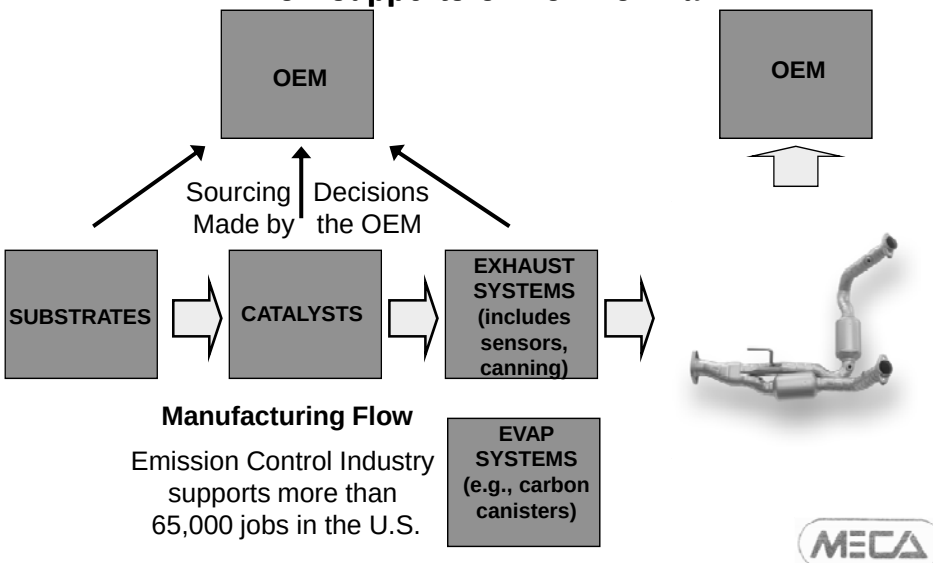
www.meca.org

## U.S. Heavy-Duty Vehicle Emission Control Experience

- MECA Introduction
- Heavy-duty Highway Diesels: DPF + SCR for U.S. 2010/EU Euro VI Compliance
- Off-road Diesels: More Diverse Clean Diesel Technology Options
- Diesel Retrofits for Older Trucks & Buses

## Emission Control Industry Has Long Standing Relationships with CARB, EPA, Vehicle and Engine Manufacturers

### MECA supports CVEC in China



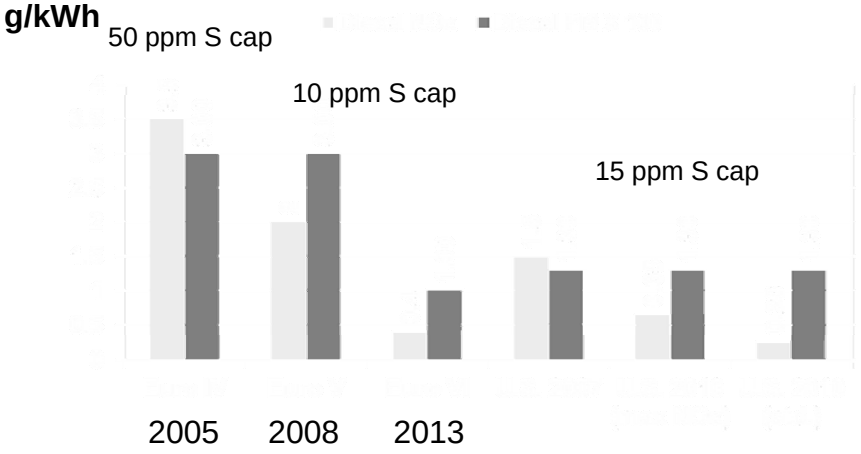

**Manufacturing Flow**

Emission Control Industry supports more than 65,000 jobs in the U.S.

## Ultra-low Sulfur Fuels Enable High Efficiency Exhaust Control Technologies

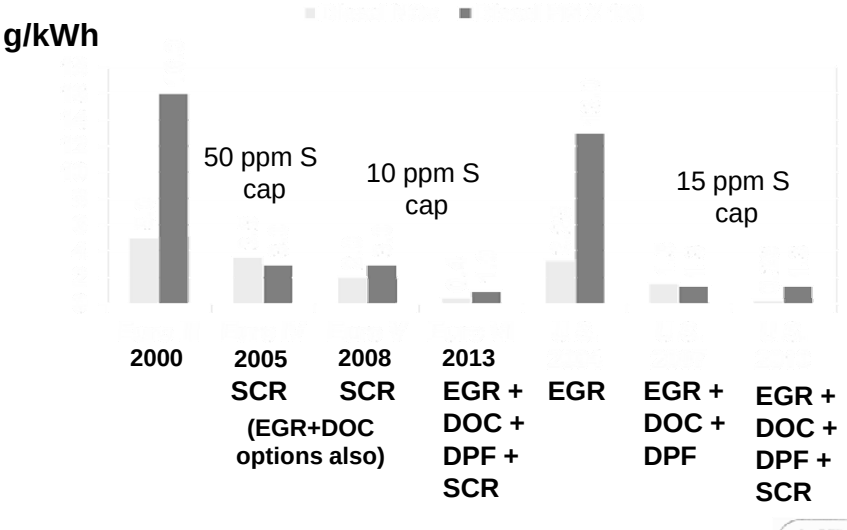
- United States (U.S. EPA)
  - **Tier 1** gasoline: 350 ppm S average, 1000 ppm S cap
  - **Tier 1** diesel: 500 ppm S cap for highway fuel
  - **Tier 2** gasoline: 30 ppm S average, 80 ppm S refinery cap in *2006*
  - ***Tier 2 diesel: 15 ppm S cap for highway fuel in Oct. 2006; for off-road diesel in mid-2010; & for marine/locomotive diesel in mid-2012***
  - **Tier 3** gasoline: 10 ppm S average starting in *2017*
- California (CARB)
  - Pre-1996: 300 ppm S cap for gasoline
  - Phase II reformulated gasoline: 30 ppm average, 80 ppm S cap in 1996
  - Phase III reformulated gasoline: 15 ppm average starting in 2004; 60, 30, & **20 ppm** S caps starting in 2004, 2006, **& 2012**
  - ***Mid-2006: 15 ppm S cap on highway and off-road diesel***
  - ***2007 15 ppm S cap on marine/locomotive diesel***

## U.S. vs. Euro Heavy-Duty Engine Transient Cycle Emission Standards



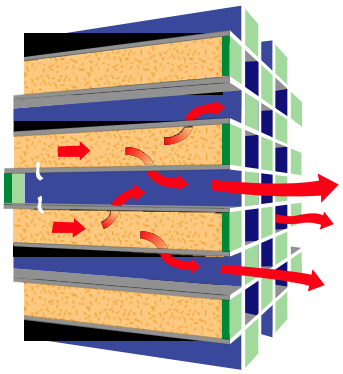

Euro VI uses WHTC (0.46 g/kWh NOx limit) & includes 6 X $10^{11}$/kWh diesel particle number limit

## U.S. vs. Europe: Heavy-Duty Primary Exhaust Emission Control Technologies



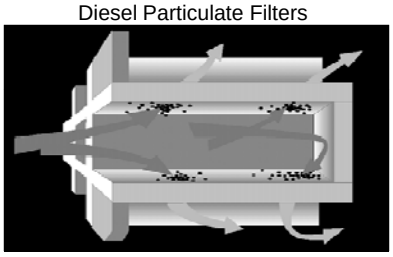
## Diesel Particulate Filters (DPFs)

- 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)

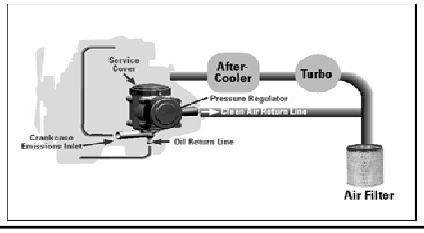


## DOCs and DPFs Form the Technology Base for Reducing PM Emissions from US 2007 Diesel Engines

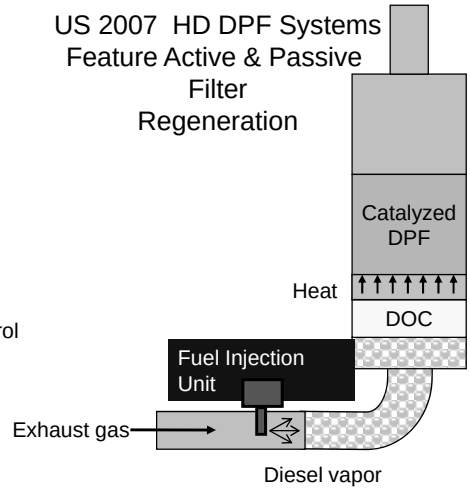
Diesel Particulate Filters



Crankcase Filters Provide Additional PM Control




US 2007 HD DPF Systems Feature Active & Passive Filter Regeneration

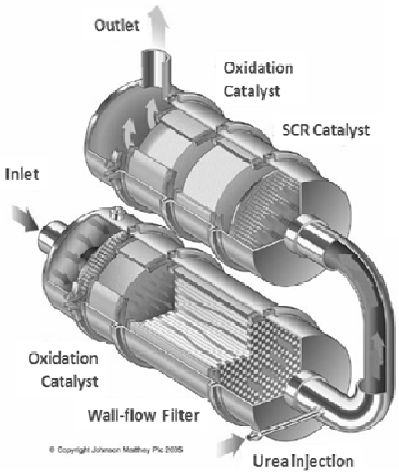


# Filter Cleaning Equipment & Services Needed for DPF Ash Cleaning

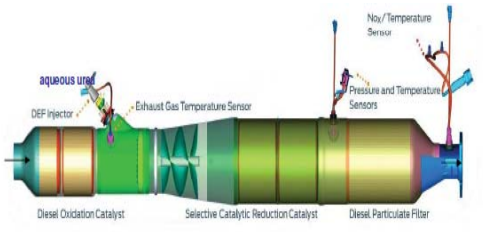
- Ash derived primarily from lubricant additives, results in increasing engine backpressure, low ash oils introduced to minimize filter ash build-up
- Engine maintenance important for filter durability (injectors, EGR, turbo)
- Typical filter maintenance occurs after about 200K miles for long haul trucks (can be lower in some vocational truck applications)

# U.S. EPA 2010 Compliant Heavy-duty Systems

- Heavy-duty trucks: DOC+DPF+SCR configurations

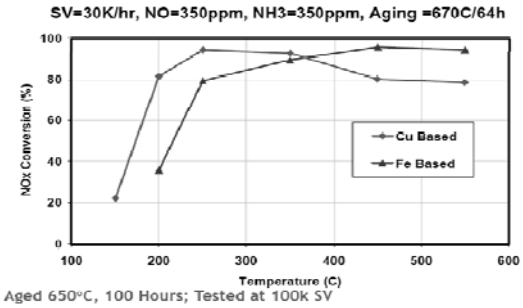


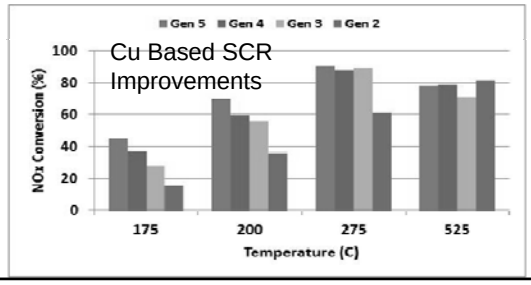

- Medium-duty trucks: DOC+SCR+DPF designs for cold-start NOx control

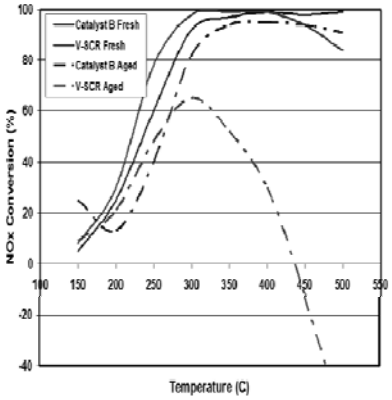



- 32.5% urea/water meets defined standards (API run quality program)
- Post-SCR oxidation function for minimal ammonia slip
- Other features include reductant mixers, thermocouples, NOx sensors
- Stoichiometric natural gas engines use proven precious metal, three-way catalysts

## Zeolite SCR Catalysts Developed for Mobile Source Applications with Broad Temperature Windows and Good Thermal Stability

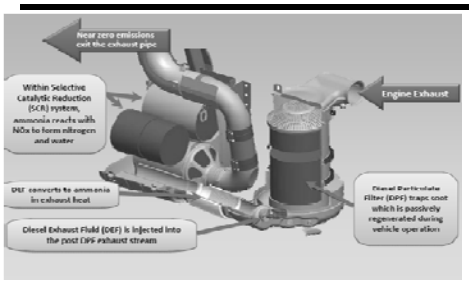


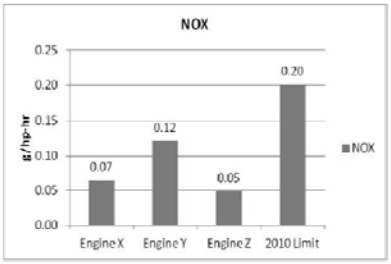



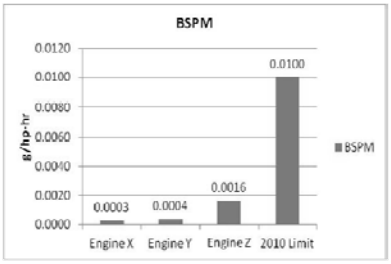




**SCR catalysts aged 50 hours at 700C**

## US 2010 Technologies Deliver Surplus Health Benefits

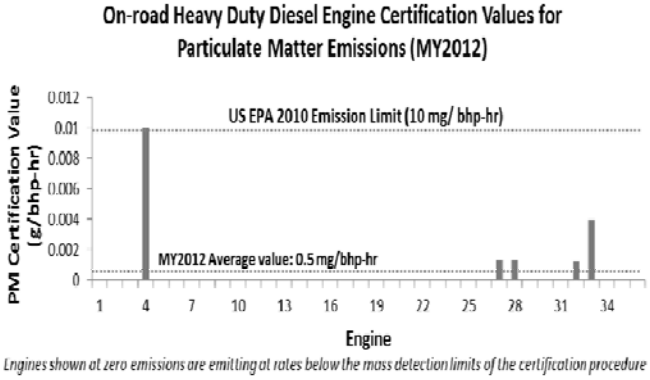


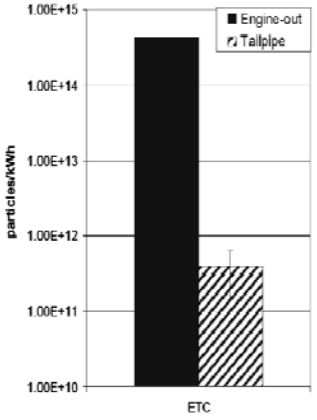

- 2010 on-highway emission controls employing Cu and Fe based SCR catalysts have evolved into 2nd generation technologies.
- U.S. ACES study shows that 2010 commercial emission control technology significantly exceeds the standards, esp. on PM.
- > 3 million DPF equipped trucks & buses operating on U.S. highways

## DPF-equipped HDDs Have Certification PM Levels Well Below 10 mg/bhp-hr US 2010 EPA Standard

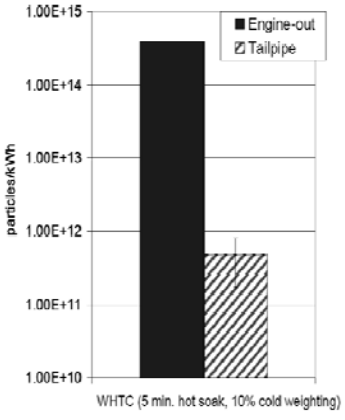



## DPFs Have High PN Filtration Efficiency: Heavy-duty Diesel Engine Example

- ETC tailpipe emissions ~ 4 x $10^{11}$/kWh
- DPF Efficiency > 99.9%




- WHTC tailpipe emissions < 5 x $10^{11}$/kWh
- DPF Efficiency > 99.8%




DPFs Capture Ultrafine Diesel Particulates

## U.S. 2007 HD Emission Performance Provides Significant Reductions in PM, CO, Air Toxic HCs

| | 2007 EPA Standard (g/hp-hr) | Average ACES Engine Emissions (g/hp-hr) | ACES Emissions % Reduction Relative to the 2007 Certification Standard |
|---|---|---|---|
| CO | 15.5 | 0.33 | 98 |
| NMHC | 0.14 | 0.0064 | 95 |
| PM | 0.01 | 0.0011 | 89 |
| $NO_X$ | 1.2 [a] | 1.075 | 10 |

[a] Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr

| Compounds | % Lower Than 2004 Engine Technology | |
|---|---|---|
| | 16-Hour Cycle | CARBx-ICT |
| Single Ring Aromatics | 82% | 69% |
| PAH | 79% | 26% |
| Nitro PAH | 81% | 49% |
| Alkanes | 85% | 84% |
| Polar | 81% | 12% |
| Hopanes/Steranes | 99% | 99% |
| Carbonyls | 98% | 78% |
| Inorganic Ions | 38% | 100% |
| Metals and Elements | 98% | 90% |
| Organic Carbon | 98% | 78% |
| Elemental Carbon | 99% | 100% |
| Dioxins/Furans[a] | 99% | N/A |

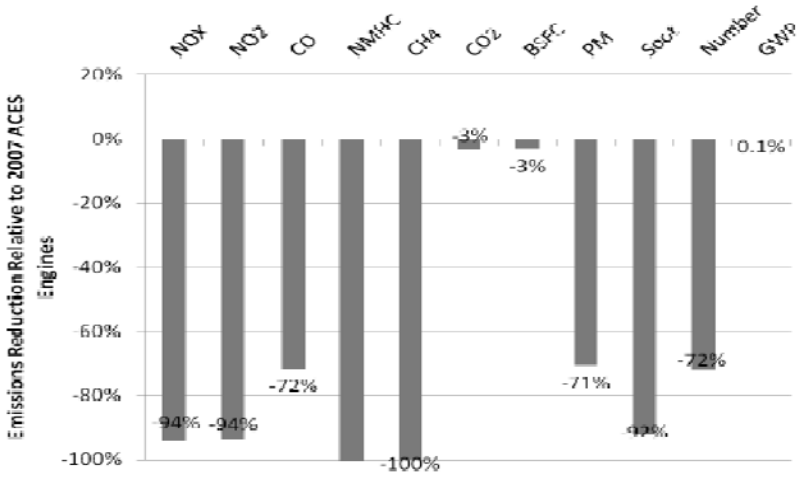
[a] Relative to 2010 Engine Technology

Source: CRC Phase 1 ACES Report;

2010+ Engines Delivering Even Lower

Toxic HC Emissions than 2007 Engines

## US2010 engines (EGR+DOC+DPF+SC): greatly reduced PN and criteria pollutants vs. US 2007 (EGR+DOC+DPF).

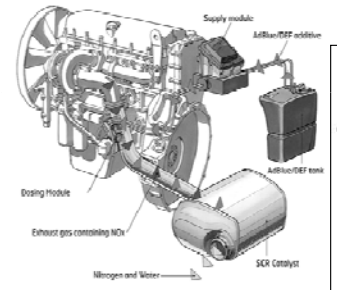



US2010: No DPF regeneration needed, reducing emissions; SCR reduced NOx and $NO_2$

CRC 4/13

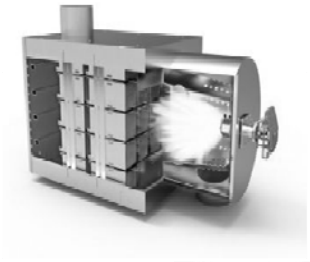
## Clean Diesel Technology Expanding into U.S. Off-road Applications with & without DPFs

Tier 4 Interim Tractors with SCR




Tier 4 Interim Machines with DPFs

Locomotives with DPFs and/or SCR systems



## Tier 4 U.S./Stage IV EU Off-road Diesels Offering a Wider Range of Emission Controls

EPA Tier 4 Interim / EU Stage IIIB  EPA Tier 4 Final / EU Stage IV

| kW | EPA | HP | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-18* | | 0-24 | (7.5) / 6.6 / 0.40 | | | | | | | | | |
| 19-36 | | 25-48 | (7.5) / 5.5 / 0.30 | | | | | (4.7) / 5.0 / 0.03 | | | | |
| 37-55 | | 49-74 | (4.7) / 5.0 / 0.30 Option 1) | | | | | | | | | |
| 56-129* | | 75-173 | | | | | 3.4 / 0.19 / 5.0 / 0.02 | | | 0.40 / 0.19 / 5.0 / 0.02 | | |
| 130-560* | | 174-751 | | | | 2.0 / 0.19 / 3.5 / 0.02 | | | | 0.40 / 0.19 / 3.5 / 0.02 | | |
| >560 | | >751 | | | | 3.5 / 0.40 / 3.5 / 0.10 | | | | 3.5/0.19 /3.5 /0.04 | | |

| kW | EU | HP | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18-36 | | 24-48 | Stage IIIA (7.5) / 5.5 / 0.6 | | | | | | | | | |
| 37-55 | | 49-74 | | | | | | (4.7) / 5.0 / 0.025 | | | | |
| 56-129* | | 75-173 | | | | | 3.3 / 0.19 / 5.0 / 0.025 | | | 0.4 / 0.19 / 5.0 / 0.025 | | |
| 130-560 | | 174-751 | | | | 2.0 / 0.19 / 3.5 / 0.025 | | | | 0.4 / 0.19 / 3.5 / 0.025 | | |

(NOx + HC) / CO / PM  (Oxides of Nitrogen + Hydrocarbons) / Carbon Monoxide / Particulate Matter (g/kW-hr)
NOx / HC / CO / PM  Oxides of Nitrogen / Hydrocarbons / Carbon Monoxide / Particulate Matter (g/kW-hr)
* Combines regulatory power bands with same emission levels

50% higher off-road limits:

<u>PM (g/kWh)</u>
0.020 off-road
vs.
0.013 on-road

<u>NOx (g/kWh)</u>
0.40 off-road
vs.
0.26 on-road

Tier 4 Final includes a variety of emission control solutions including: <u>EGR+DOC, EGR+DPF, DPF+SCR, DOC+SCR</u>

EU considering a Stage V standard that could be similar to Euro VI, including a PN limit; EU Stage IIIB/IV and U.S. Tier 4 Standards utilize the Nonroad Transient Cycle (NRTC)

## SCR Applications Moving from Stationary to Mobile Sources: Urea Infrastructure Needed

Tier 4 Off-Road Engines

2010 Heavy Duty Vehicles

Power Plants

Gas Turbines

Tier 4 Locomotive Engines

SCR Products

Waste Incineration

Marine Engines

Diesel Passenger Cars

Stationary Engines

## Clean Diesel Vehicles Include Sophisticated Sensors and Diagnostics

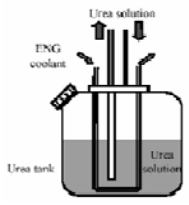
Combined $O_2$/NOx Sensor

Ammonia Sensor

Soot Sensor

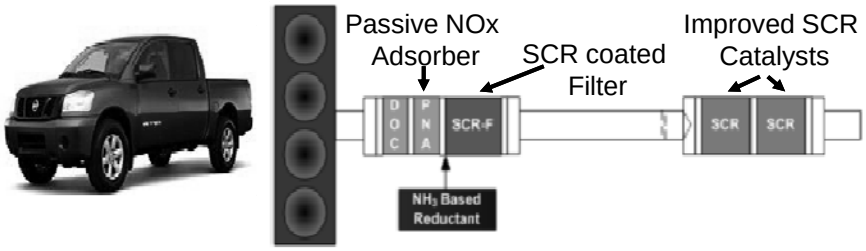
Urea Quality Sensor

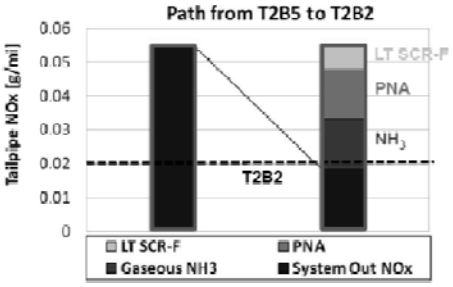

Diagnostic Systems




Heated Urea Tanks

## Advanced Emission Technologies Targeting NOx Reductions at Lower Exhaust Temperatures



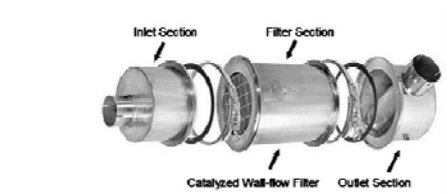



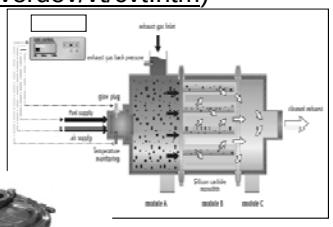

- Similar emission control approaches will be available for evaluation in CARB's HD Low NOx test program from MECA
- CARB committing $1.6 million over 3 years; MECA has committed an additional $250K in funding

Cummins DEER 10-2012

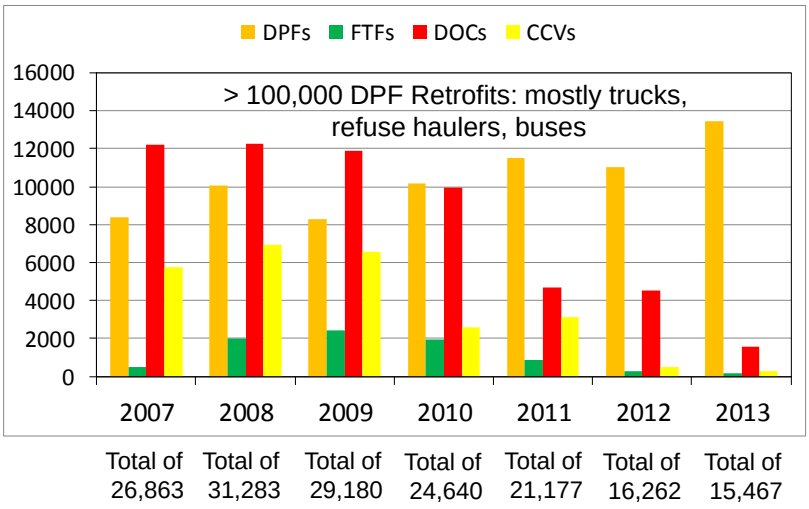
## Availability of ULSD Enables Variety of CARB/EPA Verified Diesel Retrofit Technologies

- **On-Road & Off-Road DPFs with Active Soot Regeneration**
- **On-Road & Off-Road DPFs with Passive Soot Regeneration**
- **Retrofit DPFs for Stationary Diesel Engines**
- **SCR Retrofits for On-Road & Off-Road Engines**
- U.S. EPA (epa.gov/cleandiesel/verification/verif-list.htm)
- California ARB (www.arb.ca.gov/diesel/verdev/vt/cvt.htm)



## U.S. Diesel Retrofit Sales Survey Results: Retrofits Driven by Incentive Funds (EPA DERA), CARB DPF Regulations




## Technical Considerations for Successful Retrofit Projects

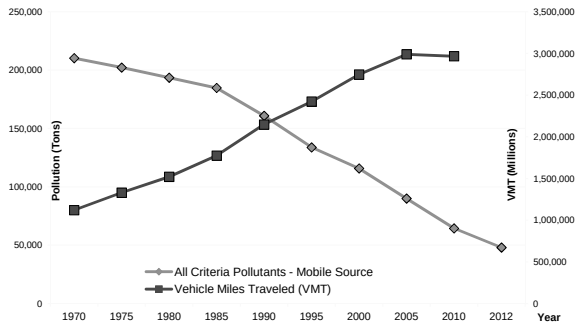
- Vehicle should be properly maintained before considering retrofit
- Application engineering – Matching the right technology to the specific piece of equipment and application
- Proper professional installation – Retrofits can be installed safely (visibility concerns addressed)
- On-vehicle monitors – Provide important user feedback on performance (don't ignore warning lights)
- Maintenance – Vehicle/equipment and retrofit device require inspection and maintenance

<u>Successful Retrofits Require a Cooperative Effort Between Fleet Owners, Operators, and Technology Providers</u>

## EPA & CARB Vehicle Programs Have Strong Emissions Compliance Efforts

- Heavy-duty highway vehicles
  - Rigorous new engine emissions certification process
  - On-board diagnostic requirements to monitor important emissions-related components
  - In-use testing program run by engine manufacturers using PEMs equipment
  - Recall authority to deal with significant emissions-related problems
- Diesel retrofits
  - Defined verification requirements that include 1000 hour durability demonstrations and in-use testing requirements

## Emission Control Industry's History of Success in U.S.




- Since 1970, total vehicle emissions have dropped by 75% while we have tripled our use of cars and trucks.
- Without affordable, dependable emission controls and other devices made by our industry – reliance on engines for moving people and goods would be impossible without choking our cities and towns with un-breathable air.

## Conclusions

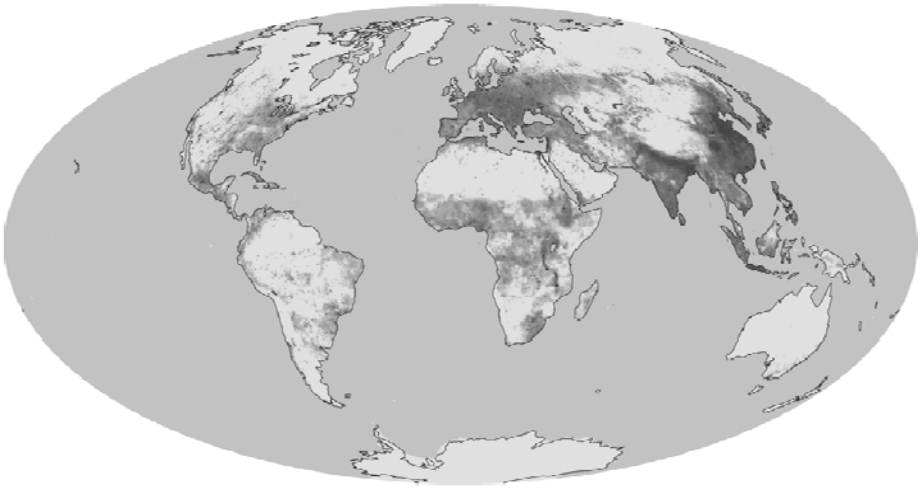
- U.S. Has Successfully Implemented Clean Fuel/Clean Vehicle Programs that are Delivering $billions in Health Benefits
- DPF+SCR Emission Controls Used to Meet US 2010 Heavy-duty Highway Engine Emission Standards
- Clean Diesel Technologies Moving into Off-road Sector for US Tier 4 Compliance – Variety of Emission System Configurations
- ULSD Availability has also Allowed for the Application of DPF Retrofits on more than 100,000 Diesel Engines in the U.S. (see ARB and EPA lists of verified diesel retrofit technologies)

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


- New Ultrafine particulate report with Executive summary in Mandarin
- Emission control technology white papers and fact sheets
- Retrofit technology descriptions
- Case study reports
- Regulatory info

**Back-up Slides**

## Particle Emissions Especially High in East/Southern Asia & Central Europe



NASA Modeling of highest PM2.5 mortality rates

## Clean Diesel Technology Driven By a Decade of U.S. EPA Mobile Source Emission Regulations

***Average Benefit:Cost = 20:1***

**Tier 2 Light-Duty**
final rule 1999
**fully phased in** 2009
Diesels held to same standards as gasoline vehicles
**Diesel sulfur now 15 ppm**

**Ocean-going Vessels**
final rule 2009; IMO ECA in 2010
**ECA: 1000 ppm Sulfur by 2015; 80% lower NOx by 2016**

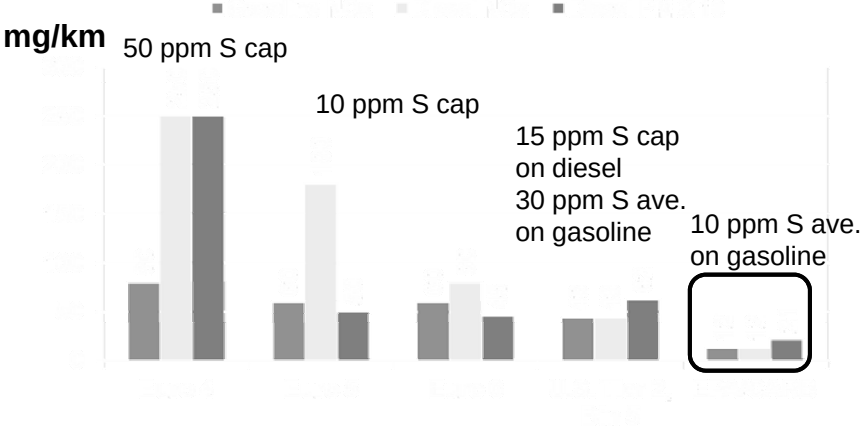
**Heavy-Duty Highway**
final rule 2000
**Sulfur now 15 ppm**
**fully phased in** 2007-2010

**Locomotive / Marine Tier 4**
final rule 2008
**Sulfur now 15 ppm**
**fully phased in 2017**

**Nonroad Diesel Tier 4**
final rule 2004
**Sulfur now 15 ppm**
**fully phased in** 2015

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

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



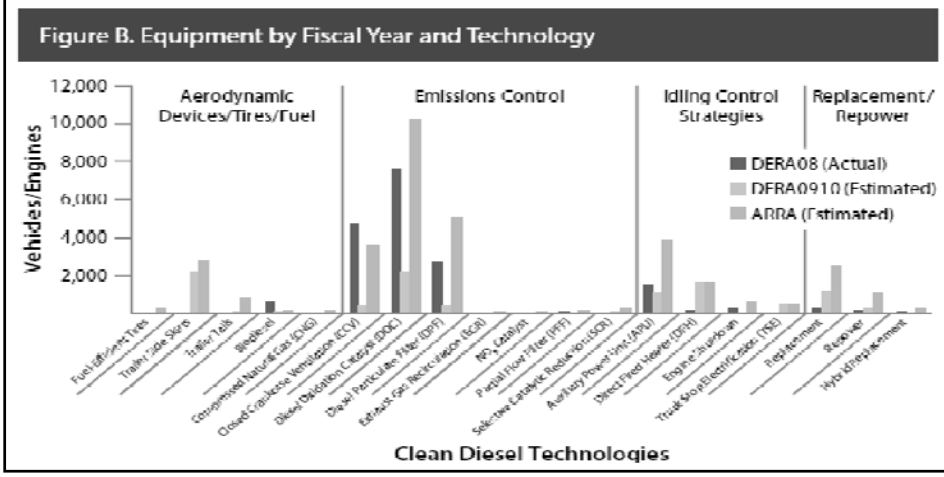

Euro 5+ (2011) and 6 include 6 X $10^{11}$/km diesel particle number limit; Euro 6c includes PN limit for GDI

# Fuel Sulfur Limits in Other Key Markets

- European Union
  - Euro 3: 150 ppm S cap for gasoline; 350 ppm S cap for diesel
  - Euro 4: 50 ppm S cap for gasoline; 50 ppm S cap for diesel
  - Euro 5: 10 ppm S cap for gasoline; 10 ppm S cap for diesel
- Japan
  - Pre-2004: 100 ppm S cap for gasoline; 500 ppm S cap for diesel
  - 2004: 100 ppm S cap for gasoline; 50 ppm S cap for diesel
  - 2005: 10 ppm S cap for gasoline; 10 ppm S cap for diesel
- China
  - 350 ppm S cap for diesel nationwide in July 2013; 150 ppm S cap for gasoline nationwide in 2010
  - 50 ppm S caps for gasoline & diesel by end of 2014
  - 10 ppm S caps for gasoline & diesel by end of 2017

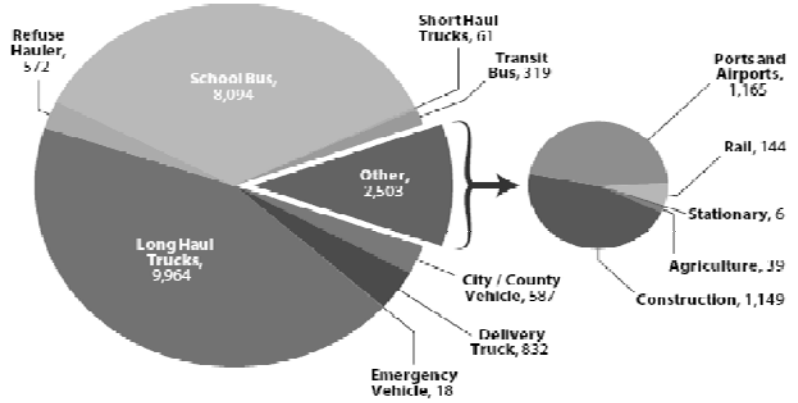
# U.S. EPA DERA Funding Used for Reducing Emissions from Older Diesel Engines

- FY 2008: $49 M; FY 2009+2010: $120 M; ARRA: $300 M - $469 M total
- FY 2011: $50 M; FY 2012: $30 M; FY 2013: ca. $20 M; FY 2014: $20 M - $120 M total



## U.S. EPA DERA Funding: Strong Focus on Highway Trucks/Buses

Figure 2. Equipment Retrofitted, Replaced, or Repowered by DERA 2008 and 2009/2010 Grants




## Significant On-Road Retrofit Experience, Off-Road Experience Growing

- >300,000 on-road DPF retrofits and >50,000 off-road DPF retrofits worldwide; > 100,000 DPF retrofits in the U.S.
- >1 million DOC retrofits worldwide
- Significant experience with retrofit technologies exists for on-road vehicles
  - School buses, transit buses, long- and short-haul trucks, refuse haulers, utility vehicles
- Retrofit experience is growing for many off-road applications
  - Construction equipment
  - Port vehicles/equipment
  - Marine engines and locomotives
  - Stationary internal combustion engines used for power generation