Emission Control Technology
Highlights for Gasoline & Diesel Engines

July 2006

Manufacturers of Emission Controls Association
www.meca.org
www.dieselretrofit.org
MECA Background

- Founded in 1976 to be The Technical Spokesperson for Our Industry
- Membership Open to Manufacturers of Emission Controls Primarily for Sale to Others
  - Associate Membership available to those developing emission control technologies/products
- Currently, 38 Members and 4 Associate Members
- Member companies have over 30 years of experience and a proven track record of success in developing and manufacturing emission control technology
- Members cover diverse range of emission control technologies for both new and existing engines/vehicles:
  - Catalytic converters (all fuels)
  - Diesel particulate filters
  - Exhaust components/exhaust system integration
  - Sensors
Gasoline Emission Control Technology: Extending Automotive Experience to All Gasoline Engines

- Tier 2/LEV II automotive systems combine advanced TWCs with advanced engine controls to achieve near-zero exhaust emissions
  - PZEVs include state-of-the-art emission systems for achieving near-zero exhaust and evaporative emissions
- Advanced catalysts can provide HC and NOx reductions for other gasoline engines:
  - Aftermarket automotive converters
  - Motorcycles
  - Off-road applications: handheld equipment, non-handheld equipment, fork lifts, generators, marine engines, recreational equipment
High Cell Density, Thin Wall Substrate Utilization Increasing Worldwide to Meet Tighter Emission Standards

Substrate Market Penetration, %

North America & Western Europe

Japan

Reference: MECA 2003
Advanced TWCs & Substrates Focused on High Performance and Precious Metal Utilization

4.6 Liter Light Duty Truck Application:
Pd concentrated in upstream zone for fast HC light off.
Low loaded catalysts located downstream for NOx control.
Aged system meets LEV2 (Tier 2, Bin 5).

4.6L V8 Engine

Zoned CC

Total Catalyst Volume: 4.2 L (< 15 g/ft³ ave. PM)

Reference: SAE 2004-01-1271
MECA PZEV Test Program: Advanced Emission Technology Demonstration

- Goal - PZEV/SULEV tailpipe emissions on two large light-duty trucks:
  - 2004 Ford F150, 5.4L Triton V8
  - 2004 GMC Yukon Denali, 6.0L Vortec V8

- Integration of advanced TWC systems with modified engine calibrations
- FTP Evaluations on “de-greened” and engine aged advanced emission systems
GMC Denali Advanced Catalyst System Design

Total TWC Catalyst Volume: 4.46 L (0.74 SVR)

6.0L V8 Engine

- 0.67 L (900 cpsi ceramic)
- 0.67 L (CC)

- 1.56 L (600 cpsi ceramic)
- 1.56 L (UF)
Baseline FTP Emissions (4K mi, stock) and Program Emission Targets

- LEV-I ULEV (100k)
- LEV-I ULEV (50k)
- LEV II – ULEV (120k)
- SULEV (120k)
- PZEV (150k)

**4K stock Denali**
**4K stock F150**

Denali & F-150 with 4K advanced catalyst system:
- 9-13 mg/mi NMOG
- 10-12 mg/mi NOx
GMC Denali Fully Aged Advanced Emission System
FTP Performance - Below 50K ULEV2 Limits

FTP Emissions, mg/mi

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<tr>
<th></th>
<th>NMOG/NMHC</th>
<th>NOx</th>
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<tr>
<td>SULEV</td>
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<td>ULEV2 - 50K</td>
<td>40</td>
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<tr>
<td>Denali - adv. TWCs, fully aged</td>
<td>26</td>
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<td>ULEV2- 120K</td>
<td>55</td>
<td>70</td>
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GMC Denali Fully Aged Advanced Emission System
SFTP Performance - Below Current ARB 4K Limits

NMHC + NOx, g/mi

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<th>US06</th>
<th>SC03 (A/C)</th>
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<td>0.14</td>
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<td>0.25</td>
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- **ARB 4K PC/LDT1**
- **ARB 4K LDT2**
- **Denali - adv. TWCs, fully aged**
Light-Duty Vehicle Emission Technology Developments Beneficial to Full Range of Spark-Ignited Engine Applications

- High Performance Aftermarket Converters
  - CARB OBD-Compliant Aftermarket Converters
- Medium & Heavy-Duty Engines
- Motorcycles/Mopeds
  - Closed-Loop TWC Systems for California/U.S. Motorcycles
- Recreational Vehicles & Engines
  - ATVs, Off-road Motorcycles, Marine engines
- > 25 hp Off-Road Applications
  - Advanced Closed-Loop TWCs to Achieve 2010 ARB Proposed Standards on Fork Lifts, GSE, Generator Sets
  - Closed Loop TWC Retrofit Systems
- Handheld Equipment & Non-Handheld Equipment
  - Blowers, String Cutters, Chain Saws, Lawn Mowers, Riding Mowers
- Alternative Fuels
  - E-85, CNG, Propane
OBD-Compliant Aftermarket Converters Utilize Advanced TWC Materials for Improved Performance & Durability

FTP, g/mi

OBD Aftermarket Converters Superior Performance Can Also Provide Emission Benefits on Pre-OBD Vehicles

Test vehicle: 1997 Chevy Astro Van, 4.3 L

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<tr>
<th></th>
<th>NMHC</th>
<th>CO/10</th>
<th>NOx</th>
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<tr>
<td>First Gen. CA AM</td>
<td>1.91</td>
<td>1.67</td>
<td>4.16</td>
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<tr>
<td>CA OBD AM</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
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<tr>
<td>CA OBD AM - aged</td>
<td>0.17</td>
<td>0.21</td>
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MECA
Large Experience Base with Catalysts on Small SI Engines

- Tens of millions of small 2-stroke and 4-stroke SI engines have been engineered, manufactured, and produced with catalysts for a variety of world markets since the early 1990s – thermal management a key design parameter

- The experience base with catalysts on small SI engines include:
  - Handheld equipment (largely 2-stroke engines, including chainsaws, string trimmers, hedge trimmers, leaf blowers)
  - Non-handheld equipment (including 4-stroke lawn mowers, portable generators)
  - Motor scooters, mopeds, and other small engine motorcycles (many with < 200 cc displacement, 2- and 4-stroke engines)
Catalysts for Smaller SI Engines Derived from Motorcycle/Moped Applications

- Catalysts for mopeds and motorcycles take many forms
  1. Coated expansion cone for 2-S moped muffler (Europe)
  2. Heat tube for 4-S bike (India)
  3. Large diameter (60-90mm) high cpsi metal monolith
  4. Small diameter (33-40mm) low cpsi metal monoliths
  5. Ceramic substrates

- Motorcycles & mopeds systems include thermal management strategies for limiting muffler surface temperatures (catalyst size, PM loading, muffler design, convection cooling, passive secondary air, heat shields, etc.)
TWCs Provide HC + NOx Reductions on Small 4-Stroke Engines

* Catalyzed vs. Uncatalyzed Baseline
CARB Verified Closed-Loop TWC Retrofit Systems for SI LPG Fork Lifts Now Available

Reduces HC+NOx exhaust emissions from 12 g/bhp-hr (uncontrolled engine) to 1 g/bhp-hr, > 90% system efficiency
Diesel Emission Control Technology Is Making Significant Progress

- Commercial Applications of Diesel Emission Control Technologies Expanding in Many World Markets Due to Tighter Emission Standards
  - Diesel Particulate Filters for Reducing PM Emissions
    - U.S./Canada 2007 heavy-duty diesel engines
    - Japan 2005 heavy-duty diesel engines
    - Most new diesel passenger car models in Europe
    - Tier 2, Bin 5 compliant light-duty diesel introductions in North America
  - NOx Emission Control Technologies
    - SCR in Europe for Euro IV/V heavy-duty compliance
    - NOx adsorber catalysts introduced on limited number of light-duty diesel vehicles in Japan & Europe
    - NOx adsorber to be available on 2007 Mercedes E 320 launch in North America; SCR to follow in 2009

- Diesel Retrofit Technology Options and Programs Expanding for Reducing Emissions from In-use Engines
DOCs and DPFs Form the Technology Base for Reducing PM Emissions from New and In-Use Diesel Engines

**Diesel Oxidation Catalysts**
- CO
- Aldehydes
- HC
- PAH
- SO$_2$
- NO$_x$

**Flow through monolith with catalytic coating**
- Applicable to nearly all diesel engines; significant retrofit & OE experience base
- PM control through SOF oxidation – significant reduction of toxic HCs

**Diesel Particulate Filters**
- CO$_2$
- H$_2$O
- SO$_2$/SO$_3$
- NO$_x$

- Standard on all on-road heavy-duty engines for 2007 in U.S. & Canada
- Significant experience base with LDD in Europe (> 2 million vehicles)

DOCs & DPFs can be combined with Crankcase Filters for additional PM control
2007-Compliant HDD is using Active Filter Regeneration with Auxiliary Fuel Injection Systems
DOC + CSF Systems are Lighting Off at Lower Temps with Pt-Pd Catalyst Formulations

DOCs w/ Pt&Pd have lower light-off temperature and better durability than with Pt only.

CSF with Pt-Pd has 50% lower HC and 75% lower CO emissions than Pt CSF, despite lower PGM loadings.
DPF+SCR Systems Are On the Road
Strong Interest for 2010 New Engines & Retrofits

15 L Engine: 74-82% NOx Reduction thru 75,000 mi

12 L Engine: 81-91% NOx Reduction thru 2 years of operation

- 10 trucks operated for more than 2 million cumulative miles (2 refuse, 8 tractors; 3 emission tested)
- 45 liters of SCR cats./engine (200 cpsi)


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<th>Component</th>
<th>Dimensions</th>
<th>Volume</th>
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<tr>
<td>CR-DPF DOC</td>
<td>12” x 6”</td>
<td>11.0 litres</td>
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<tr>
<td>CR-DPF Filter</td>
<td>12” x 15”</td>
<td>27.5 litres</td>
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<tr>
<td>SCR</td>
<td>4 off 9.5” x 6”</td>
<td>27.8 litres</td>
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<tr>
<td>Clean-Up Catalyst</td>
<td>2 off 9.5” x 4”</td>
<td>9.2 litres</td>
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Interest is Increasing in SCR for Light-Duty Diesel Vehicles in North America

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

Issues:

Adequate controls to ensure urea is in the tank

Urea infrastructure

About a 1% urea consumption is anticipated. A 16 liter tank will be filled at oil drain intervals and can last 16,000 to 27,000 miles.
NOx Adsorber Catalyst Development Continues to Show Progress:
Example – Low Temperature NOx Performance

Note: first baseline LNT and advanced LNT are Ba-based; Second baseline LNT is K-based

Source: SAE Paper No. 2006-01-1369
Lean NOx Trap Catalysts are Being Designed for Light-Duty and Heavy-Duty Applications

For engine (dyno) cert, the issue is high temp. efficiency at 500 C under high flow rate and NOx flux.

For chassis cert, the issue is cold start and low temp. NOx efficiency.
Favored Design Approach in Most Applications is to Put NOx System After the Filter System

- **Advantage**
  - Filter acts as a thermal reservoir for the SCR bed. The SCR stays closer to isothermal.
  - The filter can take advantage of higher transient temperatures.
  - Particulate, SOF and ash are removed prior to the SCR bed.
  - \( \text{NO}_2 \) formation on the CSF will lead to higher SCR activity.

- **Disadvantage**
  - Cold start NOx control will be difficult due to thermal mass of the filter.
  - An exotherm from the CSF may damage the SCR catalyst.
Most demanding NTE regime - temperatures are 500-520°C

US HD NTE: Emissions Can Not Exceed 1.5X the Standard
(0.3 g/bhp-hr NOx, 0.015 g/bhp-hr PM)
Operating with SCR-only in 2010 will increase ultrafine particulate emissions relative to 2007 engines with DPFs.

Filters drop ultrafine particulates by 3 orders of magnitude (99.9%). Advanced combustion engines using only SCR to meet a mass based regulation, will have higher ultrafine PM emissions relative to engines with filters.

TTM, June 2005
NOx Sensors in Production – Active Development Focused on Diesel Applications

- 12V version (1st gen. sensor)
  - is in serial production since mid 2002

- 24V version (2nd gen. sensor)

- 2nd gen. sensor introduced in mid 2005

- 12V version (2nd gen. sensor)

- NOx sensors recently completed 6000 h durability evaluation on a heavy-duty diesel engine (SAE paper no. 2005-01-3793)
- Work underway on low NOx range/high accuracy sensor
Experience Base Expanding with Diesel Particulate Filters (DPF) for Retrofits

- 200,000+ retrofits worldwide
- Many regions are mandating their use
- Variety of technologies for a variety of applications
- Not universally applicable, but expanded applications and technologies developing
DPFs with Active Soot Regeneration Strategies Available for Retrofits

- Example: uncatalyzed wall-flow filter with electrical regeneration
  - 1-8 hour regeneration cycle
- Example: uncatalyzed wall-flow filter with a fuel burner
- Suited for on- and off-road applications with low exhaust temperatures including locomotives & marine engines
“Flow-Thru” or “Partial” Filter Technologies Emerging for Diesel Retrofits

• Verified for 50-75% PM reduction
• Soot regeneration can be facilitated by a catalytic coating, DOC, or a fuel-borne catalyst
• Has applicability on older engines, light-duty vehicles
• Filtering achieved with sintered metal sheets or wire meshes
• Resistant to plugging
DOC + Partial Filter Retrofit Performance

% Reduction - Hot FTP Test

Reference: SAE Paper No. 2006-01-0213
Growing Variety of Diesel Retrofit Strategies Employed Across the U.S.

Diverse Technologies Reduce Diesel Emissions

Clean diesel projects currently underway employ a wide range of strategies to achieve reductions in diesel emissions. This chart illustrates the percentage of vehicles/engines that use a particular technology to reduce diesel emissions.

Source: EPA NCDC 2006 Progress Report
Growing Diversity in U.S. Retrofit Projects: More than 250 projects documented in recent report prepared for EPA

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<th>Retrofit Technology</th>
<th>School Buses</th>
<th>Transit Buses</th>
<th>Utility Vehicles</th>
<th>Freight/Delivery Vehicles</th>
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<th>Nonroad Engines</th>
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Retrofit experience report available at: [www.epa.gov/cleandiesel/publications.htm](http://www.epa.gov/cleandiesel/publications.htm)
JUST ADDED:
Updated Diesel Retrofit Technology Report & Case Studies for Retrofits on Construction Equipment
Summary

- Technology Forcing Standards are an Important Driver for Continued Emission Control Innovations and Investments

- Tailpipe And Evaporative Emission Technologies Developed for Light-Duty Gasoline Vehicle Applications Provide Solutions for the Full Range of Spark-Ignited Engines

- A Variety of Technologies are Available and Emerging for PM, NOx, and Toxic HC Emission Control for New Diesel Engines
  - Technology will migrate from on-road to off-road engines

- Retrofit Experience Is Growing Worldwide with a Variety of Technology Options Available for Controlling PM and NOx Emissions from On- and Off-Road Diesel Engines
  - In the absence of regulations, incentive funds critically important for driving the application of retrofits on in-use engines
Pending Regulatory Actions

- **EPA**
  - PM NAAQS: final rule due end of Sept.
  - Small SI Engine NPRM; due by year-end
  - Locomotive & Marine Diesel NPRM; due by year-end or 1st quarter of 2007
  - SI Marine NPRM due by year-end or early 2007
  - Tier 4 Non-road Diesel Technical review in 2007
  - Stationary SI NSPS and NESHAP Proposals: comments due by early Oct.
  - 2010 on-road heavy-duty diesel implementation

- **Environment Canada**
  - MMT review process to begin by year-end
Pending Regulatory Actions

ARB

- OBD revisions for light-duty/medium-duty: Board action by year-end
- Stationary Ag Engines PM Reduction Rule: Board action in Oct. 2006
- Harborcraft PM Reduction Rule: Board action in Nov. 2006
- OBD-compliant aftermarket rule & converter replacement guidelines: Board action in early 2007
- Private On-road Fleet PM Reduction Rule: Board action by mid-2007
- Full useful life SFTP requirement: Board action in 2007
- ZEV program review: 2006-2007
- Additional tightening planned for off-road motorcycles & ATVs: Board action in 2007