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


Corning Incorporated

Light Duty DPFs

Many mid- and large-sized European light-duty diesel cars will have deNOx added to them for NOx and CO2 reductions. This increases system back pressure. Smaller platforms desire more efficient regeneration behavior to reduce CO2. 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>
<thead>
<tr>
<th>Approach</th>
<th>Porosity</th>
<th>Pore Size Distribution</th>
<th>Cell design</th>
<th>SML</th>
<th>Pressure Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>DuraTrap® AT</td>
<td>~50%</td>
<td>Base</td>
<td>300/13 ACT</td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td>DEV AT LP</td>
<td>~45%</td>
<td>Improved</td>
<td>300/13 ACT</td>
<td>+ 2-3 g/l</td>
<td>~ Base</td>
</tr>
<tr>
<td>DEV AT TW</td>
<td>Reduced wall thickness</td>
<td></td>
<td>300/10 ACT</td>
<td>~ Base</td>
<td>~ 20-25%</td>
</tr>
</tbody>
</table>

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 thinnest 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\textsubscript{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.](image-url)
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.
• CO₂ 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
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

No adjustments for test cycle differences. Japan has a HC limit of 50 mg/km (33% CH$_4$ adjustment here).

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 CO₂ 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% per year reduction in LD CO$_2$ emissions. By 2025, 6% per year brings near-parity with Europe of 2020.
### Technology Needed for Compliance - 2025 Models

<table>
<thead>
<tr>
<th>Stringency, % GHG change/yr</th>
<th>Mass Reduction*</th>
<th>Advanced engine, %</th>
<th>HEVs, %</th>
<th>Plug EV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>658</td>
<td>18</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>4%</td>
<td>733</td>
<td>20</td>
<td>63</td>
<td>18</td>
</tr>
<tr>
<td>5%</td>
<td>733</td>
<td>20</td>
<td>49</td>
<td>43</td>
</tr>
<tr>
<td>6%</td>
<td>712</td>
<td>19</td>
<td>44</td>
<td>47</td>
</tr>
</tbody>
</table>

* Limited to a maximum 20% in this Scenario B

CARB, CTI Forum, 5/11
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 transit 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.
**HD engine** CO₂ 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.

<table>
<thead>
<tr>
<th>GVWR CLASS</th>
<th>FUEL</th>
<th>MODEL YEARS</th>
<th>CO₂ REDUCTION FROM REFERENCE CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHD (8a-8b)</td>
<td>Diesel</td>
<td>2014-2016</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2017+</td>
<td>6%</td>
</tr>
<tr>
<td>MHD (6-7) and LHD 4-5</td>
<td>Diesel</td>
<td>2014-2016</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2017+</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>2016+</td>
<td>5%</td>
</tr>
<tr>
<td>LHD 2b-3</td>
<td>Gasoline</td>
<td>2016+</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2016+</td>
<td>9%</td>
</tr>
</tbody>
</table>

**Total Vehicle Reductions**

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

General: Proposed engine CO₂ 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.

N₂O: 0.050 g/bhp-hr on FTP; 3% of carbon footprint; 2X 2010 capability

CH₄: 0.050 g/bhp-hr; at 2007 capability

Line Haul Engine SET 2010 industry baseline is 490 g CO₂/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.
CORNING

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.

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

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.

Chrysler, SAE FE Panel 4/10

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

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.

<table>
<thead>
<tr>
<th>Technology Scope for T2B5 LDDs</th>
<th>Technology Scope for Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Segment</strong></td>
<td><strong>Small</strong></td>
</tr>
<tr>
<td>Technology</td>
<td></td>
</tr>
<tr>
<td><strong>Diesel</strong></td>
<td></td>
</tr>
<tr>
<td>Engine</td>
<td>Not feasible? (1:3)</td>
</tr>
<tr>
<td>Boosting</td>
<td>Optimized VNT</td>
</tr>
<tr>
<td>EGR-System</td>
<td>HP &amp; LP EGR</td>
</tr>
<tr>
<td>Optimized Combustion</td>
<td>Lowered Compr.</td>
</tr>
<tr>
<td>Aftertreatment</td>
<td>DPF / LNT</td>
</tr>
<tr>
<td>Manual / Automated</td>
<td>AMT, DCT</td>
</tr>
<tr>
<td>Gears</td>
<td>5-speed</td>
</tr>
<tr>
<td>Clutches Dry / Wet</td>
<td>Dry</td>
</tr>
<tr>
<td>Electric / Hydraulic</td>
<td>Electrical</td>
</tr>
<tr>
<td>Start/Stop</td>
<td>BISG</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Restricted, 3KW</td>
</tr>
<tr>
<td>Optimized Operation</td>
<td>Limited</td>
</tr>
<tr>
<td>Electric Drive (&lt;10km)</td>
<td>-</td>
</tr>
</tbody>
</table>

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.

Toyoda, 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 been 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.

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**
- 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**
- 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.

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

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

Issue: Quite low octane fuel is used (“one of the refinery streams”)
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.
Low NOx engine calibrations require much technology. Engine hardware, fuel consumption and aftertreatment trade-offs.

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

Cold FTP Results

<table>
<thead>
<tr>
<th>FTP Phase</th>
<th>Without Thermal Mgt</th>
<th>With Thermal Mgt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Cycle</td>
<td>0.364 g/HP-hr</td>
<td>0.301 g/HP-hr</td>
</tr>
<tr>
<td>Hot Cycle</td>
<td>0.357 g/HP-hr</td>
<td>0.031 g/HP-hr</td>
</tr>
<tr>
<td>Composite</td>
<td>0.358 g/HP-hr</td>
<td>0.069 g/HP-hr</td>
</tr>
</tbody>
</table>
HD HEVs are seeing about 20-30% FC savings, use Li-ion batteries, and have a parallel architecture

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

Source: OEM websites and public information
T4f approaches depend on EGR rates, SCR efficiency, and high or low-load application

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.

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

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
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 10°C/min, 40-550°C.

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

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

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 150-400°C.

Other multi-metal formulations are being investigated. CuSc2 and CuFeLa show promise, among others.
Improved vanadia SCR catalyst has durability to 750°C. Volatility below detection limits. Efficiency maintained.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>μg V/g cat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>83</td>
</tr>
<tr>
<td>CB</td>
<td>42</td>
</tr>
<tr>
<td>DA</td>
<td>N/M</td>
</tr>
<tr>
<td>DB</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>DC</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>DD</td>
<td>&lt; 2.5</td>
</tr>
</tbody>
</table>

Development catalyst is below the detection limit on vanadia volatility at 750°C. 5% H$_2$O, 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

Fe-zeolites can form N₂O if excess NO₂ is used to promote LT deNOx. At NO₂~40%, ASC N₂O in was 5 ppm, out was 10 ppm at very high NH₃ levels.

Haldor Topsoe, DEER 9-10
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.

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 (230-350°C) 600-cpsi substrates react 35% faster than 400-cpsi.

Corning, SAE Gothenburg, 9-10
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.

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

Improvements are made to the lean-rich HC cycle durability of the Cu-zeolite catalyst.
Physical mixtures of LNT+SCR on one bed performs better in fundamental experiments than two-bed system.

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.
Ford demonstrates characteristics of active and passive DPF regen. Active: No O2 impact (>2%), soot load important, little PGM influence; Passive: NO2 2.5X than w/ 15% NO2, Pt is key, zeolite had no impact.

### Active Regenerations

- a. Little impact between 2 and 5% O2; 1% needs 50C higher inlet.
- b. Soot mass more dominant
- c. Pt and Pd are similar and convert to CO2. Cu-Z similar to uncoated (CO:CO2=60:40). PGM had no impact on rate.

### Passive Regenerations

- a. 50% NO2 gives 2.5X faster rate than 15% NO2
- b. NO2 is more effective at 370C than at 485C
- c. Pt samples at 370C and 50% NO2 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
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.
Biodiesel blends burn faster and consume less fuel for regeneration.

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

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/m³ for OBD appears to be possible

Reference: SAE 2011-01-0302 & 0627
PM sensor for OBD is reported.

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

Non-accumulating PM sensor measures charged particles continually.

Sensor measure ~400X100 mm

Supplier claims PN concentration measurement.

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

Pegasor, CRC Conf 3/10
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 $\Delta T$ shift across the detection filter.

Preliminary steady-state (left) and transient testing shows promise.
Increasing injection pressure can drop PN emissions ~95%.

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

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

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

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

TU Karlsruhe, Aachen Kolloquium, 10/10
Engine calibration can drop GDI PN emissions by 65% on the NEDC.

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

65% PN reduction with new engine calibration measures.
Cooled EGR up to 12-20% can reduced GDI PN quite significantly.

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

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

SwRI PCS 8-10
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

**Graphs and Data:**

- NEDC Results
- Particle Number (#/km)
- CO2 (g/km)
- Engine with TWC
- Engine with GPF
- TWC Engine
- GPF Engine
- GPF with TWC

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

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<th>Catalyst</th>
<th>Pd (g/l)</th>
<th>Rh (g/l)</th>
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<tr>
<td>Front</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Mid</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Rear 1 or</td>
<td>2</td>
<td>0.1</td>
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<tr>
<td>Rear 2</td>
<td>1</td>
<td>0.3</td>
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EtOH impact on criterion pollutants is quantified. NOx but NMHC can go up. PM drops with the EC decreasing but OC increasing. Acetaldehyde increases.

<table>
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<th>E0</th>
<th>E10</th>
<th>E20</th>
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<tbody>
<tr>
<td>FTP FE (MPG)</td>
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<td>24.1</td>
<td>23.9</td>
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<tr>
<td>US06 FE (MPG)</td>
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<td>25.4</td>
<td>24.9</td>
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<td>NMHC (g/mile)</td>
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<td>0.044</td>
<td>0.091</td>
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<td>NOx (g/mile)</td>
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<td>0.018</td>
<td>0.009</td>
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<tr>
<td>CO (g/mile)</td>
<td>0.35</td>
<td>0.36</td>
<td>0.30</td>
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</table>

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.
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 against phosphorous.

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

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

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

Toyota, SAE 2011-01-0296
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.
• CO2 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