Particle Emissions from Diesel and Gasoline Engines

By

Imad A. Khalek, Ph.D.
Southwest Research Institute
Engine, Emissions and Vehicle Research Division
Department of Emissions R&D
Particle Science & Technology

Ikhalek@swri.org

SAE 2011 Electronic Systems for Vehicle Propulsion Symposium

November 8-9, Troy, Michigan, 2011
Heavy-Duty Highway Diesel Engine Particle Regulatory Limits in the US

![Graph showing PM emissions over years](image)
2010 Heavy-Duty Highway Diesel Engines

- 2010 diesel engines have gone through major modifications to reduce regulated emissions:
  - Water-cooled exhaust gas recirculation (EGR) and Selective Catalytic Reduction (SCR) Catalyst to reduce NO\textsubscript{x} emissions
  - Filtered crankcase ventilation to reduce blow-by particulate matter (PM) emissions
  - Catalyzed diesel particulate filter (DPF) in the exhaust to reduce PM
    - Active regeneration and/or cleaning of the catalyzed DPF accomplished by:
      - Diesel fuel injection into exhaust upstream of diesel oxidation catalyst (DOC) located before the catalyzed DPF
      - Hot gas from a fuel burner located before the catalyzed DPF
      - Active regeneration is handled and controlled by the engine control module (ECM) with no influence or control by the engine operator
  - Additional changes such as:
    - High Injection Pressure
    - Variable geometry turbocharging
    - High boost pressure
    - Improved combustion chamber design
    - Reduced oil consumption
    - Etc…
Engines

- We recently tested four 2007 production heavy heavy-duty highway diesel engines with DPF and without SCR, as a part of the Phase 1 of the Advanced Collaborative Emissions Study (ACES) [CRC, HEI, DOE, EPA, CARB, and EMA sponsorship]
- These new engines were degreened for a total of 150 hours prior to emissions testing

CAT C13, by Caterpillar

430 hp

DDC Series 60, by Detroit Diesel

455 hp

Cummins ISX, by Cummins

455 hp

Mack MP7, by Volvo

395 hp
Regulated Emissions Relative to EPA 2007 Standard Based on FTP Transient Cycle

<table>
<thead>
<tr>
<th></th>
<th>2007 EPA Standard (g/hp-hr)</th>
<th>Average ACES Engine Emissions (g/hp-hr)</th>
<th>ACES Emissions % Reduction Relative to the 2007 Certification Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>15.5</td>
<td>0.33</td>
<td>98</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.14</td>
<td>0.0064</td>
<td>95</td>
</tr>
<tr>
<td>PM</td>
<td>0.01</td>
<td>0.0011</td>
<td>89</td>
</tr>
<tr>
<td>NOX</td>
<td>1.2 (^a)</td>
<td>1.075</td>
<td>10</td>
</tr>
</tbody>
</table>

\(^a\) Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr
With regeneration, the particle number emissions average was approximately 90 percent lower than the level emitted by a 2004 engine technology, and **without regeneration** it was approximately 99 percent lower.

Average particle number with regeneration was more than a factor of 10 higher than that without regeneration (Note that there was no difference in PM mass emissions)
During DPF regeneration, real time particle number in exposure chamber increased by a factor of 10 to 100, compared to the condition without DPF regeneration. Number count w/o regen. increases above 300°C.
Sub-30 nm Nanoparticles

During Active Regeneration, sub-30 nanometer nanoparticle number dominated particle number emissions, and exceeded 95 percent of the total number.
The remaining PM mass emitted from wall-flow DPF-equipped engines is composed mainly of volatile sulfate and organic carbon species.

Much of the volatile matter collected may be due to filter artifacts.

Solid PM of metallic ash and elemental carbon comprised less than 17 percent of total PM mass.
Average Number-Weighted Size Distribution with and without Active DPF Regeneration

GNMD is the geometric number mean diameter in nanometers
Elemental and Semi-Volatile Composition of PM

- Zn: 3\% (24.4 μg/bhp-hr)
- Fe: 15.2\% (11.5 μg/bhp-hr)
- Ca: 11.5\% (13.3 μg/bhp-hr)
- P: 14\% (24.4 μg/bhp-hr)
- Na: 31\% (24.4 μg/bhp-hr)
- Cu: 19\% (2.7 μg/bhp-hr)
- Ni: 3\% (0.07 μg/bhp-hr)
- Zn: 0.59\% (0.04 μg/bhp-hr)
- Cu: 0.59\% (0.04 μg/bhp-hr)
- Ni: 0.59\% (0.04 μg/bhp-hr)
- Steanes: 0.07\% (0.04 μg/bhp-hr)
- Hopanes: 0.05\% (0.04 μg/bhp-hr)
- Alkanes: 0.05\% (0.04 μg/bhp-hr)
- Polar: 0.05\% (0.04 μg/bhp-hr)
- NitroPAH: 0.05\% (0.04 μg/bhp-hr)
- OxyPAH: 0.05\% (0.04 μg/bhp-hr)
- PAH: 0.05\% (0.04 μg/bhp-hr)

Composition of Particle Phase Semi-Volatile Compounds:
- 1: 90.0\% (3.36 μg/bhp-hr)
- 2: 10.0\% (45.0 μg/bhp-hr)
Remaining Issues

- For diesel engines with working DPF, there are two remaining issues for improving PM control:
  - Reducing particle emissions during active regeneration
  - Reducing particle emissions during storage and release processes (low to high temperature)
  - Reducing pre-cursors for secondary aerosol formation

- Functional Issues
  - Particle sensor for OBD is required to insure DPF function throughout engine life time
  - SwRI is launching a consortium to investigate Particle Sensor Performance & Durability
    - OBD particle sensor is one of the guarantors ensuring particle emissions do not exceed regulatory threshold
A similar work to the one discussed above will soon be launched by SwRI on SCR-equipped 2010 engines provided by Cummins, Detroit Diesel, and Volvo.

The work will be part of Phase 2 of the ACES, with funding from CRC, HEI, DOE, EPA, CARB, and the EMA.
Gasoline Direct Injection Particle Emissions
GDI Market Penetration and Particle Emissions Limit
Euro 6 and LEV III Light-Duty Particle Emission Regulations

- **Euro 6 (2014)**
  - Particulate Matter (PM) Mass: 4.5 mg/km
  - Solid Particle Number (SPN): $6 \times 10^{11}$ part./km (> 23 nm, NEDC)
    - For GDI, it has not been finalized yet

- **Preliminary CARB LEV III (Light-Duty, 2017-2020, 2025)**
  - 2017
    - PM Mass: 6 mg/mi (~3.8 mg/km)
  - 2020
    - PM Mass: 3 mg/mi (~1.9 mg/km)
  - 2025
    - PM Mass: 1 mg/mi (~0.6 mg/km)

- **EPA Planned Tier 3 Regulations**
  - Total PM reduction, similar to CARB Proposal?
  - Particle Number? (solid? Total?) (Discussions are to take place between EPA and CARB on these subjects)
Meeting Particle Emissions Regulations

- **Euro 6:**
  - Diesel: High Efficiency DPF is required
  - Gasoline: Multi-Port Fuel Injection, TWC
  - Gasoline: GDI, TWC, with significant PM reduction via combustion, fuel, and aftertreatment optimization:
    - Higher Injection Pressure
      - Smaller Droplets
    - Better Transient Mixing
    - Improved Cold-Start
    - Injector Location
      - Wall Guided
      - Centrally Located
    - **Fuel**
    - **High Turbo Boost and EGR**
    - **Injection Timing**
    - **Gasoline Particle Filter (GPF)? Perhaps with lean-burn GDI**

- **LEV III:**
  - Diesel: DPF is required
  - Gasoline: Multi-Port Fuel Injection, TWC
  - Gasoline: GDI, TWC, with some PM reduction combustion optimization such as those used for Euro 6
Fuel Effects on Particle mass and Number

- Fuel Effects: SAE Paper 2010-01-2117
- 2009 Vehicle with wall guided GDI Engine along with a three-way catalyst in the exhaust
- Acknowledgements: work was funded by Honda R&D America
The Double Bond Equivalent is highest for Fuel C and Lowest for Fuel B, See SAE Paper No. 2010-01-2115 on PM Index
Effect of Fuel Properties on GDI PM

Fuel with low vapor pressure and high double-bond equivalent lead to higher PM emissions.
Slope for soot was a factor of 1.5 to 2 higher than that reported by Kirchner, Vogt, & Maricq (SAE Paper No. 2010-01-0789) for Diesel with DPF
Comparison Between Two Modern GDI Vehicles during cold-start Phase 1 of FTP

Highest PM Emissions During Cold-Start Phase 1 of the FTP

PM dominated by Soot
We showed that EGR can lead to a drastic soot mass reduction, but at some engine operating conditions the number of solid particles are unchanged while the mass is low.
Two Aftertreatment Configurations

GPF: Gasoline Particle Filter
TWC: Three-Way Catalyst
Average Solid Particle Number Reduction Efficiency Between Engine Out and Tailpipe (> 23 nm)

- Similar efficiencies were obtained for particles larger than 5.6 nm
Final Thoughts on GPF/DPF

- Very high-efficiency DPF needed to meet Euro 6/VI solid particle number standard
- Less efficient GPF will be needed to meet Euro 6 with GDI at $6 \times 10^{11}$ part./km
- No GPF will likely be needed to meet LEV III with stoichiometric GDI
Comparison of Different Vehicle Technologies

- MPI Emissions based on LA 92, which is more aggressive than the FTP
- GDI Emissions based on FTP-75 composite

Expected Trend
Selected Bibliography