The Role of High Efficiency Exhaust Particle Filters in Engine Emissions Reduction- A Look Into the Future

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When it comes to particle emissions from highway and nonroad internal combustion engine sources, there are three areas of concern:

- Emissions of solid particles that are mainly soot and ash in nature
- Emissions of volatile and semi-volatile particles (unburned and partially burned fuel and lube oil, sulfuric acid, etc…) that are immediately formed as the exhaust cools and dilutes with atmospheric air
- Secondary aerosol formation that forms later in the atmosphere from exhaust precursors

The successful introduction of a particle filter in the exhaust of a diesel engine has made a quantum leap forward in achieving a significant reduction in all three aforementioned sources of particle emissions. Our recent work with modern engines showed a very substantial reduction in a large number of particle and gas phase toxic compounds, compared to unfiltered engine exhaust. Others showed a substantial reduction in secondary aerosol formation. While the continuous use of a high efficiency exhaust particle filter cannot be assured in the US with the 2007 PM mass regulations only, the introduction of the solid particle number regulation in the EU serves as an indirect mandate for the use of high efficiency filters in the exhaust of diesel engines; the solid particle number standard for light and heavy-duty vehicles in Europe makes the EU particle mass standard almost irrelevant because engines that meet the solid particle number standard emit well below the PM mass standard. Thus, the solid particle number standard ensures the use of the best available particle reduction technology onboard vehicles.

We can easily argue that the high efficiency exhaust particle filters are the champions of achieving extremely low particle emissions from diesel engines, and such a championship should serve as a role model in achieving similar emissions reductions from other combustion sources including gasoline, natural gas, alternative fuel, and hybrid vehicles. One of the biggest advantages of an exhaust particle filter that typically goes unnoticed is in its ability to maintain very low particle emissions regardless of engine operation (high and light load) and environmental conditions (hot and cold temperature, high and low altitude, etc..). This is in addition to its fundamental ability of filtering out sub-23 nm nanoparticles (not regulated via particle number) due to their high diffusion coefficient. Both of these factors are huge environmental and health benefits.

Nothing is perfect or comes maintenance free. One of the biggest future challenges is how to ensure exhaust particle filters are doing their job onboard vehicles. One can perform in-use testing, inspection and maintenance, but nothing substitute the onboard real time monitoring of an exhaust particle filter performance. We project that particle sensors for onboard diagnostics are one of the key enablers for the success of the particle filter technology. Without this key enabler, we could run into a huge environmental overburden with engines exceeding particle emissions standard. Thus, it is critical that we identify the right particle sensing technologies that can achieve this important objective. A second issue with exhaust particle filters is the infrequent increase in sub-30 nm volatile nanoparticles under active regeneration or due to storage and release processes. Our recent work showed that it takes one active regeneration in 16 hours of engine operation to elevate average volatile nanoparticle emissions by more than one order of magnitude, compared to the case without regeneration. Also, during regeneration, the real time concentration of volatile sub-30 nm particles can easily exceed unfiltered engine exhaust levels. It is worth taking a closer look at ways for minimizing the occurrence of this phenomenon. A third issue is ash accumulation in exhaust particle filters due to lube-oil-derived metallic ash deposit with some contribution from engine wear. Ash accumulation leads to an unacceptable increase in engine backpressure or clogging, unless the filter is cleaned from ash deposit off-line or replaced. Ash accumulation does not occur frequently (> ~100,000 miles for light-duty and > ~200,000 miles for heavy-duty), however, it is a shortcoming in the application of this technology. Thus, it is important to address issues related to ash loading and how they can be prevented or minimized. If we can tackle properly the above mentioned key issues, we would really have accomplished a critical milestone in achieving particle-free internal combustion engines through exhaust aftertreatment means.

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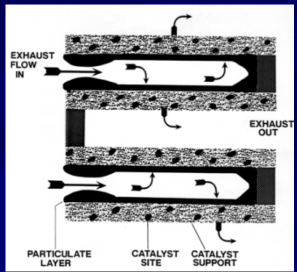
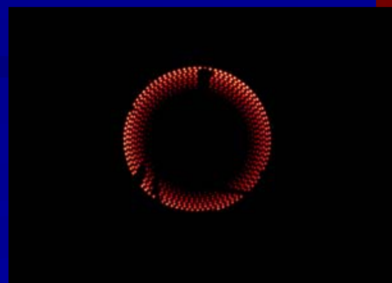
Early 1980's Application of Trap Designs

- Several Projects Evaluated for Best Efficiency Traps
  - Various Materials Examined
    - Steel Wool
    - Alumina-Coated Steel Wool
    - Cordierite Ceramic Monolith
    - Alumina Foam



  - Various Designs
    - Radial Inflow
    - Radial Outflow
    - Wall Flow
    - Axial

  - Collection Mechanism
    - Impaction, Interception
    - Diffusion



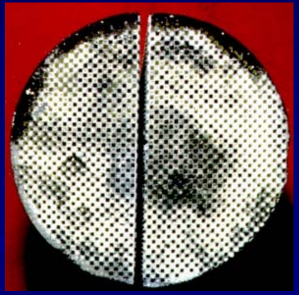
80's Regeneration Issues

(Currently, these problems still occur but to a much lesser extent)

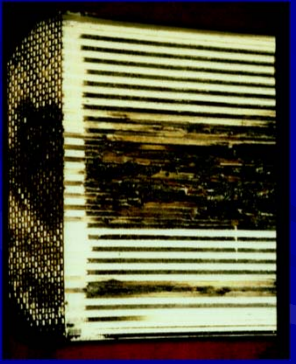
Face Plugging

- Affected By
  - Trap Design and Composition
  - Temperatures (both inlet and localized)
  - Oxygen
  - Mass of Particulate
  - Organic Content
  - Mass Flowrate
  - Distribution of Particulate in Trap

Crack



Melting of channels

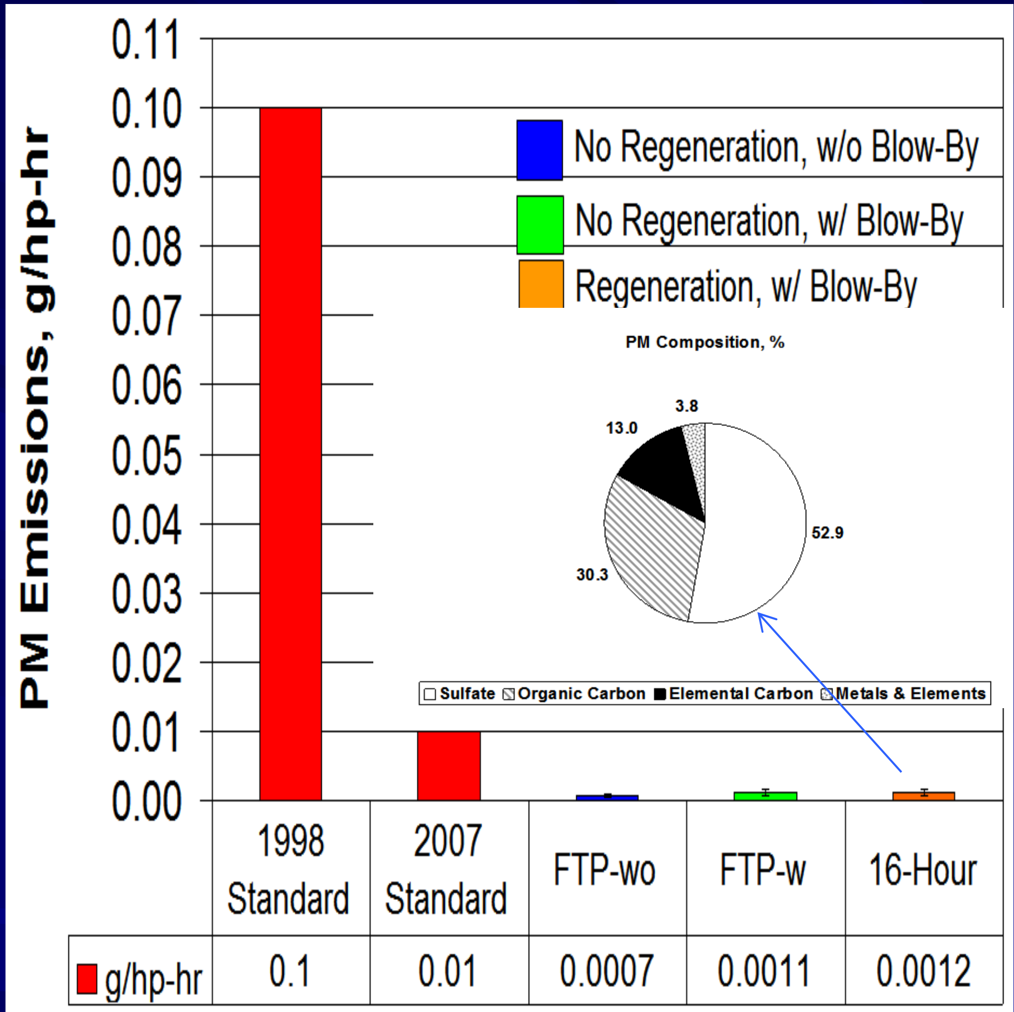


The initiation and rate of generation became a variable, based on engine operation and driver demand. This variation led to trap plugging and melting. In October 1984, SwRI launched a 28 member consortium to investigate trap related durability and regeneration issues.

Trap and Regeneration Improvement in the last two decades

- Material design and durability
  - Cordierite, SiC, Al Titanate, Mullite, and Metal
  - Cell density, wall thickness, pore size, porosity, channel shape
- Regeneration
  - Passive with catalysis
  - Exhaust Burner
  - Exhaust or Post Fuel Injection
  - Engine electronic control sophistication
- Fuel and Oil
  - Ultra low sulfur diesel fuel (< 15 ppm sulfur, Late 2006 in US)
  - CJ-4 lube oil (low sulfur, ash, and phosphorus)

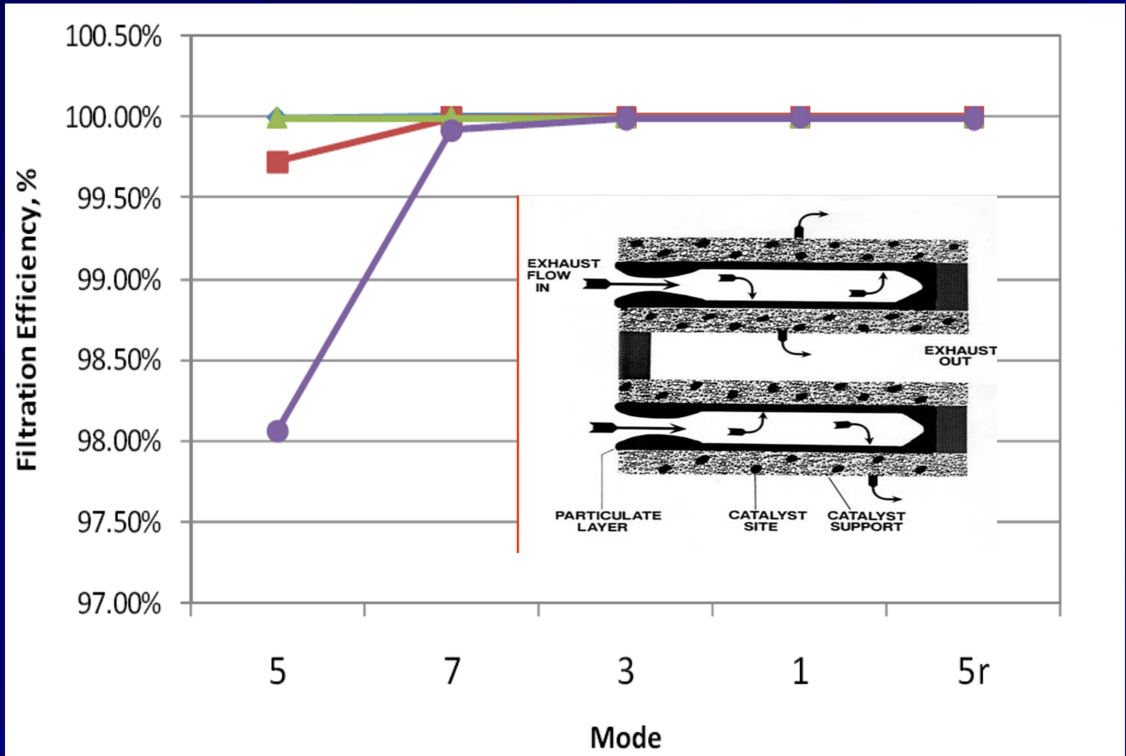
Impressive PM Mass Emission Reduction in Modern engines



- 90 percent reduction in PM emissions was mandated by US EPA for 2007 heavy-duty diesel engines and beyond
- High efficiency wall-flow DPF technology selected by the engine manufacturers achieved **more than 99 percent reduction in PM mass** emissions relative to 1998 engine technology

Because PM mass emission is much less than the standard, a less efficient diesel particle filter (DPF) may be desirable in the future, unless the US adapts solid particle number standard or similar measures to that of the EU

Ultra High Solid Particle Number Filtration Efficiency



- Except when the DPF is clean, <u>higher than 99.9%</u> efficiency is measured at all operating conditions

High Filtration Efficiency Benefit Extend Below 23 nm

Particle size class	Particle size range	Particle number before filter	Particle number after filter	Penetration [%]	Filtration efficiency [%]
1	15.4	1.33E+05	0.00E+00	0.000%	100.000%
2	20.5	6.93E+05	1.96E+02	0.028%	99.972%
3	27.4	2.01E+06	2.39E+02	0.012%	99.988%
4	36.5	4.20E+06	6.62E+02	0.016%	99.984%
5	48.7	6.49E+06	6.60E+02	0.010%	99.990%
6	64.9	8.36E+06	5.69E+02	0.007%	99.993%
7	86.6	8.82E+06	5.23E+02	0.006%	99.994%
8	115.5	7.60E+06	2.86E+02	0.004%	99.996%
9	154	5.30E+06	2.19E+02	0.004%	99.996%
10	205.4	2.82E+06	1.89E+02	0.007%	99.993%
11	273.9	8.80E+05	2.45E+02	0.028%	99.972%
overall		4.63E+07	3.54E+03	0.008%	99.992%

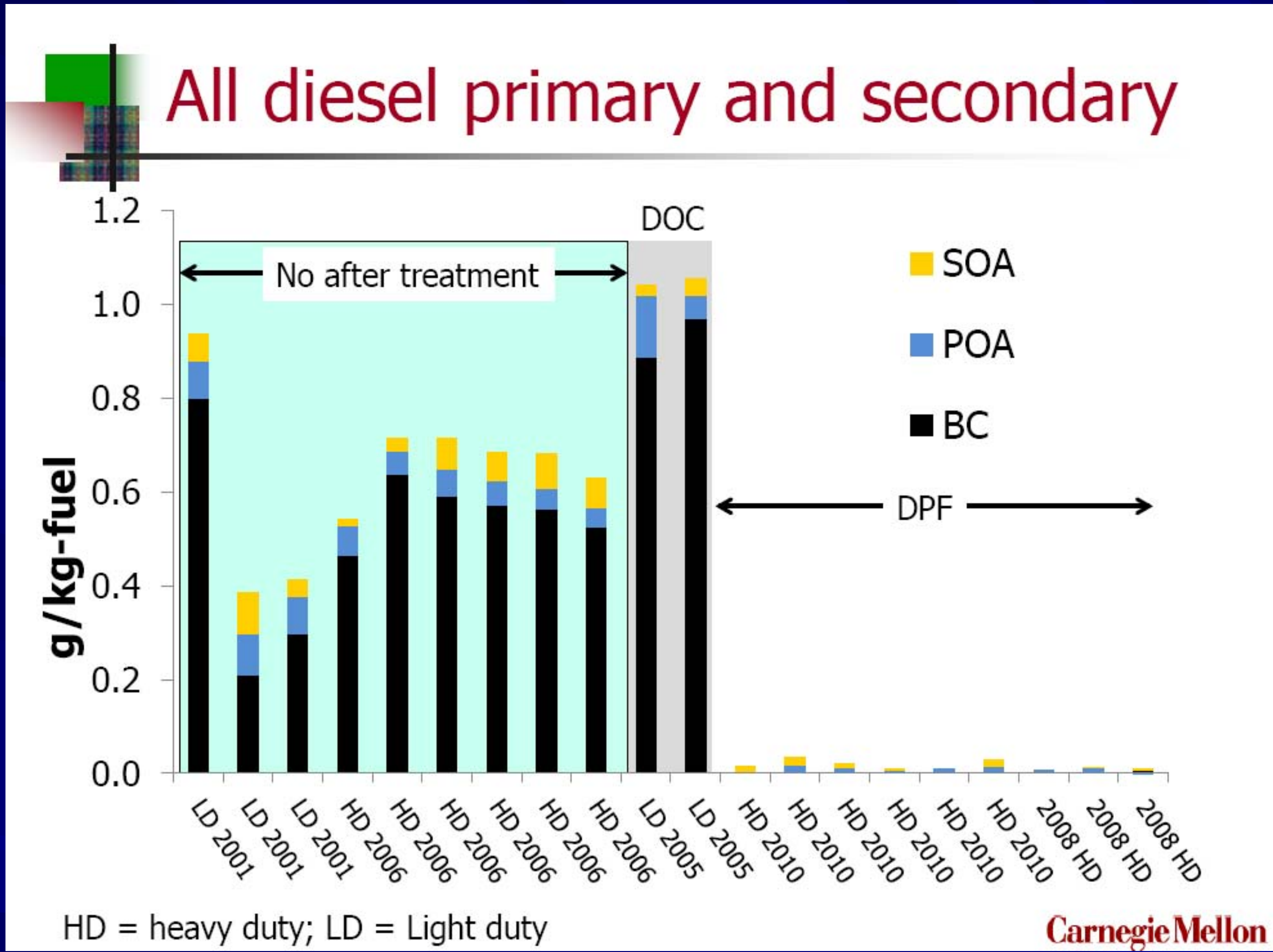
Significant Unregulated Emissions Benefit

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	96%	78%
Elemental Carbon	99%	100%
Dioxins/Furans[a]	99%	N/A

[a] Relative to 1998 Engine Technology

Due to the presence of exhaust SCR catalyst for NOX reduction in 2010 engines, NOX as well as NO2 are at least 90% lower than 2004 technology engines

Reduction in Secondary Organic Aerosol Formation



Robinson et al., 22nd CRC Real World Emissions Workshop, San Diego, CA, March 25-28, 2012

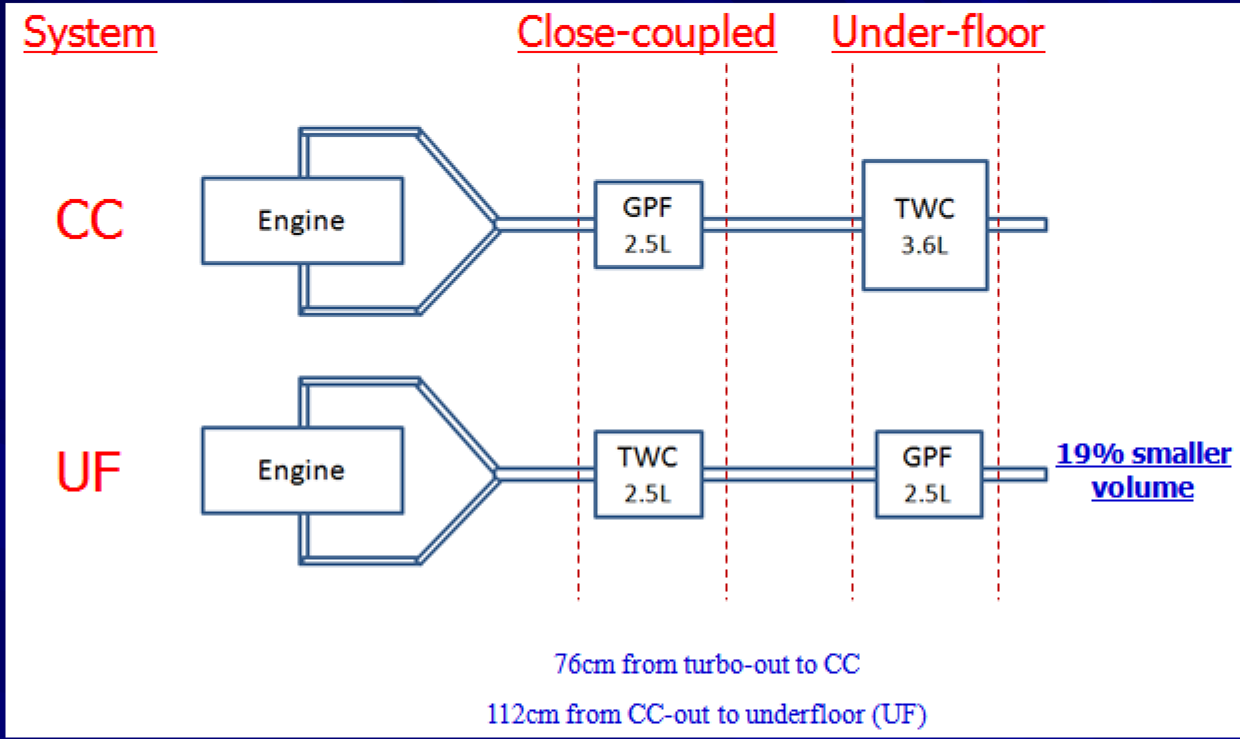
Off-Cycle Emissions Benefit

- DPFs filter solid particles via physical phenomenon such as diffusion, interception, and impaction. In principle, a DPF can be designed to result in high efficiency under:
  – Engine cold or hot-start operation
  – Ambient cold or hot environment
  – High or low altitude
  – Hybrid with frequent engine start and stop

Application of Particle Filters to Non-Diesel

- High efficiency exhaust particle filters provide a rare opportunity to reduce soot and ash from any combustion source under different environmental and operating conditions
  - The benefit from a particle filter should be recognized when addressing emissions from:
    - gasoline, natural gas, off-road, locomotive, marine, and even jet engines (how about having a jet engine with an exhaust particle filter; don't tell the passengers though)

Two Aftertreatment Configurations for a GDI Engine

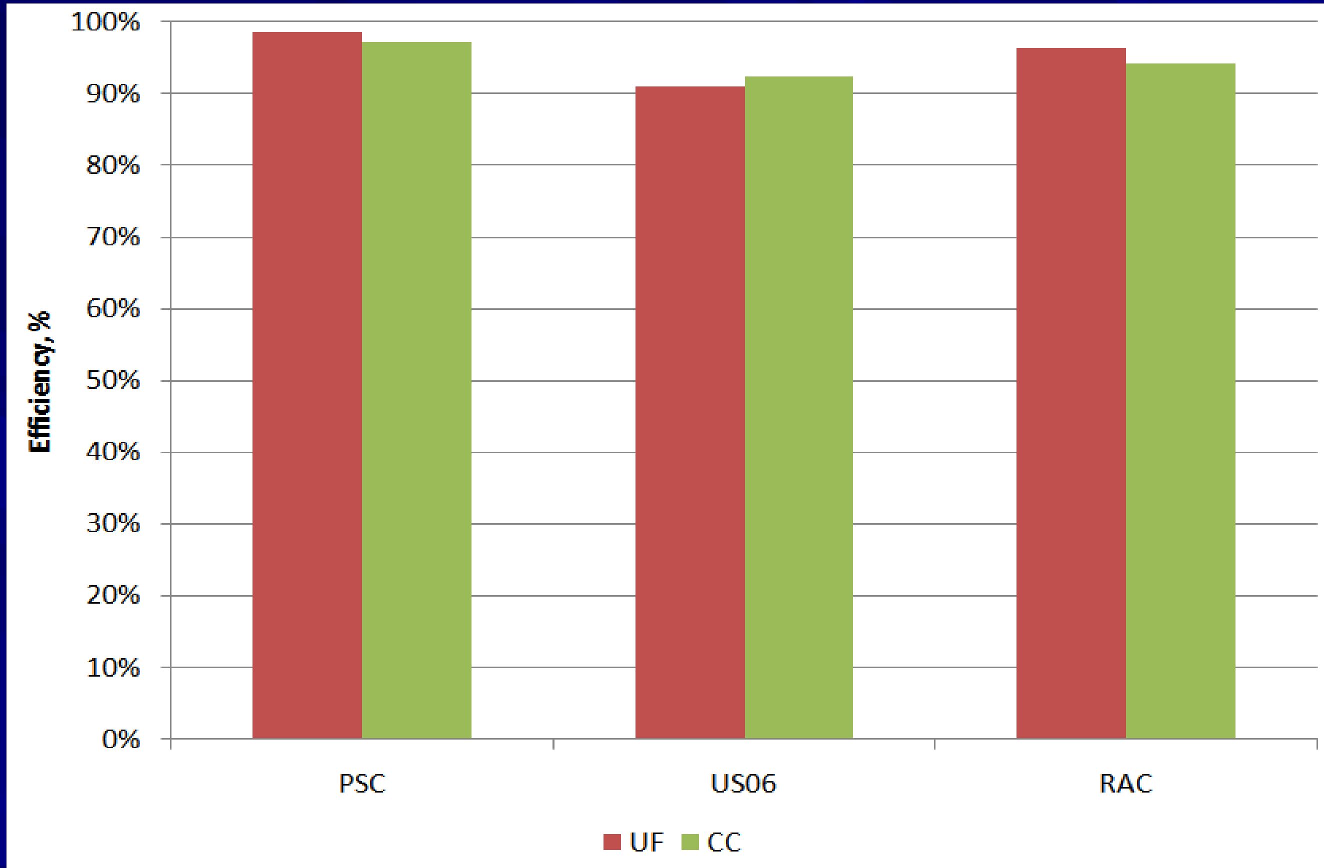


System	Close-coupled (CC) Catalyst			Under-floor (UF) Catalyst		
	Type/Dimension	PGM	REO	Type/Dimension	PGM	REO
CC	GPF, 14.4X15.2cm 200 cpsi	Low	Very Low	TWC, 19.1X 12.7cm 400 cpsi	Medium	High
UF	TWC, 14.4X15.2cm 400 cpsi	High	High	GPF,14.4X15.2cm 200 cpsi	Low	Very Low

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



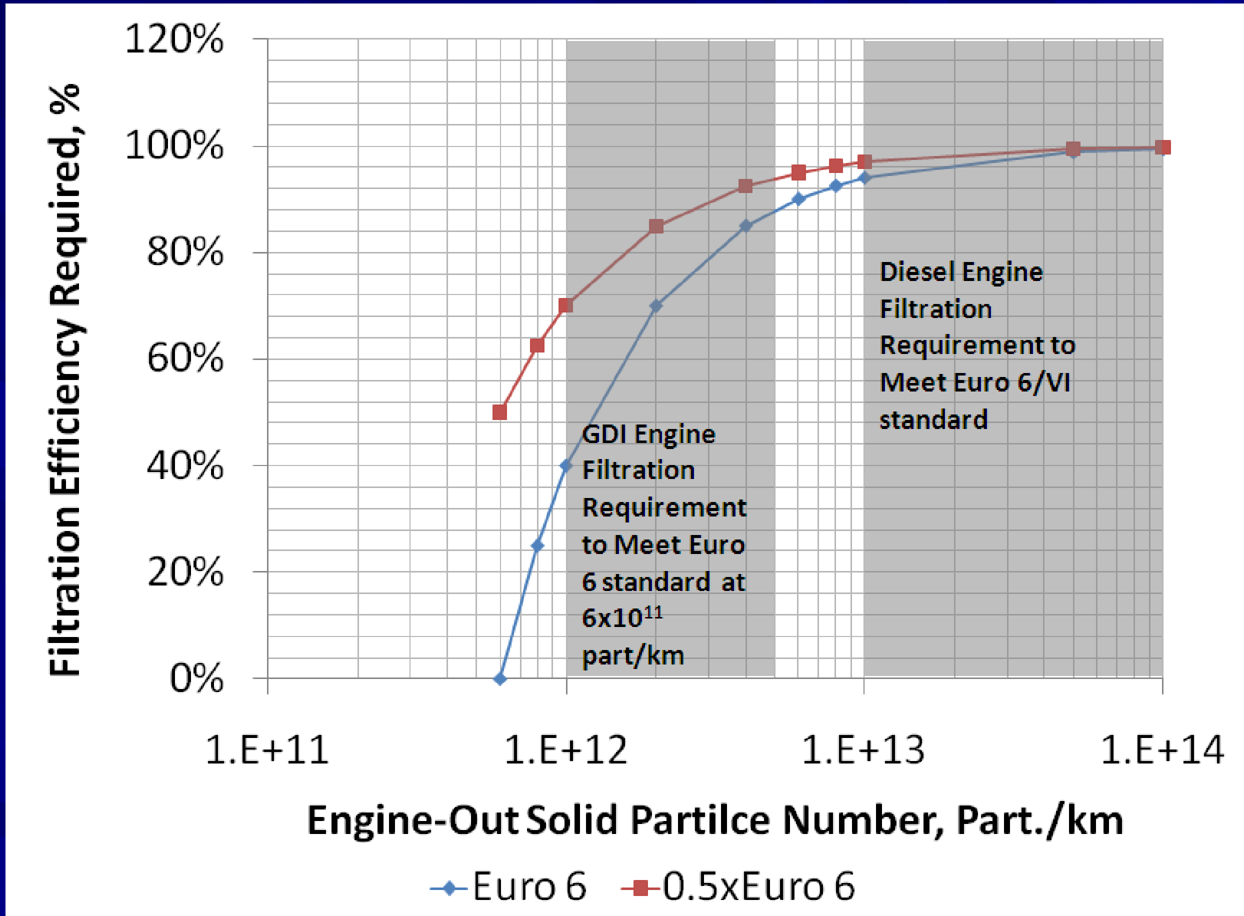
- ***PSC***: Pseudo Steady-state Cycle (13-mode)
- ***RAC***: Rapid Acceleration Cycle
- ***US06***: Simulated US06 Cycle

GPF/DPF Requirement

- 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 x 10^{11} part./km

- No GPF will be needed to meet CARB LEV III with stoichiometric GDI

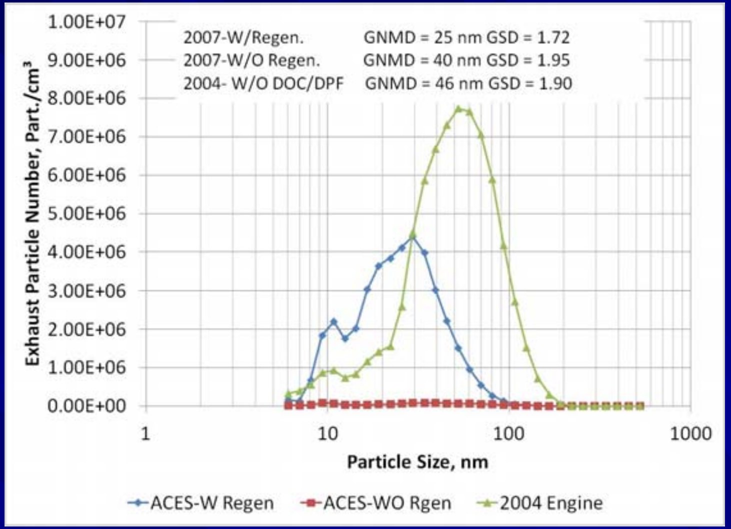


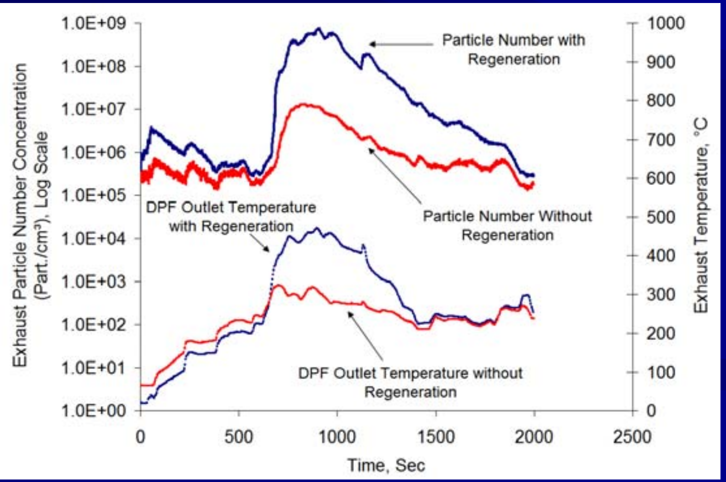
Summary

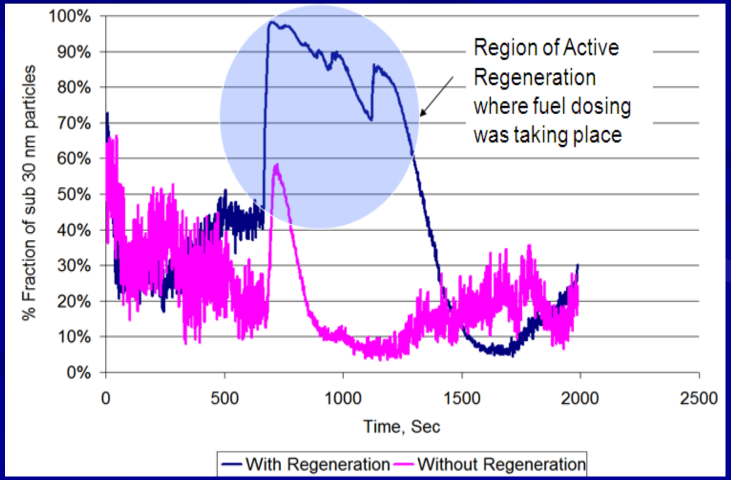
- The use of high efficiency filters in diesel engine exhaust has enabled the diesel engine to be PM-free emissions source, with significant reduction in:
  - Elemental and Organic Carbon
  - Elements including metallic ash
  - Unregulated Emissions (PAHs, Dioxins, etc…)
  - SOA Formation
  - Off-cycle emissions
- Other non-diesel emissions sources can benefit from exhaust particle filters, especially in the area of soot and ash reduction, and sub-23 nm particle size range

Problem Area 1

- Volatile Nanoparticle formation:
  - Storage and Release
  - Active DPF Regeneration
    - The frequency of active regeneration has been reduced in 2011 heavy-duty diesel engines with SCR.
      - The question then, what happens when the DPF is actively regenerated, less frequently



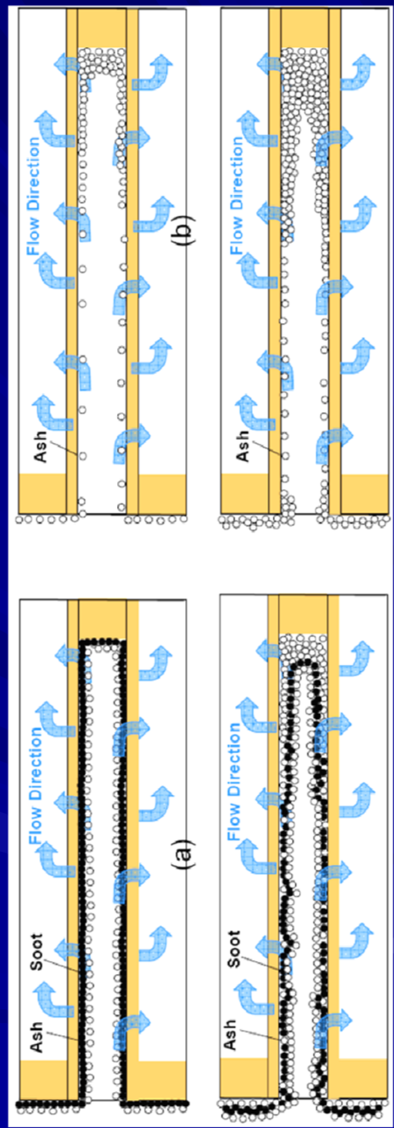




Fujii et al., 2010-01-2171

Problem Area 2

- Ash Loading
  - Metallic ash from the lube oil is trapped in the DPF, causing an increase in engine backpressure as a function of time
    - Traps are required to be cleaned before their life time warranty in heavy-duty engines-~435,000 miles, ~150,000 in light duty
    - What happens after life time?
    - Do we keep managing this problem or do we have an engineering solution for it?
  - Less frequent active DPF regeneration in modern engines is changing the landscape of ash distribution, affecting backpressure rise as a function of time
    - Higher backpressure



Problem Area 3

- DPF field failure detection (cracks, leaks, etc…)
  - In-Use Testing (not enough)
  - Inspection and Maintenance (not enough)
  - Onboard particle sensor monitoring is a key enabler for the continuous success of the DPF technology
    - SwRI has recently launched a particle sensor performance & durability (PSPD) consortium (work in progress) to investigate current technology particle sensing and what metric of PM they measure

Current and Future Research

- Making progress to eliminate potential counter benefit from the use of DPFs is key to their success in the long term:
  - Eliminate volatile nanoparticle formation
    - Better catalysis
    - Better engine thermal management
    - Reduced fuel and oil sulfur
  - Eliminate Ash loading:
    - More tolerant DPFs
    - Improved Oil consumption
    - Ash Reduction in lube oil
  - Manage DPF field performance failure
    - Onboard particle sensing for OBD, using well defined particle sensor performance and metric. Not dealing with failed DPFs in the field can have a significant draw back to the successful implementation of exhaust particle filters