Reducing Particulate Emissions for Future Gasoline Direct Injection Vehicles with a Gasoline Particulate Filter

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Background:

Gasoline direct injection (GDI) vehicles are receiving increased attention by auto manufacturers due to their better fuel economy and reduced CO_2 emissions [1]. At the same time, studies also showed that particle emissions from GDI vehicles could be higher than that from traditional port fuel injection (PFI) gasoline vehicles [1, 2]. Particle emissions from GDI vehicles can be reduced through adjusting the air/fuel ratio, fuel injection strategy (e.g., timing, number of injections, injection pressure), combustion phasing, and engine temperatures, which change the vehicle emission profile [3, 4]. A post-emission control strategy such as a gasoline particulate filter (GPF) may also be utilized to control particle emissions [5].

In this study, gaseous and particle emissions were quantified on a 2011 model year GDI vehicle (Hyundai Sonata; 2.4 L; 3220 km) and a 2010 model year PFI gasoline vehicle (Volvo S40; 2.4 L; 6523 km). Both vehicles contained a catalytic emission control system configured with converters in the close coupled underfloor positions. Emission tests were performed on either Tier 2 certification gasoline or a splash blended 10% by volume ethanol gasoline mixture. The U.S. Federal Test Procedure 75 (FTP-75) and US06 Supplemental Federal Test Procedure (US06) were used to evaluate the impact of driving conditions on particle emissions. A sub-set of the experiment was conducted on the GDI vehicle with a gasoline particulate filter (GPF) installed. This non-catalyzed, wall-flow, passively regenerated GPF was provided by the Manufacturers of Emission Controls Association (MECA) and has a dimension of 5.66" (14.4 cm) in diameter and 6" (15.2 cm) in length. The GPF cell density is 200 cpsi with 12 mil (0.3 mm) wall thickness and approximately 50% wall porosity.

The particle emissions were measured by two systems. The first system was the European Union Particle Measurement Programme (PMP) solid particle system, which was developed to measure the solid particle number concentration from the diluted exhaust. In addition, a TSI 3776 ultrafine Condensation Particle Counter (UCPC) was included in the PMP system to provide additional information on the existence of any ultrafine particles that were not detected by the PMP methodology. In the second system, a TSI 3090 Engine Exhaust Particle Sizer was installed downstream of a Dekati thermodenuder to measure the particle number size distribution in real time.

Particle emissions:

Figure 1(a) shows the average particle number size distributions for the stock GDI, GDI post-GPF, and PFI configurations over the FTP-75 drive cycle on E0 and E10. E10 had a small impact on particle emissions for both the stock GDI and PFI configurations. In comparison, the stock GDI configuration had a much higher particle number emission rate than the PFI vehicle as well as a Euro 4 light-duty diesel vehicle equipped with a diesel oxidation catalyst and a catalyzed diesel particulate filter (Peugeot 206; 1.6 L; 22,400 km). On the other hand, the particle number emission rate from the GDI post-GPF configuration was reduced significantly to a level below the emission level from the light-duty diesel post-DPF configuration but still higher than that from the PFI configuration. Using stock GDI emissions as a reference, the GPF was able to reduce the solid particle number emissions by 80-82% for the FTP-75 drive cycle under room temperature conditions (Figure 2(a)).

In general, particle emissions for all configurations over the US06 drive cycle were significantly lower than that from the FTP-75 drive cycle due to the warm-start of the engine (Figures 2(a) and 2(b)). Among all vehicles, the particle number emission rate from the light-duty diesel vehicle was the highest, followed by that from the GDI and then the PFI vehicles. The solid soot particles with 40-80 nm diameters were still observable from the GDI post-GPF configuration but the number concentration was greatly reduced by over 70% from the stock GDI level (Figure 2(b)). In comparison, the PFI vehicle had very low solid particle emissions but emitted many ultrafine particles with diameter as small as 10 nm during the aggressive driving condition. Emissions of ultrafine particles were also observed from the light-duty diesel vehicle.

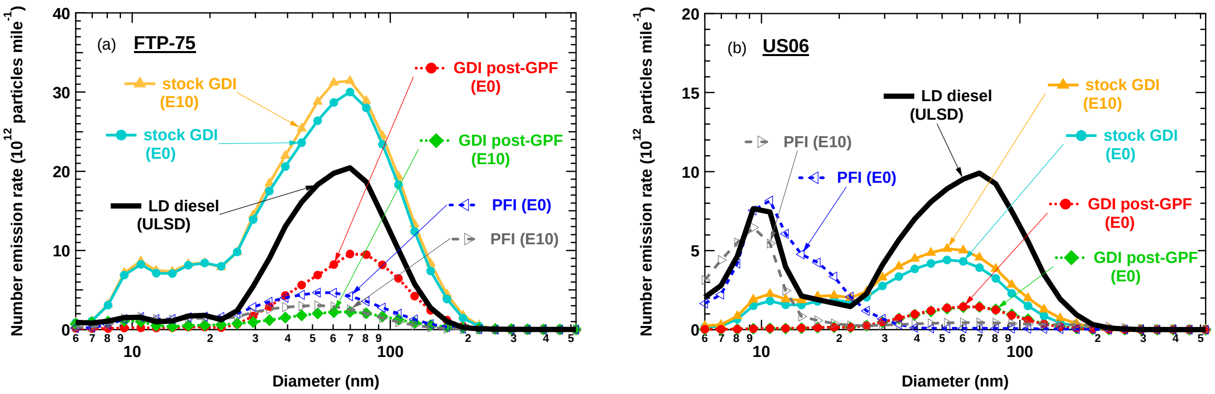


Figure 1: (a) Average particle number size distributions over the FTP-75 and (b) US06 drive cycles for the various vehicles, fuels, and configurations.

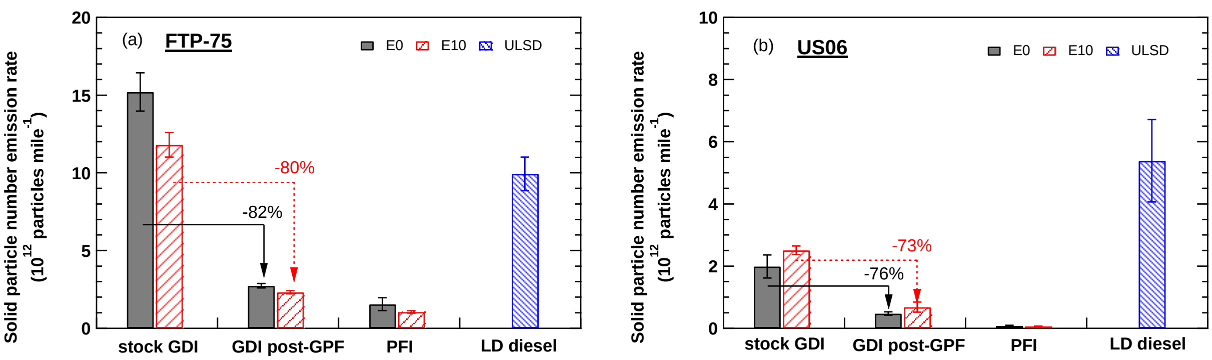


Figure 2: Particle number emission rate over the (a) FTP-75 and (b) US06 drive cycles for various configurations.

GPF soot regeneration:

A separate experiment, consisting of multiple cold-start Los Angeles Route Four (LA4) drive cycles, was carried out to investigate the different particle filtration efficiencies over the FTP-75 and US06 drive cycles. Figure 3(a) summarizes the ultrafine particle number concentration time series over a LA4 drive cycle. The thin black line represents emissions from the stock GDI configuration, whereas the thick red line and the dashed orange lines represent the emissions from the 1st (clean GPF) and the 4th LA4 (conditioned GPF) drive cycles, respectively. At 300 seconds from the start of the cycle, the post-GPF emissions had already dropped to about one tenth of what was emitted from the stock GDI configuration using an unconditioned GPF. Further towards the end of the cycle, the post-GPF emissions were at least two orders of magnitude lower than what was emitted from the stock GDI configuration. Real time particle data, together with the pre- and post-GPF temperatures suggested that the exhaust temperature generated from a LA4 (or FTP-75) drive cycle operated at room temperature was not enough to trigger soot regeneration and thus led to continued build up of a soot layer which improved the particle filtration efficiency over the subsequent tests. Results showed that an average particle filtration efficiency of 94% was achieved by the 4th cold-start LA4 drive cycle (Figure 3(b)).

Test results also revealed that the aggressive US06 drive cycle generated enough heat to trigger multiple soot regenerations in the GPF. Data also suggested that the soot layer was destroyed and rebuilt continuously over the drive cycle. As a result, a relatively lower particle filtration efficiency over the US06 drive cycle was observed compared to the FTP-75 drive cycle.

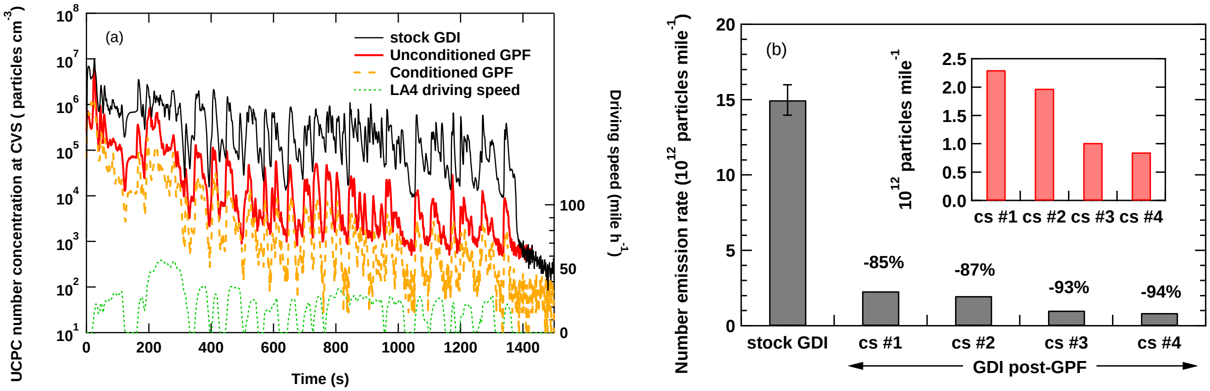
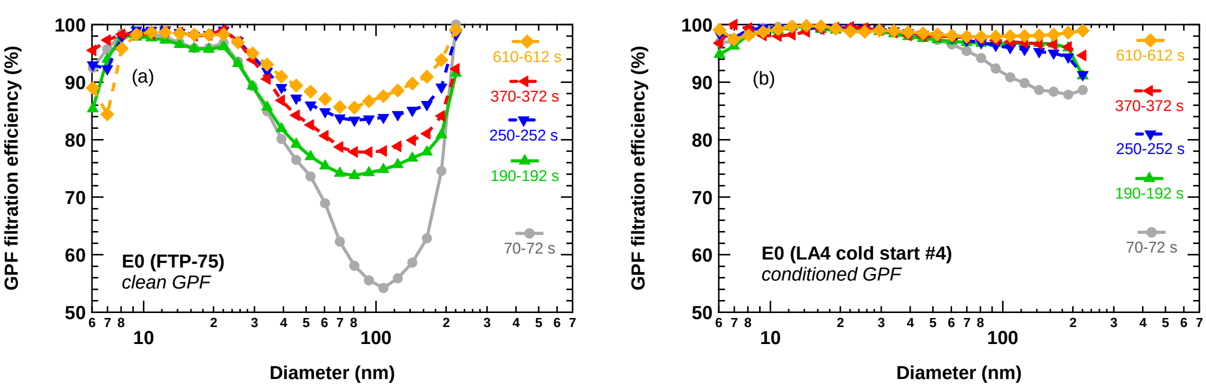


Figure 3: (a) Particle number concentration time series over the LA4 drive cycle for stock GDI and post-GPF configurations. (b) Particle number emission rates for various cold-start LA4 drive cycle for various configurations.

Gasoline particulate filter particle filtration efficiency:

The particle filtration efficiency of the GPF was further investigated by comparing the second-by-second particle number size distributions obtained from the stock GDI and post-GPF configurations over the different drive cycles. Measurements from various repeats were first aligned with the drive cycle to correct for measurement delays. Then a number of 3-second time intervals were pre-selected such that all measurements that were acquired within these intervals from all repeats were averaged. Finally, the evolution of the particle filtration efficiency, as a function of particle diameter, was derived based on the stock GDI and post-GPF measurements.

Figure 4(a) shows the evolution of the particle filtration efficiency over the FTP-75 drive cycle at room temperature operated on E0. Filtration efficiencies for particles with diameters larger than 250 nm were excluded due to their low number concentration. Results showed that the GPF was effective in removing ultrafine particles. Results also showed that there was a general progressive improvement of the particle filtration efficiency over time during the FTP-75 drive cycle which is consistent with the real time particle number concentration measurements. Figure 4(b) shows the particle filtration efficiency over time for the 4th LA4 drive cycle. This shows that a 95% overall filtration efficiency across all particle diameters was reached within 250 seconds from the start of the cycle implying the importance of the accumulated soot in contributing to particle filtration in the GPF. In comparison, Figure 4(c) shows the evolution of the particle filtration efficiency over the US06 drive cycle. The lack of progressive improvement of the filtration efficiency is an indication of the continued destruction and rebuilding of the soot layer in the GPF during the course of the US06 drive cycle. Furthermore, the data also indicate close to zero filtration efficiency for the 100 nm soot particles near the end of the cycle suggesting one US06 drive cycle is enough to completely remove any accumulated soot in the GPF in this case.



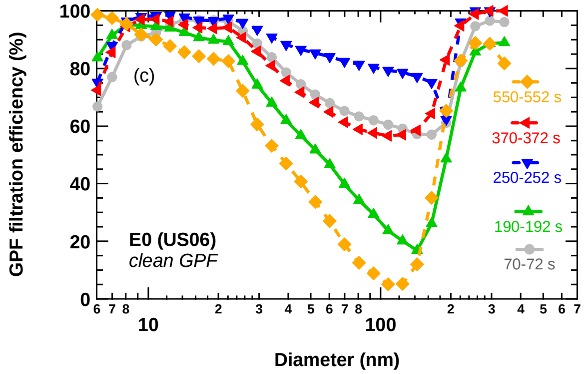


Figure 4: Evolution of the particle filtration efficiency as a function of particle diameter over (a) the FTP-75 drive cycle with an unconditioned GPF, (b) the 4th LA4 drive cycle with a conditioned GPF, and (c) the US06 drive cycles.

Conclusion:

This study compared the particle and gaseous emissions between a 2011 model year gasoline direct injection (GDI) vehicle and a comparable port fuel injection (PFI) vehicle over the U.S. Federal Test Procedure 75 (FTP-75) and US06 Supplemental Federal Test Procedure (US06) on Tier 2 certification gasoline and 10% by volume ethanol gasoline mixture (E10). Results showed that E10 on a PFI vehicle generally led to lower particle emissions. For the GDI vehicle, E10 led to a reduction in solid particle emissions over the FTP-75 drive cycle but the opposite was observed for the US06 drive cycle. Solid particle emissions from the GDI vehicle were generally higher than the PFI vehicle over both drive cycles. When the GDI vehicle was equipped with a gasoline particulate filter (GPF), the solid particle number emissions approached that of the PFI vehicle, and were lower than the particle number emissions from a Euro 4 light-duty diesel vehicle equipped with a diesel oxidation catalyst and a catalyzed diesel particulate filter. Results from this study suggest that the GPF is an effective post-emission control device for the increasingly popular GDI vehicles. For a non-catalyzed GPF, the soot regeneration in the GPF was mostly triggered by the exhaust temperature and thus, the emission control performance was closely linked to vehicle operating history. This implies that the vehicle/engine emission test procedures and the pre-test vehicle preparation are important.

References:

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Project objective

Rationale

- With increased production of vehicles equipped with gasoline direct injection (GDI) engines there is a need to understand the impact of recent GDI technologies on PM formation, emission rates, and secondary aerosol precursor emissions.

Scope

- Characterize gaseous and particulate emissions from a GDI passenger vehicle and a comparable port fuel injection (PFI) vehicle:
  - Under different operating conditions (**city vs. highway driving**; N. American FTP-75 vs. European NEDC drive cycle);
  - Under different ambient temperatures (**22 ºC**, -7 ºC, -18 ºC);
  - With various ethanol fuels (**E0, E10**, E15, E20);
  - Fuel consumption benefit on GDI over PFI (transient and steady states);
  - With iso-butanol fuels (B16);
  - With various exhaust configurations (**with and without GPF on GDI**).

Findings

- The gasoline particulate filter (GPF) is effective in reducing particulate matter and particularly ultrafine particles.
- GPF particle filtration efficiency can be improved substantially with even a small amount of accumulated soot in the filter.
- With an unconditioned GPF, solid particle filtration efficiency was typically 80+% for the FTP-75 drive cycle at room temperature. With a conditioned GPF, filtration efficiency increased to 95+% after 250s of the start of the FTP-75 drive cycle.
- The driving condition of the US06 drive cycle was enough to trigger GPF soot regeneration while no or limited regeneration occurred during the FTP-75 drive cycle.
- GPF filtration efficiency for US06 drive cycle was 73+% at room temperature due to multiple GPF soot regenerations.
- No statistically significant impact on fuel consumption with the use of GPF.
- Fuel consumption on the tested GDI vehicle is typically 3-9% better than tested PFI vehicle during transient driving and 20-22% better at steady state (60–120 km/hr).
- E10 has small impact on particle emissions on GDI and PFI vehicles.

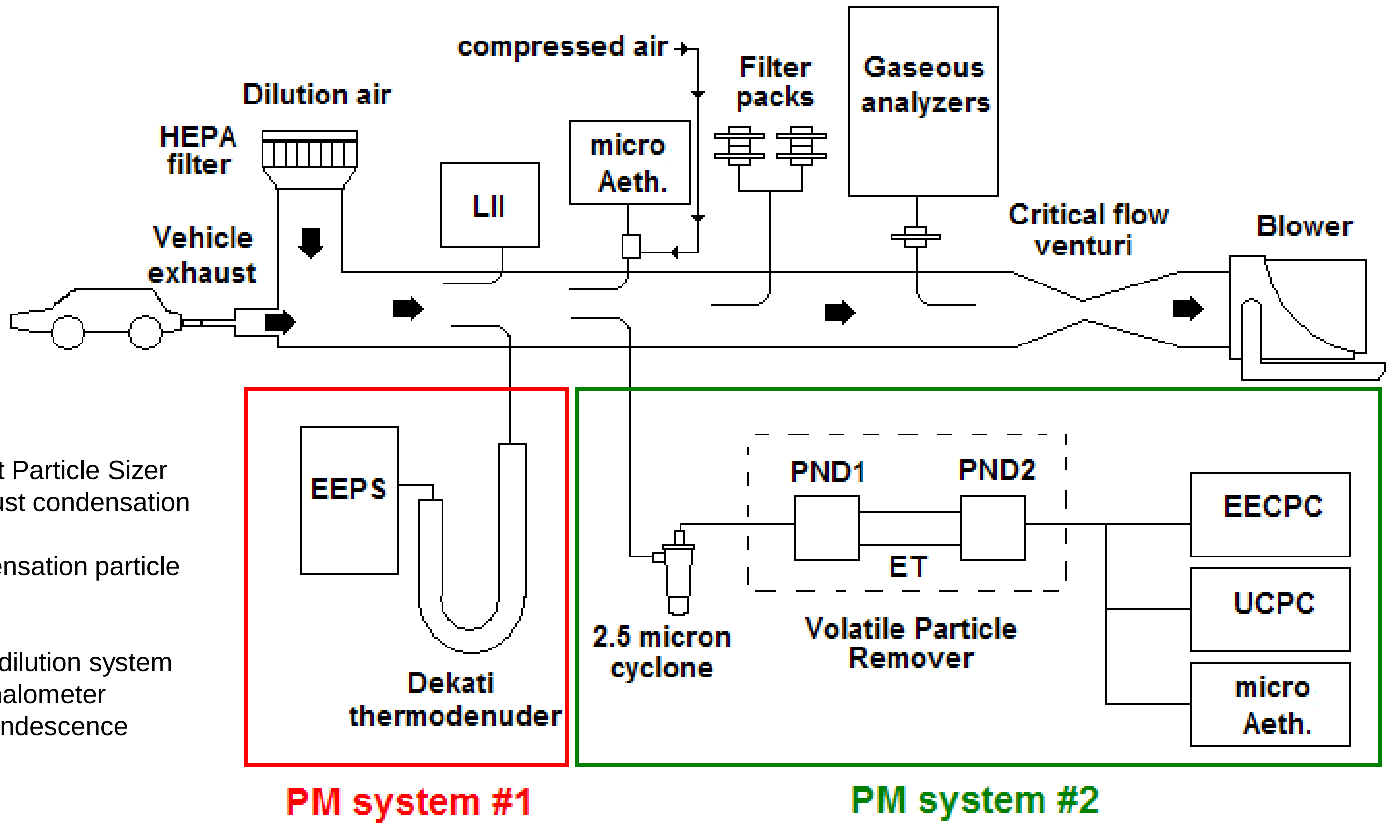
Test vehicles

- 2011 Hyundai Sonata GDI
- 2.4 L
- 3-way catalyst
- 198 HP
- 1,590 kg
- Tier 2 bin 5 (N. American)
- 3,220 km

- 2010 Volvo S40
- 2.4 L
- 3-way catalyst
- 168 HP
- 1,648 kg
- Tier 2 bin 5 (N. American)
- 6,523 km

- 2005 Peugeot 206 S16
- 1.6 L
- DOC + catalyzed DPF
- 110 HP
- 1,130 kg
- Euro 4 (European)
- 22,400 km

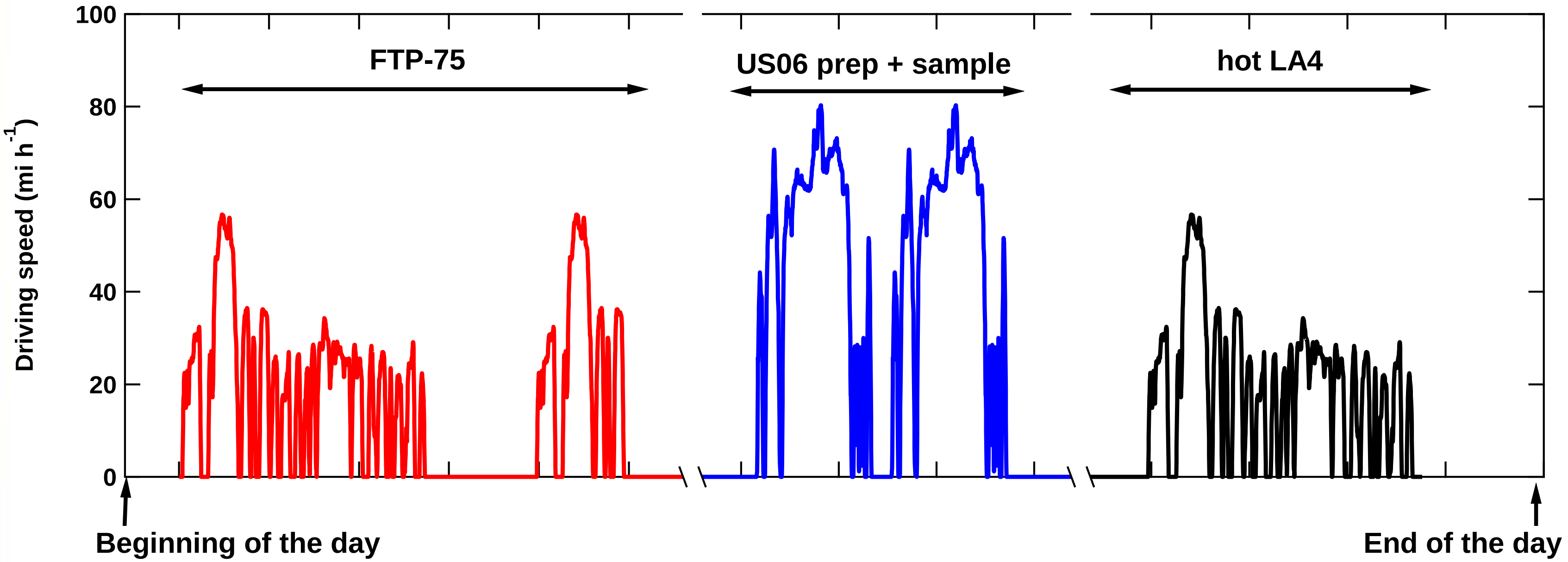
Experimental setup



EEPS: Engine Exhaust Particle Sizer
EECPC: Engine Exhaust condensation particle counter
UCPC: Ultrafine condensation particle counter
ET: Evaporation tube
PND: Particle number dilution system
Micro Aeth: micro Aethalometer
LII: Laser induced incandescence

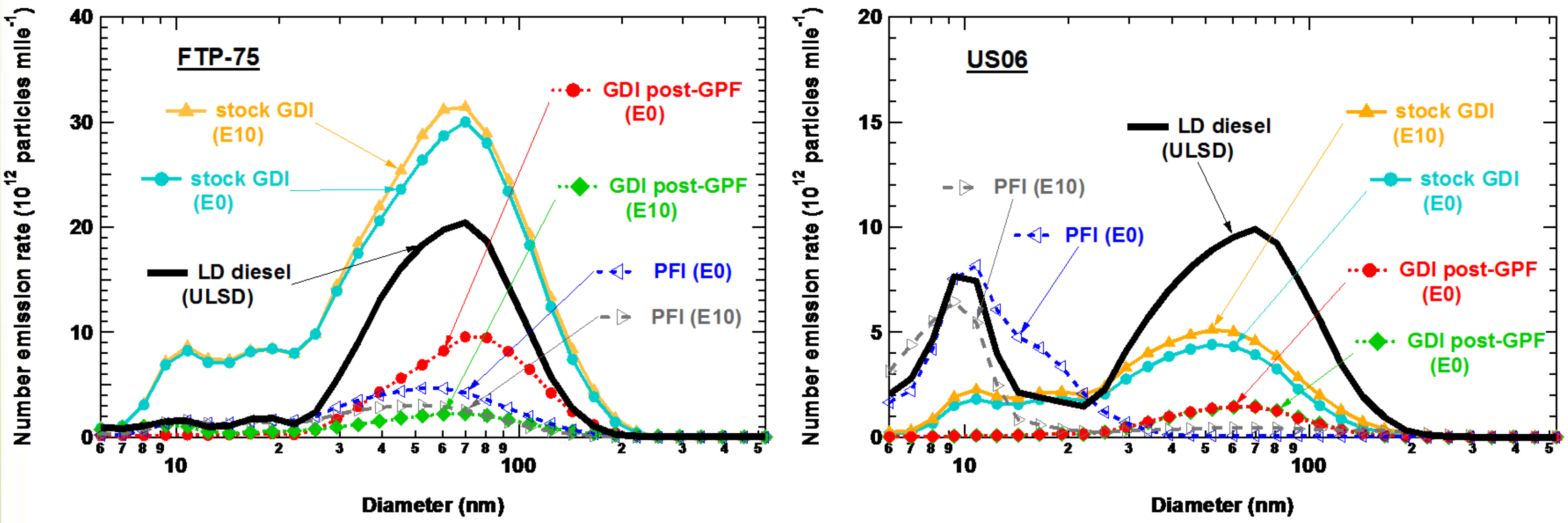
Test sequence

- Typical test day follows the following test routine. This may have had significant impact on GPF filtration efficiency and future testing consideration.



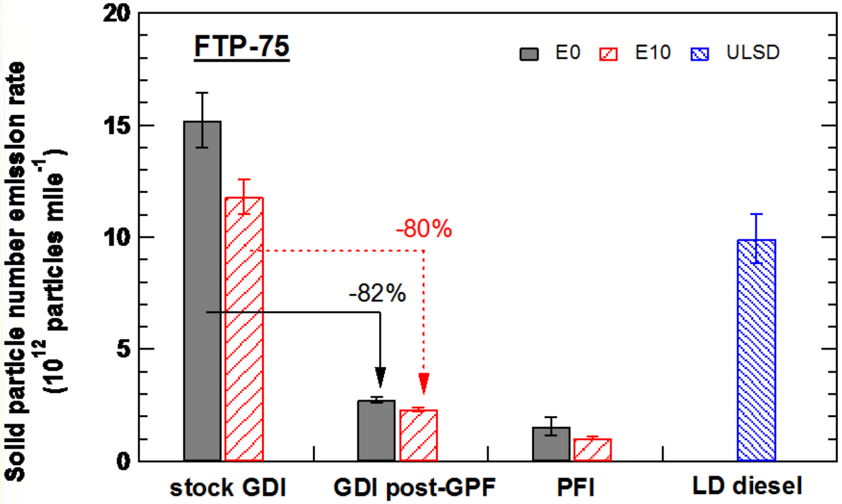
- Over 430 tests completed so far (6+ months):
  - (190+ FTP-75, 180+ US06, 30 NEDC, 20 steady states)

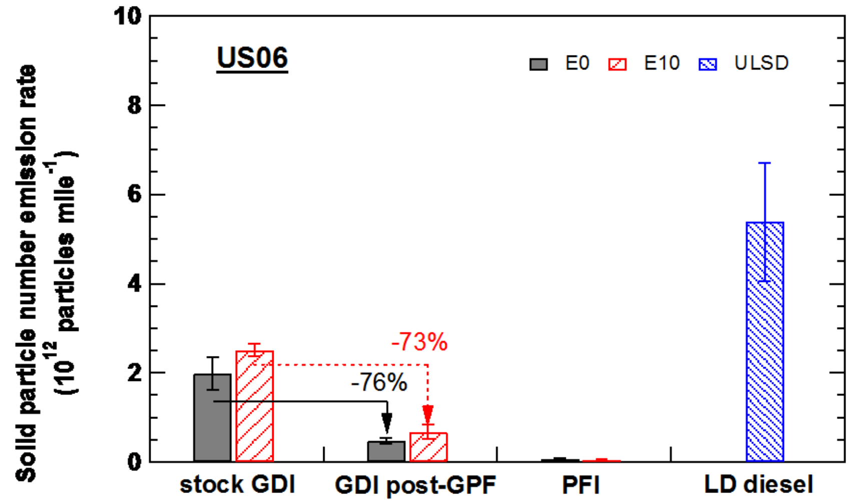
Particle number size distributions



- E10 had small impact on particle size distributions for both gasoline direct injection (GDI) and port fuel injection (PFI) vehicles at room temperature.
- Gasoline particulate filter (GPF) almost completely eliminated any ultrafine particles.
- Generally, GPF particle filtration efficiency was higher for FTP-75 drive cycle than US06 drive cycle.
- GPF was able to reduce particle number emissions from the GDI vehicle to below a Euro 4 light-duty diesel vehicle emission level.

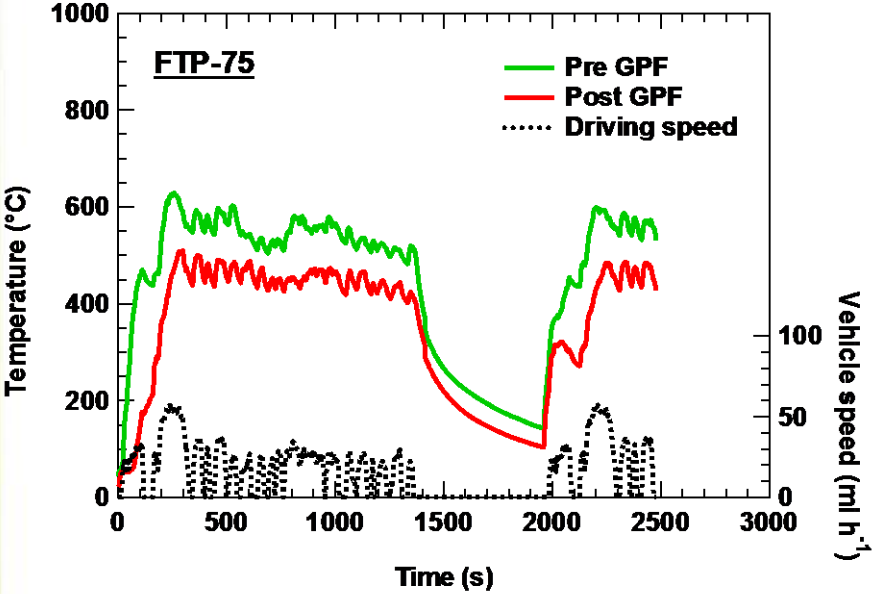
Particle number emission rates

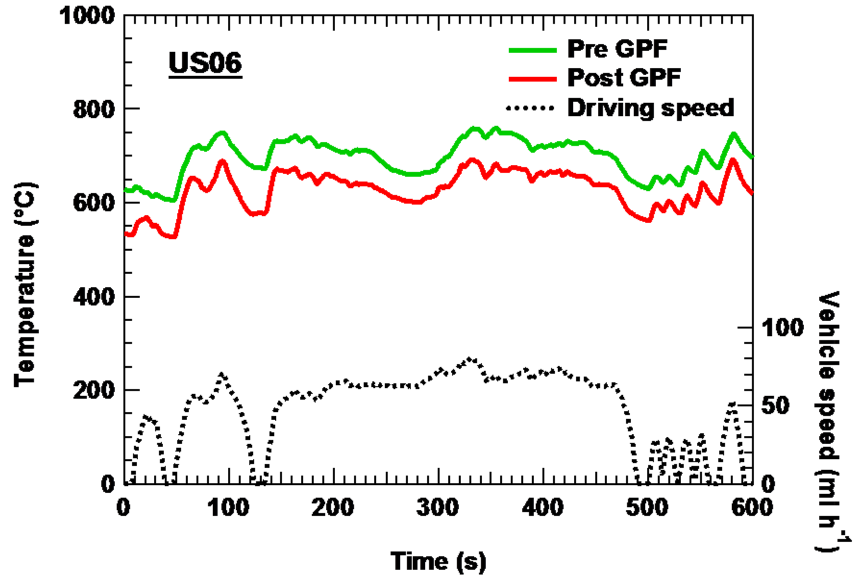




- Using an unconditioned gasoline particulate filter (GPF) at room temperature, average solid particle filtration efficiency reached 80% or above over the FTP-75 drive cycle and 73% or above over the US06 drive cycle.
- Solid particle emissions during cold-start on a gasoline direct injection (GDI) vehicle was much higher than that from a port fuel injection (PFI) vehicle. But this is just slightly higher than the particle number emissions from a Euro 4 light-duty diesel vehicle with diesel oxidation catalyst and diesel particulate filter.
- GDI post-GPF particle number emissions from both cycles were lower than that from the Euro 4 light-duty diesel vehicle despite the larger weight and higher horsepower.

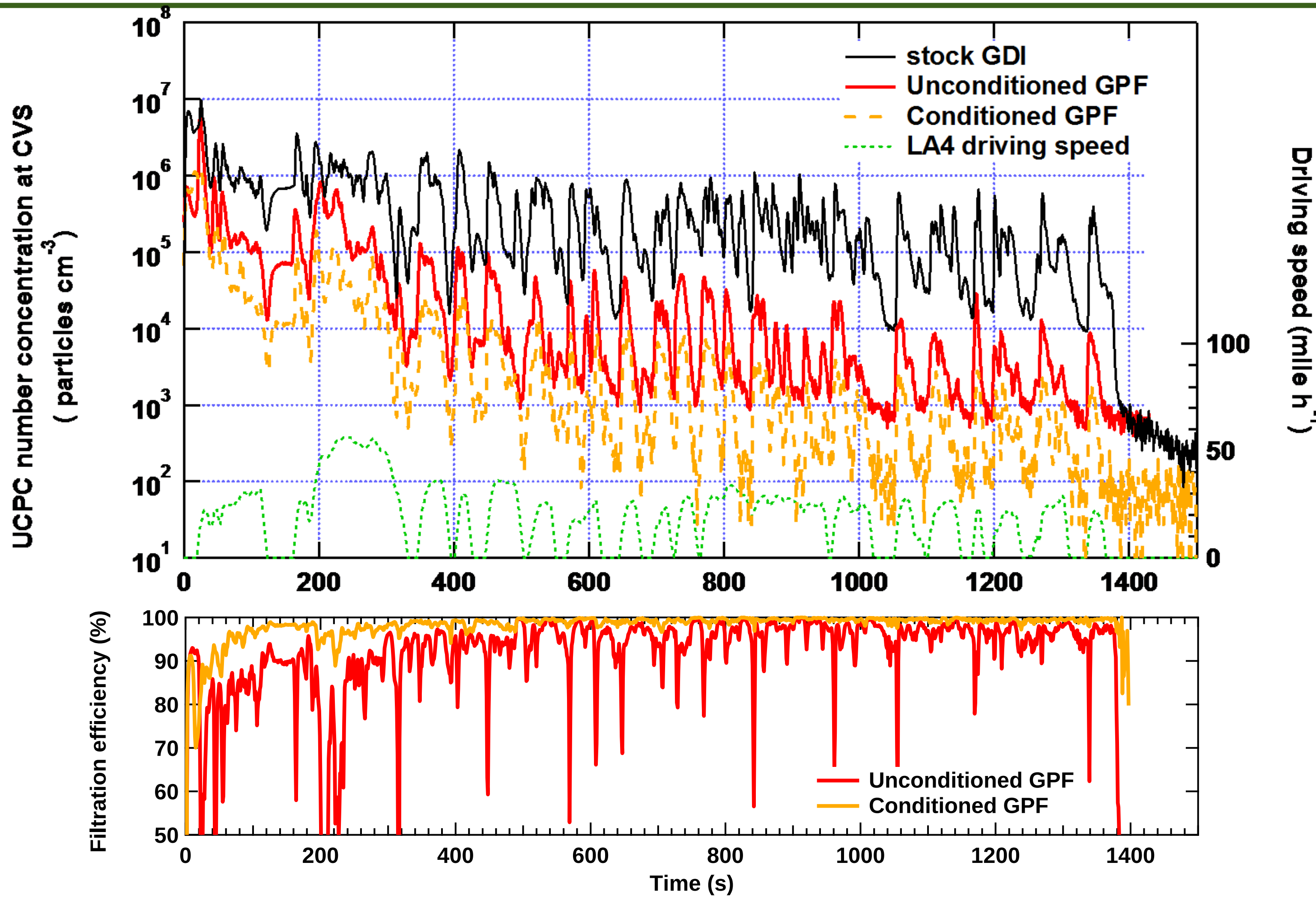
Temperature and pressure



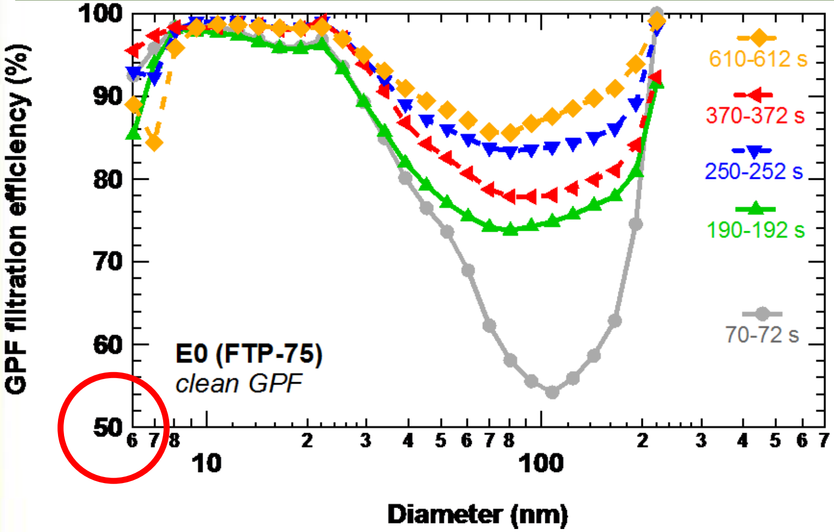


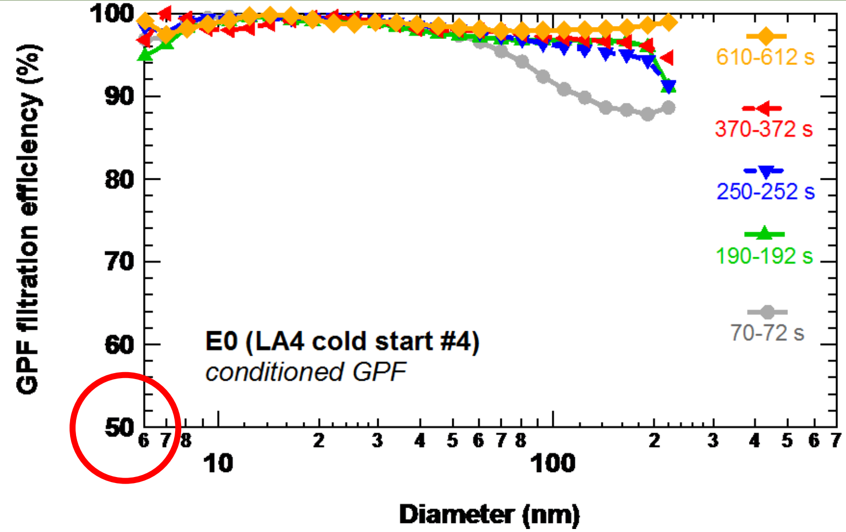
- The presence of the gasoline particulate filter (GPF) has little impact on exhaust temperatures.
- Post GPF temperature over FTP-75 was typically below 600 ºC but above 600 ºC for US06.
- Assuming GPF soot regeneration occurs when post-GPF temperature reaches 600-650 ºC, soot regeneration is likely to happen over the US06 drive cycle at various moments over the cycle. Limited or no soot regeneration is expected over the FTP-75 or LA4 drive cycles.

Number concentration time series

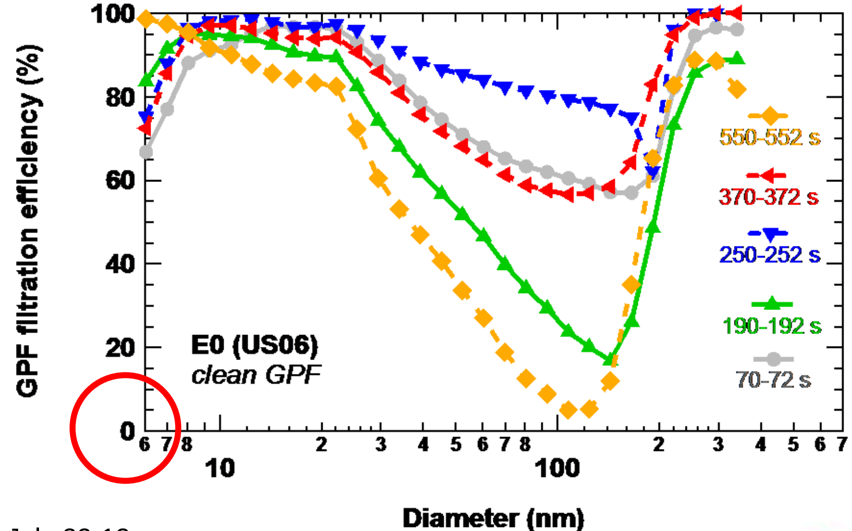


Evolution of particle filtration efficiency





- Particle filtration efficiency gradually improved over the FTP-75 drive cycle due to the build up of soot layer.
- Significant improvement of particle filtration efficiency over subsequent cold-start LA4 drive cycles.
- No temporal pattern for particle filtration efficiency over the US06 drive cycle due to continued destruction and rebuilding of soot layer.



Planned and proposed follow up work

- Additional gasoline direct injection (GDI) technology
  - GDI vehicles from different manufacturers
  - More new GDI vehicles (wall guided vs. spray guided)
  - Vehicles with direct injection and port fuel injection under the same vehicle platform
  - Older GDI vehicles
  - Aged GDI vehicles
- Iso-butanol renewable fuel
  - Various blend levels
  - Various ambient temperatures
- Gasoline particulate filter (GPF) work – pending partner support and interest
  - Filtration efficiency on aged GPF

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  - Environment Canada Renewable Fuels Strategy - Oil Gas and Alternative Energy Division
  - MECA