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Dilution Artifacts. A Significant Source of Error from Absolute Concentration and Possibly Difficult to Reproduce. PMP vs. Raw Exhaust.

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Extended abstract

1. Background

The European legislation for Particle Number (PN) emission limits requires measurement of solid particles >23nm. This is realized by following the “PMP procedure”, which consists of a “Volatile Particle Remover” followed by a particle counter with a 50% counting efficiency at 23nm particles. The removal of volatiles was addressed in order to avoid artifacts due to semi-volatile and volatile species which are formed by condensation-nucleation during the dilution and the subsequent cooling of the exhaust gas.

However, the PMP procedure is being criticized because a fraction of the exhaust gas particles is left out of measurement control. This fraction was rather low for older vehicles; however the development of new engine technologies shifted the particle size distribution towards smaller particles, hence leaving even more particles uncontrolled. In addition, particle accumulation inside the sampling system can lead to particle losses and artifacts, as particles can be desorbed from the walls when the exhaust gas temperature increases. The PMP-compliant sampling also requires expensive equipment with precise measurement of the dilution parameters as well as calculation of size specific particle losses (i.e. Particle Concentration Reduction Factor - PCRF).

In this paper we present a different approach to particle number measurement, the Pegasor Particle Sensor (PPS), which measures the undiluted, raw exhaust. The PPS is compared against PMP-compliant devices and sampling artifacts are explored.

2. Experimental Details

The PPS was installed in parallel with PMP-compliant devices during tests with a Euro 5 compliant diesel passenger car and a heavy duty (HD) diesel engine.

The HD tests focused on the performance of the PPS against a PMP-compliant instrument, the AVL Particle Counter (APC) during a Ramped Mode Cycle (RMC) test, with both instruments sampling from the tailpipe.

The vehicle tests consisted of sampling during a cold start NEDC (New European Driving Cycle) as well as during DPF regeneration events over steady speed tests. Moreover, a different approach on volatile particle removal was investigated, by placing a catalytic stripper (CS) upstream of a second PPS sensor, which was connected to the Constant Volume Sampler (CVS). The reference instruments used was the PMP-compliant "AVL Particle Counter" (APC) and the Dekati Electrical Low Pressure Impactor (ELPI) sampling downstream of a VPR. In addition, a test with a light duty diesel engine was conducted in order to evaluate the different PCRF settings of the APC and the effect on the resulting particle concentration during a steady state engine mode. The APC was sampling from the tailpipe and no aftertreatment devices were used.

3. Results

3.1. HD Engine Tests

The HD engine tests during the RMC cycle have shown an excellent correlation with the reference instrument (R^2=0.95). The absolute level of the correlation showed that the PPS reports approximately 80% higher particle number compared to the APC. The two instruments were also consistent during the transition points between different engine modes.

3.2. Passenger Car Tests

The performance of the two PPS sensor configurations at the different sampling positions during the cold-start NEDC test is shown in Figure 1. In terms of response, both PPS configurations were very consistent with the APC. The tailpipe PPS showed somewhat higher peaks compared to the PPS at the CVS, while the APC reported somewhat lower particle number during the acceleration parts compared to both PPS.

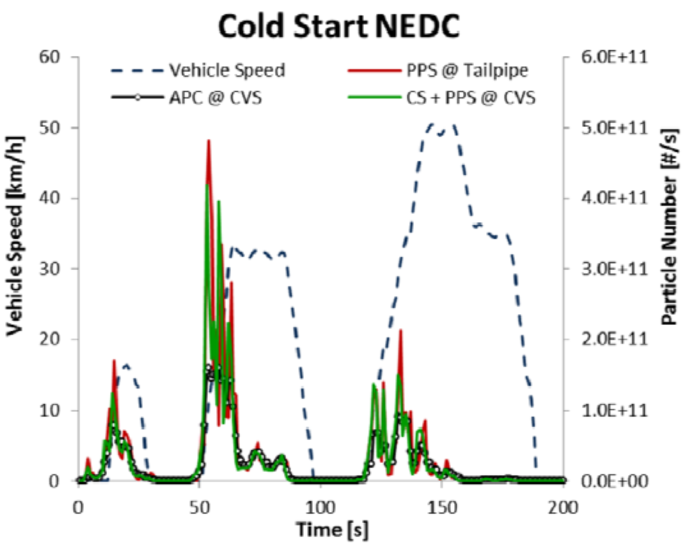

Figure 1: Comparison of the PPS (tailpipe), CS+PPS (CVS) and APC (CVS) during a cold-start NEDC test of a diesel passenger car.

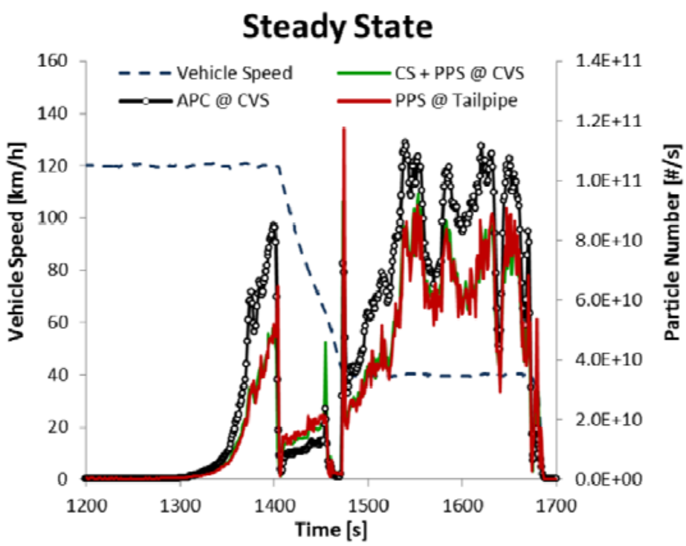

Figure 2: Comparison of the PPS (tailpipe), CS+PPS (CVS) and APC (CVS) during a steady speed with a DPF regeneration event.

Moreover, the comparison of the PPS sensors with the APC during a DPF regeneration event (Figure 2) showed a distinct deviation between the two PPS sensors and the APC response, with the latter reporting higher particle number. The peak of the CS+PPS signal around 1450s is an indication of particles generated from the CVS due to desorption, which was not detected from the PPS sampling at the tailpipe.

Additional testing with a Euro 4 compliant diesel vehicle with the PPS sampling in parallel with an APC and an ELPI during a cold start NEDC showed a generally good agreement. The cumulative particle number during the cycle (Figure 3) has shown that the discrepancies between the 3 instruments occurred mostly during the acceleration parts of the cycle. Also, the APC was consistent with the PPS and ELPI during the low speed part of the cycle, but showed higher particle number during the high speed part.

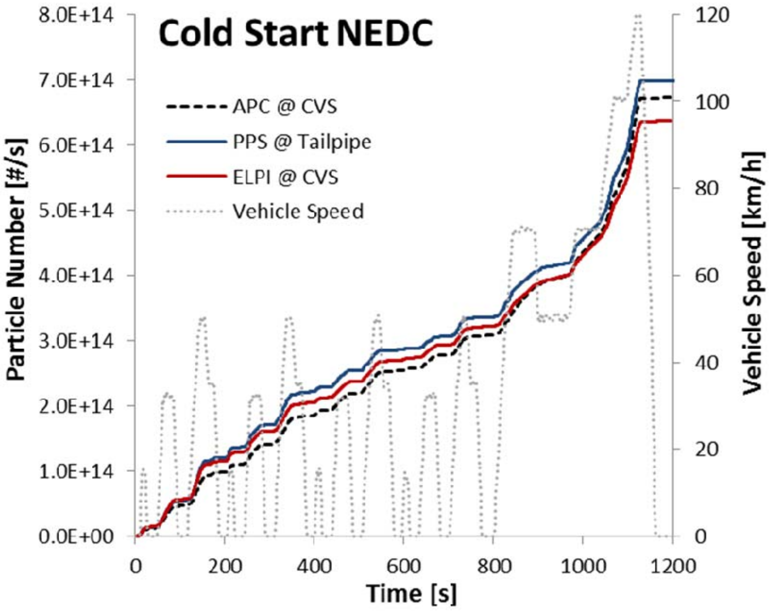

Figure 3: Cumulative particle number reported by the PPS, ELPI and APC during a cold-start NEDC of a diesel passenger vehicle.

3.3. LD Engine Tests

The LD engine tests showed that for different dilution settings of the PMP sampling system (ranging between 250-3000) the average deviation of the particle concentration was lower than 2%, after correcting for dilution and particle losses. This requires continuous measurement of the dilution air flowrates and integration of particle losses into the final result.

4. Conclusions

The general conclusions of this study are summarized as follows:

1) PMP-compliant sampling leaves a significant fraction of particles emitted from the vehicle uncontrolled.
2) PN instruments of different measurement principle and different sampling locations have shown good agreement at tests with a HD diesel engine and a diesel passenger car. However, despite the good correlation, discrepancies regarding the absolute level were observed.
3) The PPS and CS+PPS configurations have shown an excellent agreement despite the different sampling locations.

4) The particle number reported by the APC during a DPF regeneration test was significantly higher compared to the PPS. In addition, particle formation was observed which can be attributed to desorbed particles inside the CVS, as a result of the temperature increase.
5) The APC showed a small deviation on the resulting particle concentration with alteration of the PCRF. This requires continuous measurement of the dilution air and sample flowrates as well as integration of particle losses.

Dilution artifacts. A significant source of error from absolute concentration and possibly difficult to reproduce. PMP vs. raw exhaust

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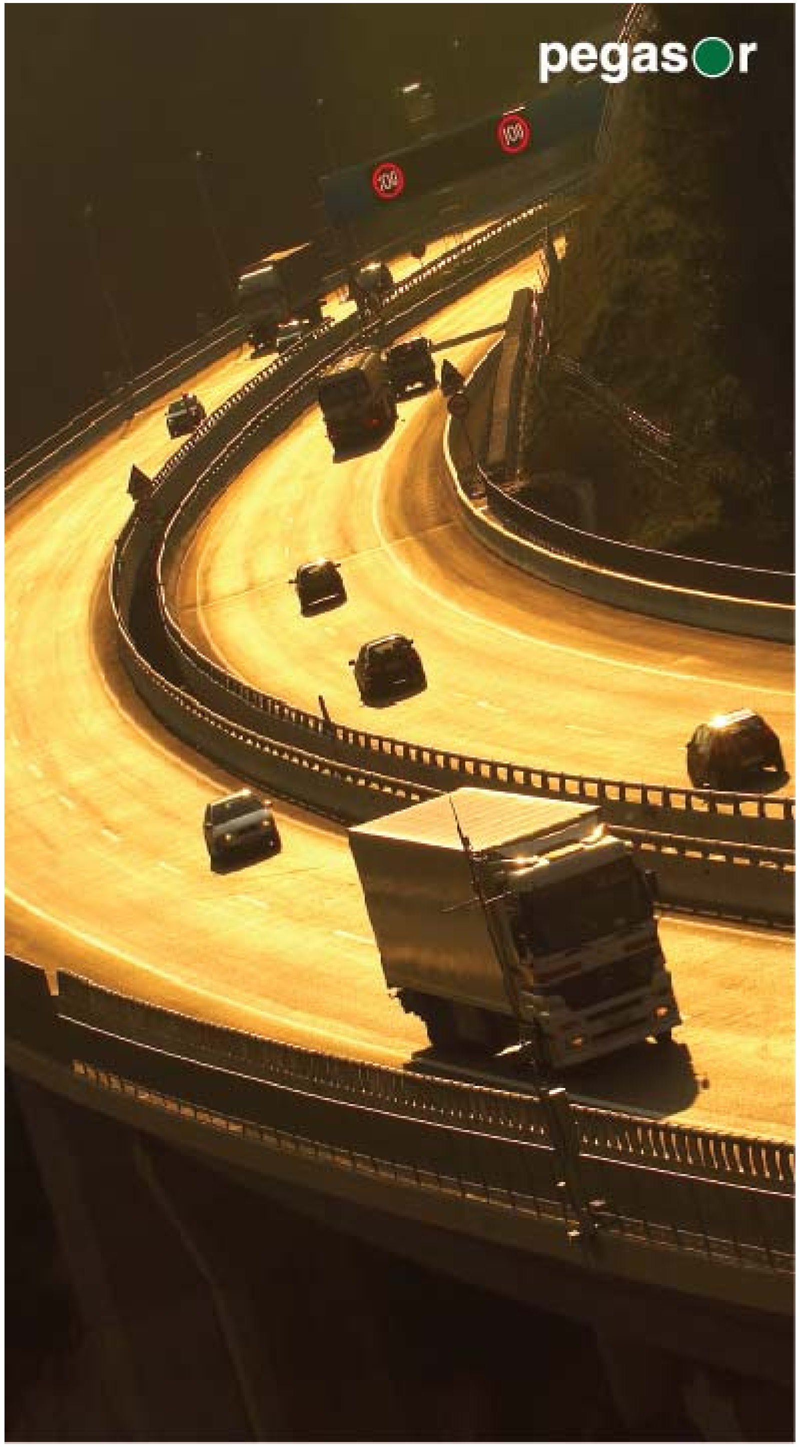


Particle Measurement Challenges

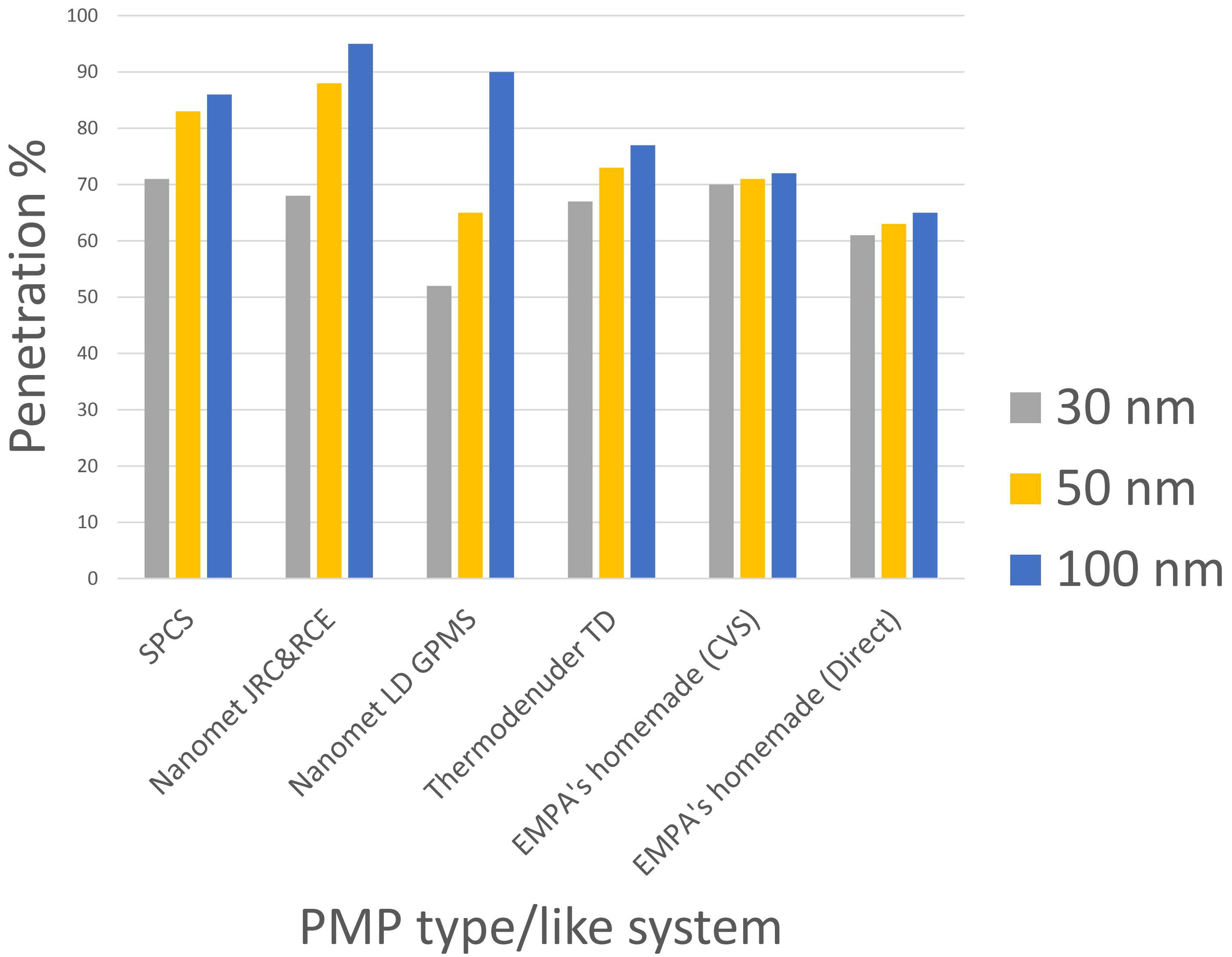
Particle Measurement Challenges

- *A significant source of error in particle number measurement is*
  - *Diluting sampling train effects*
  - *Sampling line length variations*

- *How often are these effects considered and at what accuracy when reporting data?*
  - *Losses are always a function of particle size*

- *How about the rest of the PMP sampling train*
  - *PMP PCRF (Particle Concentration Reduction Factor)*
  - *EVT (Evaporation Tube)*
  - *VPR (Volatile Particle Remover)*

PMP Dilution Chain Penetration

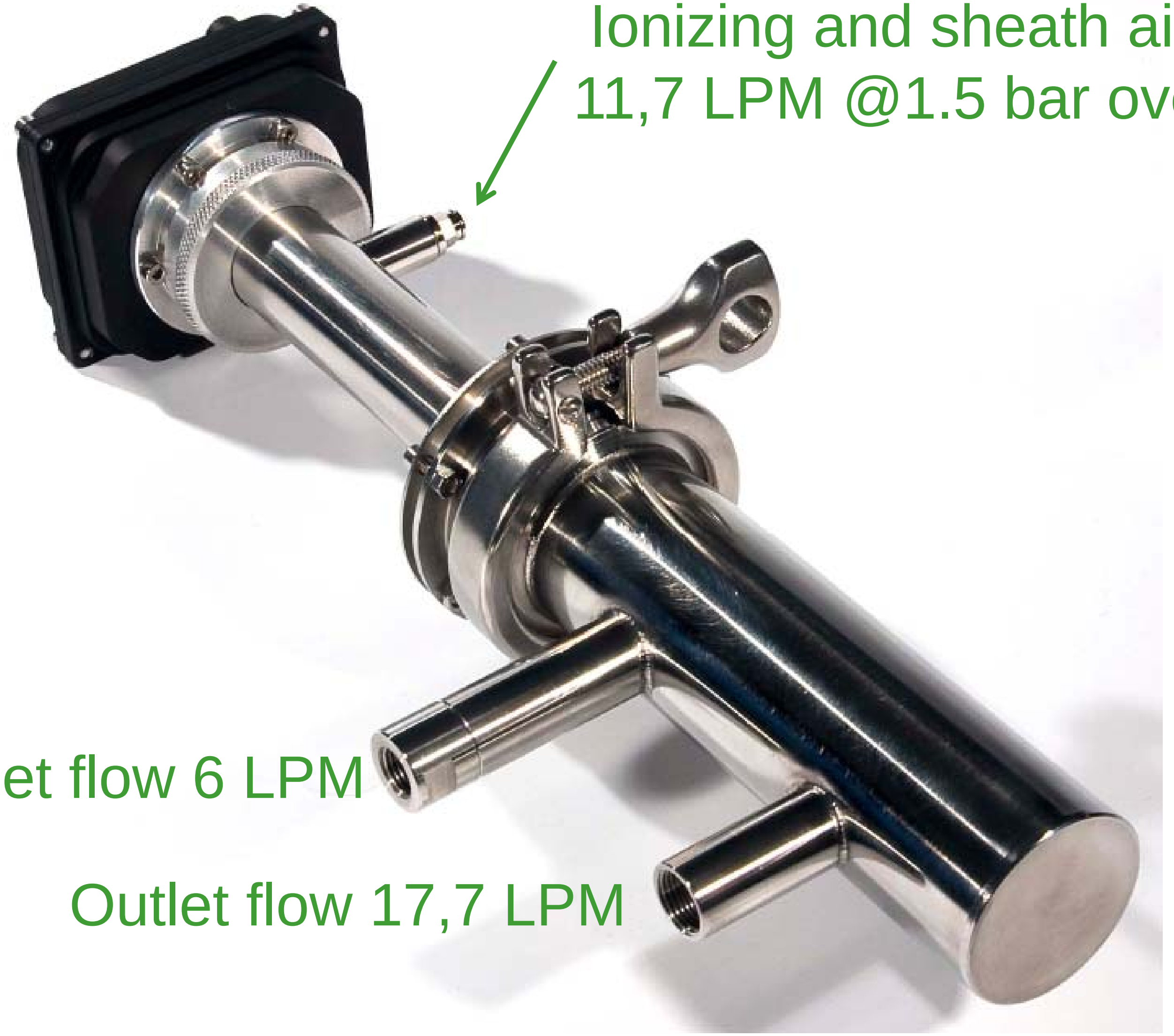


Data Courtesy of JRC

Pegasor M Sensor

PPS Operation Parameters

Ionizing and sheath air
11,7 LPM @1.5 bar overpressure



Inlet flow 6 LPM

Outlet flow 17,7 LPM

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PPS Technology

Pegasor Particle Sensor Technology is based on a novel measurement technique enabling real-time, continuous and high sensitivity and huge concentration range measurement of raw exhaust PM and PN emissions

- *No diluting sampling*
- *Fastest device in the market*
  - *No particle generation*
  - *No particle evaporation*
- *Sample extraction insensitive to exhaust gas pressure fluctuations and velocity effects*
- *Exhaust gas temperature can be anything from -20 °C up to 850 °C*
- *Sample conditioned to 200 ° C at the inlet of the sensor*

NEDC Cold Start – No Catalytic Stripper

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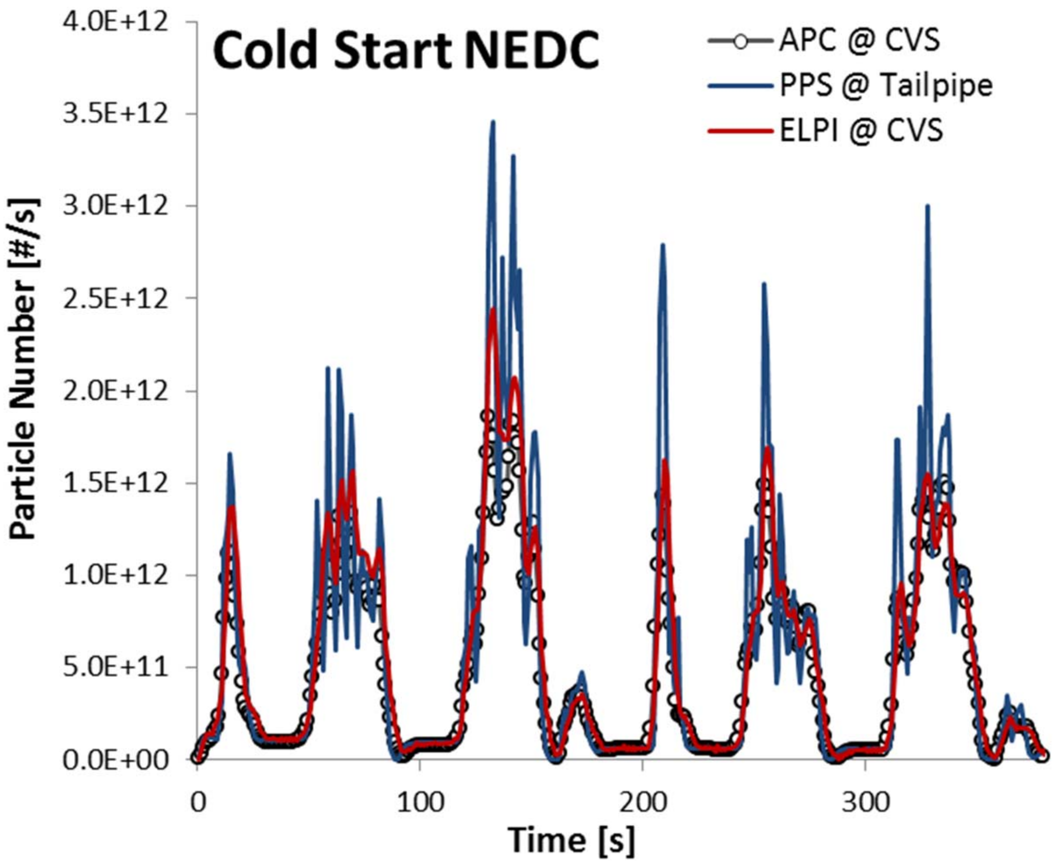
PPS comparison with APC and ELPI during a cold start NEDC test



- Cold Start NEDC with LD diesel vehicle retrofitted with compromised DPF.
- ELPI & APC sampling from CVS according to PMP (solid particles).
- PPS sampling from tailpipe.
- ELPI converted to particle number by using a typical diesel particle density profile.
- Excellent correlation between the 3 instruments
- PPS shows higher values during acceleration parts.

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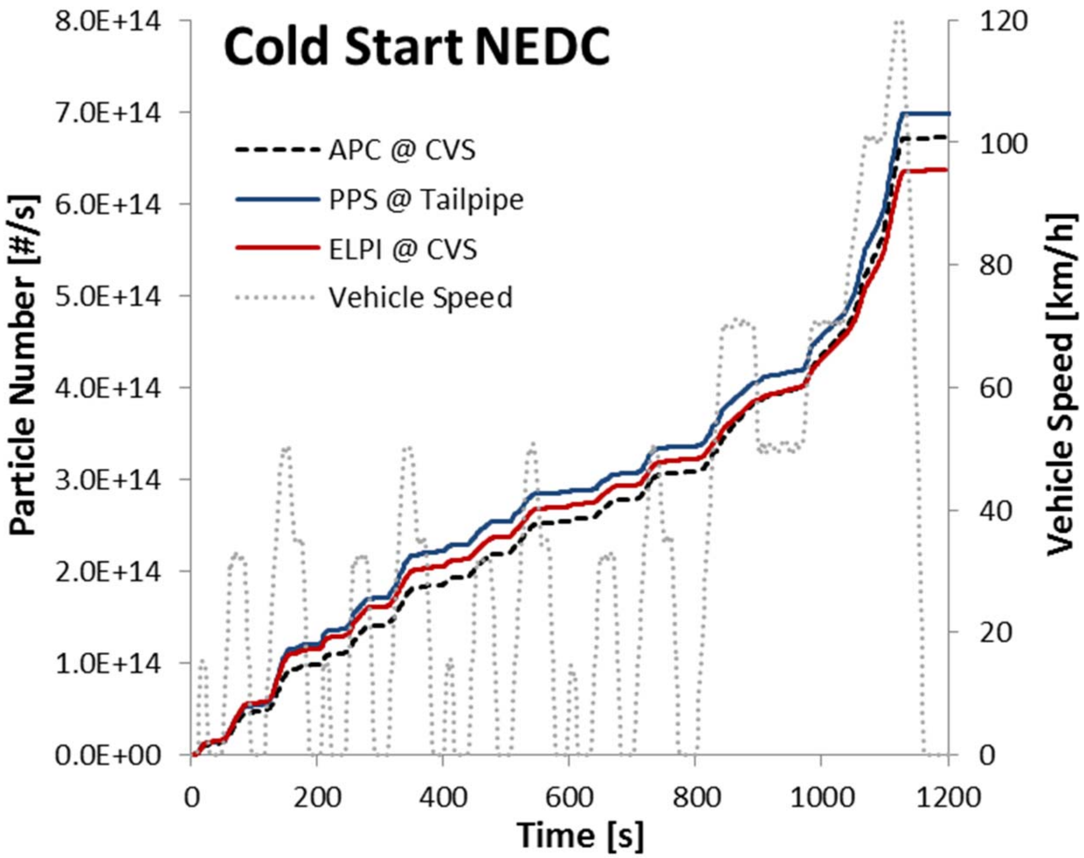
PPS comparison with APC and ELPI during a cold start NEDC test



- Cumulative particle number during NEDC.
- PPS compared to ELPI:
  - Similar response
  - Higher values at acceleration parts
- APC consistent with PPS and ELPI during the urban part.
- During extra urban part:
  - APC response is different
  - Higher values compared to ELPI and PPS.

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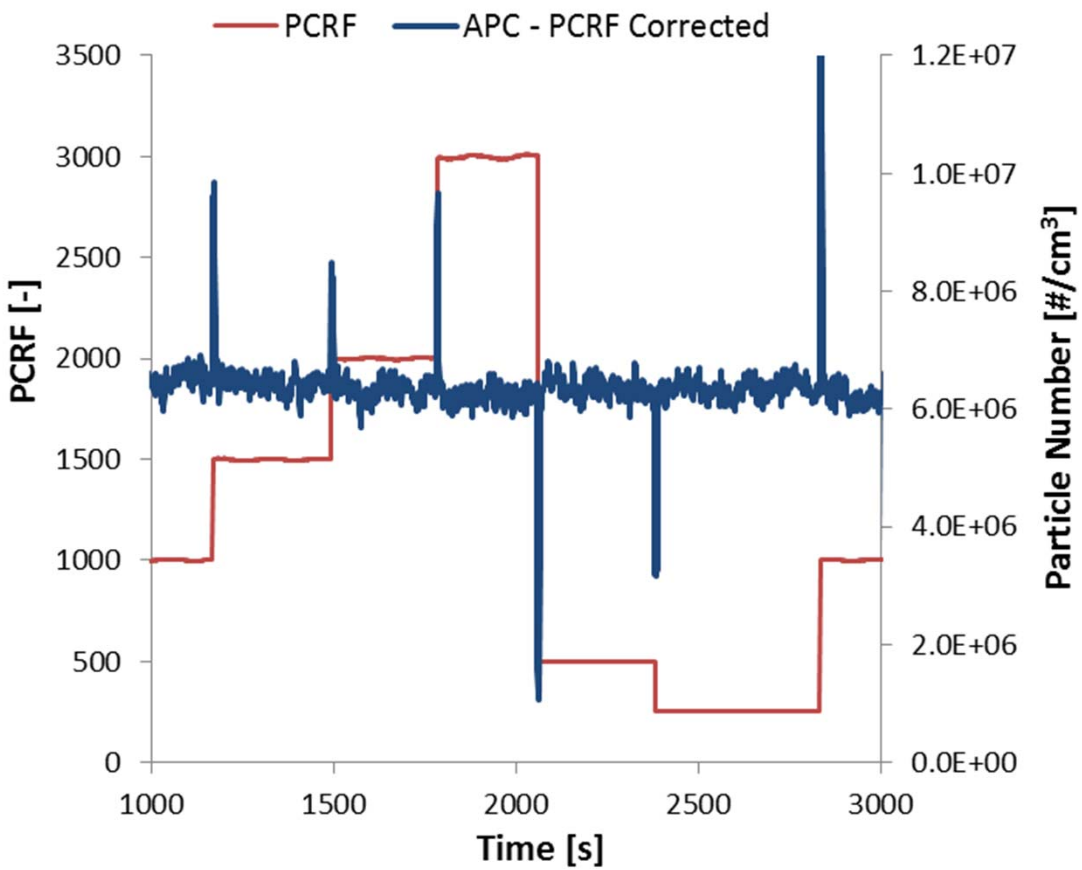
PCRF effect on particle concentration during a steady state test



- Steady state LD diesel engine test.
- PCRF adjusted between 250-3000
- Concentration is affected only during PCRF adjustment.
- Average deviation between different PCRFs <2%

NEDC Cold Start – with Catalytic Stripper

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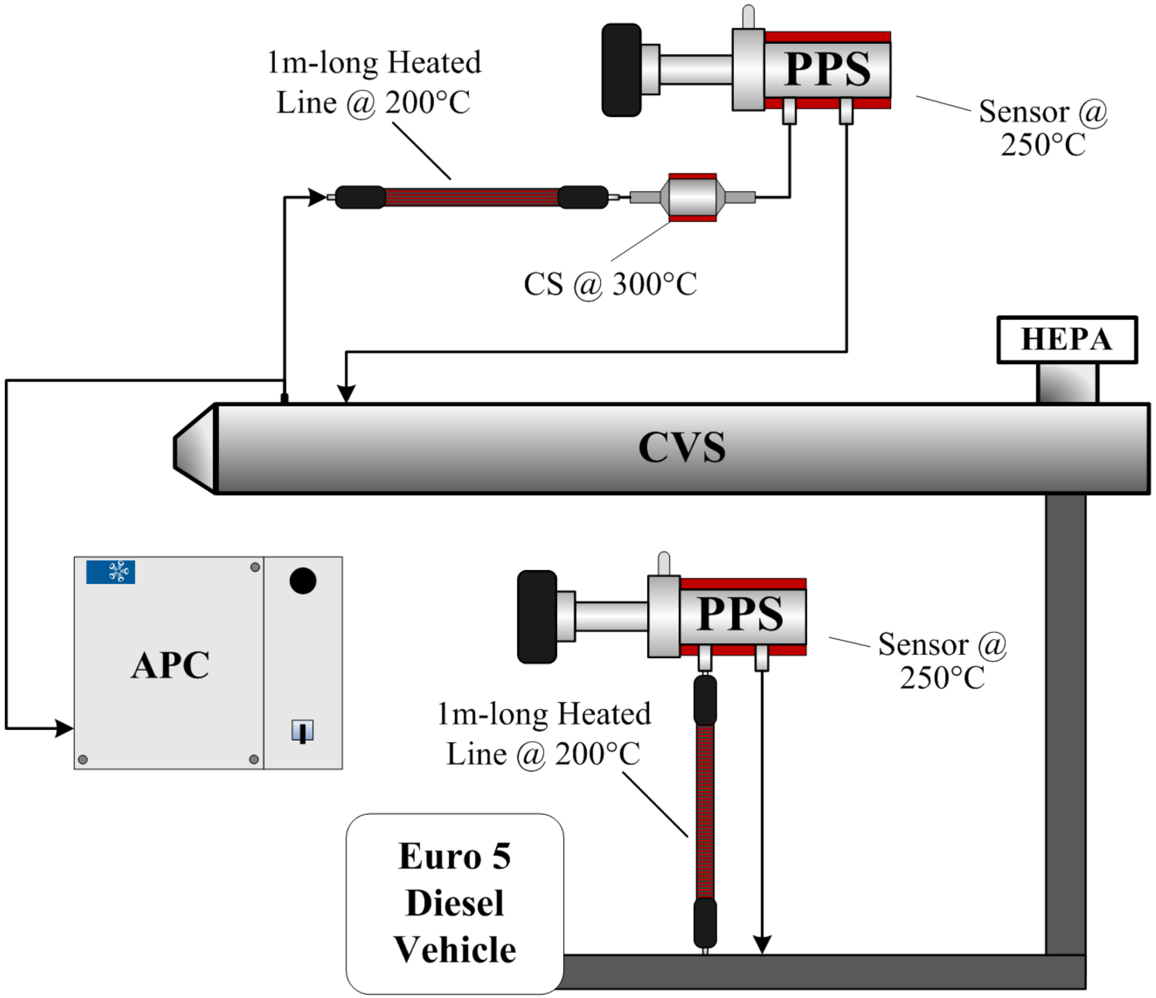
Catalytic Stripper as Volatile Particle Remover



- Catalytic Stripper is used as VPR
- Comparison between CVS with CS and tailpipe sampling
- AVL APC used as a comparison

- Tests on a Euro 5 diesel vehicle

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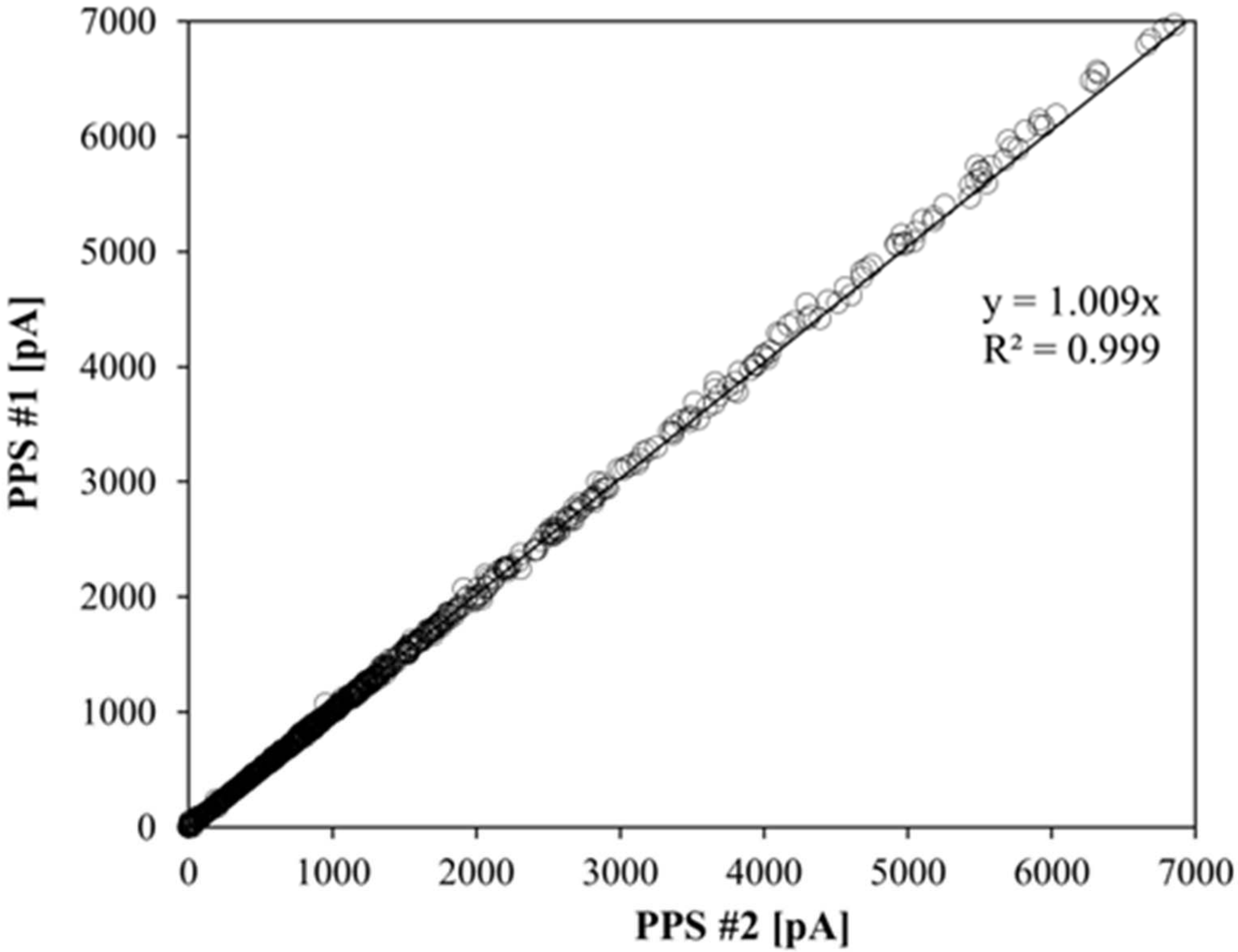
Inter-Calibration of two Pegasor M sensors



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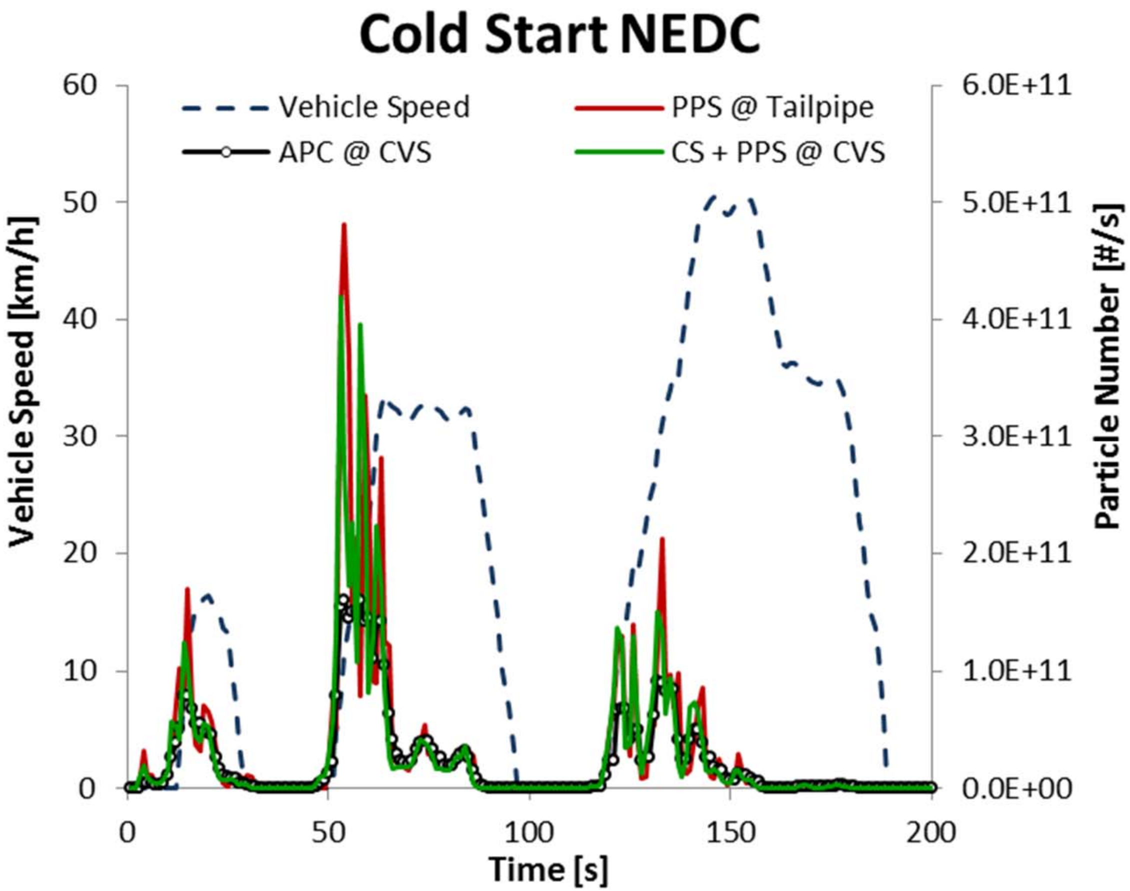
Sampling with Catalytic Stripper during the NEDC



- Particle number during the first 3 min of NEDC
- Tailpipe Pegasor M shows somewhat higher peaks than CVS Pegasor M as expected
- APC reports somewhat lower particle number during acceleration parts compared to both Pegasor M

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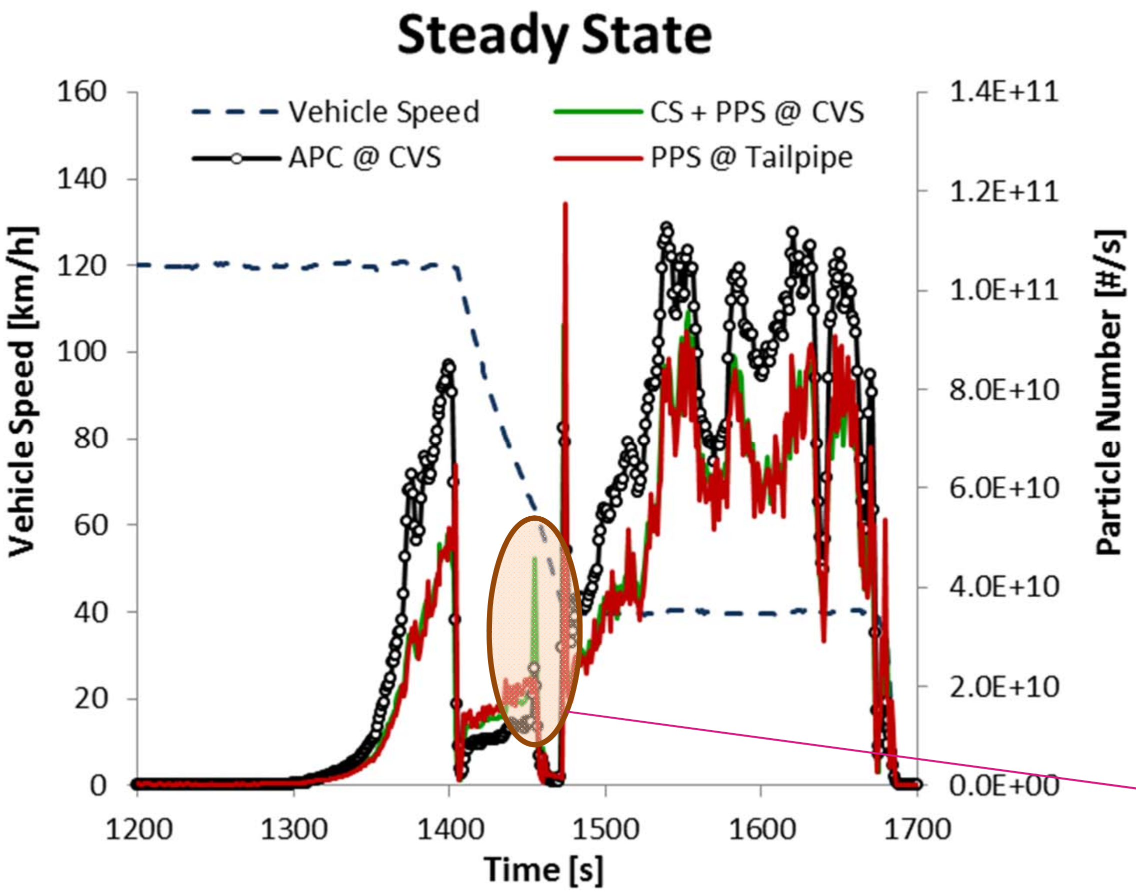
Sampling with Catalytic Stripper during a Steady State Test



- DPF regeneration is initiated during a steady state test at 120 km/h
- Similar particle number is again reported by the 2 Pegasor M sensors
- APC shows higher particle number

Desorption from the CVS, as temperature increases (not cut by CS)

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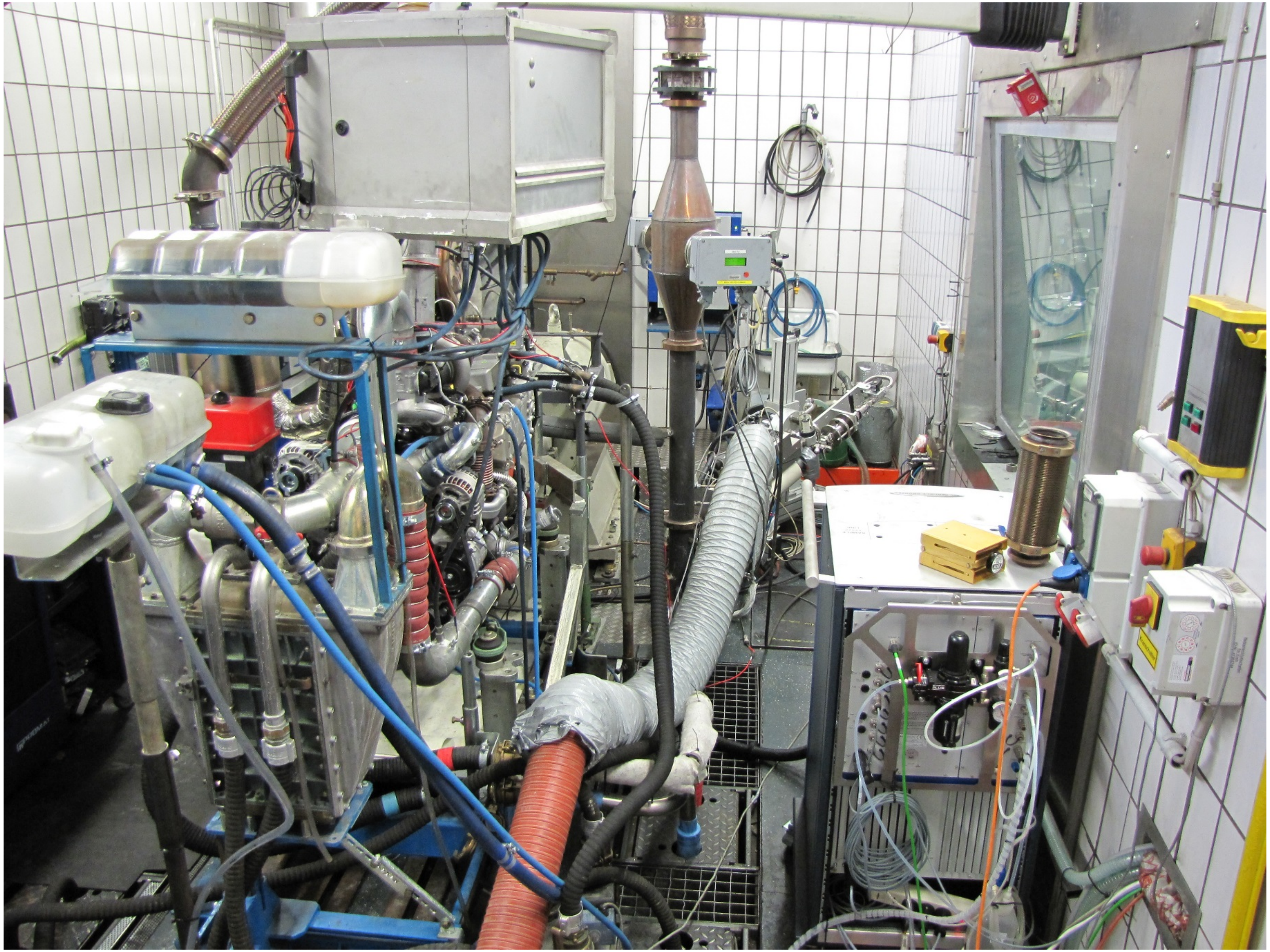
Tests on Heavy Duty Engine

Heavy Duty Engine Test Cell



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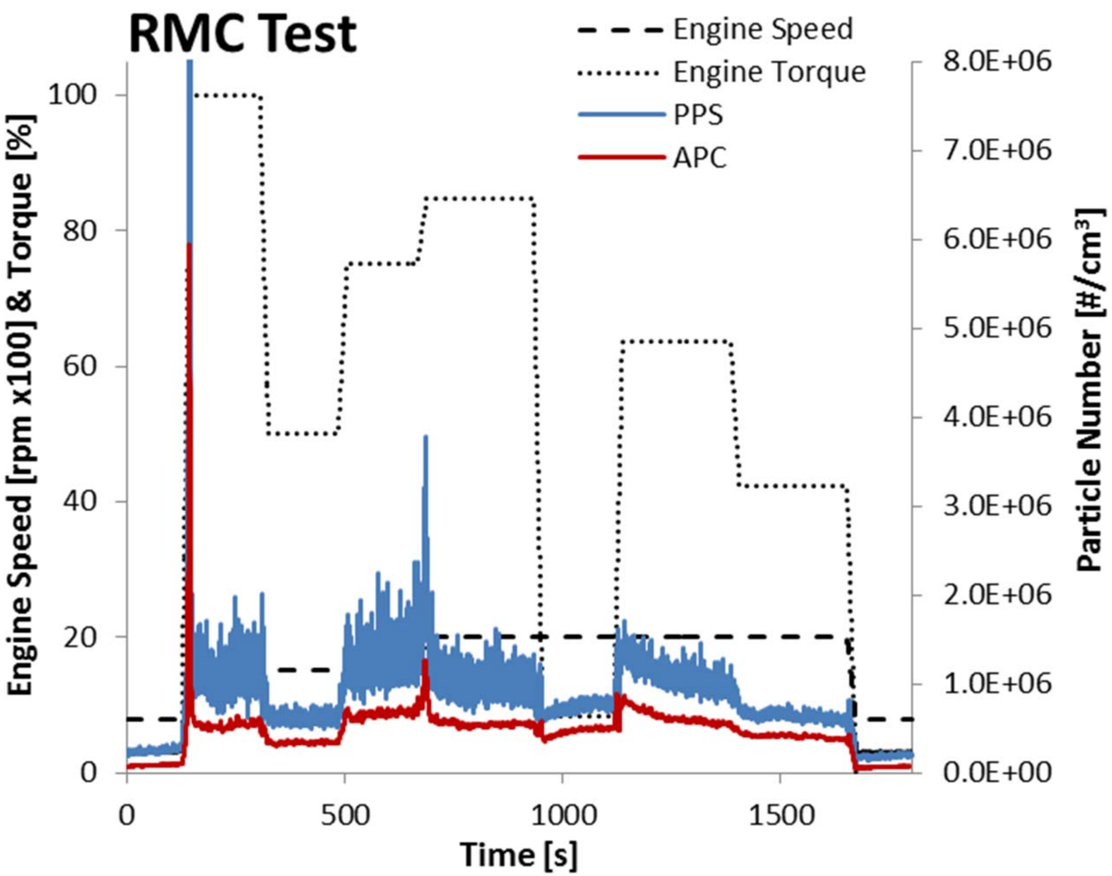
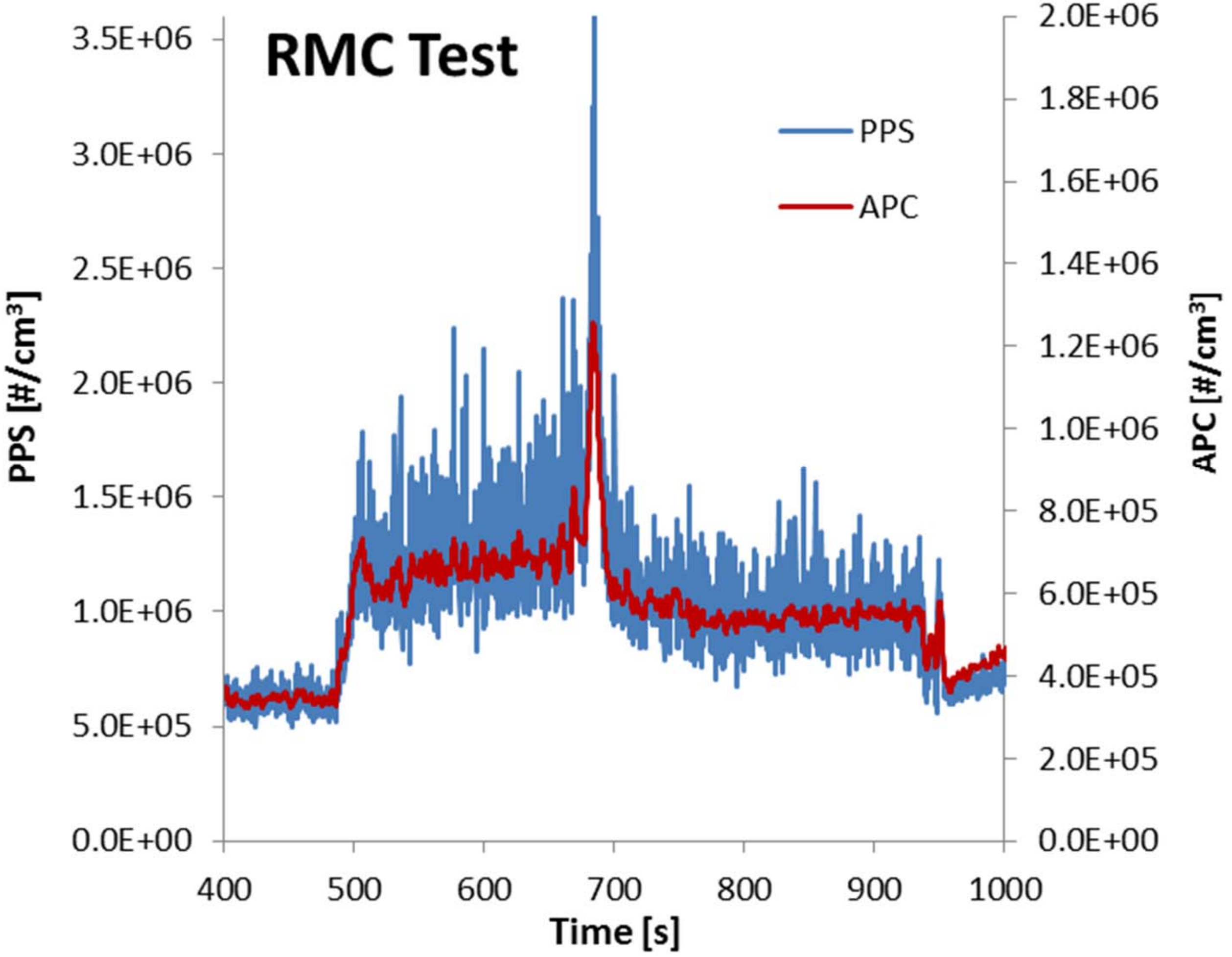
Heavy Duty Engine Tests

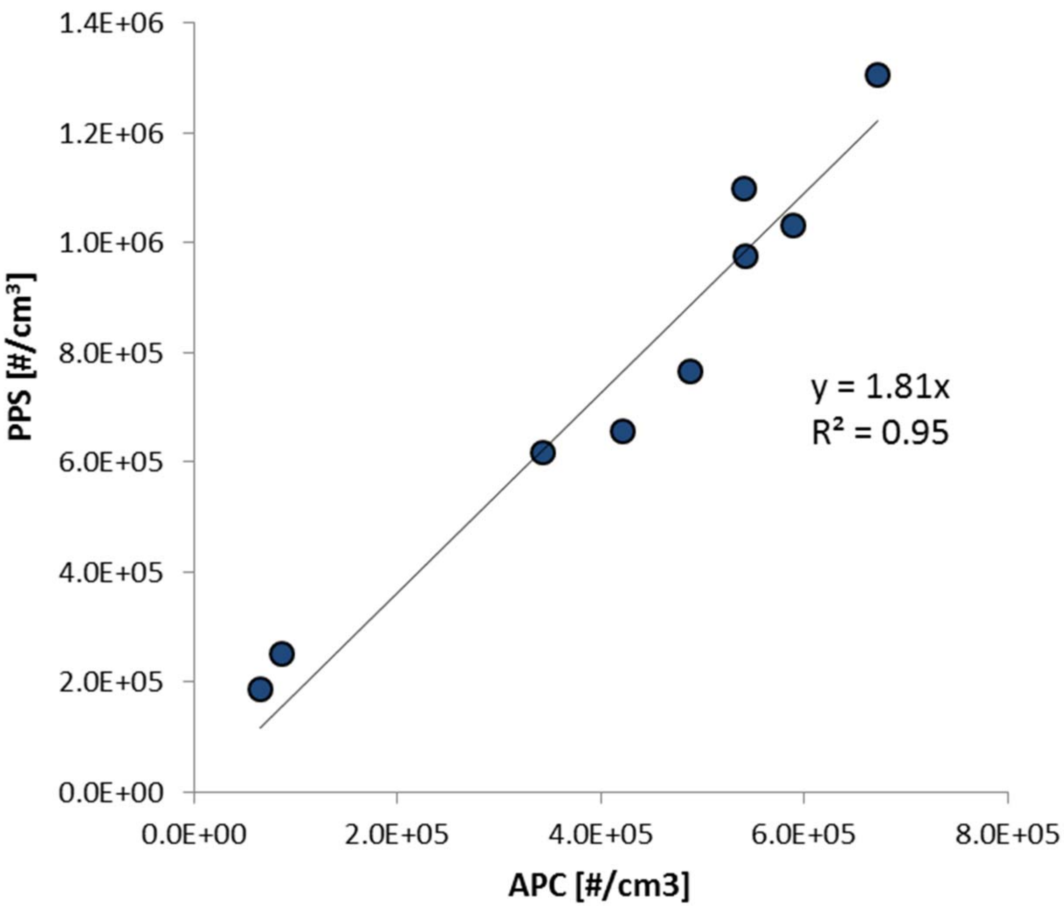


- Ramped Mode Cycle
- AVL APC shows systematically less than Pegasor M

Heavy Duty Engine Tests



Heavy Duty Engine Tests



- Average values from RMC test
- Excellent correlation between APC and PPS.
- In this measurement PPS shows 80% higher particle number compared to APC
- Consistent and good to be known

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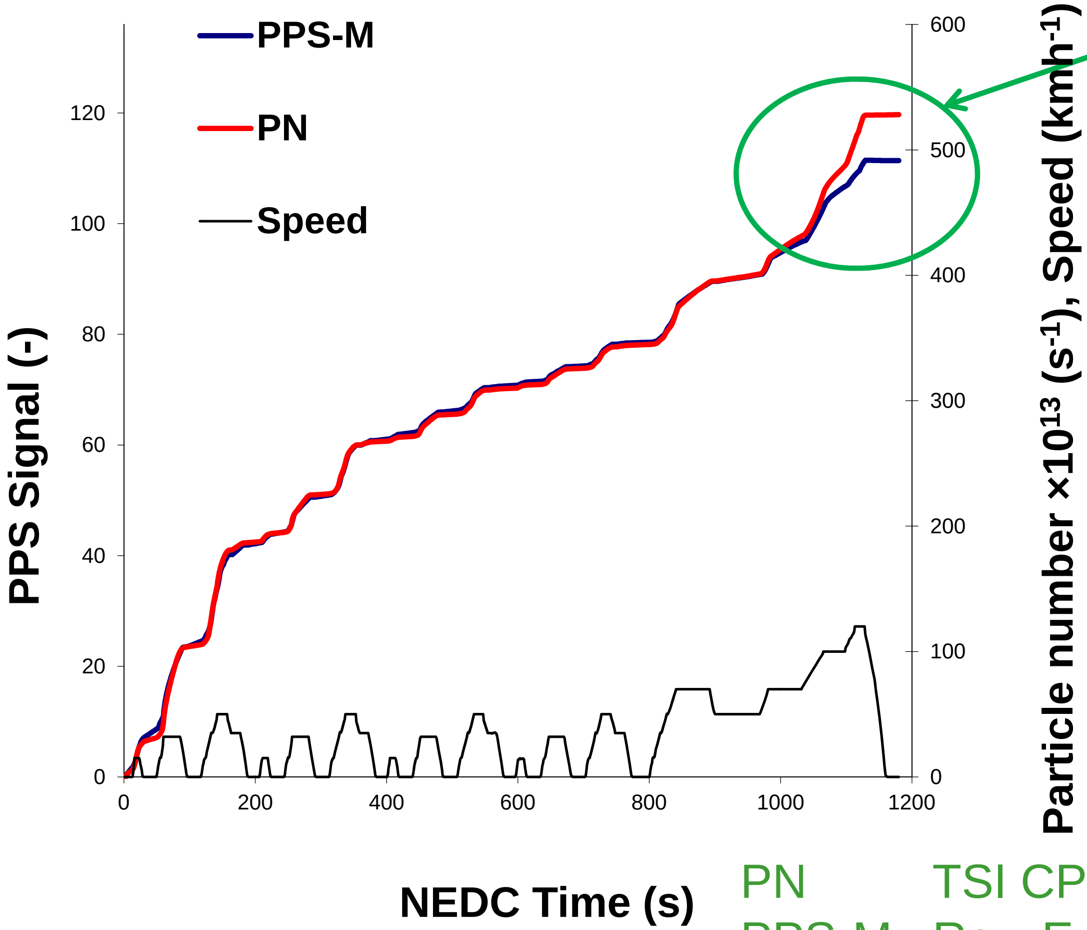
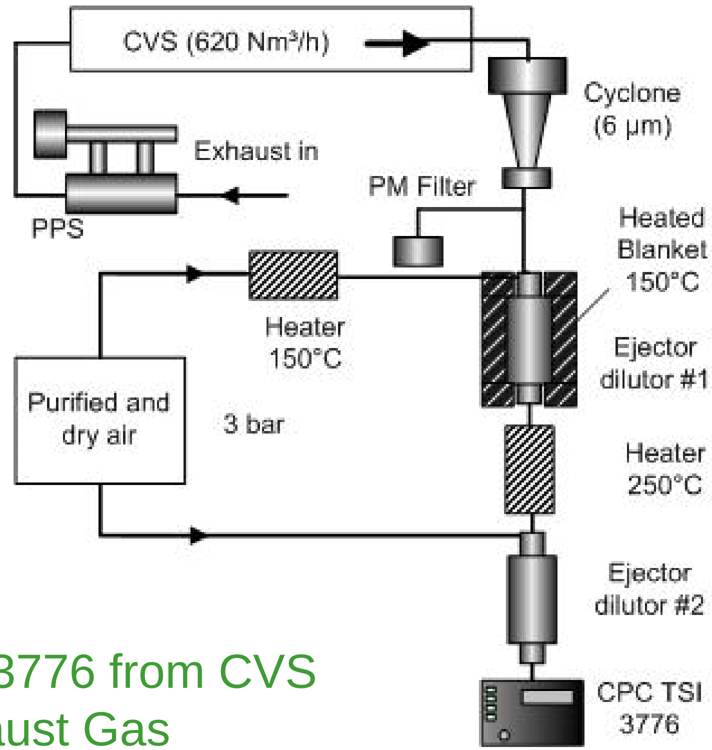
Particle Number Measurement



The total exhaust gas flowrate in the tailpipe is not known



PN	TSI CPC 3776 from CVS
PPS-M	Raw Exhaust Gas

Data Courtesy of LAT

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Conclusions

- Measuring aerosols is not easy
- Trying to establish 1:1 match for two instruments based on different measurement principle and different sampling train from different sampling positions of the exhaust is Mission Impossible
- Cold start forms particles that are measured by Pegasor M sampling raw exhaust
  - These particles disappear before APC in PMP sampling train
- DPF regeneration forms detectable particles in the diluting PMP sampling train for APC
  - These particles are NOT formed or are NOT at a detectable size when measured with Pegasor M
- Diluting sample train effects must be understood
- KISS !

Thank You for your attention!

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