An Investigation into the Particle Number (PN) and Particle Mass (PM) Reported from Different Emissions Measurement Systems During Chassis Dynamometer Testing of a GDI Vehicle

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June 2021
Paper #983732

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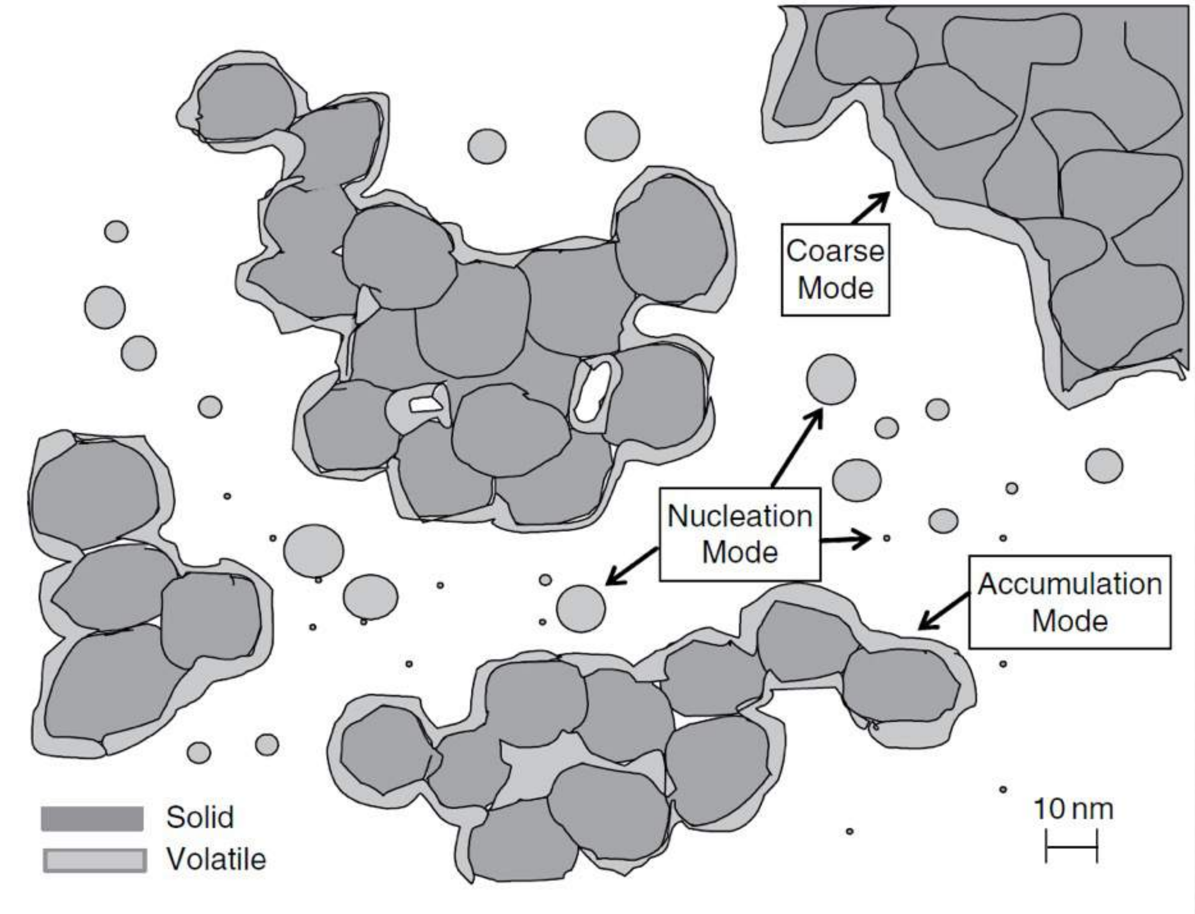
Introduction

- Accurate measurement of particulate emissions from vehicles is important.
- Though filter PM mass is still the legislated technique in the USA, it is becoming ever more difficult, as the emission limits tighten.
- EU countries have changed to a particle number (PN) metric and particle measurement protocol (PMP) for regulatory use.
- Time-resolved PM equipment has been developed for research testing.
- CVS measurements are required for most regulatory testing, but research testing can often use alternative methods, such as direct tailpipe sampling.
- Additionally, different sampling conditioning systems such as volatile particle removers and hot diluters can be used.
- There are known to be differences in the reported values when using different methodologies and equipment.

Introduction

- Particulate matter is a physically and chemically heterogeneous substance.
- The properties of particulate matter are not constant, and depend on many different factors.
- After their creation, they can be easily affected by external factors and will not maintain the same form.
- This makes the measured properties of particulate matter highly dependent upon the sampling methodology.



Source: Eastwood, P. (2007) *Particulate Emissions from Vehicles*. Chichester, UK: John Wiley & Sons, Ltd (Wiley-Professional Engineering Publishing Series). doi: 10.1002/9780470986516.

Aims

- The aim of this presentation is to highlight the wide range of ways in which particulate matter from engines can be quantified, and discuss how this affects the reported concentrations of particulate matter.
- This will be achieved through comparisons between:
  - PN and PM as metrics for particulate matter,
  - Different sampling positions and conditioning methods,
  - Different equipment operating principles.

Methodology

- Experiments were conducted at Ford Motor Company's Vehicle Emissions Research Laboratory (VERL) – a chassis dynamometer test facility.

Methodology

- Particulate measurement equipment included:
  - TSI Engine Exhaust Particle Sizer – EEPS 3090 – for particle number and size distribution (both total PN (>6nm) and 23nm cut-off PN is presented),
  - AVL Particle Counter – APC 489 – for particle number,
  - Dekati Mass Monitor – DMM-230A – for particle mass,
  - AVL Micro Soot Sensor – MSS 483 – for soot mass,
  - 3DATX – parSYNC – for particle number and mass (presented elsewhere in future work).
- Additional sample conditioning included:
  - When sampling at the Tailpipe, the EEPS and DMM were used with a Dekati Engine Exhaust Diluter (DEED) for hot dilution of sample (some VPR effect),
  - When sampling from the CVS, no additional conditioning was used,
  - The APC was always used with a VPR as per the PMP (note: EEPS is not PMP-compliant).

Methodology

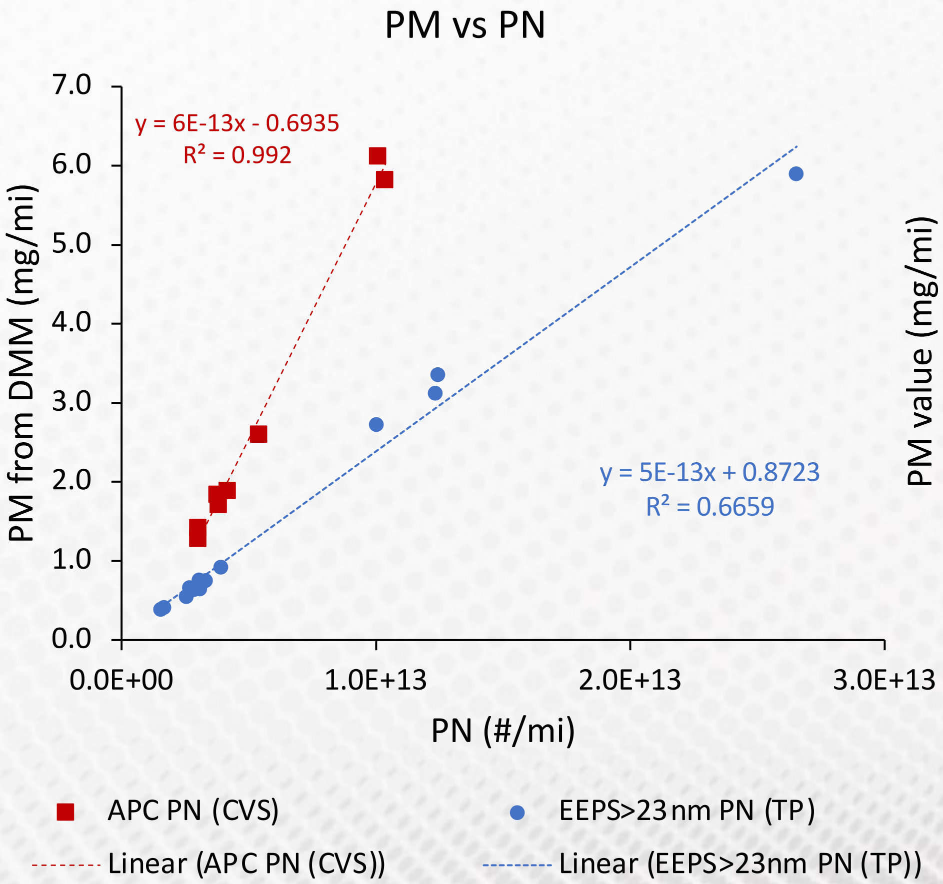
- A gasoline direct injection (GDI) *test vehicle* equipped with three-way catalyst (TWC) but no gasoline particulate filter (GPF) completed a range of different test cycles.
- Equipment was placed at various sampling positions to allow comparisons.

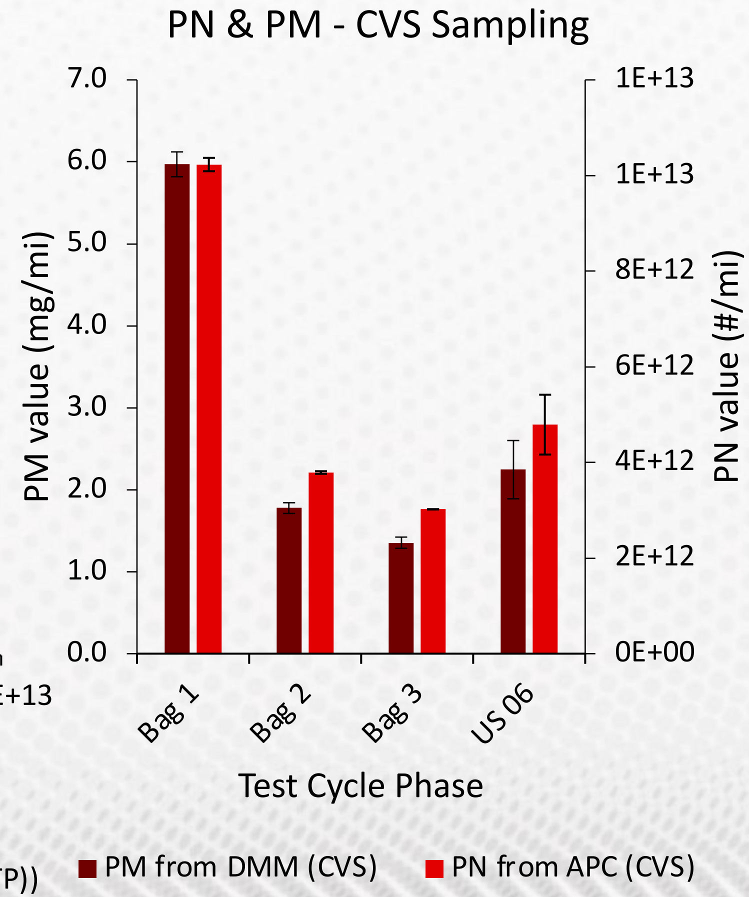
Test	Test Cycle	EEPS 3090	APC 489	DMM-230A	DMM-230A	MSS 483
1	FTP 75* followed by US 06	CVS	CVS + VPR	TP + DEED	CVS	CVS
2	FTP 75* followed by US 06	CVS	CVS + VPR	TP + DEED	CVS	CVS
3	FTP 75* followed by HWFET	TP + DEED	-	TP + DEED	CVS	CVS
4	FTP 75* followed by US 06	TP + DEED	-	TP + DEED	CVS	CVS
5	LA 92	TP + DEED	-	TP + DEED	CVS	CVS
6	FTP 75* followed by HWFET	TP + DEED	-	TP + DEED	CVS	CVS

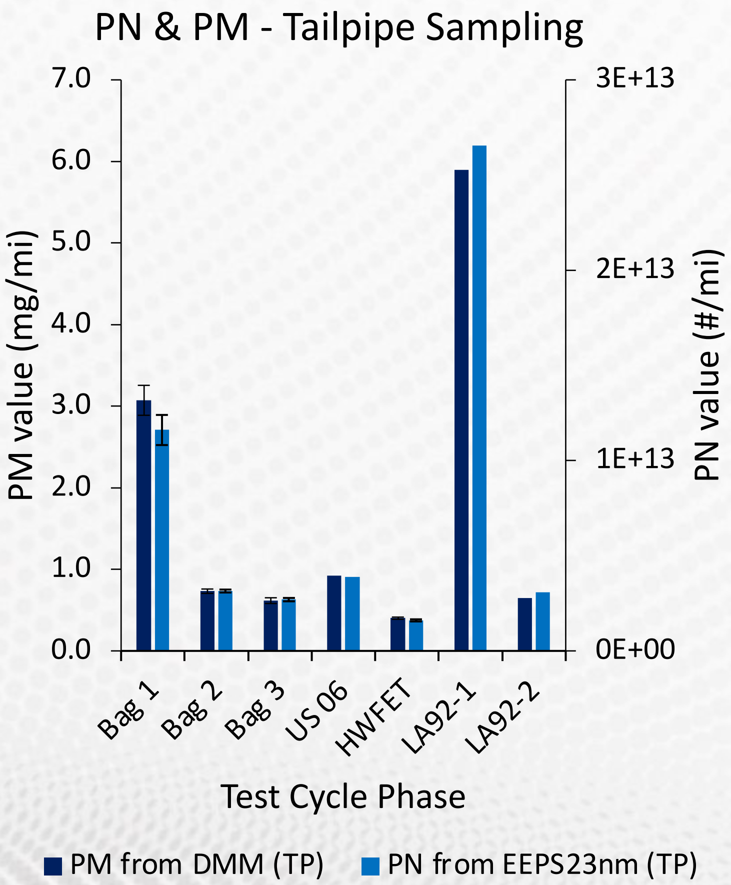
TP=Tailpipe | CVS=Constant Volume Sampler | DEED=Dekati Engine Exhaust Diluter (for hot dilution)

*The FTP 75 is split into three bags, called "Bag 1", "Bag 2" and "Bag 3" in this presentation.

Comparison of PM and PN from different equipment

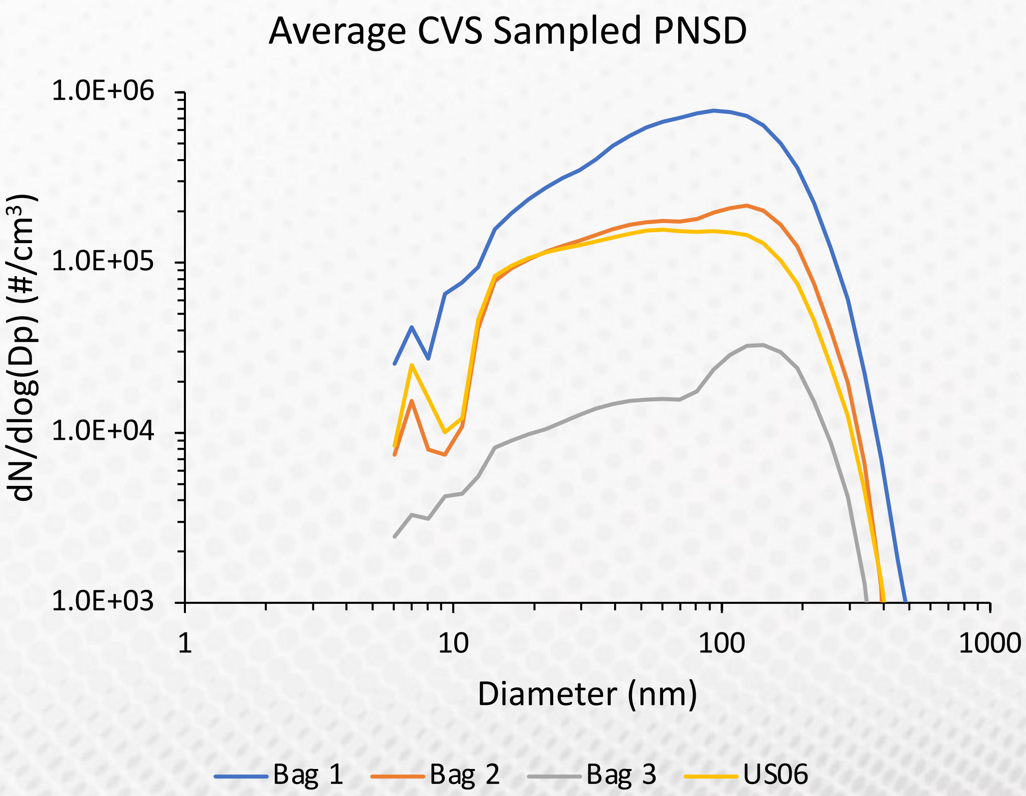


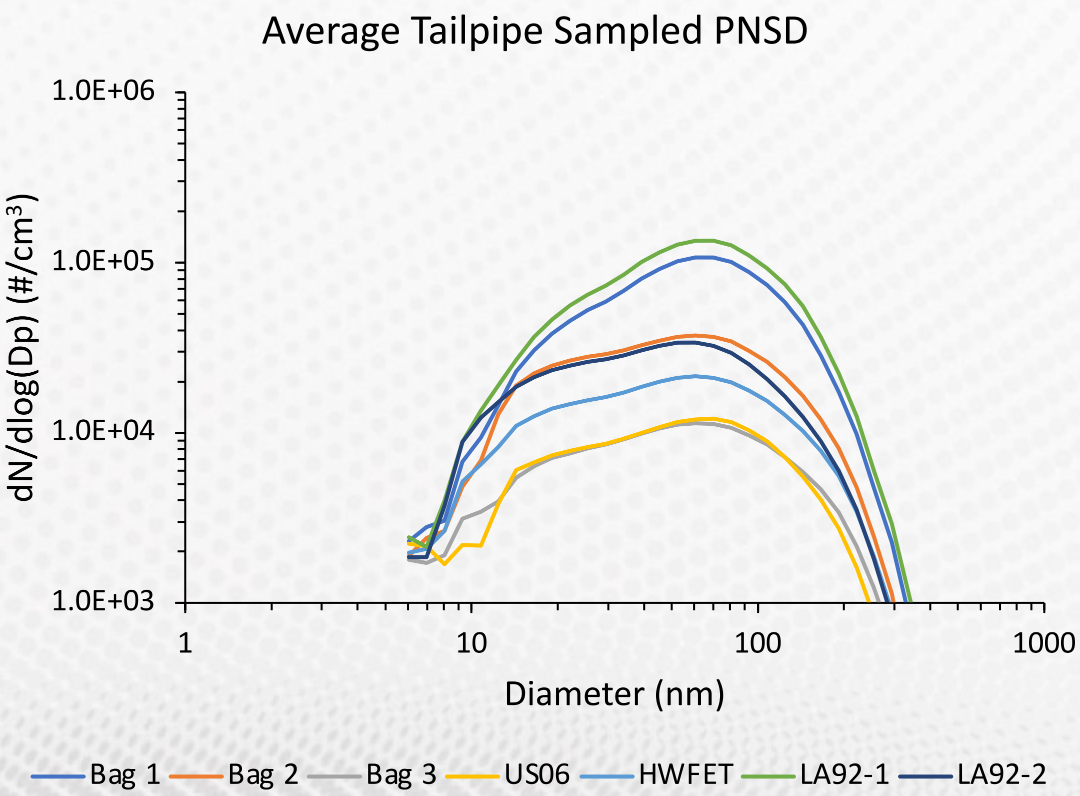




Good correlations between PM and PN seen from both tailpipe and CVS sampling methods.

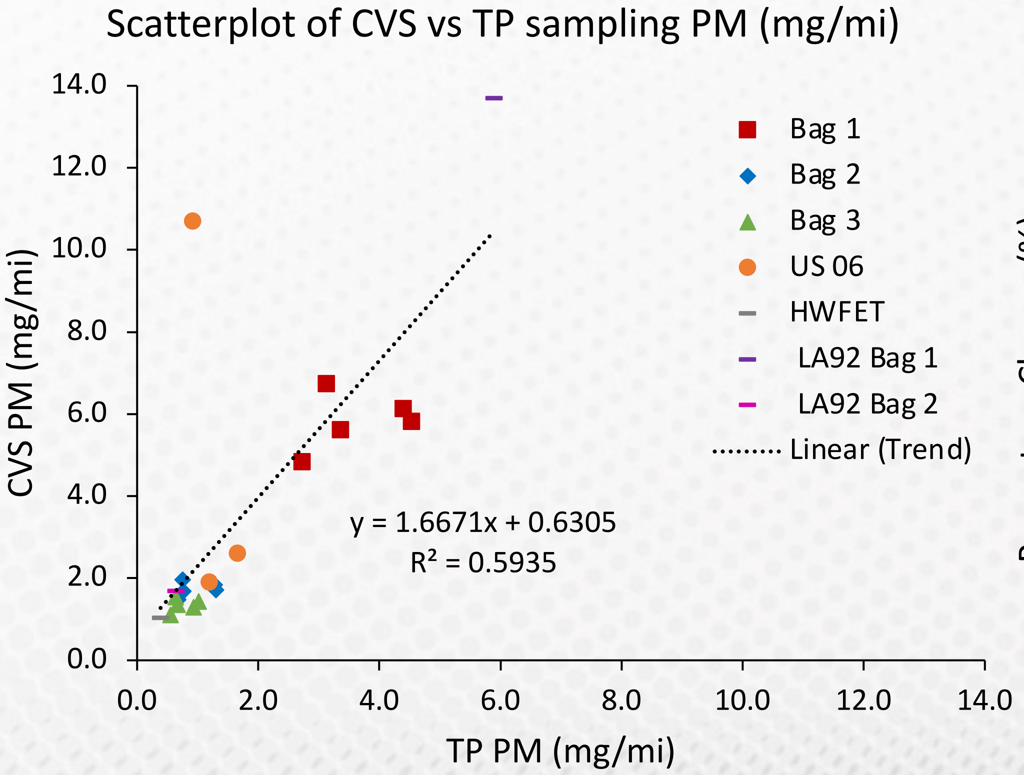
Tailpipe and CVS sampling Particle Number Size Distributions (PNSD) (from test repeats)

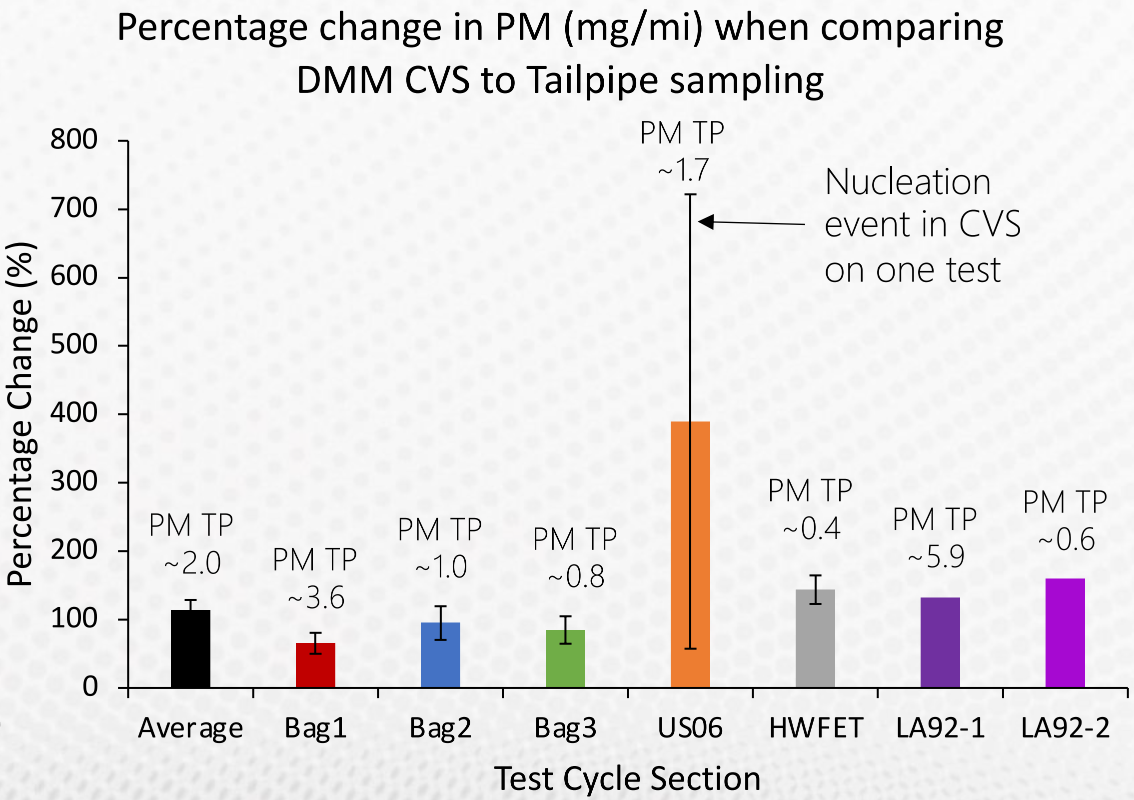




- A broader PNSD with higher maximum is seen from CVS sampling than tailpipe sampling, likely due to a lack of volatiles removal and additional particle interactions allowed from the CVS tests,
- Overall reported total PN is 6 times greater from CVS measurements than tailpipe measurements.

Comparison between Tailpipe and CVS sampling DMM PM mass results

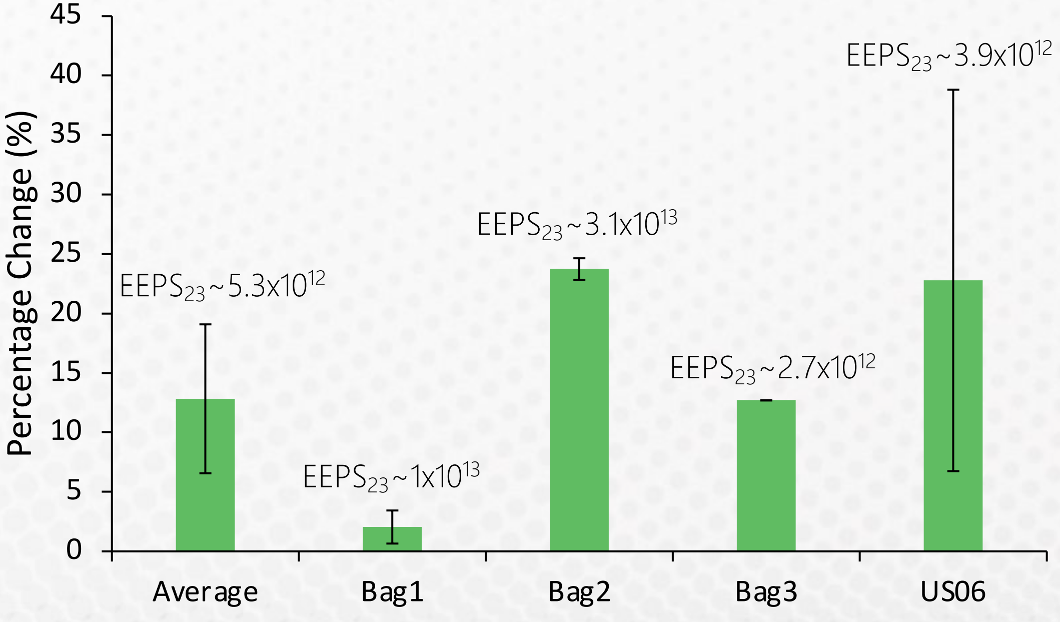




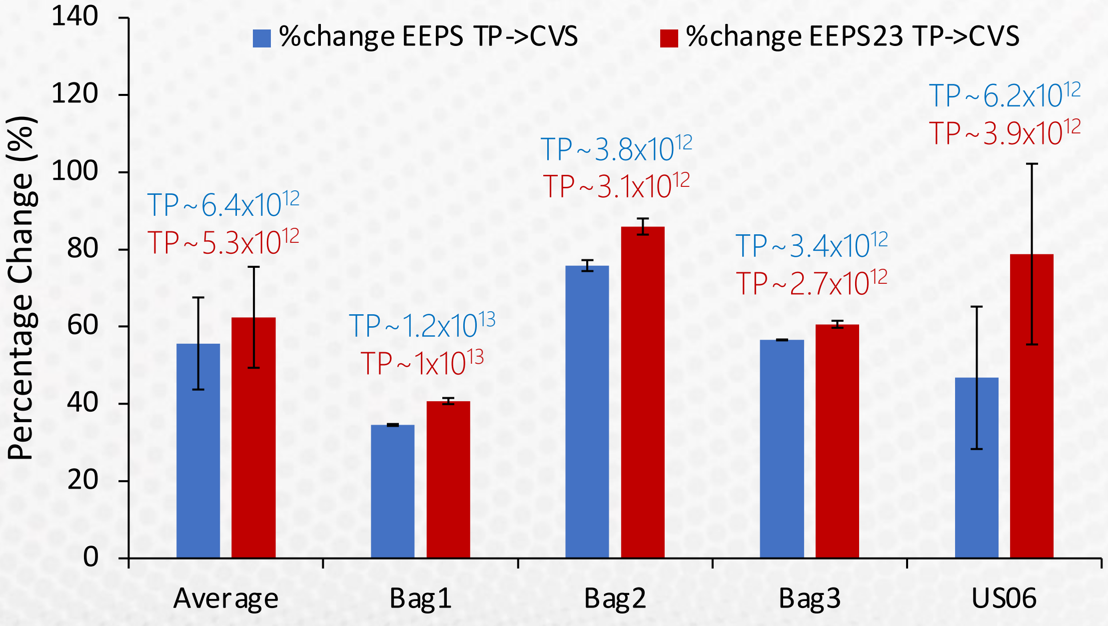
CVS sampling leads to higher PM measurements compared to tailpipe sampling from the DMM equipment because the tailpipe DEED suppresses nucleation and condensation effects, leading to lower values from tailpipe sampling. Note that nucleation leading to bimodal PNSD can render DMM measurements inaccurate.

Comparison between Tailpipe and CVS sampling PN results from repeated test cycles

Percentage change in reported PN (#/mi) comparing APC CVS to $EEPS_{>23nm}$ Tailpipe Sampling



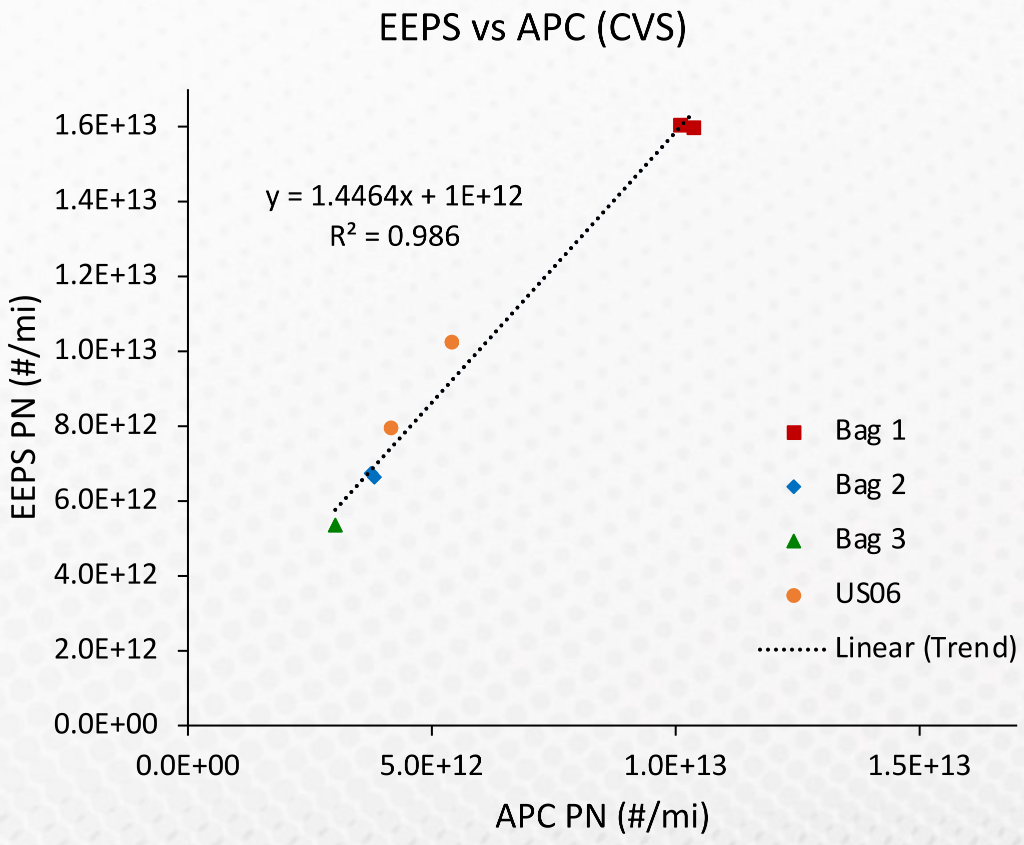
Percent change in EEPS reported PN (#/mi) when comparing CVS to Tailpipe sampling

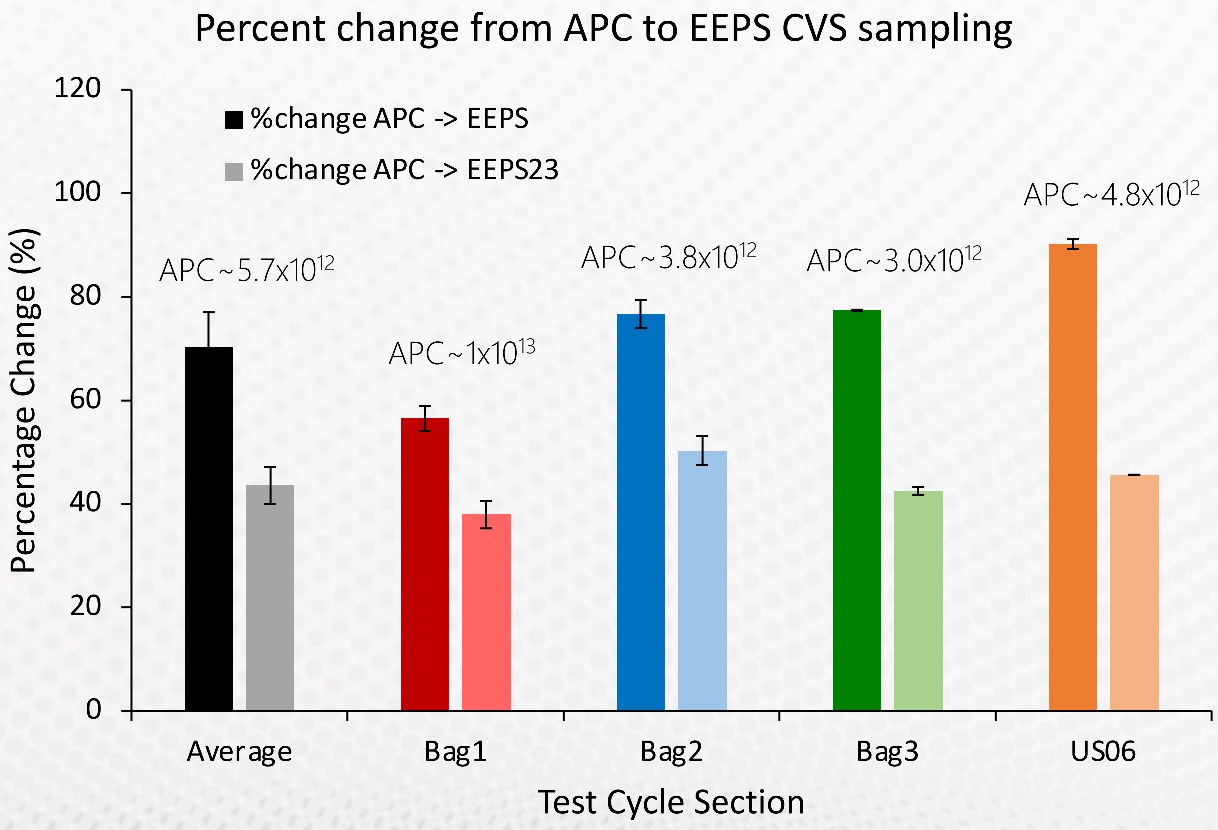


CVS sampling leads to higher PN measurements compared to tailpipe sampling, from this equipment.

- EEPS TP uses hot dilution,
- EEPS CVS uses room temperature dilution.

Comparison of EEPS and APC for PN

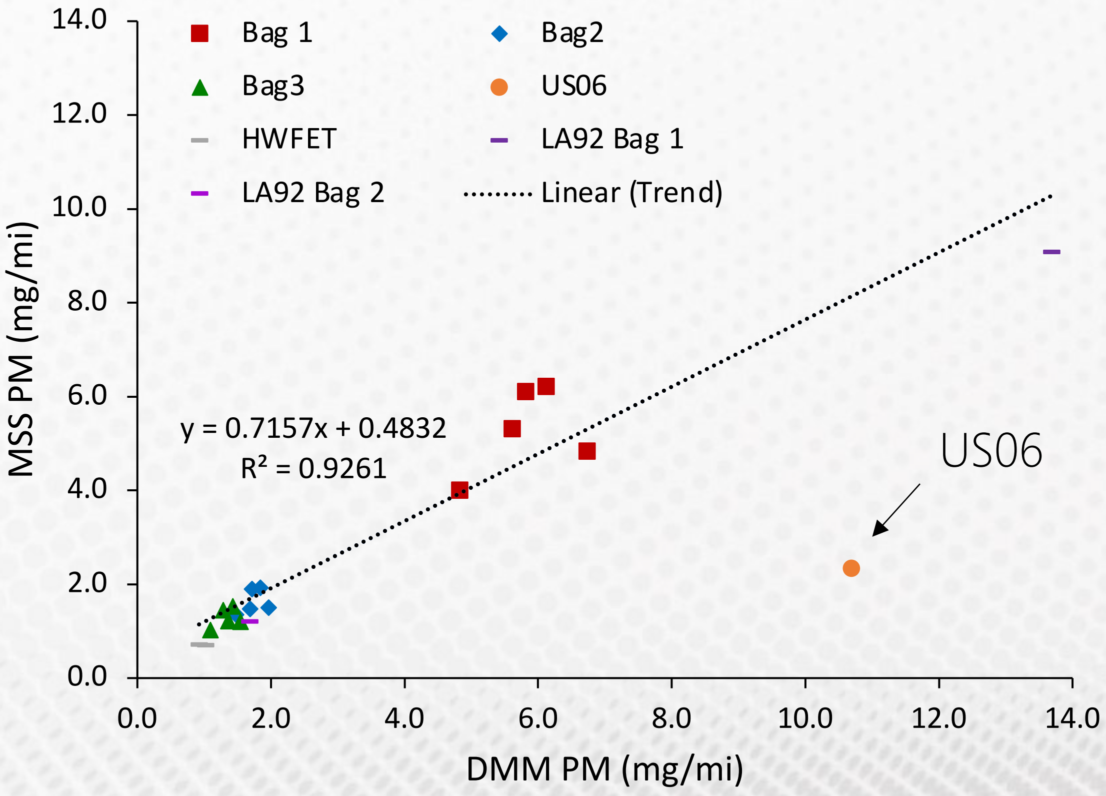




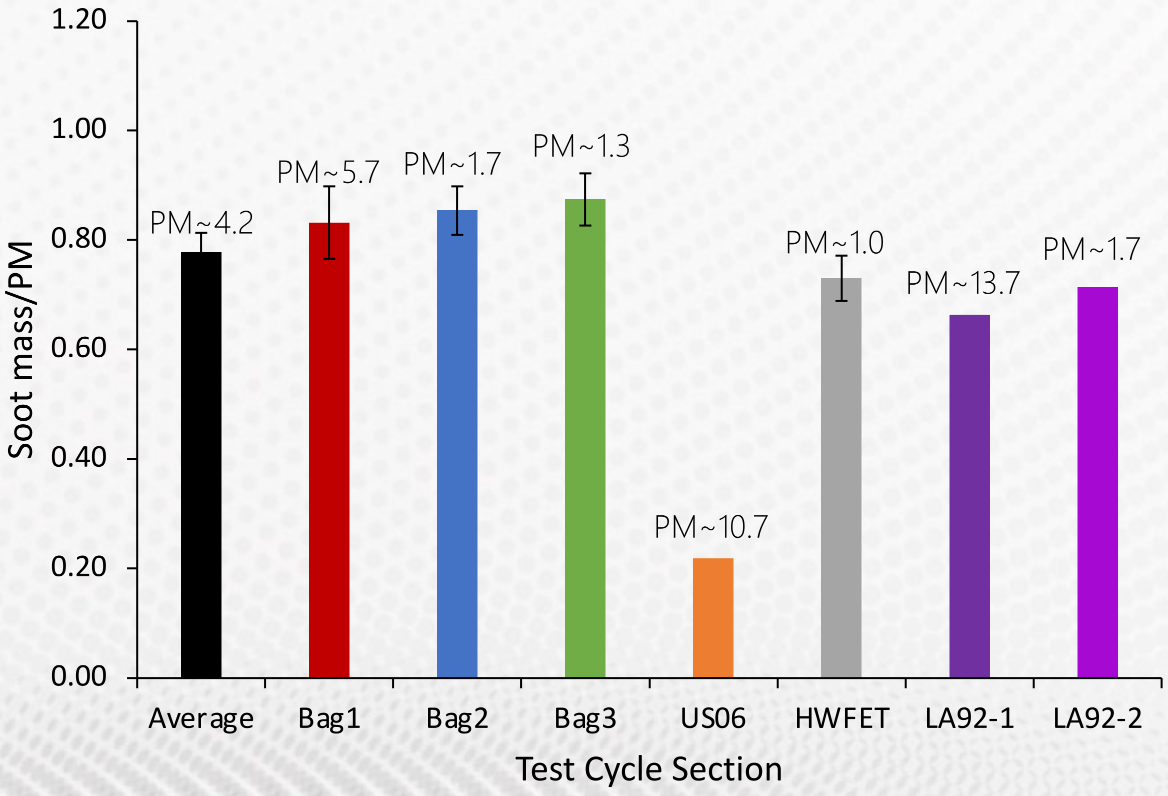
The EEPS gives greater PN readings than the APC from simultaneous CVS measurements because the EEPS measures both volatiles and solid particles, down to 6nm, whereas the APC uses a VPR so is only capturing solid particles (with 23nm cut-off).
The inversion algorithm used by the EEPS is calibrated under assumption of fractal-like soot particles.

Comparison of MSS and DMM for PM: Inference of Soot fraction

Scatterplot of MSS vs DMM PM from the CVS



Soot Fraction of Total PM across Test Cycle Sections



Fairly constant soot content of PM is seen between individual tests and cycles, except on US06 where a probable nucleation event affected the DMM's PM measurement ability.

Summary

1. The reported PN values, as well as PNSD seen, between tailpipe and CVS sampling methods vary over testing, as seen in previous literature.
   - ➢ Particulate matter characteristics are affected by transportation and sampling methods.
2. Comparison of PN equipment and with PM equipment suggests that the PM/PN ratio is fairly constant between test cycles.
   - ➢ There is good comparability between these two metrics for most test cycles.
3. PM and soot measurements give a fairly constant ratio for most cycles.
   - ➢ Soot can be a good predictor of GDI PM under moderate test cycles.

Points 2 and 3 indicate that one can employ surrogates for PN measurement when the use of PMP solid particle counters is impractical: We can still attain reasonable measurement capabilities with alternative equipment.

Thank You for Listening!

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