Prospects of meeting EU number emission standards with a diesel engine without a DPF

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27 June 2014

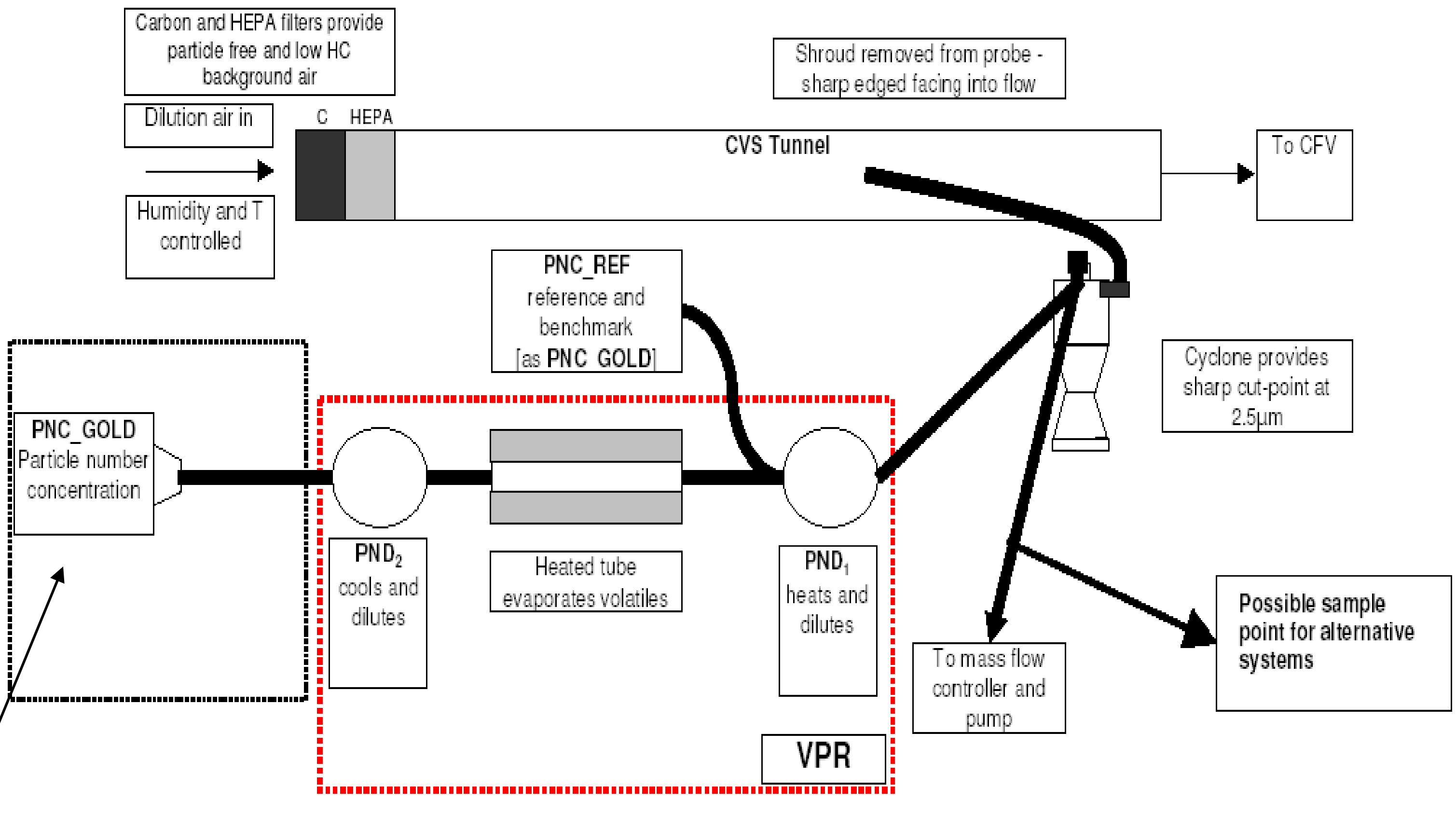
Outline

- Particle mass and number emission standards
  - The EU PMP method for measuring “solid” particles larger than 23 nm diameter.
  - Measuring particles below 23 nm
  - Issues with the current method
- Particle number and mass emissions from a Tier 4/Interim IIIB engine – designed to meet Tier 4 PM standards without a DPF
  - Apparatus and procedure
  - Test matrix
  - Summary results
- Is it likely that using a clean combustion approach, like that used here to meet the PM (mass) emission standards could be used to EU PMP PN (number) standards?

EU mass and number emission standards

- The standards are based on “solid” particles larger than 23 nm
  - Light-duty, Euro 5b, September 2011
    - The standard is 6 x 10^{11} particles/km
    - The mass emission standard is 4.5 mg/km, but the number standard corresponds to about 0.15 to 0.7 mg/km, depending on DGN – a much tighter standard!
    - An interim standard of 6 x 10^{12} has been set for gasoline vehicles, through 2017, after that they must meet diesel standard
  - Heavy-duty, Euro VI, January 2013
    - The standards are 6 x 10^{11} and 8 x 10^{11} particles/kWh on the WHTC and the WHSC, respectively
    - The mass emission standard is 10 mg/kWh, but the number standard corresponds to about 0.2 to 0.9 mg/kWh, depending on DGN – again a much tighter standard!
- Meaningful filter mass measurements are impossible at levels corresponding to these number standards
- New US light-duty standard of 0.6 mg/km
  - Measurement challenge using filter mass (CRC E99)
  - Corresponds to from 5 to 30 x 10^{11} particles/km, easily measured by number

PMP number measurement system



A specially designed CPC with a lower size cutoff (50%) of 23 nm is used

Solid particles are defined as those measured with a 23 nm cut size CPC in a diluted exhaust stream that has passed through a heated diluter and a volatile particle remover (VPR). It is an operational definition.

Why solid, why only larger than 23 nm?

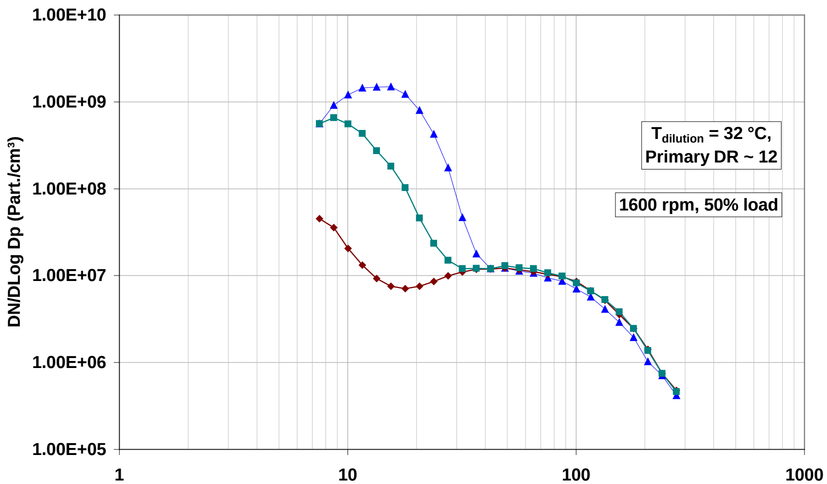
- The concentration of volatile nucleation mode particles is very dependent on sampling conditions
- Most of these particles are smaller than 23 nm

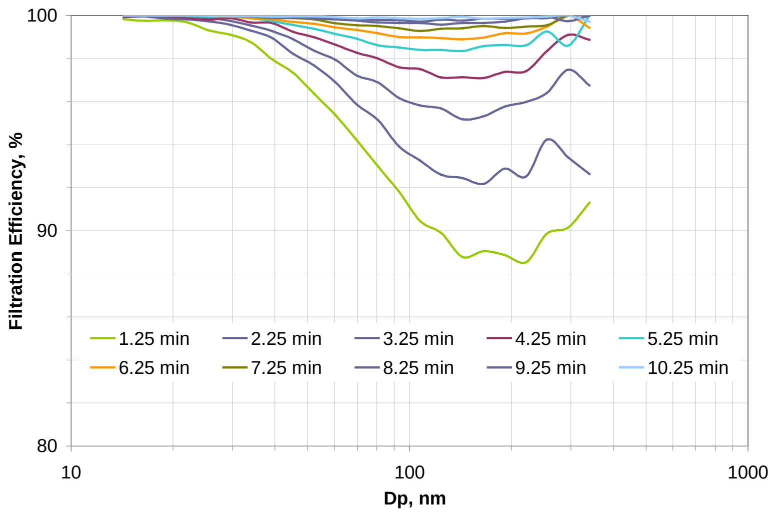
But…

- If the engine is fitted with a particle filter, particles below 50 nm or so are very effectively removed
- Thus regulating solid particles above 23 nm is really regulating soot particles is effectively regulating all particles for a trap equipped

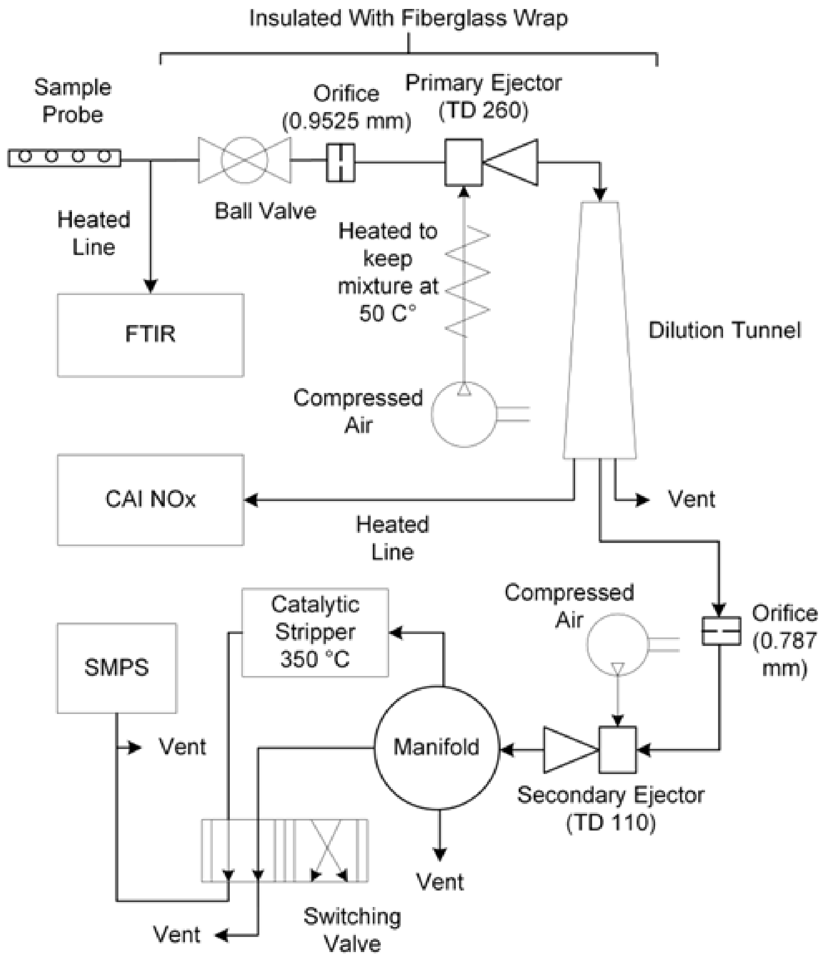
However…

- Without a trap there may be many solid particles below 23 nm as we shall see





Apparatus and test conditions - Tier 4/Interim IIIB engine

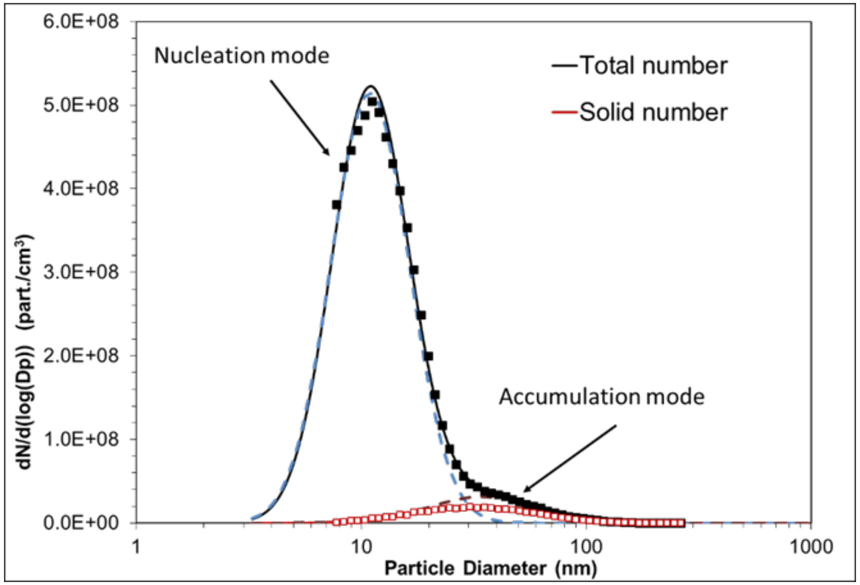


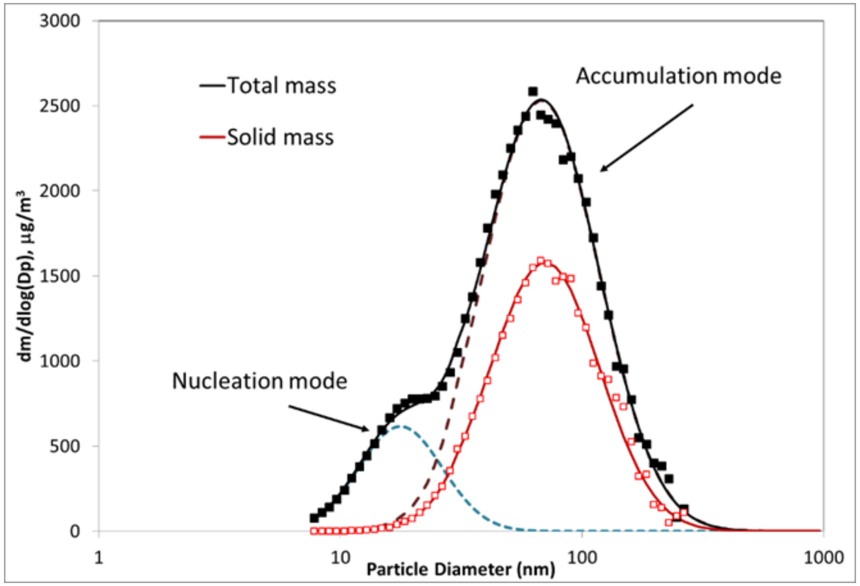
Condition	Speed, RPM		Torque, N-m		Primary Dilution		Total Dilution	
	Avg	StDev	Avg	StDev	Avg	StDev	Avg	StDev
1400 50%	1400	1.0	240.0	0.7	10.2	0.1	165.0	1.1
1400 50% CS	1400	0.9	240.0	0.6	10.2	0.1	165.0	1.1
Idle	900	1.1	25.0	1.7	9.9	0.1	160.0	1.0
Idle CS	899	2.4	25.0	1.0	9.9	0.1	160.0	1.0
2400 10%	2399	9.3	35.0	4.8	10.1	0.2	163.0	2.9
2400 10% CS	2400	8.0	35.0	5.6	10.1	0.2	163.0	2.7
2400 50%	2400	1.2	175.0	1.5	9.8	0.1	159.0	1.2
2400 50% CS	2400	1.1	175.0	1.4	9.5	0.1	154.0	0.8
Repeat								
1400 50%	1400	1.1	240.0	0.9	9.9	0.1	160.0	1.1
1400 50% CS	1400	1.1	240.0	0.9	9.9	0.1	160.0	1.1
2400 50%	2400	1.4	175.0	1.5	9.8	0.0	159.0	0.7
2400 50% CS	2400	1.3	175.0	1.3	9.8	0.0	158.0	0.7
2400 10%	2400	7.5	35.0	4.7	10.1	0.2	162.0	2.6
2400 10% CS	2400	6.3	35.0	3.7	10.2	0.2	165.0	2.6
Idle	900	0.6	25.0	0.8	10.0	0.1	161.0	0.8
Idle CS	900	1.3	25.0	0.9	10.0	0.1	161.0	0.9

Lucachick, Glenn, Aaron Avenido, Winthrop Watts, David Kittelson, and William Northrop, 2014. Efficacy of In-Cylinder Control of Particulate Emissions to Meet Current and Future Regulatory Standards, SAE paper number 2014-01-1597.

Total and solid (with CS) particle number and mass distributions, Tier 4/Interim IIIB engine, 2400 rpm, 175 N-m

- Number distribution on left, mass on right
- This condition forms large volatile nucleation mode, mainly < 23 nm, containing nearly all the number and significant mass
- On the other hand, nearly all the solid mass and much of the solid number is in the accumulation mode, mainly > 23 nm, consistent with the PMP approach

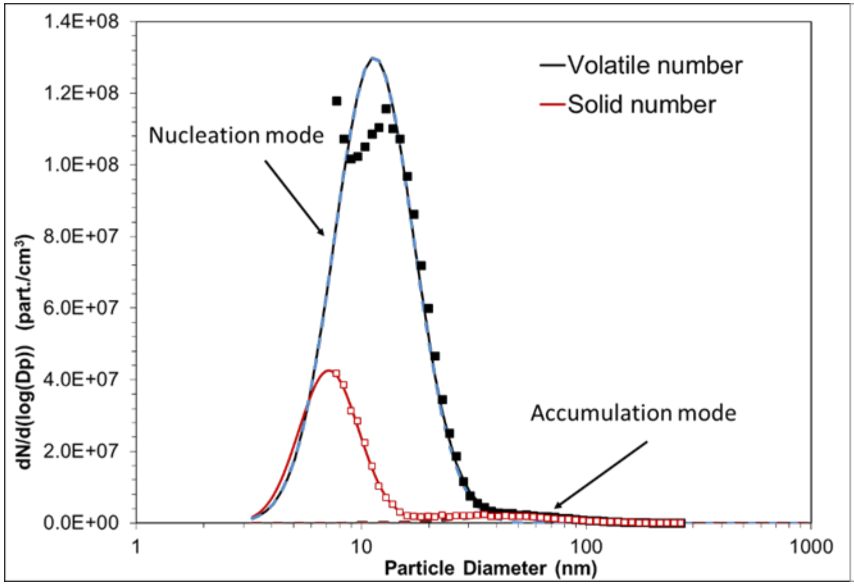


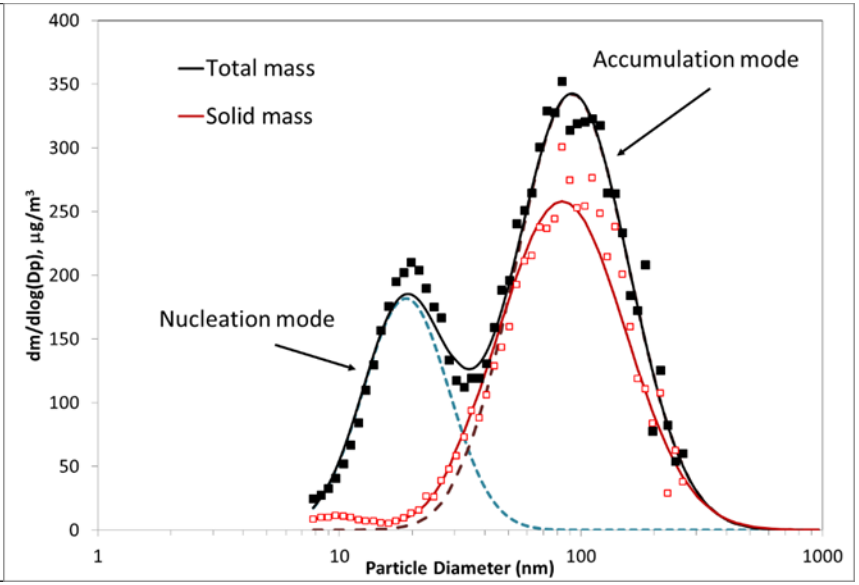


Lucachick, Glenn, Aaron Avenido, Winthrop Watts, David Kittelson, and William Northrop, 2014. Efficacy of In-Cylinder Control of Particulate Emissions to Meet Current and Future Regulatory Standards, SAE paper number 2014-01-1597.

Total and solid (with CS) particle number and mass distributions, Tier 4/Interim IIIB engine, 900 rpm, 25 N-m

- Number distribution on left, mass on right
- This condition forms large volatile nucleation mode, mainly < 23 nm, with nearly all the number and nearly half the mass
- A large solid nucleation mode is present with nearly all the solid number < 23 nm, likely a solid ash mode, these would not be counted by the PMP method – ***yet Tier 4 engines in this size range are being sold with SCR only – no DPF***





Lucachick, Glenn, Aaron Avenido, Winthrop Watts, David Kittelson, and William Northrop, 2014. Efficacy of In-Cylinder Control of Particulate Emissions to Meet Current and Future Regulatory Standards, SAE paper number 2014-01-1597.

Summary of particle statistics derived from fitted distributions

Condition	DGN acc (nm)	sigma acc	mass µg/m³	N >10 nm part./cm³	N >23 nm part./cm³	mass mg/kWh	N >10 nm part./kWh	N >23 nm part./kWh
2400 RPM 175 Nm	32.5	1.77	1.79E+03	1.51E+08	2.38E+07	18.1	1.52E+15	2.39E+14
2400 RPM 35 Nm	43.1	1.58	3.49E+03	5.50E+07	3.95E+07	106.6	1.68E+15	1.21E+15
1400 RPM 240 Nm	35.3	1.84	6.76E+02	6.78E+06	5.25E+06	4.2	4.21E+13	3.26E+13
900 RPM 25 Nm	48.0	1.72	2.92E+02	3.83E+07	4.25E+06	11.9	1.56E+15	1.74E+14
2400 RPM 175 Nm CS	31.7	1.79	9.02E+02	1.23E+07	9.24E+06	9.1	1.24E+14	9.31E+13
2400 RPM 35 Nm CS	32.1	1.70	2.84E+03	4.41E+07	3.40E+07	86.8	1.35E+15	1.04E+15
1400 RPM 240 Nm CS	35.9	1.86	5.24E+02	4.82E+06	3.86E+06	3.3	2.99E+13	2.40E+13
900 RPM 25 Nm CS	37.2	1.85	1.74E+02	3.13E+06	1.21E+06	7.1	1.28E+14	4.97E+13

DGN acc and sigma acc refer to the geometric mean diameter and standard deviation of the accumulation mode

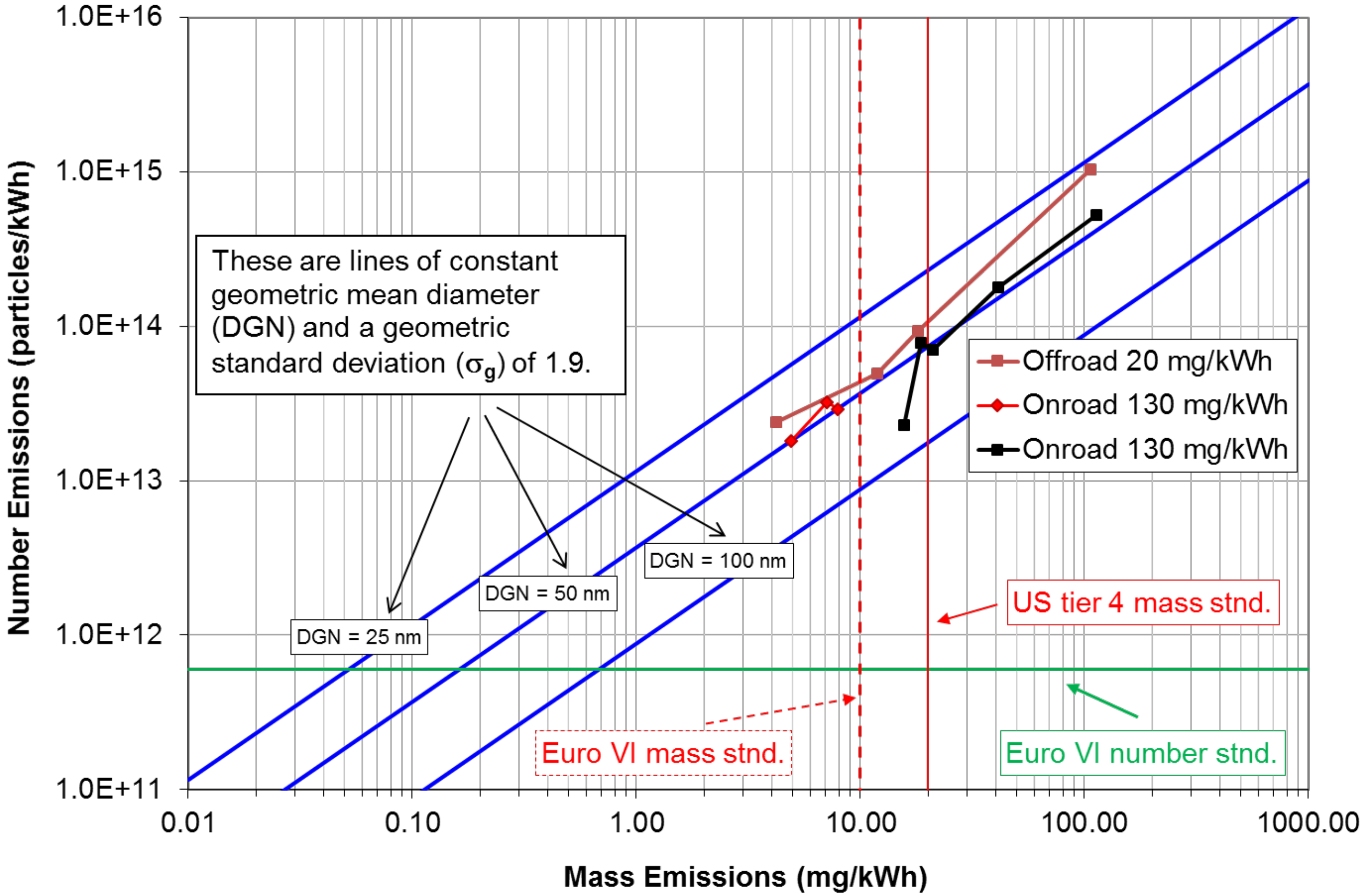
N > 10 nm and N > 23 nm refer to the number of particles larger than 10 and 23 nm, respectively

- Solid particle number emissions highlighted in yellow
- Solid number emissions are far above EU standards
- The solid particles in the accumulation mode are very small, 32 – 37 nm, such small particles are associated with clean combustion
- The 900 rpm 25 N-m case produces a tiny solid ash mode leading to many particles below 23 nm

Relationships between mass and solid number emissions

- The relationship between mass and number emissions is examined on the next slide
- The solid blue lines depict the theoretical relationship for log-normal size distributions with constant geometric standard deviation, σ_g, of 1.9 and geometric number mean diameters , DGN, of 25, 50, and 100 nm
- Experimental results are shown for 3 engines
  - The Tier 4 off-road engine described above designed to meet a 20 mg/kWh standard
  - Two pre 2007 on-road engines designed to meet the 130 mg/kWh standard
  - With one exception, all three engines follow the theoretical trend lines
  - The exception is for an engine producing a very large semi-volatile nucleation mode
- For most conditions the Tier 4 engine meets the mass emission standards without a DPF (as do the on-road engines)
- Even for the lowest mass emissions observed, number emissions are 30-40 times the PMP standard
- At constant DGN of 50 nm, mass emissions would have to be reduced below 0.2 mg/kWh to meet number standard
- Further in-cylinder combustion improvements would likely lead to smaller particles so mass would have to be reduced even more
- Such low mass emissions unlikely using conventional combustion

Relationships between mass and solid number emissions



Issues - PMP solid particle measurements

- Is 23 nm an appropriate lower limit?
  - This cut size was selected assuming a DPF would take out smaller particles
  - A new aircraft standard will go to 10 nm
- Many informal reports of calibration difficulties and CPC drift.
- Recent papers raise issues about solid particle measurements, especially when applied to particles smaller than 23 nm
  - Johnson, et al. (2009) – Evidence of volatile particles appearing as >23 nm solids under some conditions
  - Swanson and Kittelson (2010) – Evidence of significant volatile particle formation and suggestion of solid particle formation downstream of a thermal denuder (TD), a volatile particle removal device similar to a VPR
  - Zheng, et al., (2011) - Showed that the PMP method worked well under typical test conditions, but found large numbers of sub 23 nm particles downstream of the VPR under most test conditions
  - In all three of these papers found the use of a catalytic stripper reduced the formation of apparently solid artifact particles compared to the use of an evaporation tube like that used in the PMP method

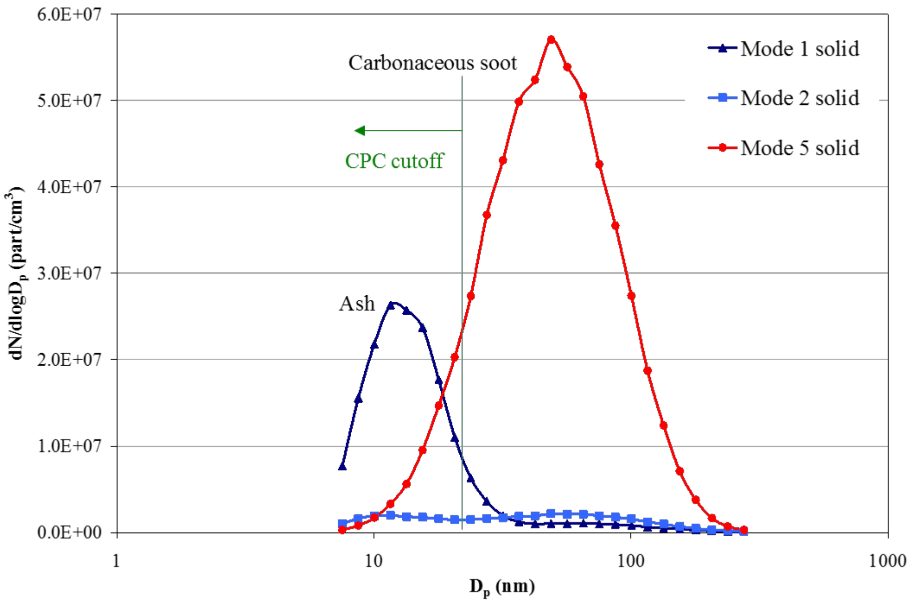
Johnson, Kent C., Thomas D. Durbin, Heejung Jung, Ajay Chaudhary, David R. Cocker III, Jorn D. Herner, William H. Robertson, Tao Huai, Alberto Ayala, and David Kittelson, 2009. Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy Duty Diesel Vehicles, Aerosol Science and Technology, 43:962–969, 2009.

Swanson, Jacob and David Kittelson, 2010. Evaluation of thermal denuder and catalytic stripper methods for solid particle measurements, *Journal of Aerosol Science*, Volume 41, Issue 12, Pages 1113-1122.

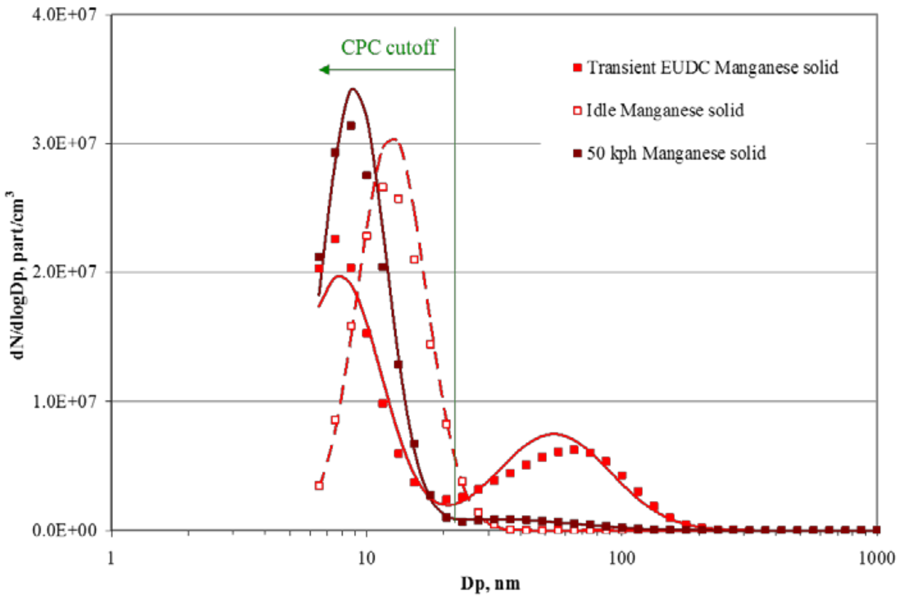
Zheng, Zhongqing, Kent C. Johnson, Zhihua Liu, Thomas D. Durbin, Shaohua Hu, Tao Huai, David B. Kittelson, and Heejung Jung, 2011. Investigation of solid particle number measurement: Existence and nature of sub-23nm particles under PMP methodology, *Journal of Aerosol Science* 42 (2011) 883–897.

Without filter both diesel and gasoline engines may produce sub 23 nm solid PN

Cummins 2004 ISM engine, BP 50 fuel, AVL modes



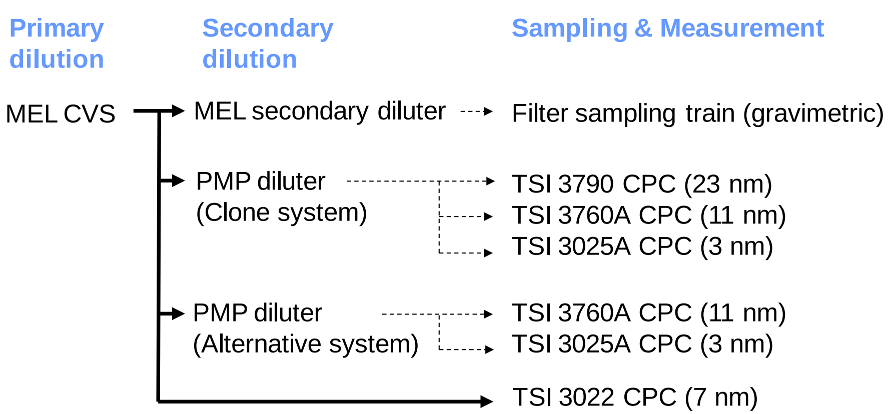
Euro 3 PFI gasoline car, 10 ppm Mn in fuel

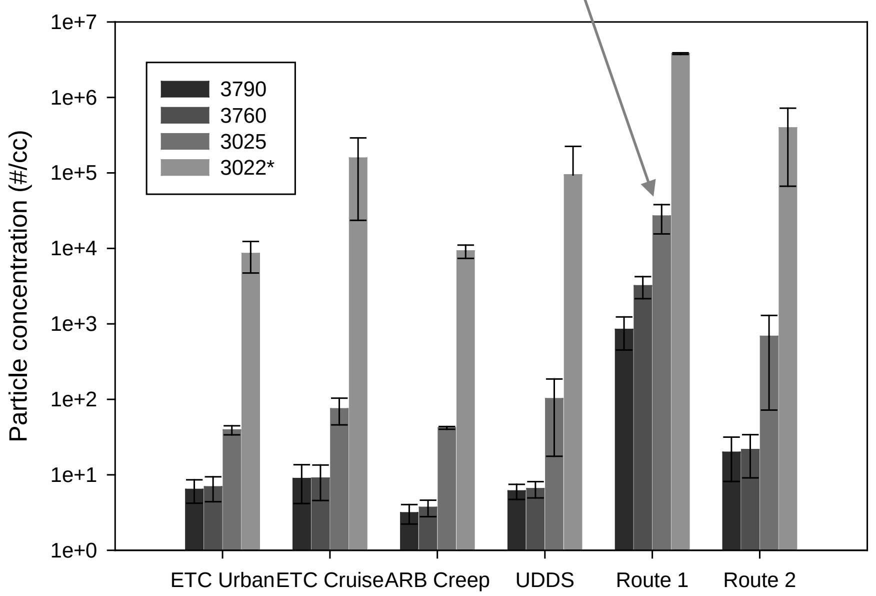


On road tests using PMP protocol show unexpected "solid" particles and many particles below 23 nm

A heavy-duty truck equipped with a CRT was tested on road and on a chassis dynamometer

- It showed large concentrations of "solid" particles below 23 nm at high load conditions
- These conditions favor sulfate particle formation.
- Filtration efficiency for particles below 23 nm is very high.

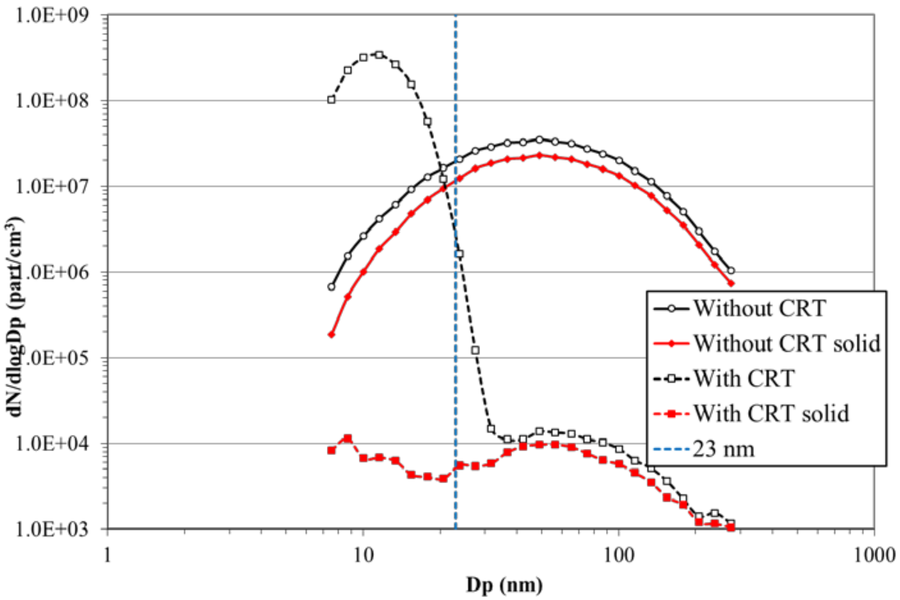




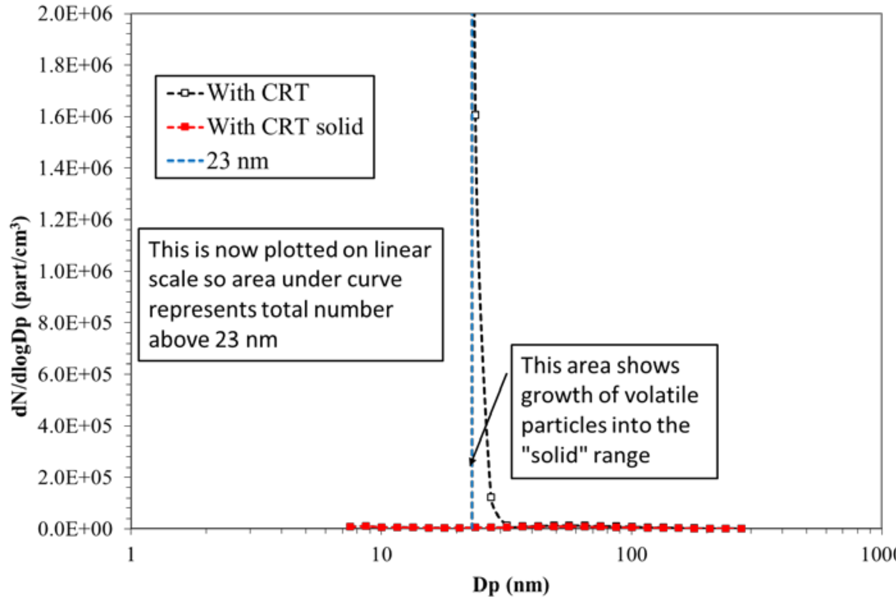
Johnson, Kent C., Thomas D. Durbin, Heejung Jung, Ajay Chaudhary, David R. Cocker III, Jorn D. Herner, William H. Robertson, Tao Huai, Alberto Ayala, and David Kittelson, 2009. Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy Duty Diesel Vehicles, Aerosol Science and Technology, 43:962–969, 2009.

Under high load conditions a catalyzed soot filter may produce a large sulfuric acid mode

Cummins 2004 ISM engine, BP 50 fuel, AVL mode 8, Total and solid particles with and without CRT



Here I have switched to a linear scale to show how breakthrough of semi-volatiles might bias "solid" N



Conclusions

- The use of modern combustion controls, advanced fuel air management, very high pressure injection, etc., can lead to very low engine out mass emissions
- PM low enough to meet standards without a DPF
- However, number emissions are still at least 1.5 orders of magnitude above EU standards
- Mass emissions would have to be reduced to well below 0.2 mg/kWh to meet these standards without a DPF
- It is unlikely that this could be achieved using conventional Diesel combustion
- Number emission standards have not yet been introduced in the US and there are issues associated with the current EU method
  - Potential artifact particles
  - Many particles may be emitted below 23 nm without a DPF
  - Should volatile particles be measured?

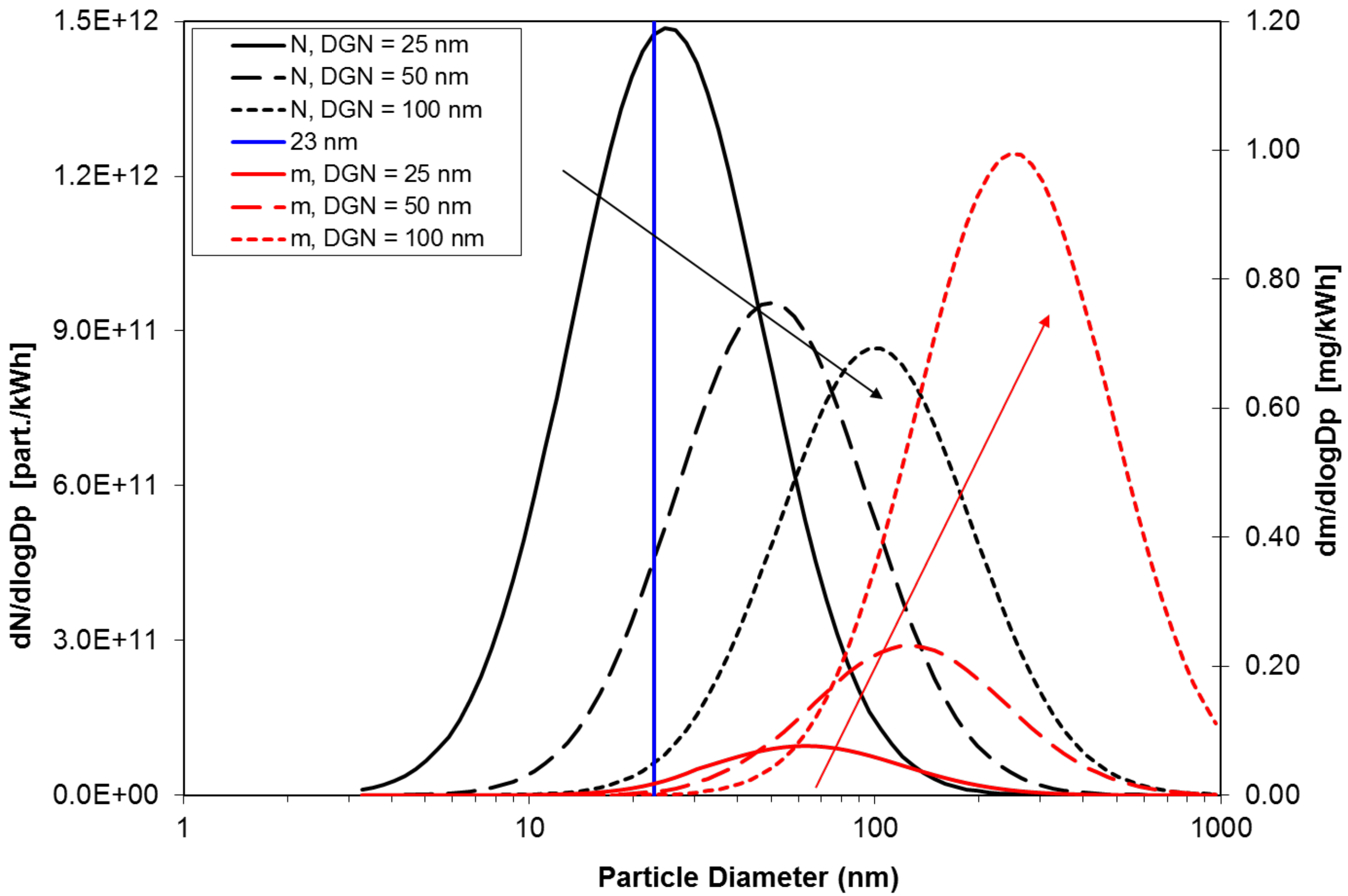
Acknowledgements

- John Deere supplied the engine used in this research, and technical support.
- A gift from General Motors provided partial research support for Mr. Avenido.
- National Science Foundation grant #CMMI-0959741 was responsible for the development of the hydrostatic dynamometer used in this project.

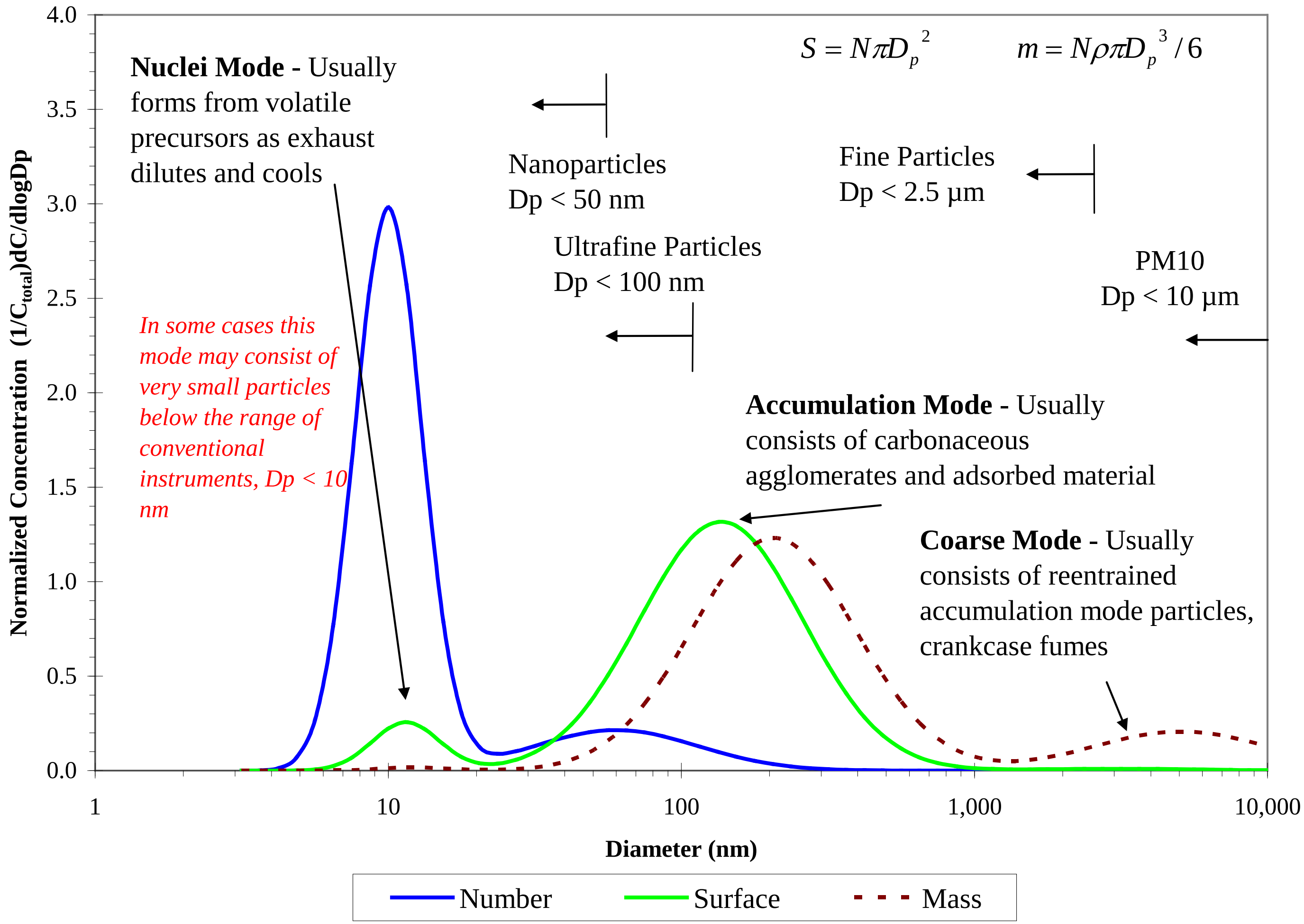
Questions?

Backup slides

Number and mass weighted size distributions corresponding to PMP number standard of $6x10^{11}$ particle/kWh

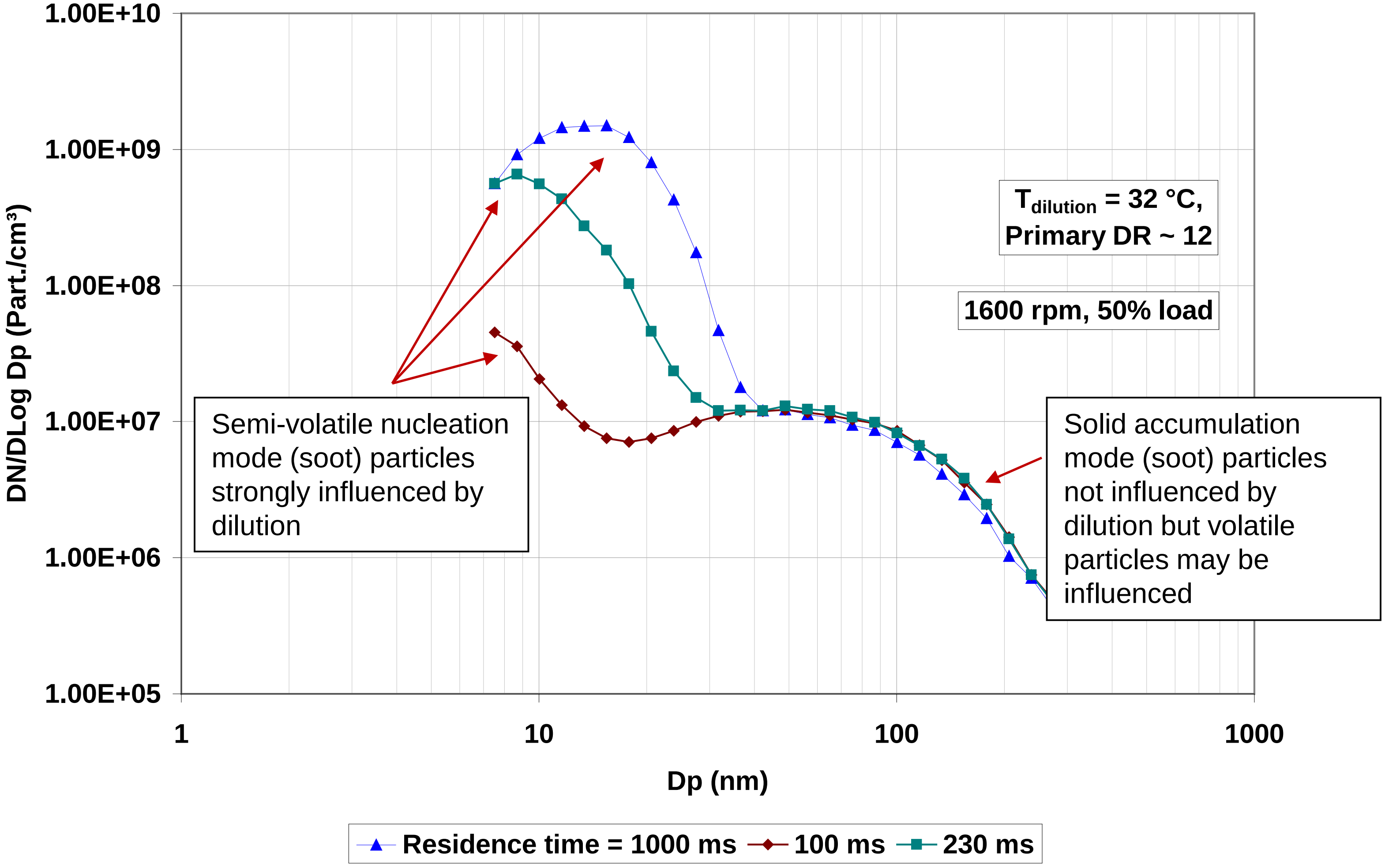


Typical engine exhaust particle size distribution by mass, number and surface area



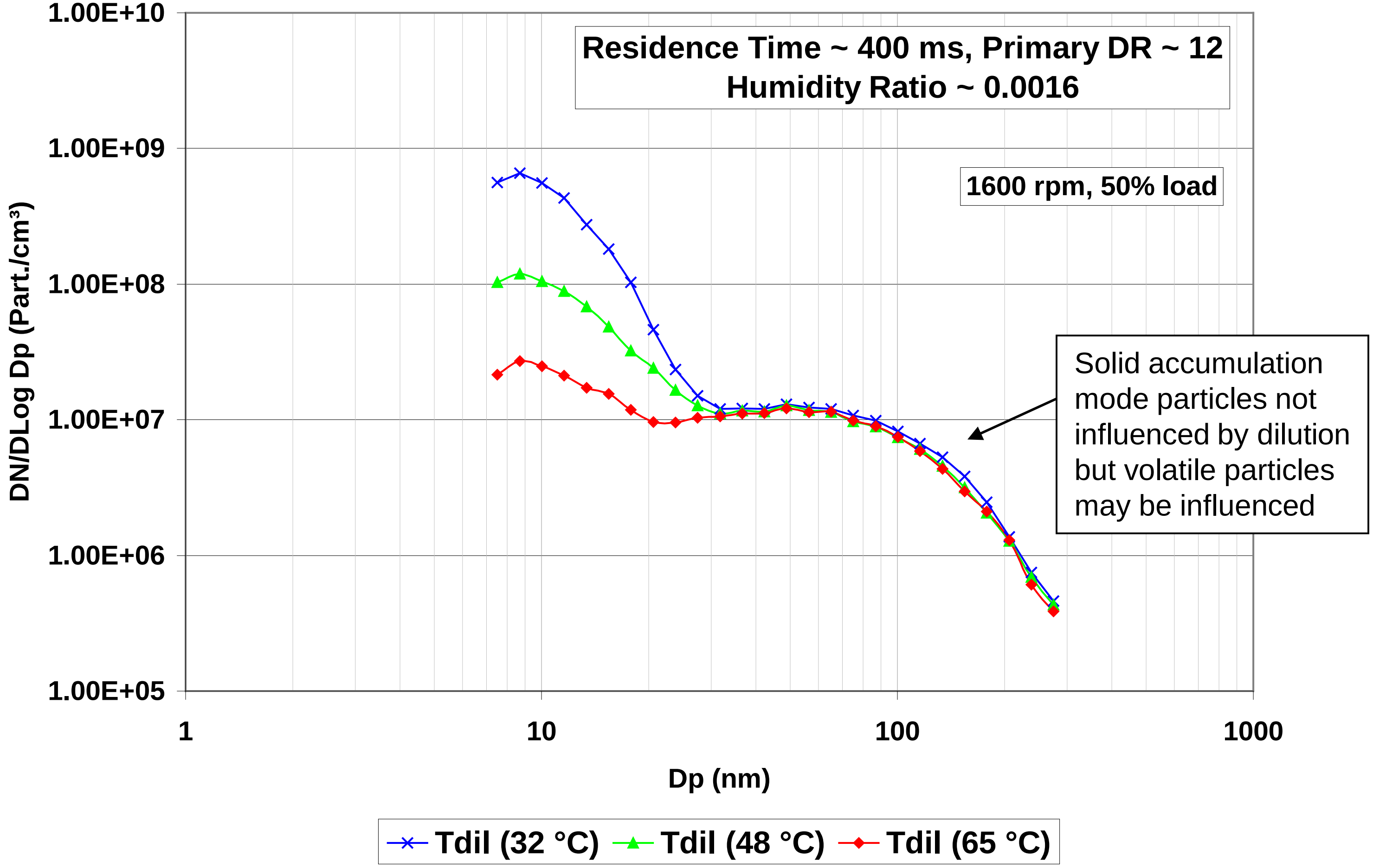
Kittelson, D.B. 1998. "Engines and Nanoparticles: A Review," J. Aerosol Sci., Vol. 29, No. 5/6, pp. 575-588, 1998

Influence of residence time on number weighted size distributions



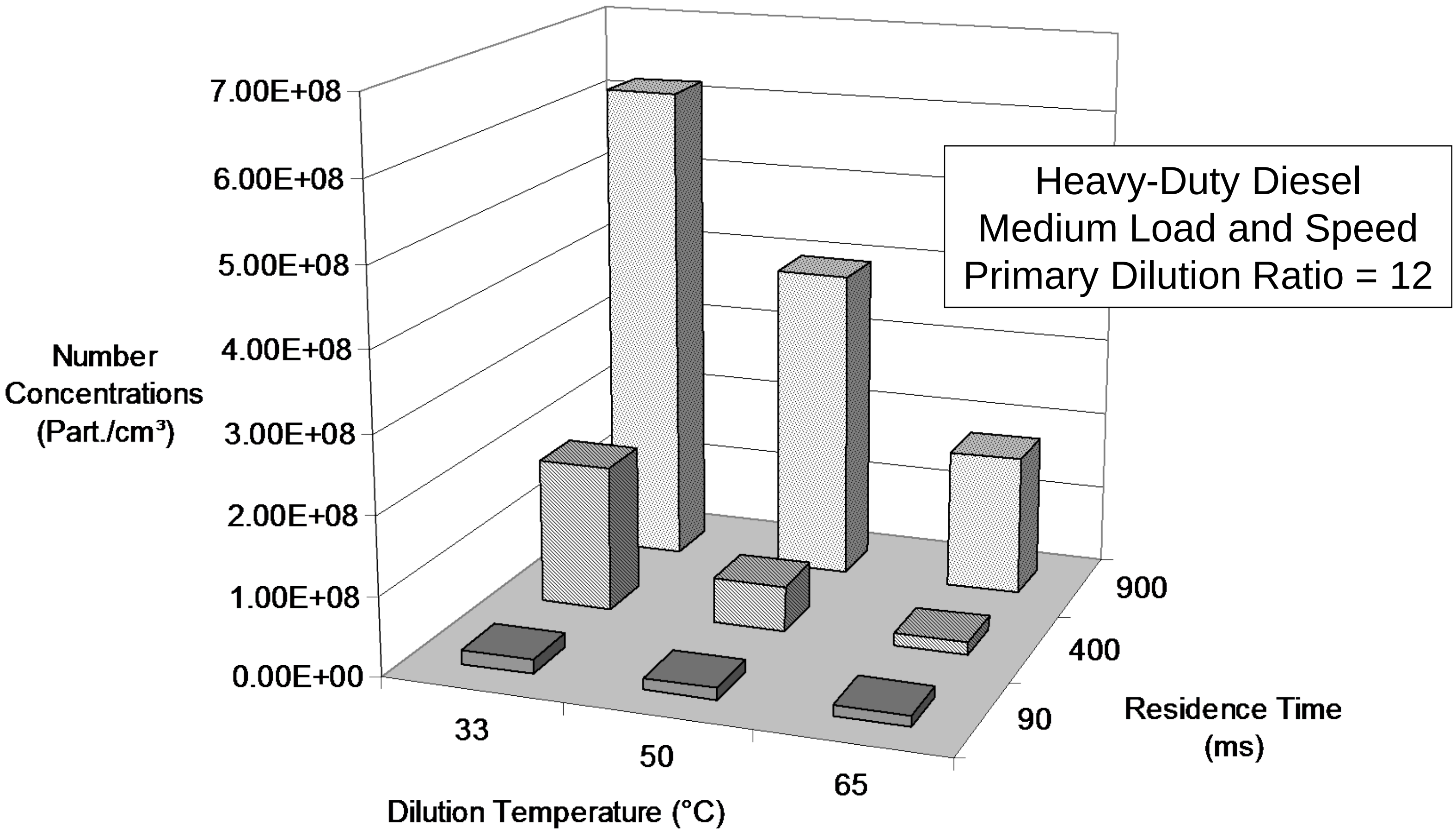
Abdul-Khalek, I., D.B. Kittelson, and F. Brear. 1999. "The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements," SAE Paper No. 1999-01-1142, 1999.

Influence of dilution temperature on number weighted size distributions



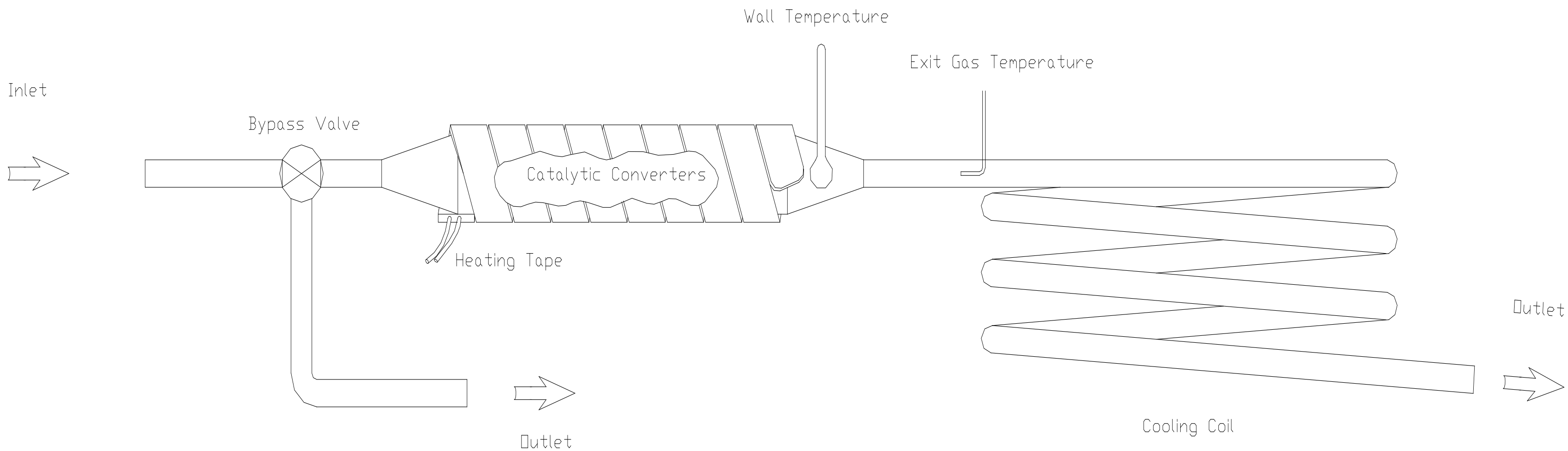
Abdul-Khalek, I., D.B. Kittelson, and F. Brear. 1999. "The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements," SAE Paper No. 1999-01-1142, 1999.

Sensitivity of diesel particle number emissions to dilution conditions - residence time and temperature effects



Abdul-Khalek, I., D.B. Kittelson, and F. Brear. 1999. "The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements," SAE Paper No. 1999-01-1142, 1999.

The University of Minnesota alternative to the evaporation tube VPR: the catalytic stripper (CS)

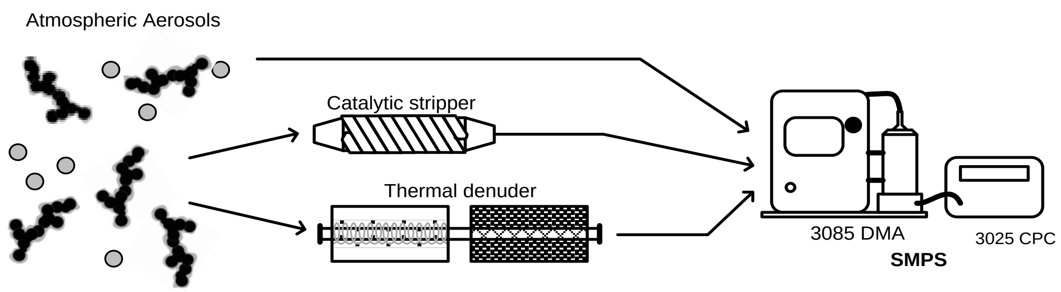


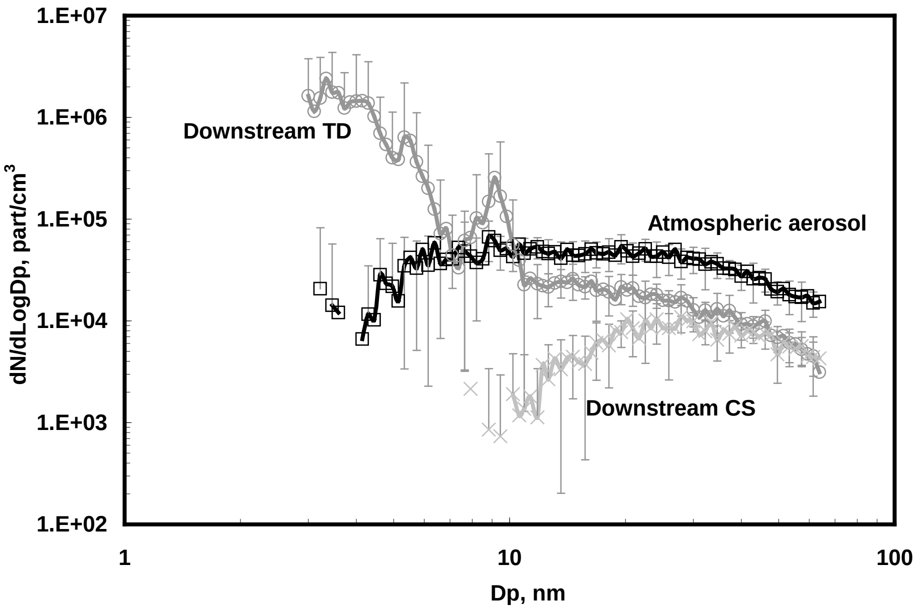
- Our strippers consists of a 2 substrate catalyst (provided by Johnson-Matthey) followed by a cooling coil
- The first substrate removes sulfur compounds
- The second substrate is an oxidizing catalyst
- Diffusion and thermophoretic losses present but well defined

Kittelson, D. B., W. F. Watts, J. C. Savstrom, J. P. Johnson, 2005. "Influence of Catalytic Stripper on Response of PAS and DC," Journal of Aerosol Science 36 1089–1107.

Swanson, Jacob and David Kittelson, 2010. Evaluation of thermal denuder and catalytic stripper methods for solid particle measurements, Journal of Aerosol Science, Volume 41, Issue 12, Pages 1113-1122.

Performance of thermal denuder and catalytic stripper with ambient aerosol





Swanson, Jacob and David Kittelson, 2010. Evaluation of thermal denuder and catalytic stripper methods for solid particle measurements, Journal of Aerosol Science, Volume 41, Issue 12, Pages 1113-1122.