Recent Advances in Measurement Technology for Low Particulate Emissions in A Legislative Framework

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UNDERSTANDING, ACCELERATED

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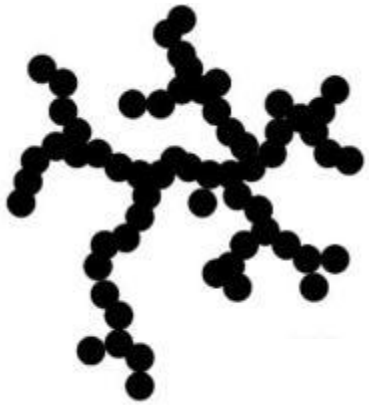
Outline

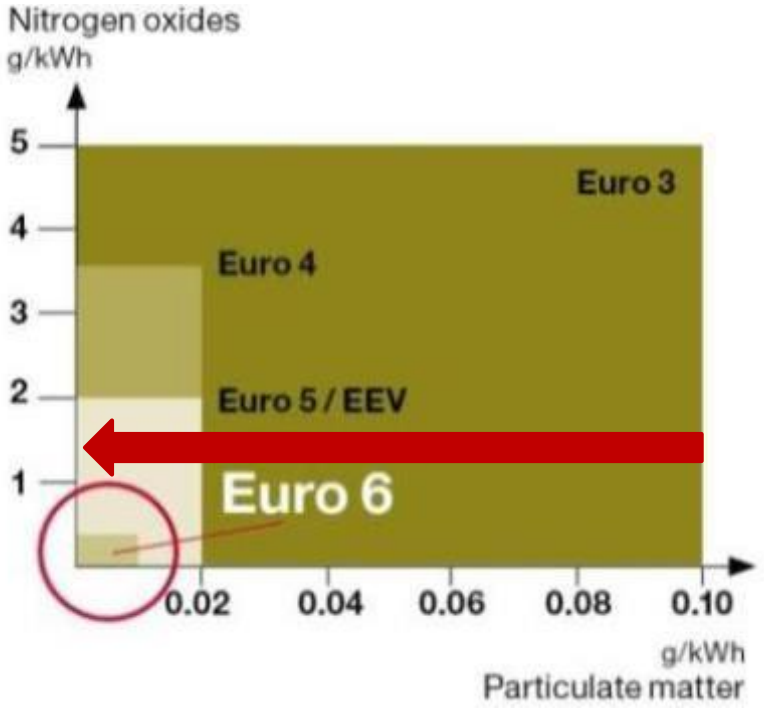
+ Background
+ Recent Developments
  - Emissions legislation (particles)
  - In the lab and in-use
+ Measurement Solutions
  - Method and in practice
+ Future Challenges
  - Solid Particles <23 nm
  - Size of PN



Background

+ Legislation mandates much lower PM emissions

- Tighter emission standards due to modern engine technologies and Diesel Particulate Filters (DPF)
- For HD Vehicles
  - Euro VI: 10 mg/kWh
    → 90% reduction since Euro III
- Requires very efficient emission control



Graph © Scania AB (publ.)

Problems with Low PM Emission (1)

+ DPF's are very effective, with >99% efficiency
+ Meaningful particle mass measurements very difficult at such low levels, actually often fail
  - Filter mass measurements
    - PM collected is <1/1000 of total filter mass, "weighing nothing is difficult"
    - Volatile fraction on filter can be many times mass of solid particles
  - Conventional online methods fall short as well
    - Opacimeters reach limits at smaller particle sizes and low concentrations[1] around type approval limit

[1] J. Spiegel et al. (ENV02 Report, 2014)

Problems with Low PM Emission (2)

+ PM mass methods insensitive to DPF fill state or porosity
+ DPF can
  - Fail in the field
  - Be destroyed or removed
+ Inspection & periodic control necessary
  - Very hard for mass/opacity based methods to detect

→ Talk of Th. Lutz

Photos courtesy of B. Osmondson (TSI)

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Solution for Low PM Testing

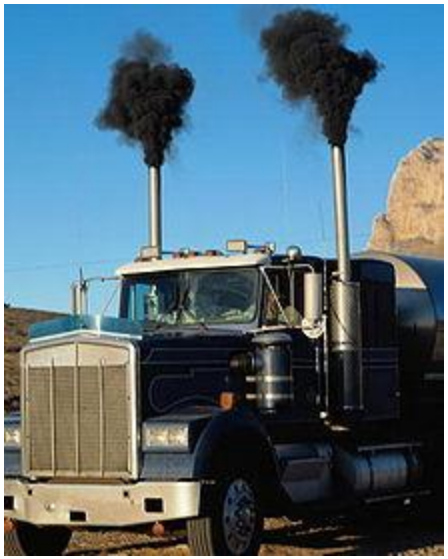
+ Measure solid Particle Number (PN)
+ Superior to gravimetric PM mass method in terms of precision and speed
  - Can be accomplished with 'relative ease'
  - Can detect DPF damage, even at low idle
  - Added benefit: Can be used to estimate health impacts of ultrafines, largest contributor to particle number

    → Talk of Prof. P. Gehr
+ Led to number-based emissions standards in 2011

PN Emissions Legislation – Diesel

Heavy Duty Diesel

- Euro VI
- Since 2013
- Requires measurement of particle number (PN) emissions



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PN Legislation – HD Diesel

+ **Particle number (PN) legislation is fully** implemented by EU for type approval
  - PN limit for number of solid particles >23 nm added to standard that limits PM mass
  - Regulation No. 49 for Heavy Duty, January 2013
    - Euro VI emissions level: 8×10^{11} particles/kWh (WHTC)
    - Conducted *in emissions lab* (chassis dyno)
  - Based on → Particulate Measurement Programme (PMP) method for solid PN [2]
    - Requires Condensation Particle Counter (CPC)

[2] Giechaskiel et al. (AS&T, 2008)

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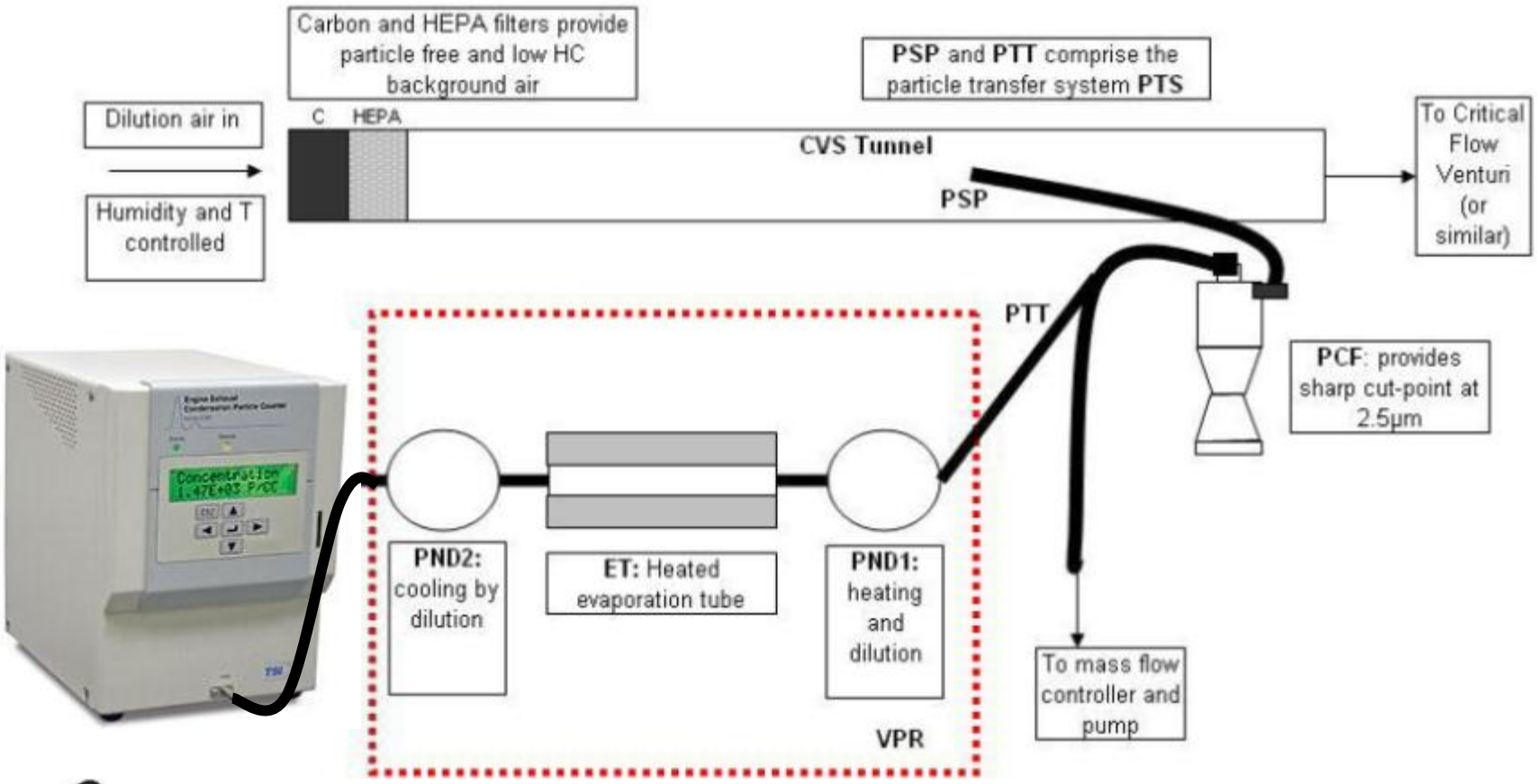
PMP Method for Solid PN



Regulation No. 49 (UNECE)

PMP Method – Turn-key Solutions in Practice

MAHA-AIP Solid Particle Counter SPC 8000

HORIBA MEXA-2000SPCS

Photos © MAHA-AIP GmbH & Co. KG; HORIBA, Ltd.

PN Legislation – Off-Road

Off-Road Construction Machinery

- Switzerland
- Since 2014
  VAMV includes measurement of nanoparticle number

PN Legislation – Off-Road (2)

+ Swiss Ordinance of Air Pollution Control (VAMV) is first to limit PN emissions *in the field*
  - Regulation SR 941.242 mandates in-use compliance testing of for off-road vehicles
    → Construction machinery DPFs
  - Up to now bi-annual tests with opacimeters
  - From 2017 requires test for PN emissions & certification
    - Limit value of 250,000 particles/cm^3 as pass/fail threshold
  - In future buses & other non-road mobile machinery
    - DFP and (in-use) filter performance control
      → Talk of Dr. Tatarkovsky

Field-Test Method – Solution in Practice

Nanoparticle Emission Tester (TSI 3795)

+ Solid PN counting test instrument
  - Follows PMP method to focus on non-volatile particles
  - Relies on Condensation Particle Counter
  - Tested and approved by METAS
    - Switzerland's Federal Institute of Metrology

Field-Test Method – Solution in Practice

Nanoparticle Emission Tester (TSI 3795)

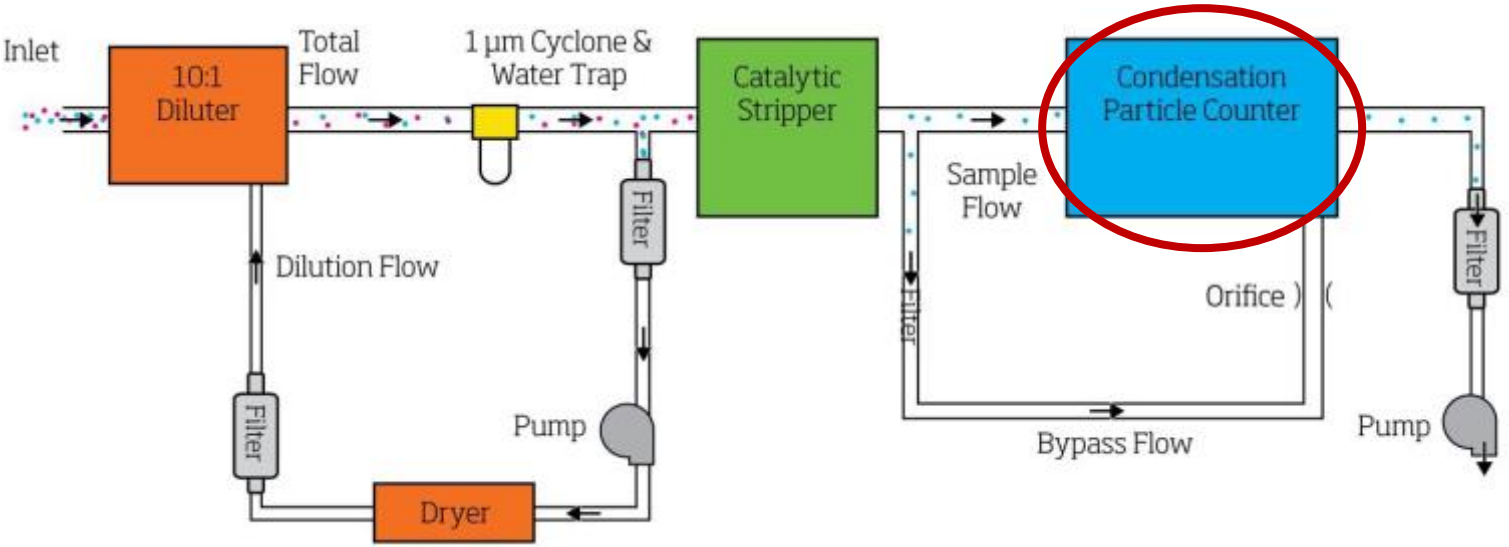
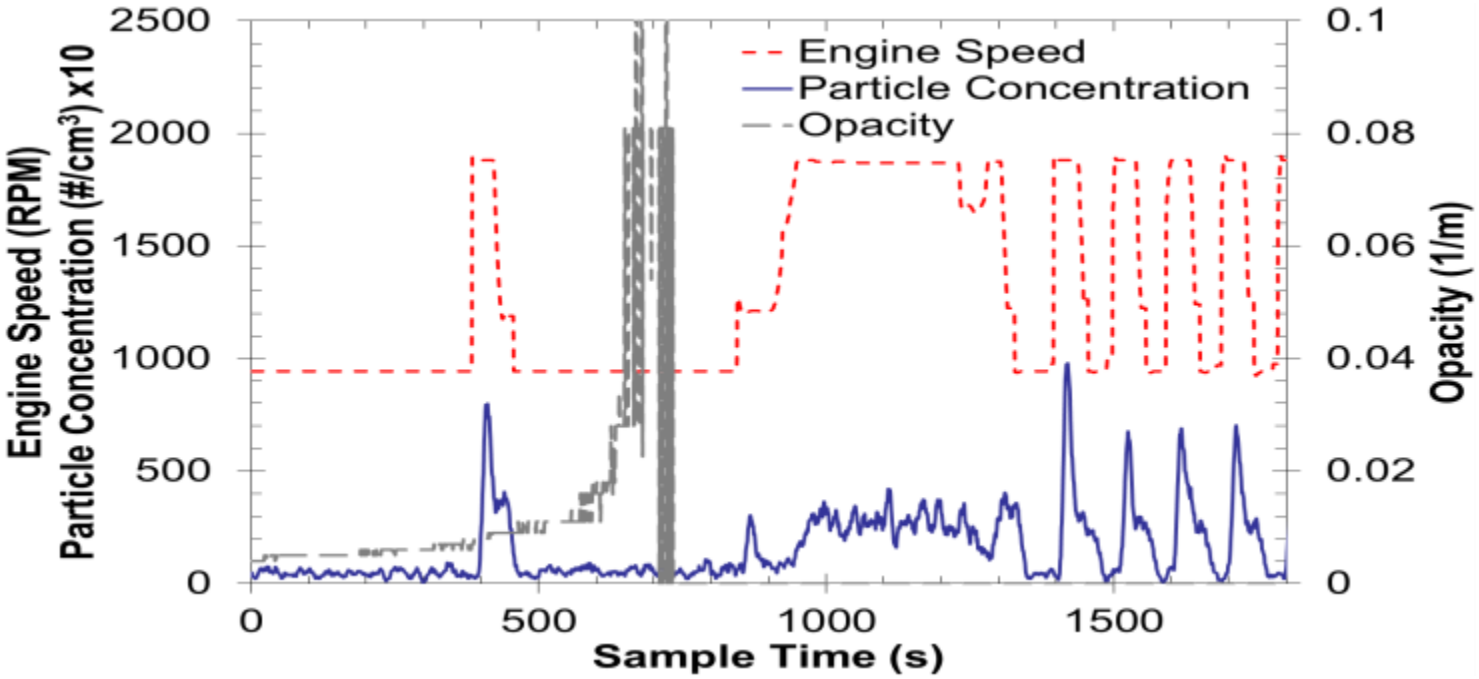


Photo and schematic © TSI Inc.

Field Data – Official Test Mode

Large Excavator (built 2013), 4 L engine, DPF

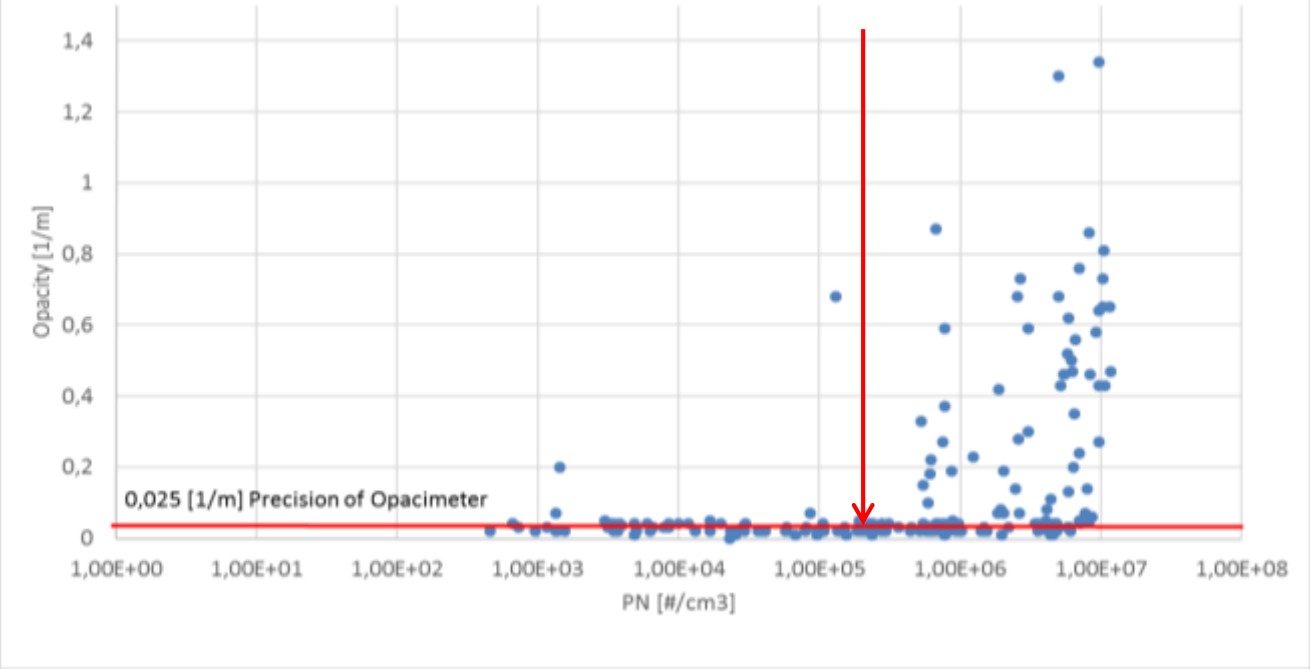


Field Data – In-Use Roadside Tests

+ Large project in Chile
  - Retrofit program and fleet update of new buses with DFP
+ Internal study organized by Dr. A. Mayer, with local support (GEASUR)
  - Random PN roadside measurements of 400 buses to check DPF-quality
    - Tests during free acceleration
  - Many buses with excellent results (10x below ambient air!)
+ Solid PN data measured by NPET
  - Much more sensitive than opacity

Field Data – NPET vs. Opacity

+ Free acceleration testing of Santiago buses
  - 30% of opacimeter results close to zero opacity [1/m], even though PN showed significant concentrations



Data courtesy of Aliosha Reinoso (Geasur), VERT Forum 2016

Future Challenges

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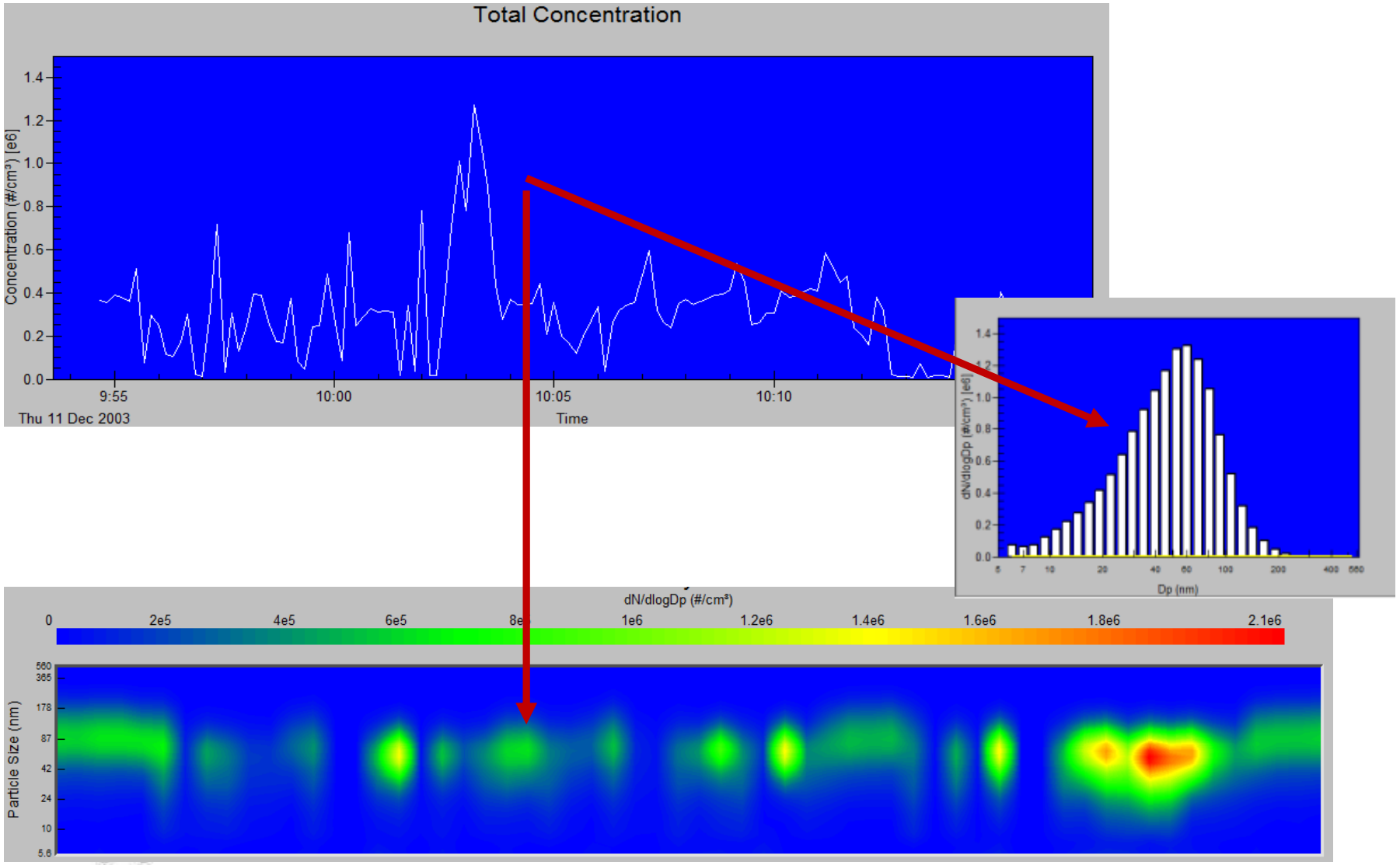
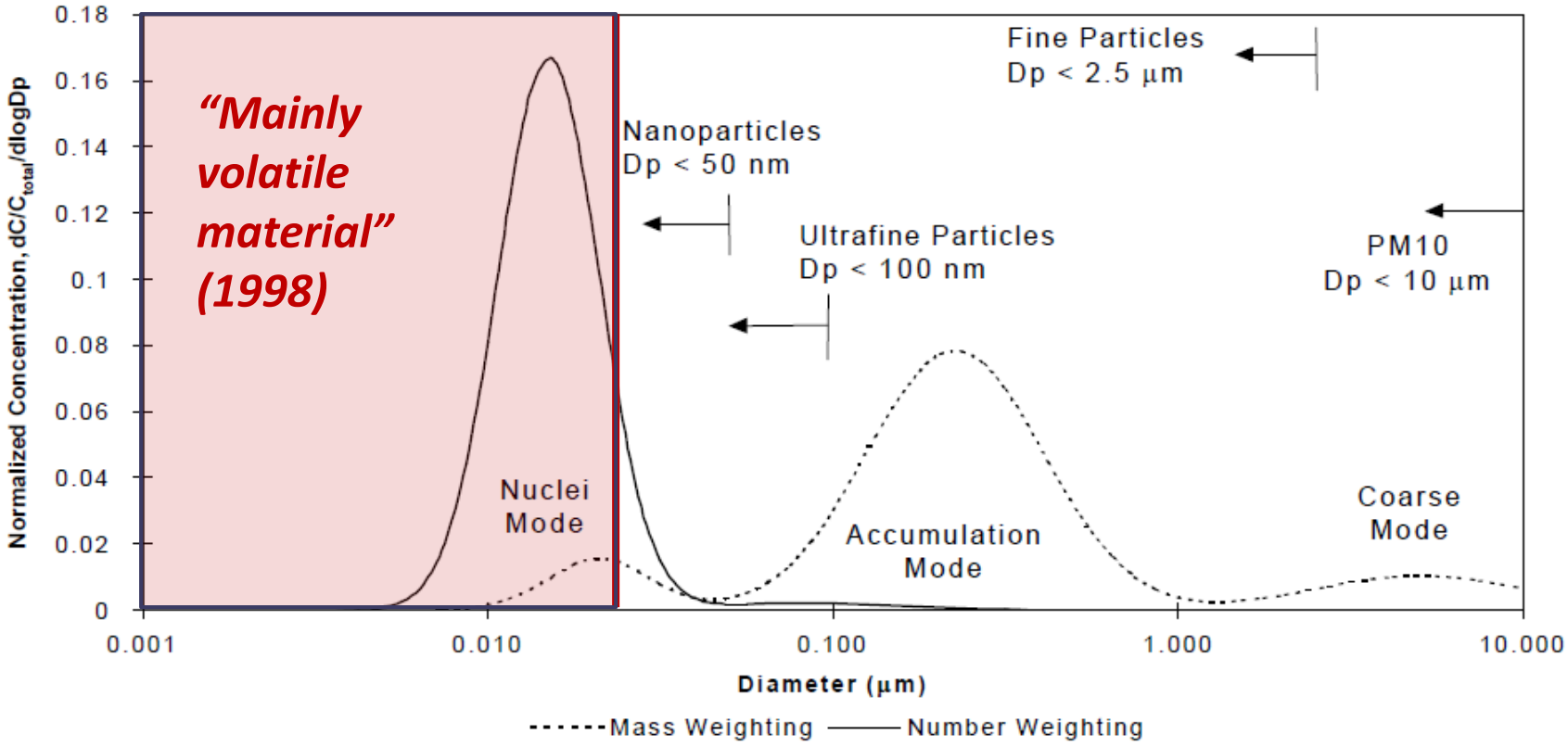
Solid PN and Particle Size



Solid Particles < 23 nm (1)



D. Kittelson (J. Aerosol Sci., 1998)

Solid Particles < 23 nm (2)

+ PMP's strict 23 nm cut-off more or less arbitrary
  - Metal-based additives in oil and fuel can generate large numbers at small sizes (Kittelson, CRC 2012)
  - Vehicles can emit small semi-volatile particles during high engine load (Karjalainen, Atmos. Env. 2014)
+ Real concern
  - Has been major factor in reluctance of U.S. to decide on Particle Number legislation
  - EU sees no evidence to change procedures (PMP)
    - Will gather more sub-23 nm emission data

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Particle Size of PN Emissions

Proceedings 5th Conference on Propulsion Technologies for Unmanned Aerial Vehicles, Haifa, Israel, January 28, 2016

Reduction of nanoparticle emissions by retrofitting in-service buses with diesel particulate filters

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Keywords: Nanoparticles; Diesel engine; Diesel particulate filter; Retrofitting

Engine Exhaust Particle Sizer (TSI 3090)

Measures ten particle size distributions from 5.6 to 560 nm per second (=10 Hz sampling rate)

Summary

+ Advanced engine technology and aftertreatment (should) have great impact on particle emissions
  - Results are → low emissions, also quantitatively
+ Solid PN method more sensitive than PM mass
  - Can indicate changes in DPF fill state & detect DPF failure
+ In Europe emissions legislations are in effect that limit solid particle number (PN)
  - Show that great reductions are achievable
    - Yet limited to new engines and standard test cycles
  - Only CH also addressed need for periodic control
    - Testing of individual off-road machinery in the field

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Thank You Very Much
For Your Attention!

Any Questions?

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