Comparison of particle mass and particle number emissions from a heavy-duty diesel vehicle under on-road driving conditions and a standard testing cycle

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It is important to understand the differences between emissions from standard laboratory testing cycles and those from actual on-road driving conditions, especially for solid particle number emissions now being regulated in the Europe. This study compared particulate matter (PM) mass and particle number (PN) emissions from a heavy-duty diesel vehicle operating over the urban dynamometer driving schedule (UDDS) and actual on-road driving conditions. PM mass emissions were calculated using integrated particle size distribution (IPSD) method. Liu et al. (2009) have proposed the IPSD Method, in which they determine total particle mass by integrating fractional mass obtained by multiplying effective density of particles to particle volume concentrations at each volume bin. PN and PM mass measurements were dominated by nucleation particles for the UDDS and uphill driving and by accumulation mode particles for cruise and downhill driving.

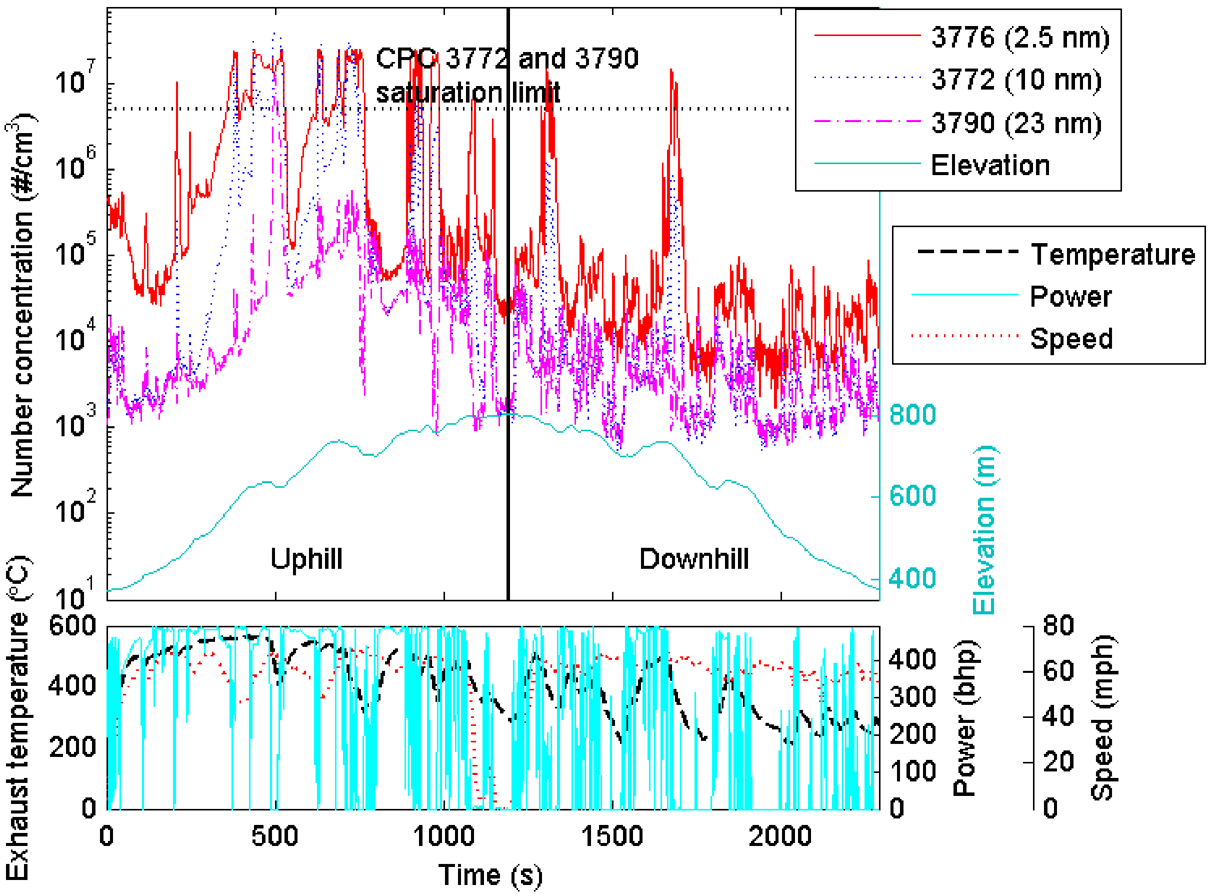

Figure 1 Real-time PN concentrations downstream of the PMP for the on-road flow-of-traffic test.

Figure 1 shows the real-time PN concentrations downstream of the PMP system for the on-road, flow-of-traffic uphill and downhill driving tests. Elevation, vehicle speed, engine power, and exhaust temperature are also shown in Figure 1. The dashed horizontal line in Figure 1 is the PMP PCRF corrected saturation limit of the CPC 3772_10 and CPC 3790_23. Above this saturation limit the concentrations measured by CPC 3772_10 and CPC 3790_23 are underestimated. The CPC 3772_10 and 3790_23 reached their saturation limits during some time periods of uphill driving. The CPC 3776_2.5 was under its saturation limit throughout the entire test.

The CPC 3776_2.5 concentrations were always higher than the CPC 3772_10 and CPC 3790_23 concentrations for the uphill driving, which was expected and consistent with the UDDS results. The CPC 3772_10 and CPC 3790_23 agreed well at the beginning of uphill driving. As the test proceeded to t = ~250 seconds, however, the CPC 3772_10 concentrations gradually increased to levels well above those of the CPC 3790_23 and to levels that were closer to those of the CPC 3776_2.5. This is attributed to excessive growth by condensation of the re-nucleated particles downstream of the PMP system, caused by the increase of nucleation mode particle concentrations in the CVS (ranged from 1.0×10^7 to 3.6×10^7 particles/cm^3 for particles smaller than 30 nm), as measured by the EEPS. Following their formation through re-nucleation downstream of the PMP system, particles begin to grow through condensation. If enough volatile vapors are available downstream of the PMP system, due to extremely high concentrations of the nucleation mode particles in the CVS, the re-nucleated particles will grow to larger than 10 nm and will be detected by the CPC 3772_10, which will cause the CPC 3772_10 concentrations to increase relative to both the CPC 3790_23 and the CPC 3776_2.5. Once this period of elevated condensation was over, the CPC 3772_10 and CPC 3790_23 tracked well again from around t = 750 seconds to the end of the entire test, except for a few time periods where excessive re-nucleated particles downstream of the PMP system occurred.

The downhill driving test cycle showed smaller differences between the CPC 3776_2.5, CPC 3772_10, and the CPC 3790_23. This indicates that the particles are predominantly in the accumulation mode. Two periods of excessive re-nucleation were observed for the downhill driving segment shown in Figure 1, one at ~1300 seconds and one at ~1670 seconds. The first nucleation peak can be attributed to the truck accelerating up to driving speed after the vehicle turned around at the top of the hill. The second nucleation peak appears to be related to a short uphill segment that occurred during the course of the downhill driving segment, as seen from the elevation in Figure 1. It should be noted, though, that these two periods occurred in 3 out of the 4 repeats of the on-road, uphill and downhill driving tests, which causes relative large variations for the integrated CPC_3776_2.5 and CPC 3772_10 concentrations,

The IPSD PM mass emissions for the UDDS and on-road tests were more than 6 times lower than the U.S. 2007 heavy-duty PM mass standard as Figure 2 shows. The IPSD PM mass emissions for the UDDS fell between those for the on-road uphill and downhill driving. The PN emissions were ~3 times lower than the Euro 6 heavy-duty PN limit for the UDDS and downhill driving, and ~4 to 5 times higher than the Euro 6 PN limit for the uphill driving.

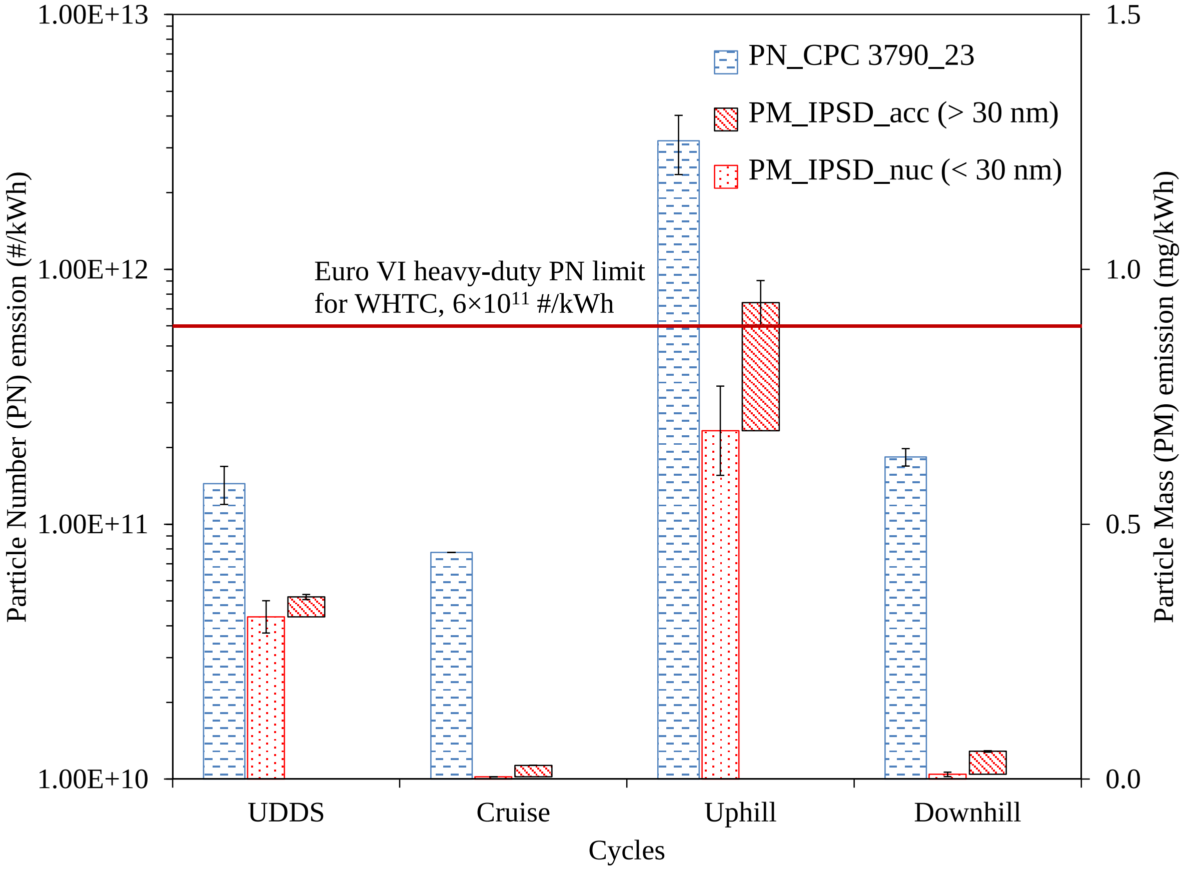

Figure 2 PM mass and PN emissions over the on-road and UDDS tests. The left y axis (PN emissions) is on a logarithmic scale and the right y axis (IPSD PM mass emissions) is on a linear scale.

Figure 3 shows PN vs PM_{IPSD_Acc} (Acc means accumulation mode) using the same data presented in Figure 2. The power relationship between PM and PN is quite impressive, although it is difficult to generalize our finding due to the limited number of driving conditions. A similar relationship was not found between PN and PM_{IPSD}. This topic requires further study to better understand PM and PN relationship at low PM levels.

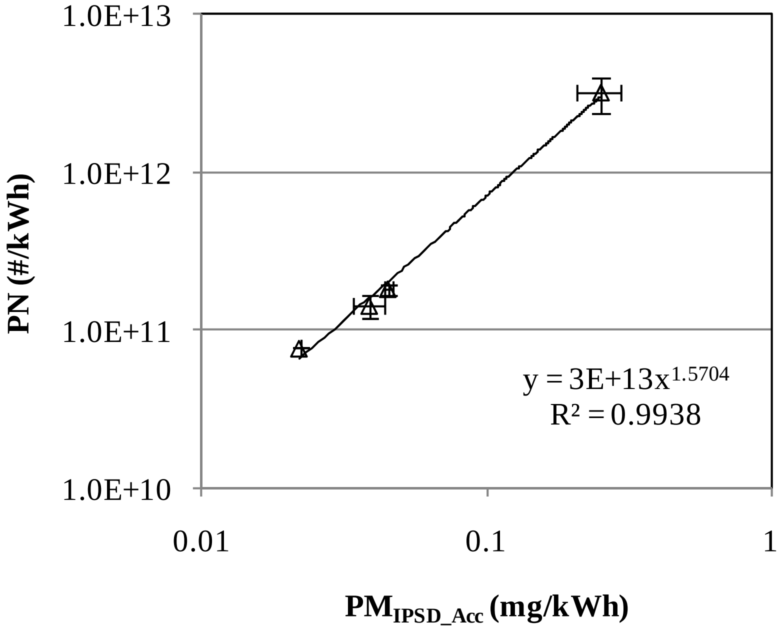

Figure 3. Power relationship between PM_{IPSD_Acc} and PN over different driving conditions.

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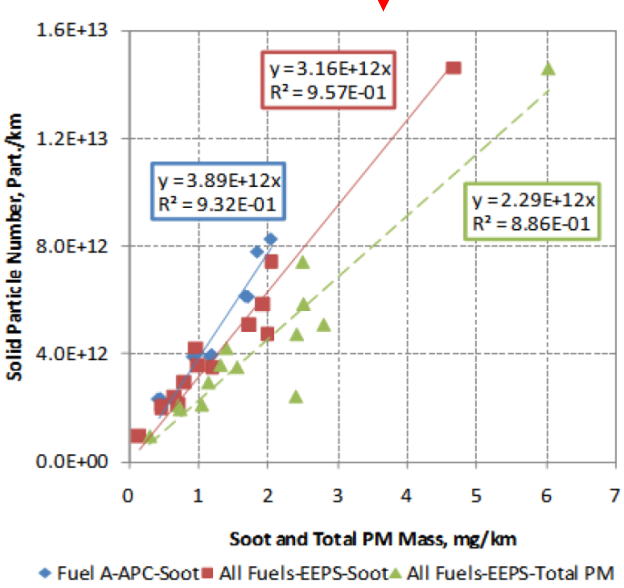
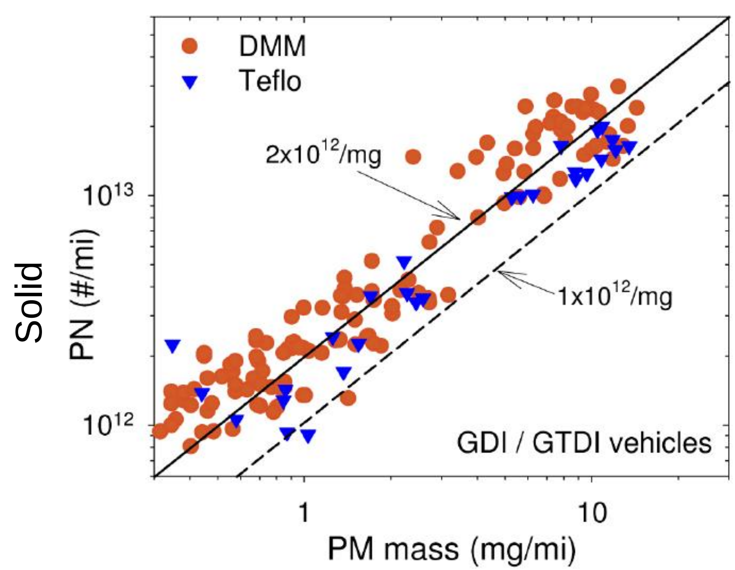
Previous studies on LDV

ILCE_LD final report (2007): The linear relation between PM and PN appears to hold true for conventional diesel, lean GDI and the vehicle equipped with the increased porosity DPF. The PM vs PN relationship will breakdown with efficient wall flow filters.

Diesel, Kirchner, Vogt and Maricq SAE 2010-01-0789
GDI, Maricq, Szente, Loos and Vogt, SAE 2011-01-0623
GDI, Khalek, ETH 2010 presentation



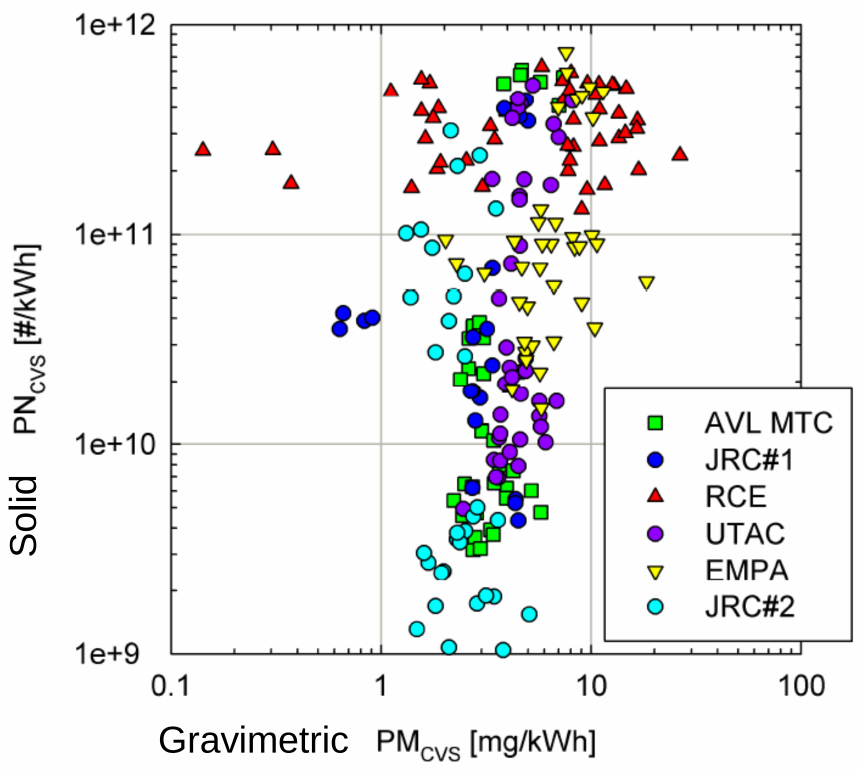


PM vs PN relationship appears to exist when PM is EC dominant.

Previous studies on HDV

Andersson, 2010, ETH presentation
ILCE_HD

PM is dominated by volatile materials. Then PM vs PN relationship does not exist.



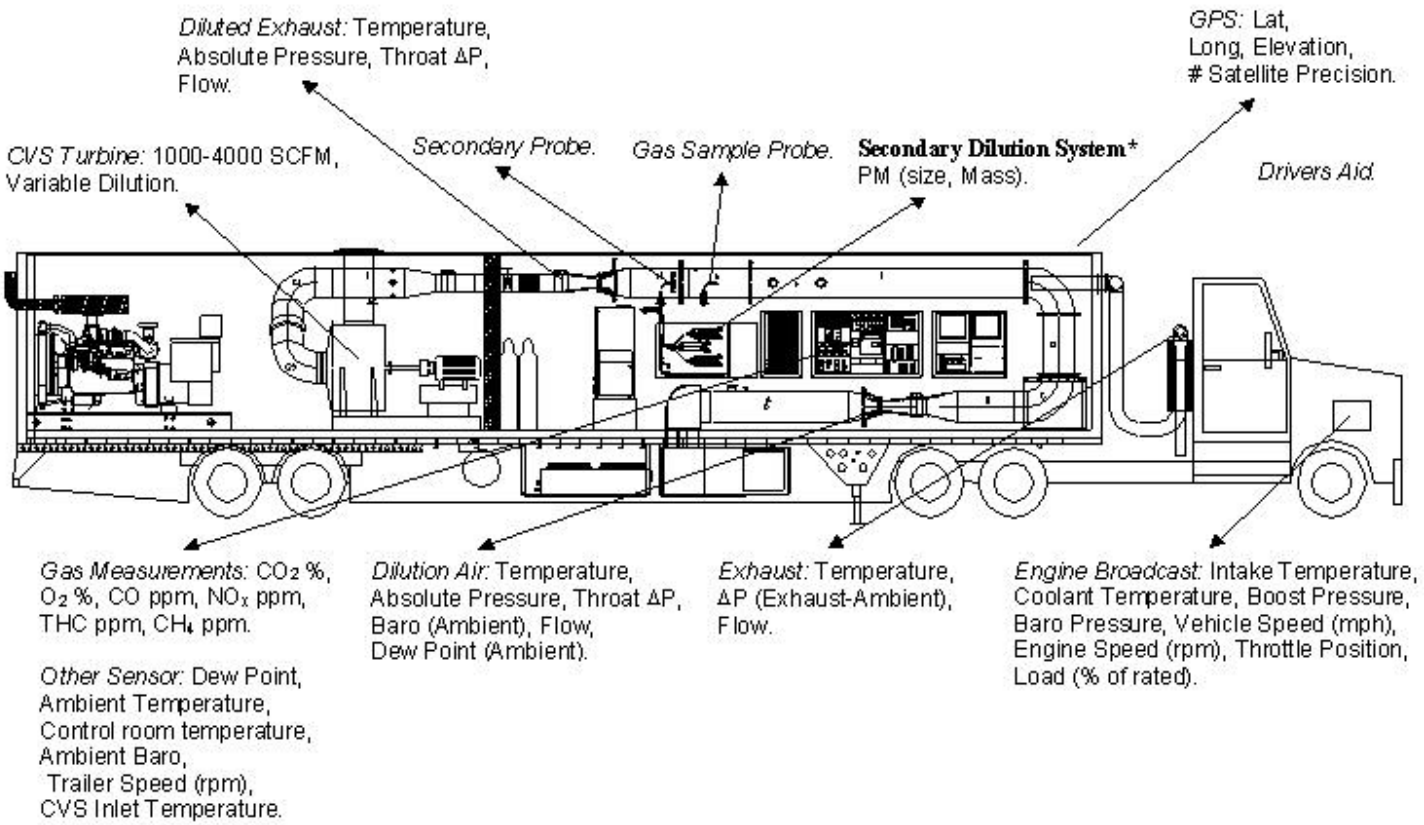
Objective

- To answer how PM and PN emissions vary under on-road driving and a standard driving testing cycle.
- Note for this study PM was determined from particle size distribution and PN means solid PN (SPN) following PMP method.

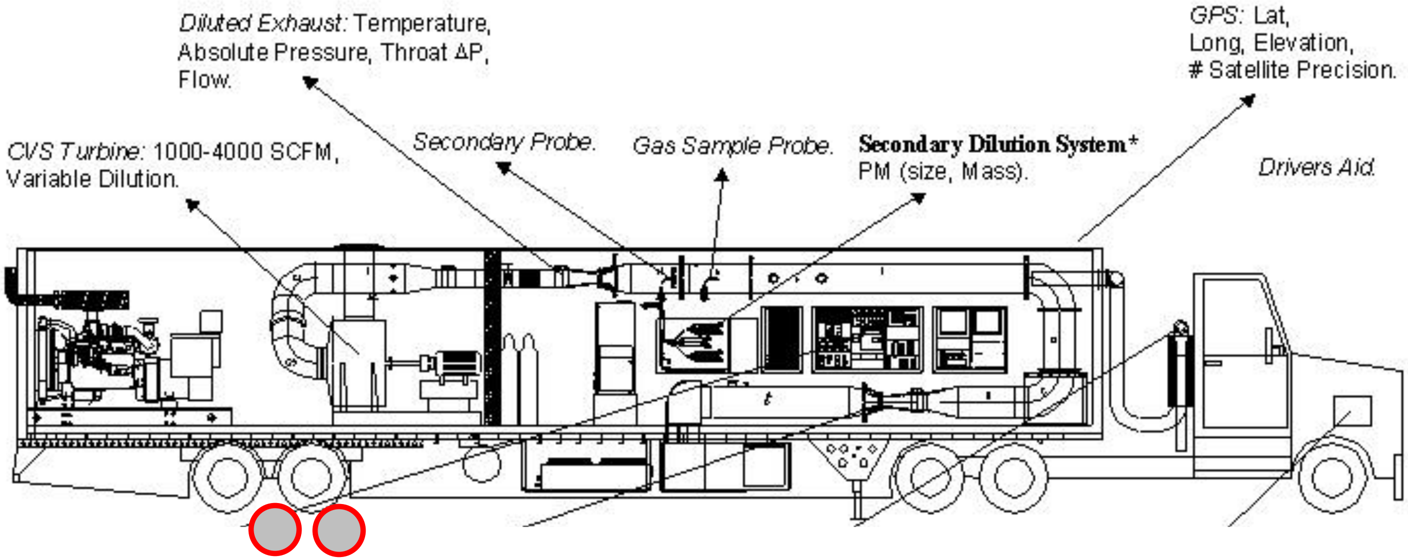
Test conditions

- UCR Mobile Emission Lab was used for both chassis and on-road test.
  - Freightliner class 8 truck with 14.6 liter, 2000 Caterpillar C-15 engine, equipped with Johnson Matthey Continuously Regenerating Trap (CRT™).
- Driving conditions
  - Urban Driving Dynamometer Schedule (UDDS) on chassis dynanometer- 3 repeats.
  - Three on-road flow-of-traffic driving conditions: cruise, uphill and downhill driving.
    - Cruise- average 50-70 mph on flat part of the US interstate-10 (I-10) highway - only one data set.
    - Uphill and downhill driving +/- 1.6 grade on I-10- 4 repeats.

Mobile Emission Lab

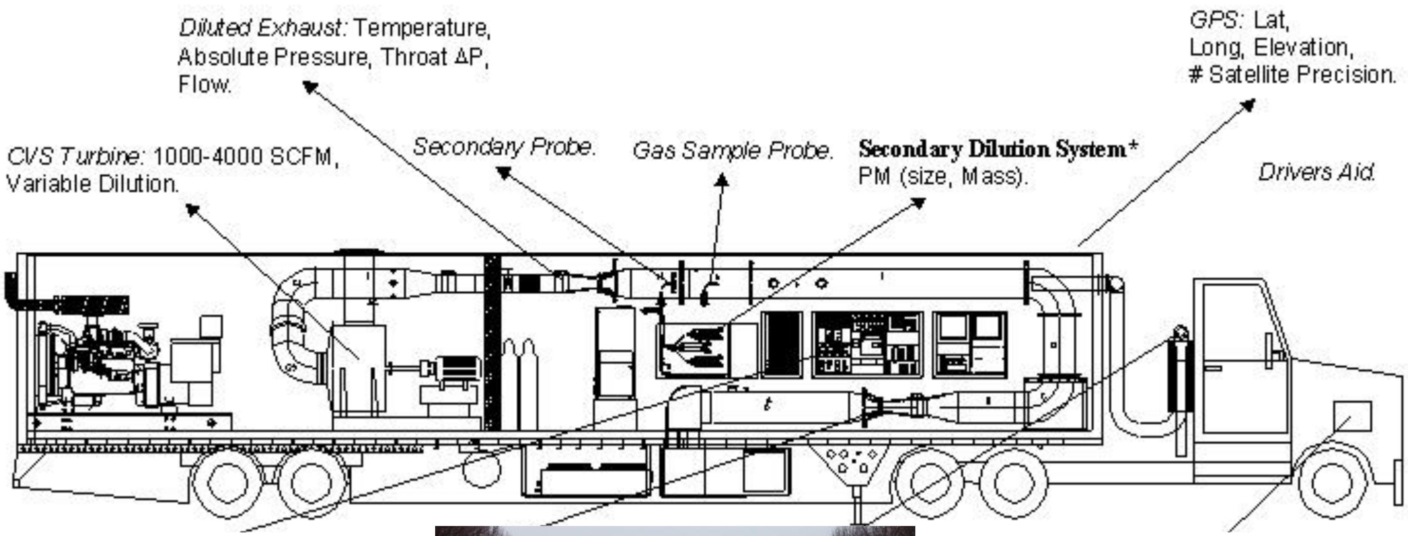


Mobile Emission Lab



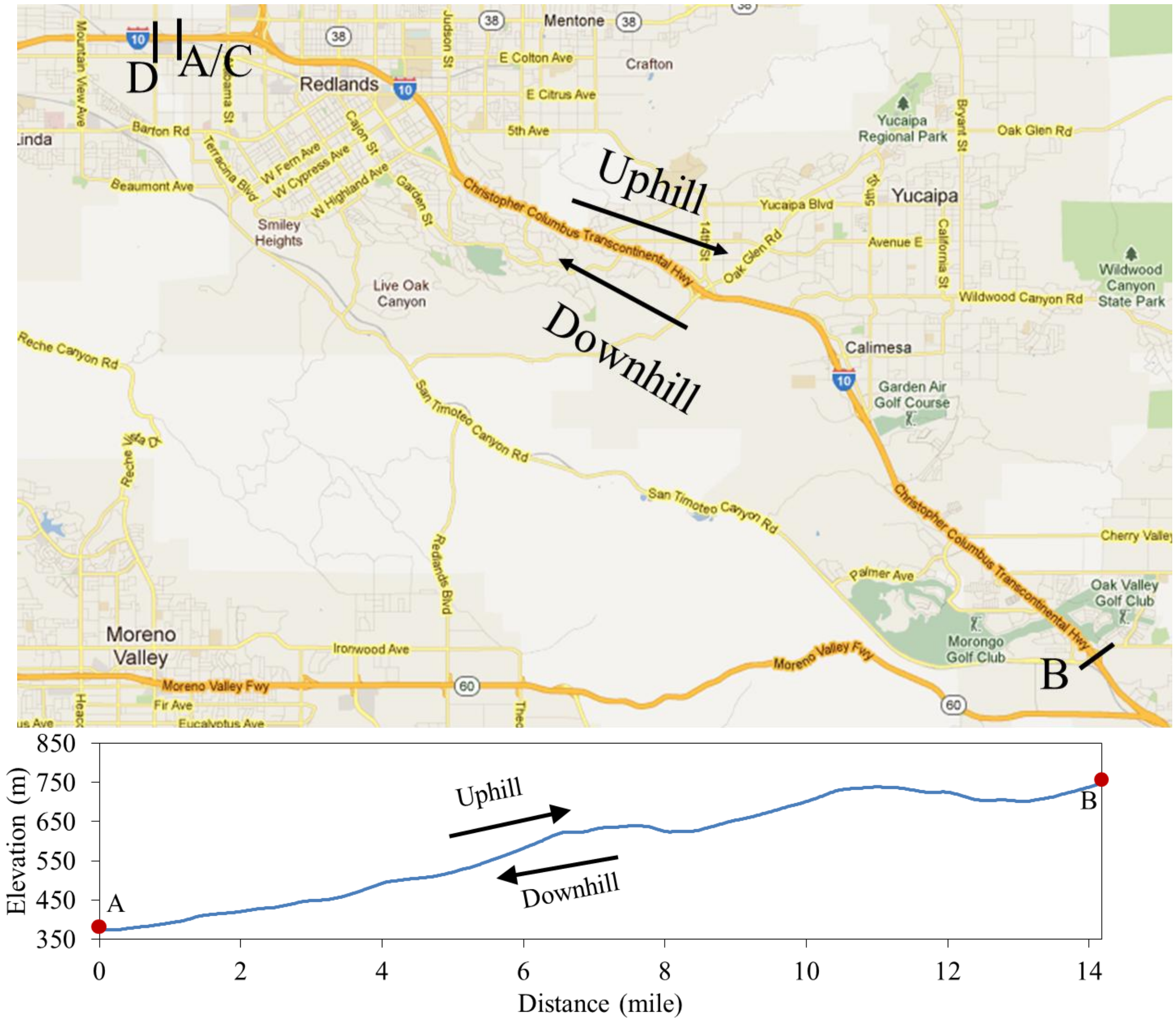
Chassis dynamometer for UDDS cycle

Mobile Emission Lab

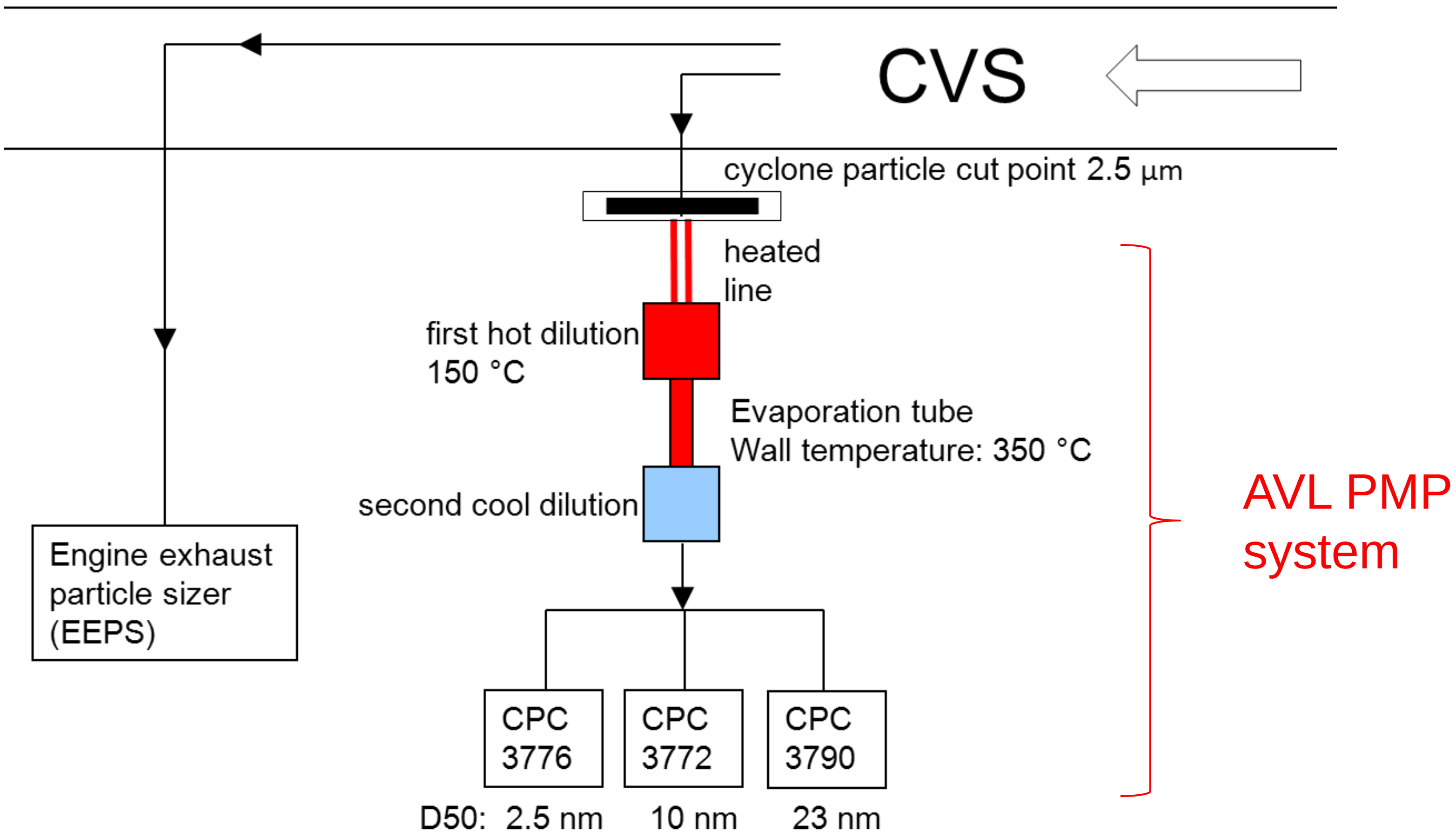


On-road: uphill, downhill and cruise conditions

Map and elevation of up and downhill on-road driving route



Experimental set up



PM (particulate mass) calculation

- PM determined by IPSD (Integrated Particle Size Distribution method) from EEPS measurement. Particle effective density from Maricq and Xu (2004).

$$PM_{IPSD} = \sum_i \rho_{eff,i} \times \left(\frac{4}{3}\pi \times \left(\frac{D_{p,i}}{2} \right)^3 \right) \times n_i$$

Liu et al. (2009)

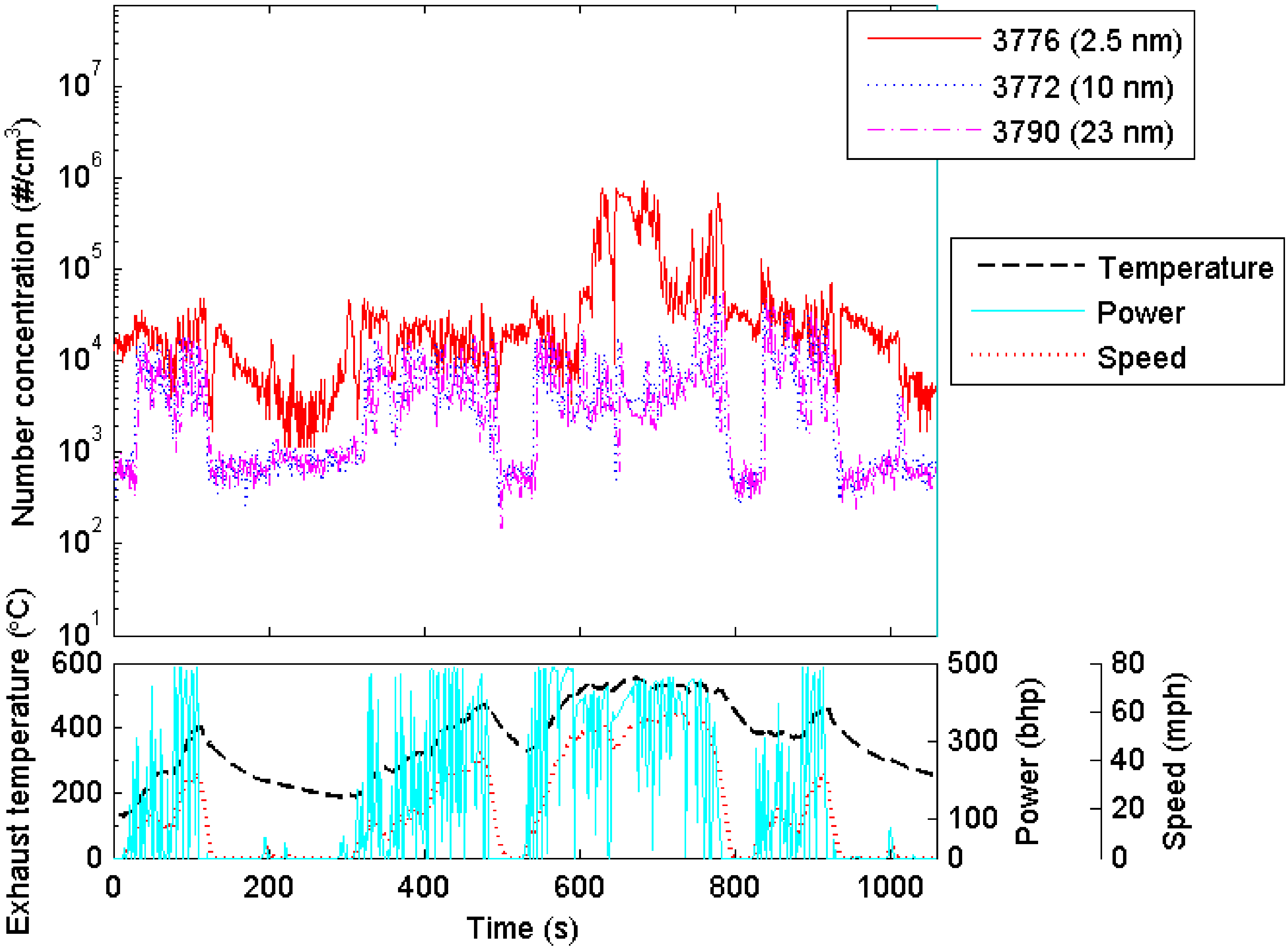
$$\rho_{eff\_Acc,i} = \rho_0 \times \left(\frac{D_{p,i}}{D_{p0e}} \right)^{d_f - 3}$$

$$\rho_{eff\_Nuc,i} = 1.46\,\mathrm{g/cm}^3$$

Maricq and Xu (2004)

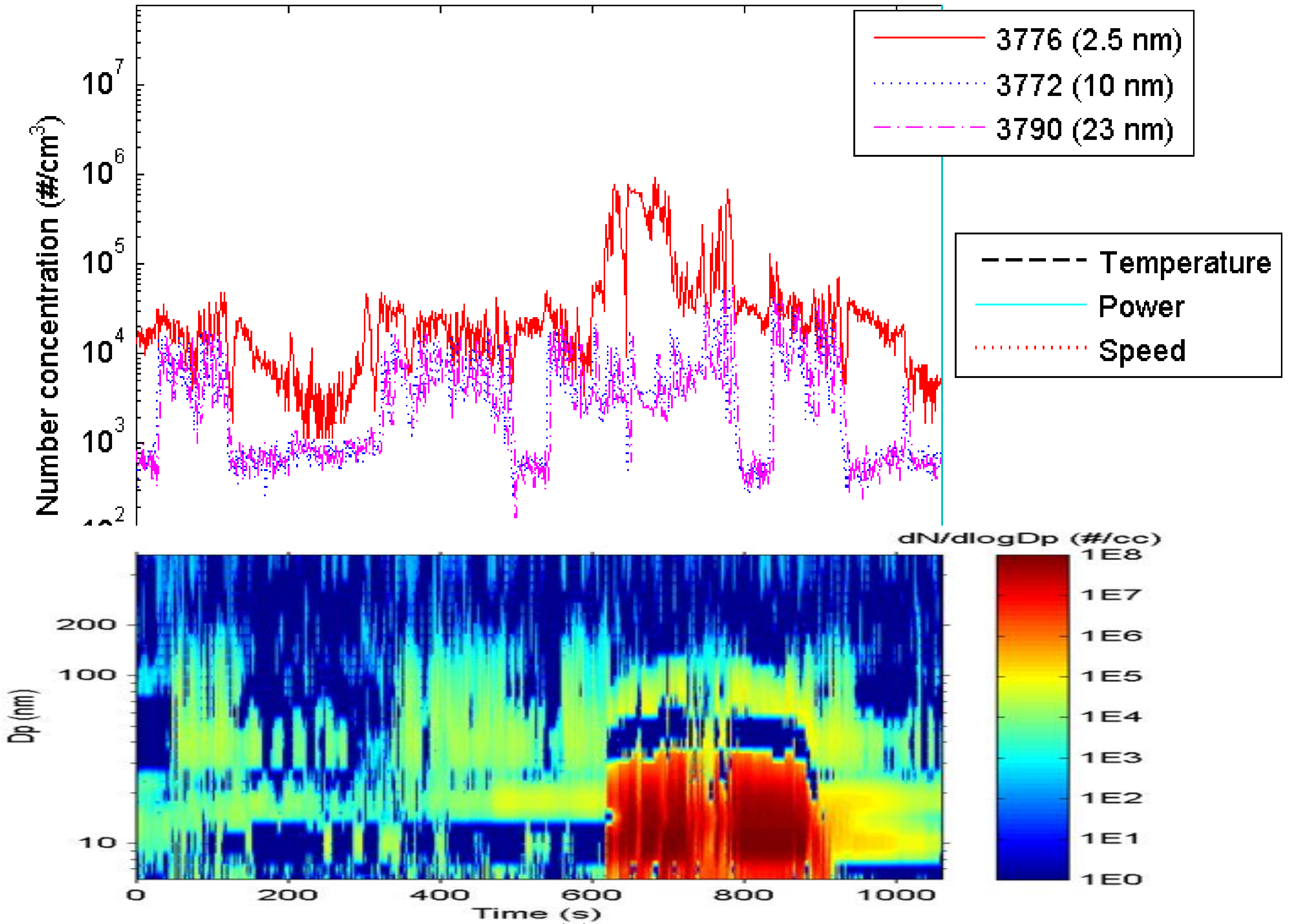
Results:
Real time data

UDDS

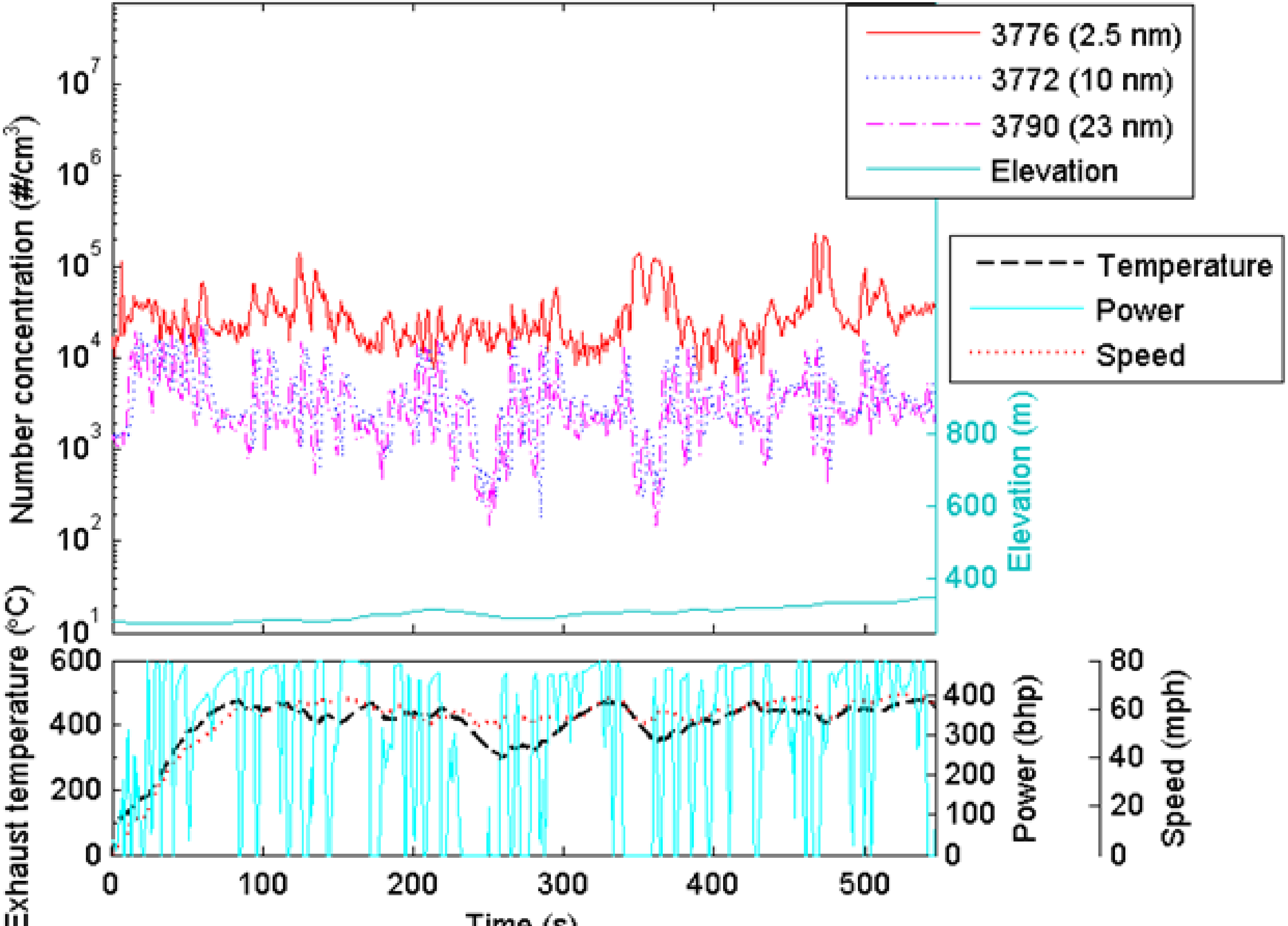


3776 (2.5 nm)
3772 (10 nm)
3790 (23 nm)
Temperature
Power
Speed
Number concentration (#/cm^3)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Exhaust temperature (°C)
600
400
200
0
Power (bhp)
500
300
100
0
Speed (mph)
80
60
40
20
0
0
200
400
600
800
1000
Time (s)

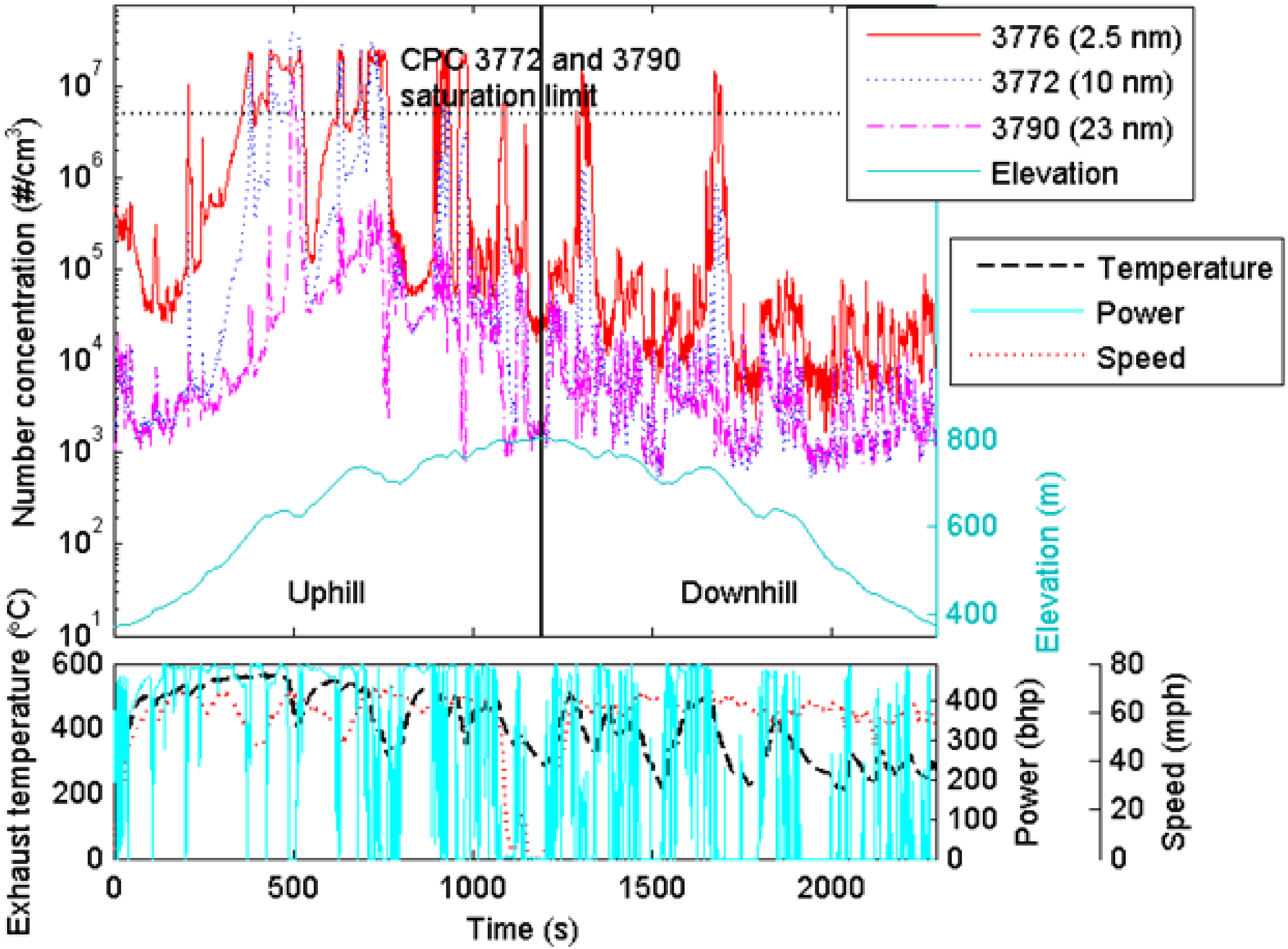
UDDS


3776 (2.5 nm)
3772 (10 nm)
3790 (23 nm)
Temperature
Power
Speed
Number concentration (#/cm^3)
10^7
10^6
10^5
10^4
10^3
10^2
dN/dlogDp (#/cc)
1E8
1E7
1E6
1E5
1E4
1E3
1E2
1E1
1E0
Dp (nm)
200
100
10
0
200
400
600
800
1000
Time (s)

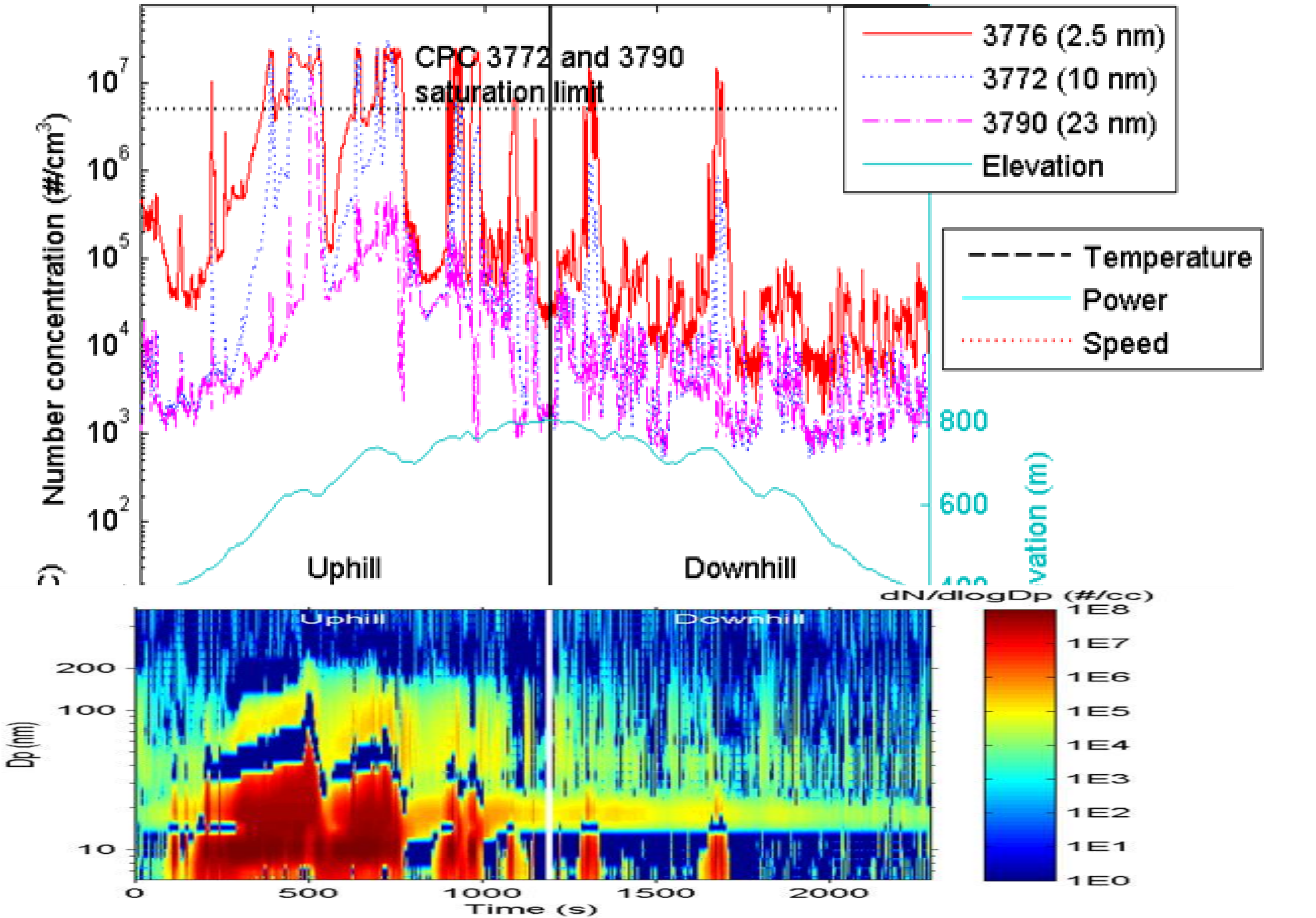
Cruise on-road test



Uphill and downhill on-road test

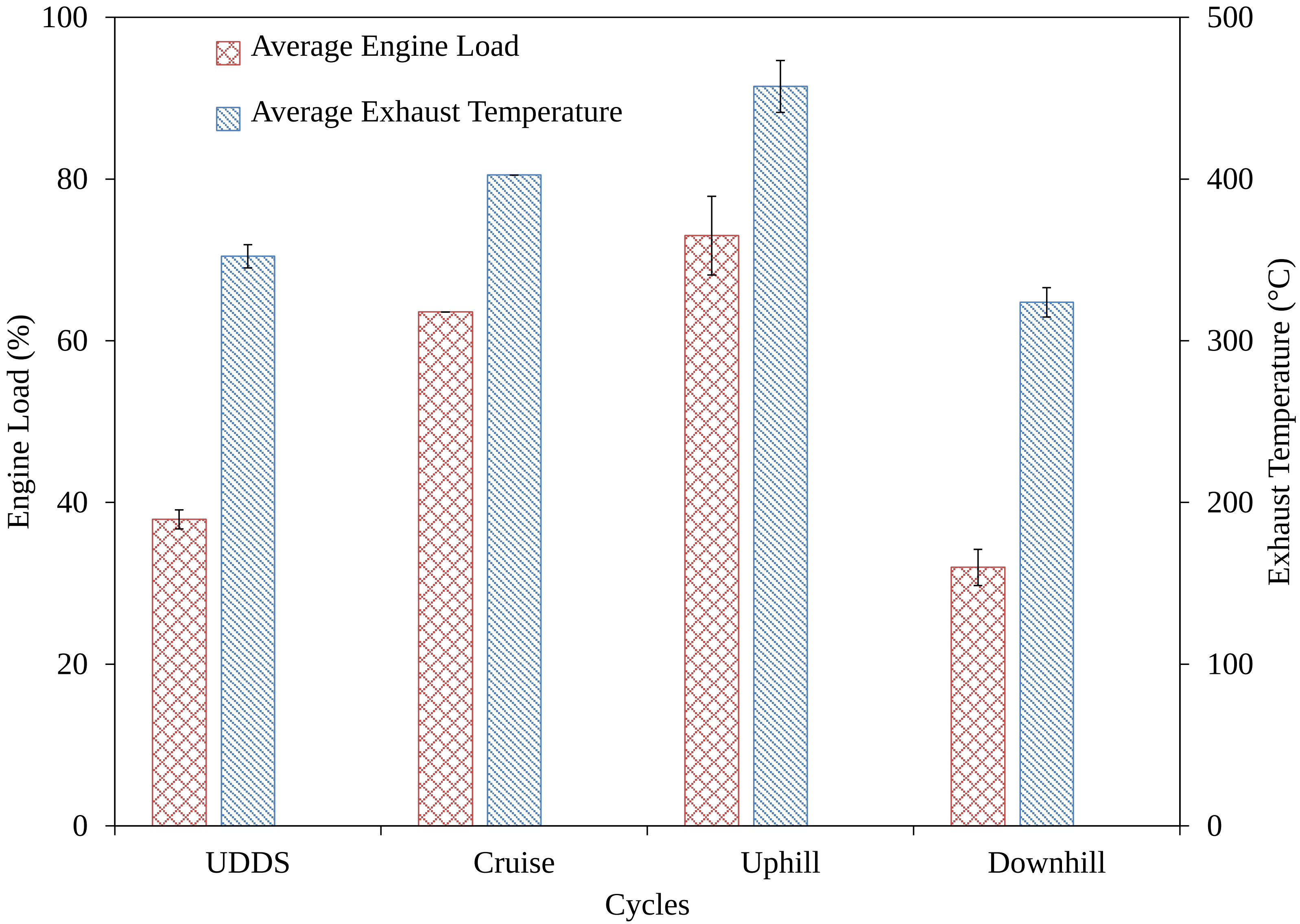


Uphill and downhill on-road test

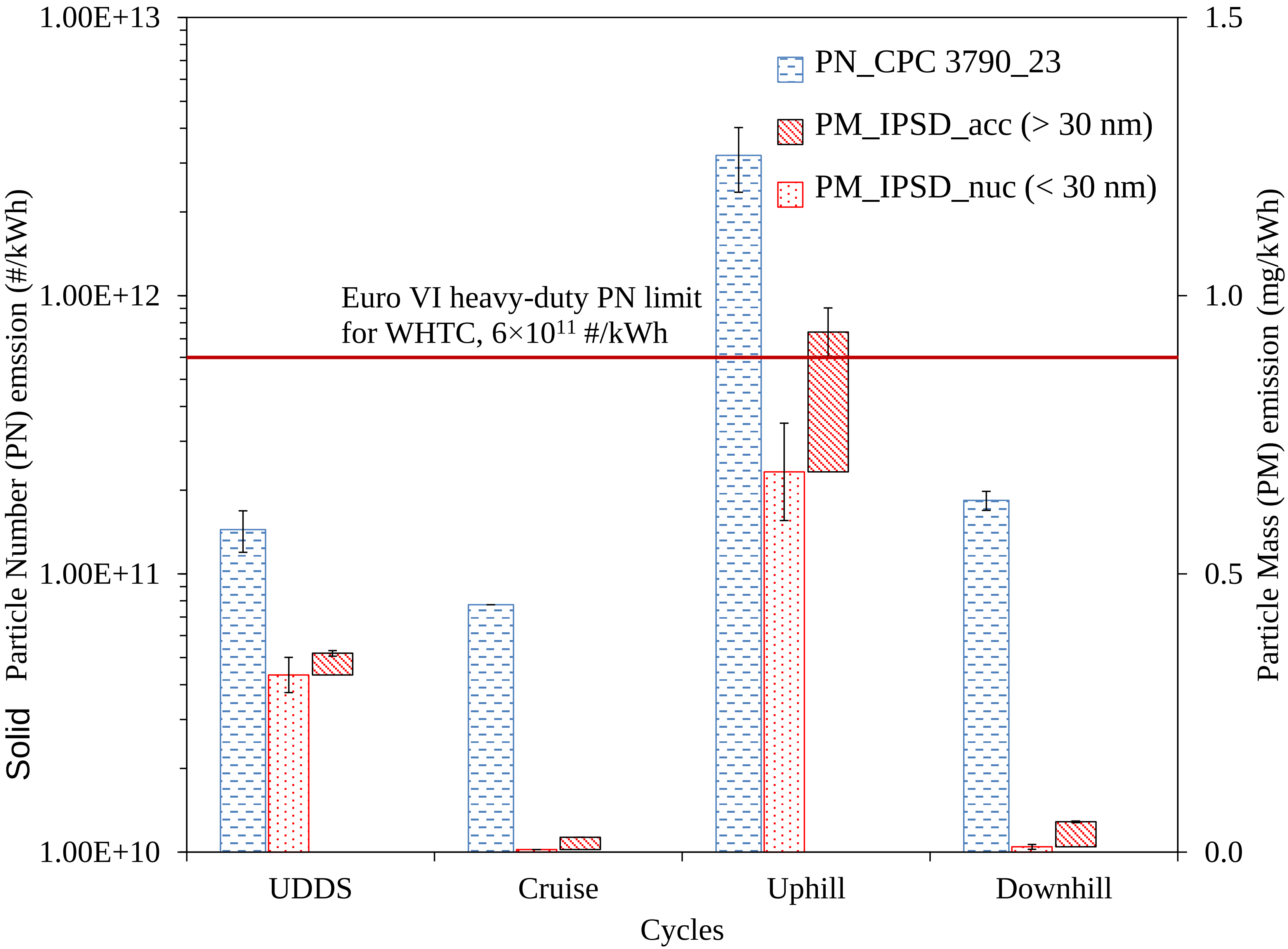


Results:
PM vs PN

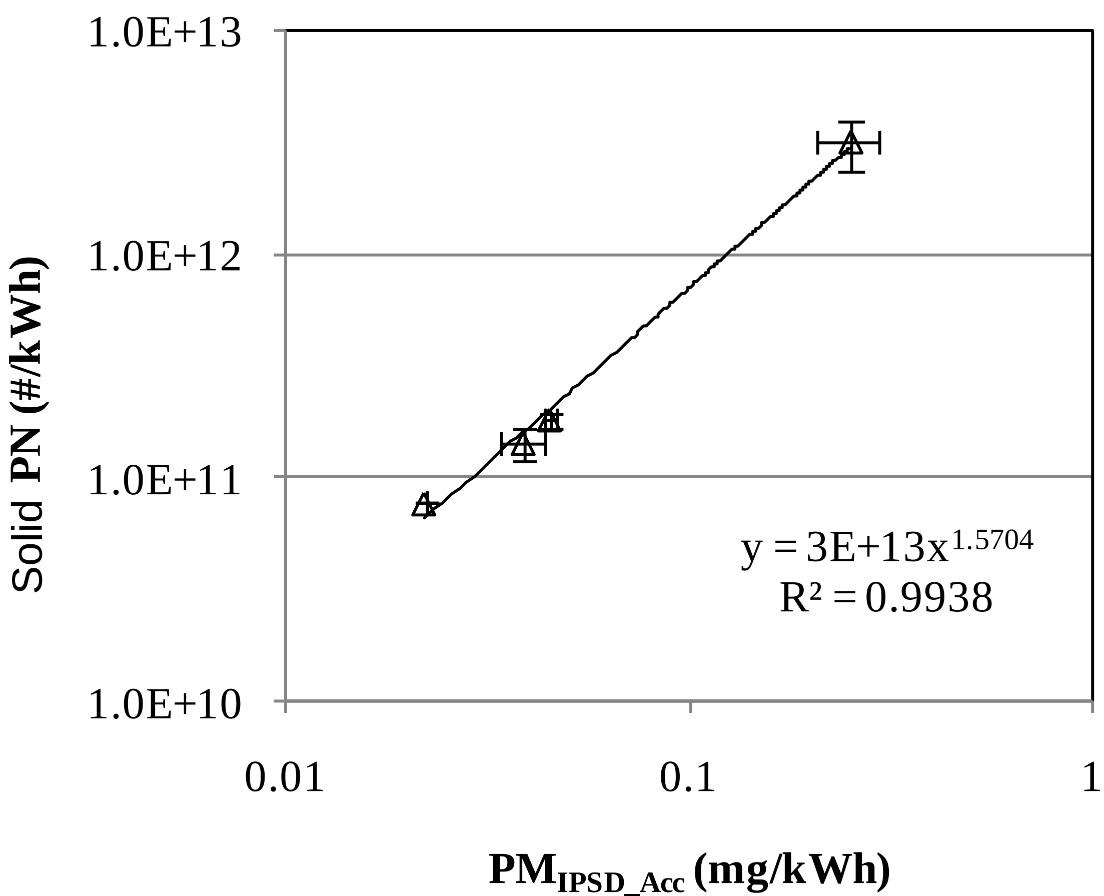
Average engine loads and exhaust temperatures



Comparison of PM and S_PN



PM_acc vs S_PN


1.0E+13
1.0E+12
1.0E+11
1.0E+10
Solid PN (#/kWh)
0.01
0.1
1
PM_IPSD_Acc (mg/kWh)
y = 3E+13x^1.5704
R² = 0.9938

Conclusion

- Real time particle number concentrations from different cut-off diameter CPCs showed re-nucleation and condensational growth of sub 23nm semivolatile particles.

- PM_IPSD_Acc : UDDS~downhill~cruise
  PM_IPSD_Total :UDDS~6*cruise~6*downhill~1/3*uphill

- Strong power relationship was found between PM_IPSD_Acc and SPN. Further study is required to generalize this finding.PM determination by particle size distributions avoid contribution of artifacts therefore beneficial for low PM quantification.

Investigation of PMP by UCR/CARB collaboration

2007 PMP study

- Johnson et al. (2009), Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy Duty Diesel Vehicles, ASnT, 43, 962-969

- Zheng et al. (2012), Nature of Sub-23-nm Particles Downstream of the European Particle Measurement Programme (PMP)-Compliant System: A Real-Time Data Perspective, ASnT, 46, 886-896

2009 PMP study

- Z. Zheng et al. (2011), Investigation of solid particle number measurement: existence and nature of sub 23 nm particles under PMP methodology, JAS, 42, 883-897

- **Current presentation**

Acknowledgements

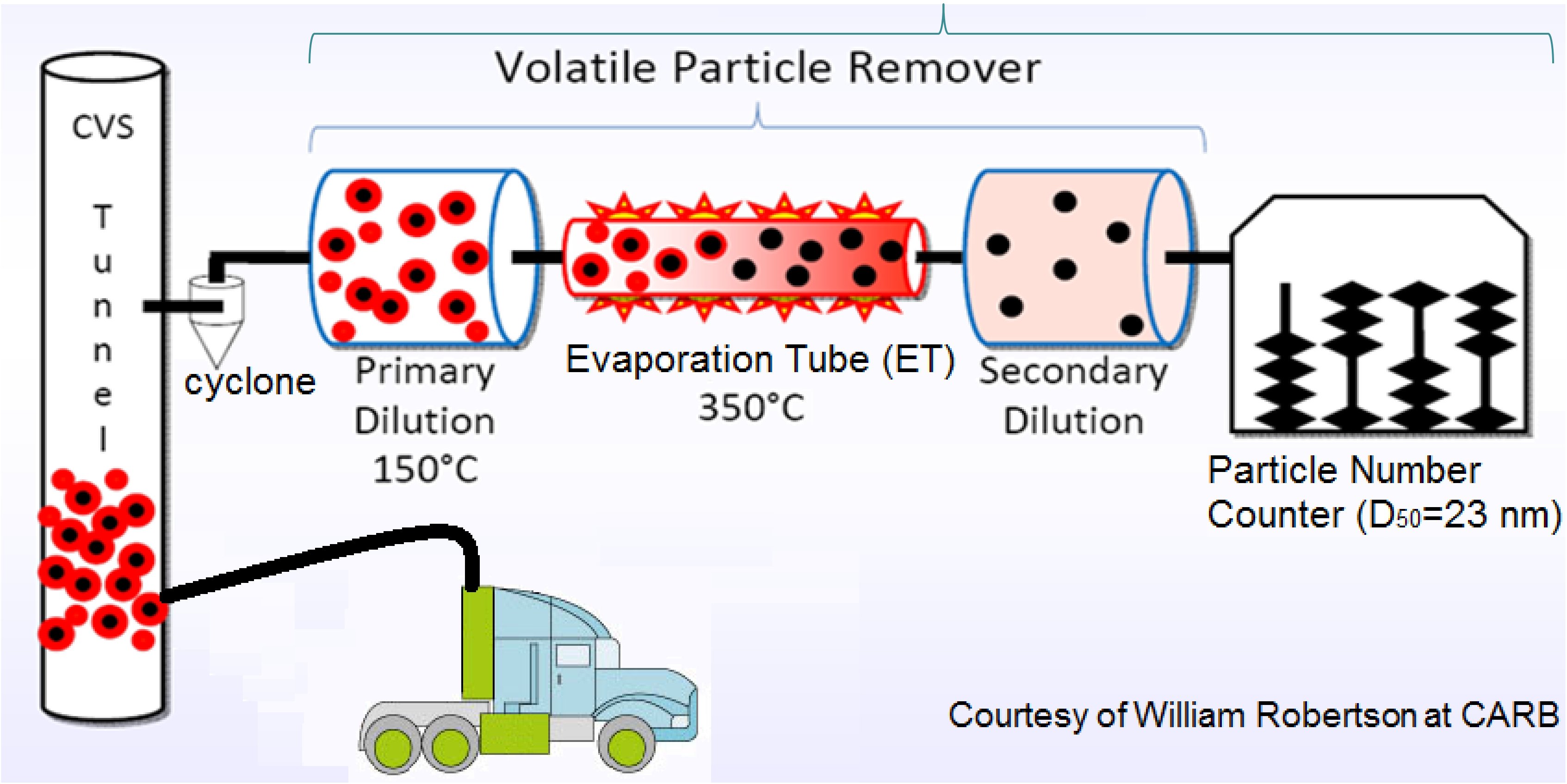
- **CARB**
  - For funding (08-302) and instruments.

- **AVL LIST GmbH Inc.**
  - Providing an AVL particle counter and technical support.
  - B. Giechaskiel, M. Linke, R. Frazee, S. Roeck, & W. Silvis

Thank You

Backup slides

Particle measurement programme



Red: Semivolatile particles

Black: Solid (mostly soot) particles