# Phenomena in sampling diesel and CNG particles with full flow and partial flow dilution systems

Maija Lappi[1], Päivi Aakko[1], Hannu Vesala[1] & Jorma Jokiniemi[2]

Name.Surname@vtt.fi

[1]Technical Research Centre of Finland, VTT Processes, Engines and Vehicles, Espoo, P.O.Box 1601, FI-02044 VTT, Finland
[2] Technical Research Centre of Finland, VTT Processes, Energy and Environment, , P.O.Box 1602, FI-02044 VTT, Finland

A set of sampling systems to monitor nucleation and accumulation mode particles from diesel vehicles have been studied during several experimental periods and setups. The sampling systems used have been two full flow dilution tunnels (CNG, DI) of CVS system + secondary ejector diluter (ED), VTT designed porous tube diluter (PRD1)[1], another porous tube diluter (PRD2)[2,3], these as such or interfaced with an ejector diluter (ED) or a mixing tube, and AVL SPC 472 partial flow diluter "Smart Sampler"(SS). In the three partial flow diluters dilution air temperature, humidity and dilution ratio were controllable. Primary dilution ratio was between Dr 12 – 60. Tests have been made for diesel and CNG buses and a light-duty diesel vehicle. Particles were recorded either with ELPI or DMA+CPC in the 5 nm – 10 µm size range.

For the very low particle emitting vehicles like CNG buses the coincidence of the CVS CNG tunnel+ED and PRD1 particle emissions for both nano and accumulation mode sizes was excellent over the transient Braunschweig city bus test cycle. This was the case despite uncontrolled parameters like dilution air RH and T and the momentary dilution ratio of the CVS system. With another kind low emitter, CRT bus, it became evident that in CVS having low momentary primary dilution ratios (Dr 4 or higher) secondary diluter is fundamental for good correlation with well controlled partial flow diluters. Mixing at PRD1 was incomplete in certain measurement conditions related to different vehicle + CVS systems, in which differential pressures in the system after the exhaust pipe were critical, if a secondary ED or an additional mixing tube was not used. In the transient Braunschweig cycle excess for diesel soot particle numbers obtained with PRD1 only was 2 to 2.5 fold compared to CVS+ED due to inadequate mixing. For these tests PRD1 dilution ratio was Dr 40-56.

To further study dilution with PRD1, and to compare PRD1 and the "Particulates" PRD2 steady state tests were made with a model year 2005 truck. Vehicle load was 100 kW (80 km/h). PRD1 and PRD2 were positioned identically, to intimate orthogonal position with the exhaust pipe. Only probe was inserted inside the pipe. No dilution air cooling was used. Primary dilution ratio for both partial flow diluters was Dr 12 – 60 (1.3 – 9 l/min raw exhaust). With Dr 12 particle number emissions for both diluters were identical regardless of the presence or absence of secondary ejector/mixing tube. For higher primary dilution ratios than Dr 20 (lower than 5 l/min raw exhaust flow rate through the porous tube) mixing in PRD1 was incomplete and dependent on exhaust and CVS system. However, complete mixing was ascertained by a secondary ED. When using 130 cm mixing tube instead losses of accumulation mode particles were noticed above dilution ratios Dr 40. Particle number results obtained with PRD2 were insensitive to primary dilution ratio between Dr 12 – 60, use of ED, and they were identical with PRD1 + ED particle numbers.

PRD1 and PRD2 have shown good correlation in many steady state measurement conditions, though. For instance, particles of a turbo-charged direct-injection diesel passenger car at constant speeds of 40 and 80 km/h were measured with DMA + CNC and with ELPI and showed no systematic differences for soot mode particles between PRD1, PRD2 and SS diluters at Dr 12 - 40. Results for nucleation mode particles were more deviating for the three diluters.

## References

[1] Lyyränen, J., Jokiniemi, J., Aakko, P. & Vesala, H. 2004. Characterising dilution method for diesel particle measurement. European Aerosol Conference EAC Budapest, Hungary 6.-10.9.2004.

[2] Mikkanen, P., Moisio, M., Keskinen, J., Ristimäki, J. & Marjamäki, M. 2001. Sampling method for particle measurements of vehicle exhaust. SAE Paper No. 2001-01-0219. 6 p.

[3] Ntziachristos, L., Giechaskiel, B., Pistikopoulos, P., Samaras, Z., Mathis, U., Mohr, M, Ristimäki, J., Keksinen, J., Mikkanen, P., Casati, R., Scheer, V. & Vogt, R. Performance evaluation of a novel sampling and measurement system for exhaust particle characterization. SAE Paper No. 2004-01-1439.

# Phenomena in Sampling Diesel and CNG Vehicle Particles with Full Flow and Partial Flow Dilution Systems

Maija Lappi, Päivi Aakko, Hannu Vesala & Jorma Jokiniemi
name.surname@vtt.fi

*Several kinds of dilution systems are available for particle measurements, e.g. full and partial flow dilution tunnels, porous & perforated tube diluters, as well as ejector and rotating disk type samplers. Different techniques are originally designed to different purposes. Full and partial flow tunnel systems with long residence times (RT) are originally aimed at gravimetric measurement of particle mass on emission directive basis. Partial flow diluters with short RT and flexibly adjustable dilution ratio are primarily dedicated to size and number measurement of unchanged primary particles. Different techniques tend to show both benefits and drawbacks. With CVS type dilution tunnels many important parameters, like RH, Dr and T are uncontrollable, ejector diluters have constant Dr, and with them as primary diluters high temperature of the exhaust needs to maintained. With porous type diluters care has to be taken to provide adequate flow rates and differential pressure between the sampler and the exhaust duct (+ CVS system) to allow complete mixing. The purpose of the work was to study behaviour of partial flow diluting systems in respect to each other and to full flow dilution tunnels in sampling vehicle exhaust particle numbers and size classes.*

## SYSTEM DESCRIPTION

Sets of diluting systems were used to monitor nano and accumulation mode particles from diesel and CNG vehicles in several experimental periods and setups.
The systems used are, **figure 1**:

1. Two **full flow** dilution tunnels of CVS systems + a secondary ejector diluter (ED): **a)** for HD **diesel** vehicles, **b)** for 'clean' **CNG** vehicles.
2. Three **partial flow** diluters: **c)** one porous tube diluter designed at VTT **(PRD1)**[1], **d)** the other from "Particulates" project **(PRD2)**[2,3]; these as such or interfaced with an ejector diluter (ED) or a 130 cm mixing tube, **e)** third was the AVL SPC 472 partial flow micro dilution tunnel "Smart Sampler" **(SS)**. PRD installations "as such" comprised a bypass and $NO_x$ measurement right after the diluting unit. SS was reconstructed to avoid long transfer line from tailpipe to tunnel.

PRD1 and PRD2 diluters were positioned by the tailpipe, at closest possible distance. Interface tube of 4 cm was insulated. For PRD1, PRD2 and SS dilution air was at ambient T, dry and dilution ratio adjustable. Primary dilution ratio varied between Dr 12 - 60. Exhaust from the tailpipe was directed to CVS system. Dilution tunnels of the CVSs were used with normal flow settings of 40 - 80 m³/min. Sampling from full flow tunnels and from partial flow diluters were made in parallel.

The CVS tunnel and partial flow sampler correlation tests were made from buses of Euro II diesel w/o catalyst to CNG buses of current or future EEV/Euro V emission levels. Transient driving cycle on chassis dynamometer was **Braunschweig CBC**. **HD constant speed** tests were made from a 12 l, model year 2005 truck w/o cat with 60 and 100 kW (80 km/h), and some additional tests from a m.y. 2003 truck with ox.cat (truck 1 in fig.3). For **LD diesel** tests with partial flow diluters model year 1996 TDI 1.9 car (EGR+ox.cat) was used. Particles were recorded either with two ELPIs with a filter stage or with an ELPI and DMA+CPC in 5 nm - 10 µm size range.

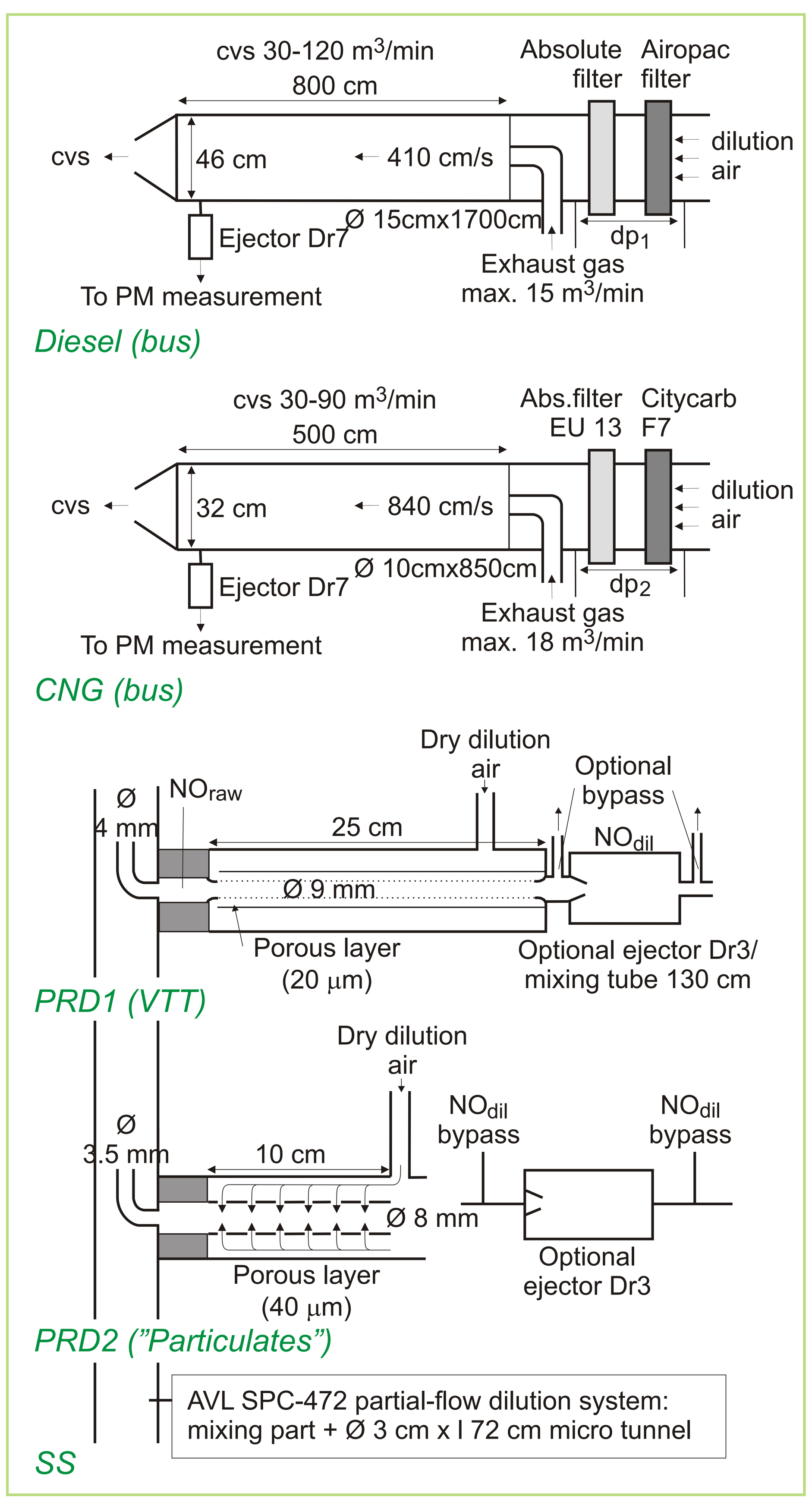


*Figure 1. Diluting systems for HD particles.*

## RESULTS

For the very low PM emitting vehicles like **CNG** buses coincidence of the CVS tunnel+ED and PRD1 particle emissions for both nano and accumulation mode sizes was very good over the transient Braunschweig city bus test, **figure 2**. This despite the inability to control CVS system parameters like dilution air RH and T and the momentary dilution ratio. Particles were not dried, either. PM emissions of these vehicles lacked the soot mode entirely. With another kind low PM emitter, **CRT** bus, it became evident that in CVS with low momentary primary dilution ratios (from Dr 2-4 up) secondary diluter is fundamental for good correlation with well controlled partial flow diluters. The tunnel PM number without ED was 50-100 times higher than that of PRD1 # over the whole size spectrum. Increase phenomenon is probably associated with sulphate aerosol formation tendency of CRT trap with high concentrations of $SO_4$ and water.

For **diesel** vehicles the correlation between CVS tunnel+ED and PRD1 PM emissions was not so straightforward, **figure 2**. Nano sized emissions equalled neatly, but there was a notable increase in soot mode particles for PRD1. From both Braunschweig of diesel buses and steady state tests with a 30-38 % loaded truck this "excess" for diesel soot particle numbers obtained with PRD1 (no sec ED) was 2 to 2.7 fold compared to CVS+ED. For these tests dilution ratio of PRD1 was Dr 40-56 and flow rate to the diluter at its lowest, 1.8 - 2.6 l/min.

To further study **dilution in the porous tube PRD1**, and to compare PRD1 with other partial diluting media, steady state tests were made with trucks, PRD1 and PRD2 placed identically, to intimate orthogonal position with the exhaust pipe. Only probe was inserted inside the pipe. Primary dilution ratio for both diluters varied between Dr 12 - 60 (1.3 - 9 l/min raw exhaust). To ascertain mixing in the PRDs they were also interfaced with a secondary ED (Dr 3-4) or a mixing tube, bypass after the PRD being removed and the total flow running to the additional mixing space.

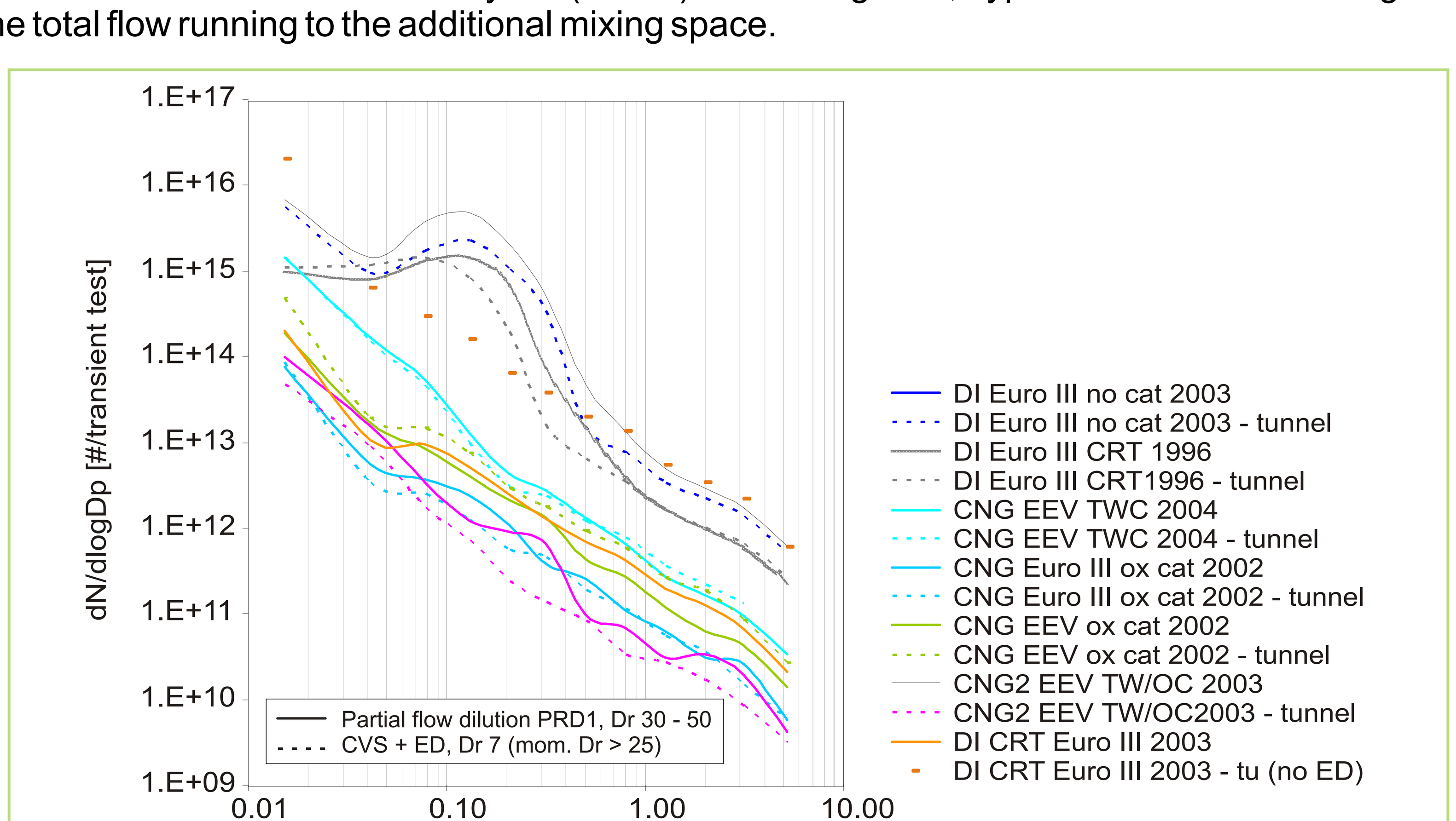


*Figure 2. Particle emission behaviour in CVS tunnels (+ED) vs. partial flow diluter PRD1 over transient Braunschweig driving cycle (ELPI).*

The first installation revealed that mixing potential of PRD1 as such was dependent on raw exhaust flow rate into the diluter. With Dr 12 particle number emissions for both PRD diluters were identical regardless of the presence or absence of secondary ED/mixing tube, **figure 3**. For higher primary dilution ratios than Dr 20 (lower than 5 l/min raw exhaust flow rate through the porous tube) mixing in PRD1 as such proved incomplete. This yielded increasing particle numbers with increasing Dr. This was consequence of particular measurement conditions related to certain vehicle, loading and CVS systems, in which differential pressures in the system after exhaust became critical for mixing. Magnitude of this phenomenon was effected by raw exhaust flows in the pipe as well as the CVS system volumetric flows, which is shown e.g. by the different slopes of the dark blue and dotted lines in **figure 3**. Complete mixing was achieved by insertion of a secondary ED and removal of bypass line after PRD1. When using 130 cm mixing tube instead slight losses of accumulation mode particles were noticed above dilution ratios Dr 40 (yellow line). In the tested conditions particle number results, both nucleation and accumulation modes, obtained with **PRD2** were insensitive to primary dilution ratio between Dr 12 - 60, with or without secondary ED.

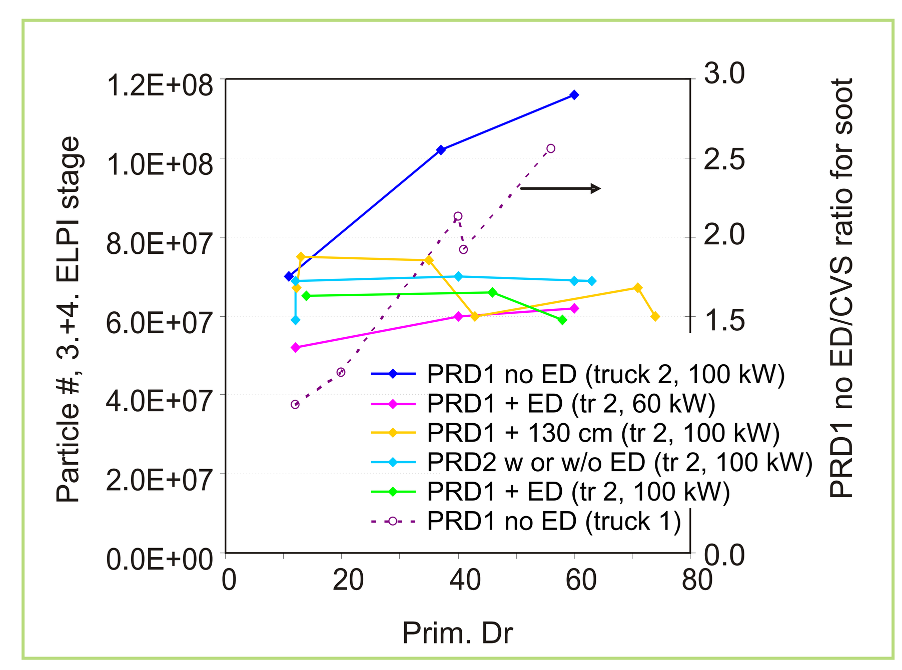


*Figure 3. Behaviour of various particle diluter setups with changing dilution ratio (two trucks, two loads).*

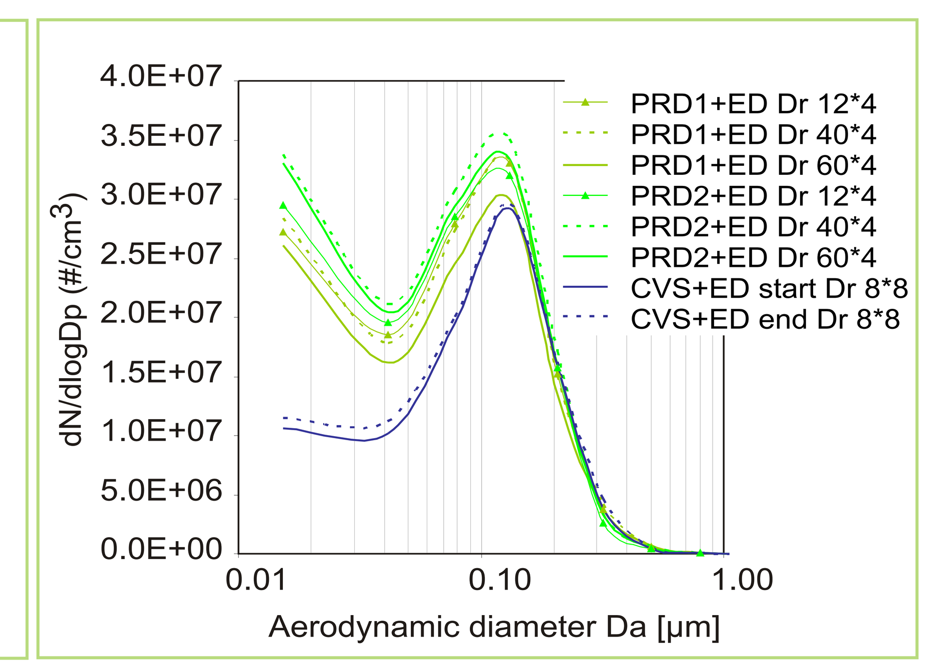


*Figure 4. Particle emission correlation of two porous tube diluters PRD1 and PRD2 in relation to diesel CVS tunnel after ensuring PRD mixing with ED (12 l model year 2005 truck, 100 kW, 80 kph).*

**PRD2** (with or w/o ED) gave identical results with **PRD1 + ED** particle numbers regardless Dr, **figure 4**. As the installations for PRD1 and PRD2 were identical, differences in their behaviour without ED are due to different geometries or physical dimensions of the porous spaces (**figure 1**). Combination of PRD+ED, is also less sensitive to pressure variations in the emission duct and CVS systems.

**PRD1 and PRD2 as such** have, however, shown good correlation in other steady state measurement surroundings. For instance, particles of a TDI **diesel passenger car** at constant speeds of 40 and 80 km/h measured with ELPI and DMA + CNC[1] have shown no systematic differences for soot mode between PRD1, PRD2 and SS diluters at Dr 12 40, **figure 5**. Sizing and flow conditions in the light-duty CVS + dilution tunnel are different from HD installations. Results for nucleation mode particles were more deviating for the three diluters[1]. In this setup PRD2 was positioned inside the tailpipe according to ref.[3]. No dilution air cooling was used.

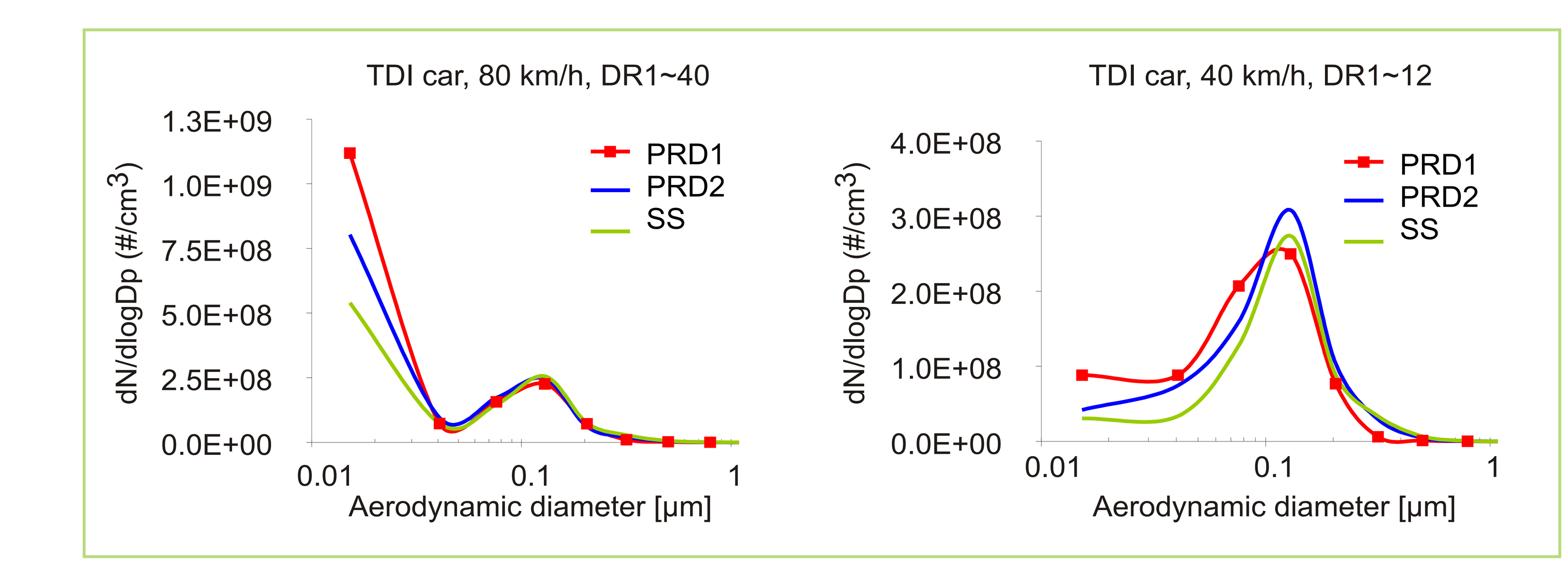


*Figure 5. Comparison of PRD1, PRD2 and SS diluters in particle measurement of a light duty vehicle (LD CVS system).*

## CONCLUSIONS

- Both nano and accumulation sized particle numbers measured from HD CVS full flow dilution tunnel compare well with those of VTT designed partial flow diluter PRD1 (transient cycles). For CVS tunnels secondary dilution is a prerequisite.
- The higher than expected diesel soot particle numbers obtained with PRD1 w/o ED from diesel tunnel were explained by inadequate aerosol mixing within the porous dilution tube at low raw exhaust flow rates. Exhaust, CVS and tunnel systems have different pressure conditions, i.e. exhaust volumetric flow rates, velocities, dimensions, geometries, filters etc. To avoid problems in critical system, it is recommended that:
    1. PRD1 is supplemented with an additional mixing space, e.g. ED or porous.
    2. Flow rate to the diluter is kept high enough (> 5 l/min).
- PM # results from VTT's PRD1+ED and "Particulates" PRD2+ED installations were equivalent for all particle size classes.

References

1. Lyyränen, J., Jokiniemi, J., Aakko, P. & Vesala, H. 2004. Characterising dilution method for diesel particle measurement. European Aerosol Conference EAC Budapest, Hungary 6.-10.9.2004.
2. Mikkanen, P., Moisio, M., Keskinen, J., Ristimäki, J. & Marjamäki, M. 2001. Sampling method for particle measurements of vehicle exhaust. SAE Paper No. 2001-01-0219. 6 p.
3. Ntziachristos, L., Giechaskiel, B., Pistikopoulos, P., Samaras, Z., Mathis, U., Mohr, M, Ristimäki, J., Keskinen, J., Mikkanen, P., Casati, R., Scheer, V. & Vogt, R. Performance evaluation of a novel sampling and measurement system for exhaust particle characterization. SAE Paper No. 2004-01-1439.

Technical Research Centre of Finland, VTT Processes, Engines and Vehicles, Espoo, FI-02044 VTT, Finland