Real-time engine exhaust solid particle measurement with a prototype particle counting system

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Abstract

A solid particle counting system (SPCS) has been developed in Horiba. It measures engine exhaust solid particles in real-time. The performance of the instrument meets the recommendation of the European PMP draft regulation for Light-duty diesel vehicle on solid particle number emission.

The instrument consists of pre-classifier, hot diluter, evaporation unit, cold diluter, and condensation particle counter (CPC), data acquisition and control system, etc. All units have been integrated in one single system. A transfer line which is shorter than 1000 mm connects the instrument to the sampling probe on the Constant Volume Sampler (CVS). Many functions, including normal measurement and calibration, have been automated to make the instrument easily operate.

Solid particle emission from gasoline and diesel vehicles has been studied with this instrument. Transient test cycles such as US EPA ftp 75, US EPA HWFET (highway fuel economy), and NEDC (new European driving cycle) have been tested on the gasoline and diesel vehicles. The repeatability of the instrument has been evaluated on the diesel vehicle for three continuous days. The instrument shows good repeatability. The differences for EPA ftp 75, EPA HWFET, and NEDC in three continuous tests, respectively, are in $\pm$ 3.5%. The instrument is very sensitive as well, and detects the driving differences.

A large number of solid particles are found during the hard acceleration from both the gasoline and the diesel vehicles. Solid particle emission decreases quickly at deceleration and approaching constant speed. High concentration of solid particle emission has been observed during cold and hot starts with the gasoline vehicle, due to gasoline engine running rich at the start. The solid particle emission in unit particles/km strongly depends on the driving cycles on the gasoline, but not on the diesel.

The diesel vehicle with diesel oxidation catalyst (DOC) emits over 100 times more solid particles (particles/km) than the gasoline vehicle at the same test cycle, while the gasoline vehicle solid particle emission is close to 1011 particles/km. It demonstrates the instrument is good for measuring solid particles from the engines or vehicles with different technologies.

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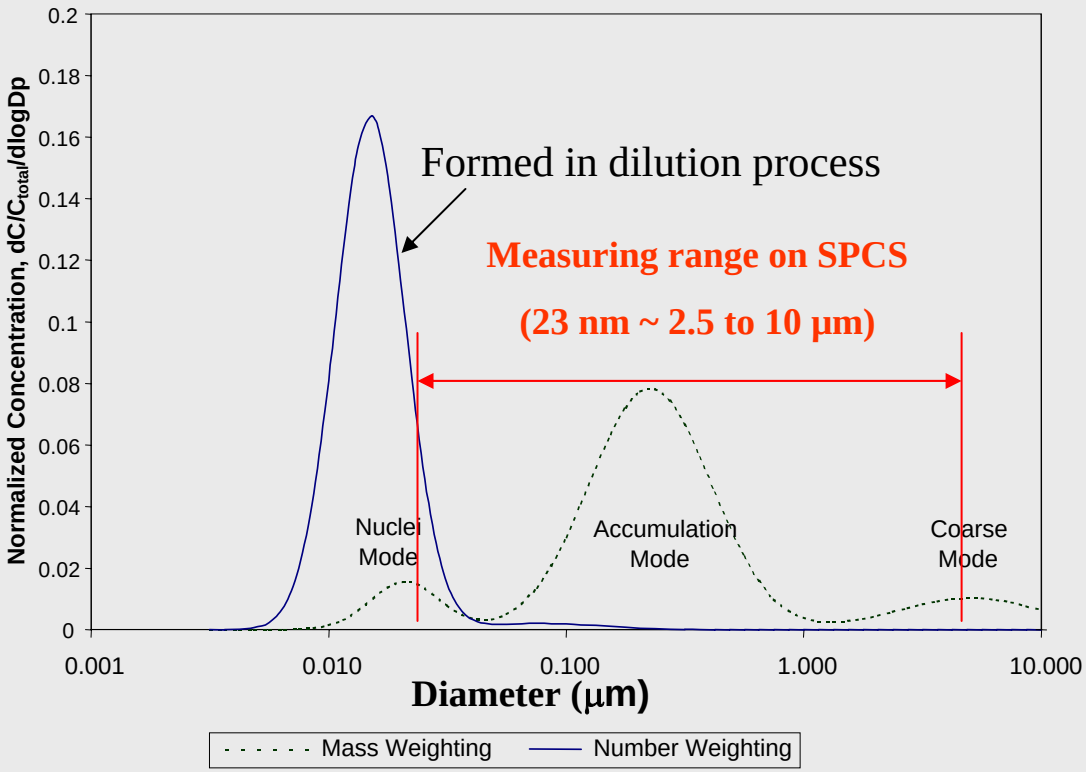
Outline

- **Background**
  - **Diesel aerosol**
  - **Draft regulation**
- **SPCS design**
- **Performance and vehicle tests**
- **Conclusions**

Background

Typical diesel aerosol size distribution



Reference: Kittelson D. B., J. Aerosol Sci., 28: 575-580, 1998

Draft regulation

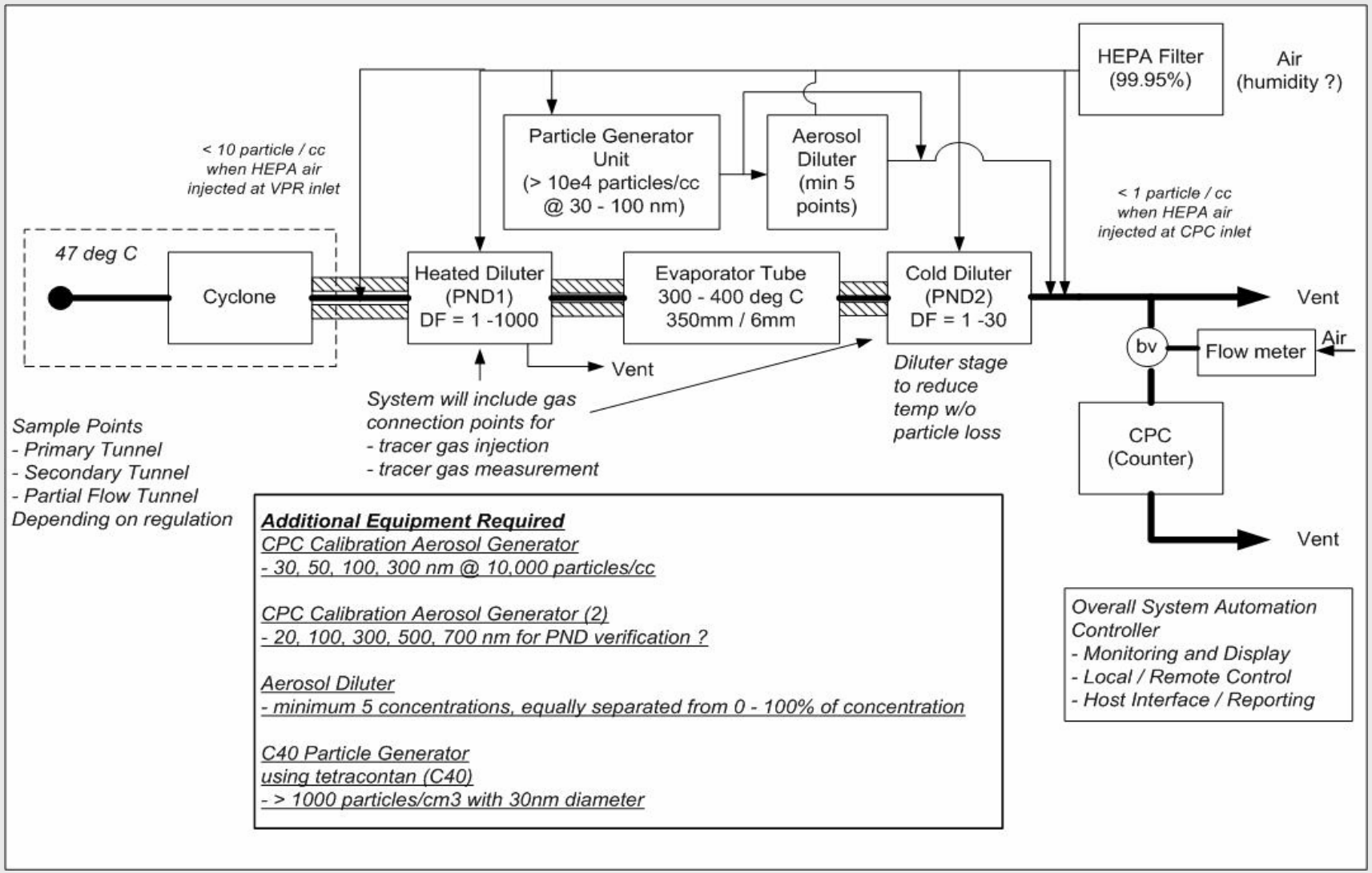
- **PMP draft regulation**
  - **Sampling from CVS**
  - **Solid particle number only**
  - **Size: 23 ± 3 ~ in 2,500 ~ 10,000 nm**
  - **Hot dilution on the first stage**
  - **Cold dilution after evaporation unit**
  - **No maximum limit**
  - **No effective date**

Reference: Conclusions on improving particulate mass measurement procedures and new particle number measurement procedures relative to the requirements of the 05 series of amendments to regulation No. 83, GRPE-48-11-Rev. 1, 2004

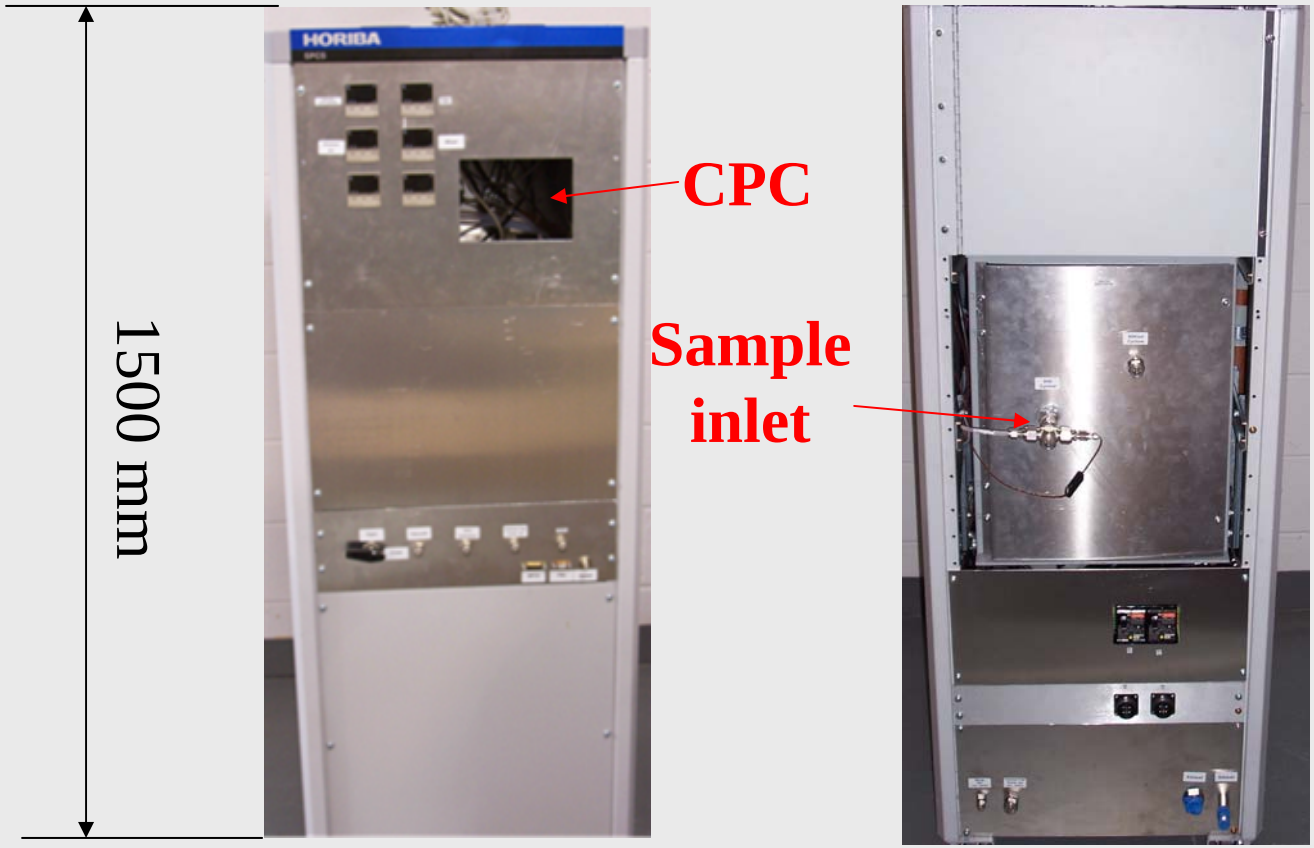
SPCS design

- **Objectives:**
  - **Integrate dilution system, evaporation unit, calibration, and CPC in one system**
  - **Reliable, repeatable, and accurate**
  - **Operate and control easily**
  - **Work for vehicles with different technologies**
  - **Follow PMP draft regulation**

SPCS overview



Prototype SPCS



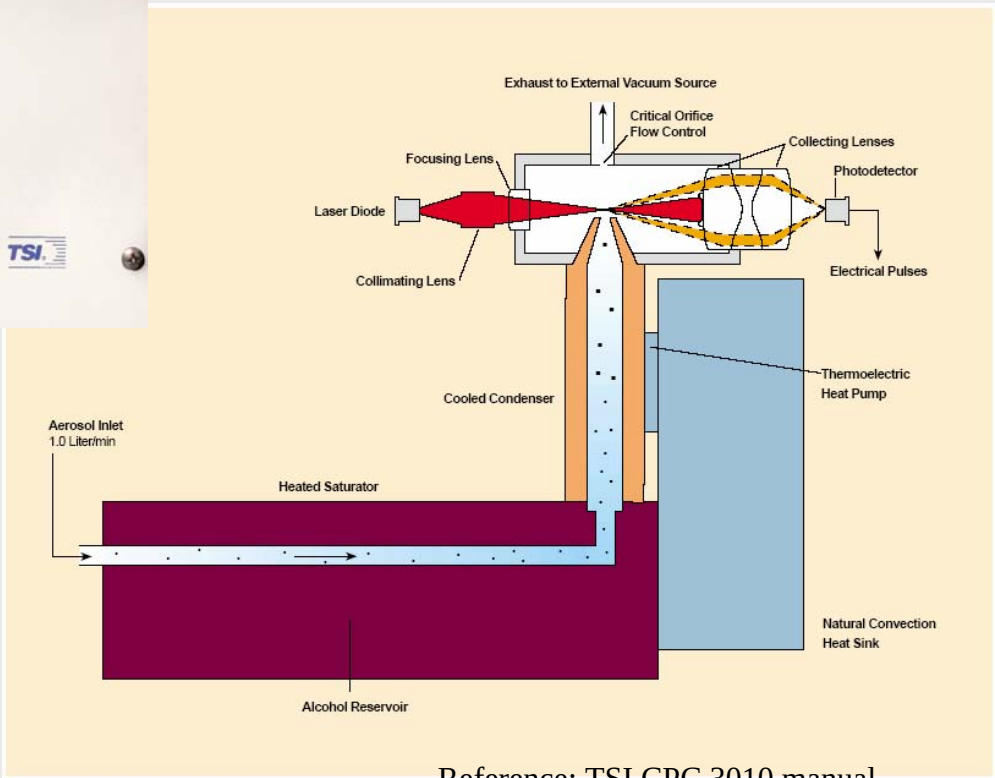
Front

Back

New TSI Instrumentation

Condensation particle counter (CPC)

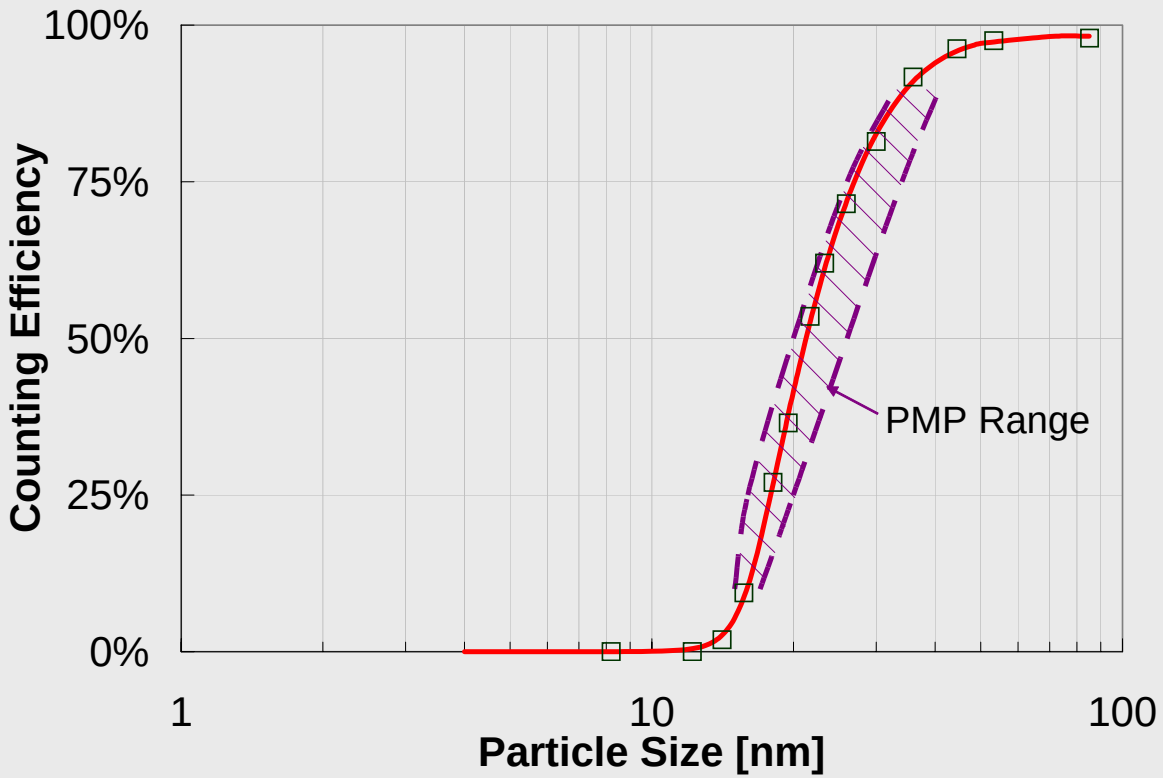
Front panel for the rack mount CPC



Reference: TSI CPC 3010 manual

- **Measures particle number concentration in real-time**

TSI CPC for PMP program



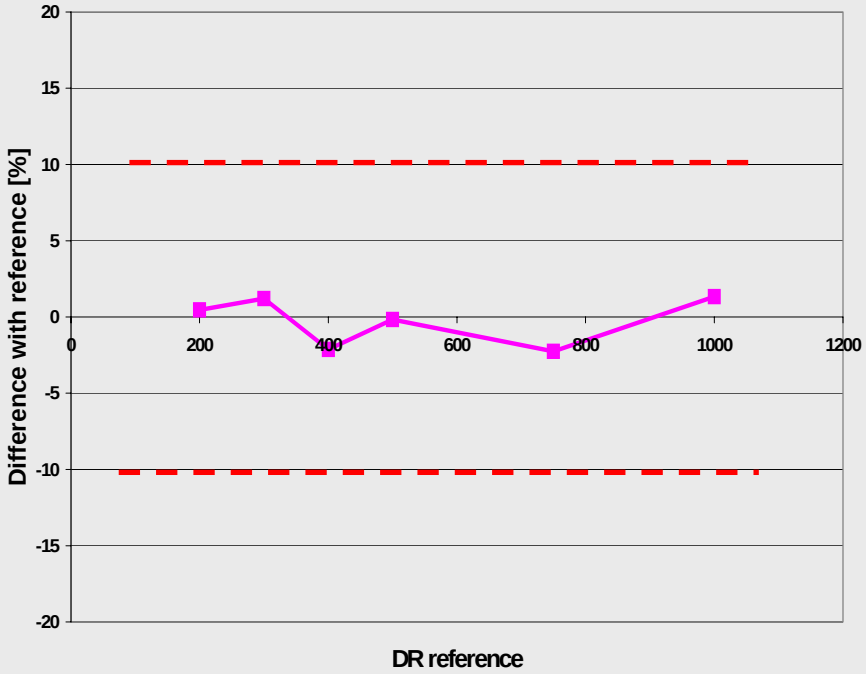
- **Achieve PMP requirement for CPC**
- **New features:**
  - **Anti-spill/optics flooding**
  - **Condensate removal**
  - **Removable saturator**

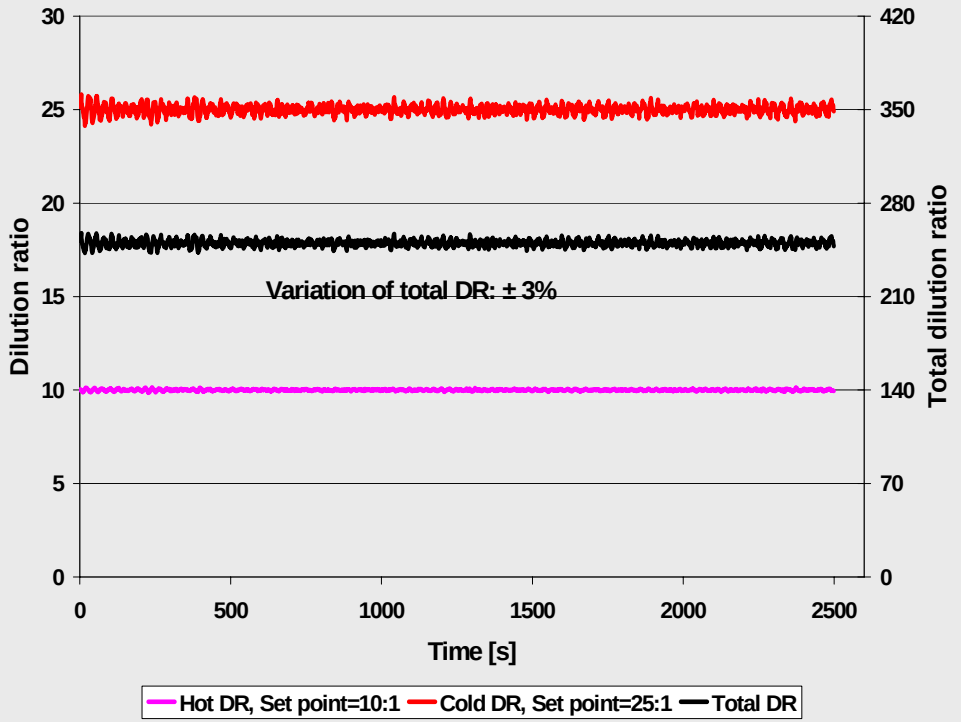
Main display for control software

- **Automated functions**
- **Configurable data log**
- **Data log rate up to 5 Hz**
- **Real-time dilution ratios**
- **Easy to operate**

Performance of SPCS

Dilution ratio

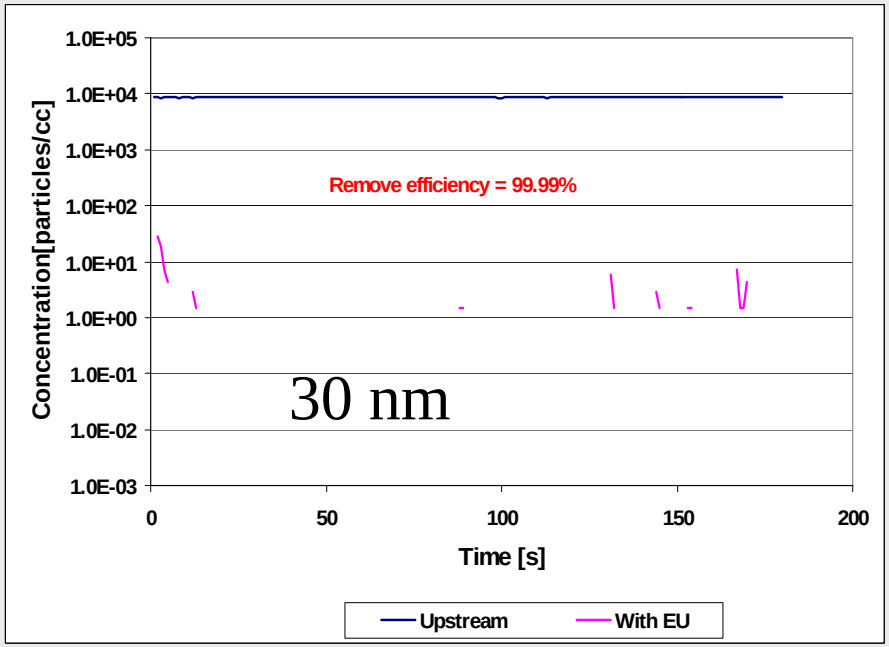


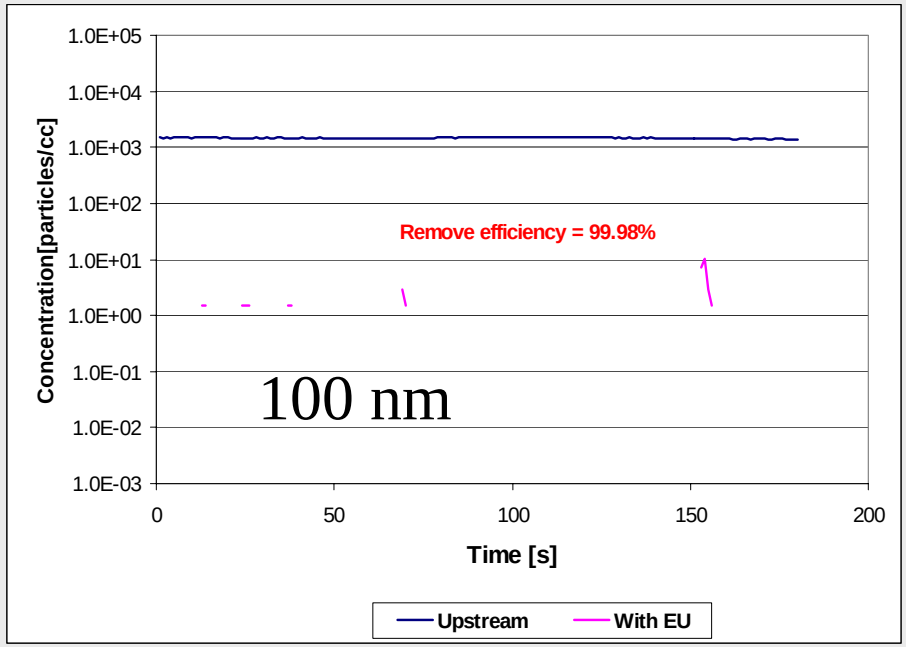


- SPCS operated at the normal measurement condition, all temperatures set at expected values
- SPCS dilution ratios against those measured with a HC analyzer
- Good accuracy on the SPCS, normally in ± 3%
- Accuracy not decreasing with the increase of dilution ratios
- Real-time dilution ratio
- More accurate emission data could be obtained from the real-time dilution ratio

Performance of SPCS

Remove efficiency of Evaporation unit (EU) (Calibrated with $C_{40}H_{82}$)

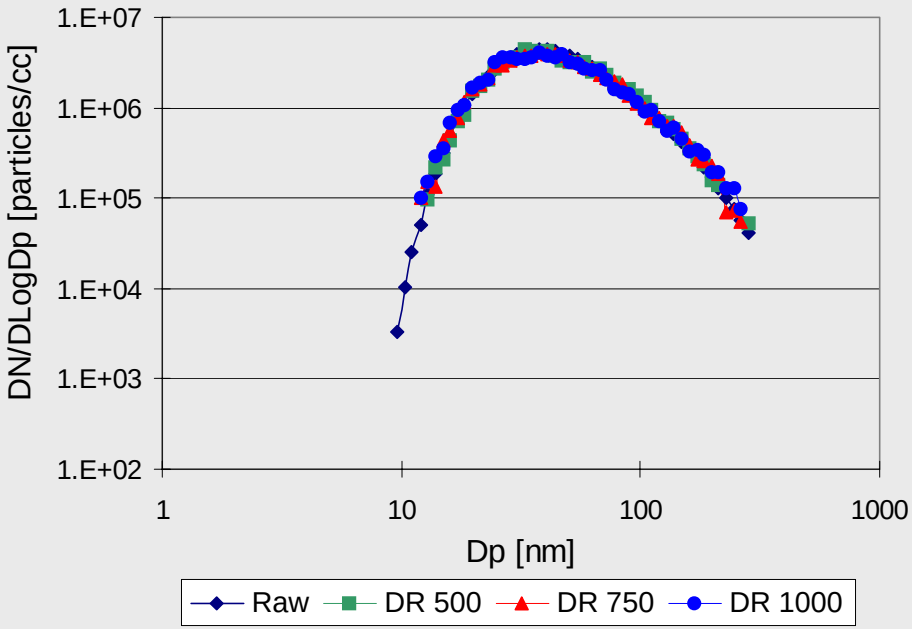


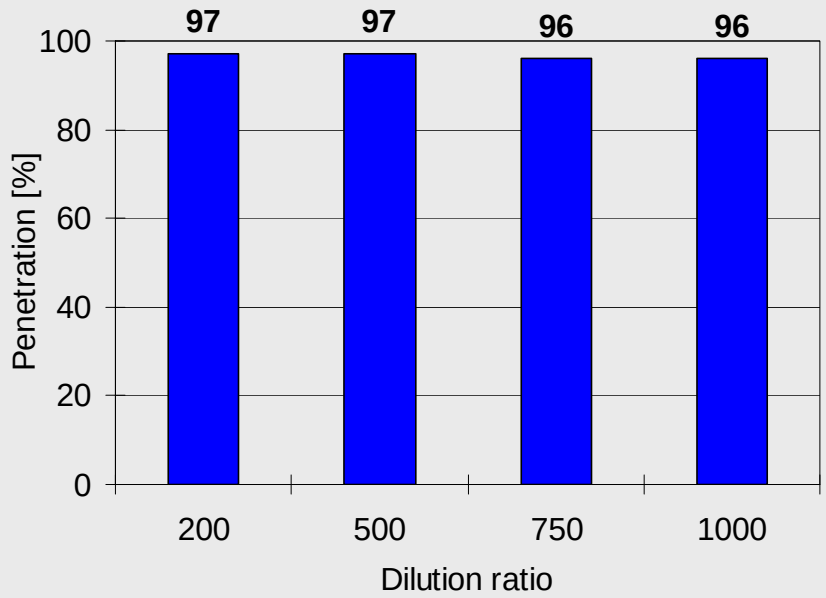


- **EU temperature controlled at 320 ºC**
- **EU with a cold dilution**
- **High remove efficiency for C40 particles > 99%**

Performance of SPCS

Penetration for solid particles (NaCl)





- **SPCS operated at normal measuring condition, and all temperatures set at expected values**
- **Diluted size distribution similar to the raw size distribution**
- **High penetration with solid particles, even at high dilution ratio**
- **Over all penetration > 95%**

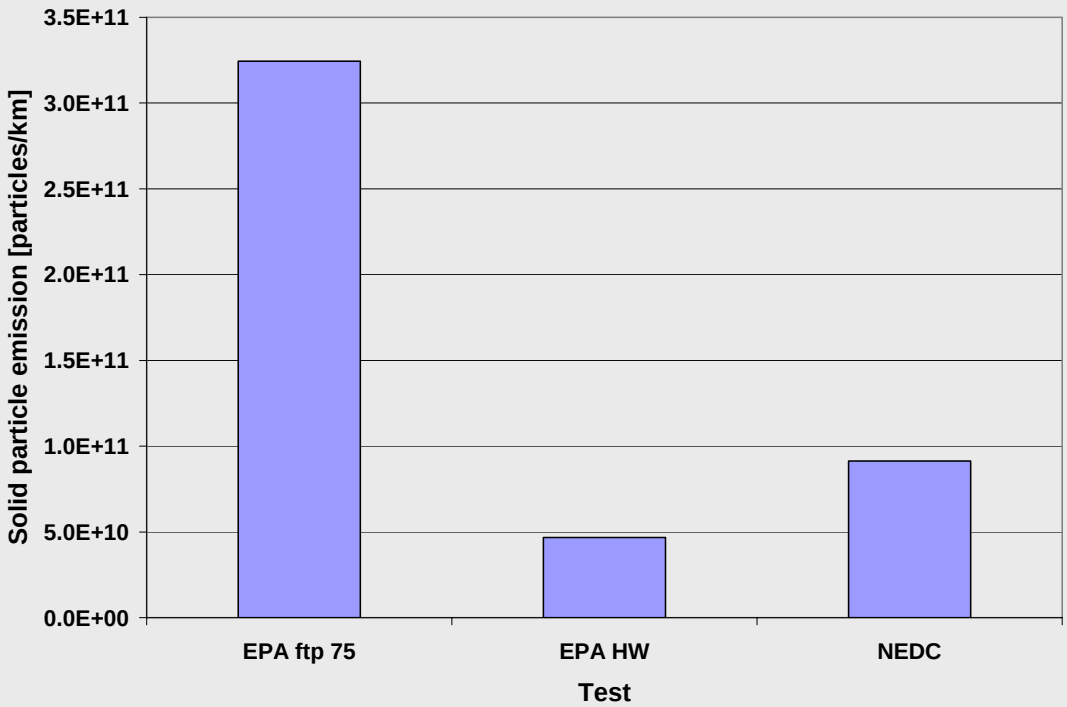
Vehicles in test

- **Gasoline**
  - 1999 Ford Windstar, auto transmission
  - 3.8 L, EGR, SFI
  - Three-Way Catalyst (TWC)
  - Ultra low emission
  - California emission standard
  - Robot driver in emission tests
- **Fuel**
  - California Phase II
    - < 2.2% oxygen

- **Diesel**
  - 1998 VW Beetle, manual transmission
  - 1.9 L TDI
  - Diesel oxidation catalyst only
  - California emission standard
  - Human driver in emission tests
- **Fuel**
  - Certified fuel
    - Sulfur < 300 ppm in mass

Note: TSI CPC 3010 with 10 nm cutoff size in vehicle tests

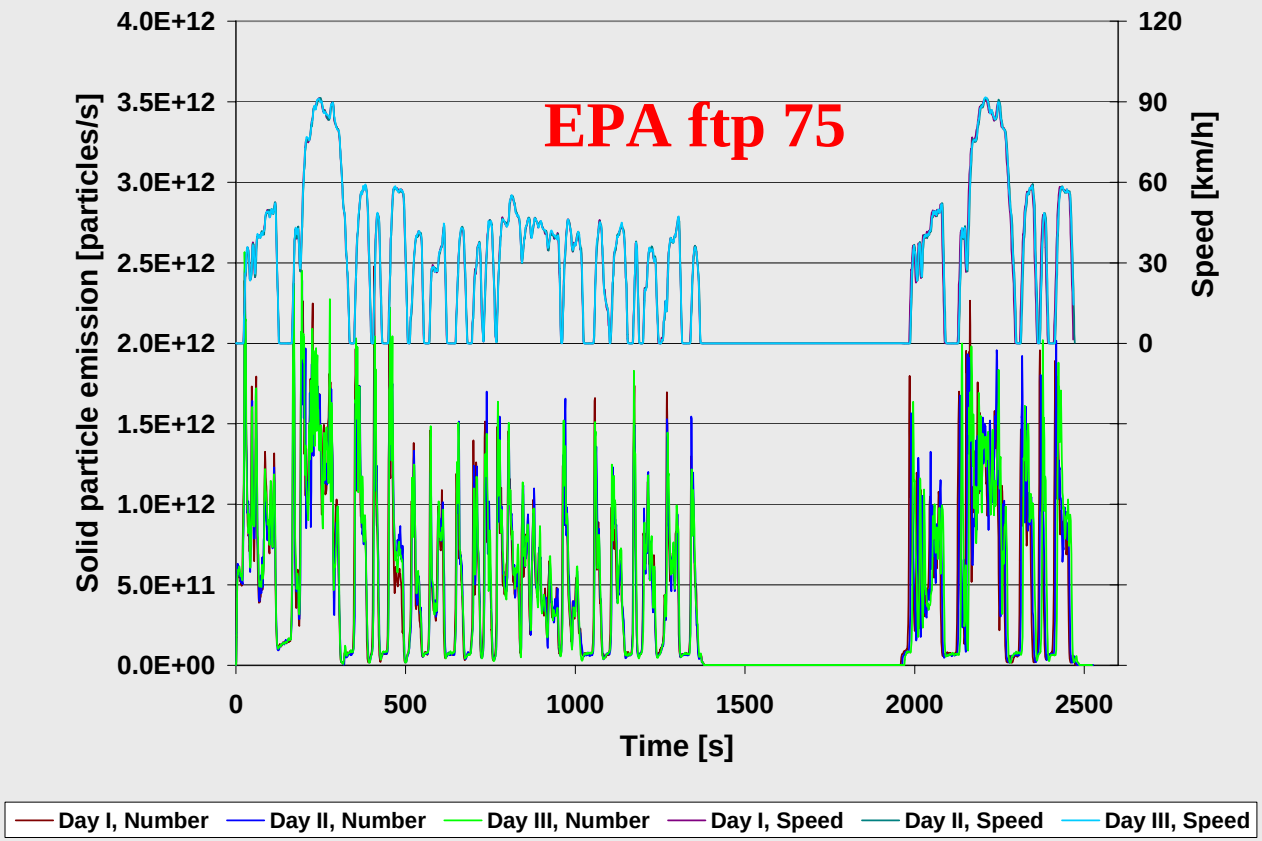
Gasoline vehicle



- **Solid particle emission strongly depends on test cycles**
- **Max. number emission is observed in EPA ftp75**
- **The max. emission (EPA ftp) is factors 6 higher than the min. emission (EPA HWFET)**

Vehicle test

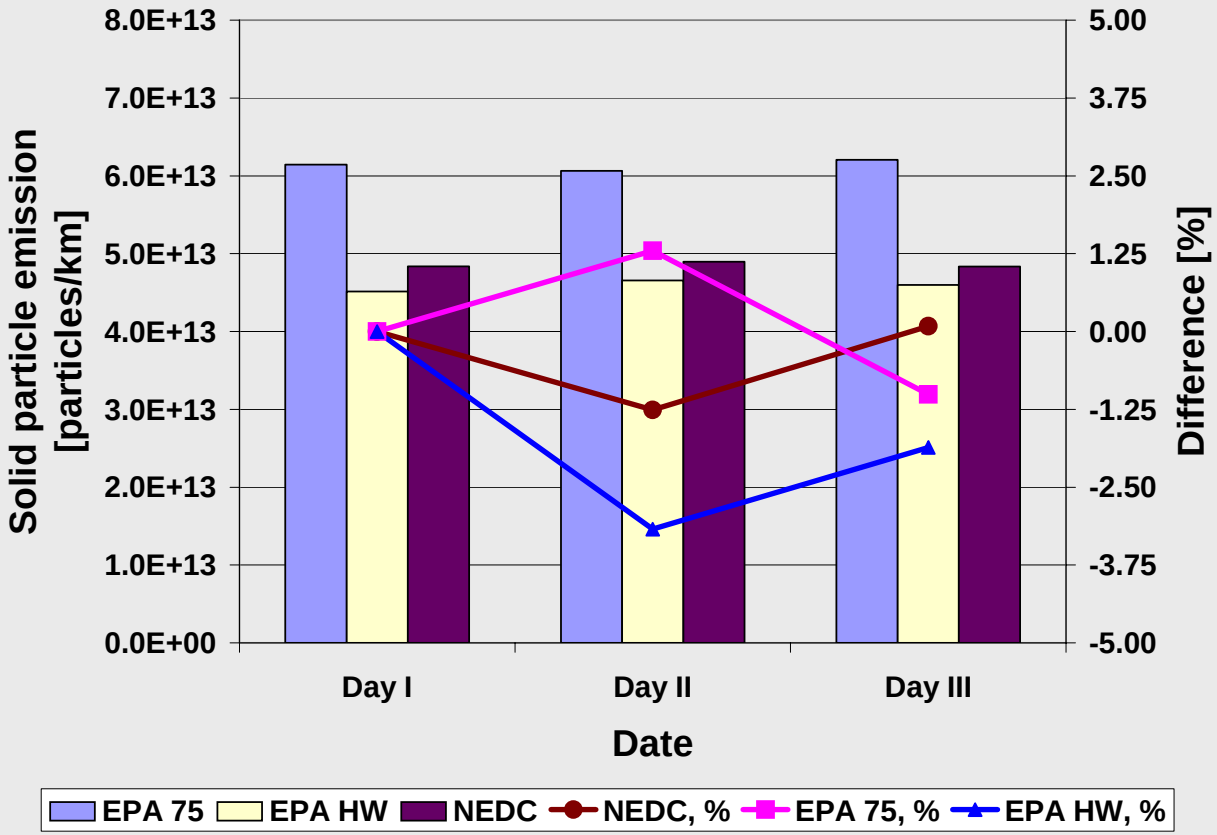
Diesel vehicle (1998 VW)



- Comparing to Gasoline vehicle, no large amount of solid particles emitted during engine start and warm up on diesel
- Higher concentration observed during hard acceleration
- Concentration decreasing during deceleration
- Good repeatability
- Good sensitivity

Vehicle test

Solid particle emission and variation on SPCS (1998 VW)



- Good repeatability on instrument and vehicle
- Day to day variation within ± 3.5 %
- EPA ftp showing max. solid particle emission
- Solid particle emission less dependent of test cycles on diesel
- Solid particle emission from diesel with Diesel oxidation catalyst is over factors 100 higher than the gasoline tested in the study

Conclusion I

- **The SPCS is designed to follow the recommendation in PMP draft regulation, and meets the recommendation:**
  - ***Error of dilution ratio < 10%***
  - ***Remove efficiency of EU for 30 nm C40 > 99%***
  - ***Penetration for solid particles > 90%***
- **Many functions on the SPCS have been automated. It is easy to operate**
- **The major objectives have been achieved; however, the design of the SPCS could be optimized**
- **The SPCS shows good repeatability on solid particle measurement**
- **It can be used on vehicles and engines with different technologies**

Conclusion II

- Solid particle emission on gasoline strongly depends on the test cycle, but not on diesel
- The tested gasoline vehicle emits solid particles in order of 10^{11} particles/km while the diesel vehicle with diesel oxidation catalyst emits in order of 10^{13} solid particles in the same test cycle
- Large number of solid particles were observed during hard acceleration on both gasoline and diesel; particle emissions decrease quickly while gasoline and diesel were decelerating or approaching a constant speed
- Gasoline vehicle emits large fraction of solid particles during engine start and warm-up, but not on diesel
- More solid particles emit in EPA ftp 75 test cycle from both gasoline and diesel. It may be due to cold and hot starts, and more acceleration events involved

Future plans

- **Test SPCS at National Traffic Safety and Environmental Laboratory (NTSEL, Japan) as a part of PMP Inter Lab Correlation Exercise**
- **Evaluate at different laboratories**
- **Optimize based on the test results**
- **TSI and HORIBA are collaborating on future particle measurement systems**
- **2006 SAE Papers, with more details from ILCE**

Acknowledgement

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