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Automotive Test Systems

On Board PM Mass Measurement for US and EU In Use Compliance

Cambridge Particle Meeting

16th May 2008

Introduction

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- Concept of Vehicle On Board Measurement for “In Use Compliance” was introduced by EPA
  - Certification Requirement as consequence of the 1998 Consent Decree against the HDD Engine Manufacturers
    - Caterpillar, Cummins, Detroit Diesel, Volvo, Mack/Renault, Navistar
  - One of the provisions was the acceptance of SET (Supplemental Emissions Test : steady state) and NTE (Not To Exceed) limits of 1.25 times the FTP applicable mass emissions limits
  - Equipment generically known as PEMS (Portable Emissions Measurement Systems)
  - NTE testing to be measured as “Field Testing” under test procedures and equipment defined under 1065 regulations : subpart J
    - Gaseous systems specifications : now confirmed
    - Real Time PM mass measurement systems : under evaluation at present time to determine accuracy allowance against CVS principle
      - ✓ Currently auditing candidate systems performance with simulations
      - ✓ Engine testing phase to begin shortly . . .

NTE (Not To Exceed) Zone

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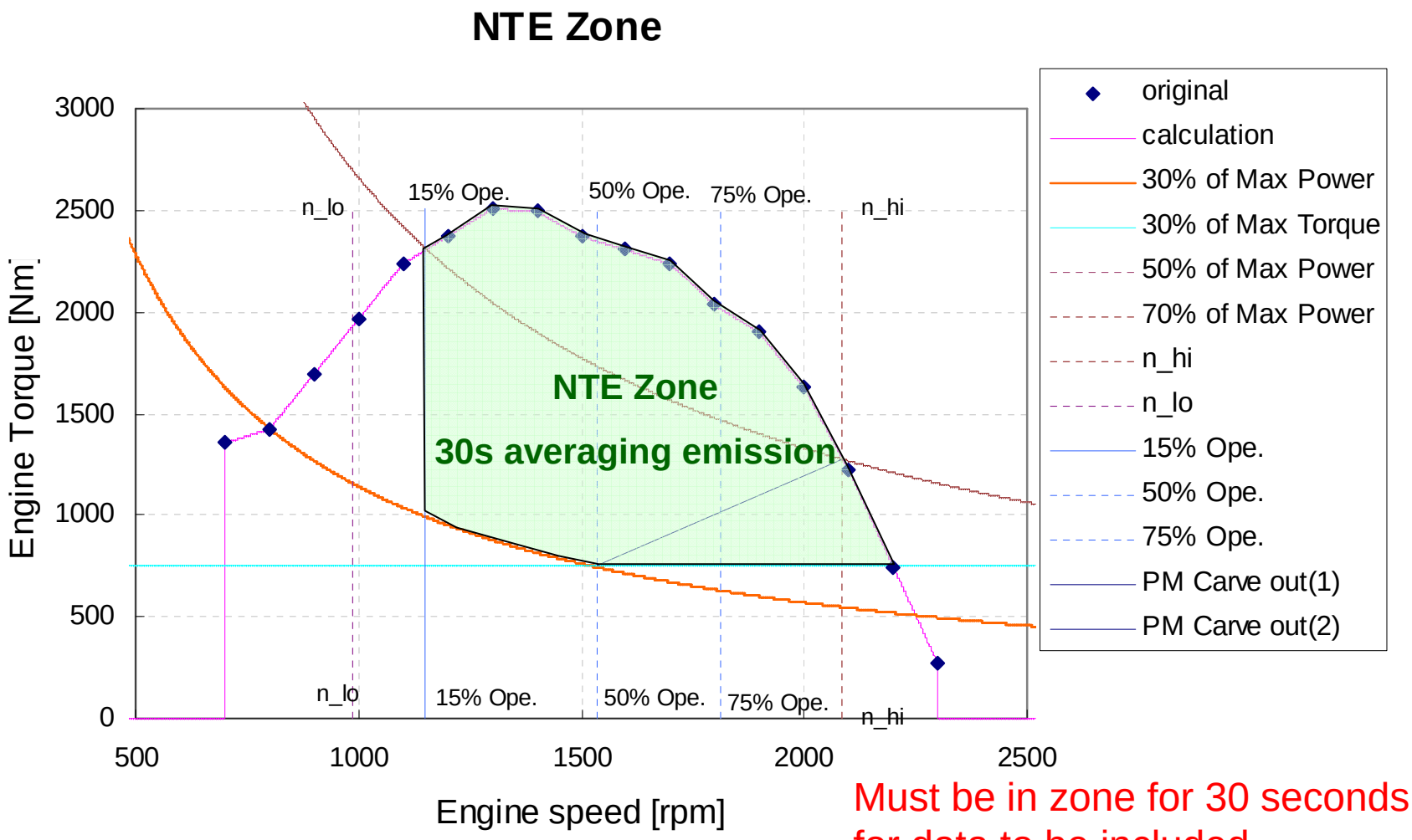

Must be in zone for 30 seconds for data to be included

European Background
Directive for In Service Conformity

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Legislative framework of in-service conformity

Directives 2005/55/EC, 2005/78/EC (Euro IV-V):

- correct operation of the emission control devices during the normal life of the vehicle under normal conditions of use is confirmed
- conformity of properly maintained and used in-service vehicles/engines is ensured

Euro VI proposal (COM(2007) 851 final):

- In order to better control actual in-use emissions including OCE and to facilitate the in-service conformity process, a testing methodology and performance requirements based on the use of portable emission measuring systems (PEMS) should be adopted.

2

European Background

Directive for In Service Conformity

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Legislative framework of in-service conformity

ISC can be demonstrated by:

1. Presenting test data as measured on the test cycles
   - as required by Directives 2005/55/EC and 2005/78/EC
   - but: removal of engine is cumbersome, time consuming and costly

2. Data obtained through the use of mobile measuring equipment fitted to vehicles
   - this method is considered as the most cost-effective one for ISC checking
   - measurement is easier to perform

⇒ A new PEMS-based ISC framework needs to be established, if possible for Euro V

3

Status of the EU PEMS Program

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- EU PEMS gaseous study program successfully completed
  - Defined gaseous mass measurement procedures / calculations
- Moved to Pilot Program Stage for HDD On Road
  - Gaseous program in progress
  - PM program commencing in late 2008/9
- Pilot Program Participants
  - European Commission
    - General co-ordination: DG ENTR
    - Technical co-ordination: DG JRC
  - Member State authorities
  - Technical services
  - Vehicle and engine manufacturers
  - PEMS equipment manufacturers
  - Consultants (TNO, TUG, TÜV Nord etc)
- Application Of PEMS Equipment / Procedures for NRMM
  - Mainly agricultural machinery and construction equipment at present
  - Initial feedback from testing (may lead to modified procedures/specifications)

OBS-2200 : PEMS for Gases

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Laptop-PC

ECU

ECU interface (rpm/load)

Option
extended data logging channels

All in one package

LAN

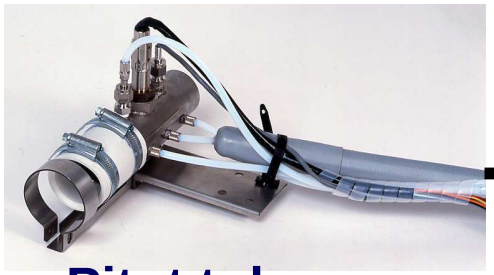
GPS

Temp/Humid.

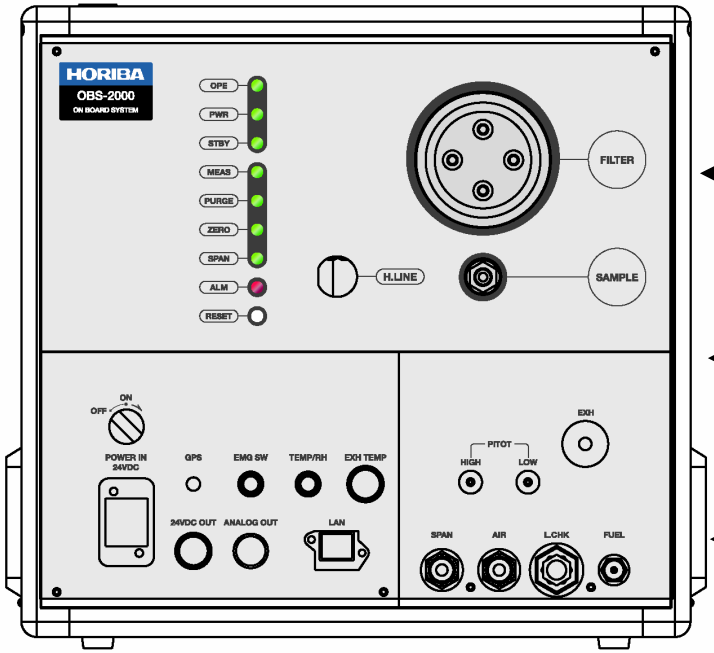
Battery

DC 20-30V

Attachment



Pitot tube
exhaust flow meter



CO, CO_2, HNO_x, HTHC analyzer

EU Problem with NTE

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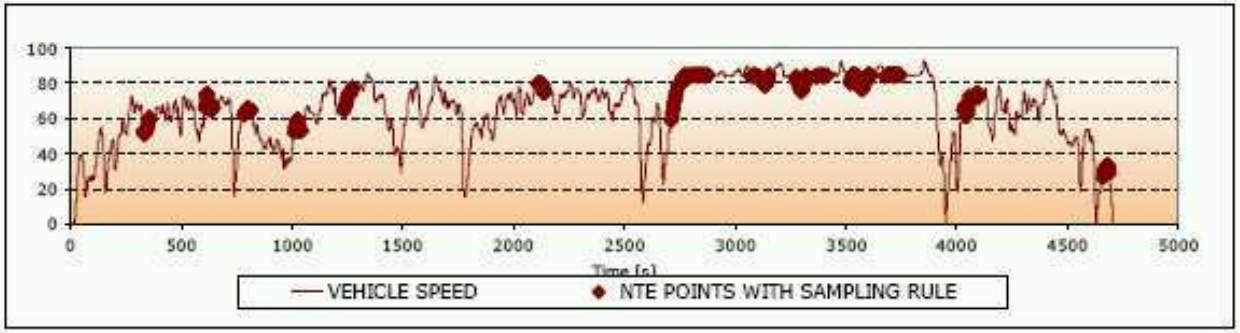
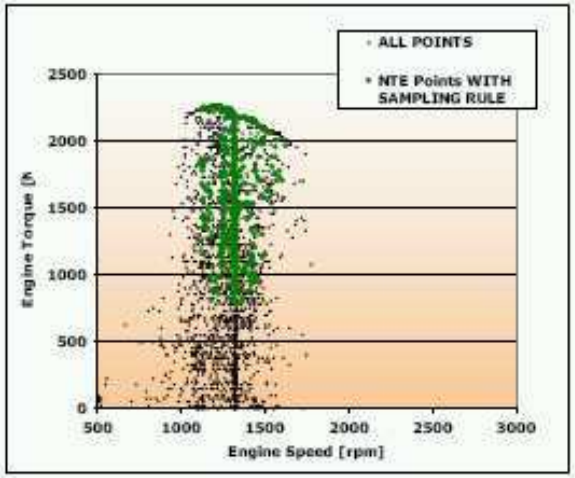
DIRECTORATE-GENERAL
Joint Research Centre

Joint Research Centre

- Case 1: Long-haul vehicle, fully loaded (40 tons)





- Control Area: US NTE
- Minimum Sampling rule: 30s
- % Points in the control area: 47%
- % Points considered for the calculation: (Application of the sampling rule): 18% of all data

EC DG JRC – June 21, 2006

ies

Explore the future

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EU Problem with NTE

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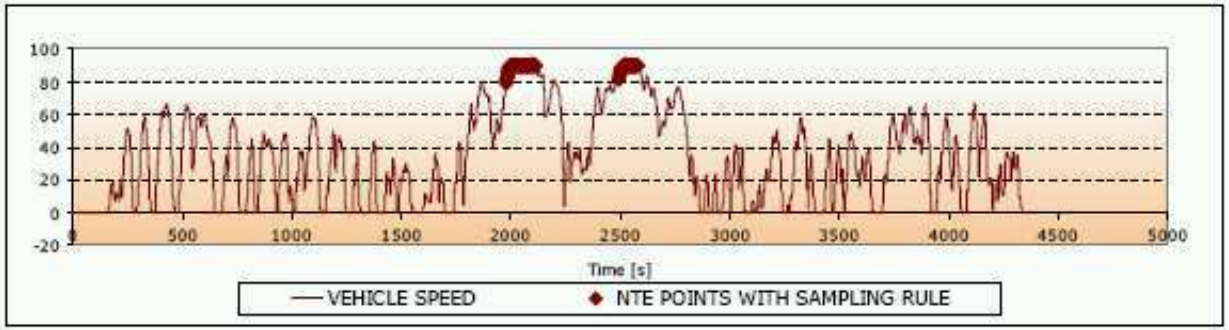
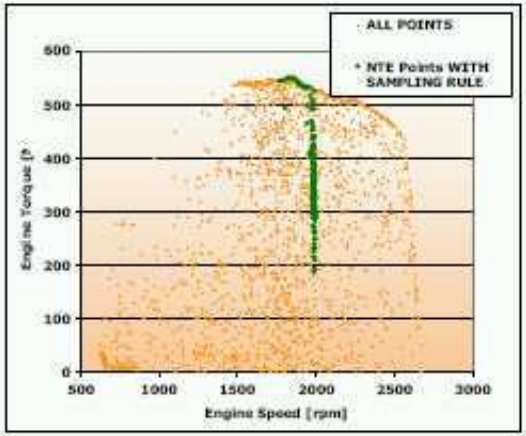
- Case 2: Local delivery truck, highly loaded (12 tons)





- Control Area: US NTE
- Minimum Sampling rule: 30s
- % Points in the control area: 36%
- % Points considered for the calculation: (Application of the sampling rule): 5% of all data
- Without motorway high velocity operation: 0%

EC DG JRC – June 21, 2006

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Alternatives to US NTE

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- EU JRC now reviewing the options for calculating, reporting and confirming Pass/Fail criteria
  - Modified NTE
    - Extending the “zone” to include lower speeds/loads
    - Decreasing the time window for valid data
  - Moving “work window” approach
    - All data is included but emissions are calculated and averaged over a window related to a defined amount of work, related to the maximum power of the vehicle
    - Criteria under consideration (maximum window time validity check)
  - Other calculation/reporting bases are being considered
    - For NRMM engines that do not have ECUs to indicate engine speed and torque/load then alternative pass / fail calculations must be considered

Alternatives to US NTE

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EU PEMS PM Program Status

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List of candidate instruments

- HORIBA OBS-TRPM : Portable “Mini-Tunnel + DCS-100
  - Filter based PM mass measurement using portable proportional diluter combined with a real time particle indicator, sampling diluted exhaust
- SENSORS PPMD
  - using flow proportional exhaust dilution
  - multiple QCMs (quartz crystal microbalances with complex sampling / conditioning sequence)
  - Not a real time PM mass measurement (hence proportional flow diluter)
- DEKATI DMM-230
  - Using fixed ratio dilution (variable setting)
  - Real time measurement
- CONTROL SISTEM Portable “Mini-Tunnel + DEKATI ETAPS
  - Filter based PM mass emissions plus real time “in-situ” soot indicator
- AVL 483 Micro-Soot Sensor
  - Using fixed ratio exhaust gas diluter

EU PEMS PM Program Status

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- Laboratory Testing / Correlation Phase
  - June/July 2008
  - Comparison of candidate instruments with reference CVS system for PM Mass
    - No real time PM mass reference device
    - Particle number measurements also taken “for reference only”
  - Decision on acceptable instrument / principles at end of laboratory correlation phase
- Field Testing Phase
  - October 2008 onwards
- EPA PM Mass Measurement Program
  - Continuous exchange on measurement methods and procedures
  - Alignment of requirements is anticipated

PM is a complex, variable mixture of several components

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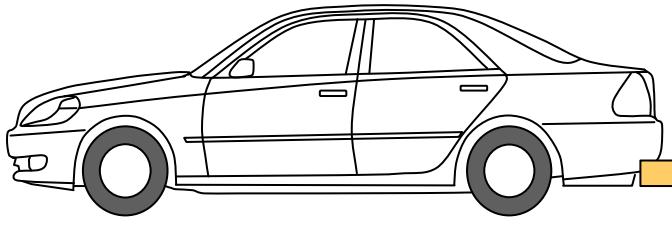
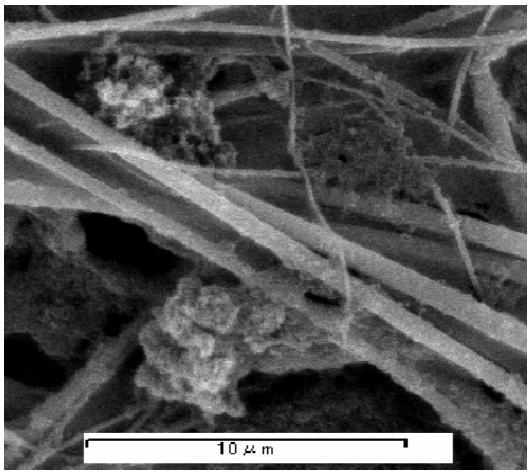
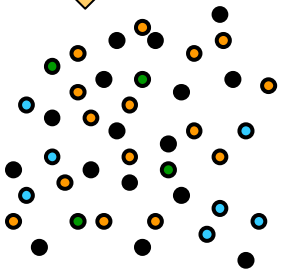


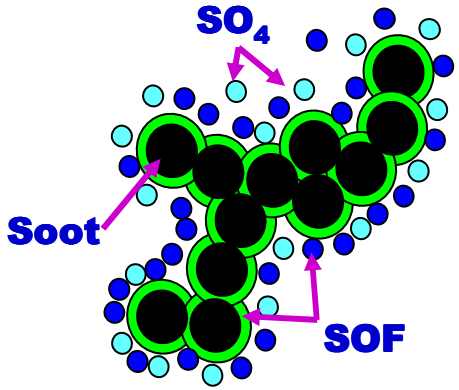
Tail Pipe





Ash
Carbon
HC
Nitrate
SO_4
H_2O

Formation continues in upon dilution with air



Soot: Carbonaceous Solid (Combustion Generated)

SOF: Heavy HC condensed/absorbed on soot (Unburned fuel, Oil, Compounds formed during combustion)

SO_4 : (Sulfur from the Fuel and Oil) combined with H2O

Nitrate : Formed as by-product from some exhaust after-treatments

Ash : solid particles formed from combustion of oil or additives in fuel

Soot is not enough ?

Not for this vehicle, fuel, driving cycle etc

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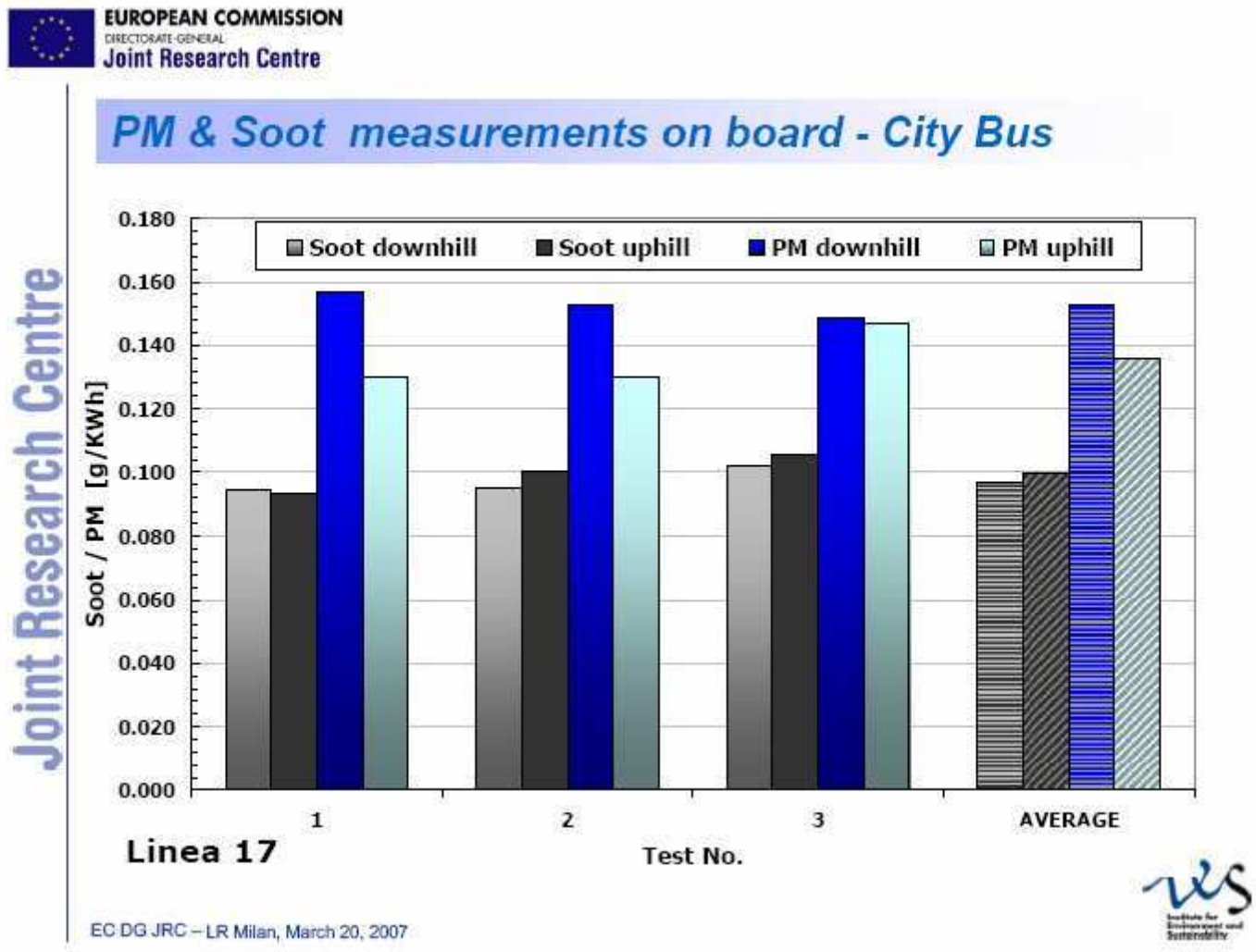

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PEMS Real Time PM Mass Measurement

Technical Difficulties

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- Accuracy / Correlation To Legislative Method
  - Specifically, correlation to the filter based gravimetric measurement principle that is used currently for all engine / vehicle certification . . And In Real Time
- Sensitivity
  - Requires higher sensitivity than filter gravimetric principle
    - Laboratory has whole test cycle for PM loading, real time can have as little as 30 seconds of PM mass loading
- Traceability
  - Calibration method
  - Traceability to a mass standard
- Repeatability / Reproducibility
  - Short term and long term drift potential
- PM Sensitivity to Fuel Composition, After-Treatment, Test Cycle, Ambient Conditions, Vehicle Pre-Conditioning/History etc
  - PM mass / composition can change with the above
- Rugged and Practical for On Board Use
  - Insensitive to vibration, ambient temperature change, altitude, ambient humidity
  - Size, power consumption, control signals etc

Combination of PFDS and Real Time Detector

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Filter Gravimetric Method

Advantage

- Conventional Method
- Gravimetric result

Disadvantage

- Low Sensitivity
- Batch result

Real Time Instruments

Disadvantage

- Correlation ?
- Traceability ?

Advantage

- High sensitivity
- Real time result

Basic Components for the HORIBA Combined System

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- A partial flow diluter with filter for mass measurement (proportional dilution controlled by exhaust flow rate signal)
  - Dilution and PM sampling at 47 deg C, same as EPA 1065
  - Pitot tube flow meter and OBS-2200 providing exhaust flow signal for real time proportional dilution control
- A diffusion charge sensor (DCS) used as a real-time PM detector
  - OEM version of TSI EAD (Electrical Aerosol Detector)
  - Measure particle length in real-time
  - Wide size range : 10 – 1000nm
  - High sensitivity and wide dynamic range : 0.01 – 2500 mm/cm3
  - Response Time : < 3 secs
- Integrated DCS signal is calibrated against PM mass, post test, to provide a factor for real time PM mass indication

Schematic For OB-PFDS Module

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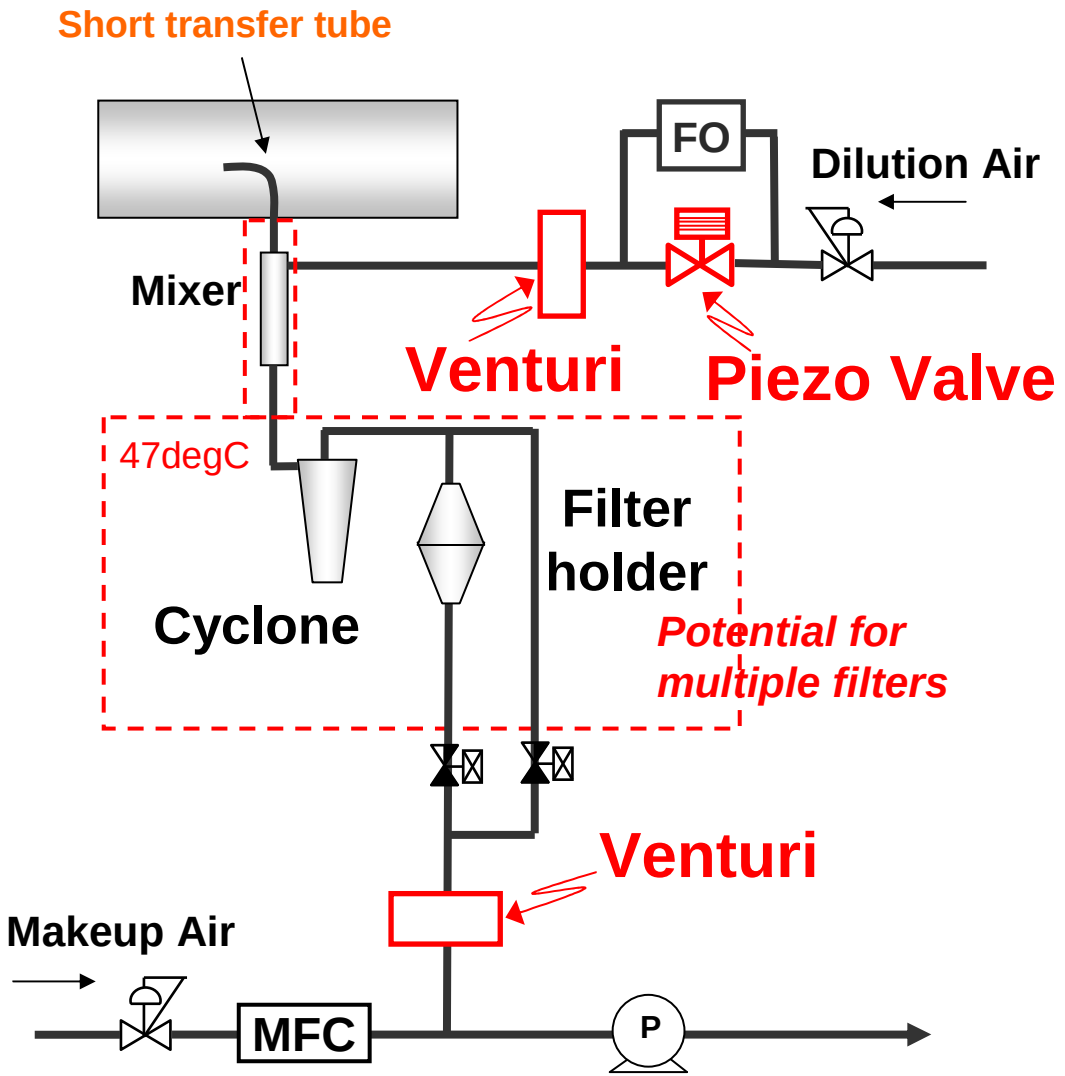

Accurate Flow Measurement

Venturi flow meter has small influence by exhaust composition

Fast Dilution Air Flow Control

Piezo Valve & Flow Orifice is applied for dilution air flow control

Layout for the prototype PFDS

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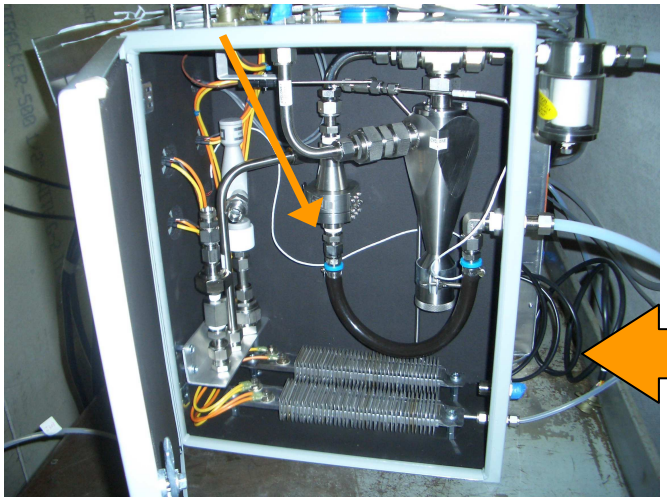
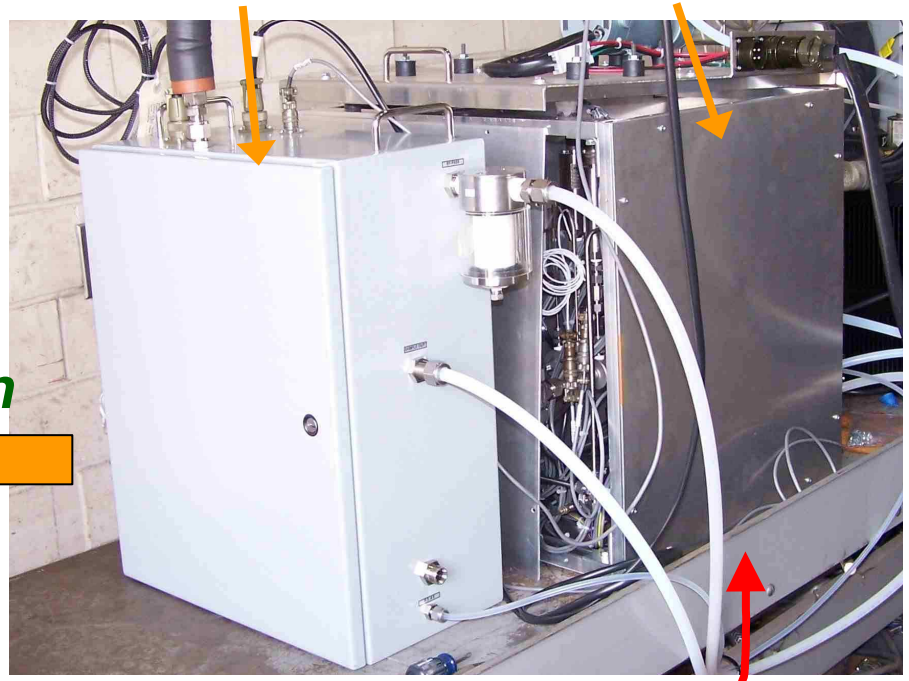
47mm Filter holder (47±5 degree C)



Open

Heated Enclosure

Control Unit



Exhaust Flow Signal

(for proportional dilution control)

Dilution Ratio Verification

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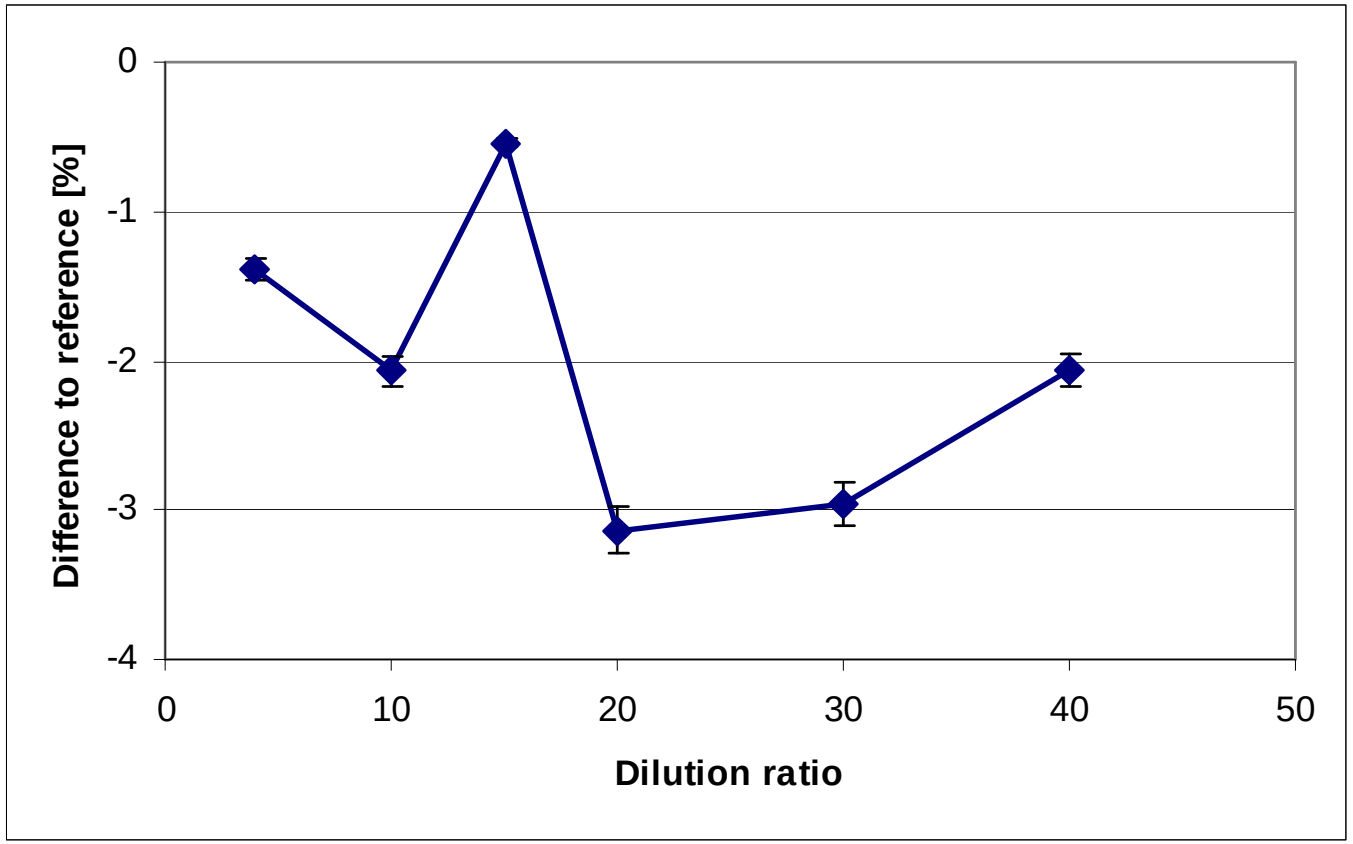

Dilution factor verified using high accuracy flow measurement of net sample flow rate under steady state conditions

Proportional Control for FTP cycle
Using air flow + fuel flow data

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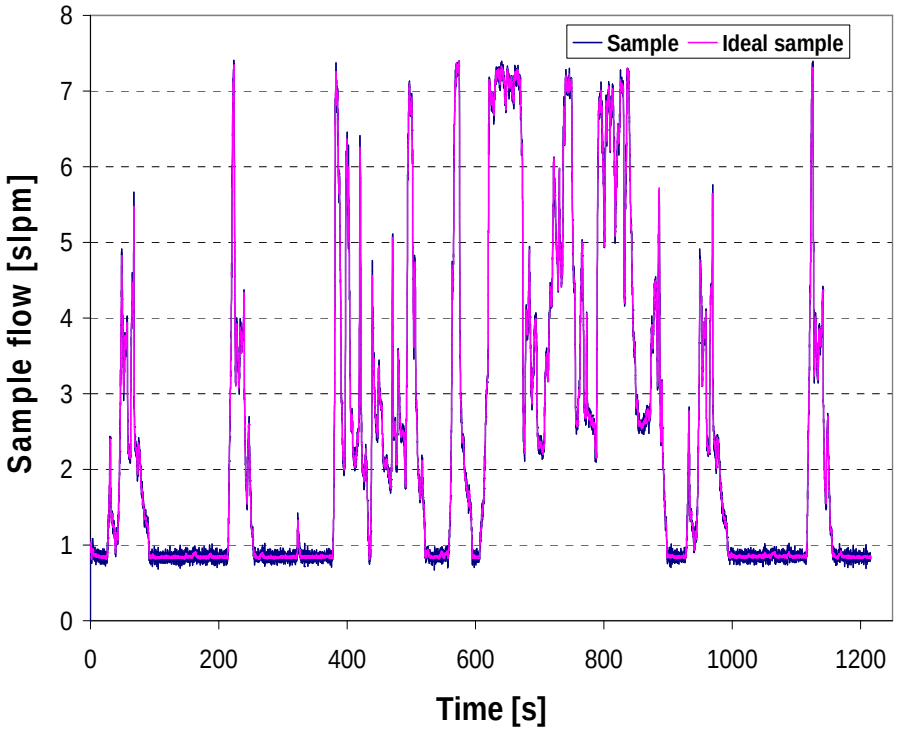
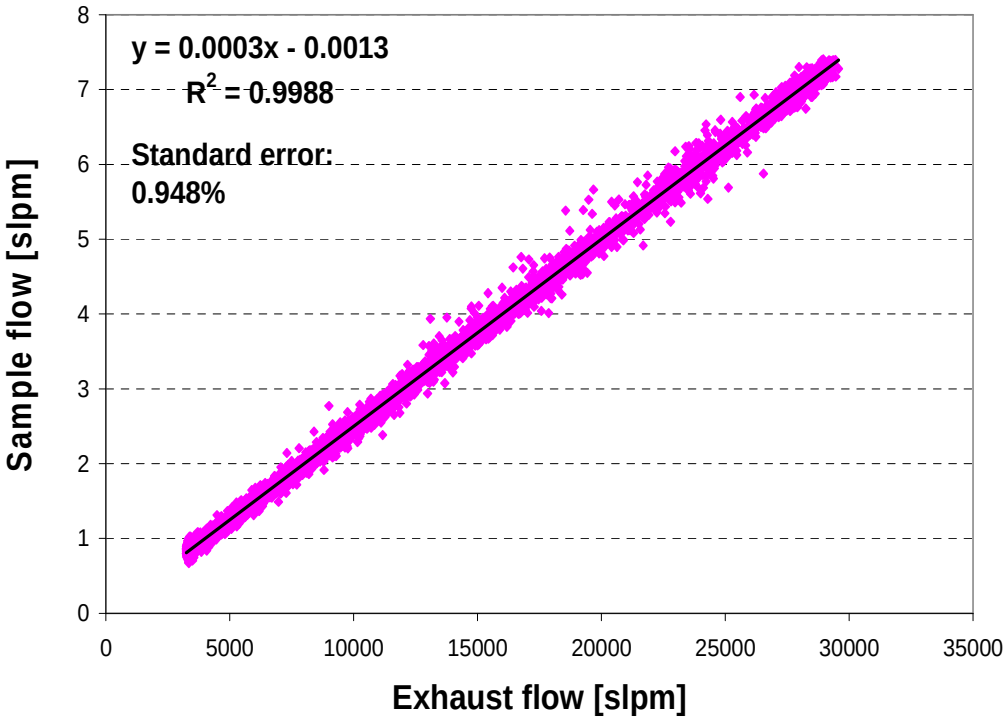
Sample ratio: 4000:1





Standard Error = 0.9988 (>0.95 ; ISO-16183)

Correlation Coefficient(R^2) = 2.93% (<5.0% ; ISO-16183)

Proportional Control for FTP cycle
Using exhaust flow meter

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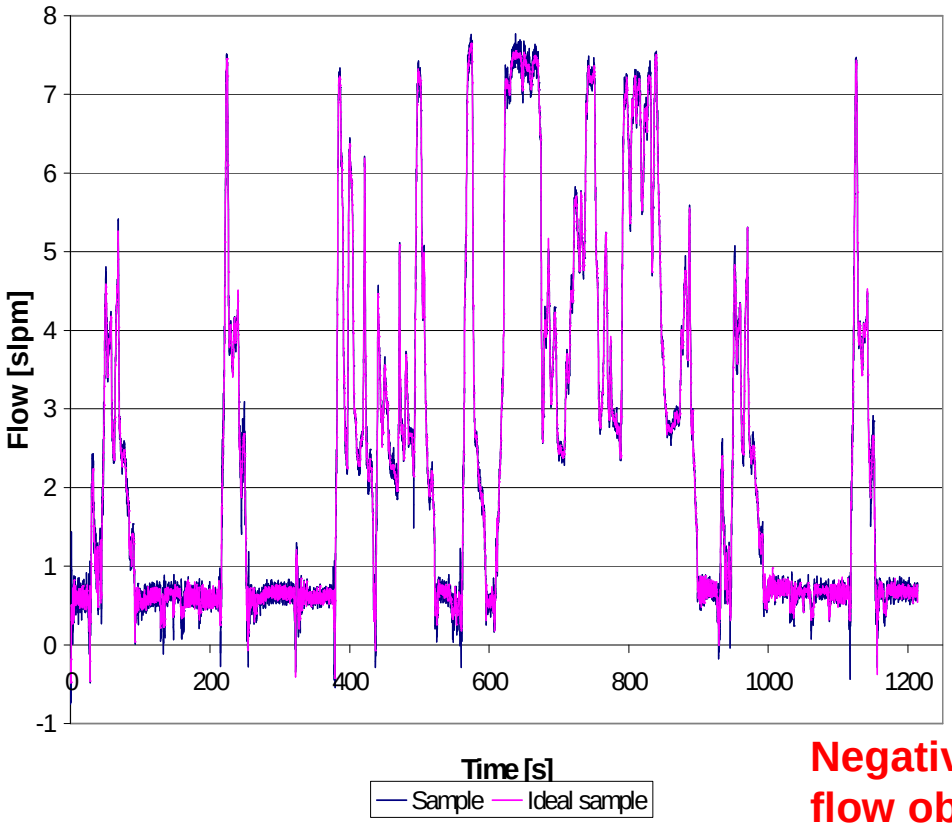

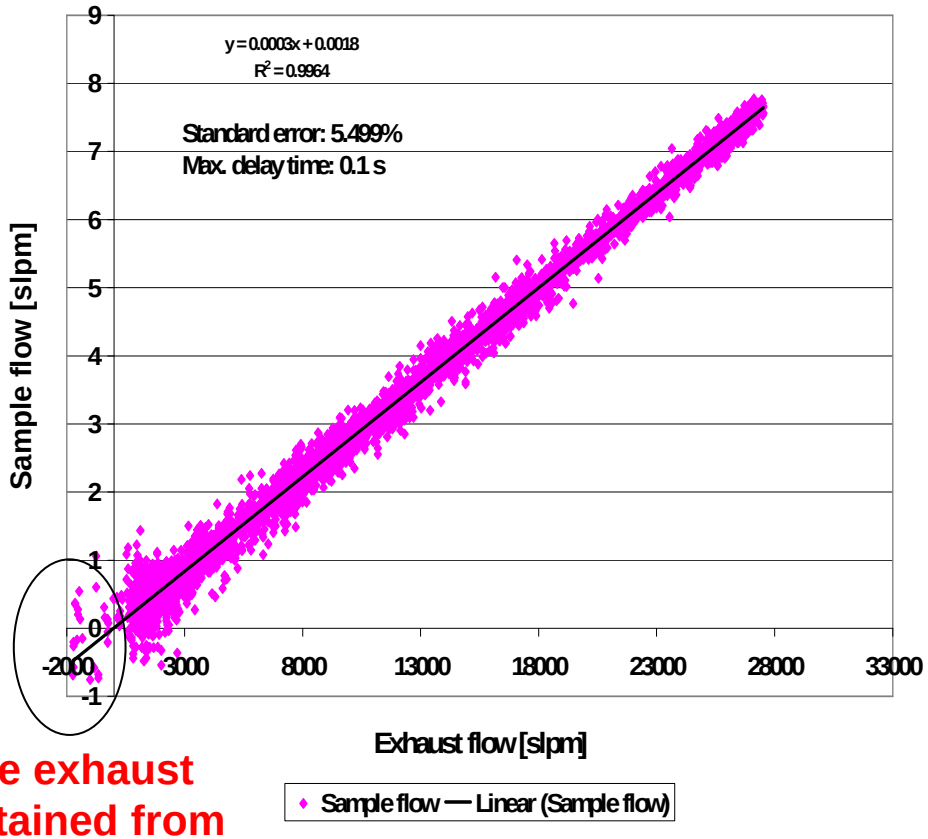

Negative exhaust flow obtained from exhaust flow meter

Exhaust flow metering system accuracy / characteristics are important factor in the performance of PM Mass measurement

Test Engine Configuration @ SWRI

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Test Engine Specification

Description	Specification
•Model Year Designation	•1998
•Engine Family	•DDC Series 60 •with CRT-DPF
•Power Rating	•400hp at 1810rpm
•Torque Rating	•1550 lb-ft at 1200rpm

Test Configuration @SWRI

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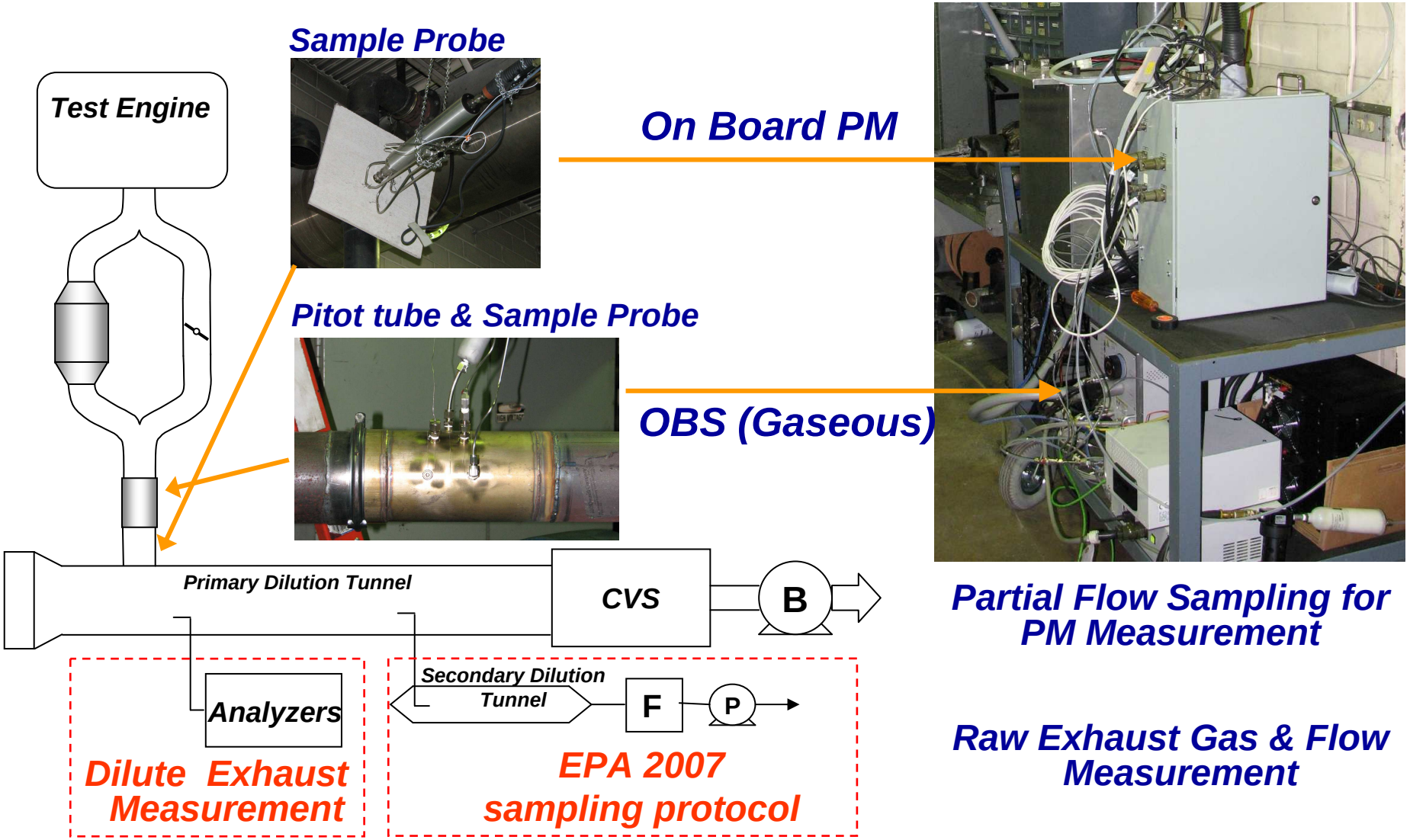

PM Mass Emission Results

OBS-PM Filter v CVS Reference Method

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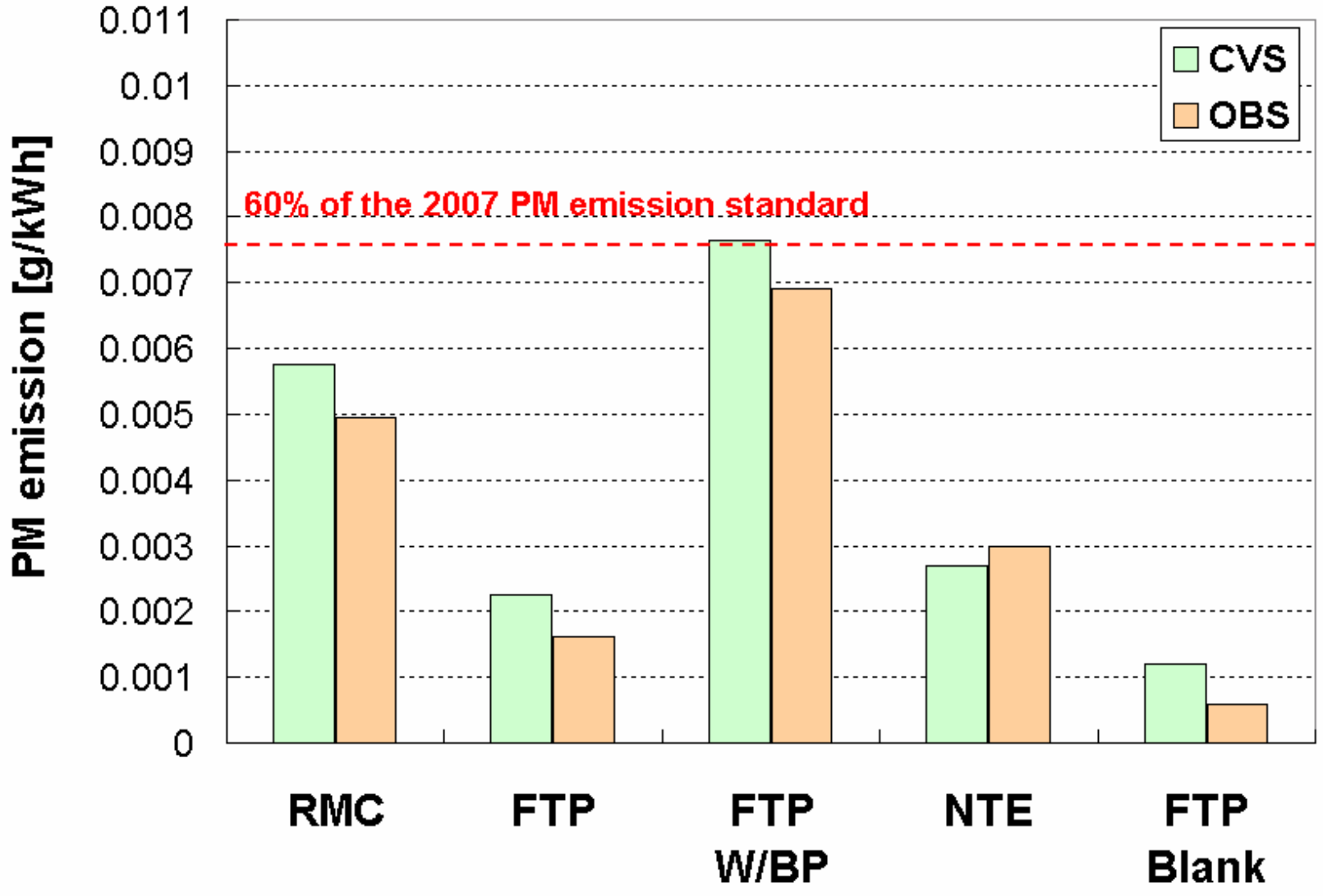

Combination of PFSS and EAD

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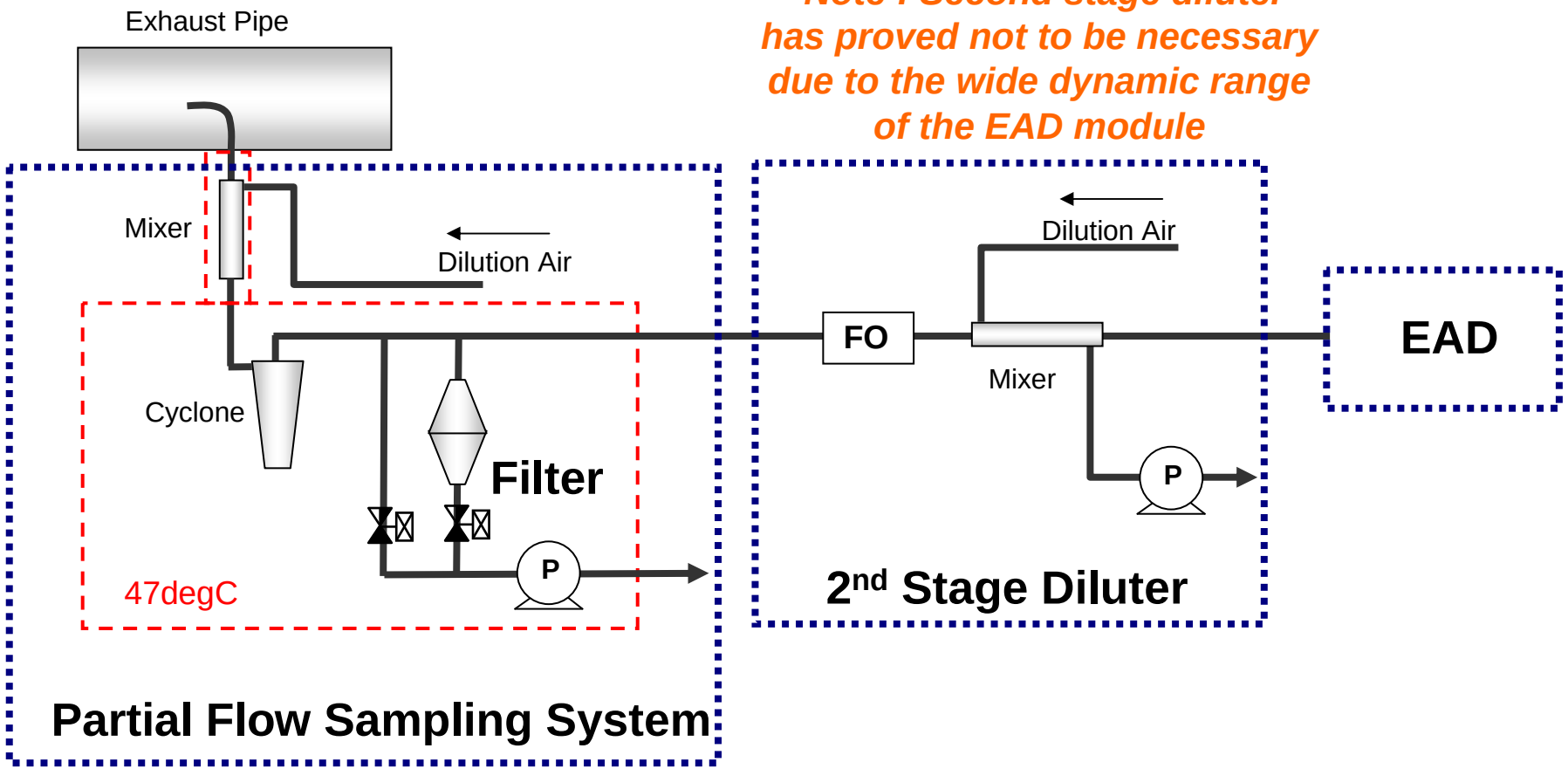
Note : Second stage diluter has proved not to be necessary due to the wide dynamic range of the EAD module



Concept for NTE or real time PM mass measurement procedures

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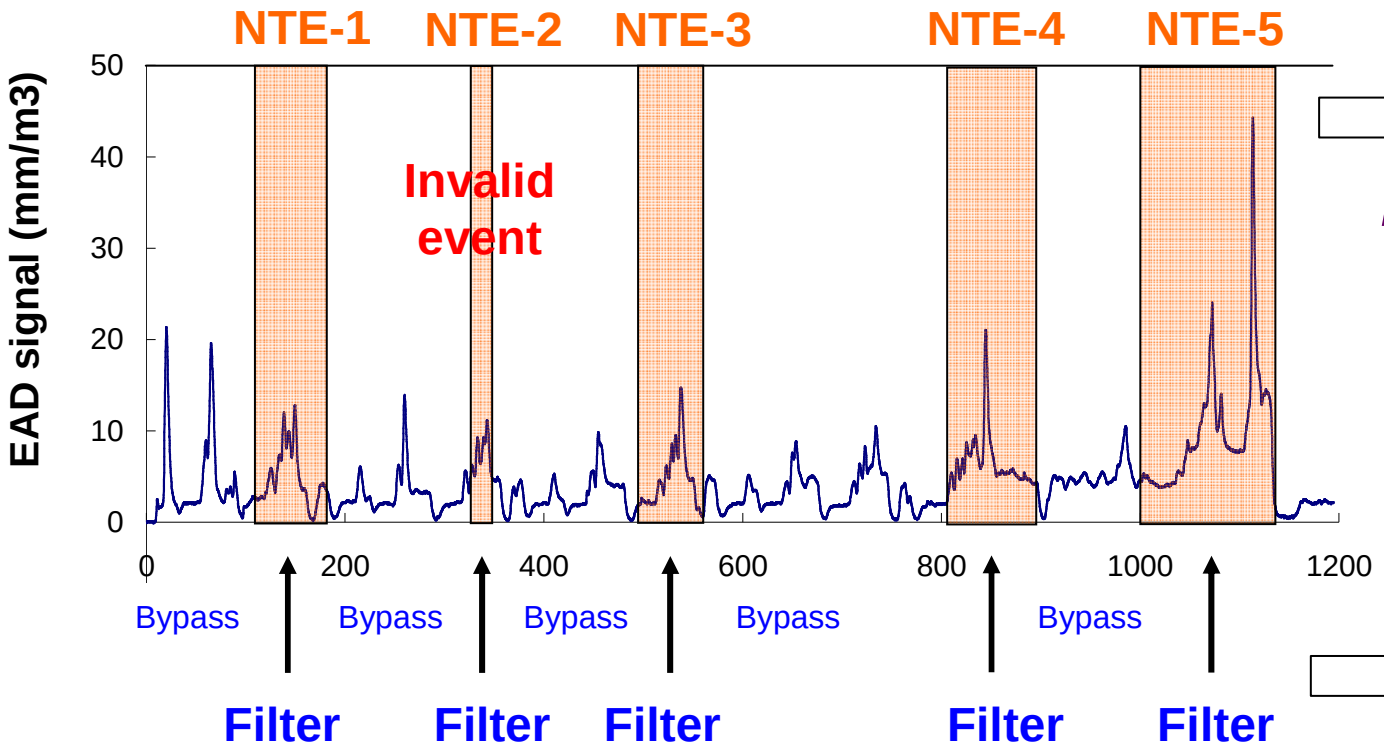

EAD

Ratio of PM

$$\frac{(\sum EAD_t)_i}{\sum_{i=1}^{n}(\sum EAD_t)_i}$$

PFDS

Total PM

PM mass in VALID NTE events = **Total PM X Ratio**

Advantage of the combination method

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Advantage

- **Total PM measurement over NTE events same as conventional method.**
- **Filtering PM in NTE region (with 0 secs averaging) for more than 2 hours should typically load sufficient PM on the filter (depending on the road cycle)**
- **EAD has sensitivity for real time measurement of post 2007 PM standard.**
- **EAD measures all particles soot, sulfate, volatile particle etc from 10 – 1000 nm**

Minimizing the Assumptions

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Assumptions; Same size distribution, Same density

Minimizing factors

- **By using filter gravimetric mass result as reference on each specific engine , this will eliminate assumption errors for engine family, after treatment strategy, etc.**
- **By using EAD to gravimetric mass ratio, we will reduce the impact of different PM species on measurement.**
- **Method can be adapted for a variety of measurement models (NTE, Moving Work Window etc)**
- **Assumed Composition, Density or Size Distribution parameters are not used to calculate mass**

Real Time Data : EU Stage 3 vehicle on Chassis Dynamometer

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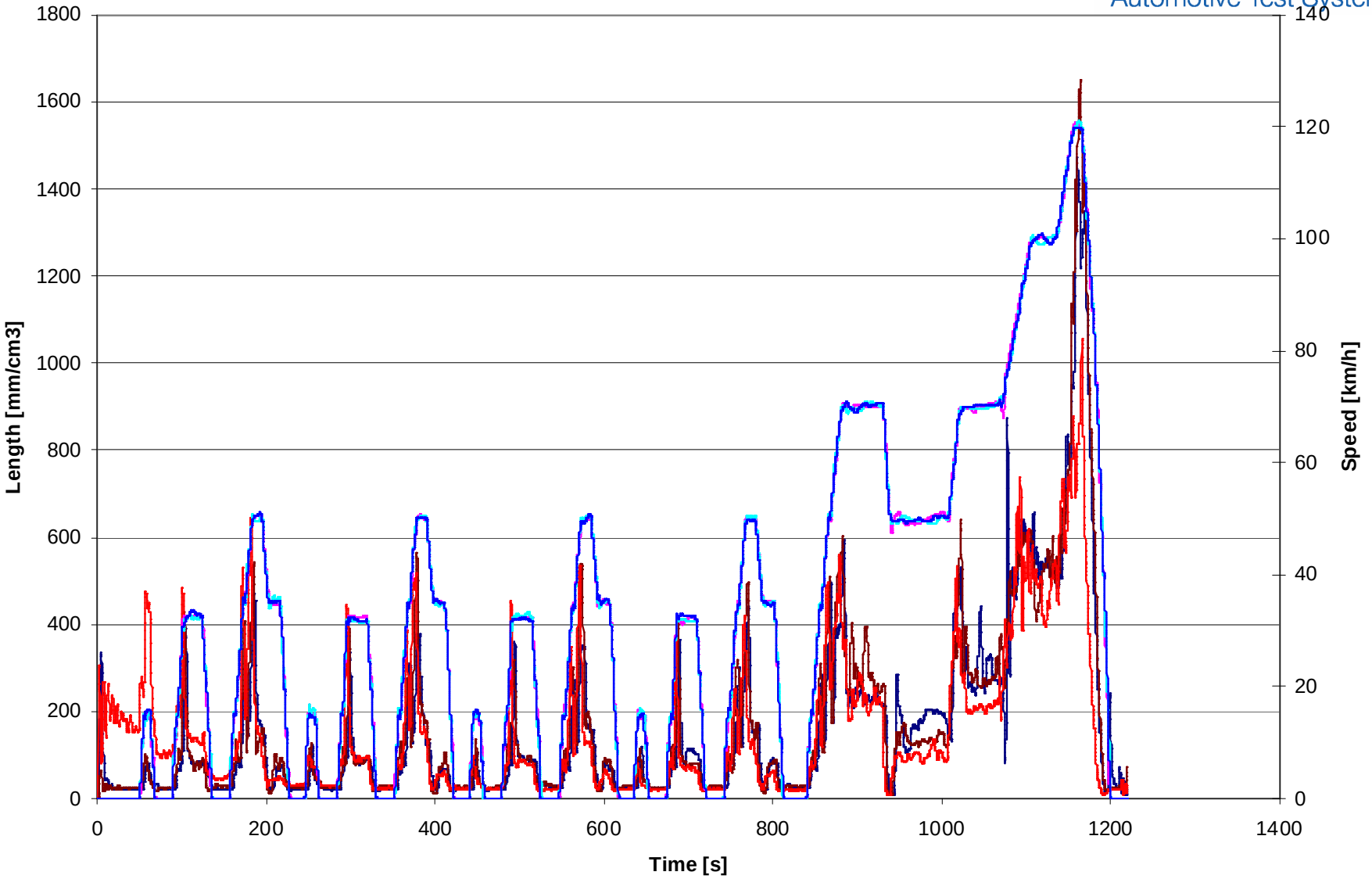

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Real Time and Accumulated particle diameter length v time

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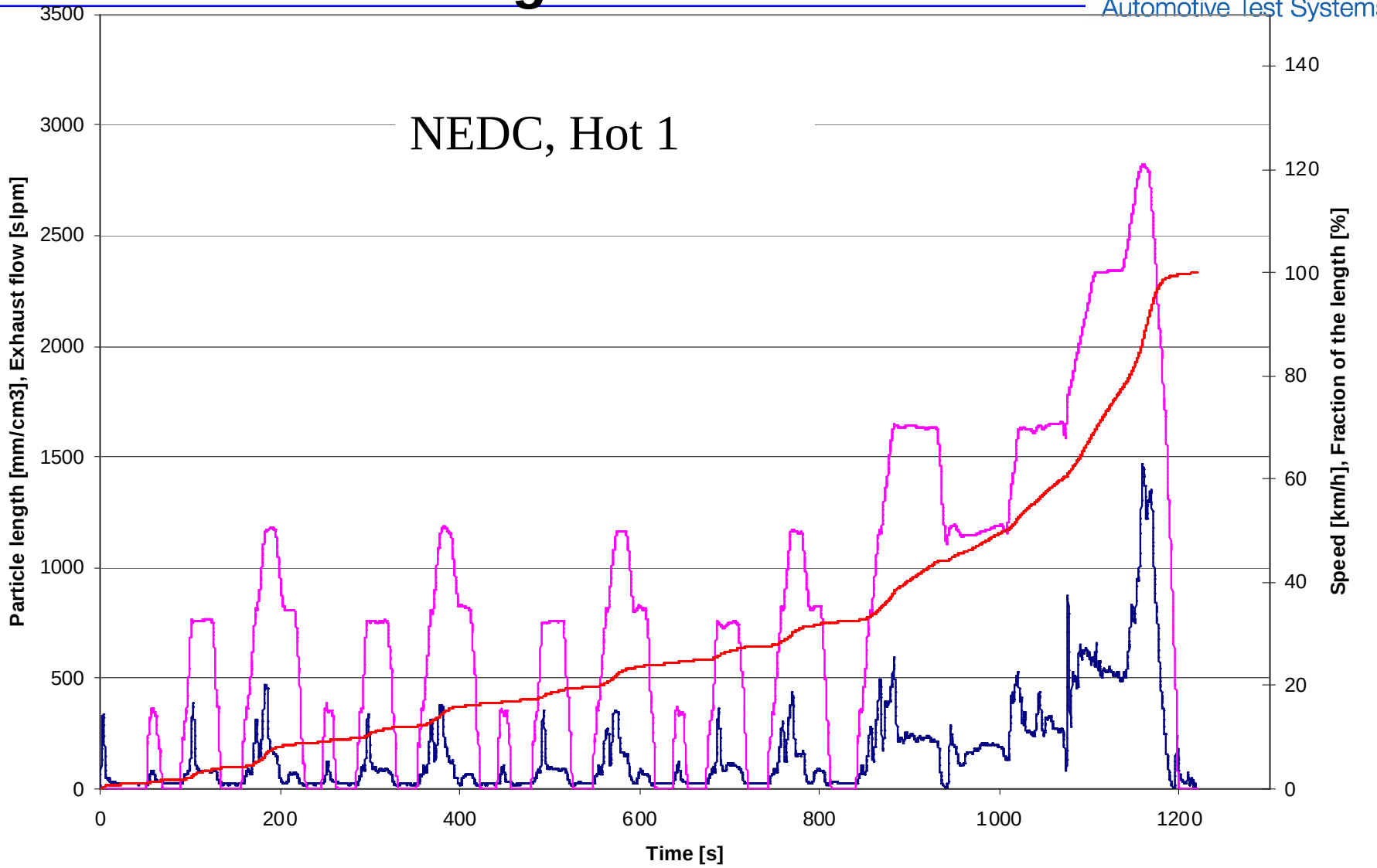

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Accumulated particle diameter length v Gravimetric PM Mass

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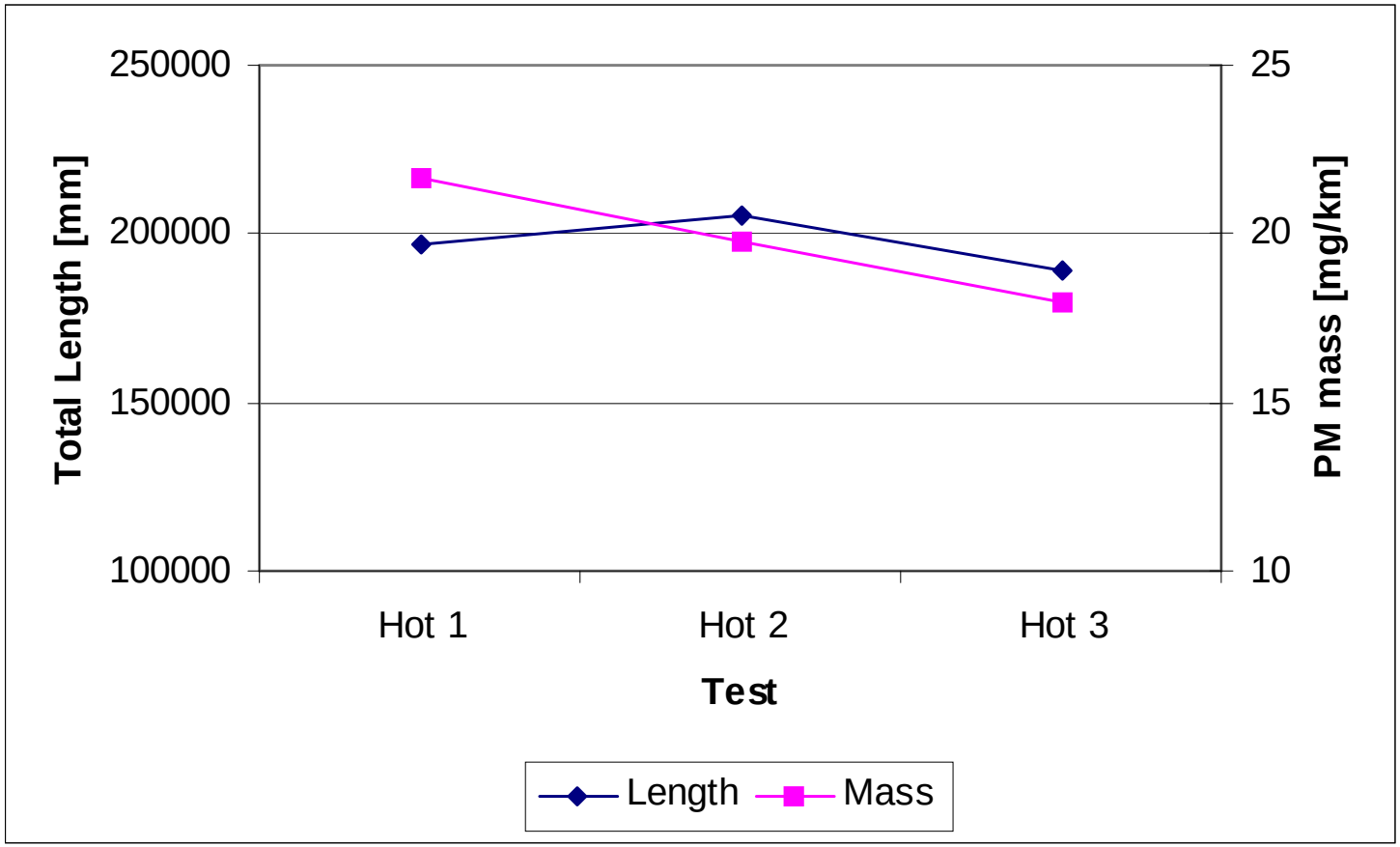

CE-CERT Trial Installation

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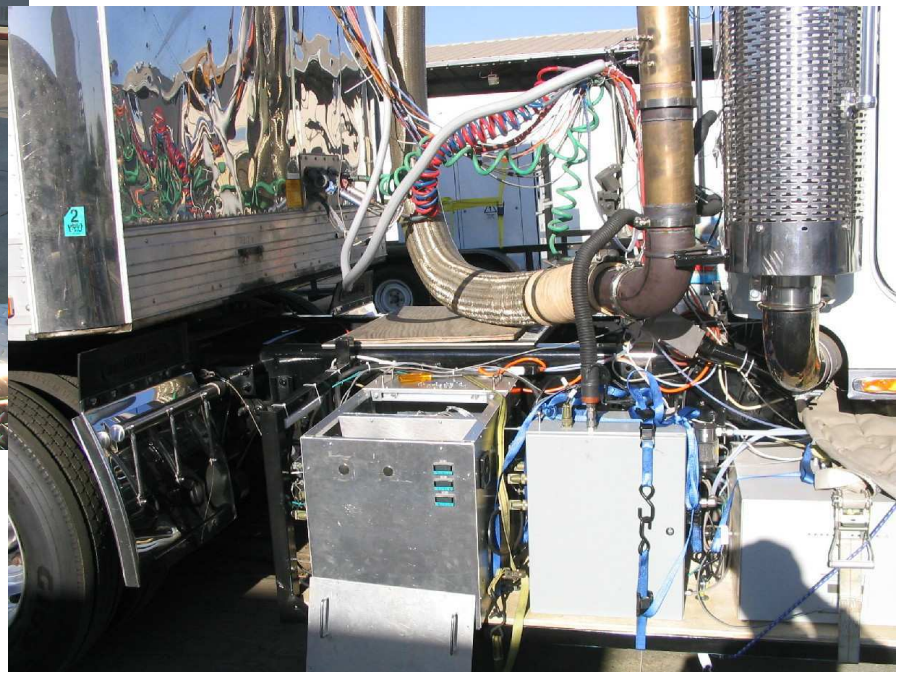

Current Status : EPA PM Mass Measurement Allowance Program

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- Three systems supplied to SWRI
  - Systems are undergoing preliminary evaluation
  - Auditing, calibration, simulation
  - Engine test phase to start in near future

- Additional systems
  - Under quotation to interested regulatory and technical authorities
  - Participation in the EU PEMS-PM program

Thank you

Any questions ?