Particle Sensor for Diesel Combustion Monitoring

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This program is supported under DOE Cooperative Agreement DE-FC04-02AL67636
Honeywell, prime contractor, University of Minnesota, subcontractor.

PM Sensor Program Philosophy

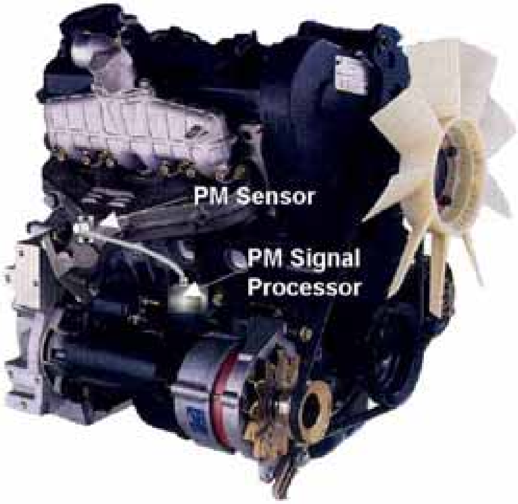
Goal: To develop a particulate matter sensor for use in diesel engine applications that is **low cost**, **robust** to harsh environments, and **manufacturable** in high volume.

Application: The sensor would be used for engine monitoring and control applications as opposed to highly accurate laboratory measurements.

Approach: IMAGE CHARGE Monitoring

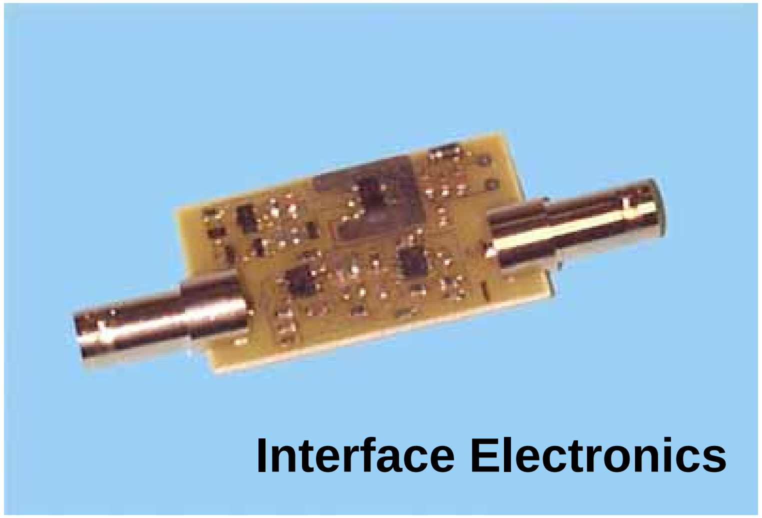
Teaming: DOE funded contract with Honeywell Laboratories in collaboration with the University of Minnesota Diesel Engines Laboratory.

	Instrument Grade PM Sensing System	PM Sensor
Use	Measurements of particle count and size distribution	Act as a control signal to an ECU
Accuracy	High	Low
Environmental	Lab use only	High Temp / High Vibration / Very Dirty Environment
Manufacturability	Low Volume	High Volume
Cost	Thousands of Dollars	Low Cost



Technical Approach and Rational

Probe



Interface Electronics

- <u>IMAGE CHARGE MONITORING</u> has been our primary focus for reasons of
  - expected probe (electrode) simplicity.
  - expected probe ruggedness.
  - electronics simplicity.
  - expected speed of response.
  - expected background effects.
- It has demonstrated a very good response
  - well defined signals.
  - very fast response.
  - reproducible (much more so than the engine itself).
  - applicable across multiple engine sizes and types.
- The probe has demonstrated very good life in harsh, high temperature, particulate-filled environments.

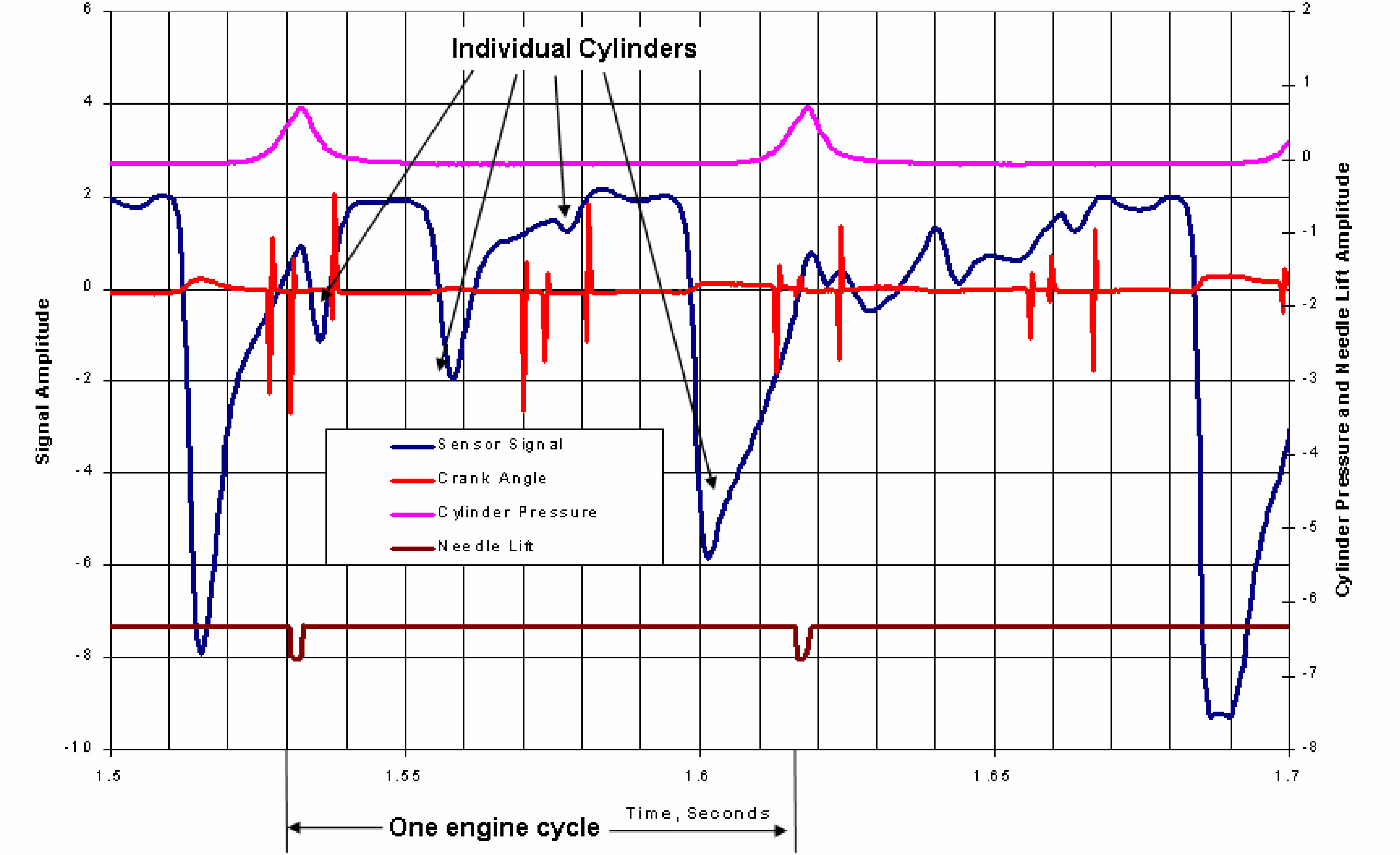
Basic sensor response characteristics

- We see large signal pulses from each cylinder
- Large cycle to cycle and cylinder to cylinder differences
  - Are they related to actual particle concentrations?
  - Correlation with fast optical scattering

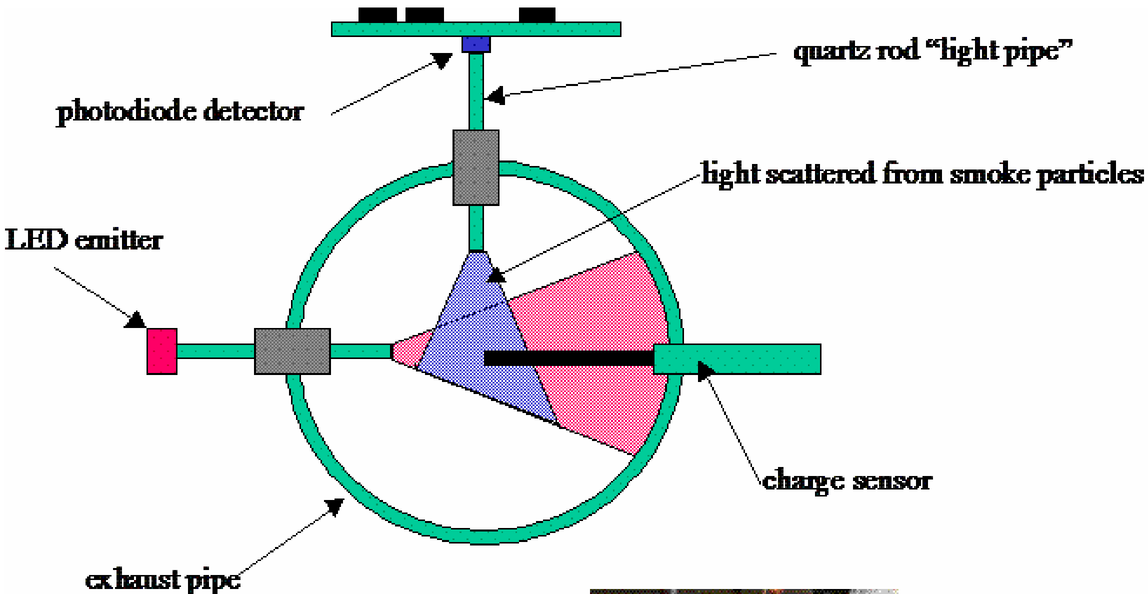
Sensor resolves soot pulses from each cylinder

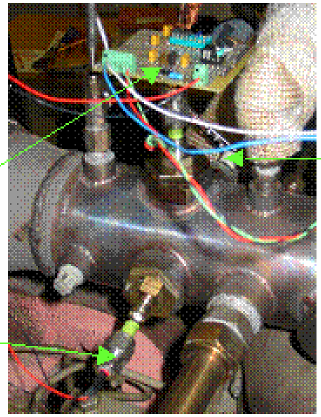
Older Deere 4045T engine, rotary pump, cylinder to cylinder, cycle to cycle differences.

Are these signals soot related or a measurement artifact?



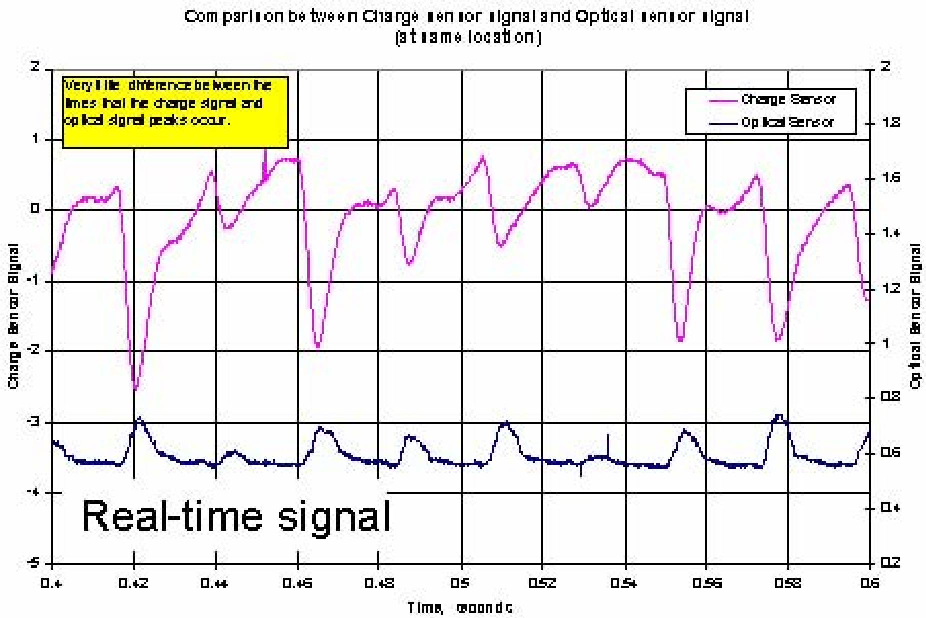
Correlation to Optical Scattering

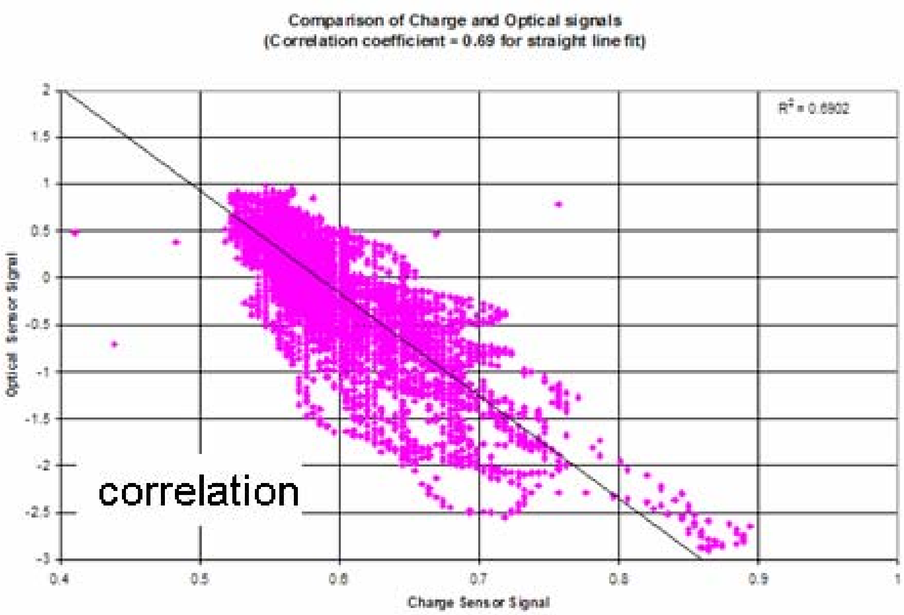




- The sensor detects pulses from each exhaust stroke – an optical system was built to see if they were particle related.
- A rapid optical scattering device was fabricated to relate instantaneous particle concentration to our sensor signal.
- Source and receiver electronics and mechanics were designed and fabricated in Honeywell Labs.
  - Source and receiver were mounted orthogonal to one another with the scattering volume centered on the pipe.
  - The sensor probe was placed directly in the scattering volume.
  - Quartz rods were used as light pipes to bring the light into and out of the exhaust.
  - The rods also acted as thermal isolations between the hot exhaust pipe and the emitter and detector electronics.

Correlation to Optical Scattering





- No attempts we made to keep the rods clean over the duration of the tests.
  - Approximately 10 seconds of data could be collected before fouling of the optical windows caused a significant baseline shift in the optical signal.

- The optical signal shows a very strong correlation to the charge-based particulate signal, with a correlation $R^2 = 0.6902$.

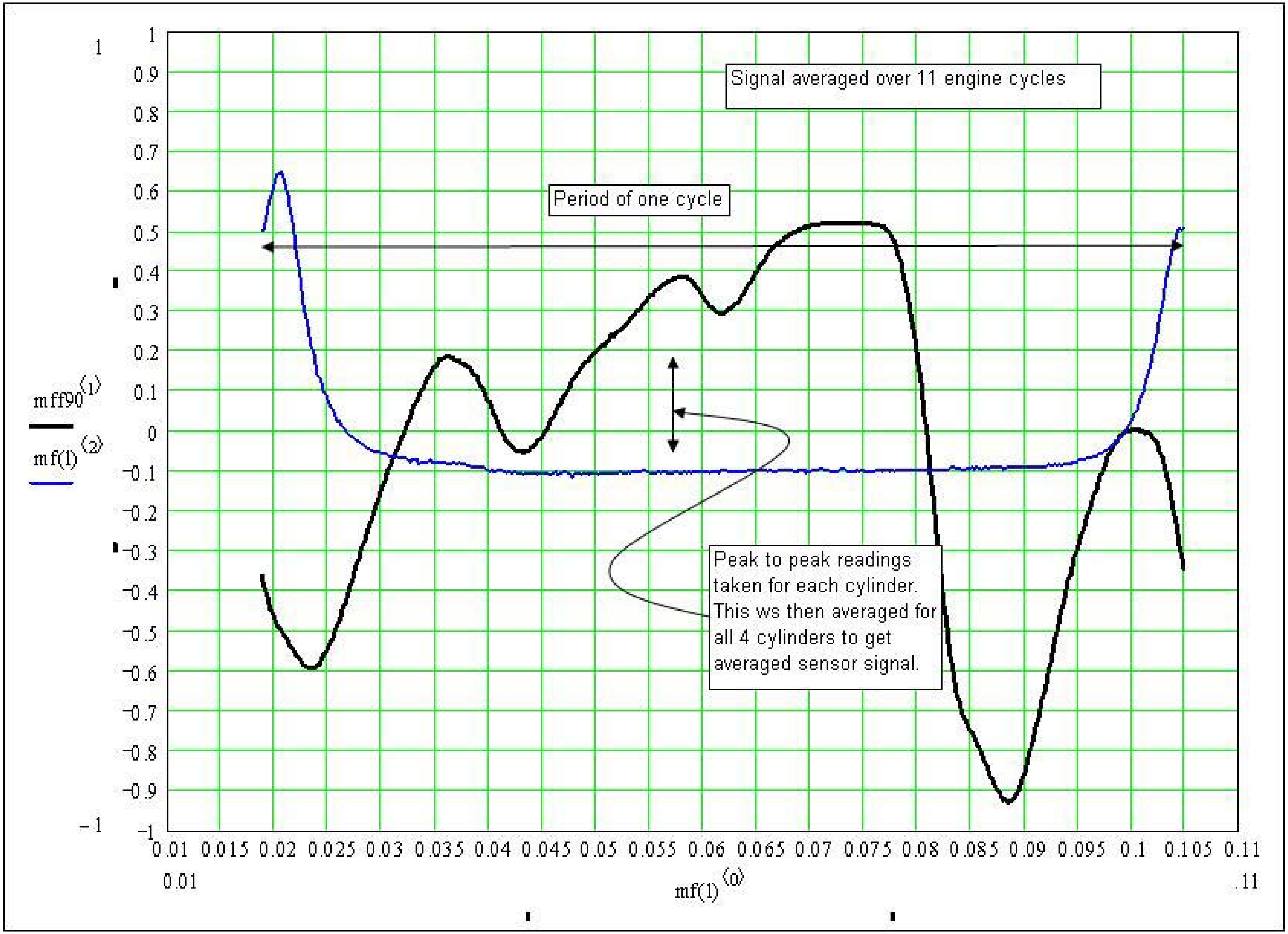
- Similar experiments correlating the charge-based particulate sensor to a Kistler piezoelectric pressure sensor placed in the same location showed *no discernable correlation*.

Data was taken on a John Deere 4045T Engine at 1400 rpm and 90% load.

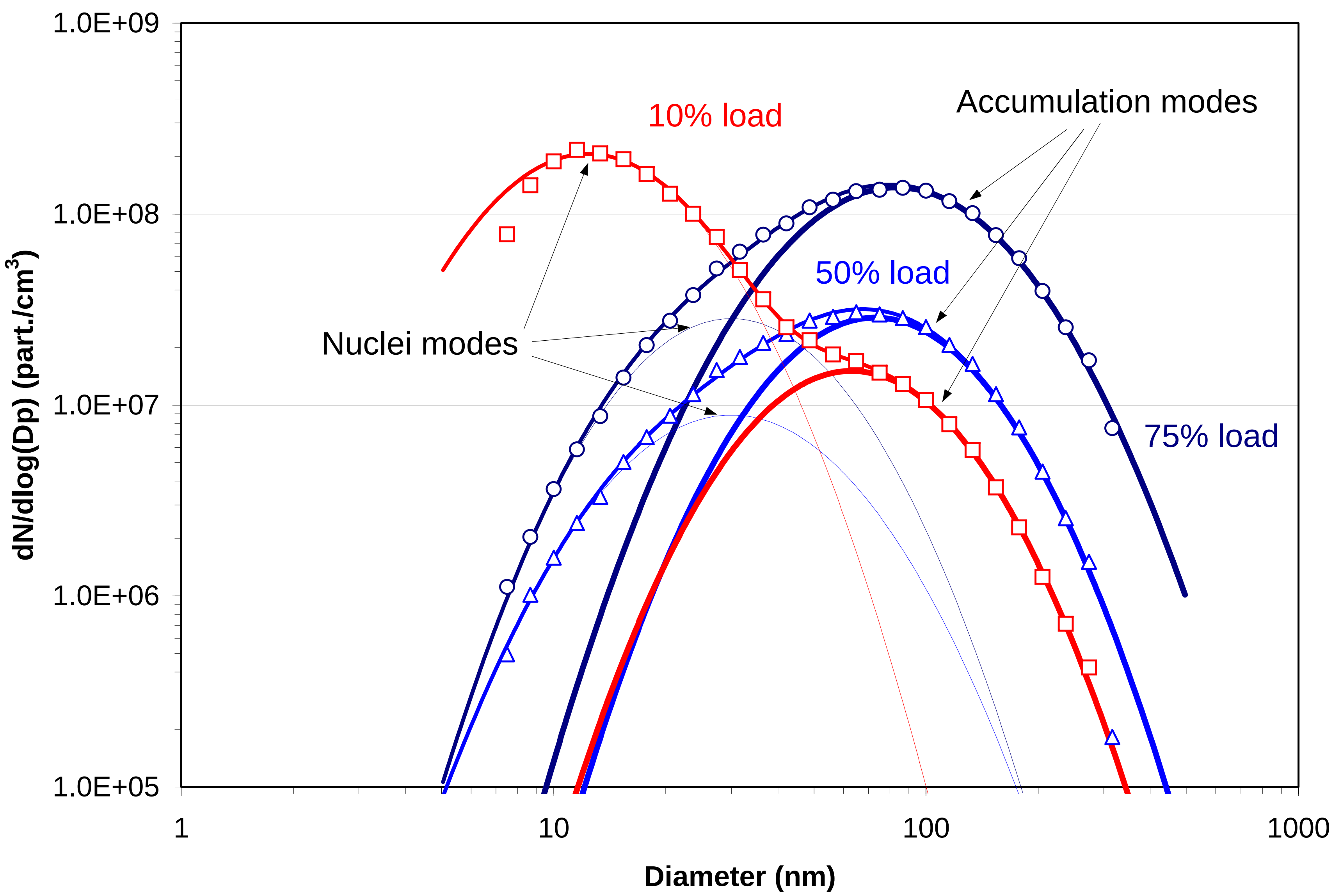
Relating sensor response to other instruments

- **Signal processing**
- **Response to accumulation mode or soot mode**
- **Soot mode and aethalometer response – black carbon**
- **Sensor response vs. black carbon**
- **Transient sensor and black carbon response**

Processed sensor signal uses peak to peak averages

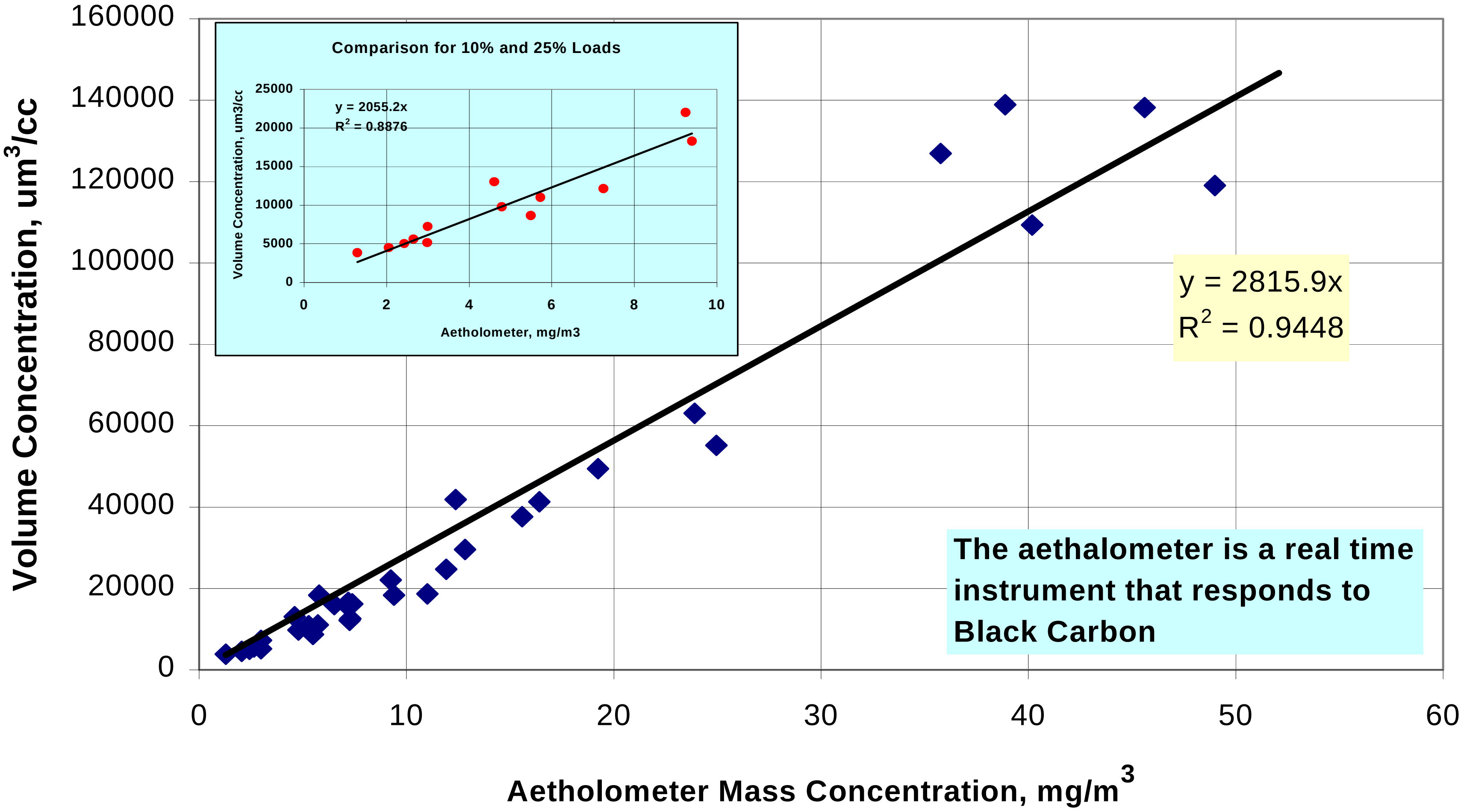


Typical size distributions – the sensor responds to the accumulation (or soot) mode



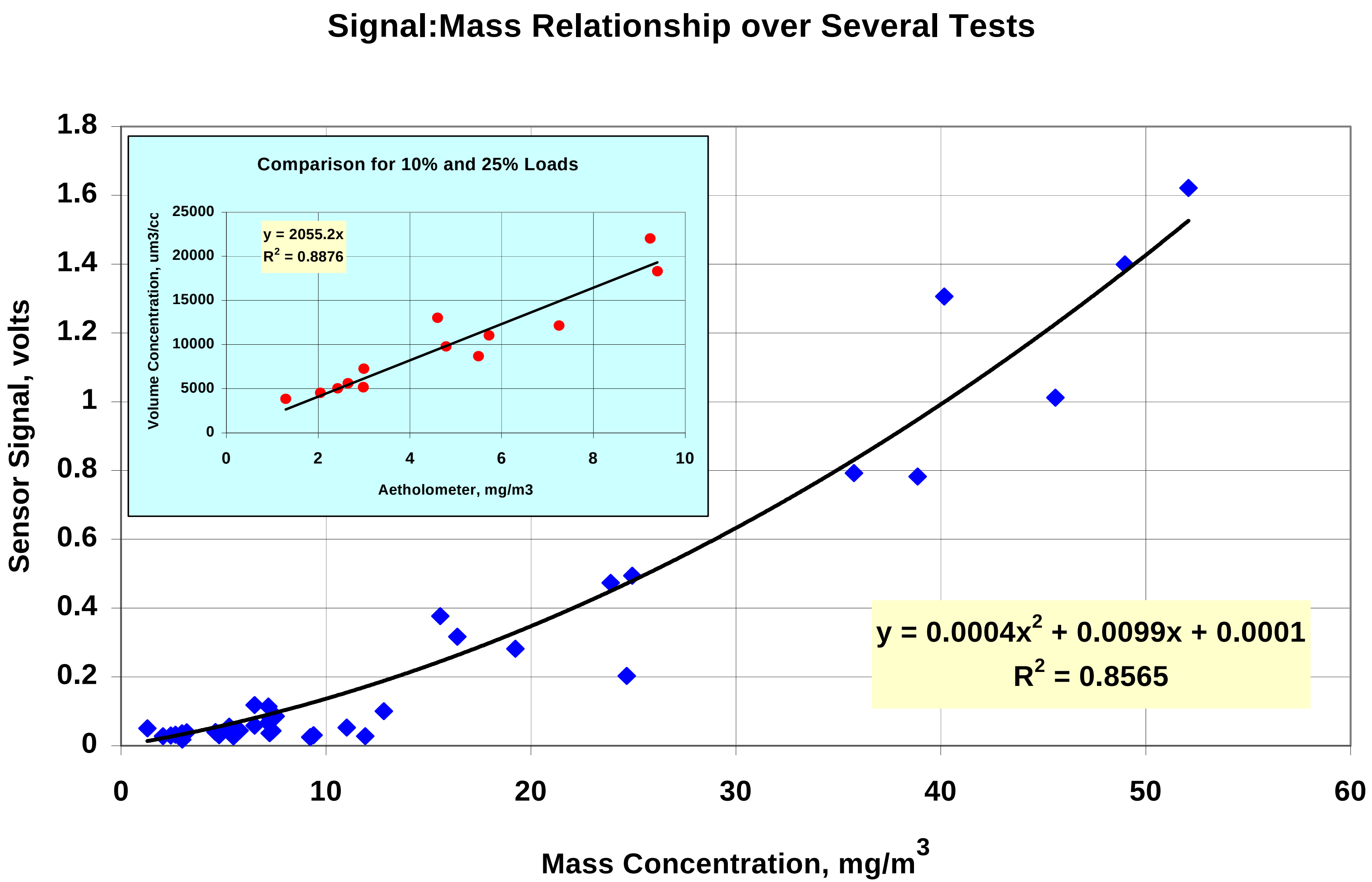
For most tests a fast response aethalometer was used instead of the SMPS

Aethalometer signal is strongly correlated to accumulation mode volume

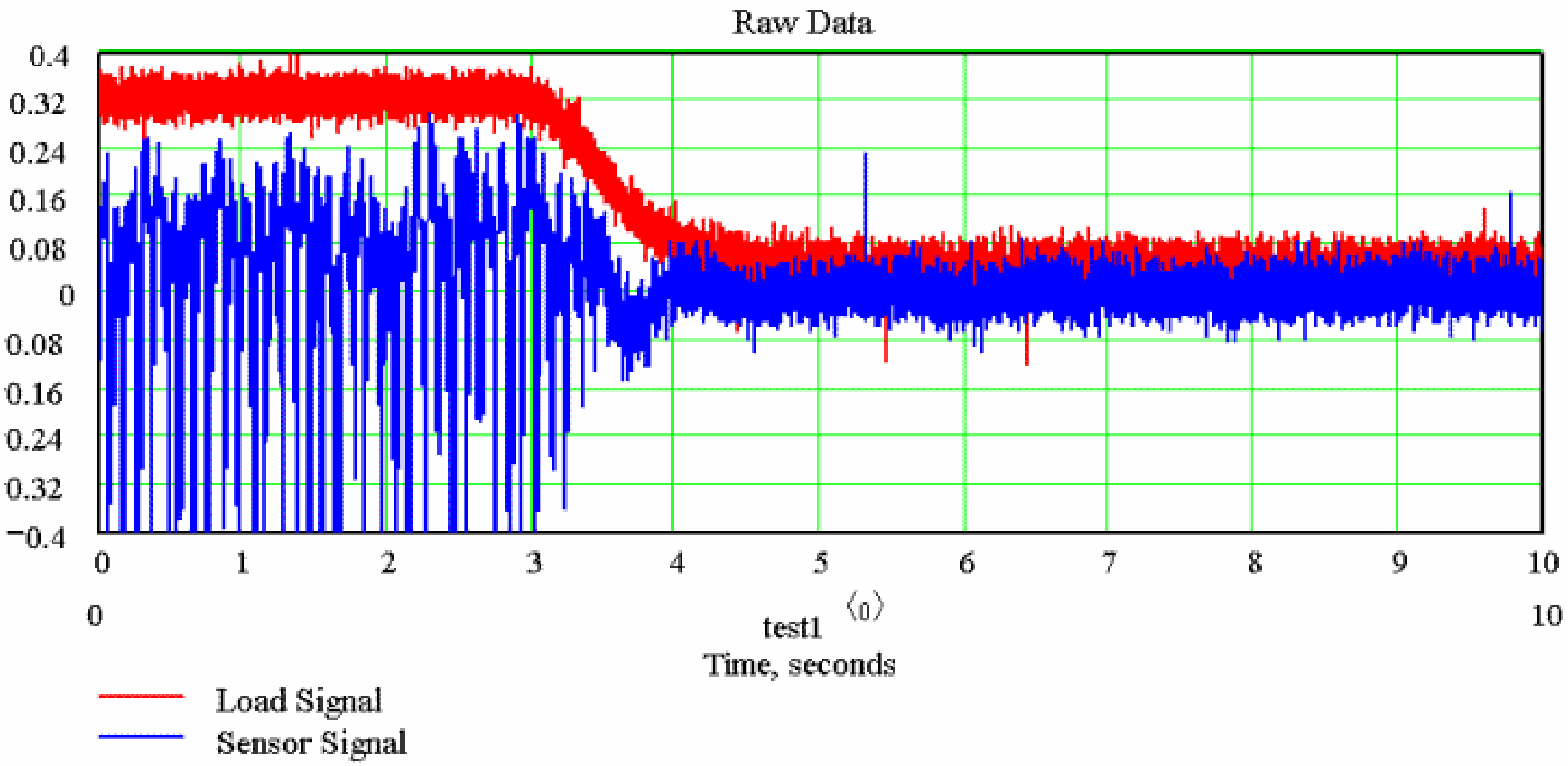


The aethalometer is a real time instrument that responds to Black Carbon

Sensor signal strongly correlated with aethalometer (black carbon) mass

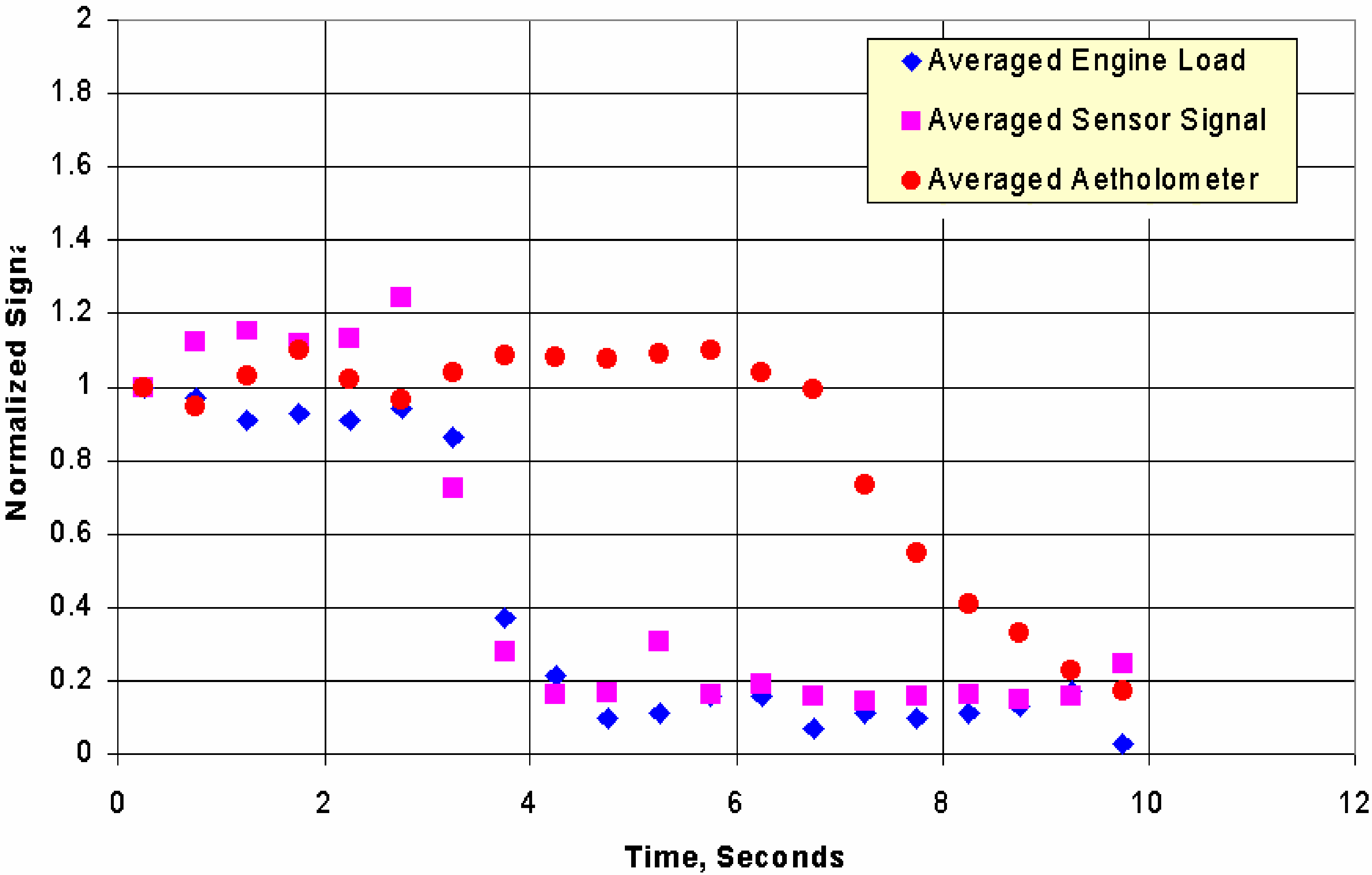


Raw sensor response to step change in load



Sensor and aethalometer response to step change in load – and soot emissions

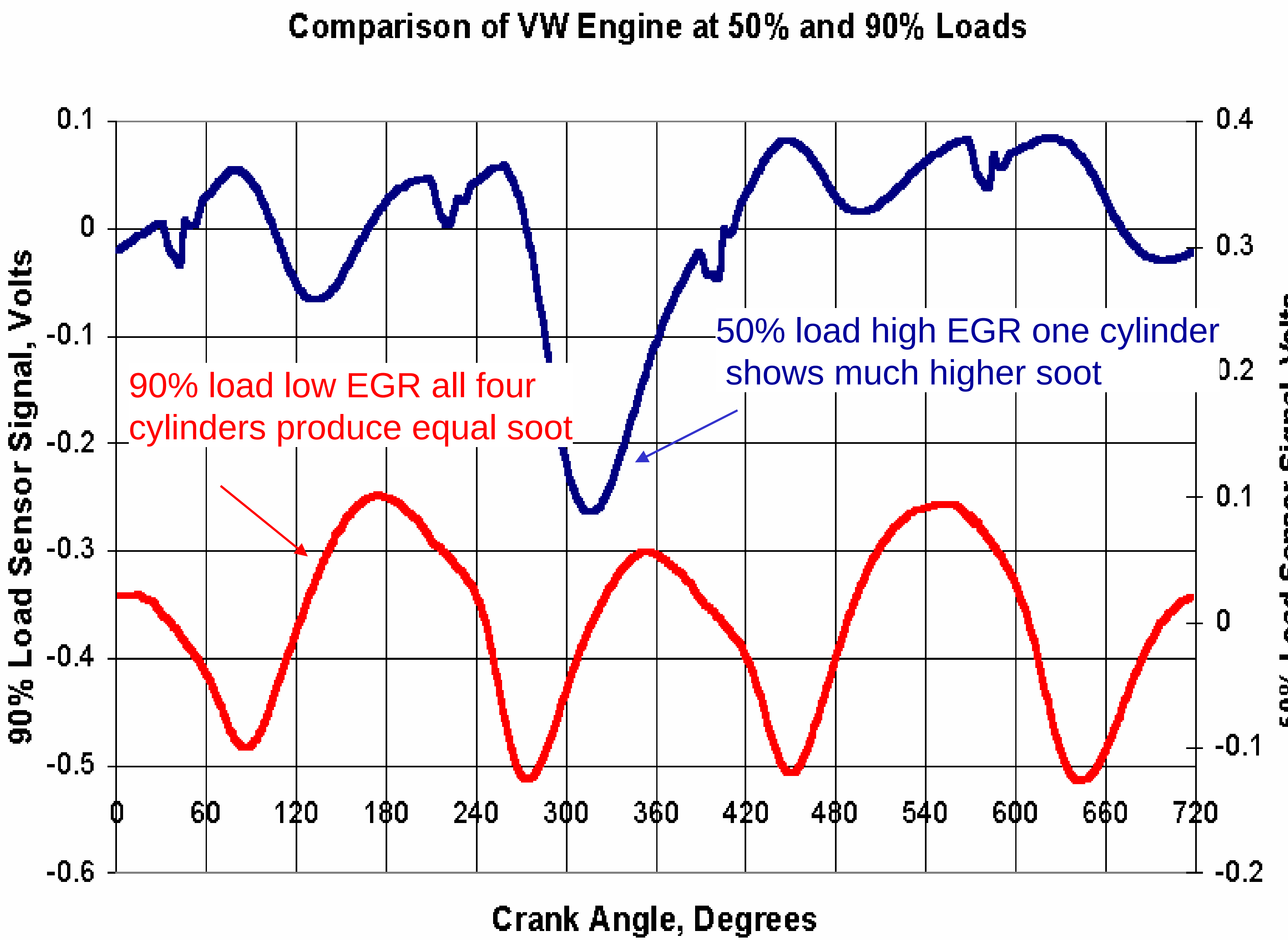
Sensor signal drops nearly instantaneously as load drops – aethalometer lags behind but eventually tracks sensor



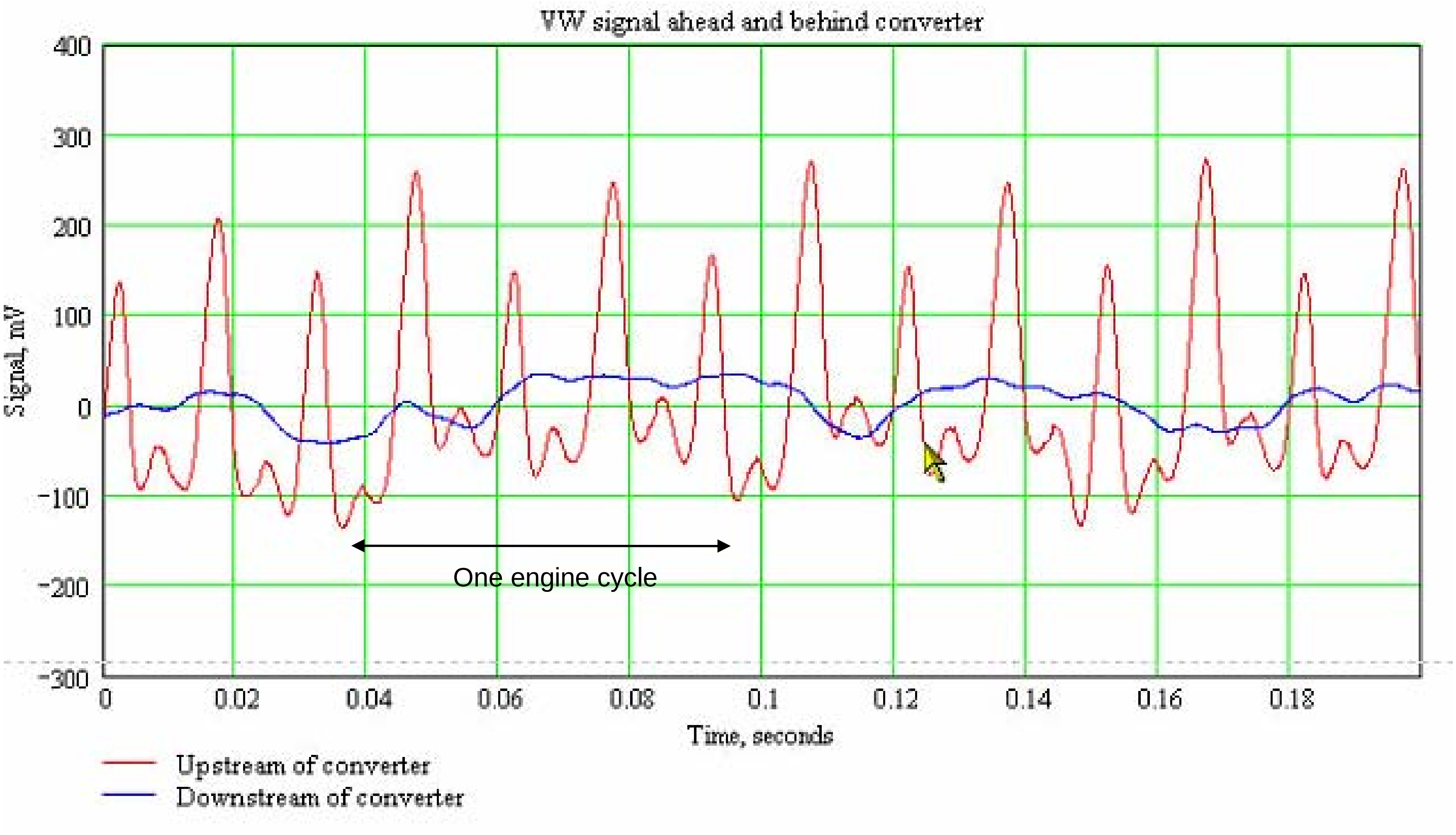
Response to modern engines

- **Euro IV VW TDI – Influence of load (EGR) on cylinder to cylinder soot differences**
- **Euro IV VW TDI – Sensor response up and downstream of catalytic converter**
- **Caterpillar C12 – Sensor response upstream and downstream of CRT**

Sensor shows poor cylinder to cylinder distribution due to (EGR) – Euro IV VW TDI



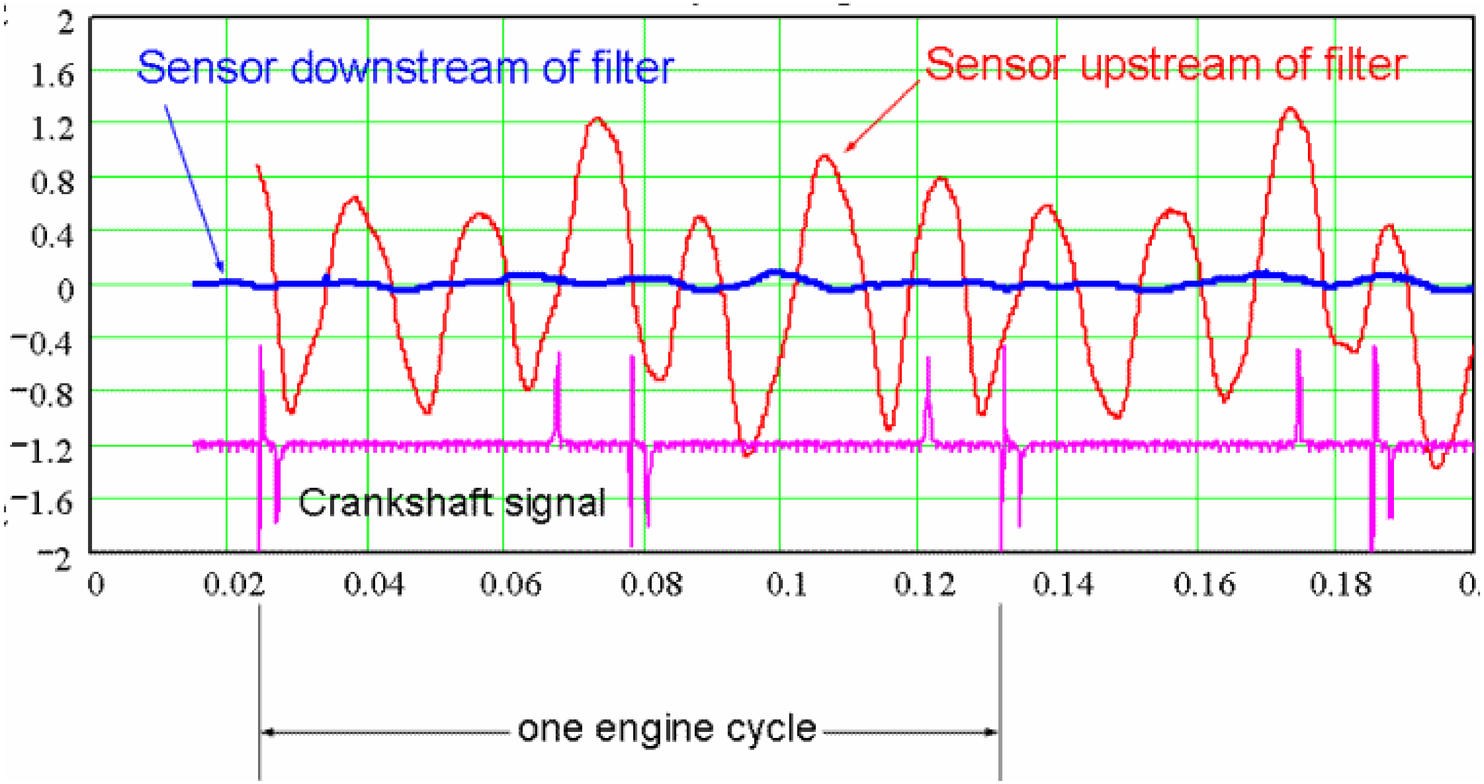
Sensor response upstream and downstream of catalyst



VW TDI Euro IV Engine

Sensor response upstream and downstream of CRT

Upstream of filter all 6 individual cylinder soot pulses are seen - downstream they are essentially eliminated



Caterpillar C12 engine

Conclusions

- **A low cost Diesel particle sensor has been developed**
- **Its response is strongly correlated to instantaneous black carbon (BC) mass concentration in the exhaust**
- **Its response time is adequate to detect BC from individual cylinders**
  - **The sensor can detect imbalanced injection**
  - **It can also detect EGR maldistribution**
- **Using a very simple signal processing approach its sensitivity is better than 1 mg m^{-3}**
  - **This is more than sufficient to monitor engine out emissions from modern low emission engines like a Cat C12 and a Euro IV VW TDI**
  - **No signal is detected downstream of a CRT on a Cat C12**
- **Sensors have been operated for several hundred hours with little signal loss**