Real-time hardware and virtual soot sensors for on-board measurements of diesel particles

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ABSTRACT

As diesel emission regulations become increasingly stringent the use of Diesel Particulate Filters (DPFs) has become unavoidable. DPFs exhibit very high filtration efficiencies, however they need to be periodically or continuously cleaned (regenerated) in order to achieve efficient and safe operation of the vehicle. The regeneration method selected for each application has to take into account the current state of the filter and the engine operating conditions. This fact introduces the need for on-board diagnostics for diesel emission control systems, in order to arrive at an optimized emission reduction system. A very attractive concept is that of a real-time on-board soot sensor. Knowledge of the amount of soot load in the filter is an important prerequisite for the intelligent management and control of the emission reduction system.

The present work involves the development of a prototype, real-time on-board soot sensor and its experimental cross-assessment against an array of particulate measuring methods based on gravimetric, electrical mobility, aerodynamic, diffusion charging, photoelectric ionization and optical extinction techniques. In addition, the concept of a virtual soot sensor is developed and validated with experimental data. Practical use of the hardware and virtual soot sensors is demonstrated under steady state and transient conditions in the exhaust of a modern light-duty diesel engine.

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INTRODUCTION

The state of filter soot loading is an important parameter and must be known for reliable and effective control of regeneration. Therefore, capitalizing on our recent research on soot deposit microstructure and flow resistance properties we have developed on-board hardware and virtual soot sensors for engine and filter management and control.

CONCLUSIONS

On-board hardware soot sensors were developed exploiting contactless and contact based principles. The contact based soot sensor was shown to provide good correlation to gravimetric measurements under steady state conditions and to a multitude of real-time laboratory scale particle instruments. A virtual sensor based on continuous measurements of the filter pressure drop as well as the mass flow rate and the temperature of the exhaust was developed that could predict accurately the soot mass load of diesel particulate filters when compared to experimental data collected during steady state and transient operation. The developed sensors can be implemented for the on-board control of the timing and frequency of filter regeneration, thus ensuring safe and fuel efficient operation of the vehicle.

SLIDE PRESENTATION

Real-Time Hardware and Virtual Soot Sensors for On-Board Measurements of Diesel Particles

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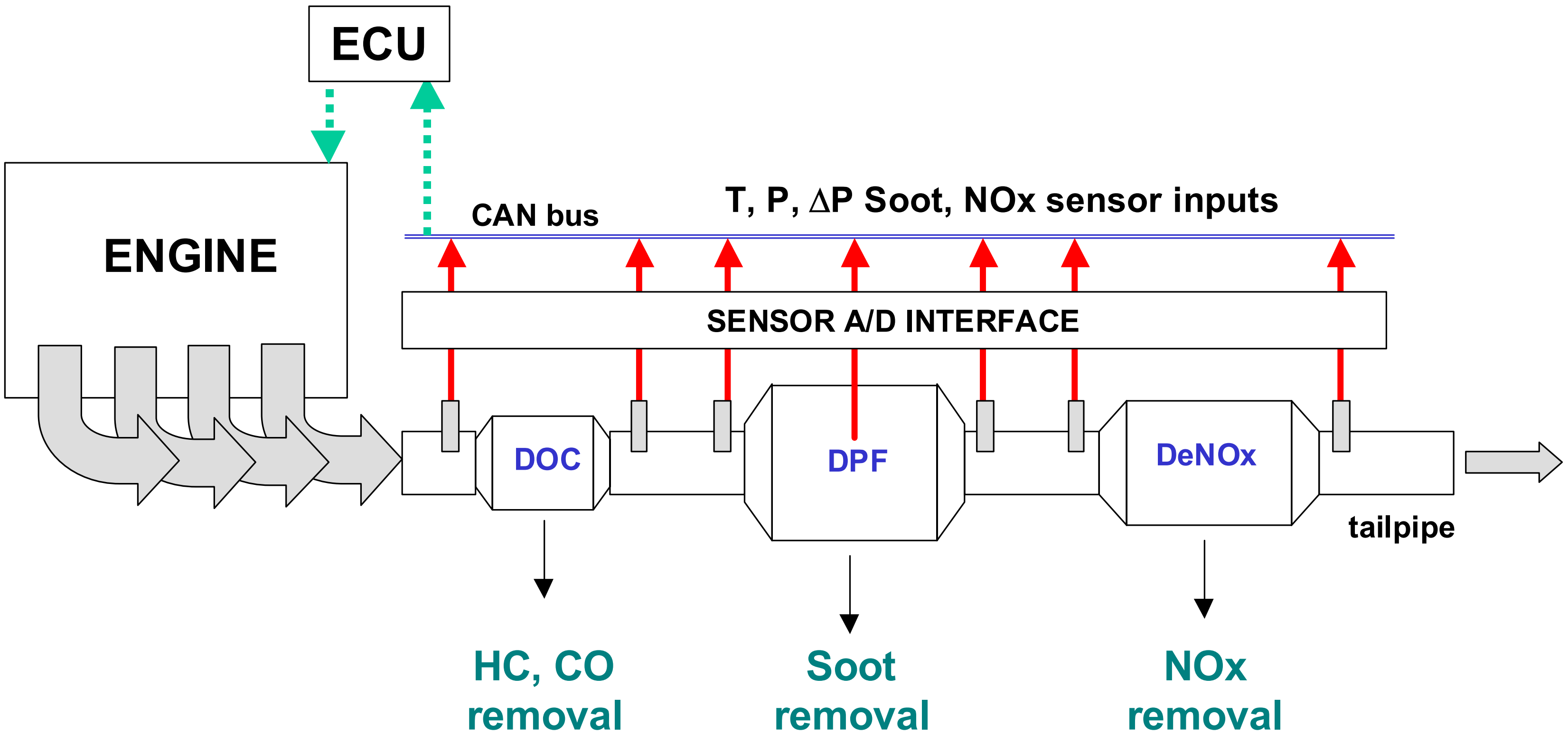
OUTLINE

- Motivation
- Introduction
- Hardware sensors
- Virtual sensor
- Conclusions

MOTIVATION

Future emission control systems:

Assemblies of reactors, hardware and virtual sensors



Konstandopoulos et al 2001

INTRODUCTION

- State of filter soot loading must be known for reliable and effective control of regeneration
- Capitalize on our recent research on soot deposit microstructure and flow resistance properties
- Develop on-board hardware and virtual soot sensors for engine and filter management and control

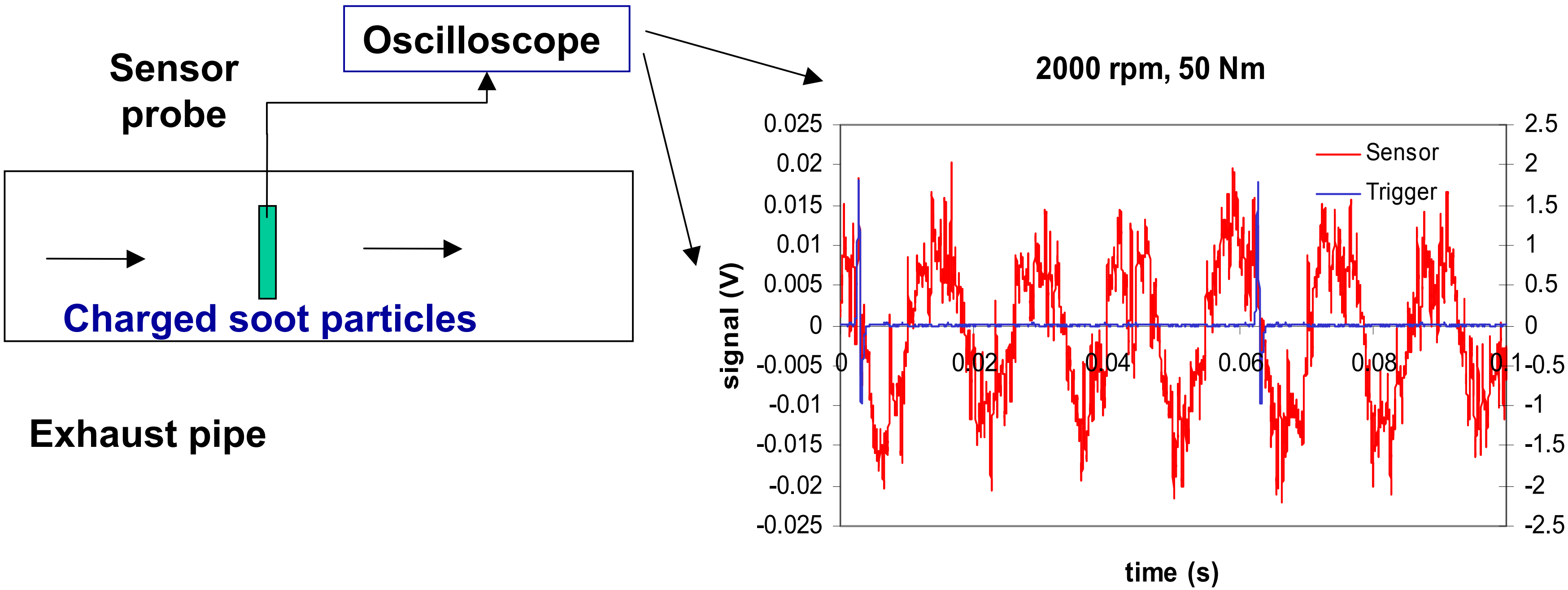
ON-BOARD SOOT SENSING PRINCIPLES

- **Contactless** methods (sensing of a suitable metric of the particles in suspension)

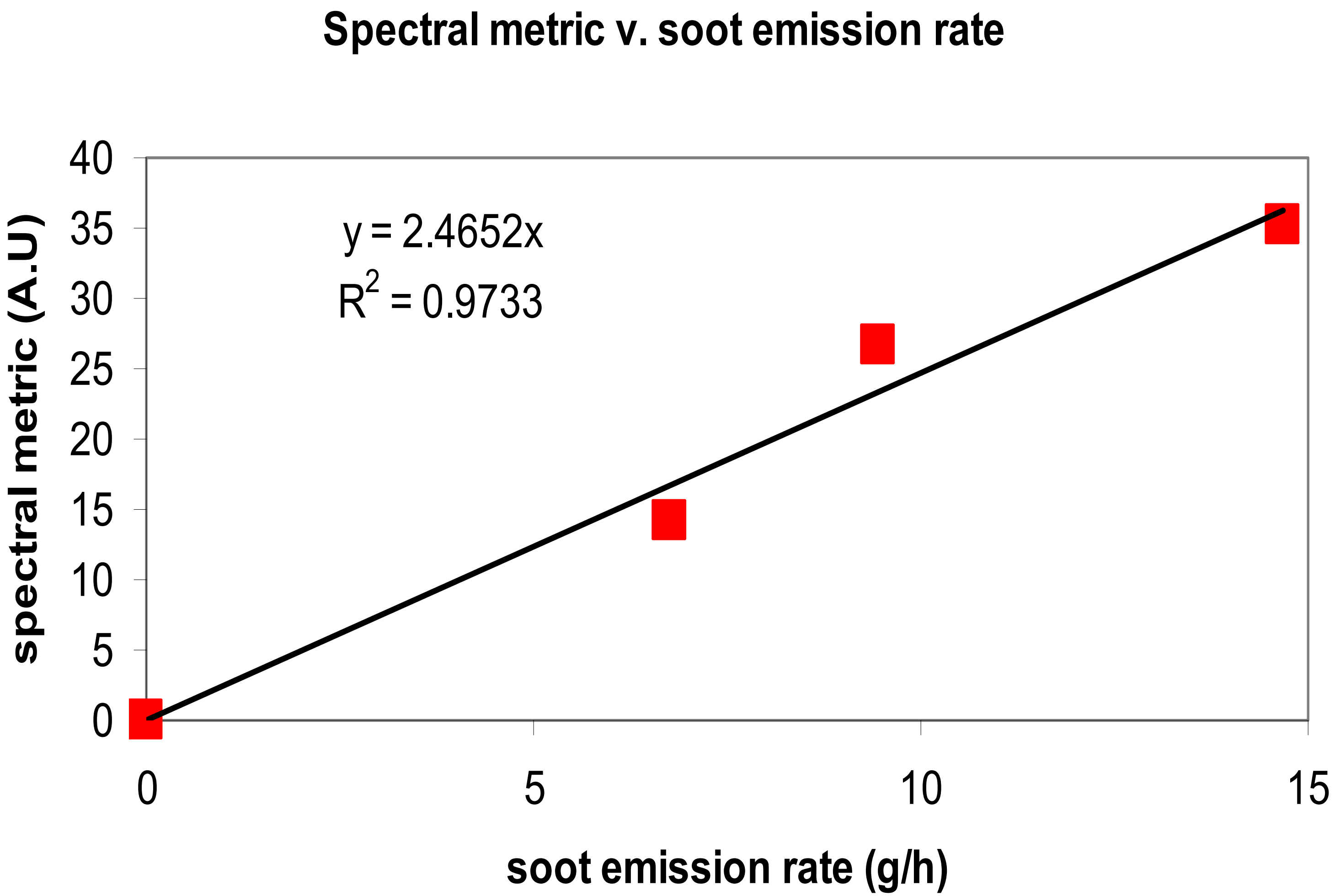
- **Contact-based** methods (sensing of a suitable metric of particles after their collection)

CONTACTLESS SENSOR

Responds to the charge on soot particles emitted from diesel engines

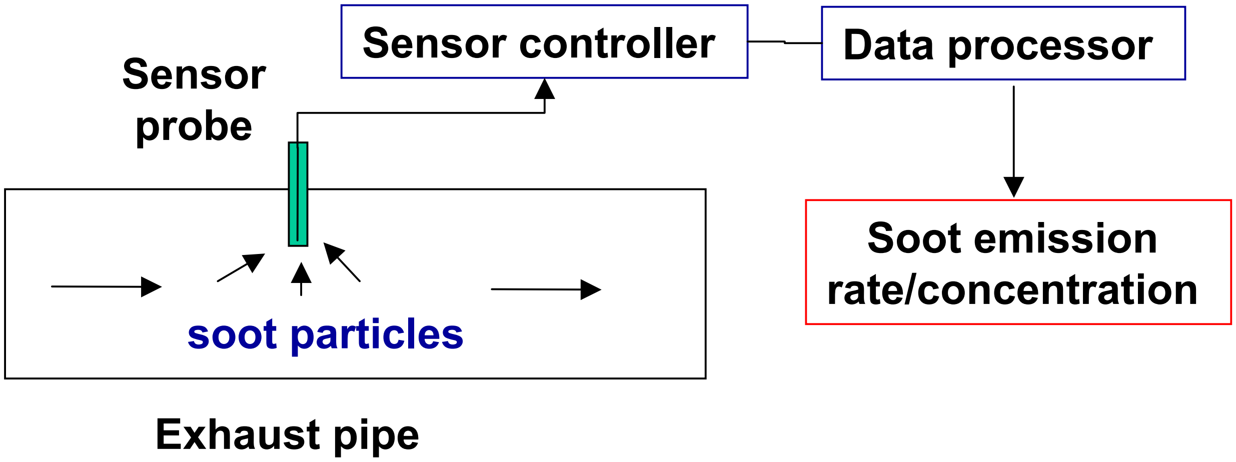


CONTACTLESS SENSOR
Signal Analysis



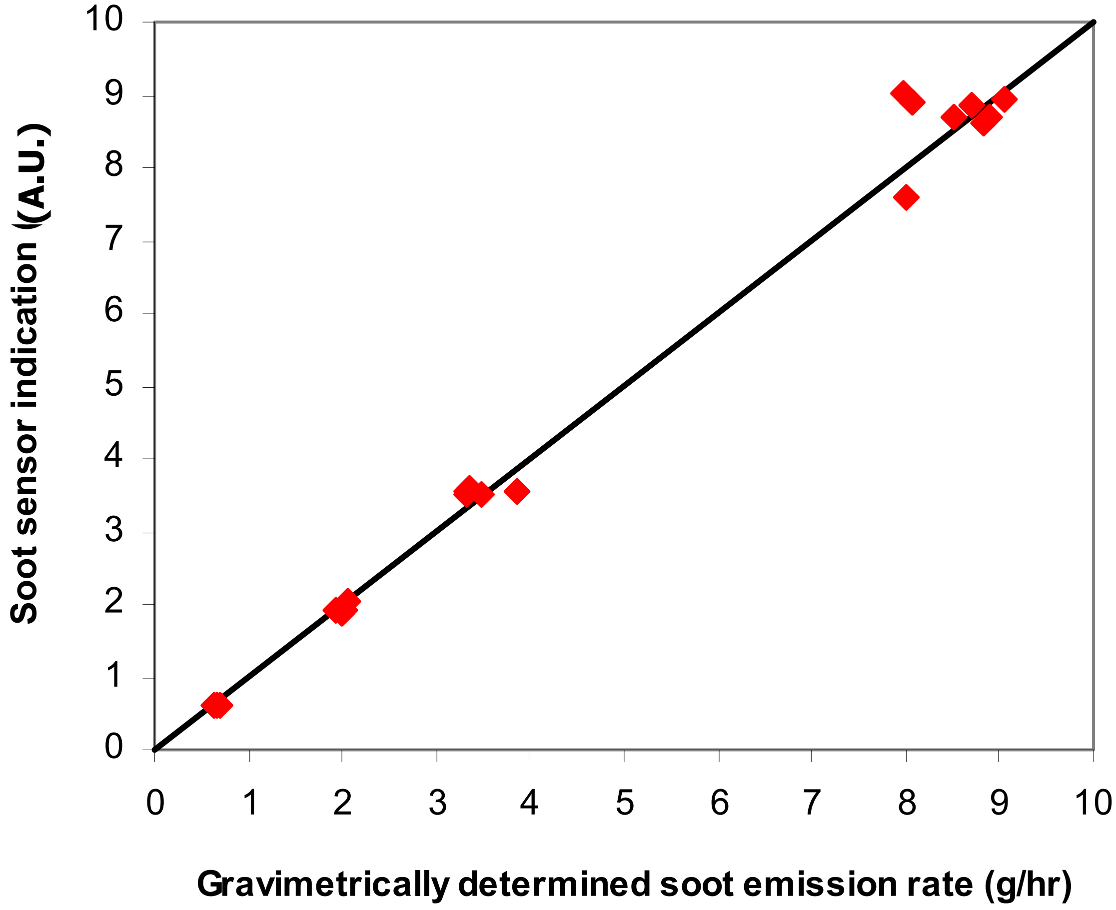
Konstandopoulos et al (2001)

CONTACT BASED SOOT SENSOR



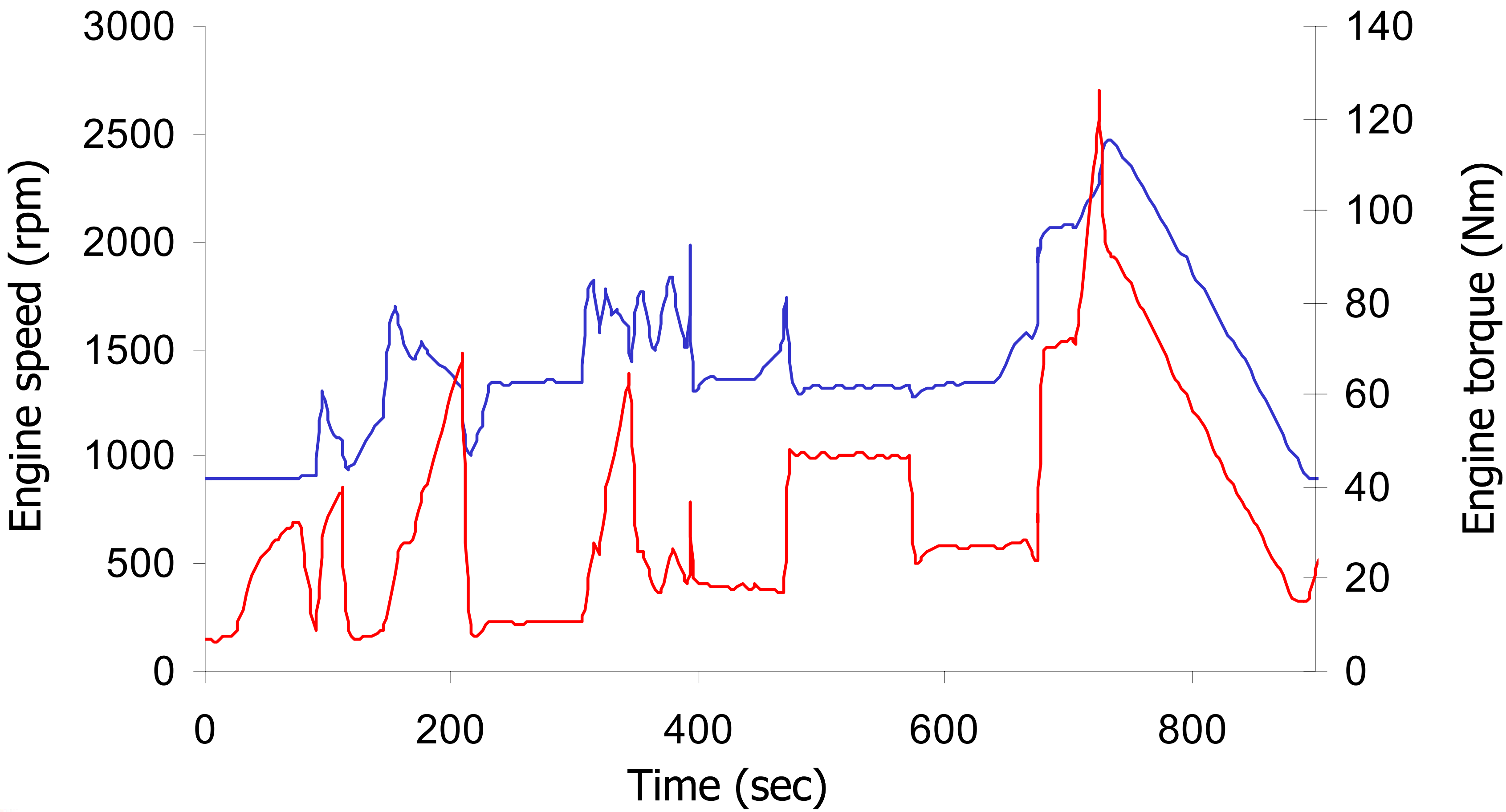
- Sensing of soot particles collected on an element exposed to the exhaust flow
- Incorporates heater for burning of collected particles
- On-board signal processing provides a signal proportional to the soot particle emission rate and concentration

STEADY STATE SENSOR CALIBRATION

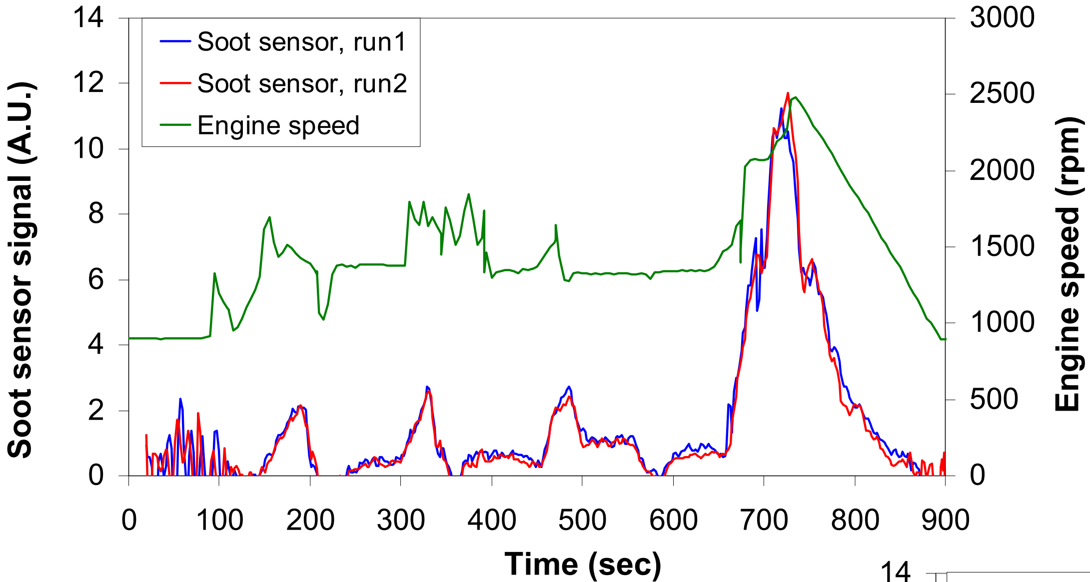


APT TRANSIENT CYCLE

A transient cycle simulating the NEDC accelerations/decelerations on the engine bench has been developed and is referred to as APT transient cycle

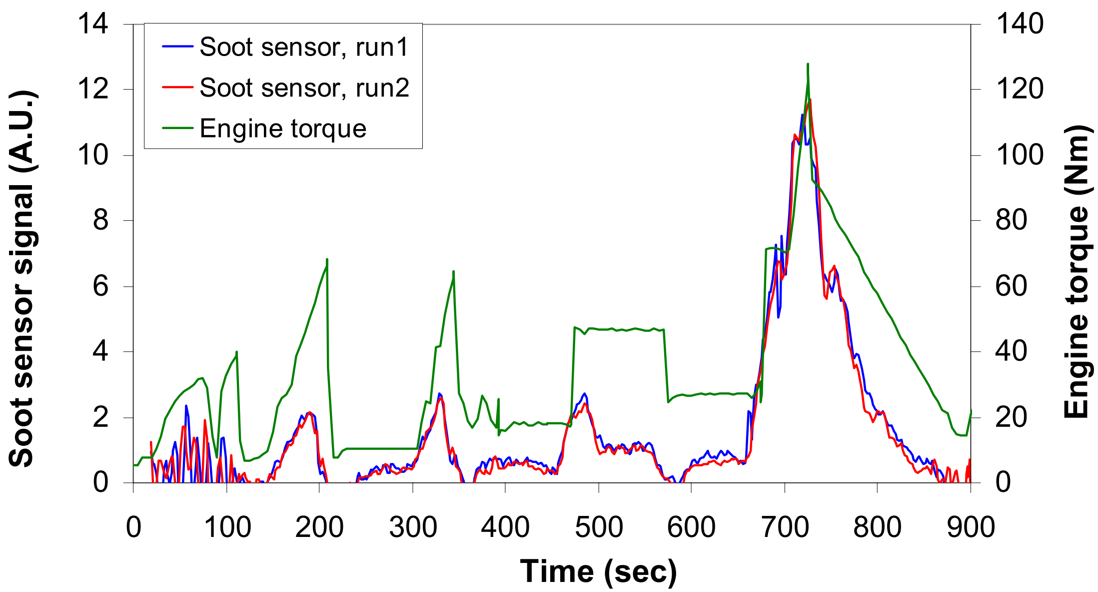


SENSOR TRANSIENT RESPONSE



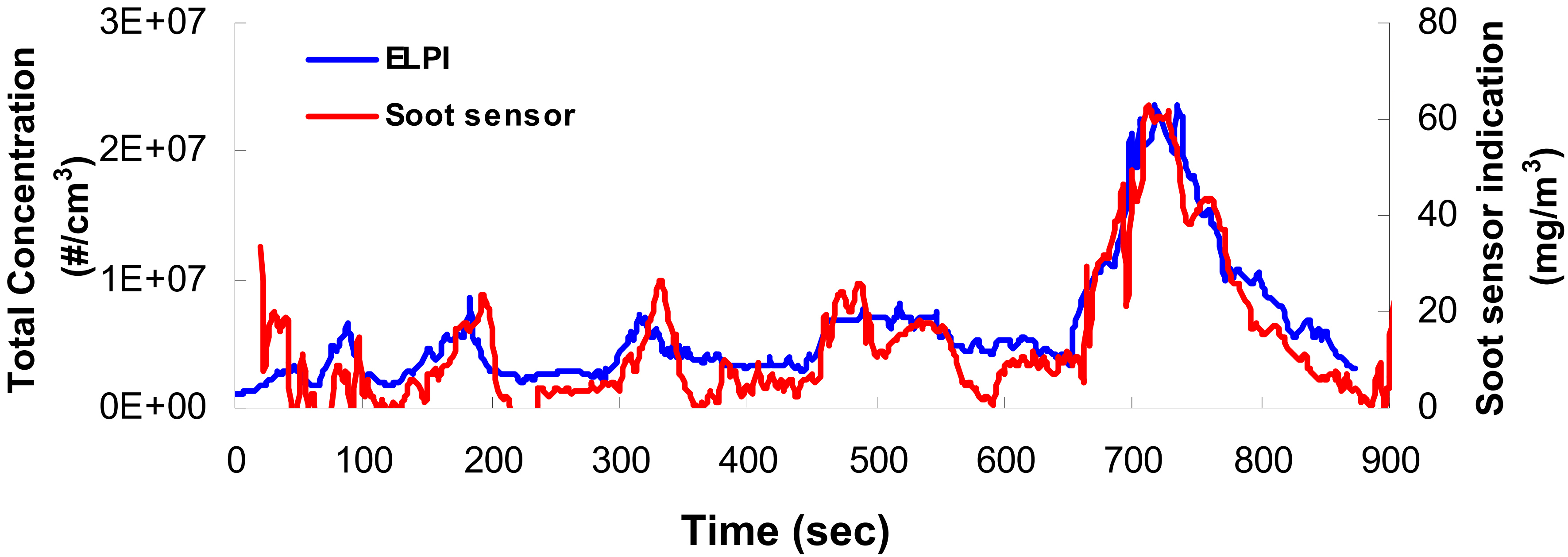
Sensor responds in synchronization with speed and torque changes over engine transient cycle

Cumulative error of integrated sensor signal over the cycle against gravimetric measurement of soot emission over the cycle is 3%



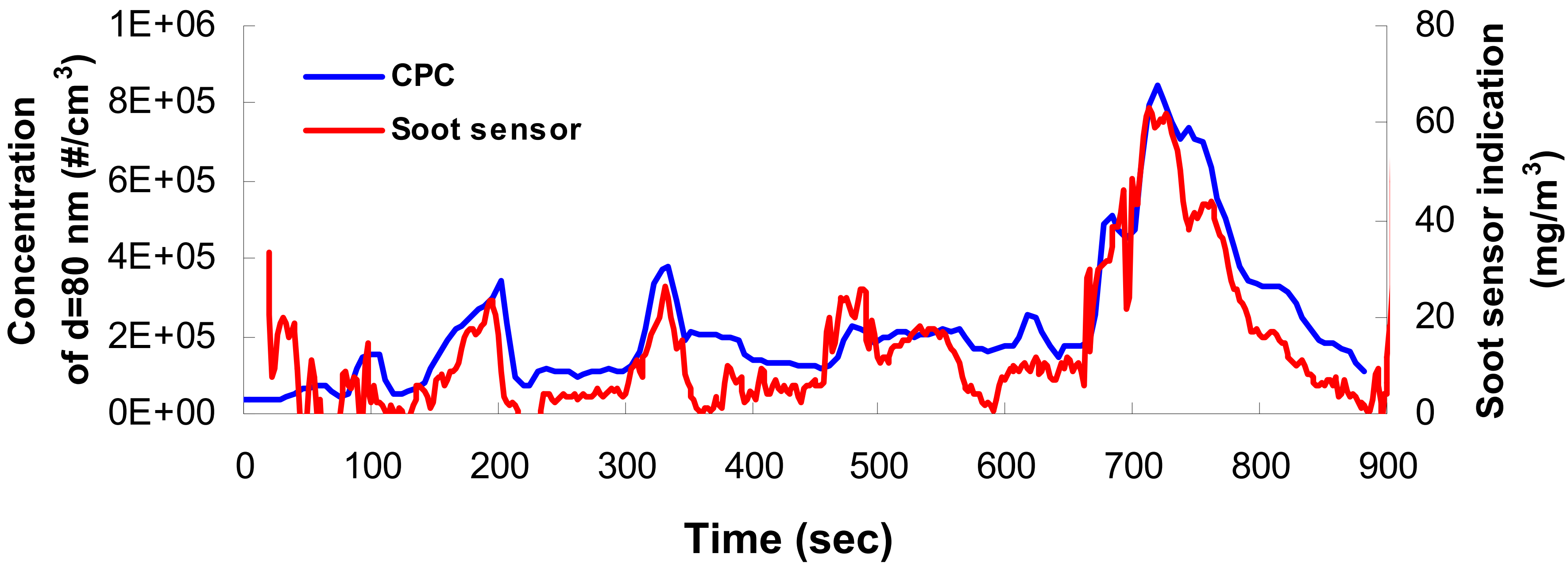
SENSOR TRANSIENT COMPARISONS-1

Sensor vs. Electric Low Pressure Impactor (ELPI)



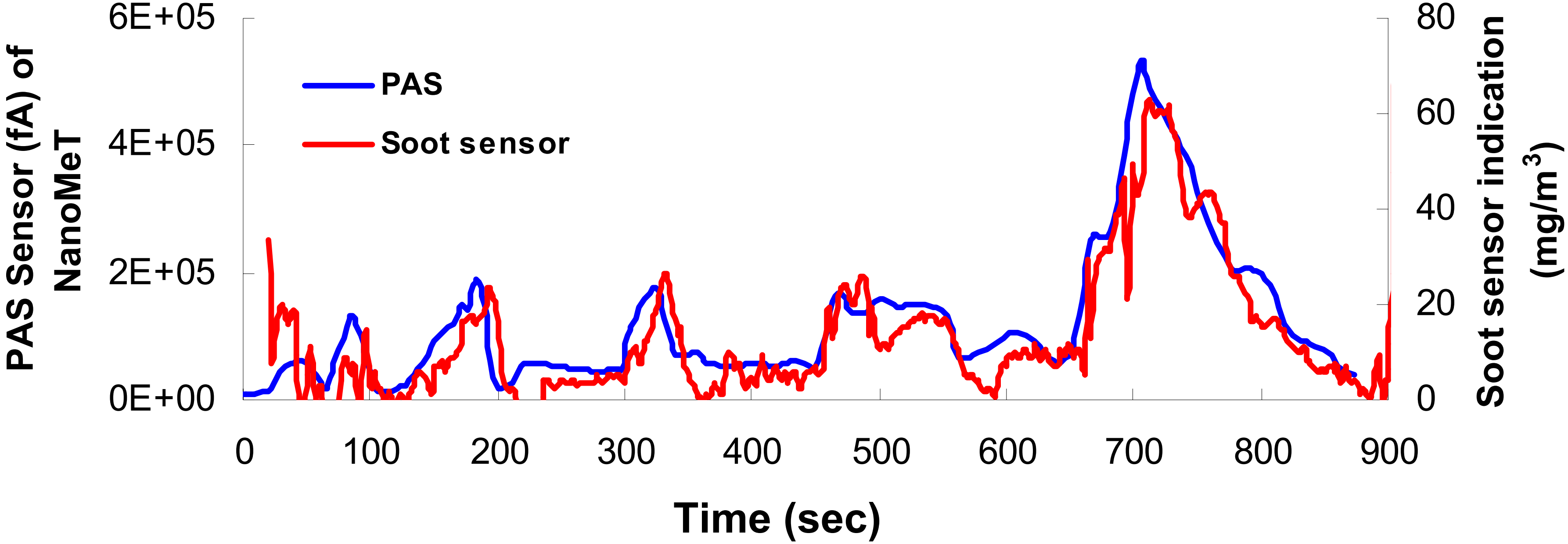
SENSOR TRANSIENT COMPARISONS-2

Sensor vs. Condensation Particle Counter (CPC)



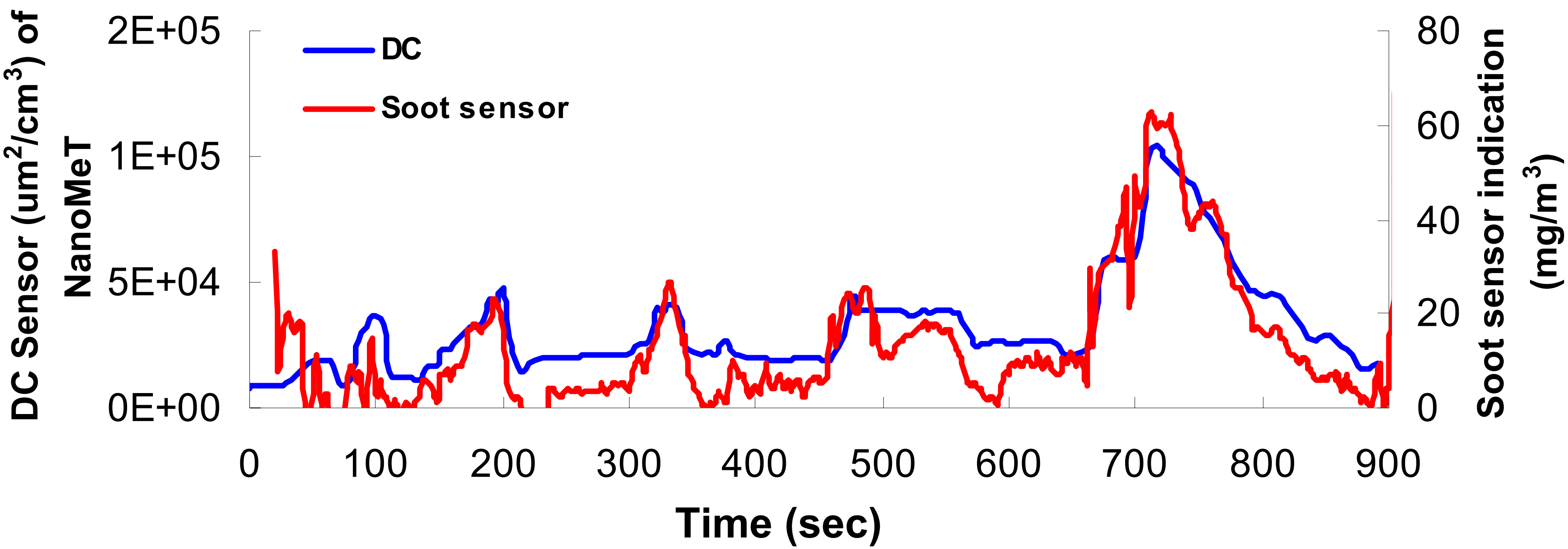
SENSOR TRANSIENT COMPARISONS-3

Sensor vs. Photoelectric Aerosol Sensor (PAS)



SENSOR TRANSIENT COMPARISONS-4

Sensor vs. Diffusion Charger (DC)

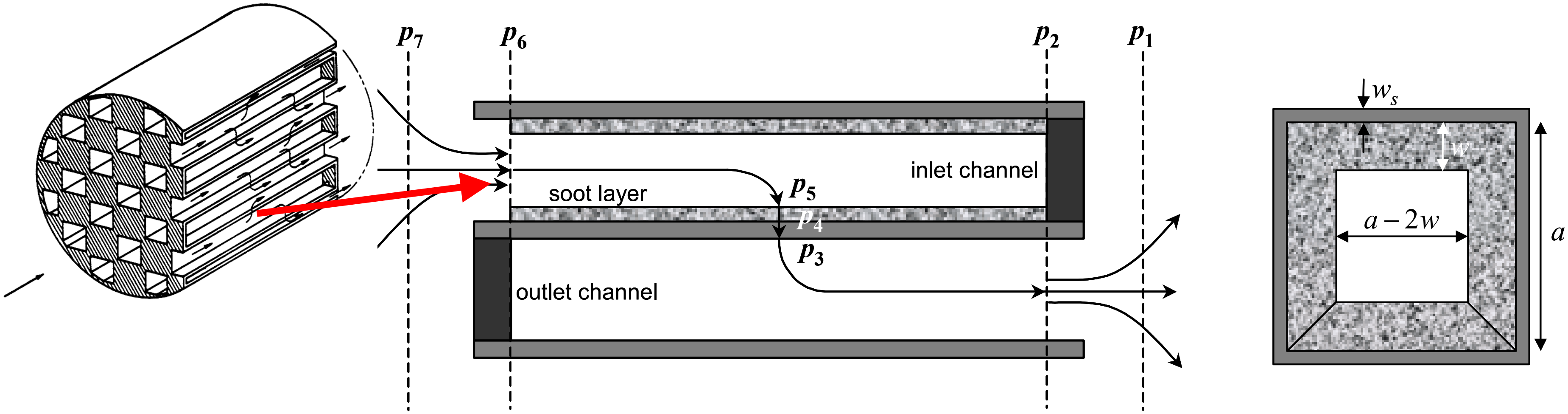


VIRTUAL SENSOR DEVELOPMENT

BACKGROUND PAPERS

- **Konstandopoulos et al. (2000)** ***SAE Tech. Paper 2000-01-1016*****.**
- **Skaperdas & Konstandopoulos (2001) "Prediction of Diesel Particulate Filter Loading Behavior for System Control Applications",** CD AUTO 01, **3rd Int. Conf. on Control and Diagnostics in Automotive Applications**
- **Konstandopoulos et al. (2002)** ***SAE Tech. Paper 2002-01-1015*****.**
- **Konstandopoulos & Kladopoulou (2003) "A Virtual Sensor for On-board Diagnostics and Control of Diesel Particulate Filters ", CD AUTO 03, 4th Int. Conf. on Control and Diagnostics in Automotive Applications**
- **Kladopoulou et al. (2003)** ***SAE Tech. Paper 2003-01-0842.***

COMPONENTS OF DPF PRESSURE DROP



Total pressure drop:

$$\Delta P = p_7 - p_1 = \underbrace{(p_7 - p_6)}_{contraction} + \underbrace{(p_6 - p_5)}_{inlet\ channel} + \underbrace{(p_5 - p_4)}_{soot\ layer} + \underbrace{(p_4 - p_3)}_{filter\ wall} + \underbrace{(p_3 - p_2)}_{outlet\ channel} + \underbrace{(p_2 - p_1)}_{expansion}$$

Average soot deposit thickness: $w = \dfrac{\alpha - \sqrt{\alpha^2 - \dfrac{m_{soot}}{N_{cells} L \rho_{soot}}}}{2}$

ANALYTICAL MODEL

(including exhaust gas compressibility)

$$\Delta P_{expansion} = p_2 - p_1 = \sqrt{p_1^2 + \frac{8}{3}\frac{\zeta \dot{m}^2 RT}{MW}\frac{(a+w_s)^4}{V_{trap}^2 a^2}\left(\frac{L}{a}\right)^2} - p_1$$

$$\Delta P_{outlet\ channel} = p_3 - p_2 = \sqrt{p_2^2 + \frac{\mu \dot{m} RT}{MW}\frac{(a+w_s)^2}{V_{trap}}\frac{4FL^2}{3a^4}} - p_2$$

$$\Delta P_{filter\ wall} = p_4 - p_3 = \sqrt{p_3^2 + \frac{\mu}{k_w}\frac{\dot{m} RT}{MW}\frac{(a+w_s)^2}{V_{trap} a} w_s + \beta \frac{\dot{m}^2 RT}{MW}\frac{(a+w_s)^4}{2V_{trap}^2 a^2} w_s} - p_3$$

$$\Delta P_{soot\ layer} = p_5 - p_4 = \sqrt{p_4^2 + \frac{\mu}{k_{soot}}\frac{\dot{m} RT}{MW}\frac{(a+w_s)^2}{2V_{trap}}\ln\left(\frac{a}{a-2w}\right)} - p_4$$

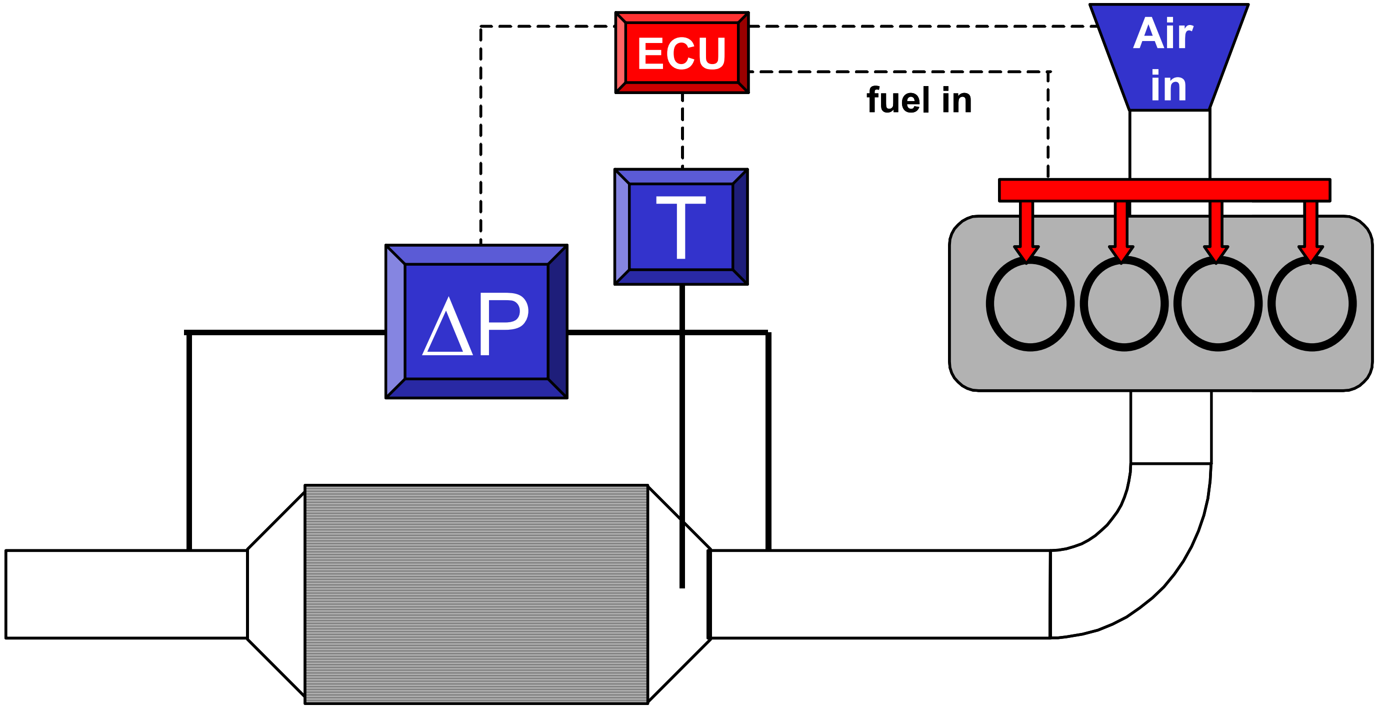
$$\Delta P_{inlet\ channel} = p_6 - p_5 = \sqrt{p_5^2 + \frac{\mu \dot{m} RT}{MW}\frac{(a+w_s)^2}{V_{trap}}\frac{4FL^2}{3(a-2w)^4}} - p_5$$

$$\Delta P_{contraction} = p_7 - p_6 = \sqrt{p_6^2 + \frac{4}{3}\frac{\zeta \dot{m}^2 RT}{MW}\frac{(a+w_s)^4}{V_{trap}^2 a^2}\left(\frac{L}{a}\right)^2} - p_6$$

VIRTUAL SENSOR APPLICATION

Required signals for virtual sensor:

- **Transducer for filter pressure drop**
- **Exhaust gas temperature sensor**
- **Exhaust mass flow rate from ECU**

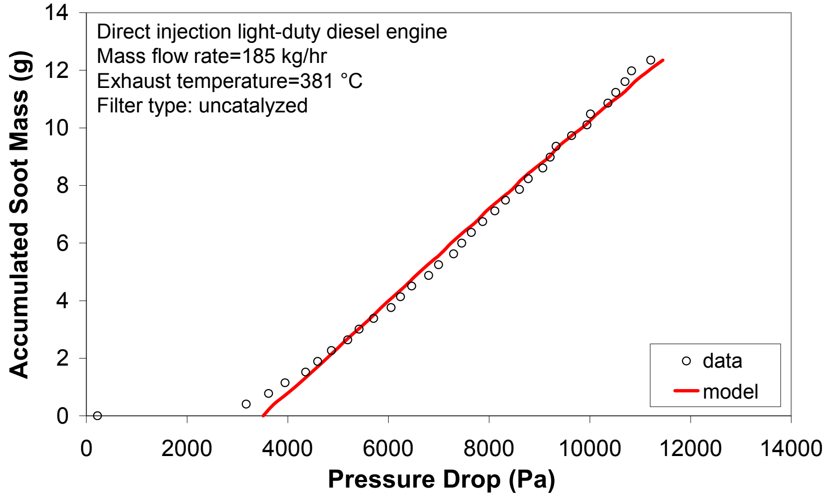


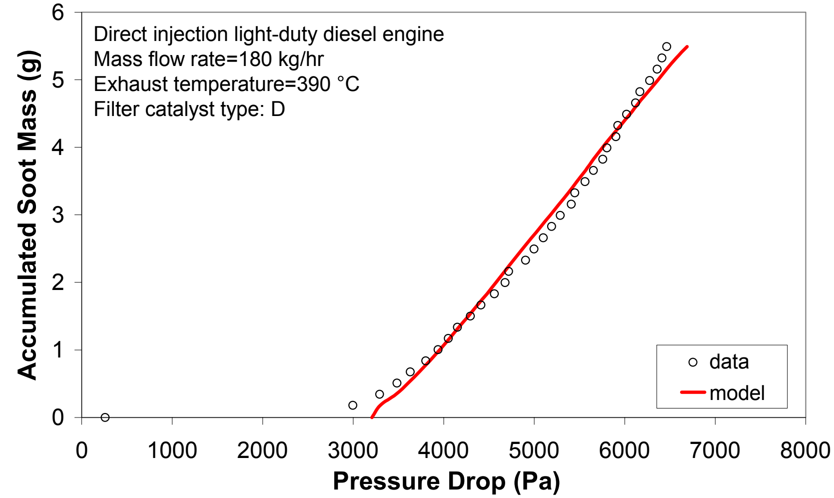
TEST MATRIX FOR VIRTUAL SENSOR

Filters			Engines	
Dimensions	**Name**	**Catalyst type**	**LD-Euro II**	**LD-Euro III**
5.66″x6″ 181 cpsi 14 mil	SI001	A	-	steady state, transient
	SI002	B	steady state	steady state
	SI004	None	steady state	-
	SI007	C	steady state	-
	SI011	D	steady state	-
	SI013	E	-	steady state

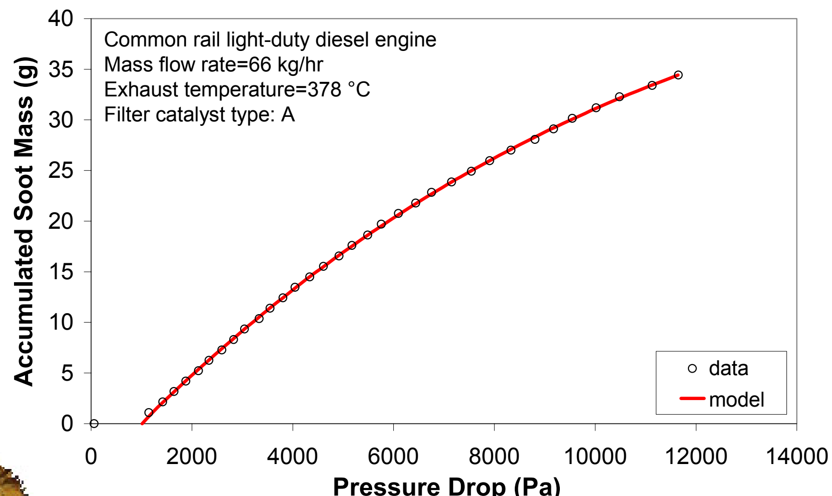
VIRTUAL SENSOR VALIDATION

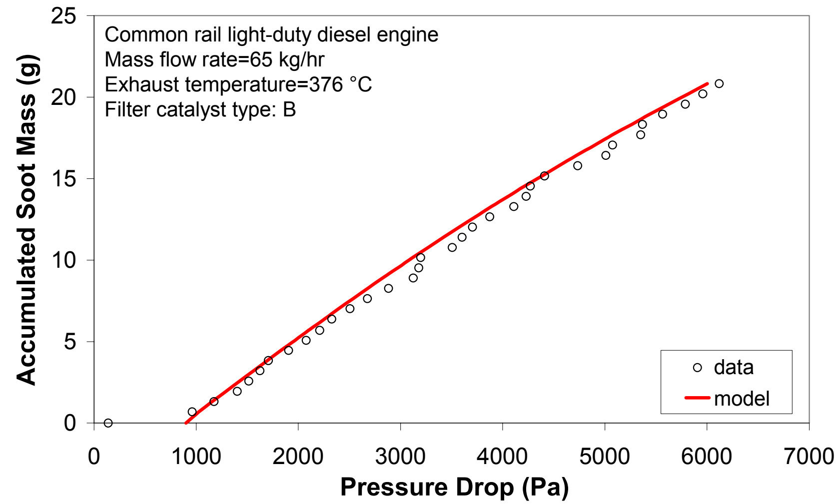
EURO II TDI ENGINE





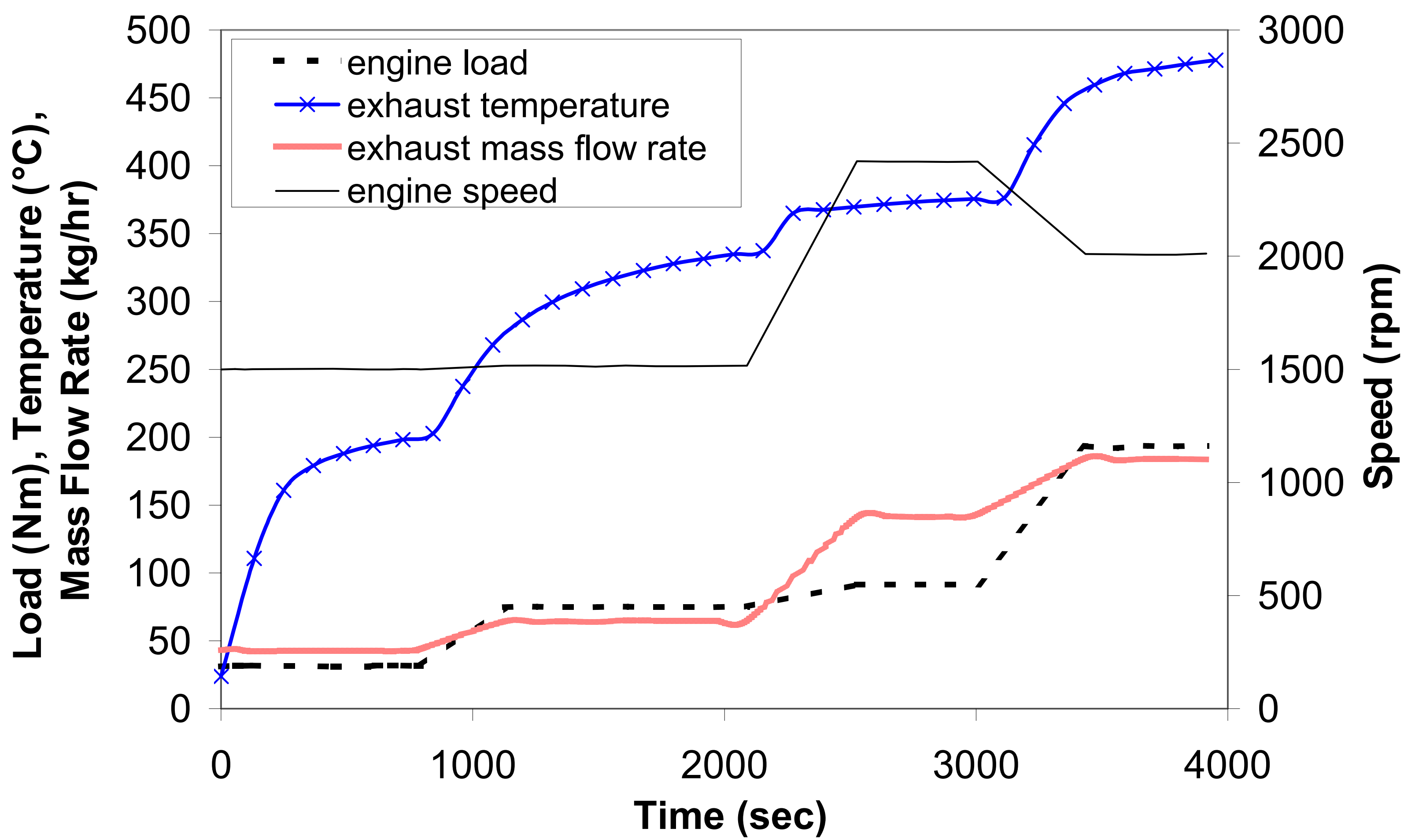
EURO III CR TDI ENGINE



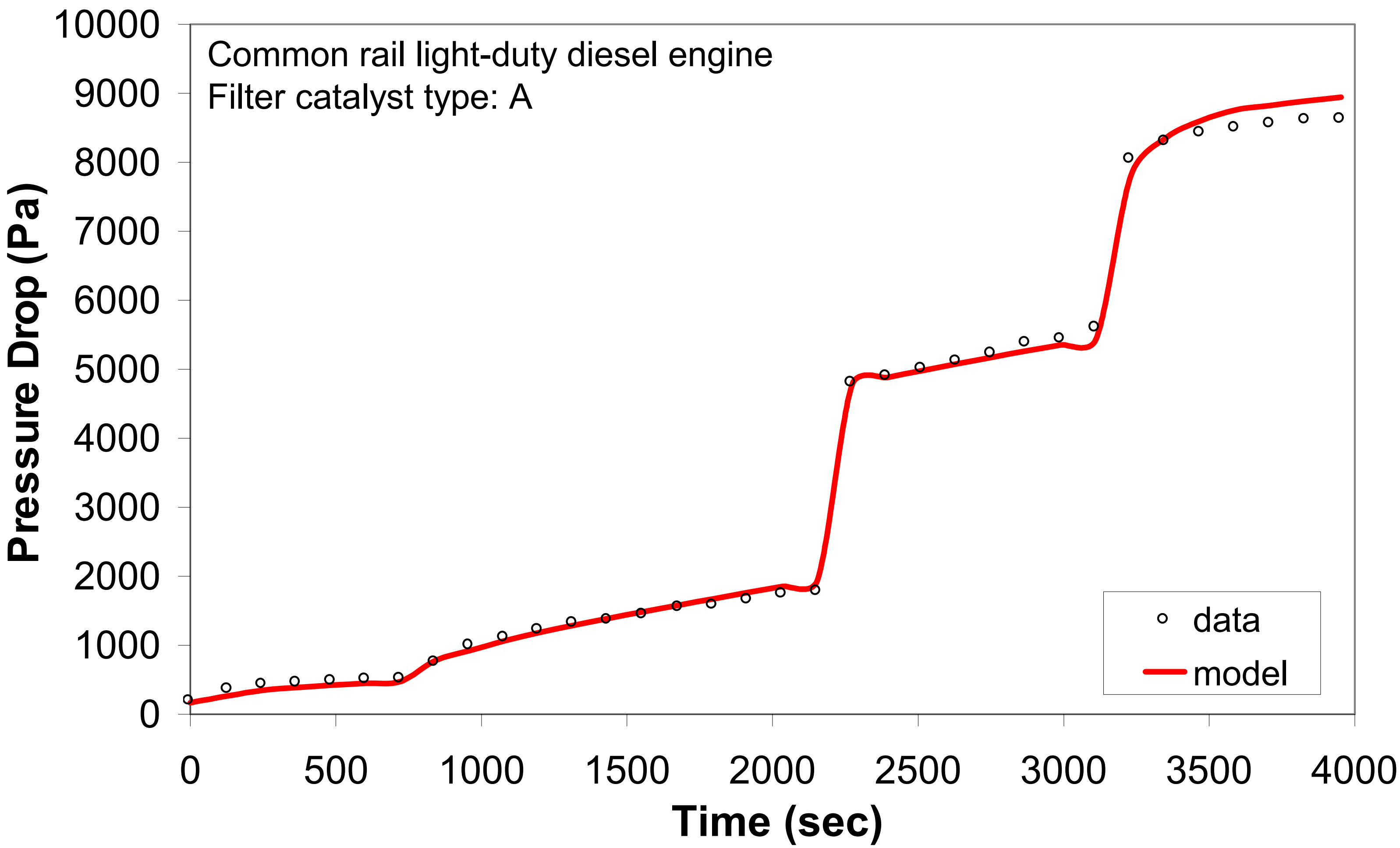


VIRTUAL SENSOR APPLICATION

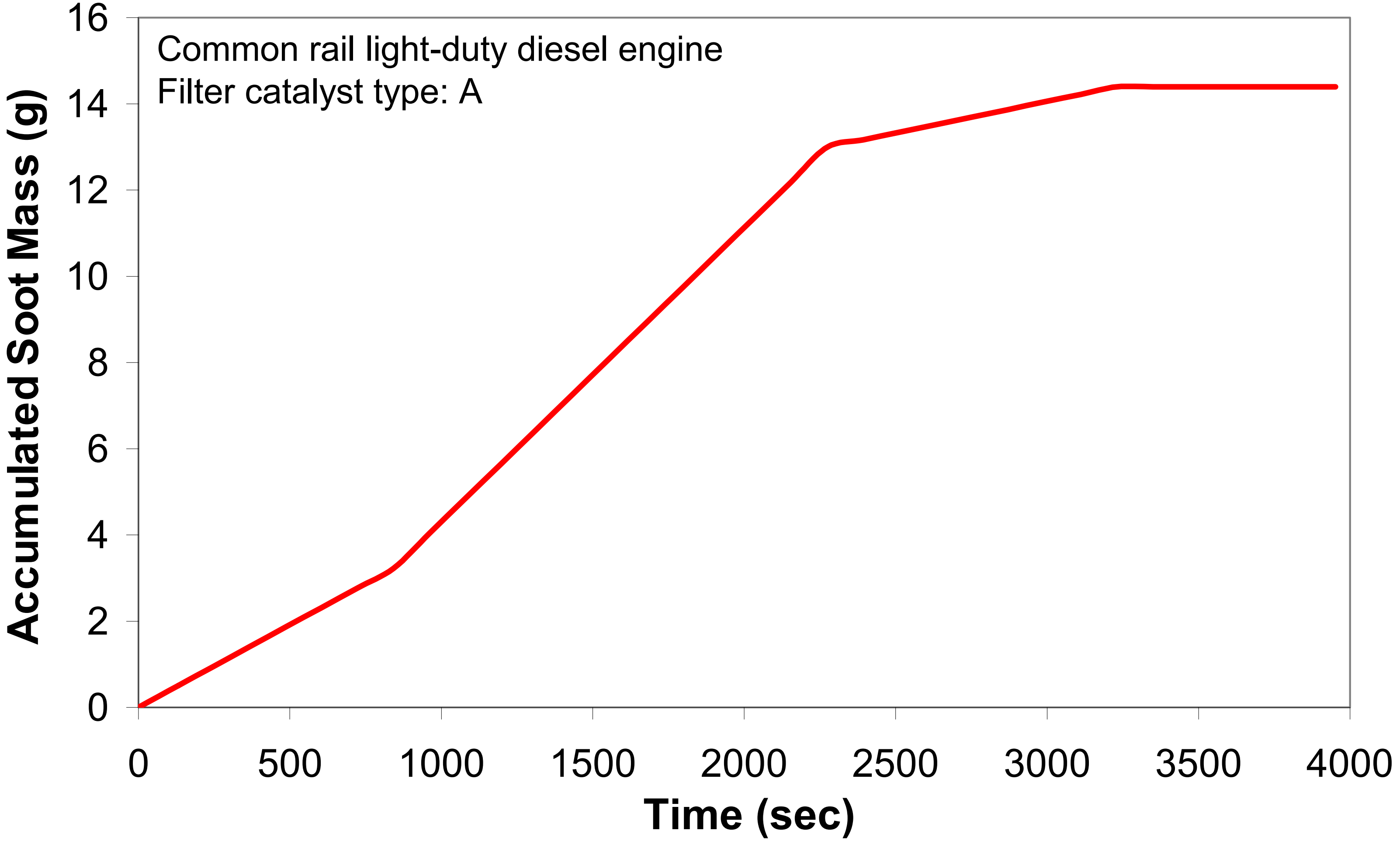
EURO III CR TDI ENGINE IN TRANSIENT OPERATION



DPF PRESSURE DROP EVOLUTION



VIRTUAL SENSOR OUTPUT



CONCLUSIONS

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ACKNOWLEDGEMENTS

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