

Innovative Techniques for On-Board Exhaust Gas Dynamic Properties Measurement

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ABSTRACT

The purpose of this paper is to present some innovative techniques developed for an unconventional utilization of currently standard exhaust sensors, such as HEGO, UEGO, and NOx probes. In order to comply with always more stringent legislation about pollutant emissions, intake-exhaust systems are becoming even more complex and sophisticated, especially for CI engines, often including one or two UEGO sensors and a NOx sensor, and potentially equipped with both short-route and long-route EGR. Within this context, the effort to carry out novel methods for measuring the main exhaust gas dynamic properties exploiting sensors installed for different purposes, could be useful both for control applications, such as EGR rates estimation, or cost reduction, minimizing the on-board devices number.

In this work, a gray-box model for measuring the gas mass flow rate, based on standard NOx sensor operating parameters of its heating circuit, is analyzed. Its accuracy is then compared to the one of a similar model applied to the UEGO probe, presented in a previous paper, to on-board standard MAF and speed-density measurements, and to a simple pressure loss-flow characteristic model, whose robustness derives from the particular NOx probe location in the exhaust pipe. The comparison is performed for steady-state tests. The sensitivity to model input variables is also considered, that is gas temperature and pressure, leading to the introduction of a complementary physical model and besides describing an adaptive method for estimating exhaust gas static pressure, which is based on the pressure-current dependence of UEGO and NOx sensors.

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INTRODUCTION

To comply with future even more demanding pollutant emissions legislations, car manufacturers are often forced to adopt complex exhaust layouts, especially for what concerns CI engines, usually incorporating an increased number of after-treatment devices and related sensors (e.g. UEGO, NOx, and temperature sensors), and including one or two EGR routes. The key idea behind this paper is to propose some innovative techniques to estimate specific gas dynamic properties of the exhaust flow by exploiting information available from instruments installed for different purposes, and to demonstrate the feasibility of the proposed approach by means of experimental tests. The final goal is to prove that the proposed methods are successful in terms of providing estimations with an accuracy level comparable to those obtained by standard instruments, thus achieving the primary target of avoiding the installation of additional sensors or

even removing existing ones. For such a purpose, oriented to on-board applications, the mathematical formulation of the estimator should be kept simple. The paper is divided into two main parts:

1. NOx/UEGO based exhaust gas mass flow rate estimation techniques.
2. UEGO-based exhaust gas pressure estimation method.

As far as the first objective is concerned, the purpose of establishing a gas mass flow rate measurement is investigated thanks to two different physical-based models. Both are valid in general for any exhaust sensor heated at constant temperature (i.e. HEGO/UEGO/NOx probes), assuming some standard operating parameters of the given sensor, normally available to the ECU, to be known as model inputs. More precisely, the first section of this study is focused on the extension of a gray-box estimator, whose feasibility has been demonstrated in [1] for a UEGO sensor application to a NOx

sensor, adopting a similar computational procedure and equivalent model inputs. The second approach is relative to the development of an alternative and more physical model, with the attempt of dealing with some of the issues arisen during the previous modeling activity, especially regarding the model sensitivity to some of its key input variables. To think of one of the possible applications of the proposed methodologies, the likely Euro6-compliant CI engine layout depicted in [Figure 1](#) could help. The necessary installation of a UEGO and a NOx sensor, along with the presented mass flow rate observer, could lead to the measurement of the exhaust mass flow rate or, when combined with the AFR value provided by the UEGO itself, to a measurement of the intake air mass flow rate. This information may be considered as a possible alternative to MAF signal, if appropriate gas dynamic delays (to be identified considering the different probes position in the exhaust pipe) are taken into consideration, with respect to the desired variable to be estimated (i.e., air mass flow entering or leaving the intake manifold).

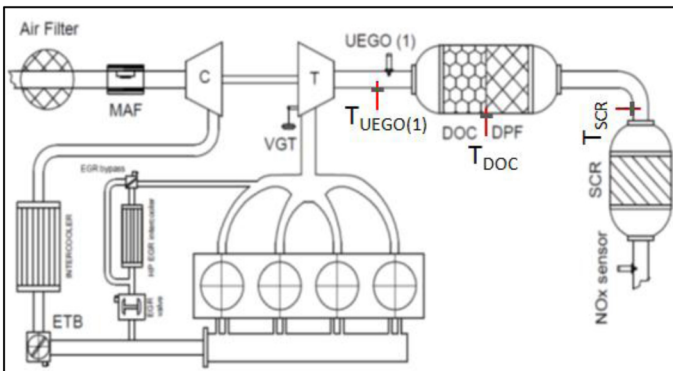


Figure 1. Likely Euro5/Euro6-compliant automotive diesel engine layouts (comprising UEGO and NOx sensors and HP EGR circuit)

On the other hand, if a measure or estimation of the exhaust gas mass flow rate is available (e.g. combining the airflow meter or the speed-density outputs with the fuel injected quantity estimation, or the lambda probe AFR signal), the UEGO itself can be directly used as a pressure estimator. As demonstrated in the paper, this result may be achieved by means of an adaptive algorithm, capable of reconstructing the time-variant mass flow-pressure loss characteristic curve of the exhaust system. This patented technique ([7]) exploits the known relationship existing between the gas static pressure and the UEGO controller output current, which is strongly dependent on the exhaust gas equivalence ratio.

GAS MASS FLOW RATE ESTIMATION TECHNIQUES

Throughout the following section, a mathematical description of the proposed methods is given. For what

concerns the NOx sensor-based estimator, physical assumptions are only briefly recalled, since a detailed explanation can be found in [1], relatively to the application of the model to a UEGO sensor [8,9,10].

NO_x Sensor-Based Gray-Box Model

Model Description

A general thermal balance expression, taking into account all the different power sources applied at the boundaries of a control volume around the sensing element of a NOx sensor, as illustrated in [Figure 2](#), can be expressed as follows [11, 12]:

$$\dot{P}_H - \dot{Q}_{cond} - \dot{Q}_{conv} - \dot{Q}_{rad} - \dot{Q}_{chem} = \frac{dU_s}{dt} \quad (1)$$

where $\dot{P}_H$ denotes the electrical power dissipated by Joule effect in the sensor incorporated heater, $\dot{Q}_{cond}$ the conductive thermal power exchanged between the sensor housing and the exhaust pipe walls, $\dot{Q}_{conv}$ the power removed by convection from the gas flowing inside the probe, $\dot{Q}_{rad}$ and $\dot{Q}_{chem}$ the radiation term and the thermal power arising from exothermic chemical reactions respectively. The quantity on the left side must equal, at each time instant, the variation of the sensor internal energy U_s .

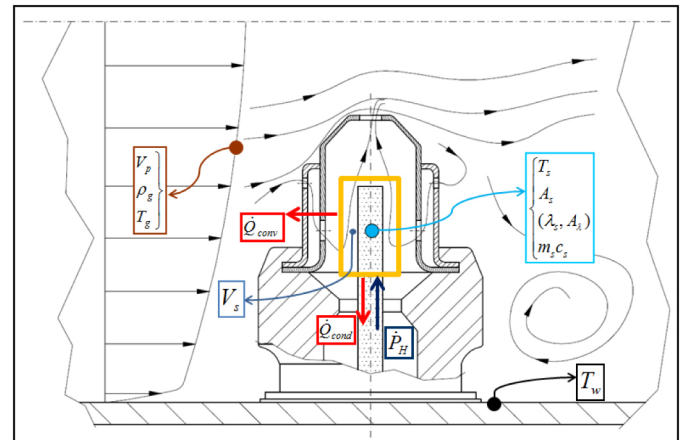


Figure 2. Main physical variables involved in thermal balance around NOx sensor probe in exhaust pipe

The overall acceptable performance of the described estimation method, as later illustrated, reinforces the hypothesis of neglecting the radiation term (especially in the case of the NOx sensor where, due to its position, even at high engine loads the gas temperature is relatively low and varies in a narrower range, and the protective shrouds can also exert the effect of radiation shields) and the chemical one, which would also lead to a more complex model formulation. [Equation \(1\)](#) can then be rearranged in the form of [Equation \(2\)](#):

$$R_H \cdot I_H^2 - \frac{\lambda_s}{L_c} A_\lambda (T_s - T_w) - \tilde{h}_s A_s (T_s - T_g) = m_s c_s \frac{dT_s}{dt} \quad (2)$$

where the physical quantities of interest, that will serve as model inputs, such as the gas and sensor temperatures T_s and T_g , the heater internal resistance and current R_H and I_H and other basic geometric and thermodynamic properties of the sensor and exhaust gas are highlighted. The term $\tilde{h}_s$ is the average convective coefficient between gases and NOx sensor element over the surface area A_s . The other terms represent the pipe wall temperature T_w , the sensor element mass and specific heat m_s and c_s , the sensor conductive cross sectional area, coefficient and length A_λ , λ_s and L_c . Moreover, the derivative term of the sensor internal energy can be neglected, since the sensing element temperature T_s is kept at a constant value by a closed-loop controller. This is especially true when considering the model parameters identification procedure, performed on steady-state engine operating points, or more in general in all the conditions when the temperature PID controller, illustrated in the schematic of Figure 3, ensures a fast response to keep the sensor temperature constant.

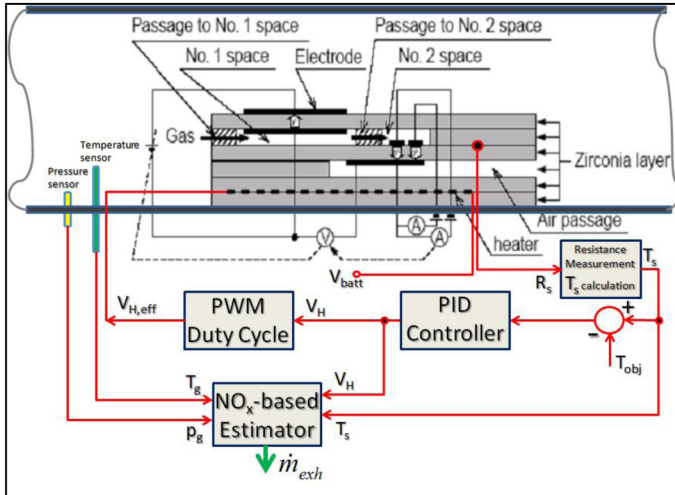


Figure 3. Schematic of NOx Tip temperature controller operation, with the implementation of the proposed estimation technique

From the previous considerations, together with a simplified linear approximation of the conductive thermal power loss as a function of the gas temperature $\varepsilon(T_g)$, the following expression can be derived for the estimated value $\tilde{h}_s$ of the convective coefficient:

$$\tilde{h}_s = \frac{R_H \cdot I_H^2 \cdot (1 - \varepsilon)}{A_s (T_s - T_g)} \quad (3)$$

The convective coefficient $\tilde{h}_s$ depends on ECU-available physical variables, such as the sensor temperature and the effective heater current flowing in the resistive circuit (heater voltage is the standard controller variable), constant quantities (A_s and R_H , since the temperature is kept constant) and the measured or estimated exhaust gas temperature at the pipe section where the sensor is located. Hence, given the estimation of the convective coefficient, the next modeling challenge deals with finding an appropriate relationship between this quantity and the gas speed inside the NOx probe V_s . Equation (4) represents a possible solution to such problem. Starting from a well-known correlation between thermal exchange non-dimensional numbers, a very simplified form of the desired expression may be recovered by recalling King's Law of anemometry [13, 14]. This approach leads to satisfactory results, once the unknown coefficients C_0 and C_1 have been experimentally identified.

$$\begin{cases} \overline{Nu}_s = \frac{\tilde{h}_s L_s}{k_g} \\ \overline{Nu}_s = a + b \cdot Re_s^{0.5} = a + b \cdot \left(\frac{\rho_s \cdot V_s \cdot L_s}{\mu_s} \right)^{0.5} \\ \tilde{h}_s = \frac{\overline{Nu}_s k_g}{L_s} \approx C_0 + C_1 \cdot \sqrt{V_s} \end{cases} \quad (4)$$

Since the target of the proposed method is to perform a measurement of the gas mass flow rate, which could be expressed in a simple form as the one reported in Equation (5), it follows the necessity to establish a proper analytical relationship between the estimated value of the gas speed inside the sensor (V_s) and the average exhaust gas speed at the NOx sensor location section, V_p .

$$\dot{m}_{exh} = \frac{p_g}{R_g T_g} \cdot \Omega_p \cdot V_p \quad (5)$$

Figure 4 illustrates the best polynomial fit obtained by considering the pipe average speed values, V_p , calculated by means of Equation (5), as a function of the estimated sensor gas speed values, V_s (Figure 4a), calculated by combining Equations (3) and (4), and the corresponding regression curve (Figure 4b). As confirmed by Figure 4b, the choice of recovering the desired speed values by means of a single variable (V_s) is not adequate.

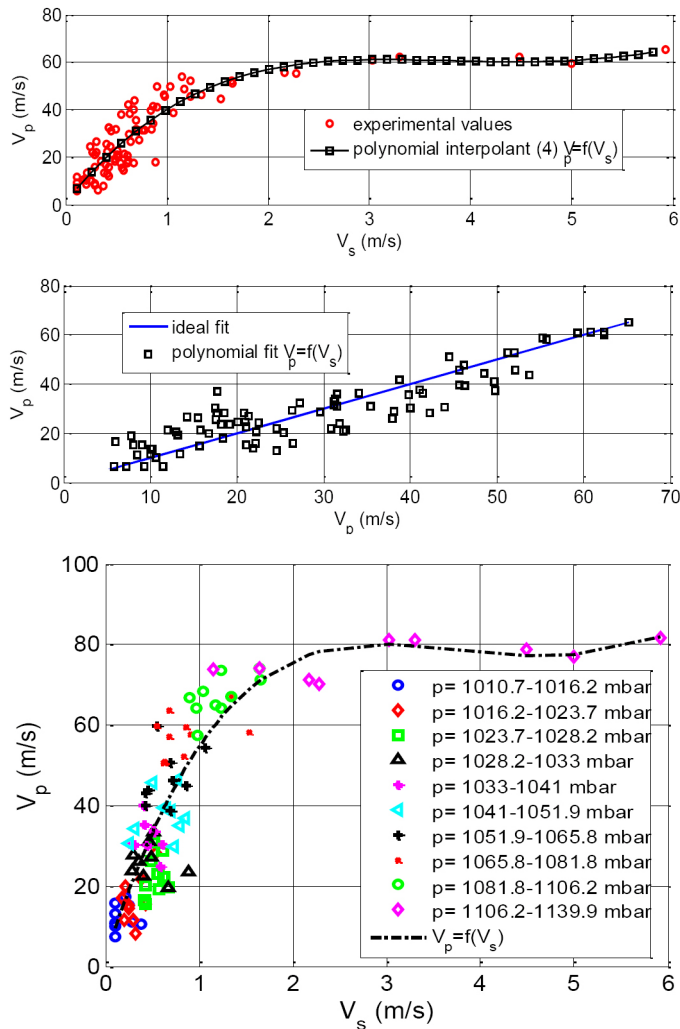


Figure 4 a, b, c. Regression diagram obtained with a polynomial interpolating function: $V_p = f(V_s)$ (4a, 4b). Relationship between the speeds inside sensor V_s and average pipe value V_p grouped for different static pressure values (4c)

As a consequence, the effect of additional parameters has been investigated, leading to the identification of the exhaust gas static pressure, whose effect is highlighted in Figure 4c, as the only further input variable to be considered at this calculation stage.

The objective function can be represented in the form expressed by Equation (6), which still complies with the prerogative to keep the mathematical relationships involved in the model as simple as possible, to be compatible with on-board implementation requirements.

$$V_p = \sum_{n=1}^N \sum_{m=1}^M k_{nm} \cdot V_s^n \cdot p_g^m \quad (M = N = 2) \quad (6)$$

In the schematic of Figure 5, a detailed representation of the model structure is given.

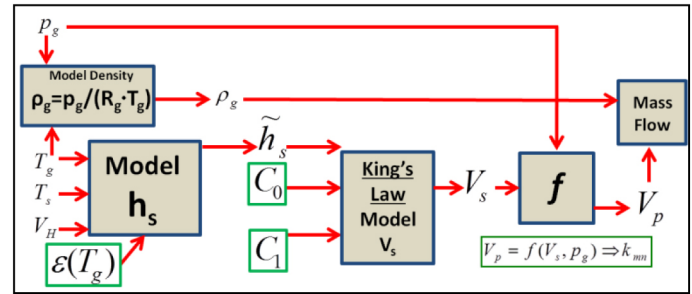


Figure 5. Schematic block diagram representing detailed computational algorithm for the NOx-based estimator (see also Figure 3) of the exhaust gas mass flow rate

Experimental Setup

Test bench experiments were conducted on a 1.3L TDI engine to identify and validate the performance of the proposed NOx sensor-based model. The engine main characteristics are summarized in Table 1.

Table 1. Test engine characteristics

Engine type	FIAT 1.3 Multi-Jet EU5
Displacement – cylinder disposition	1248 cc - 4L
EGR	HP EGR upstream turbine
Supercharging	Turbocharged, with VGT
Injection system	Common Rail DDI
Max Power - Max Torque	70 kW @ 4000 rpm 210 Nm @ 1750 rpm

During the experimental tests, the variables listed in Table 2 represented the most important parameters to be monitored. The sum of intake air mass flow rate (provided by on-board calibrated airflow meter) and fuel mass flow rate (measured by a laboratory mass flow meter) was chosen as a reference value for the exhaust gas mass flow rate.

Table 2. List of main experimental measured or estimated variables

Name	Units	Description	Measurement
p_g	Pa	Gas static pressure in NOx sensor position	Measured + estimated in ECU
T_g	K	Gas temperature in NOx sensor position	Measured + estimated in ECU
$\dot{m}_{air,in}$	kg/s	Intake air reference mass flow rate	ECU-available measurement
x_{VGT}	-	VGT actuator relative position	ECU-available measurement
T_s	K	NOx sensor tip temperature	NOx controller-available
I_H	A	NOx heater circuit Voltage-Current	NOx controller-available

The model robustness was investigated with respect to the number of identification points required to calculate its numerical coefficients. For this purpose, a small set of