

Real-Time Estimation of Intake O₂ Concentration in Turbocharged Common-Rail Diesel Engines

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ABSTRACT

Automotive engines and control systems are more and more sophisticated due to increasingly restrictive environmental regulations. Particularly in both Diesel and SI lean-burn engines NO_x emissions are the key pollutants to deal with and sophisticated Engine Management System (EMS) strategies and after-treatment devices have to be applied. In this context, the in-cylinder oxygen mass fraction plays a key-role due its direct influence on the NO_x formation mechanism. Real-time estimation of the intake O₂ charge enhances the NO_x prediction during engine transients, suitable for both dynamic adjustments of EMS strategies and management of after-treatment devices.

The paper focuses on the development and experimental validation of a real-time estimator of O₂ concentration in the intake manifold of an automotive common-rail Diesel engine, equipped with turbocharger and EGR system. The paper analyzes the air intake process and the influence of the exhaust gas recirculation system based on a mean value modeling approach. All variables required are available at EMS level, thus allowing an on-board implementation without extra costs for additional sensors.

The accuracy of the developed estimator is assessed by comparing simulated and experimental trajectories of O₂ concentration, measured by a Universal Exhaust Gas Oxygen (UEGO) sensor located in the intake manifold. The experimental tests were carried out at the test bench, imposing severe engine transients. The results evidence that the O₂ estimator presents a good accuracy vs. experiments and offers significant opportunities for improving engine control and after-treatment devices management during transient operation.

CITATION: Arsie, I., Cricchio, A., Pianese, C. and De Cesare, M., "Real-Time Estimation of Intake O₂ Concentration in Turbocharged Common-Rail Diesel Engines," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-0343.

INTRODUCTION

NO_x and soot emissions are still the most critical and challenging issues for Diesel engines. As increasingly stringent regulations on emissions are imposed, new technologies for lower emissions and higher efficiency are developing very rapidly. Among others, complex after-treatment technologies, as Selective Catalytic Reduction (SCR), Lean Nox Trap (LNT) and Diesel Particulate Filter (DPF), have been introduced to meet the imposed NO_x and particulate limits.

The knowledge of gas composition in several sections of the air/exhaust paths (e.g., intake manifold, engine outlet, upstream and downstream the catalysts) is fundamental to optimize combustion process, emissions formation and after-treatment devices management. In particular, for the SCR

system, NO_x evaluation upstream and downstream the catalyst is essential for control and diagnosis purposes. Typically a NO_x sensor is placed at SCR outlet while inlet NO_x concentration is usually estimated by look-up tables or real-time simulation models [1], [2], [3], [4].

The NO_x formation process is extensively modeled via the Zeldovich mechanism [5], [6], [7], [8]. It presents a strong, non linear dependence with respect to both in-cylinder temperature and oxygen concentration; thus either precise measurements or estimates of these variables are needed to achieve satisfactory model accuracy. Unfortunately, reliable measurements of local in-cylinder temperature and oxygen concentration are not feasible. Therefore NO_x estimation methodologies need indirect process information, which are made available by sensors already installed on commercial engines; this avoids extra-costs for additional components

[1]. Boost pressure, injection timing and pulse width, EGR rate and engine speed are commonly used as input variables for on-board NO_x modeling.

The accuracy achievable with models for on-board application, whose inputs are based on engine operating and control variables, may be very poor. They need a large experimental databases to compensate for the lack of physical information available. Thus, either the measurement or the estimation of variables directly related to the chemical process of interest may improve the accuracy of the NO_x model being implemented. In this context, the knowledge of the intake oxygen concentration would be especially useful to enhance NO_x estimation, improving model accuracy and generalization.

Since oxygen sensors in the intake manifold are not available on commercial engines, due to costs and reliability issues, the development of real-time models and estimation methodologies is of great interest. Most of the studies related to in-cylinder oxygen concentration, are based on Mean Value Engine Models (MVEM) based on mass and energy equations [9], [10], [11]. Diop et al. [12] investigated the observability issues of this modeling approach for on-board implementation. Furthermore, a wide range of models has been proposed including linear parameter varying [13], [14] and empirical models [15]. The mentioned approaches do not account for the time-varying transport delay between exhaust and intake manifold, that has been instead considered in [16] and [17].

The present paper deals with a comprehensive MVEM of a Diesel engine, with variable-geometry turbocharger and high pressure EGR. The model allows estimating in real-time the intake manifold O₂ concentration during engine transient operation, based on available measurements on the engine, specifically intake manifold pressure and air flow rate. It's worth noting that the use of available measurements allows reducing model complexity, computational demand and calibration issues.

A key feature of the proposed approach is its capability to use any combination of measured and computed engine variables. Therefore a reduction of both model complexity and tuning parameters may be achieved. Moreover, the model flexibility makes its application feasible for several engine control architectures and may improve costs saving objectives.

An application of the intake O₂ dynamic model presented herein is shown in [Figure 1](#), where the scheme of a computational structure for Internal Combustion Engine (ICE) NO_x on-board estimation is sketched. In the scheme the NO_x virtual sensor receives as input operating and control variables detected by the EMS and the intake O₂ concentration estimated by the dynamic model.

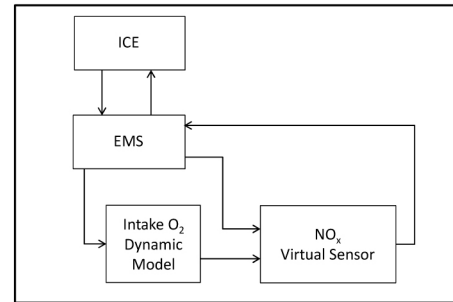


Figure 1. Modeling structure for the on-board estimation of NO_x - The inputs are fed by EMS and O₂ model.

SYSTEM MODELING

Model Description

The model is aimed at estimating the oxygen fraction in the intake manifold by simulating the air intake process and the exhaust gas recirculation. The engine layout is depicted in [Figure 2](#), where the high pressure EGR path is noticeable.

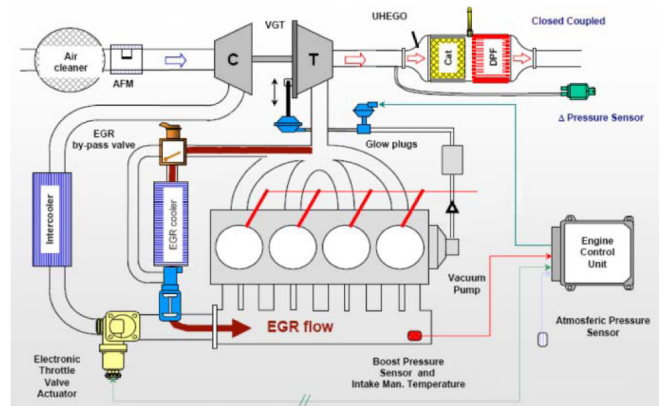


Figure 2. Engine layout.

The model is based on a mean value approach with lumped parameters, ensuring satisfactory accuracy and low computational demand, suitable for on-board implementation. The engine components of interest (i.e. intake/exhaust manifolds, EGR system) are modeled as control volumes in which the dynamics of the state variables have a time scale slightly larger than the engine cycle; thus the cycle-to-cycle variations can be disregarded [9]. Following the Filling and Emptying formulation, mass and energy conservation is applied in any control volume, along with information on incoming and outgoing mass flow rates. Furthermore homogeneous pressure, temperature and chemical composition inside the manifold are assumed together with instantaneous and perfect mixing of incoming flows.

The system model presents four states, corresponding to the intake oxygen concentration and temperature, the exhaust temperature and pressure; furthermore two algebraic

equations are solved to calculate EGR and in-cylinder mass flow rates.

Intake Manifold

The intake manifold model is based on mass and energy equations applied to ideal gases [10], [14], [18], [19]:

$$\frac{d(m_{man})}{dt} = \dot{m}_{air} + \dot{m}_{egr} - \dot{m}_{cyl,in} \quad (1)$$

$$\begin{aligned} \dot{m}_{air}h_{air} + \dot{m}_{egr}h_{egr} - \dot{m}_{cyl,in}h_{cyl,in} \\ = \frac{d(mu)_{man}}{dt} \\ = \dot{m}_{man}c_vT_{man} + m_{man}c_v\dot{T}_{man} \end{aligned} \quad (2)$$

which lead to the following two states system, namely temperature and oxygen mass fraction:

$$\begin{aligned} \dot{T}_{man} \\ = \frac{\dot{m}_{air}c_{p,air}T_{amb} + \dot{m}_{egr}c_{p,exh}T_{egr}}{m_{man}c_{v,man}} \\ - \frac{\dot{m}_{cyl,in}c_{p,cyl}T_{cyl,in} + \dot{m}_{man}c_{v,cyl}T_{man}}{m_{man}c_{v,man}} \end{aligned} \quad (3)$$

$$\begin{aligned} \dot{O}_{2man} = \frac{R_{air}T_{man}}{P_{man}V_{man}} [(O_{2exh} - O_{2man})\dot{m}_{egr} \\ + (O_{2amb} - O_{2man})\dot{m}_{air}] \end{aligned} \quad (4)$$

In eq. (4), O_{2amb} and O_{2exh} are the oxygen concentrations in the ambient air (i.e. 20.9 %) and in the exhaust manifold, respectively. This latter may either be measured by a UEGO sensor located downstream of the turbine or estimated by the engine model, as shown in the next section. The intake manifold pressure (P_{man}) and the air flow rate ($\dot{m}_{air}$) are measured by a pressure sensor and an air flow meter, respectively, while the intake mass flow rate can be estimated by the speed-density equation as function of the volumetric efficiency:

$$\dot{m}_{cyl,in} = \frac{\lambda_v P_{amb}^n V_d}{120 R_{air} T_{amb}} \quad (5)$$

The volumetric efficiency is estimated by a polynomial regression as function of intake manifold pressure and temperature and engine speed:

$$\lambda_v = f(P_{man}, T_{man}, n) \quad (6)$$

The polynomial regression was identified from a set of about 200 experimental data, measured in steady state conditions at the engine test bench for different engine speed, load and EGR rates. The proposed regression does not include any dependency on the exhaust pressure, thus neglecting the effect of altitude; nevertheless it is still suitable

for the experimental and numerical analyses presented and for the purpose of the paper. The experimental volumetric efficiency was calculated based on air flow meter and gas analyzer measurements. Particularly, the CO_2 concentration in the intake and exhaust manifolds was measured to calculate the EGR rate.

The influence of the EGR rate on the volumetric efficiency is indirectly accounted through the intake manifold temperature, which depends on the mixing between fresh air and recirculated gases. Figure 3 shows the comparison between measured and predicted volumetric efficiency by eq. (6), evidencing a very good fitting ($R^2 = 0.991$).

Following the intake mass flow rate estimation (eq. 5) and the air flow meter measurement, the EGR mass flow rate is evaluated by the following equation:

$$\dot{m}_{egr} = \dot{m}_{cyl,in} - \dot{m}_{air} \quad (7)$$

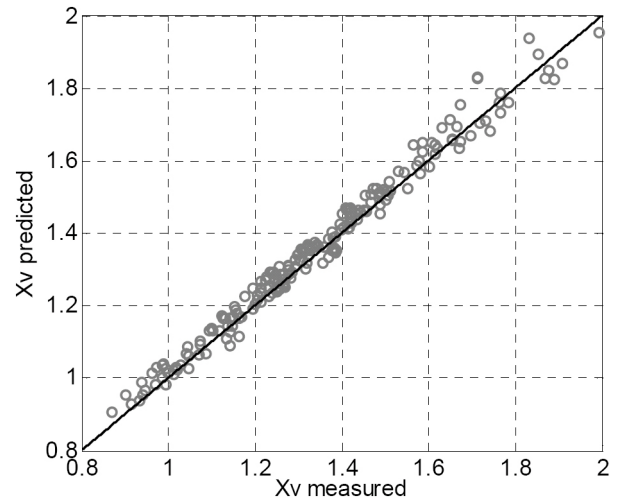


Figure 3. Comparison between predicted and measured volumetric efficiency. $R^2 = 0.991$.

The intake manifold temperature evaluation is based on the thermodynamic modeling of the intercooler and the EGR system. The inlet plenum receives fresh air and burned gases and their interaction is represented through mass and energy equations (eqs. 1 and 2) with the assumption of perfect mixing. The air temperature downstream the intercooler is computed by modeling the efficiency of the heat exchanger as [9]:

$$\varepsilon = \frac{C_h(T_{hi} - T_{ho})}{C_{min}(T_{hi} - T_{ci})} \quad (8)$$

where C_{min} is the minimum heat capacity between hot and cold fluids evolving in the exchanger and C_h is the heat capacity of the hot fluid. In equation (8) it is assumed that the outlet cooling air temperature (i.e. T_{co}) reaches the same value of the inlet hot gases (i.e. T_{hi}). For the intercooler under