

Fast Oxygen Based Transient Diesel Engine Operation

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ABSTRACT

Due to the advancements in passenger car Diesel engine design, the contribution of transient emission spikes has become an important fraction of the total emissions during the standardized test cycles, hence the interest of this work on dynamical engine operation, in particular on the improvement of NO_x and PM emissions. This paper proposes to use a UEGO sensor (universal exhaust gas oxygen sensor) in the upstream of the turbine in combination with a Kalman filter to estimate the target quantities, namely in-cylinder oxygen concentration before and after combustion. This information is used to define the fuel injection as well as the values of the air path actuators. Test bench measurements with a production Diesel engine are presented, where the oxygen based approach is compared to the standard calibration during a fast load increase. It is shown that the torque response could be maintained while NO_x as well as PM emission peaks were reduced significantly.

INTRODUCTION

There are now many well known solutions for tailpipe emission abatement both for SI and CI engines, but they are not for free, so that the reduction of raw emissions is still one of the main concerns in the automotive industry. As far as CI engines are concerned, besides hydrocarbons (HC) and carbon monoxides (CO) that are caused by incomplete combustion, the main gaseous emissions are nitric oxides (NO_x) and particulate matter (PM), which are always present during standard Diesel combustion. Unfortunately, the measures for NO_x reduction are mostly in contradiction to reduction of PM and vice versa. Consequently, these quantities can be depicted by a trade-off – Figure 1 presents a measured

tradeoff for a common rail direct injection (CRDI) Diesel engine.

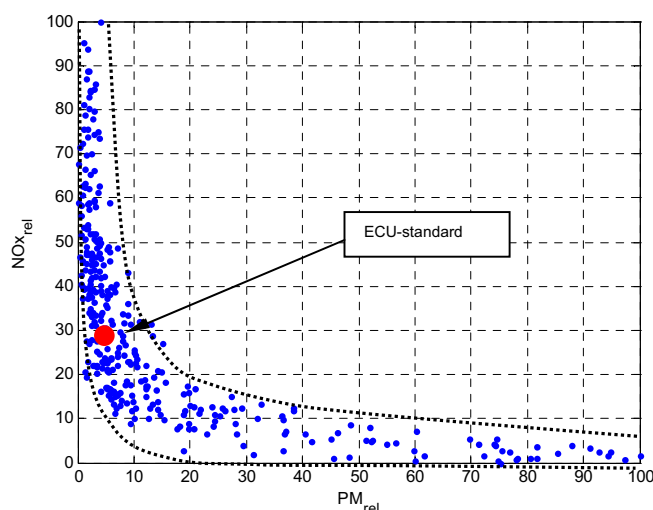


Figure 1: NO_x -PM tradeoff for a constant load point

Due to the continuous improvement of the engines (e.g. high pressure direct injection, multiple injections, high boost and cooled EGR) in particular the steady state emissions could be reduced. As a consequence, the emissions during the transients become more important. Indeed, the contribution of the transient spikes to the overall emissions during a test cycle can be even higher than the steady state fraction. Figure 2 underlines this statement, where a part of the FTP75 is shown (for the same engine than in Figure 1; more details are explained in the next section). Here, a major potential for improving the transients lies in engine control.

Traditional Diesel engine control relies on the use of intake manifold pressure (MAP) and fresh mass airflow

(MAF) as reference quantities for control. Several works concentrated on alternative targets for control. For instance in [1] different control strategies are compared, also to control the EGR fraction, or in [2] the EGR loop is used to control the air fuel ratio. [3] uses the intake oxygen concentration and the boost pressure for a MIMO control of the air path. In [4] an interesting approach was presented, where the air fuel ratio λ and the EGR rate were used for emission control and in a further work of the same author a transient cycle by cycle control of the combustion was implemented [5].

In production engines mostly a wide band lambda sensor (UEGO) downstream of the turbine is used to correct the information obtained by the mass airflow sensor and the model of the air path to estimate the quantity and composition of the intake gas. The availability of this information inspired many works. In [6] a closed loop control of λ was presented, [7] uses the UEGO signal for estimating the individual cylinder air-fuel ratio and [8, 9] balance the air-fuel ratio of several cylinders on the base of a single AFR sensor in the exhaust.

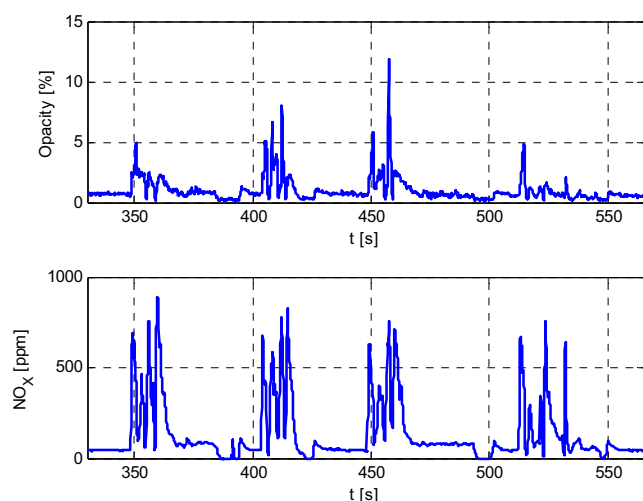


Figure 2: NO_x and PM emissions during a FTP75

In this work we propose to change the position of the standard UEGO sensor from downstream to the upstream of the turbine. New target quantities are introduced, namely the in-cylinder oxygen concentration before and after combustion. Hence, not only the amount of EGR flow is taken into account but also its quality, in other words the oxygen contained in the recirculated gas. The new sensor position has the advantage of a faster response, but the challenge of high pressure and pressure oscillations, too. To keep the advantage while discarding the disadvantage, a model based filter is used to estimate reliably and without time delay the target quantities and to compensate the pressure dependency of the lambda sensor. The estimator relies on redundant information, e.g. in a narrow time scale the change of exhaust oxygen concentration can be reduced to a change of injected

fuel quantity whereas for slow dynamics the UEGO sensor delivers proper signals.

Finally, test bench measurement results with a passenger car CRDI Diesel engine are presented, where based on the fast information of the target quantities an optimization of the actuators was done for a load increase. The torque response could be maintained and NO_x as well as PM emissions were reduced significantly.

SYSTEM

A BMW 4-cylinder EU4 CRDI production passenger car Diesel engine was used for this work. The variable geometry turbocharger (VGT) in combination with an intercooler as well as cooled exhaust gas recirculation represents a common understanding of today's engine design (Figure 3).

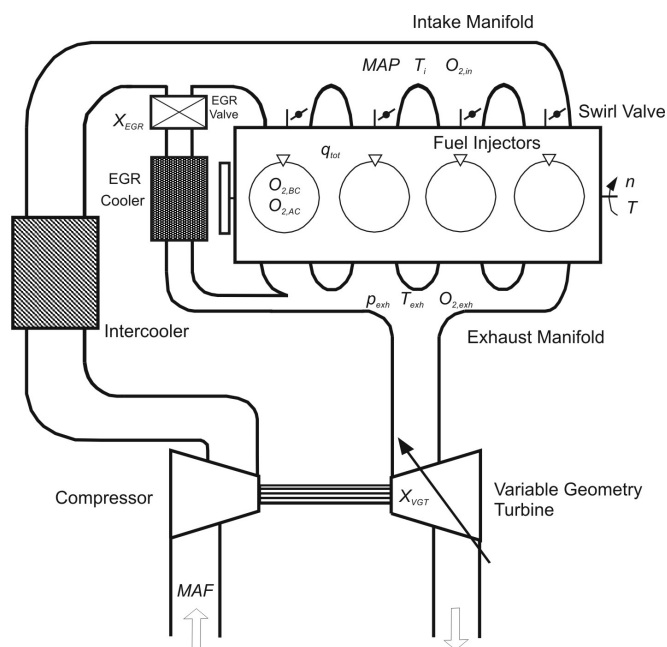


Figure 3: Diesel engine

The analyses presented in the following always compare to a standard calibration. Therefore, an open ECU was used, where either the production calibration was applied or a bypass allowed real time modifications of the appropriate control values. Hence, it was guaranteed to have the same baseline.

TARGETS FOR CONTROL

The system of Figure 3 has 3 different dynamical orders. The fuel injection is the fastest system and acts more or less instantaneously. The turbocharger characterizes the slowest time constant of the engine and the EGR path is somewhere in between. These different dynamics need to be considered by the choice of proper target quantities as well as later by the control design.

STANDARD SETUP - Traditionally, engine control is separated into air path control and control of the fuel injection. The user's demand is engine torque which can roughly be transferred to injected fuel quantity. Consequently, fuel is the dominating quantity and determines the references for the air path control. As mentioned before, the air path shows a slower dynamics than the fuel path which is unfortunate for the controller cascade. To overcome this problem different measures, especially smoke maps, are used to limit the fuel. This solution works but nevertheless this cascading might provide potential for improvement. In the air path loop usually the boost pressure (mean absolute pressure, MAP) and the fresh mass airflow (MAF) are used as references. Although significant cross couplings exist, MAF is controlled with the EGR valve and MAP with the position of the VGT, i.e. two independent single input single output (SISO) controllers are applied. Obviously, tuning of SISO loops is easier and much more intuitive for a calibration engineer than the design of a MIMO control. However, a combined control of the actuators would correspond to the physics and is assumed to bring an advantage (see e.g. [10-15]).

MODIFIED CONTROL TARGET – Many works were dedicated to modeling of emissions [16-20]. However, in contrast to these works here the main focus was to use (control applicable) reference quantities that are determining combustion in its quality, i.e. the complexity needs to be kept low to make it suitable for control while the dominating effects need to be represented well. It turned out, that oxygen concentrations can fulfill the requirements. In detail, we propose to use as references the oxygen concentrations in the combustion chamber before combustion ($O_{2,BC}$) and after combustion ($O_{2,AC}$). $O_{2,BC}$ is mainly relevant for NO_x emissions and $O_{2,AC}$ represents the equivalence ratio of fuel and oxygen, thus corresponds to PM. Here the key issue is to define the in-cylinder quantities as the references. In the next sections an approach is presented, where these quantities are estimated based on available measurements on the engine.

REALIZATION

Although in-cylinder oxygen concentration can be measured with test-bed equipment (e.g. by fast gas extraction), an application for control purposes is not realistic from today's point of view. These devices are primarily dedicated to steady state measurements and do not provide the dynamical capabilities for control. Therefore, an approach based on the fusion of available measurements and a model was developed, where advantage was taken of the standard measurements at the engine. The production engine is equipped with an oxygen sensor in the downstream of the turbine. In steady state operation the oxygen content of the gas at this sensor position is equal to $O_{2,AC}$. Furthermore, by knowledge of the total charge trapped in the combustion chamber and the injected fuel amount, $O_{2,BC}$ can be calculated. Due to the presence of time delays and the EGR-path dynamics this assumption does not hold for

transients. Hence, an estimator was designed to estimate the instantaneous oxygen concentration $O_{2,AC}$ based on a modified exhaust gas oxygen concentration measurement position.

EXHAUST GAS OXYGEN CONCENTRATION MEASUREMENT - Wide band lambda sensors for automotive applications are ZrO_2 oxygen sensors which measure the partial pressure of oxygen in the exhaust (see e.g. [21]). The sensor delivers a fast measurement provided that it is heated to a constant temperature of approximately $750^\circ C$ [22, 23]. The ceramics is sensitive to temperature gradients and therefore water condensation might destroy the sensor. Hence, an application at the intake side is not recommended, furthermore due to a limited heating power and a significant drift of the sensor signal at low temperatures infeasible. On the contrary, temperatures up to $900^\circ C$ and more are unproblematic, which makes it well suited to be used in the exhaust. To minimize the transport and mixing delays the sensor position was changed in this work, from the downstream of the turbine to the upstream, i.e. a UEGO sensor was mounted directly in the exhaust manifold. The benefit is not only related to the transport delays but also to the faster sensor response due to the higher temperature. However, as a result of the partial pressure measurement principle, the repositioning to a measurement at overpressure leads to incorrect results. Fortunately the pressure dependency is deterministic and thus can be compensated.

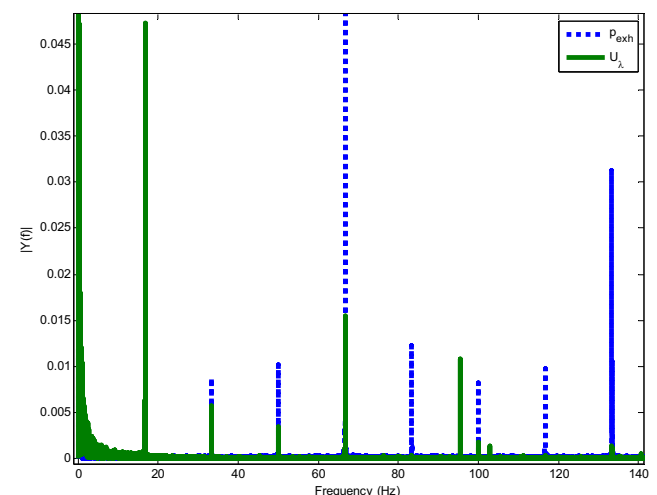


Figure 4: FFT for exhaust pressure and lambda voltage

Figure 4 depicts a FFT of the oxygen sensor voltage and the exhaust pressure for an engine speed of 2000rpm ($\hat{=} 33.3\text{Hz}$), which confirms the pressure influence on the sensor signal. In the relevant operating range up to the second order of the engine speed the peaks in the UEGO voltage coincide with the exhaust pressure peaks.

For the following the impact of the exhaust pressure on the sensor signal was assumed to be instantaneous, or in other words the dynamics of the pressure influence