

Transient EGR in a High-Speed DI Diesel Engine for a set of different EGR-routings

2010-01-1271

Published
04/12/2010

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ABSTRACT

EGR has been proven to reduce NOx emissions from diesel engines significantly and is nowadays widely used in production engines. To reach future emission legislation standards, alternative EGR-routings that deliver higher EGR-rates get into the focus of researchers. As the steady-state emissions are reduced more and more, the emission peaks in transient parts of driving cycles gain importance. Therefore it is interesting to analyze the transient behavior of different EGR-routings.

In this work, a 1-D simulation is performed in GT-Power for a 1.9 liter passenger car diesel engine equipped with cooled short-route EGR and a variable geometry turbine. For calibration of the simulation, load transients are measured including the measurement of transient EGR-rates using a fast CO2-analyzer and cylinder pressure to obtain heat-release data. A database with heat-release rates for transient combustion is collected to enable the simulation to run with real combustion data at all points of the transients. The transient EGR-rate as well as the intake pressure are used as criteria to choose the right heat-release rate for a certain cycle.

A set of different ways of supplying EGR, namely hybrid EGR, pump-assisted EGR and a reed valve in the EGR-circuit are then implemented in the simulation software and analyzed with respect to transient response and fuel consumption. Another aspect of the analysis is the possibility to control the EGR-rate during the transient. This includes positive load transients with EGR-shutoff as well as negative load transients with need for fast EGR-delivery.

INTRODUCTION

To be able to fulfill future emission regulations, the emissions of Diesel engines have to be further reduced. Especially the

reduction of NOx-emissions is a challenging task. The two main different methods for this are the reduction of raw-emission with the help of EGR on the one hand, and aftertreatment systems, namely SCR, on the other. The SCR-system is dependent on the adding of a urea-solution leading to a high system cost. In the same time SCR could prove to be beneficial for fuel consumption [1]. The use of EGR has proven to reduce NOx-emissions substantially [2], with a low system-cost compared to after-treatment systems. This leads to a high interest in EGR-systems, which are enablers for cost-efficient compliance with emission regulations.

The short-route system is state of the art and used in most production engines nowadays. In combination with a VGT it can be used to achieve high EGR-rates over the whole engine operation range. The VGT can be used to provide high exhaust backpressure to drive the EGR-flow. At the same time this lowers the turbocharger efficiency, thus lowering the overall engine performance. The long-route system can be used to overcome this problem. Here, the turbine always gets the whole exhaust stream and the VGT can be used to adjust for best turbocharger performance. The needed driving pressure for the EGR can then be provided by an exhaust-throttle [3]. A problem that comes up with long-route systems is the fouling in the intake system. Especially the compressor is a part that needs attention, as it is sensitive to acids or droplets of condensed water.

For compliance with the upcoming emission regulations the transient parts of driving cycles gain more and more importance. While the emission formation in steady-state driving conditions is controllable with EGR, the events during transient events make the control of EGR-flow harder. The pressure changes on both sides of the EGR valves, the turbocharger acceleration and the smoke limitation all have to be taken into account. A too low EGR-level leads to peaks in

NO_x formation, while an excess of EGR leads to smoke formation and corrupts load response. [4,5,6,7]

The aim of this study is to investigate advantages and disadvantages of advanced EGR system in both transient and steady-state driving conditions. Namely a hybrid EGR system, a long-route system with an EGR-pump and a short-route system using a reed valve are analyzed.

EXPERIMENTAL SETUP

The measurements were carried out on a Euro 4 1.9 liter passenger car diesel engine with cooled short-route EGR and variable turbine geometry. Temperatures and crank-angle resolved pressures were measured at the following locations: intake, exhaust, before/after turbocharger and charge-air cooler, after EGR-cooler.

A fast CO₂ measurement system allowed analyzing the EGR-rates during transients. The Horiba Mexa 1300 FRI has a response time of 30 ms, thus providing one measurement per engine revolution at 2000 rpm.

The charge air cooler used in the test cell does not correspond to the one installed in a car. Instead, an air/water cooler with regulated coolant flow is used. The coolant flow is regulated in such a way that the intake temperature obtained in the engine test-cell corresponds to the one in a car.

SIMULATION MODEL

To simulate the engine, the commercial software GT-Power was used. In a first step, an engine model was built according to the test-cell setup. This model was used for calibration of pressure losses, heat transfers and turbocharger performance.

In a second step the exhaust system of the test cell was replaced by a model of the original exhaust system provided by the engine manufacturer. This to assure realistic pressure drops in the exhaust system, as the exhaust system in the test cell has unrealistic low pressure losses compared to a car, because the particulate filter is missing.

To realize the long-route EGR-system, the tubing of the short route system was moved to the low-pressure side of the turbocharger. The piping length can be assumed to be sufficient to realize a long-route system.

Systems description

This article treats three different alternatives of EGR-systems. The hybrid system, which is a combination of the short-route system and the long-route system. Here, the EGR-valve of the short-route path is placed on the hot side of the EGR-cooler, for transient performance.

The second system analyzed is a long-route system where a pump is used to drive the EGR-flow. This allows having an unthrottled exhaust flow, reducing the backpressure behind the turbine. The pump used here is assumed to be electrically driven and to have a constant efficiency of 0.7. For the calculation of the engine's efficiency in steady-state, the driving power of the pump is subtracted from the engines brake power. To account for the efficiencies of generator and electrical motor, an overall efficiency of 0.9 is assumed for those two.

The flows of the exhaust gases as well as of the intake gases of an internal combustion engine are highly pulsating. This can lead to temporary higher pressure in the intake system than in the EGR-system, thus reducing the EGR mass flow or even creating a backflow in the EGR-system. The third system analyzed here uses a reed valve, e.g. a one-way-valve, to eliminate these effects. To be able to estimate the potential of such a system, an ideal reed valve is used here, working without time delays or pressure losses. It can even be used to create EGR-flow in a situation where the average intake pressure is higher than the average exhaust pressure [8].

All three systems are shown in Figure 1 a through c.

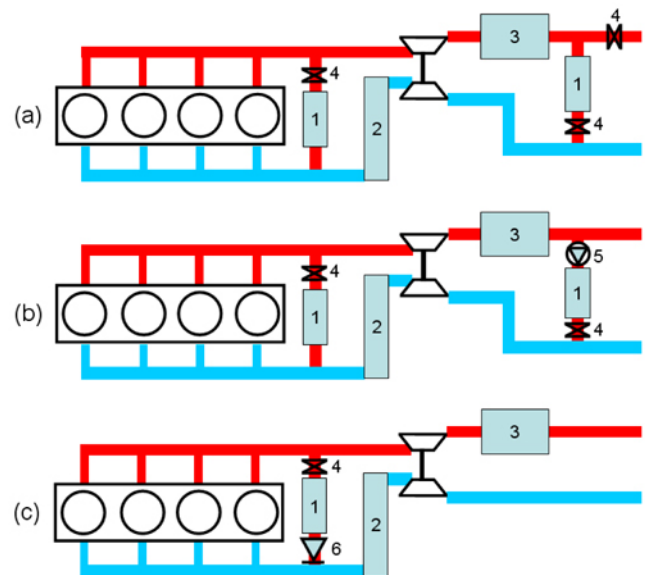


Fig. 1. Hybrid EGR-system (a), Driven Pump in LR (b), Reed valve in SR(c), with: 1. EGR-cooler, 2. Intercooler, 3. DPF, 4. Throttle / Valve, 5. Pump, 6. Reed valve

Heat-Release Rates

For diesel simulations it is common to use measured heat release rates for the combustion. The simulation of the combustion itself would otherwise be a very demanding task. For transient simulation as described in this paper, it is important to use realistic heat-release rates. When going from

a low engine load to a high engine load, the shape of the heat-release rate changes. As the different EGR-systems result in different reaction of the turbocharger and the EGR-loop during the transient, the different intake conditions that appear during the transient have to be met by matching heat-release rates (HRR).

To obtain shapes of HRR for different intake conditions, ten to fifteen transients were run in the test cell for each of the three analyzed full-load transients, to collect a heat-release database. The positions of the VGT as well as of the EGR-valve were varied during these tests. This way, a wide spreading of intake conditions at different loads was achieved. The collected heat-release rates for individual cycles were then sorted after the measured intake conditions. Figure 2 shows a collection of the different heat-release rates obtained.

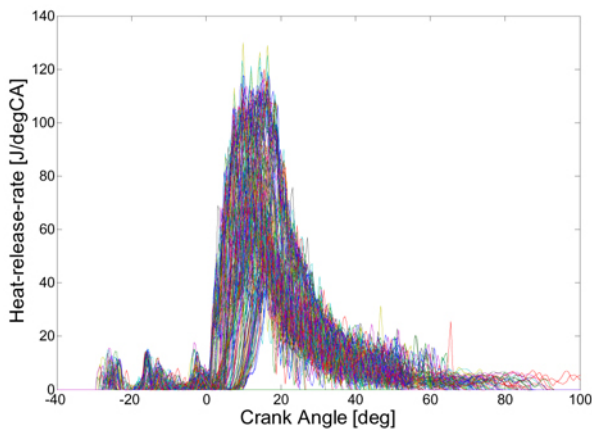


Fig 2. All heat-release rates collected over a transient

The heat release rates were then sorted into look-up tables following two criteria to characterize them. By performing this sorting several times, with changing criteria, it was found that sorting after EGR-rate and intake pressure gave groups with similar-looking heat-release rates, Figure 3. A first attempt of sorting after air/fuel ratio was dismissed as very many cycles lay on the smoke limit, thus having a similar air/fuel ratio. This resulted in a big spreading of shapes of the HRR on a small interval of air/fuel ratio. To find the right heat-release rates to be used during the transient simulation, heat-release rates were placed in a look-up table in GT-Power. For every cycle GT-Power then senses the actual intake pressure and EGR-rate and chooses the matching HRR for the combustion. The height of the heat-release rate was scaled to match the amount of injected fuel.

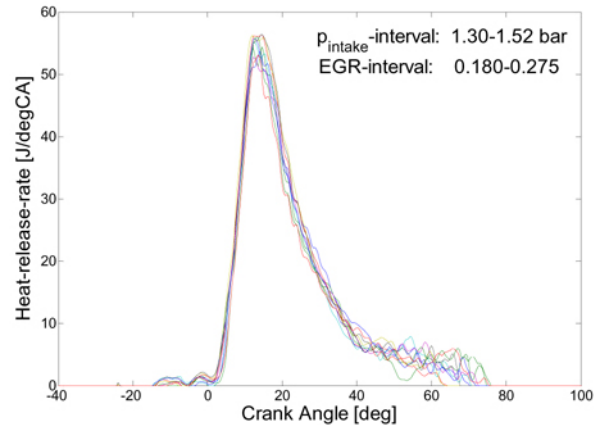


Fig 3. One group of HRR, for a certain range of intake pressure and EGR-rate

Computed Cases

For the steady-state simulations a group of load points was chosen, that is representative for the European driving cycle, Table 1. The transient simulation uses the three points with low load as the starting points for the positive load-transients. The goal of the transients is the full load curve. The negative load transients start at full load and end at the point with lowest load at the respective engine speed.

Table 1. Load points

Load Point	Speed [rpm]	BMEP [bar]	Torque [Nm]	EGR [%]
1	1500	2	30	35.4
2	1500	4.9	75	22.8
3	1500	7.9	120	4.9
4	2000	2	30	44.6
5	2000	4.9	75	29.4
6	2000	7.9	120	16.8
7	2500	2	30	23.3
8	2500	4.9	75	17.7
9	2500	7.9	120	15.1

The EGR-rate is defined as the mass-fraction of exhaust gas in the intake gas:

$$\text{EGR [\%]} = \frac{\dot{m}_{\text{exhaust, intake}}}{\dot{m}_{\text{exhaust, intake}} + \dot{m}_{\text{air, intake}}}$$

Calibration of the Model

The model was first calibrated in steady state. Especially the cases with very low turbo-speed showed a need for correction. This was due to the fact that the turbocharger-maps only include data down to speeds around 70000 rpm while some cases had speeds with only around 30000 rpm.