

Experimental and Computational Analysis of Different EGR Systems for a Common Rail Passenger Car Diesel Engine

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ABSTRACT

Different EGR system layouts (a Long Route, a Short Route, and a combination of the two) were evaluated by means of both numerical simulation and experimental tests.

In particular, a one-dimensional fluid-dynamic engine model was built in order to evaluate the potential of a Long Route EGR system as well as the potential of different EGR combinations between Long and Short Route.

By means of the one-dimensional model, used as a virtual test bench, the estimations of the NO_x emissions, based on the Extended Zeldovich Mechanism (EZM), for the different solutions, were compared and valuable information for the calibration of the coordinated EGR LR, EGR SR and Variable Geometry Turbine (VGT) control systems was obtained.

Using the Long Route EGR layout, or a proper combination of LR and SR, substantial reductions of the NO_x emissions both under steady state and transient operating conditions were achieved, while the numerical simulation allowed obtaining some fundamental knowledge for controlling the EGR flow rate more accurately.

INTRODUCTION

Exhaust Gas Recirculation (EGR) nowadays plays a fundamental role for automotive diesel engines in achieving emission figures able to comply with increasingly tightening regulations, due to the severe

difficulties that have to be faced for the development of cost-effective NO_x aftertreatment systems [1], [2].

System architectures that can be used in order to introduce EGR into engine cylinders through an external circuit include both Short Route (SR) and Long Route (LR) layouts, as well as “hybrid” or dual loop layouts obtained by a combination of the two.

While in the Short Route EGR system a fraction of the exhaust gas is diverted from the exhaust manifold - upstream of the turbine - to the intake manifold - downstream of the compressor (see Figure 1), in the Long Route EGR the exhaust gas portion to be recycled is taken from the main exhaust flow downstream of the turbine and of the aftertreatment system, and it is recirculated upstream of the compressor (see Figure 2). The SR and LR architectures can also be combined together, thus obtaining what is usually called a hybrid or dual loop system (see Figure 3).

Although the SR architecture has been so far the preferred solution for passenger car diesel engines, the increasing diffusion of Diesel Particulate Filters (which will become mandatory to achieve emission levels complying with Euro 5 regulations) and moreover their Close Coupled mounting, has encouraged the use of LR systems [3-6], since the recirculation of a “clean” exhaust flow substantially reduces the drawbacks related to compressor wheel damages and charge air cooler fouling, and greatly simplify the “plumbing” of the circuit with an acceptable permeability level.

The LR system offers the opportunities of achieving higher EGR rates while maintaining low intake temperatures as well as of attaining a more uniform

mixing between exhaust and fresh charge, minimizing non homogeneous distributions from cylinder to cylinder.

However, the LR EGR may often show a poor transient response, due to the rather high volume of the system, and may require some special attention as far as its closed loop control design is concerned [3], [4]. Even though the combination of SR and LR in a dual loop system may substantially improve the transient performance, the increased system complexity increases the control issues, thus suggesting an extensive use of the numerical simulation as a virtual test bench for controls tuning and calibration. The EGR flow rate control is indeed quite complex, due to the need of coordinating the simultaneous actuations of the EGR valve, in order to achieve a certain EGR target and of the Variable Geometry Turbine (VGT), to reach a certain boost level (see Figure 4), as well as to the need of properly actuating a throttle valve in the intake system that can be necessary to increase the pressure gradient between the exhaust and intake systems and therefore the recirculated rate.

The aim of this work is therefore to set-up and calibrate a fluid-dynamic engine model in order to evaluate the potential of different EGR layouts (SR, LR, and dual loop) as far as both steady-state and transients operating conditions are concerned.

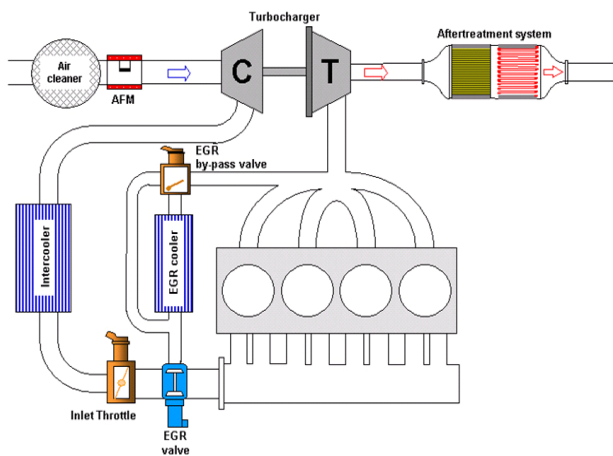


Fig. 1 – Sketch of a typical Short Route EGR system for passenger car diesel engines.

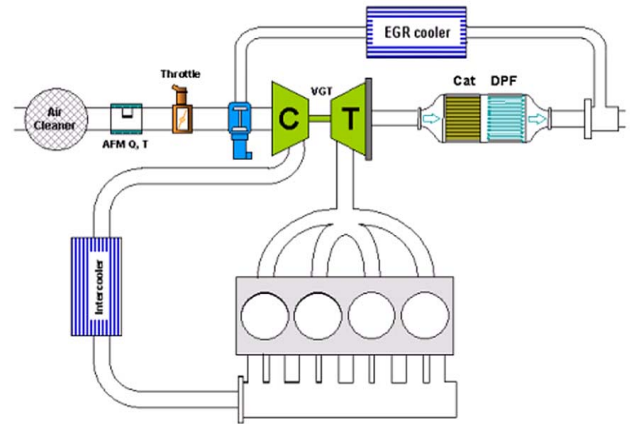


Fig. 2 – Sketch of a typical Long Route EGR system for passenger car diesel engines.

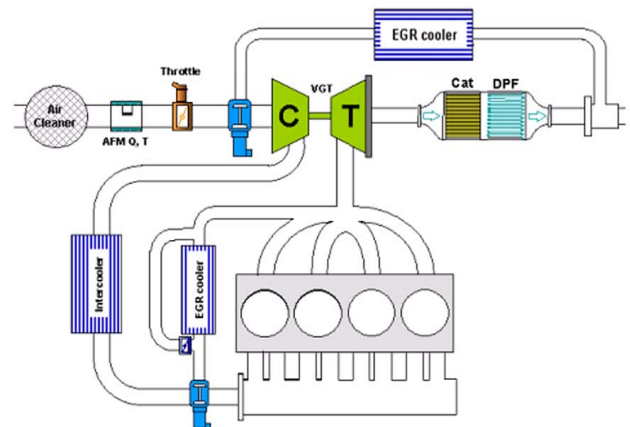


Fig. 3 – Sketch of a typical dual loop EGR system for passenger car diesel engines.

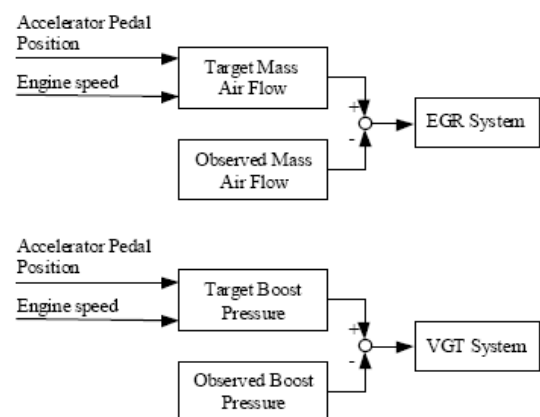


Fig. 4 – Typical EGR and VGT control approach.

ENGINE CHARACTERISTICS AND EXPERIMENTAL SET- UP

A Common Rail turbocharged 2.0 liters displacement diesel engine was selected for this analysis, the main features of which are listed in Table 1.

The engine, which was originally equipped with a SR EGR system as shown in Figure 1, was modified by adding a LR EGR circuit, thus obtaining a dual loop system as shown in Figure 3.

All experimental tests on the reference engine were carried out on an AVL high-dynamic test bed, which was recently set-up at ICE Advanced Laboratory of Politecnico di Torino.

Engine type	DI Turbocharged Diesel EURO4
Displacement	1910 cm ³
Bore x stroke	82.0mm x 90.4mm
Compression ratio	17.5:1
Turbocharger	Single-stage with VGT
Fuel injection system	Common Rail 2 nd gen. CRI2.2 – 1600bar
Maximum power and torque	110kW @ 4000rpm 320Nm @ 2000rpm

Table 1 – Main design features of the test engine.

The test rig is equipped with an ELIN AVL APA 100 cradle-mounted dynamometer featuring maximum torque and power of 525 Nm and 200 kW, respectively, as well as a maximum speed of 12000 rpm. The facility is capable of realizing full four-quadrant operation with high speed and torque dynamics, including simulation of zero torque and gear shifting oscillations in the drivetrain.

The instantaneous fuel consumption was measured through an AVL KMA 4000 system, which is based on a servo-controlled positive displacement counter and can perform measurements over a range of 0.02 – 380 kg/h with a reading accuracy of 0.1%.

As far as the exhaust gas analysis is concerned, the test facility is equipped with a Pierburg AVL AMA 4000 raw exhaust-gas analyzer, which is made up of two analyzer groups which can be operated in parallel, both allowing the measurements of the concentrations of unburned hydrocarbons (HC), nitrogen oxides (NO_x), CO, CO₂ and O₂. The measurement of pollutant levels can therefore be carried out simultaneously in two different locations of the engine intake and exhaust systems (for

instance, in the exhaust manifold upstream of the aftertreatment system and in the intake manifold, in order to evaluate the EGR ratio). Finally, as far as smoke emissions are concerned, the dynamic test bed is equipped with an AVL 415S smokemeter for steady state measurements and with an AVL 439S opacimeter for transient measurements.

Glow plug piezoresistive pressure transducers, coupled with a high-resolution crankshaft encoder, allow in-cylinder pressure measurement in all cylinders. Moreover, gas temperatures and pressures in the most important locations of the exhaust and intake system of the engine (i.e. upstream and downstream of the compressor and turbine, of air and EGR coolers, etc.) are measured by means of K-type thermocouples and piezoresistive pressure transducers respectively.

All of the described measurement devices are controlled by PUMA Open 1.3.2 automation system, which also includes ISAC 400 software for the simulation of vehicle (road load, road gradient and moments of inertia of the driveline components that are not physically present on the test bed) and driver behavior (use of clutch, accelerator pedal and gear shifting), thus allowing the user to reproduce the driving cycles which are usually carried out on the whole vehicle on the chassis dynamometer.

PRELIMINARY EXPERIMENTAL TESTS

Some preliminary experimental tests were initially carried out by running the engine over the New European Driving Cycle (NEDC), and simulating the coupling with an European Sedan passenger car, featuring a 1700 kg IW (see Figure 5), in order to provide validation data for the engine model as far as transient operating conditions are concerned.

Afterwards, 31 steady state operating points, as representative of the engine usage over NEDC (see Fig. 5 and Table 2), were selected for experimental tests in order to provide validation data for the engine model as far as steady-state operating conditions are concerned.

SETTING UP THE ENGINE MODEL

Simulations were carried out using GT-Power, a one dimensional fluid-dynamic code developed by Gamma Technologies for engine performance prediction. The general features of the code are described in detail in [7], [8], [9], while the model construction and the validation process will be briefly summarized here below.

The baseline model construction requires a careful and detailed schematization of the engine and of the intake and exhaust system geometry, as well as accurate and extensive experimental data, which have to be carefully analyzed to properly set heat

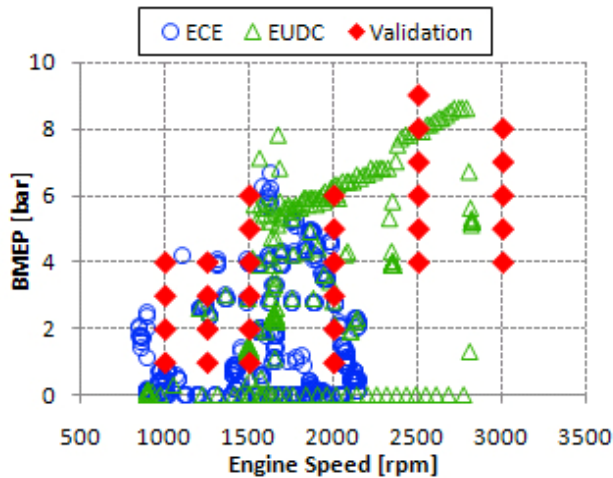


Fig. 5 – ECE-EUDC operating points and model validation points.

transfer and friction loss coefficients, combustion heat release profiles and engine friction estimation. In particular, as far as the combustion model is concerned, the heat release profiles obtained by the analysis of experimental in-cylinder pressure traces were used for the baseline model, while engine friction losses were evaluated through motoring tests. The heat exchange process inside the intake charge coolers (intercooler, short route and long route EGR coolers) was modeled by means of experimentally derived performance maps providing coolers effectiveness as a function of gas flow rate. The pressure drop across the coolers was calibrated by means of the experimental data acquired during experimental steady state tests. The simulation results were then compared with the experimental results under both steady-state and transient operating conditions, as shown in the following paragraphs.

MODEL VALIDATION: STEADY STATE

The closed loop engine controls for VGT rack position, injected fuel rate and EGR valve position were simulated by means of three PID controllers aiming to reach target values of intake manifold pressure, BMEP and air mass flow rate respectively. Comparisons between experimental and simulated values of BSFC and O₂ concentration in the intake manifold are shown in Figures 6 and 7 respectively as an example of the model validation process for part load operating conditions.

The agreement between simulated and measured data is more than satisfactory and the model could therefore be regarded as calibrated with reasonable accuracy as far as steady-state operating conditions are concerned.

Speed [rpm]	bmeP [bar]
900	idle
1000	1
	2
	3
	4
1250	1
	2
	3
	4
1500	1
	2
	3
	4
	5
	6
2000	1
	2
	3
	4
	5
	6
2500	4
	5
	6
	8
	9
3000	4
	5
	6
	7
	8

Table 2 – Steady state engine operating points selected for experimental tests for model validation.

MODEL VALIDATION: TRANSIENT

Further validations were then performed for transient operating conditions. The comparison between measured and simulated injected fuel rate over a portion of the NEDC is shown in Fig. 8 as an example, while measured and simulated O₂