

An Experimental and Numerical Study of an Advanced EGR Control System for Automotive Diesel Engine

F. Millo, E. Pautasso and P. Pasero
Politecnico di Torino

S. Barbero and N. Vennettilli
General Motors Powertrain Europe

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ABSTRACT

In this study, a new EGR control technique, based on the estimate of the oxygen concentration in the intake manifold, was firstly investigated through numerical simulation and then experimentally tested, both under steady state and transient conditions.

The robustness of the new control technique was also tested and compared with that of the conventional EGR control technique by means of both numerical simulation and experimental tests. Substantial reductions of the NO_x emissions under transient operating conditions were achieved, and useful knowledge for controlling the EGR flow rate more accurately was obtained.

INTRODUCTION

Exhaust Gas Recirculation (EGR) is one of the most effective methods for reducing Nitrogen Oxides (NO_x) emission from diesel engines, and nowadays plays a fundamental role for automotive engines in achieving emission figures able to comply with increasingly tightening regulations, due to the severe difficulties that have to be faced for NO_x aftertreatment. However, a high level of accuracy in the control of the EGR flow rate is mandatory, because an excessively large flow rate may cause a substantial and unbearable increase of Particulate Matter (PM) emissions. Moreover, the EGR flow rate control is quite complex [1-5], due to the need of coordinating simultaneous actuations of the EGR valve, of the Variable Geometry Turbine (VGT) and also of a throttle valve in the intake system that can be used to increase the pressure gradient between the exhaust and intake systems and therefore the recirculated gas rate (see Fig. 1).

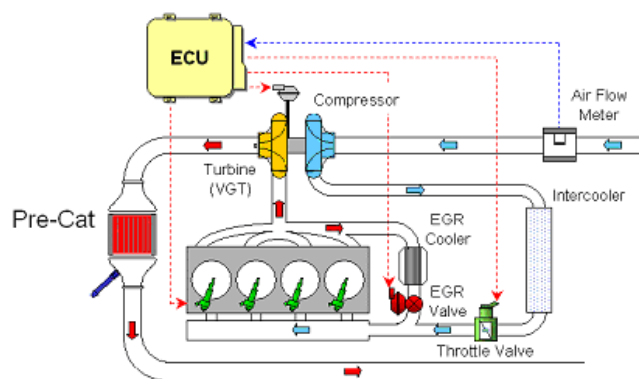


Fig. 1 – Sketch of a typical EGR system for passenger car diesel engines.

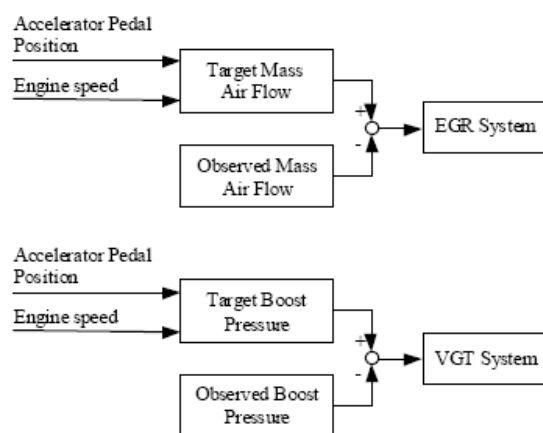


Fig.2 Typical EGR and VGT control approach (from [2]).

Furthermore, in a conventional EGR system (see Fig. 2), the EGR flow control is based on a look-up table of the Mass Air Flow (MAF), and the ECU actuates

the EGR valve trying to reach the target MAF value which has been set up for each engine operating condition with a preliminary steady state calibration, while the VGT position is controlled independently to match a target boost pressure level.

In this way, the EGR flow is controlled indirectly by controlling the total intake flow through the boost level, and assuming that the EGR flow is the difference between the total intake flow and the fresh air flow. However, during transients, due to the gas dynamics in the intake and exhaust systems and to the turbocharger inertia, the actual EGR flow can be substantially different from the nominal value, resulting in a significant worsening of NOx emissions [2].

Since, as shown in Fig. 3 [6], NOx emissions are extremely sensitive to O₂ concentration in the intake manifold, because the amount of the inert exhaust gas fraction in charge gas determines the maximum flame temperature, which in turn approximately determines the amount of NOx emission according to the well established Zeldovich's extended NOx formation mechanism, new advanced EGR control systems have been proposed [1-5], aiming to control the charge oxygen concentration to its target value. In this way, substantial improvements in NOx emissions during transient operation could be achieved, as well as advantages as far as the control robustness, since the controlled variable (i.e. the oxygen concentration) is more directly related to the NOx formation than the air mass flow used in the conventional EGR control.

However, the use of an oxygen sensor in the intake manifold to track the controlled variable is usually impossible for reasons concerning cost, sensor contamination and durability, and therefore alternative solutions to achieve the O₂ concentration through the use of a dynamic observer have been proposed [2,3].

Nevertheless, since the designing and tuning of such a control system is a time consuming activity, several efforts have been made to explore ways that could lead to significant reductions of the development process: in particular, the use of numerical simulation to build engine models by which control strategies can be tested and tuned "on a desk" seems to be very promising.

The aim of this work is therefore to evaluate the potential of the use of a fluid-dynamic engine model for the development of an advanced EGR control strategy during transients and for the assessment of its robustness.

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.

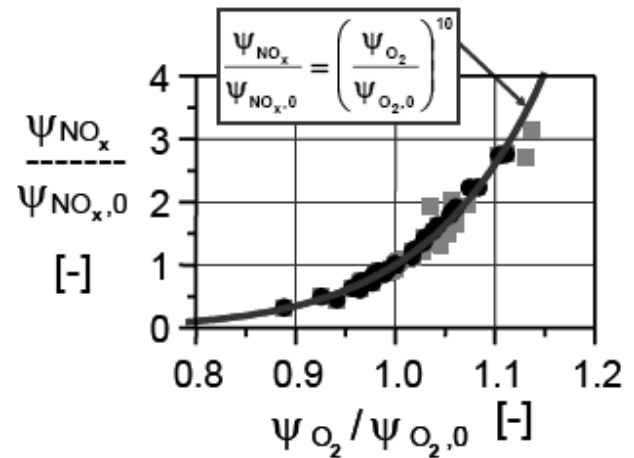


Fig. 3 – Correlation between NOx emissions and O₂ concentration in the intake manifold [6]: Ψ_{NO_x} represents the emission level which is obtained with a certain O₂ concentration in the intake manifold, normalized through the reference $\Psi_{NO_{x,0}}$ emission which is obtained with a reference O_{2,0} concentration in the intake manifold under steady state operating conditions. Different symbols correspond to different engine operating conditions.

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.

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. 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 cylinders #1 and #3. 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.

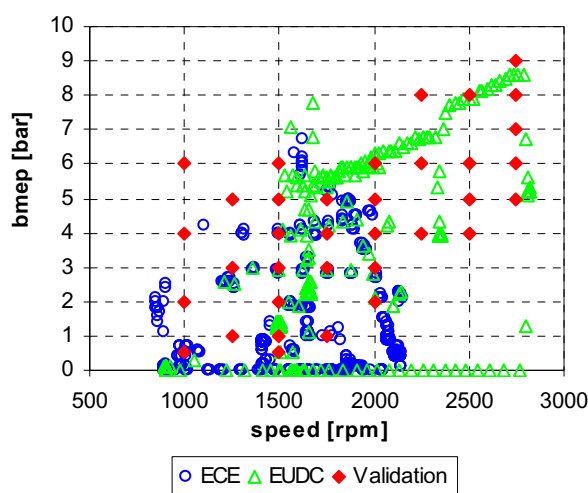


Fig. 4 – ECE-EUDC operating points and model validation points.

PRELIMINARY EXPERIMENTAL TESTS

Some preliminary experimental tests were initially carried out by running the engine (with the conventional EGR control) over the New European Driving Cycle (NEDC), and simulating the coupling with an European Sedan passenger car, featuring a 1700 kg IW (see Fig.4), in order to provide validation data for the engine model as far as transient operating conditions are concerned.

Afterwards, 35 steady state operating points, as representative of the engine usage over NEDC (see Fig. 4 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.

Speed [rpm]	bmep [bar]
1000	0.5
	2
	4
	6
1250	1
	3
	5
1500	0.5
	1
	2
	3
	4
	5
1750	6
	1
	3
	4
2000	5
	6
	2
	3
	4
2250	5
	6
	8
2500	4
	5
	6
	8
2750	5
	6
	7
	8
	9

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