

Assessment of Cooled Low Pressure EGR in a Turbocharged Direct Injection Gasoline Engine

Konstantinos Siokos, Rohit Koli, and Robert Prucka
Clemson University

Jason Schwanke and Julia Miersch
Robert Bosch LLC

ABSTRACT

The use of Low Pressure - Exhaust Gas Recirculation (EGR) is intended to allow displacement reduction in turbocharged gasoline engines and improve fuel economy. Low Pressure EGR designs have an advantage over High Pressure configurations since they interfere less with turbocharger efficiency and improve the uniformity of air-EGR mixing in the engine. In this research, Low Pressure (LP) cooled EGR is evaluated on a turbocharged direct injection gasoline engine with variable valve timing using both simulation and experimental results. First, a model-based calibration study is conducted using simulation tools to identify fuel efficiency gains of LP EGR over the base calibration. The main sources of the efficiency improvement are then quantified individually, focusing on part-load de-throttling of the engine, heat loss reduction, knock mitigation as well as decreased high-load fuel enrichment through exhaust temperature reduction. Synergies between EGR and features of the modern multi-actuated engines are investigated to provide a deeper understanding of this technology. Several limitations of this approach are also addressed. The EGR dilution effect on combustion variability for different operating conditions is characterized using experimental results. In addition, water condensates passing through the compressor as well as the cooling capacity of the EGR cooler and intercooler could also be limiting factors for this technology.

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INTRODUCTION

Rising fuel costs and the increasingly stringent emission regulations require the automotive industry to search for technologies that enable more fuel-efficient operation. Aiming to reduce fuel consumption, auto makers have introduced low displacement turbocharged gasoline engines. These powertrains are able to achieve the performance of the larger naturally-aspirated engines already in the market. At the same time, the higher levels of specific power output associated with the reduced engine displacement minimize operation at the lowest loads which are governed by significant pumping losses due to throttling [1].

The turbocharger and the higher compression ratios of modern downsized engines increase knocking propensity and produce high exhaust temperatures upstream of the turbine during high-load operation. The introduction of cooled Exhaust Gas Recirculation (cEGR) proves to be an effective method to suppress knock and reduce fuel enrichment for exhaust temperature reduction [2].

In [3,4,5,6], the comparisons between High Pressure (HP) and Low Pressure (LP) EGR systems were presented. Based on the operating conditions, the authors study the benefits and drawbacks for each configuration and propose the most appropriate architecture for each operating regime of the modern downsized turbocharged engine. Cooled LP EGR is the preferred solution for speeds and loads above the knock limit of the engine where knock mitigation and/or exhaust temperature reduction is required. Uncooled HP EGR proves to be more effective for thermally de-throttling the engine at low-load operation.

The authors in [4,7] compare catalyzed with non-catalyzed EGR and evaluate the pressure differential that drives LP EGR. Non-catalyzed EGR provides higher pressure difference and extends the LP EGR delivery range. Combustion of non-catalyzed EGR is faster than catalyzed, due to the effect of CO and H₂ on laminar flame speed. However, the basic advantage of catalyzed EGR is the reduced NO_x concentration. In [8,9,10] the authors focus on the importance of NO_x concentration on knock mitigation and identify that elimination of NO_x in EGR significantly enhances knock suppression. Besides, "clean" EGR reduces the possibility of compressor and EGR circuit fouling since HCs are oxidized in the catalyst. Thus one of the most

important benefits of the Low Pressure configuration over High Pressure is the possibility to extract EGR downstream of the three-way catalyst.

Moreover, the authors of [11] quantify the fuel efficiency benefits of using cooled EGR for two different fuels (E0 and E85). Fuel economy improvements were in the range of 3% to 5% for both fuels. Finally, in [12] the fuel economy gains of cooled EGR are evaluated on a downsized boosted gasoline engine under two different geometric compression ratios. Besides the pumping loss reduction, the authors showed the efficiency gains of increasing compression ratio while maintaining advanced combustion phasing, due to knock mitigation effects of cooled EGR.

This study is focused on the benefits and limitations of Low Pressure EGR aiming to cover the entire operating regime of a turbocharged direct-injection gasoline engine. A high-fidelity simulation model is calibrated through experimental data and uses predictive combustion modeling to provide the proper burn rate for the various operating conditions being studied. Both simulation and experimental results are used to identify the main sources of efficiency improvement. Part-load de-throttling of the engine, heat loss reduction, knock mitigation effects and decreased high-load fuel enrichment as a result of EGR dilution are quantified and discussed in detail. Additionally, synergies between EGR and features of the modern multi-actuated engines are investigated to provide a deeper understanding on the integration of these systems in modern gasoline engines. Limitations of this technology, associated with high EGR dilution, cooling capacity and water condensation are also assessed and discussed.

This paper is organized as follows. First, a brief description of the experimental and simulation setup is presented. Next, simulation-based optimized calibrations are used to identify fuel efficiency gains of using LP cEGR. Experimental validation of the optimized results is also conducted to evaluate the accuracy of predictions. Then, the main sources of efficiency improvement are examined individually and results are discussed. Finally, limitations of the LP EGR configuration are evaluated, before final conclusions are derived.

EXPERIMENTAL SETUP

A 430 kW AC engine dynamometer is used for the experimental portion of this research. Crank angle resolved data acquisition is performed using an AVL-671 32-channel system. Cylinder pressures are measured using AVL GH12D piezoelectric sensors. Piezo-resistive Kulite transducers are used for dynamic pressure measurements in both the intake and exhaust ports of the test engine. Dedicated liquid cooling circuits have been utilized for exhaust manifold pressure transducers. The data are sampled at 0.5 crank angle degree intervals to properly capture all relevant gas exchange characteristics. K-type thermocouples are utilized for measurement of temperatures at specific locations on the engine.

Table 1. Engine characteristics

Engine Type	In-line 4-cylinder SI
Displacement	1998 cc
Bore x Stroke	86 x 86
Compression Ratio	9.5:1
Intake System	Twin-Scroll Turbocharger (waste-gate controlled) with Intercooler
Valve Train	DOHC, 4-valves/cylinder with Continuously Variable Valve Timing
Fuel Injection System	Direct injection
EGR System	Low Pressure cooled EGR

The engine (Table 1) is a turbocharged 2.0L Inline-4 with direct fuel injection, and is equipped with dual-independent camshaft phasing systems. The combustion chamber bowl on the head has four valves and a pent-roof shape with a cavity for the fuel injector. The piston crown is shaped to allow wall guided spray injection. Ignition is achieved using high-energy coil-on-plug coils triggered by TTL level ECU signals. A BorgWarner K03-2074 twin-scroll turbocharger with internal waste-gate and blow-off valve is installed on this engine. A Low Pressure EGR configuration is also implemented (Figure 1). Exhaust gases are extracted downstream of the turbine. EGR passes through a cooler and is delivered to the intake air-path system upstream of the compressor. The EGR cooler is a tube-core type chosen for low pressure differential. Twin liquid-to-air intercoolers have been used to allow high boost/load capability. Production-intent engine controllers have been modified to include software hooks on specific engine control parameters.

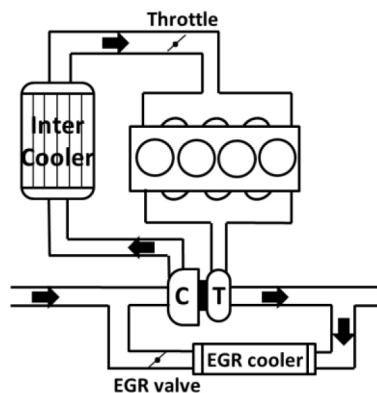


Figure 1. Schematic of the engine layout with the Low Pressure EGR configuration

SIMULATION SETUP

The engine is modeled using the 1D simulation software GT-Power provided by Gamma Technologies Inc (GTI). Detailed measurements of the engine configuration are taken, with emphasis given on the intake and exhaust manifolds. Precise turbine and compressor maps are used and detailed CAD models of the combustion chamber geometry are added to the simulation. The 3D models are used to calculate in-cylinder heat transfer by determining the area fractions that are in contact with the burned and unburned gases. Since the

burn rate and thus the Wiebe fit-coefficients, are not known in advance, the Predictive Combustion modeling option is used. This model, which uses the detailed combustion chamber geometry, ensures that proper burn rate response to actuator positions (e.g. cam timing, ignition timing, EGR, etc.) is achieved.

To compare experimental and simulation data under similar operating conditions, the crank angle location of 50% mass fraction burned (CA50) is used as the combustion anchoring option. In this way, simulation and experimental combustion phasing are matched closely. Moreover, a tuned throttle controller and EGR controller are used to set the load and EGR dilution. These controllers actuate on the throttle and EGR valve, respectively. For knock prediction, the Kinetics-Fit model, which is based on detailed kinetics simulations and is developed by GTI, is implemented in order to account for EGR dilution effects on knock propensity.

Experimental data from dynamometer operation are used to calibrate the simulation model. The combustion model is calibrated by adjusting the flame kernel growth, turbulent flame speed and dilution effects of EGR on burn rate. Additionally, temperature and mass flow measurements are used to identify intercooler efficiency, while an engine friction model is also calculated through several different experimental operating points.

Aiming to capture the effect of EGR in a wide range of operating conditions, a Design of Experiments (DoE) approach is used. Due to the multi-actuation engine architecture and the wide range of possible values for each actuator, applying a Full Factorial DoE is very computationally intensive. Instead, a Latin Hypercube partial factorial DoE is implemented. In comparison with other partial factorial methods, this approach is also favorable since it does not require prior knowledge of the fitting equation that would describe the resulting response surface [13,14,15].

The engine is actuated through intake and exhaust cam phasings, waste-gate valve position, EGR dilution and ignition timing, with the latter being controlled through user-commanded CA50. In part-load operation, stoichiometric and homogeneous air-to-fuel mixture is used. In high-speed and high-load conditions, exhaust temperature limitations would normally require enriched mixture operation and thus lambda value is also a factor in the design matrix. According to the engine speed and load which are set for each operating condition, waste-gate valve opening is fixed to a constant value, thus reducing the number of actuators.

The number of DoE experiments conducted for each operating point is important since it affects both the accuracy and the computational time required to study the entire operational regime of the engine. A sensitivity analysis was conducted on this model to determine the optimum accuracy with the least computational effort. The results show that using 400 different combinations of actuators to populate the design matrix for each operating point provide reliable results. Table 2 shows the range of operating conditions along with the range of values for each actuator.

Table 2. DoE operating points and actuators' range

	Part-load	High-load
Engine Speed	1500 – 3000 rpm	3000 – 4000 rpm
Engine load	2 – 8 bar BMEP	16 – 20 bar BMEP
Exhaust Cam Location	5 – 70 CAD aTDC (Exhaust Valve Closing)	
Intake Cam Location	-60 – 5 CAD aTDC (Intake Valve Opening)	
Combustion Phasing	8 – 20 CAD aTDC 50% Burn Point	8 – 35 CAD aTDC 50% Burn Point
EGR dilution	0 – 20% EGR	0 – 10% EGR
Lambda	Set to 1	0.7 – 1.0

To investigate the effect of each actuator/parameter on engine operation and perform the optimization tasks, a DoE post-processor provided in the GTI software is used. The basis of this application is to apply a mathematical surface fit to the results of the DoE process. Once this map-fit is calculated, it is possible to investigate the significance of each actuator on engine performance, the accuracy of these predictions, as well as perform optimizations using the desired constraints.

Besides the independent actuators (factors) that dictate engine operation, dependent variables (responses) are selected in order to provide the appropriate data for the map fitting process. These variables consist of the optimization goals and constraints. Aiming to optimize fuel economy, Brake Specific Fuel Consumption (BSFC) is the most important response that needs to be map-fitted. However, during the optimization process several constraints are taken into consideration in order to exclude results that do not represent viable solutions.

Cycle-to-cycle combustion variability is a crucial constraint during optimization. One of the major limitations for EGR applications is increased combustion duration. In the same way, in VVT-controlled engines, extreme valve overlap could result in high internal residual that would negatively affect combustion variation. COV_{IMEP} is a representative measure for cycle-to-cycle combustion variation. The engine simulation software however, unlike real engine operation, is not able to capture such cycle-to-cycle inconsistencies through the predictive combustion model. This 'ideal' operation dictates the need of identifying other parameters that can be correlated with combustion variability to account for limitations in COV_{IMEP} . Combustion duration from 10% to 90% burn point (CA10-CA90) is used in this study [16].

Experimental measurements for various operating points provide a correlation between COV_{IMEP} and CA10-CA90 (see Figure 2). The correlation is determined by sweeping combustion duration either by changing EGR dilution or controlling the valve overlap (to account for internal residual). Thus, an initial constraint on combustion duration is set during the optimization process in order to ensure that COV_{IMEP} remains less than 3% in the final results.