

Experimental Investigation of Transient Response and Turbocharger Coupling for High and Low Pressure EGR Systems

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ABSTRACT

The transient response of an engine with both High Pressure (HP) and Low Pressure (LP) EGR loops was compared by conducting step changes in EGR fraction at a constant engine speed and load. The HP EGR loop performance was shown to be closely linked to turbocharger performance, whereas the LP EGR loop was relatively independent of turbocharger performance and vice versa. The same experiment was repeated with the variable geometry turbine vanes completely open to reduce turbocharger action and achieve similar EGR rate changes with the HP and LP EGR loops. Under these conditions, the increased loop volume of the LP EGR loop prolonged the response of intake O₂ concentration following the change in air-fuel ratio. The prolonged change of intake O₂ concentration caused emissions to require more time to reach steady state as well. Strong coupling between the HP EGR loop and turbochargers was again observed using a hybrid EGR strategy. The potential benefit of the HP EGR loop's smaller volume and shorter residence time was largely negated by the simultaneous use of the larger LP EGR loop. Under these conditions, the intake charge oxygen concentration responded more quickly to actuation of the LP EGR valve than the HP EGR valve.

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INTRODUCTION

Transient engine operation has the potential to produce unintended engine operating states that can increase exhaust emissions. Several studies have shown that one of the main causes of these sub-optimal conditions is the difference between the fuel system response and the air system response during transients. While fuel system parameters such as injection timing and fuel quantity can change very rapidly, boost pressure and intake O₂ concentration can take much longer to reach steady state optima [1,2,3]. The air system includes EGR, which is widely used to reduce steady state NO_x and PM emissions. However, slow rates of change in EGR flow rate and composition relative to the changes in fuel injection parameters during transients can affect emissions formation. Glewen et al. [3] showed that the rates of change of Air Fuel Ratio (AFR) during transients are different than those of the intake O₂ concentration. Intake O₂ concentration takes longer to approach steady state due to the residence time in the EGR loop(s) of the exhaust gas from previous cycles at different AFR's. This change in O₂ concentration during the transient was shown to have an impact on emissions formation especially for combustion strategies implementing high EGR fractions.

LP or long route EGR has recently been introduced primarily as a supplement to HP EGR to provide further reductions of NO_x and PM emissions [4,5,6]. Instead of diverting exhaust gas flow from before the turbine directly to the intake manifold, LP EGR passes through the turbine and the after-treatment devices before mixing with fresh air upstream of the compressor inlet. Some advantages of LP EGR include the additional capacity for heat rejection, improved turbocharger performance, and improved EGR distribution in the intake manifold. Potential disadvantages include increased DPF loading, compressor and charge cooler fouling or corrosion, and decreased transient response [7,8,9,10]. The potential for decreased transient response with the addition of a LP EGR loop is the topic of this study. The LP EGR loop has the potential to exacerbate the differences between fuel and air system response times which ultimately cause sub-optimal engine performance during transient operation.

Several studies have investigated the transient response of HP, LP, and hybrid (combined HP and LP) EGR strategies. Han et al. [11] conducted both increasing-speed and increasing-load transients using a HP EGR system and showed that the EGR rate deviates from the steady state level during transient engine operation. The magnitude of this deviation increased with the rate of the speed or load change. These differences

were attributed to variations in pressure drop across the EGR valve caused by turbocharger lag, and resulted in elevated exhaust smoke opacity. Reifarth and Angstrom [7] investigated the rate of EGR change for different fractions of HP and LP EGR during increasing-load transients computationally using GT Power. That study showed a delay in the change of EGR fraction with the addition of LP EGR due to the increased loop volume. Millo et al. [12] also used GT Power to conduct step changes of EGR fraction with both the HP and LP EGR valves. In addition to the delay in the change of EGR fraction with LP EGR seen by Reifarth and Angstrom, Millo's simulation showed that the LP EGR loop reached the final EGR target more quickly during an increasing-step change in EGR fraction, illustrating a difference in the relationship between EGR rate and the turbocharger behavior for the two loops. While these studies show many of the aspects of transient EGR loop performance, none capture the iterative change of intake O₂ concentration change demonstrated by Glewen et al. [3].

EXPERIMENTAL CONFIGURATION

Engine and Controls

The experiments were performed on a General Motors Z19DTH 1.9 liter Euro-4 specification four-cylinder diesel engine equipped with primarily standard production hardware including variable geometry turbine (VGT), high pressure EGR cooler, and variable swirl intake system. Table 1 contains detailed engine specifications, and an engine system schematic is shown in Figure 1. Standard production hardware was used with the exception of the intercooler, engine control unit (ECU), and the movement of the particulate filter unit from the production under-floor placement to just downstream of the turbine outlet. An air-to-water intercooler was used in the laboratory to replace the production air-to-air intercooler, but cooling water temperature and flow rate were controlled to replicate the cooling capacity of the original production system. A Bosch ECU modified with an Embedded Tool Kit (ETK) system from ETAS allowed real-time access and modification to the engine maps and other control parameters via INCA software installed on the laboratory computer. This system enabled injection timing(s), rail pressure, EGR valve opening, VGT position, and other parameters to be adjusted to apply different combustion or control strategies. These parameters as well as other command set-points and measured values used by the ECU were recorded once per crankshaft revolution to provide an overview of the control system state and to supplement the data provided by other external instrumentation.

The fuel injection quantity is calculated by the ECU based on the rail pressure and injection command duration. This estimation method can produce significant errors due to rail pressure dynamics, particularly for short injections and when using a pilot injection, but comparisons to a fuel mass flow meter have confirmed that the estimated quantities are

qualitatively correct and repeatable for a given set of injection parameters. More importantly, an estimated quantity can be provided for each individual injection event which is not possible with a fuel flow meter when injection quantities change rapidly from cycle to cycle.

Table 1. Engine Specifications.

Engine Type	Euro 4 Diesel
Bore	82 mm
Stroke	90.4 mm
Displacement	1.9 liters
Cylinder Configuration	Inline 4 4 valves per cylinder
Swirl Ratio	Variable (2.2-5.6)
Compression Ratio	17.5
Turbocharger	Garrett M53 VGT
EGR	Hybrid High/Low Pressure, Cooled
ECU	Bosch EDC16
Injection Pump	Bosch CP1H3
Injectors	Bosch CRIP2-MI 149° Included Angle 7 holes 440 flow number

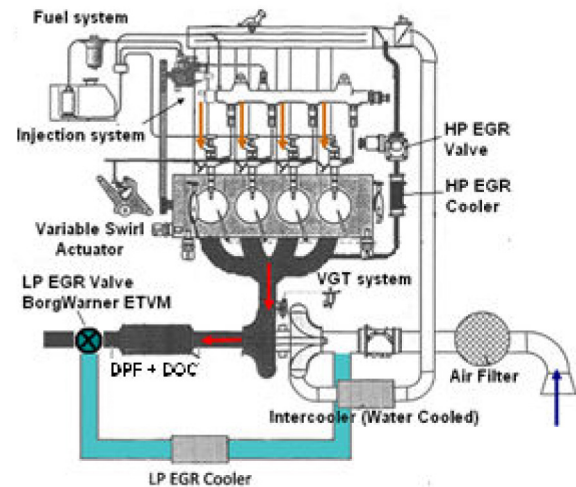


Figure 1. Schematic overview of the GM 1.9 liter multi-cylinder engine system with LP EGR loop added.

A low pressure EGR loop was designed and fabricated based on technical guidance provided by BorgWarner [13] in order to optimize system performance and enhance the overall capability and flexibility of the air handling system. The production catalyst and DPF unit was moved from its downstream location corresponding to a vehicle under-floor position and mounted as close to the turbine outlet as possible in order to minimize the LP EGR system volume and response times. An exhaust throttle valve module (ETVM) provided by BorgWarner served the combined functions of a LP EGR valve and exhaust throttle to obtain additional backpressure as

needed to increase the LP EGR flow rate. Additional information on the design and function of the ETVM is available in [6]. Engine coolant is used in the EGR cooler as with typical production engine applications to minimize condensation of exhaust gas components and to ensure a realistic amount of cooling power is applied. LP EGR is introduced to the intake air path via a Y fitting immediately upstream of the compressor, as schematically illustrated in [Figure 1](#). The total volume of the LP EGR system from the turbine outlet to the intake manifold including the after-treatment devices, coolers, and plumbing is approximately 3.5 engine displacement volumes. This increases to 5.2 displacement volumes if the intake and exhaust ports and manifolds are considered. For comparison, the HP EGR cooler and plumbing contain roughly 0.2 engine displacement volumes, or 1.9 displacement volumes when the ports and manifolds are included.

Instrumentation

In order to maintain precise time resolution, all data acquisition was hardware triggered based on the engine crankshaft encoder. This ensured that data from all systems was recorded at precisely the same points during a given cycle, providing a comprehensive data set describing the condition of the engine at a specific instant in time. Cylinder and manifold pressures, injection current, fresh air flow rate from a laminar flow element (LFE), and Cambustion™ fast emissions analyzers were sampled at 1024 points per crankshaft revolution while other instruments were sampled once per crankshaft revolution. Data is presented as a function of engine cycles rather than time because many transient processes such as gas exchange in the air system proceed as a function of the number of engine cycles completed as opposed to elapsed time. Using engine cycles as the independent variable effectively normalizes elapsed time with respect to engine speed and provides a more fundamental indication of transient rates of change.

Cylinder pressure measured in cylinder number two was used to calculate the apparent rate of heat release as well as certain combustion metrics such as the crankshaft location of the 50% mass fraction burned point. The combustion ringing intensity was calculated according to the correlation proposed by Eng [14]. This correlation provides a more accurate indication of combustion noise by including the influence of cylinder bulk gas temperature, pressure, and engine speed in addition to the maximum rate of pressure rise per crank angle degree.

High speed measurements of NO and UHC were provided by Cambustion CLD 400 and HFR 500 fast response emissions analyzers, respectively. The 10-90% response time of these instruments is just a few milliseconds, so near-crank-angle time resolution is possible. For this work, data points collected during one engine cycle were mass-flow-averaged to obtain a single average NO or UHC concentration for each cycle. All

emissions reported in this work were engine-out measurements made directly downstream of the turbine and before any after-treatment devices.

Transient exhaust smoke opacity was measured using an AVL 439 Opacimeter and converted to an approximate mass values using existing correlations described in [15,16]. The mass correlations are not believed to be quantitatively accurate for LTC PM emissions, but can reliably indicate cycle-to-cycle trends and offer the benefit of intuitive, physically meaningful units for PM emissions. Oxygen concentration is measured in the intake near cylinder 2, in the intercooler, and in the exhaust. These three measurements allowed the fractions of HP and LP EGR to be calculated independently. Pressure and temperature measurements were made at critical locations in the air system including the intake and exhaust manifolds, EGR system, and charge air cooler. An HBM T-40 inline torque transducer measured crankshaft torque. This combination of available instrumentation provided a comprehensive view of the engine system state during each individual combustion cycle.

Procedure

In order to illustrate the differences between HP and LP EGR loops, step changes were conducted with both EGR loops between the same starting and ending fresh air flow rates. Fueling parameters including fuel quantity, rail pressure, injection timing as well as engine speed were all held constant. The step changes were conducted at an engine operating point of 1500 RPM 2 bar BMEP. The EGR valve step changes were first conducted with only HP followed by only LP EGR. The step changes were then also conducted with a hybrid EGR strategy where the position of one of the valves (e.g., the HP valve) was held constant, while a step change in the position of the other valve (i.e., LP valve) was initiated. While steps of the EGR valve positions at constant speed and load are not representative of common control strategies, they serve well the intended purpose of isolating and observing the fundamental differences in response rate characteristics between the two loops.

The combustion strategy used for these experiments was based on a Euro 4 production calibration strategy utilizing a pilot injection with a later main injection near TDC. Baseline engine parameters for a 1500 RPM 2 bar BMEP engine condition can be found in [Table 2](#). The AFR and emissions values shown there will not match those seen in these experiments because fresh air flow rates were altered during the step change in EGR valve position. An illustration of injection command, pressure trace, and apparent heat release rate for the combustion strategy at the baseline operating condition can be seen in [Figure 2](#).