

LPL EGR and D-EGR® Engine Concept Comparison Part 2: High Load Operation

Raphael Gukelberger, Jess Gingrich, Terrence Alger, and Steven Almaraz
Southwest Research Institute

ABSTRACT

The ongoing pursuit of improved engine efficiency and emissions is driving gasoline low-pressure loop EGR systems into production around the globe. The Dedicated EGR (D-EGR®) engine was developed to minimize some of the challenges of cooled EGR while maintaining its advantages. The D-EGR engine is a high efficiency, low emissions internal combustion engine for automotive and off-highway applications. The core of the engine development focused on a unique concept that combines the efficiency improvements associated with recirculated exhaust gas and the efficiency improvements associated with fuel reformation. To outline the differences of the new engine concept with a conventional LPL EGR setup, a turbocharged 2.0 L PFI engine was modified to operate in both modes. The second part of the cooled EGR engine concept comparison investigates efficiency, knock resistance, combustion stability, and maximum load potential at high load conditions. These results document the superior knock tolerance and stability of the D-EGR concept over the LPL EGR embodiment and how to overcome the combustion limitations that have historically limited SI engine efficiency at high EGR dilution levels. This study also demonstrates that the reformat is the source of the improved knock mitigation of a D-EGR concept by comparing the D-EGR results to a LPL EGR engine with and without supplemental H₂ and CO at high loads.

CITATION: Gukelberger, R., Gingrich, J., Alger, T., and Almaraz, S., "LPL EGR and D-EGR® Engine Concept Comparison Part 2: High Load Operation," *SAE Int. J. Engines* 8(2):2015, doi:10.4271/2015-01-0781.

INTRODUCTION

The transportation industry is facing significant challenges from the combination of high fuel prices and increasing regulatory pressure caused by the concern over climate change and energy security. By 2025, the automotive industry will be required to have reduced CO₂ emissions by at least 30% and pollutant emissions by a factor of 3. The more stringent emissions and efficiency regulations force manufacturers and researchers alike to develop new engine concepts and improve current systems. Current technology trends for high efficiency gasoline engines include, but are not limited to: direct injection, downsizing in conjunction with boosting, down-speeding, and hybridization. Alternative routes involve the use of dilution in the form of fresh air or cooled EGR. Lean burn concepts offer great efficiency but are challenged by their high NO_x emissions, and costly hardware is required to comply with modern emissions criteria. Cooled EGR concepts are becoming more prevalent as is evidenced by several production applications for high efficiency SI engines when maximum power output is not paramount [1, 2, 3, 4, 5]. Efficiency improvements with cooled EGR can be realized by increasing the indicated cycle efficiency and reducing heat transfer and throttling losses. EGR also improves the knock resistance and enables high compression ratio operation and / or an extended operating range with optimal combustion phasing. Heat transfer and knock resistance are improved since cooled EGR has a high specific heat capacity and acts as a diluent in the combustion process. As a result, in-cylinder gas temperatures can be lowered. EGR dilution also improves efficiency by increasing the ratio of specific heats

during the cycle. In addition to improving the engine efficiency, the use of high levels of EGR reduces NO_x, CO, PM, and PN emissions [6]. With relatively minor engine modifications, allowing the utilization of cooled EGR, real-world and NEDC fuel consumption improvements of > 5 % can be achieved while reducing emissions by an even larger margin.

In general, the thermodynamic efficiency of a gasoline engine cycle is simply governed by the ratio of specific heats (γ) and the compression ratio (CR) as given below in the equation for the Otto cycle efficiency [7].

$$\eta_{Otto} = 1 - \left(\frac{1}{CR^{(\gamma-1)}} \right) \quad (1)$$

Based on this equation, it is desirable to increase the CR for efficiency improvements. However, with the CR elevation auto-ignition increases due to higher compressed gas temperatures thereby setting ceiling for achievable spark ignition (SI) engine efficiency. In fact, in boosted gasoline engines the CR is lower when compared to their naturally aspirated counterparts. Therefore, for further engine efficiency gains, it is of utmost importance to improve knock mitigation in SI engines. Reducing the in-cylinder gas temperatures by lowering the intake manifold temperatures or taking advantage of the charge cooling effect of direct injection ultimately lowers the propensity to knock. Also, switching to high octane fuels, such as

natural gas or alcohols allows the boost levels or CR to increase with modest hardware modifications. Ethanol and Methanol, with their high latent heat of vaporization, have not only high octane ratings but also greatly increase the charge cooling effect [8, 9]. Another approach for enhanced knock resistance is greater combustion chamber cooling through water-jacket optimizations [10]. Researchers have shown a torque increase of ~3% is possible with increased cooling of the upper part of the cylinder liner [11]. The engine described in one investigation used an Alumite coating applied to the piston crown surface as well as a top piston ring made of a high thermal conductivity material [3]. Both methods reduced the piston surface temperature and thus knock tendencies. Baek et al. found the same results when high thermal conductivity valve guides and valve seat inserts were used [12]. Utilizing a GDI engine with variable intake and exhaust cams, another knock mitigation technique is the use of scavenging. Especially at low engine speeds and high loads, the cylinder can be scavenged with fresh air by adjusting the camshafts to yield a large valve overlap. Similar to EGR, the cooling effect of the fresh air reduces the knock sensitivity of the engine [13]. Additionally, the scavenging of fresh air to the exhaust flushes out hot residual gases and enables operation with rich in-cylinder mixtures to provide stoichiometric AFR upstream of the catalyst. The net rich in-cylinder AFR further reduces knock propensity and can increase peak torque [14]. Variable intake cam timing can also be used to reduce the effective compression ratio through late intake valve closing (LIVC). LIVC on a NA engine is often referred to as Atkinson cycle and has been shown to reduce auto-ignition [15]. The modification and optimization of the intake ports, combustion chamber, and spray targeting proved to be excellent knock mitigation techniques owing to high in-cylinder charge motion and homogenization [16, 17].

Whereas most SI engine technologies are trying to improve knock resistance for maximum efficiency or performance, only few engine concepts attempt to improve the second variable- the ratio of specific heats found in [equation \(1\)](#). Gingrich et al. showed how the in-cylinder fuel reformation process of a D-EGR engine improves both the knock tolerance as well as the ratio of specific heats for greatly improved brake thermal efficiency in an SI engine [18, 19].

DEDICATED EGR CONCEPT

The D-EGR engine concept is an engine configuration where the exhaust of a sub-group of power cylinders is routed back to the intake of all the cylinders creating EGR for the engine with the exhaust of only a few cylinders. In a four cylinder application the exhaust of one cylinder will be used as EGR for the entire engine resulting nominally in full time 25% EGR. This minimizes the need for active EGR control across the speed load range. By having dedicated EGR, the D-EGR cylinder(s) can operate at any equivalence ratio since their exhaust will not exit the engine before passing through another cylinder operating at a stoichiometric air fuel ratio (AFR). This offers the option of varying the gaseous composition of the EGR. In particular, it allows the D-EGR cylinder to run rich and produce hydrogen (H_2) and carbon monoxide (CO) through in-cylinder fuel reformation. The reformation process recovers some of the waste heat, normally rejected to the atmosphere, while still generating power in the dedicated cylinder(s). The presence of reformat

enhances the flame speeds, combustion, and knock tolerance of all the cylinders [20] and can hence overcome combustion limitations that have historically limited SI engine efficiency at high EGR dilution levels. Since only stoichiometric exhaust leaves the engine, a conventional three-way catalyst can be utilized to reduce pollutant emission. The net result of this engine architecture has demonstrated high engine efficiency with a low associated cost. Moreover, the D-EGR engine is capable of operating on a variety of alternative fuels, including ethanol and natural gas, and has thereby shown further efficiency and CO_2 improvements.

The mechanisms by which reformat improves efficiency in a spark ignited engine are well known and have been understood for several years [21, 22, 23]. Several researchers have pursued external reformer technologies to improve the EGR dilution tolerance of gasoline engines. In general, the presence of reformat increases the burn rates and EGR dilution tolerance of the engine. In addition, the fast burn rates and high RON values of H_2 and CO lead to considerable extra knock resistance. The combination of high EGR tolerance - which increases knock resistance - and the increased knock resistance from the reformat allows the engine to be operated at very high compression ratios.

The primary objective of this study was to investigate potential differences between the LPL EGR and D-EGR engine configurations at high load conditions and at different compression ratios. In particular, combustion stability, efficiency, and knock tendency were examined at selected operating conditions.

EXPERIMENTAL SETUP

This study has been carried out on a turbocharged, inline four cylinder 2.0 L engine with port fuel injection. The engine was equipped with variable camshaft phasers on the intake side. In its baseline configuration, peak torque of 300 N-m was reached starting at 2250 rpm and maximum power delivery was 180 hp at 5500 rpm. One measure of the engine modifications for this work included the replacement of the production turbo charger with a dual-scroll unit designed for a 1.6 L engine to account for EGR dilution. Additionally, a Dual Coil Offset (DCO[®]) high ignition energy system was employed. The DCO system is a fully variable, continuous discharge ignition system. It can operate in single strike, multi strike, or DCO mode. The level of primary ignition energy, re-strike offset, and amount of re-strikes can be adjusted. A more detailed description can be found in previous publications [24]. Unless otherwise noted, the ignition system was always operated in DCO mode and the ignition energy was controlled to ~400 mJ and 5 DCO re-strikes. To take full advantage of the improved knock resistance with high levels of EGR, tests were conducted with various compression ratios. For these tests, the stock compression ratio of 9.1:1 was increased to 12.5:1. The fresh intake air was conditioned to 25°C and the humidity controlled to a dew point of 15°C. The backpressure of both engine configurations was set to 30 kPa at 4000 rpm and 18 bar BMEP. [Table 1](#) gives a description of the relevant physical parameters of the engine in stock form. To enable a direct comparison between the LPL EGR and D-EGR setups, both configurations used the identical engine long block, boosting, and fueling hardware as well as ignition system. The main discrepancies can be found in the intake and exhaust plumbing

Table 1. Base engine specification

Displaced volume	1998 cc
Stroke	93 mm
Bore	82.7 mm
Connecting Rod	144 mm
Compression ratio	9.1:1
Number of cylinders / valves	4 in line / 16
Maximum power	180 hp @ 5500 rpm
Maximum torque	300 Nm @ 2250 rpm
Injection	Multipoint sequential

A schematic of the LPL EGR configuration can be seen in [Figure 1](#). The expanded EGR was drawn post turbine, cooled via an EGR cooler, and introduced to the fresh air mass flow by a Venturi mixer. The Venturi mixer was developed for EGR control simplicity. When installed in a LPL EGR system, the Venturi mixer reduces the level of control complexity. At low engine speeds and loads, where EGR tolerance is usually inferior, the Venturi mixer inducts small amounts of EGR. As engine speed and load increases, the EGR flow increases naturally. This creates synergy since the engine tolerates more EGR at higher engine loads and speeds and greater EGR dilution is required for knock mitigation. An EGR valve was still required primarily to enable shut-off of EGR during certain conditions - that is cold conditions or at high power levels. For research purposes, it was also used to regulate the amount of EGR. In cases where the inlet pressure was greater than the backpressure of the engine, an inlet throttle was utilized to create the required negative delta pressure to drive the EGR flow.

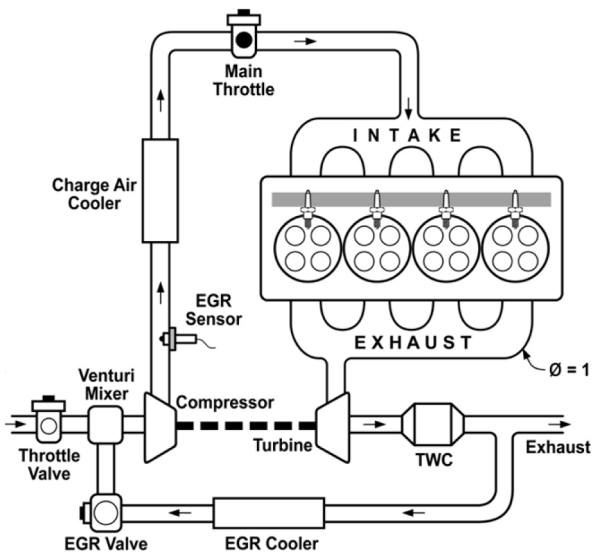


Figure 1. Schematic of a turbocharged 4-cylinder engine in a LPL EGR configuration

An embodiment of the D-EGR concept is shown in the schematic in [Figure 2](#). In this graphic, only one of the cylinders is used to produce the entirety of the EGR inducted by the engine. A wide-band UEGO sensor in the dedicated exhaust stream was used for fueling feedback and control. A prototype EGR mixer was designed to allow good

temporal EGR mixing to evenly spread the exhaust gas expelled from one cylinder across all four and minimize cylinder to cylinder EGR imbalance and will be the topic for a future publication. The mixed gas is cooled through an oversized intercooler, eliminating the need for an EGR cooler. It is expected, however, that any series application will need both an EGR cooler and a charge air cooler.

The control architecture for both engine configurations included two parallel controllers. The majority of the engine systems, such as fuel, boost and ignition timing, were controlled with an open ECU provided by the engine OEM. The new systems, including the EGR valve, inlet throttle valve, DCO ignition for the LPL EGR architecture and dedicated cylinder fuelling and spark timing in the D-EGR embodiment, were controlled with a separate and fully flexible control unit.

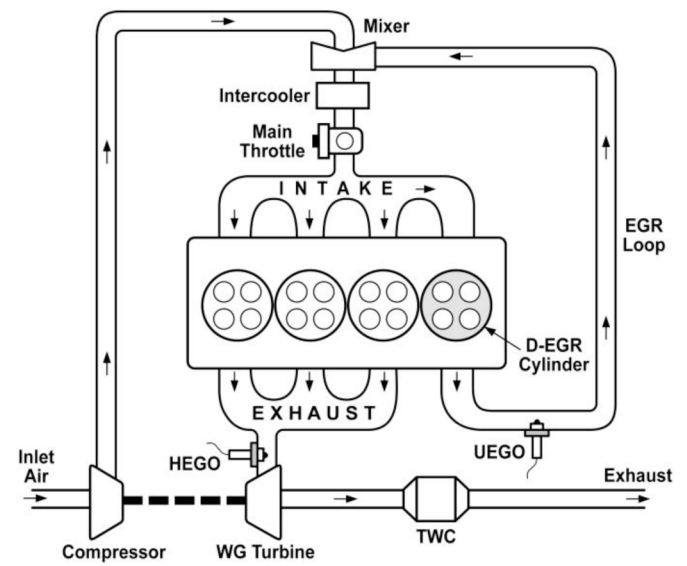


Figure 2. Schematic of a turbocharged 4-cylinder engine in a D-EGR configuration

Haltermann EEE certification gasoline was used for the majority of the engine testing. The fuel had a lower heating value (LHV) of 42.89 MJ/kg, an Anti knock Index (AKI) of 92 and Hydrogen to Carbon ratio (HCR) of 1.862. Investigations with the lower octane fuels are marked in the text. [Table 2](#) states the specific chemical properties for all gasoline fuels used.

Table 2. Test gasoline specifications

	Haltermann EEE	Haltermann 87 AKI	Pump grade 87 AKI
LHV [MJ/kg]	42.89	43.096	43.613
RON	97	91.9	91.2
MON	87.9	84	83
Carbon [wt.-%]	86.5	86.67	86.74
Hydrogen [wt.-%]	13.48	13.33	13.52
Oxygen [wt.-%]	<0.05	0	<0.1
Sulfur [ppm]	30	29	30.6
HCR	1.862	1.863	1.87
OCR	0.001	0	0.002