

Dedicated EGR Vehicle Demonstration

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ABSTRACT

Dedicated EGR (D-EGR) is an EGR strategy that uses in-cylinder reformation to improve fuel economy and reduce emissions. The entire exhaust of a sub-group of power cylinders (dedicated cylinders) is routed directly into the intake. These cylinders are run fuel-rich, producing H_2 and CO (reformat), with the potential to improve combustion stability, knock tolerance and burn duration.

A 2.0 L turbocharged D-EGR engine was packaged into a 2012 Buick Regal and evaluated on drive cycle performance. City and highway fuel consumption were reduced by 13% and 9%, respectively. $NO_x + NMOG$ were 31 mg/mile, well below the Tier 2 Bin 5 limit and just outside the Tier 3 Bin 30 limit (30 mg/mile).

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INTRODUCTION

Federal emissions regulations continue to drive emissions limits lower. Currently, the EPA Tier 2 regulations require fleet-average emissions to conform to Bin 5 (90 mg/mi non-methane organic gas (NMOG) and 70 mg/mi NO_x). These limits are further reduced in the new Tier 3 regulations. The new regulation limits the fleet-averaged $NO_x + NMOG$ emissions to 30 mg/mi. Figure 1 depicts the reduction graphically.

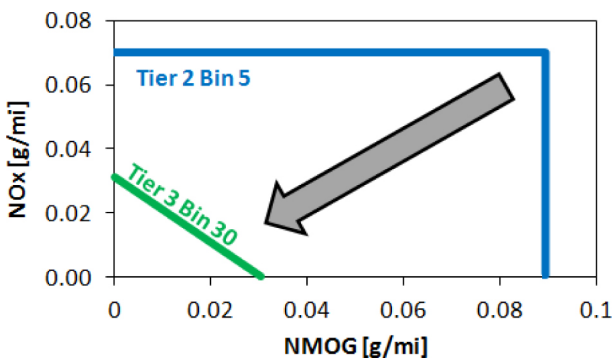


Figure 1. Transition from Tier 2 to LEV-III emissions regulations.

Additionally, concerns over energy independence and climate change have led to increases in the regulated efficiency of light duty vehicles. A fleet-average target of 54.5 MPG has been established for MY2025

vehicles in the US, while a 95 g/km CO_2 requirement is set for MY2020 vehicles in the European Union. The automotive industry is seeking solutions to these regulatory challenges in many forms: improved combustion systems, hybridization and alternative energy, among others. This paper will focus on a combustion system improvement solution called Dedicated Exhaust Gas Recirculation (D-EGR).

D-EGR is an engine concept in which the entire exhaust from one or more cylinders (D-EGR cylinders) is routed into the intake system [1]; a schematic of the D-EGR engine is shown in Figure 2. The D-EGR cylinders are operated fuel-rich to benefit combustion for the entire engine via in-cylinder reformation of the gasoline to products including hydrogen (H_2) and carbon monoxide (CO). The H_2 and CO produced from the rich combustion in the dedicated cylinders speeds combustion, improves knock resistance and extends EGR tolerance [2,3].

There are other ways of making reformat in-cylinder. Besides D-EGR, fuel injection into the negative valve overlap (NVO) period is a method of producing H_2 and CO in situ [4]. This method is often applied on HCCI engines, though the chemistry remains unchanged for D-EGR. Szybist et al. demonstrated increased H_2 and CO reformation with ethanol compared with iso-octane [5]. As with D-EGR, NVO fuel reformation also extended EGR tolerance [6].

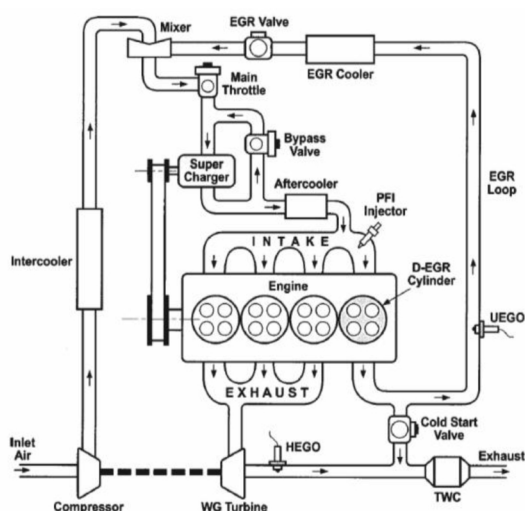


Figure 2. D-EGR Schematic.

Alger et al. have demonstrated reduced fuel consumption and emissions with D-EGR in a test cell [7]. This paper aims to establish the benefits on a production-intent vehicle platform, address a few of the impediments to production intent D-EGR development, and demonstrate a 10% improvement in combined fuel economy on US test cycles.

EXPERIMENTAL SETUP

The experimental setup consists of the test engine, which was modified to be in D-EGR form and tested on an engine dynamometer bench, and the prototype vehicle, with the modified engine and control system. Both will be described here.

Test Engine

The engine used was a General Motors 2012 LHU. Figure 3 contains an image of the base engine. Table 1 lists the engine specifications before and after conversion to D-EGR.



Figure 3. GM LHU 2.0 L turbocharged DISI engine.

While the D-EGR engine was a modified GM LHU, the fuel economy and emissions results were compared to the base engine for two variants of the Buick Regal, the Regal GS which was powered by the 2.0 L turbocharged GM LHU, and the Regal Premium, powered by the 2.4 L naturally aspirated GM LEA.

Table 1. 2012 LHU engine specifications, Stock and D-EGR.

	Regal Premium Baseline	Regal GS Baseline	Regal GS D-EGR
Designation	GM LEA	GM LHU	
Displacement	2384 cc	1996 cc	
Stroke	98 mm	86 mm	
Bore	88 mm	86 mm	
Compression Ratio	11.2:1	9.3:1	11.7:1
Number of Valves	4		
Valve Actuation	Dual Independent Cam Phasers		
Induction	Naturally Aspirated	Twin-Scroll Turbocharger	Clutched Supercharger; Twin-Scroll Turbocharger
Maximum Torque	233 Nm @ 4900 RPM (12 bar BMEP)	400 Nm @ 2400 RPM (25 bar BMEP)	270 Nm @ 1500–5500 RPM (17 bar BMEP)
Maximum Power	136 kW	200 kW	156 kW (78 kW/L)

The target power and torque of the D-EGR engine was designed to exceed the specifications of the GM LEA. Figure 4 illustrates the torque and power curves of the LEA and D-EGR LHU.

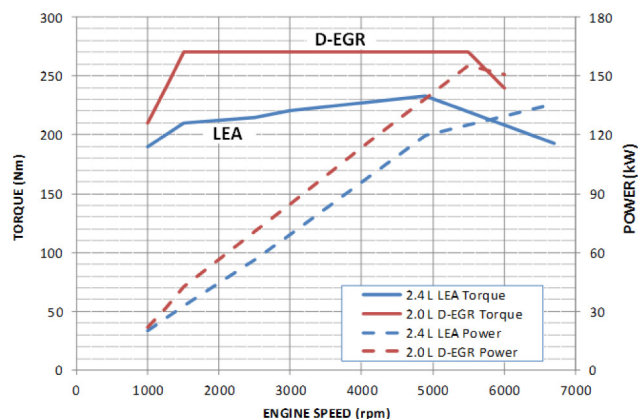


Figure 4. Comparison of D-EGR power and torque to the baseline vehicle engine.

The fuel used for all testing was Haltermann EEE gasoline. The specifications for this fuel can be found in Table 2.

Table 2. Haltermann EEE gasoline specifications.

	Haltermann EEE
LHV	42.89
Ethanol Content	0%
H/C	1.862
O/C	0.001
RON	97
MON	88

The conversion to D-EGR consisted mainly of external modifications to the air handling, fueling, and ignition systems. As noted in [Table 1](#), the only internal engine modification was an increase in compression ratio.

As indicated in [Figure 2](#), the exhaust manifold was modified so that the entire dedicated cylinder exhaust was routed through an EGR cooler to the intake via a mixer, [Figure 5](#). The mixer was analyzed using CFD to validate the spatial and temporal mixing performance [8,9]. A "cold-start" valve allowed some amount of EGR to be bypassed into the exhaust system. When in this configuration, the dedicated exhaust entered the exhaust system immediately before the catalyst, bypassing the turbocharger.

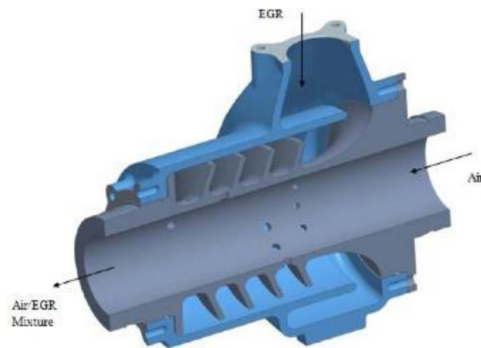


Figure 5. EGR Mixer design.

The knock tolerance improvement permitted higher compression ratio pistons. The final configuration used forged 11.7:1 compression ratio pistons ([Figure 6](#)).



Figure 6. D-EGR high compression piston (left) compared to stock 9.3:1 piston (right).

Test Vehicle

The engine was installed in a 2012 Buick Regal GS ([Figure 7](#)). There are two versions of the vehicle that are discussed in this paper: the Regal Premium and the Regal GS. The Regal Premium uses the 2.4 L GM LEA engine (naturally aspirated) and the Regal GS uses the 2.0 L GM LHU (turbocharged). Additionally, the Premium version was only sold with an automatic transmission. The GS was offered with both automatic and manual transmission options; a manual transmission was selected so that a recalibration of the shift strategy

was not required for the D-EGR configuration. Comparison of the GS to Premium vehicle data requires an accounting for the different final drive ratios for the two vehicles.



Figure 7. D-EGR vehicle.

Laser scanning of the vehicle engine bay was performed to aid in packaging the additional components of the D-EGR system. [Figure 8](#) illustrates the packaging of the D-EGR system in the Buick Regal engine bay.



Figure 8. D-EGR vehicle engine bay with complete D-EGR system.

There were several components required for the D-EGR conversion that were sourced from automotive suppliers. Eaton provided a V400A prototype supercharger with electromagnetic clutch, Diamond Electric provided a Dual Coil Offset (DCO[®]) ignition system including a 43 V DC-DC converter and GM provided a calibration ECU. The ECU was flashed with software that enabled a CAN layer to receive actuator commands from the ETAS ES1000 controller. BorgWarner provided the EGR cooler as well as the EGR valve.

Vehicle Control Strategy

The engine was controlled with a suite of independent controllers: the production GM ECM, ETAS ES1000, and a National Instruments Compact Rio. A diagram of the controller can be seen in [Figure 9](#).