

The Interaction between Fuel Anti-Knock Index and Reformation Ratio in an Engine Equipped with Dedicated EGR

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ABSTRACT

Experiments were performed on a small displacement (< 2 L), high compression ratio, 4 cylinder, port injected gasoline engine equipped with Dedicated EGR[®] (D-EGR[®]) technology using fuels with varying anti-knock properties. Gasolines with anti-knock indices of 84, 89 and 93 anti-knock index (AKI) were tested. The engine was operated at a constant nominal EGR rate of $\sim 25\%$ while varying the reformation ratio in the dedicated cylinder from a $\phi_{D-EGR} = 1.0 - 1.4$. Testing was conducted at selected engine speeds and constant torque while operating at knock limited spark advance on the three fuels. The change in combustion phasing as a function of the level of overfuelling in the dedicated cylinder was documented for all three fuels to determine the tradeoff between the reformation ratio required to achieve a certain knock resistance and the fuel octane rating. These results indicated that the effective increase in knock resistance of the engine was linear with the reformation ratio and that the slope of this improvement was roughly constant across fuel types. In general, a 10% increase in overfuelling in the dedicated cylinder was equal to a 1.8 AKI increase in fuel octane. In addition to the constant torque testing, a series of tests across a range of engine speeds was performed to determine the knock-limited peak torque at varied enrichment rates with the three test fuels. As expected, the higher octane fuels with higher enrichment levels showed the highest knock limited torques but with some overlap between the fuels, indicating that overfuelling in the dedicated cylinder could be used to overcome knock challenges with low octane fuels. In addition, to understand the impact of ethanol, two fuels were procured with a 93 AKI, one as an E0 and the other as an E10 fuel.

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INTRODUCTION

Challenges to achieve future regulation goals for fuel economy and reduction in noxious emissions are paramount. As modern powertrains are required to meet new fuel economy standards and emissions regulations, high efficiency / high power engines are evolving to meet the challenge. Spark ignited (SI) engines are approaching efficiency levels typically seen in their compression ignition (CI) counterparts by employing technologies such as cooled EGR, advanced boosting devices and low bore to stroke ratios. Companies, such as Honda and Toyota, now produce SI engines that utilize high compression ratio, low pressure loop (LPL) exhaust gas recirculation (EGR) and bore to stroke ratios as low as 0.67 [1, 2].

Compared to CI engines, SI engines have lower efficiency at both low and high loads, despite the inherent efficiency advantage of the Otto-cycle over either the Diesel-cycle or combined cycle [4]. At traditional drive-cycle conditions, the SI engine is significantly less efficient than a diesel engine. While there are several reasons for the difference in efficiency, including the gasoline engine's lower compression ratio, higher pumping losses and lower cycle-averaged γ , the pumping losses lead to the greatest

difference at these points. Most of the pumping losses can be traced to the use of a three-way catalyst for emissions compliance. This aftertreatment system is a robust, relatively inexpensive and proven technology to produce ultra-low emissions. However, the three-way catalyst requires a stoichiometric exhaust stream to operate properly, which fixes the engine's air/fuel ratio (AFR). To control load, the engine must therefore be throttled, which results in the aforementioned pumping work. Even if the engine could run lean, the lean limit of gasoline is such that pumping losses would still be incurred at the lightest loads, unless alternative forms of combustion, such as HCCI or stratified charge, are used [5].

Given the reality of pumping losses in stoichiometric gasoline engines at low loads, a common proposed solution is to reduce engine displacement and use a boosting device to increase the engine's specific power output. Since the vehicle power requirements will not change, the reduced engine displacement will lead to a shift in the engine's drive-cycle operating range to higher levels of specific power output, greatly reducing the need to operate the engine at the lowest loads [6]. In addition, shrinking the engine size and operating at higher specific power levels can reduce the relative penalty of frictional losses.

Pumping losses, however, are not the only significant impediment to high-efficiency gasoline engines. Knock and the measures required to overcome it also reduce efficiency. The first step in addressing knock in a boosted engine is to retard spark timing. Since knock is strongly influenced by the temperature history of the charge, retarding spark timing can reduce knock by lowering the end-gas temperatures and increasing the ignition delay of the end gas during the combustion event. High levels of spark retard are often employed in modern, boosted engines. At low engine speeds, where the challenges from knock are the highest, spark timing can often be retarded by 30° or more from the optimum condition. As engine speed increases, the need for extreme spark retard is reduced but not, however, eliminated. Spark retard has several negative effects on efficiency, including increased specific fuel consumption and higher exhaust gas temperatures. At high speeds (i.e. greater than 2000 rpm) the exhaust temperatures can exceed 900°C, which currently requires the use of fuel dilution to cool the exhaust.

While spark retard is effective in reducing the knock tendency of the engine, there is a limit to the amount of spark retard that can be employed before the engine becomes unstable. If the specific power requirements of the engine are higher than the load at which the engine can be stably operated, then the only option remaining is to reduce compression ratio. As the downsizing and boosting trend has taken hold, the average compression ratio of a production gasoline engine has fallen significantly. Even the most advanced gasoline engines reduce the compression ratio by at least 1.5 when going from a naturally aspirated (NA) to boosted application [7]. When discussing future powertrains and the requirement for high efficiency, it is worth remarking that, on a fundamental level, the only two factors that influence the ultimate efficiency of an engine operating on the Otto-cycle are the compression ratio and the ratio of specific heats of the working fluid (γ) [8]. While it is possible to reduce compression ratio and achieve adequate fuel consumption results at some mid-to-high load conditions [9], the fuel consumption at low to part load in these engines is often compromised from their high compression ratio, NA counterparts. In addition, the downsized engine will often encounter reduced efficiencies at high loads [10], due to some combination of knock-related spark retard and, at high engine speeds, the enrichment that accompanies retarded spark timing. Enrichment may also be necessary even at optimum combustion phasing to improve the durability of engine hardware at high specific power levels. However, over-fuelling at high power levels prevents aggressive downsizing by making it difficult or impossible to meet modern emissions requirements and significantly increasing specific fuel consumption. Downsizing in this manner may offer the potential to reduce CO₂ emissions, but lower fuel consumption at high loads will be necessary to fully implement a downsizing strategy.

In previous studies of boosted engines, the presence of some EGR has been shown to decrease exhaust temperatures [11, 12, 13] and reduce or eliminate the requirement for over-fuelling [11, 13-14]. In addition, higher levels of EGR (EGR rates > 15%) have been shown to have a significant effect on efficiency by reducing knock, leading to improved combustion phasing [11, 12, 13, 14, 15] and the ability to operate at high loads at compression ratios above 12:1 [16-17]. Elevated EGR levels also serve to substantially reduce the emissions of CO [8, 13], NO_x [8, 11, 13] and particulates (both number and

mass) [18-19] through a reduction in combustion temperatures. While the sources of improvement in high dilution engines continue to improve the fuel economy potential as the EGR rate increases, a combination of real-world challenges limits the ultimate level of improvement. The combination of a reduction in the burn rate and high exhaust emissions, caused by unstable operation and low post-flame temperatures, reduces the brake thermal efficiency improvement at EGR rates above 20-30% in most engines [20]. Thus, a major challenge for high dilution engines is to improve their dilution tolerance, through enhanced ignition systems [21, 22, 23, 24] or by supplementing the charge with high reactivity compounds, either pure H₂ [25-26] or reformed fuel, consisting of CO and H₂ in some proportion [27, 28, 29, 30, 31]. The addition of these highly reactive compounds results in significantly faster flame propagation rates, improved engine stability at high dilution levels and better engine performance, e.g. [25, 26, 27, 31, 32, 33].

In previous publications [3, 34], the concept of using one (or more) cylinders dedicated to EGR production was proposed as a method of reducing some of the demerits involved with on-vehicle reformation of hydrocarbon fuels (discussed in [3]). In these applications, however, the work was limited to initial proof of concept testing. The results indicated that, while the concept has some promise as a high efficiency architecture, there are some challenges involved with using a dedicated cylinder [3] and in full-time operation at very high EGR rates [34]. In addition, previous work on high dilution applications indicated that there are considerable challenges in designing a boosting system that will provide the correct combination of low speed torque, specific power (in terms of kW/L) and transient response for a high dilution engine [35].

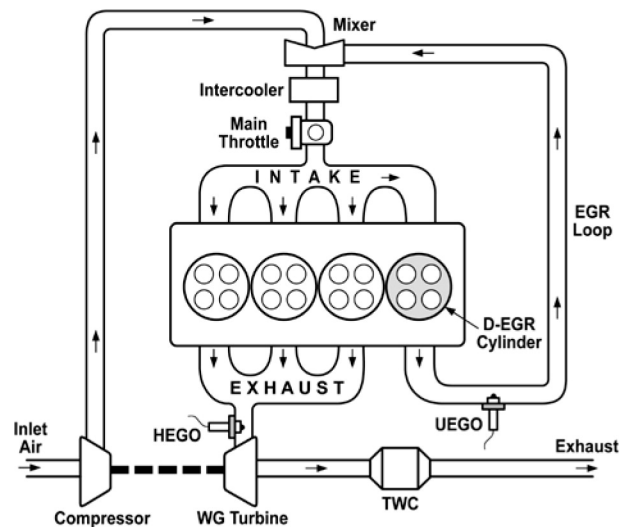


Figure 1. Schematic of a turbocharged 4-cylinder engine in a DEGR configuration

In addition to lowering emissions by improving efficiency in the engine, CO₂ emissions on a well-to-wheel basis must be considered. Future fuels enabling high efficiency SI engines will have to not only satisfy advanced engine requirements, i.e. high knock resistance, but also produce less CO₂ emissions in the refinery. [3] If a less processed fuel, such as a low octane gasoline, can be utilized in an engine it similar brake thermal efficiency to that of SI engines, then there is a considerable potential for lower well-to-

wheels CO₂ emissions.. Concepts such as the aforementioned dedicated EGR concept could enable the use of the low quality fuel and further reduce overall CO₂ emissions.

DEDICATED EGR CONCEPT

An embodiment of the D-EGR concept introduced in the previous section is shown in the schematic in [Figure 1](#). In this schematic one of the cylinders is used to produce the entirety of the EGR used by the engine. The D-EGR cylinder is labeled as such in the schematic. In this case, one cylinder is producing the EGR for all four cylinders of the engine, and the engine will run with nominally 25% EGR. A feature of the D-EGR concept is that the EGR rate is not proportionately controlled; the engine will continuously run with a nominal 25% EGR rate, thereby making control less complex. By having a cylinder dedicated to EGR production, 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 (H₂) and carbon monoxide (CO) through in-cylinder fuel reformation. The presence of reformat enhances the flame speeds, combustion, and knock tolerance of all the cylinders [3] and can hence overcome combustion limitations that have historically limited SI engine efficiency at high 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 [36]. Moreover, the D-EGR engine is capable of operating on a variety of fuels, including potentially low RON gasoline, and has some possible incremental efficiency and CO₂ improvements.

The mechanisms by which reformat improves efficiency in a spark ignited engine are well known and have been understood for several years [3, 36, 37]. 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 to the knock tolerance improvement afforded by EGR, the D-EGR concept provided additional knock resistance when incylinder reformation was used in the D-EGR cylinder. In-cylinder reformation was realized by running the D-EGR cylinder rich of stoichiometric. A typical operational target was to run an equivalence ratio between 1.3 and 1.4 in the dedicated cylinder. Rich combustion produced reformat consisting of carbon monoxide (CO) and hydrogen (H₂), that have Research Octane Numbers (RON) of 106 and 130 respectively. When the D-EGR cylinder was run with an equivalence ratio between 1.3 and 1.4 the knock resistance was predicted to be similar to an increase in RON of the fuel of approximately two points, based upon a calculation of the mass averaged octane of gasoline (96 RON), CO and H₂ ([Figure 2](#)) [37]. EGR and reformat have a compounding influence on knock mitigation and therefore engine efficiency. The primary objective of this study was to investigate potential differences between fuel

grades/quality on a D-EGR engine at part and high load conditions. In particular, combustion stability, efficiency, and knock tendency were examined at selected operating conditions.

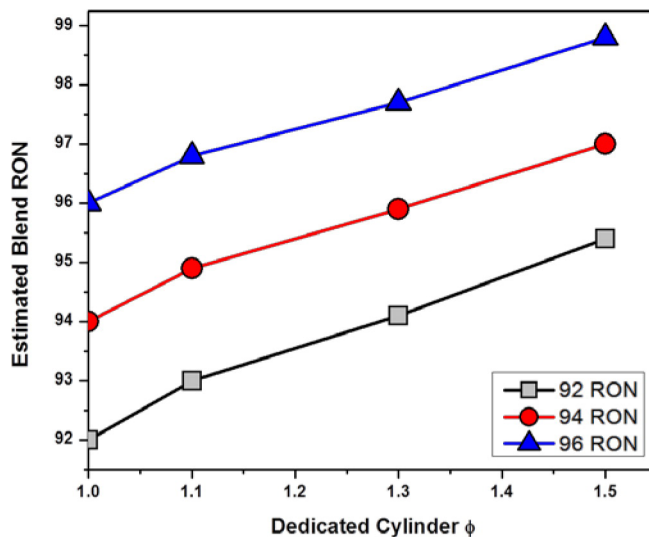


Figure 2. Estimated blend RON for a variety of fuels based on the level of over fuelling in the dedicated cylinder of a 4 cylinder DEGR application.

EXPERIMENTAL SETUP

The engine used in this study was a 2015 MY 1.5 L, MPI inline 4-cylinder. The engine was instrumented with typical engine instrumentation including engine speed, torque, fuel flow, air flow, and various temperature and pressure measurements. In-cylinder indication was performed with Kistler 6052C pressure transducers and a SwRI-developed high speed data acquisition system.

The 1.5 L engine, summarized in [Table 1](#), has a peak torque of 145 N-m @ 4600 rpm and a peak power of 85 kW @ 5500 rpm. The engine was port fuel injected and also employed variable camshaft phasing on the intake cam. In stock form, the engine operates at 13.5:1 compression ratio. The ignition system for these tests was SwRI's Dual Coil Offset® (DCO®) ignition system, which has been described in a previous publication [24].

Table 1. Test engine specifications

Displaced volume	1496 cc
Stroke	89.4 mm
Bore	73 mm
Compression ratio	13.5:1
Actuation	Intake only cam phaser
Injection	Port Fuel Injection
Maximum Torque	145 Nm @ 4600 rpm (11.4 bar BMEP)
Maximum Power	85 kW @ 5500 rpm

A prototype Dedicated EGR system ([Figure 3](#)) was installed on the test engine. The system consisted of an EGR cooler and mixer [39]. The D-EGR concept inherently requires little in the way of active control since there is no need for proportionate EGR control, which can be achieved with low pressure loop or high pressure loop EGR configurations.