

Investigation of Alternative Ignition System Impact on External EGR Dilution Tolerance in a Turbocharged Homogeneous Direct Injected Spark Ignited Engine

Matthew Bresler, William Attard, and Ronald Reese
FCA US, LLC

ABSTRACT

Dilution of a stoichiometric spark ignited (SI) charge with exhaust gas recirculation (EGR) has been shown to improve thermal efficiency and fuel consumption through improved combustion phasing and heat transfer losses at the knock limit in conjunction with a reduction of heat transfer losses and pumping losses at throttled conditions. However, combustion stability can be adversely affected by EGR dilution. The degradation in combustion stability can be mitigated by selecting an ignition system that can successfully propagate a self-sustaining flame kernel in the presence of a high concentration of diluent and increase the apparent burn rate. This investigation examines improvements to EGR dilution tolerance and brake specific fuel consumption (BSFC) for multiple alternative ignition systems at various engine operating points while maintaining a stoichiometric air-fuel ratio. The work was performed on a high compression ratio (CR) turbocharged 4-cylinder direct injection (DI) engine with cooled external EGR. Two configurations of an inductive ignition system were evaluated in addition to four alternative ignition technologies with no attempt to optimize the combustion system hardware. The use of alternative ignition technologies in this investigation show the potential to realize improvements in EGR dilution tolerance and fuel consumption compared to current production technology, normalizing for the parasitic power loss of each ignition system. The results show that utilizing advanced ignition technologies can improve BSFC by 2.4% at the conditions tested.

CITATION: Bresler, M., Attard, W., and Reese, R., "Investigation of Alternative Ignition System Impact on External EGR Dilution Tolerance in a Turbocharged Homogeneous Direct Injected Spark Ignited Engine," *SAE Int. J. Engines* 8(4):2015, doi:10.4271/2015-01-9043.

INTRODUCTION

Corporate Average Fuel Economy (CAFE) targets in the United States [1] as well as CO₂ regulations in Europe for 2020 model year [2] and by the Environmental Protection Agency (EPA) for 2025 model year [3] are driving continuous efficiency improvement of internal combustion engine technology. Knock tendency of SI engines at high load puts limitations on CR, the region of stoichiometric operation, and optimum combustion phasing.

The trend of SI engine technology has been to utilize downsizing, turbocharging, direct injection and diluents such as air or EGR to improve efficiency [4]. The use of external cooled EGR has been shown to reduce pumping and heat transfer losses in addition to reduced NO_x emissions and knock tendency [4, 5]. Furthermore, the decreased knock tendency at high load diminishes the requirement for fuel enrichment [4, 5, 6].

However, the benefits of EGR dilution are limited by combustion stability and relatively slower burn rates caused by the inherent increase in activation energy required to maintain a self-sustaining flame kernel. Employing the use of high charge motion at low speeds and low loads can improve the burn rate of the mixture. However, this strategy is compromised at high load due to high in-cylinder

pressure rise rates when dilution is not used. Another important factor contributing to instability is the reduced effectiveness of the ignition system in a dilute combustion environment.

Combustion stability is commonly measured in terms of Coefficient of Variance (CoV) of Gross Indicated Mean Effective Pressure (IMEP_g). A limit of 3% CoV of IMEP_g was used to define the combustion stability limit on an Engine Lump Sum (ELS) basis. Where ELS CoV of IMEP_g is the standard deviation of IMEP_g of all cycles measured across all cylinders divided by the average IMEP_g of all cycles measured across all cylinders. The main drivers of high CoV of IMEP_g are the variation of both cyclic and cylinder to cylinder heat release. These variations are undesirable and must be minimized. Lowest Normalized Value (LNV) of IMEP_g considers the lowest IMEP_g cycle in a given data set, which is another critical parameter used to supplement CoV of IMEP_g. The acceptable level for LNV in this study was 80%. Conventional inductive coil ignition systems have limitations in both efficiency and energy delivery which restrict flame kernel development under stressed combustion conditions, which can negatively affect both CoV and LNV of IMEP_g.

Limitations of the traditional ignition system have been addressed using variants of the conventional ignition system design to deliver energy in different ways [7, 8]. For example, multiple ignition systems can be used to initiate multiple flame kernels. However, this

can have adverse effects on engine packaging, weight, heat transfer and cost. High energy single or multiple strikes have shown improvements over the conventional systems [4, 6] but can increase electrical energy consumption, radiated electromagnetic emissions, and spark plug erosion rates. Alternative ignition technologies such as continuous arc, corona discharge, or plasma discharge systems have shown potential benefit [6, 9, 11], but can have some of the demerits previously listed in addition to requiring a high voltage system architecture. Nonetheless, more effective ignition systems have shown to contribute a net BSFC benefit in conjunction with a higher EGR dilution tolerance and reduced NOx emissions [6, 9, 10].

The following studies are some examples of research which are relevant to this particular experiment. Alger, et al. [6] evaluated high energy continuous discharge ignition with the use of high current density coils to extend EGR dilution beyond the limitations when operating the same coil in either a single strike or multi-strike mode. The results of this study concluded that the continuous strike mode had been successful in delivering more energy to the combustion chamber, thereby increasing EGR dilution tolerance at multiple operating conditions. Chen, et al. [9] investigated the effects of continuous and discontinuous discharge strategies on EGR dilution for a turbocharged DI engine. The results showed significant combustion stability benefit from a continuous, long duration spark discharge event with respect to a discontinuous discharge at smaller spark plug gap sizes. This is significant because high breakdown voltages experienced at high load operation drive smaller spark plug gap sizes in order to sustain an effective discharge. Zhang, et al. [10] examined multi-strike ignition strategies on an optical combustion vessel with EGR dilution and lean air-fuel ratio while simulating high charge motion with high local flow velocities. Various levels of offset between discharges were observed via Schlieren imaging to quantify flame kernel growth rates in order to identify the most optimum settings. The results showed that the time between discharge events was critical to successfully combine separate flame kernels and promote ignition of the bulk gases. Hampe, et al. [11] performed studies comparing the performance of high frequency corona discharge ignition relative to a traditional inductive coil system. Lean homogeneous air-fuel ratio sweeps were performed in an optical single cylinder normally aspirated DI engine at low speed, low load conditions for different fuels. The outcome showed significantly faster burn rates, resulting in an overall lean limit extension regardless of fuel type.

The goal of this study is to examine the EGR dilution tolerance and resultant BSFC benefit afforded by several different alternative methods of 1-plug ignition compared to an inductive 3-plug ignition system in a turbocharged homogeneous DI combustion system with external cooled EGR dilution. This offers potential to improve packaging, weight, heat transfer, and controls flexibility for future downsized engine applications.

OBJECTIVES

The specific objectives of this study were:

1. Characterize the extension of EGR dilution at steady state for each alternative ignition technology relative to the 1-plug baseline ignition system at the combustion stability limit.

2. Quantify the steady state BSFC improvement for each technology over the baseline system.
3. Correlate the 0-10% and 10-90% burn durations to BSFC and dilution improvement for each ignition system.
4. Narrow a select set of ignition systems for future development.

EXPERIMENTAL SETUP

Test Engine Configuration

The engine used in this experiment was developed for research funded by the United States Department of Energy. The 2.4L four cylinder turbocharged DI engine (Figure 1) had a 11.7:1 CR and variable independent camshaft phasing for both the intake and exhaust cams. The valve train was dual overhead cams (DOHC) which consisted of two intake valves and one exhaust valve per cylinder. The head geometry was specifically designed to accommodate three spark plugs per cylinder. The turbocharging system comprised of a two stage boosting strategy. The fuel system was homogeneous direct injection with a side mounted injector. This engine also had a cooled low pressure loop (LPL) EGR system which redirected post catalyst exhaust gas flow through an EGR cooler and introduced it into the intake before the turbocharger compressor. The intake, port geometries and cylinder head design were such that it delivered a high tumble flow to the combustion chamber [12]. Table 1 contains a description of the engine hardware.

The engine was mounted to an alternating current (AC) dynamometer. Each cylinder was instrumented with a flush mounted piezoelectric pressure transducer, the intake was instrumented with a pressure transducer for pegging reference, and an encoder was mounted on the end of the crankshaft for pressure based crank angle resolved combustion analysis. An inductive current probe was used to measure the primary current signal on cylinder 1 which served as reference for the start of combustion. A water-to-air EGR cooler setup was used. Various critical temperatures, pressures and angular speeds were monitored. EGR was sampled and the rate was calculated by an exhaust gas analyzer as the ratio of the levels of intake and exhaust CO₂ corrected to the ambient CO₂ level. An open ECU control software was used to manually control vital engine parameters.

Table 1. Engine Hardware Description

Displaced volume	2.36 L, 4-cylinder
Stroke	97 mm
Bore	88 mm
Compression ratio	11.7:1
Valvetrain	DOHC w/ dual independent cam phasing, 3 valves per cylinder
Ignition System	Baseline system: 3 Inductive coils, 3 spark plugs per cylinder (Single fine wire Ir-Pt w/ 0.8mm gap)
Turbocharging	Two stage boosting
Fuel System	Homogeneous Side Mounted Direct Injection
EGR System	LPL EGR



Figure 1. 2.4L Engine Image

Ignition Systems Setup and Calibration

Alternative ignition technologies exist to satisfy the demand for more ignition energy delivered from a single location, therefore some of these technologies were selected to be evaluated for this purpose. The scope of this publication will include the comparison of six different ignition systems at two representative speed load operating conditions chosen from a specific vehicle and powertrain combination run on the EPA federal test procedure city cycle test (FTP-75). A sweep of external EGR percentage was performed at each operating point until the CoV of IMEP_g limit of 3% was exceeded. Each EGR sweep was repeated with every ignition system configuration evaluated.

All ignition systems were supplied with a constant 14.5V from an automotive battery coupled in parallel with a power supply to minimize voltage fluctuation on the primary circuit. This power supply was stand alone and the battery was not charged by the alternator, therefore BSFC was corrected for ignition system power consumption. The default ignition switching controls were handled by standard insulated-gate bipolar transistor (IGBT) type drivers located on the electronic control unit (ECU). Production hall-effect type camshaft and crankshaft position sensors mounted on the engine provided engine position information to the ECU for use in controlling ignition timing. Primary current was measured on all systems by an inductive current probe on cylinder 1 in order to calculate input energy to the ignition coil. This probe was positioned as near as possible to the coil for best measurement accuracy.

Inductive Coil Systems

This engine was optimized for an inductive coil based single strike ignition system comprised of multiple coils and spark plugs per cylinder (Figure 2).

The spark plugs were of standard design and spark gap for a turbocharged application. The spark plugs were manufactured with a low suppression resistance which matched the resistance of the spark plug leads. This optimized configuration was considered to be the

efficiency benchmark for this study. All coils were controlled by a single driver per cylinder. Coil dwell calibrations were retained at the original settings.



Figure 2. 2.4L Cylinder Head Image

A subset of the aforementioned system, driving only the centrally located ignition coil and spark plug combination was used as the benchmark to which all other ignition systems were compared. Any additional systems were removed from each cylinder and the spark plugs were replaced with electrically isolated “dummy” plugs as to maintain sealing performance and volume at top dead center (TDC) as close as possible to the original configuration. This single ignition site arrangement was carried out for each subsequent system tested. Original calibrations were maintained for each ignition system so that a true baseline could be attained for each variant. Each ignition system tested was installed in the same position with a common spark plug ground electrode orientation.

Multi-Strike Ignition

A low inductance, fast charging multi-strike ignition system functioned in such a manner to fire the least amount of strikes per combustion event to sustain successful ignition. The number of re-strikes and the time between each re-strike was determined by a closed loop feedback on secondary current of each preceding discharge.

The multi-strike operation was calibrated for the most beneficial dwell time, primary current and re-strike offset. This was accomplished by running several EGR sweeps from 0% EGR to the maximum attainable percentage at the combustion stability limit. These EGR sweeps were performed at several different dwell times to establish the most effective setting. Then, several of the same EGR sweeps were performed at different re-strike secondary current levels. Ignition system power losses were optimized to minimize BSFC.

Continuous Discharge Ignition

Additionally, a dual coil continuous ignition system was assessed in a continuous arcing mode, where the coils are charged and discharged in an alternating fashion to maintain a high mean secondary current over a long duration.

Continuous discharge ignition required an auxiliary controller integrated with a step-up transformer to operate at a high primary voltage level. This controller was retrofitted downstream of the ECU and received ignition control signals as input for spark timing only. Such a system utilized proprietary algorithms to control spark discharge per several input parameters defined via a software interface. Primary current and discharge duration were optimized for the best BSFC and system efficiency. This was done by performing several EGR sweeps at different levels of primary current to determine the best optimization of dwell time and secondary current variation. Additional EGR sweeps were performed to determine the maximum effective discharge duration to balance EGR dilution and power consumption.

Plasma Ignition

Plasma ignition is an inductive based system which initiates a normal breakdown and arc phase, but creates a plasma discharge at the arc phase by way of a pulse width modulated (PWM) signal. This oscillates the secondary current at a very high frequency and amplitude to maintain a positive mean secondary current over a long duration. The secondary energy output is comparable to the previous continuous discharge system.

This system was equipped with an auxiliary controller which communicated to the ECU via a controller area network (CAN) interface. This interface was used for both spark timing and diagnostics. The system was controlled via open ECU control software. The ignition module controlled several parameters including primary current, secondary current, PWM intensity and frequency, in addition to spark duration. Dwell time, secondary current and discharge duration were calibrated for maximum output. Several different levels of each parameter were evaluated with multiple EGR sweeps and optimized for dilution tolerance and power consumption.

Corona Discharge

Corona discharge is a system which releases plasma at a high voltage and a high frequency, creating a highly inhomogeneous charge locally to an igniter located in the combustion chamber. This voltage exceeds the dielectric permittivity of the combustion gases under the pressures experienced at discharge. However, the faster motion of the ion particles relative to the electrons prevent a breakdown phase from occurring. The mechanism of ignition is an ionic dissociation by way of streamers originating from the igniter. This creates a low temperature volumetric plasma discharge that can be sustained for a long duration [9].

This system was designed with an auxiliary controller which required a step-up transformer in order to function at a high primary voltage. The controller interface also required a spark timing input to initiate charging and discharging. The supplied software interface allows for

a number of user controlled parameters and feedback for system calibration. This particular system was maximized for on time and primary voltage. The limiting factor for primary voltage was the tendency for the streamers to arc to other components in the combustion chamber if voltage levels were too high for a particular operating condition. This arcing was monitored by the ignition controller and mitigated by interrupting the discharge for a short amount of time before re-establishing the discharge. [Table 2](#) shows the energy settings used for each ignition strategy.

Table 2. Ignition System Energy Settings

System Type	Primary Energy
1-plug	240 mJ
3-plug	720 mJ
Multi-strike	210 mJ
Continuous	300 mJ
Plasma	300 mJ
Corona	750 mJ

TEST CONDITIONS

Engine speed and load conditions were selected via vehicle simulation on the EPA FTP-75 city cycle test. These conditions were 1500 rev/min (RPM) at 5 bar brake mean effective pressure (BMEP) and 1500 RPM at 8 bar BMEP. Fueling was controlled to stoichiometric air/fuel ratio via a production oxygen sensor with 97 research octane number (RON) certification fuel used throughout the test. The intake and exhaust cam timing were fixed to fully retarded, which was optimum for the 3-plug configuration. The same cam timing was used for all tests to be consistent with the original engine calibration. Engine oil and engine coolant temperatures were both maintained at 90°C. Combustion phasing was set to a consistent crank angle location at 50% mass fraction burned (CA50) of 8-9°CA after top dead center (aTDC) or knock limit. Intake manifold temperatures were controlled between 35°C and 45°C. In order to minimize pumping losses, load was achieved by first adjusting the throttle angle to the desired level. If load was not achieved when the throttle was fully opened, then the turbocharger wastegate was adjusted to increase manifold pressure until the desired load was achieved.

External EGR was swept in equal increments from 0% EGR to the maximum attainable percentage at the combustion stability limit. Spark timing and manifold pressure were manually adjusted to maintain a constant load and appropriate combustion phasing. Each ignition system setting was chosen per the pre-determined optimized conditions for each case. Data were recorded under steady state conditions at each test point.

RESULTS AND DISCUSSION

Ignition Parasitic Loss Calculations

The function of an ignition system is to transfer electrical energy to the combustion chamber by either a thermal or a dissociation mechanism to initiate exothermic chemical reactions. Since it is difficult to measure the actual quantity of energy delivered or the