

Analysis of Cyclic Variability of Heat Release for High-EGR GDI Engine Operation with Observations on Implications for Effective Control

Brian Kaul, Robert Wagner and Johney Green
Oak Ridge National Laboratory

ABSTRACT

Operation of spark-ignition (SI) engines with high levels of charge dilution through exhaust gas recirculation (EGR) achieves significant engine efficiency gains while maintaining stoichiometric operation for compatibility with three-way catalysts. Dilution levels, however, are limited by cyclic variability-including significant numbers of misfires-that becomes more pronounced with increasing dilution. This variability has been shown to have both stochastic and deterministic components. Stochastic effects include turbulence, mixing variations, and the like, while the deterministic effect is primarily due to the nonlinear dependence of flame propagation rates and ignition characteristics on the charge composition, which is influenced by the composition of residual gases from prior cycles.

The presence of determinism implies that an increased understanding the dynamics of such systems could lead to effective control approaches that allow operation near the edge of stability, effectively extending the dilution limit. This nonlinear dependence has been characterized previously for homogeneous charge, port fuel-injected (PFI) SI engines operating fuel-lean as well as with inert diluents such as bottled N₂ gas. In this paper, cyclic dispersion in a modern boosted gasoline direct injection (GDI) engine using a cooled external EGR loop is examined, and the potential for improvement with effective control is evaluated through the use of symbol sequence statistics and other techniques from chaos theory. Observations related to the potential implications of these results for control approaches that could effectively enable engine operation at the edge of combustion stability are noted.

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INTRODUCTION

As emissions standards continue to be tightened along with both regulatory and market demand for increased vehicle fuel economy, it is becoming more challenging to meet both of these goals. Increasing engine efficiency to meet tighter vehicle fuel economy standards must be done in a manner that does not compromise on emissions performance. An effective approach, which is gaining widespread implementation in the market, is engine downsizing combined with turbocharging to maintain the same load capacity [1,2,3,4,5,6]. This allows the engine to remain in a more efficient high-load region of its speed/load map during normal vehicle operation on drive cycles, thus reducing pumping losses. Modern boosted, downsized engines also make use of both GDI and variable cam timing (VCT) technologies to enable additional efficiency gains. Some further gains are possible with additional optimization,

though there are also challenges to be overcome in increasing the level of downsizing [7].

Several factors limit the degree to which engines can be further downsized. At high loads, the tendency to knock imposes limits on the compression ratio of the engine and requires that spark timing be retarded from the optimal combustion phasing, reducing cycle efficiency. Additionally, the higher exhaust temperatures encountered with later combustion phasing necessitate fuel enrichment, leading to further fuel efficiency penalties. The addition of cooled EGR has a knock-reducing effect that was shown by Alger, et al. [8] to be such that each % increase in EGR is equivalent to an increase of 0.5 in fuel octane number. This allows more optimal spark timing to be used, shifting combustion phasing back to a higher efficiency point. The use of EGR as a diluent also reduces exhaust temperatures, mitigating the need for fuel enrichment. Additionally, at sufficiently high EGR levels, the reduction in pumping losses due to reduced

throttling can be significant. These enabling effects of high EGR on downsized GDI engines were noted by Alger, et al. [9]. Pirault, et al. [10] also showed cycle simulation results indicating that this concept could yield brake thermal efficiencies (BTE) of over 40% in light-duty engines with very low engine-out NO_x . Similar benefits can also be achieved through lean operation (which can be thought of as dilution by excess air rather than the addition of an inert gas). Lean operation actually offers greater potential for thermodynamic cycle efficiency gains through increased specific heat ratios, but cooled EGR has greater knock-limiting ability as demonstrated by Cairns, et al. [11] and allows for stoichiometric engine operation, making standard three-way catalysts effective for emissions control and alleviating the need for lean NO_x aftertreatment.

Two primary ways in which engine efficiency can be increased through the use of EGR are reduction of pumping losses due to the potential for unthrottled operation at lower loads and the ability to advance spark timing to achieve optimal combustion phasing due to the knock-mitigating effects of EGR. A recent parametric modeling study by Lavoie, et al. [12] has indicated the potential for vehicle fuel economy gains between 23% and 58% for high dilution SI operation, with dilution levels equivalent to EGR rates of 35-55%. Figure 1 shows data from the engine used in the current work, as load is swept down from peak brake mean effective pressure (BMEP) via normal, throttled engine operation and also without throttling by increasing EGR rate. A 3-point (approximately 10%) increase in BTE is observed for the unthrottled, high-EGR case at 12 bar BMEP with 20% EGR. As load is decreased further (below about 10 bar BMEP in this case, with 32% EGR), however, a dilution limit is reached and it becomes necessary to use throttling rather than further increasing the EGR rate. This is because the cyclic variability encountered at high dilution rates causes a significant loss in efficiency due to the occurrence of partial burn events and misfires. If information about the cycle-to-cycle dynamics encountered here can be leveraged to develop effective control strategies, this loss could be mitigated, and the dilution levels increased even further, allowing additional efficiency gains.

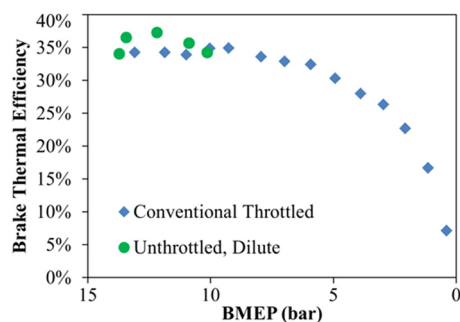


Figure 1. Brake thermal efficiency variation with decreasing load for both throttled and dilute, unthrottled engine operation at 2000 RPM

In this case, the 10.1 bar, 32% EGR operating condition had a coefficient of variation (CoV) of indicated mean effective pressure (IMEP) of 7.8%, which-in addition to reducing efficiency-would also be unacceptable from a noise, vibration, and harshness (NVH) perspective, while the 10.9 bar, 31% EGR condition had a CoV of IMEP of 2.9%, within currently accepted limits.

For port fuel-injected (PFI) engines, dilute cyclic variability was successfully modeled by Daw, et al. [13] as consisting of a deterministic feed-forward function based on the residual gas composition, combined with stochastic noise to simulate apparently random effects including turbulence, mixture inhomogeneities, and the like. The approach taken in that model has been further developed for analysis of experimental data and yielded significant insight into the origins of the combustion instabilities observed in experimental data [14,15,16]. Namely, the dependence of both the flame propagation speed and early flame kernel growth on the charge composition is nonlinear at very dilute conditions, such that small changes in the initial charge composition communicated through the residual gases from prior cycles will have significant effects on the next engine cycle. The fundamental physical reasons for the onset of cyclic variability under lean operation have also been explored in a combustion modeling study by Ayala and Heywood [17], where they show that the 0-10% burn duration, after reaching about 40°C, transitions from a steady linear increase with lambda to a much steeper, nonlinear relationship. This phenomenon causes the extreme sensitivity to initial charge composition demonstrated in the low-order Daw, et al. model.

Similar dynamics have also been shown to occur in propagating-flame SI engine combustion with inert diluent rather than with excess air as in lean combustion [18]. While those studies used “simulated” EGR consisting of bottled N_2 gas rather than actual exhaust dilution, the similarity of the dynamics observed with use of an inert diluent to those observed in lean operation further indicate that such determinism should be expected in any dilute, propagating-flame combustion regime. Similar approaches have also shown deterministic structure of cycle-to-cycle variations in HCCI and SA-HCCI modes [19,20,21,22], as well as SI-HCCI mode transitions [23,24].

Various control approaches, including enhanced ignition systems such as the SwRI continuous-discharge system [25], have been used to shift the dilution limit somewhat, to good effect; however, the approach to maintaining combustion stability at that new limit has remained one of avoidance rather than active control. The determinism present in the cyclic variations in heat release that comprise the dilution limit (whether with more effective ignition or not) implies that active control of the system should be possible. Effective control that enables operation nearer the edge of stability would thus extend the dilution limit further, yielding significant engine efficiency gains.

Some early attempts to use the information gained by studying cyclic variations using tools derived from chaos theory for the purpose of engine control have shown some improvements in engine stability, both for lean [26,27,28,29] and simulated EGR (i.e., bottled N₂ gas) [30,31] dilution, as well as for SI-HCCI mode transitions [32,33]. These controllers are designed to be able to recognize recurring patterns in the heat release data, and act to prevent undesirable events from occurring. While past efforts have been somewhat limited by controller performance and the efficacy of available control inputs to the engine, modern SI engines using GDI, VCT, and other more advanced control techniques, coupled with more powerful engine control units (ECUs) could enable more effective control of combustion stability in these regions.

In this paper, details of the cyclic variability encountered at the EGR dilution limit in a turbocharged, wall-guided GDI engine are examined, comparing and contrasting with the dynamics previously observed in lean PFI engines. Injection timing was maintained at 300°BTDC to give mostly premixed conditions. The knowledge gained is expected to be useful for designing control strategies to operate at the edge of combustion stability in modern, high dilution gasoline engines.

EXPERIMENTAL SETUP

For this study, a 2.0L 4-cylinder GM LNF engine that had been modified with a higher compression ratio for flex-fuel optimization by Bosch was further outfitted with a cooled, low-pressure EGR loop and then operated with varying levels of charge dilution. Engine specifications are listed in Table 1.

Table 1. Engine specifications

Bore	86 mm
Stroke	86 mm
Configuration	I-4
Compression ratio	10.67:1
Maximum cylinder pressure	130 bar
Ignition coil energy	100 mJ
Induction	Turbocharged
Fuel system	Wall-guided GDI

For the external EGR system, exhaust gas is diverted from downstream of the turbine, through an EGR cooler (a production unit from a 6.4L Ford/Navistar diesel), modulated by a Pierburg EGR valve (a production unit from a VW TDI application), and introduced immediately upstream of the compressor. This engine is throttled downstream of the compressor, at the intake manifold. The EGR valve is controlled via a pulse-width modulated signal generated using a LabView-based data acquisition system.

EGR rate was calculated using measurements of CO₂ and O₂ sampled from the exhaust and the intake manifold using standard NDIR and paramagnetic California Analytical gas analyzers. Additionally, Bosch LSU 4.9 UEGO sensors were installed in both the exhaust pipe and the intake manifold.

The intake UEGO pumping current was correlated to EGR rates calculated from the emissions analyzers and used for fast-response EGR estimation during engine operation and for estimation of EGR rate at low loads when intake manifold vacuum was too high for the emissions gas analyzers to draw a sample.

Engine control was provided via a Bosch MED17.5 ECU with access to override parameters through INCA software. Spark timing and fueling were manually set for each operating condition, and other values (cam phasing, injection timing, etc.) were maintained at the default map values and fixed for each operating condition to ensure that observed dynamics are due to prior-cycle effects inherent to the engine rather than controller effects, as much as possible. Engine speed was maintained at steady state using a motoring dynamometer with speed control enabled. Haltermann EPA Tier II EEE certification gasoline was used for all experiments. Fuel properties are shown in Table 2.

Table 2. Fuel Properties

Research octane number	96.6
Motor octane number	88.7
Reid vapor pressure	62.05 kPa
H/C ratio	1.841
Lower heating value	43.01 MJ/kg

RESULTS

Cycle heat release was calculated in real-time from the cylinder pressure using a Drivven DCAT data acquisition system. For each operating condition, at least 5,000 (in some cases, 20,000) consecutive engine cycles were recorded during steady state operation. The cycle-to-cycle variations in the heat release, when considered as a time series of discrete events, can be evaluated to distinguish recurring patterns like those noted in previous studies.

Symbol Sequence Analysis

Analysis Method

In order to distinguish patterns in a time series of noisy data, it can be helpful to categorize the data into discrete bins, each represented by a symbol. For example, as shown in Figure 2, the heat release values for each engine cycle can be divided at the median value, and all cases below that value assigned to the first bin, given the symbol “0,” while cycles with values above the median are assigned to the second bin, with the symbol “1.” Sequences of these symbolized values can then be considered, e.g., “1-0-1-0” would represent a sequence of four alternating high- and low-energy cycles. A greater number of partitions can also be used, yielding a greater number of discrete symbols to consider and maintaining more fidelity to the original data. Partitions are selected such that each symbol is equiprobable. This binning procedure helps to reduce the impact of noise and eliminate small, random variations from consideration, since cycles