

Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion

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ABSTRACT

Operation of spark-ignition (SI) engines with high levels of charge dilution through exhaust gas recirculation (EGR) achieves significant 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 significant 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 dynamics of operation with an external EGR loop differ substantially from those of dilute operation without external recirculation, both in time-scale and cylinder-synchronization effects, especially when misfires are encountered. This paper examines these differences and the implications for prior-cycle-based control strategies.

CITATION: Kaul, B., Finney, C., Wagner, R., and Edwards, M., "Effects of External EGR Loop on Cycle-to-Cycle Dynamics of Dilute SI Combustion," *SAE Int. J. Engines* 7(2):2014, doi:10.4271/2014-01-1236.

INTRODUCTION

Market and regulatory pressures continue to mandate significant increases in vehicle fuel economy to reduce petroleum use and CO₂ emissions, and meeting this goal while also continuing to reduce emissions of traditional pollutants is a significant challenge. Increasing engine efficiency while maintaining emissions performance is a necessary component of any solution, and an approach which has gained widespread adoption in the market is the combination of engine downsizing with gasoline direct injection (GDI) and turbocharging utilized to maintain high torque output [1,2,3,4,5,6]. This strategy shifts operation on the regulatory drive cycles into higher-efficiency regions of the engine's speed-load map, while boosting specific load capacity to maintain acceptable vehicle acceleration performance. This approach has proven effective, but there are obstacles to further increasing the level of downsizing [7].

Engine downsizing is limited by multiple factors, including the occurrence of end-gas knock at high loads and sporadic "super-knock" events brought on by low-speed pre-ignition (LSPI) events at very high loads [8,9,10,11], which can cause significant engine damage. In order to avoid end-gas knock, the compression ratio of the engine is limited, and spark timing must be retarded from the optimal combustion phasing at high loads, reducing the thermodynamic efficiency of the engine. Additionally, the higher exhaust temperatures caused by the late combustion phasing require that fuel enrichment be used

to protect the turbocharger, causing greater fuel efficiency penalties. The resulting operating conditions, with high cylinder pressures from boost and compression, along with late spark timing, allow for the occurrence of LSPI. The combination of these factors limits the compression ratio and boost that can be applied to increase efficiency and performance in downsized engines.

The addition of cooled EGR is a potential pathway to mitigating these effects. Alger, et al. [12] demonstrated that the knock-reduction effect of EGR is such that each 1% increase is equivalent to an increase of 0.5 in fuel octane number. This allows for more optimal spark timing, shifting combustion phasing towards a higher-efficiency point and reducing the time available for pre-ignition to occur. Charge dilution through EGR and earlier combustion phasing also reduce exhaust temperatures, mitigating the need for protective fuel enrichment. Pumping losses can also be decreased due to reduced throttling of the engine. These efficiency-enabling effects of EGR for downsized GDI engines were noted by Alger, et al. [13]. Cycle simulations by Pirault, et al. [14] also indicate the potential for brake thermal efficiency (BTE) of over 40% in light-duty engines using this strategy, while yielding very low engine-out NO_x emissions. Lean operation offers similar benefits, as well as improved thermodynamic cycle efficiency gains due to increased specific heat ratios. The lean also requires the use of lean NO_x aftertreatment and does not

have as great a knock-limiting ability [15]. Cooled EGR has the additional benefit of mitigating LSPI, with Amann, et al. [16] reporting that EGR rates > 10% result in substantial suppression of LSPI.

These pathways to improved engine efficiency through the use of EGR offer significant benefits. Lavoie, et al. [17] recently conducted a parametric modeling study indicating potential vehicle fuel economy gains between 23 and 58% for high-dilution SI operation, with dilution levels equivalent to 35-55% EGR rates. The knock mitigation and pumping loss benefits are also illustrated using data previously collected on the 2.0L GDI engine from this study in Figure 1, reproduced from Kaul, et al. [18]. Here, baseline throttled operation with spark retard and enrichment is shown in blue, and stoichiometric, unthrottled operation with EGR and optimal phasing is shown in green. For 12-bar brake mean effective pressure (BMEP) operation with 20% EGR, a 3-point (approximately 10%) increase in brake thermal efficiency (BTE) is observed. As load is decreased, a dilution limit is reached (in this case, at about 10 bar BMEP and 32% EGR), due to the cyclic variability in combustion encountered at high dilution rates. This cyclic variability leads to significant efficiency losses through partial burns and, eventually, misfires.

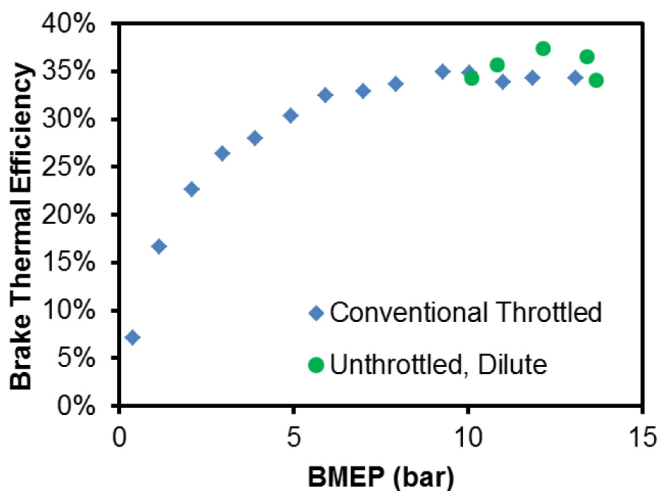


Figure 1. Brake thermal efficiency variation with decreasing load for both throttled and dilute, unthrottled engine operation at 2000 RPM, reproduced from Kaul, et al. [18]

Dilute cyclic variability for lean combustion was modeled by Daw, et al. [19] as a combination of a deterministic feed-forward function based on residual gas composition, combined with the imposition of stochastic noise on the initial conditions to simulate apparently random effects including turbulence and mixture inhomogeneity. The insights gained from this initial modeling work were also applied to the analysis of experimental data [20, 21, 22] and have yielded significant additional insights into the origins of combustion instabilities near the dilute limits. The primary driving force is the highly nonlinear dependence of flame propagation speed and early flame kernel growth on the charge composition for very dilute conditions. This nonlinear dependence causes a very high

sensitivity to changes in mixture composition, such that small changes in the composition of the residual gases in the cylinder from the prior cycle have significant effects on the results of the next engine cycle. The fundamental physical reasons for this behavior have also been examined by Ayala and Heywood [23] in a modeling study, where they showed that as air/fuel ratio is increased, the 0-10% burn duration transitions from a steady linear increase to a much steeper, nonlinear relationship once it exceeds about 40°C.A. This phenomenon is responsible for the extreme sensitivity to initial charge composition demonstrated in the low-order model of Daw, et al. An additional study by Sutton and Drallmeier [24] demonstrated similar dynamics for operation with an inert diluent (bottled N₂) to simulate EGR, rather than excess air, illustrating 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 [25,26,27,28] as well as SI-HCCI mode transitions [29,30].

In a previous study using the same experimental setup as the present one, Kaul, et al. [18] presented results showing the dynamics of cyclic variability of dilute SI combustion using an external, low-pressure, cooled EGR loop on a modern turbocharged GDI engine. In that study, similar dynamics to previous lean combustion studies were observed, though analysis of the deterministic information content of the data indicated a “memory” of a greater number of cycles - specifically, the greatest deviation from randomness as indicated by modified Shannon entropy analysis was for a sequence length of 10 cycles rather than 6 as had been found in many previous studies using lean [22,31] or bottled inert diluents [24,32]. This implies that rather than effects of residual gas composition dissipating after around 6 cycles, there is a feed-forward mechanism causing discernible differences in the heat release of events at least 10 cycles later. The external EGR loop is the most likely path for this to occur.

The determinism present in the cyclic variations of heat release that impose a limit on charge dilution implies the possibility of active control of the system. This approach will yield benefits on its own, or when combined with enhanced ignition systems (e.g. multi-strike [33] or continuous-discharge ignition systems [34,35], laser ignition systems [36,37], and pre-chamber jet ignition systems [38,39]) which shift the dilution limit. Active control based on the nonlinear dynamics of the system would allow operation at the edge of stability rather than requiring avoidance of it, thus further extending the practical dilution limit and yielding corresponding efficiency gains.

Some early attempts to use tools derived from chaos theory to identify the deterministic elements of cyclic variations and control them have yielded improvements in engine stability, for lean operation [40,41,42,43], operation with inert diluent [44,45], and SI-HCCI mode transitions [46,47]. These controllers are designed to recognize recurring patterns in the heat release data and act to prevent undesirable events from occurring based on the knowledge of prior cycles. Modeling

engines with more control inputs and modern controllers with greater capabilities could yield more effective active control now.

In this paper, the reasons for the difference in cycle length noted in the previous study [18] are explored further by examining operation at very high EGR levels, where COV is elevated and misfires occur frequently. Since the external EGR flow path is hypothesized to be the cause of the longer feed-forward period, the EGR loop length is varied in order to explore its effects in detail. While operation at these very high EGR levels is beyond where even the most effective controller is expected to be able to stabilize engine behavior sufficiently to allow operation in production, the amplified deterministic effects at these conditions enable us to more easily identify and understand the underlying behavior so that it can be utilized in active control systems and applied to more practical operation near the edge of stability.

EXPERIMENTAL SETUP

The same 2.0L 4-cylinder GM LNF engine that was used in the previous study [18] was used here. This engine was modified with a higher compression ratio for flex-fuel optimization by Bosch, and specifications are listed in Table 1. An external cooled, low-pressure EGR loop has been added to this engine. Exhaust gas is diverted from downstream of the turbine, through an EGR cooler, and introduced immediately upstream of the compressor. This engine is throttled downstream of the compressor, at the intake manifold. The EGR flow rate is controlled using a Pierburg EGR valve from a VW TDI application, which is actuated via a pulse-width modulated signal generated using a LabView-based data acquisition system.

Table 1. Engine specifications

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

In order to evaluate the effect of the external EGR flow path on the dynamics of the system, the length of the low-pressure EGR loop was varied by replacing a section of hose connecting the EGR cooler to the EGR valve, shown in Figure 2, and experimental sweeps of EGR level were conducted to observe the dynamics of cyclic variability at elevated EGR levels. No active exhaust backpressure control was applied during this study; backpressure was supplied by an original equipment

three-way catalytic converter in the exhaust stack. EGR flow rate was controlled by actuating the EGR valve, and the highest EGR rate is that with the valve fully open.

The length and volume of both the exhaust-only (unmixed) EGR loop, and the total flow path to the intake port, are shown in Table 2. EGR rate was estimated from CO₂ and O₂ concentration measurements in the exhaust and in the intake manifold, using standard non-dispersive infrared and paramagnetic emissions analyzers. Engine stoichiometry was measured using a Bosch LSU 4.9 wideband oxygen sensor. Additionally, a Cambustion HFR400 fast FID was installed in the intake runner of cylinder 4 to measure cycle-resolved hydrocarbon concentration.

The short EGR loop was the original configuration chosen for ease of installation when adding external, cooled EGR to this engine. The long loop was chosen to approximately double the length of the flow path between the turbine exit and the EGR valve inlet. The medium loop was created by using half the hose length of the long loop.

Table 2. EGR loop geometry variations

Loop Variant	Short	Medium	Long
Hose Section, m (in)	0.2 (8)	0.9 (36)	1.8 (72)
Exhaust-side Loop Length, m	2.25	2.96	3.87
Exhaust-side Loop Volume, l	7.21	7.89	8.76
Total Length, m	4.91	5.63	6.54
Total Volume, l	20.5	21.2	22.1

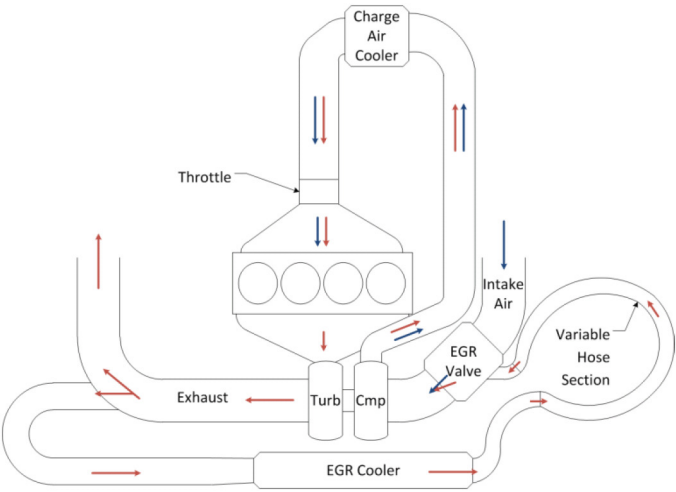


Figure 2. EGR system diagram

Engine control was provided by a Bosch MED17.5 ECU with access to override parameters using INCA software. For each condition, spark timing and fueling rate were manually specified, and other parameters (cam phase, etc.) were maintained constant at the default values for 0 EGR.