

Determination of SI Combustion Sensitivity to Fuel Perturbations as a Cyclic Control Input for Highly Dilute Operation

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ABSTRACT

Use of dilution with exhaust gas recirculation (EGR) offers substantial efficiency gains in spark ignition (SI) engines, especially when boosting and downsizing are employed. However, the onset of instabilities in engine operation, due to misfires and partial burns, limits the dilution levels. Active controls can be employed to improve engine stability during high dilution operation, with spark and fueling being the main control parameters available for cycle-to-cycle control implementation. This paper aims to understand the sensitivity of the combustion process to changes in fueling under dilute operation achieved with both excess air (lean operation) and EGR. Sinusoidal perturbations were introduced into the injected fuel quantity, and the sensitivity to these perturbations was characterized using a fast Fourier transform (FFT) analysis of the cycle cumulative heat release data. Furthermore, the minimum fueling change required to produce a measurable effect on engine operation was quantified at various levels of dilution. For fixed spark timing (similar ignition conditions), sensitivity to fuel perturbation increases nearly exponentially as EGR dilution is increased, due to the highly nonlinear relationship between combustion quality and in-cylinder charge properties at the dilution limit. However, when spark timing is advanced to compensate for the lower flame speeds of dilute combustion and maintain constant combustion phasing, this effect is suppressed and there is an initial decrease in sensitivity to fuel perturbations as EGR is increased, until the dilute limit is reached, at which point sensitivity again increases. For lean operation, response to very small perturbations was detected at all dilution levels.

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INTRODUCTION

The combination of downsizing, boosting, higher compression ratios, and gasoline direct injection (GDI) is being increasingly utilized in production engines to meet current and future targets for both engine efficiency and emissions [1,2,3,4,5,6]. However, the onset of undesirable phenomena such as end-gas knock and low-speed-pre-ignition (LSPI) limits the practical specific power output as these phenomena can cause substantial engine damage [7,8,9,10]. Consequently, to protect engine hardware, designers use restricted compression ratios as well as retarded ignition timings, both of which lead to engine performance and emissions penalties. Use of charge dilution has been shown to have good potential in delaying the onset of these undesirable phenomena, allowing for the use of optimal combustion phasing for higher fuel efficiency [11,12,13,14]. Additional, efficiency gains are also achieved under dilute operation due to thermodynamic (γ) effects [15]. However, in gasoline SI engines, the extent of charge dilution is limited by the onset of combustion instabilities. Dilution reduces flame speed [12,16] as well as the flame kernel growth rate [17], both of which lead to substandard engine performance through either partial burns or misfires. Szybist and Splitter [18] showed that these effects have a

direct impact on EGR dilution tolerance for various fuels. These flame speed and flame kernel growth effects result in increased cyclic variability, which is undesirable from both efficiency and NVH perspectives. This cyclic variability has been shown to have both deterministic and stochastic features, with sufficient deterministic content that active control strategies could plausibly stabilize combustion and suppress the cyclic variations [16,19,20,21,15].

Daw, et al. [16] modeled cyclic variability, in a lean port-fuel injected engine, as a deterministic feed-forward function of the residual gas composition. Analysis of experimental data, based on the guidelines provided by this model, has yielded enhanced understanding of the origin of combustion instabilities near the dilute limits [19,20], with the primary reported driver being the highly nonlinear dependence of the flame kernel growth as well as the flame speed on charge composition at high dilution levels. As examined by Ayala, et al. [21], the 0-10% burn duration becomes highly nonlinear as the dilution is increased. Kaul, et al. [15] explored the dynamics of cyclic variability of EGR-dilute SI combustion using an external, low pressure, and cooled EGR loop on a modern turbocharged GDI engine; wherein, a considerable amount of determinism was observed in the measured

heat release data. Other studies on dilute, propagating-flame combustion systems have also shown the presence of deterministic components in the cyclic variations [22,23].

As previously mentioned, the existence of deterministic causes for such cyclic variations implies the possibility of controlling them, and both ignition and fuel injection are important control knobs available for combustion control. The effects of various ignition strategies, such as spark timing, duration, and energy, on engine stability during dilute operation have been studied in detail in the literature [24,25]. Chen, et al. [24] explored the impact of varying ignition energy, duration, and phasing of two ignition coils on a high-dilution SI GDI engine concluded that there existed a range of discharge phasing between the first and the second spark that provided best performance at a given dilute operating condition. Jatana, et al. [26] examined the effects of such restrike spark strategies on the cyclic variations under dilute conditions and determined that deterministic effects that could be utilized for further engine control are preserved except in cases of excessively retarded spark restrike delays.

Wallner, et al. [27] studied the effects of ignition and fuel injection under lean and dilute GDI engine operation by imposing a binary low-high perturbation on either the spark timing or the injected fuel quantity. While dilution was universally observed to reduce the impact of ignition perturbations, lean operation was observed to have a higher sensitivity to fuel injection perturbations than EGR operation. The effect of these next-cycle alternating perturbations was also verified using symbol sequence analysis. Kaul [28] examined the impact of sinusoidal fuel perturbations in a single-cylinder PFI engine with nitrogen dilution and found increasing sensitivity to changes in fueling as dilution levels increased.

Smith, et al. [29] used an optical, spray-guided, SI GDI engine to study the dependence of ignition stability on dilution (with nitrogen) along with other factors such as spark plug orientation and ignition system dwell time. Using the same spark timing, dilute operation (with 18% excess nitrogen) resulted in 50% slower 0-10% burn duration and 30% slower 10-50% burn duration, when compared to stoichiometric operation.

The aim of this study is to understand the sensitivity of the combustion process to changes in the injected fuel quantity at various dilution levels. Prior work, including the model of Daw, et al. [16], indicates that dilute combustion is nonlinearly dependent on composition, particularly on the fuel/air ratio of residual gases, such that small changes in fueling from cycle to cycle should be expected to have increasing impacts on combustion as the dilute combustion limit is approached and combustion becomes more “strained.” This implies that given sufficient knowledge of the system dynamics, small changes to fueling could be a useful control input to counteract the cyclic variations encountered at dilute conditions. In order to quantify the impact of fueling changes on combustion, a sinusoidal perturbation with a 50-cycle time period was introduced on the injected fuel quantity, and the resultant effect of this perturbation on the cumulative heat release (HR) was characterized using a fast Fourier transform

(FFT) of the HR of 5000 consecutive cycles. Since this period is longer than any natural variations imposed by the engine hardware, the effects of the imposed perturbations can be distinguished from natural cyclic variability using this approach. Both excess air (lean operation) and EGR were individually used as diluents in this study. Additionally, the effect of combustion phasing on fuel sensitivity was also characterized by either keeping the spark timing constant (at non-dilute MBT) or by maintaining the CA50. Finally, the minimum fuel perturbation required to observe an effect was quantified at various dilution levels. The results of this study should provide critical insights for control model design by quantifying the relationship between fueling changes and the corresponding changes in engine combustion at various levels of dilution.

EXPERIMENTAL SETUP

This study uses a 2.0L GM LNF engine that was previously modified by Bosch in a DOE-funded E85 optimization program, and has been used in previous studies [15,26,30] of high-EGR combustion instabilities at ORNL. This engine features a higher-than-stock compression ratio, and its other specifications are listed in Table 1. The engine also features an externally-cooled, low-pressure EGR loop, with the exhaust being diverted from the turbine outlet to the compressor inlet as shown in Figure 1. The EGR flow rate was controlled using a VW TDI EGR valve that was actuated using a pulse-width-modulated signal generated by a LabVIEW-based system. No active backpressure control was applied using this study, and the backpressure was supplied by an original equipment three-way catalytic converter in the exhaust stack. Engine control was provided by a National Instruments Powertrain Controls Engine Control System (ECS) that is capable of next-cycle control action, with the integrated Combustion Analysis System (CAS) performing heat release and other combustion analysis calculations.

Intake and exhaust gas concentrations were measured using standard gas analyzers, i.e. non-dispersive infrared analyzers for CO₂ and CO, a paramagnetic analyzer for O₂, a flame ionization detector for HC, and a chemiluminescent detector for NO_x measurements. Additionally, a Bosch LSU 4.9 wideband oxygen sensor was also used to monitor engine stoichiometry. Air-fuel ratio and EGR fraction were calculated from intake and exhaust gas analyzer measurements using the LabVIEW version of the Engine Emissions & Uncertainty Analysis code by Dempsey and Ghandhi [31].

Table 1. Engine Specifications

Bore	86 mm
Stroke	86 mm
Configuration	I-4
Compression Ratio	10.67:1
Ignition System	100 mJ Inductive Discharge
Induction	Turbocharged
Fuel System	Side-mount GDI

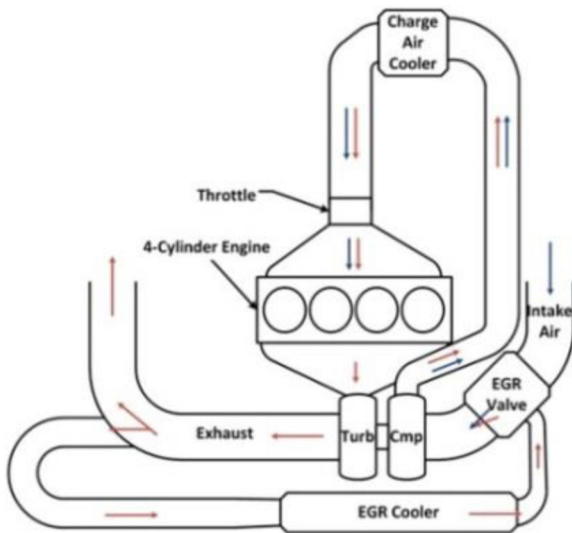


Figure 1. Engine EGR System Diagram

Water-cooled heat exchangers for engine coolant, engine oil, charge air, and EGR were independently controlled using external PID controllers. Finally, Haltermann EPA Tier II EEE certification gasoline was used for all experiments. Fuel properties are shown in [Table 2](#).

As mentioned previously, this study focuses on the effect of fuel perturbation on engine performance at different levels of dilution, and EGR and lean operation were both individually studied as the dilution mechanisms. For all cases, the engine was run at a baseline condition of 2000 RPM and 4 bar BMEP with zero dilution. Thereafter, the fueling was fixed at the baseline level for the entire study as fixed fueling, rather than fixed load, gives more repeatable results during high-COV operation. The desired dilution was achieved by adjusting the throttle and/or the EGR valve and additional care was given to maintain stoichiometric operation during dilution with EGR. Furthermore, during non-dilute operation, the fueling to each cylinder was balanced to ensure consistent IMEP across all four cylinders by applying the following weighting factors to the injection duration commanded to each injector: 0.252 for cylinder 1, 0.258 for cylinder 2, 0.248 for cylinder 3 and 0.242 for cylinder 4. The cam phasing was held constant for the entire study at an IVO of -8° and EVC of 17° ATDC.

The dilution levels used for this study are listed in [Table 3](#) for both EGR and lean operation. At all dilution levels, a sinusoidal perturbation of 1%, 2.5%, and 5% was introduced over the baseline fuel-injection duration. Additionally, smaller perturbations in 0.1% increments between 0 and 1% were imposed to determine the minimum perturbation required to create an observable effect on engine output. The 50 engine-cycle perturbation time-period chosen for this study is longer than the previously measured external EGR loop feedback timescales [30]; furthermore, the absence of a peak at the perturbation frequency in the FFT signal during operation without any fuel perturbation negates the effect of determinism present in the external EGR loop on the FFT analysis. Additionally, all

measurements were repeated for two sets of spark timing strategies. In the first set, the spark timing was advanced appropriately to maintain combustion phasing at MBT timing under dilute operation. In the second set, however, the spark timing was fixed at 29° BTDC (MBT timing for zero dilution) and the combustion phasing was allowed to float with dilution. Comparison between these two sets should give insight into the effects of combustion phasing on the sensitivity to fueling changes. Advancing the spark should compensate for the lower flame speeds expected under dilute operation, while moving the ignition process into a thermodynamically less favorable regime. Fixed spark timing, on the other hand, should maintain similar ignition conditions while amplifying the effect of slower flame speeds. As shown by Jerzembeck, et al. [32], relative to stoichiometric operation, flame propagation is slower under dilute operation and slightly faster under rich operation.

RESULTS

Cumulative heat release (HR) values calculated using the CAS were used as the metric to judge combustion performance and a 5000 consecutive engine cycles were recorded during steady-state engine operation for each test condition for the FFT analysis. These 5000-cycle data sets are sufficiently long for statistically significant identification of recurring patterns in the cyclic variations, and more than sufficient to distinguish the frequencies of interest in the FFT analysis.

Set 1: Fixed Combustion Phasing

For this set, as previously mentioned, the spark timing was advanced during dilute operation to maintain combustion phasing (CA50) at around 8° BTDC. As seen in [Table 3](#), dilution with EGR requires an earlier spark vs. comparably dilute lean operation. This is expected as high specific heat of both CO_2 and H_2O in EGR has a much larger effect on flame speed as compared to fresh air. By maintaining the CA50 at all dilution levels, the effect of flame speed on fuel sensitivity should be minimized as each case has sufficient time to achieve complete combustion. On the other hand, the advanced spark timings during dilute operation should push the flame kernel development process into a less favorable regime, thereby amplifying the relationship between fuel sensitivity and flame kernel development. At 25% EGR, the combustion was delayed enough that phasing could not be maintained even with spark advance.

[Figure 2](#) shows sample FFT power spectrums of cylinder 1 HR data during operation with 25% EGR and at various perturbation levels. [Figure 3](#) shows sample FFT power spectrums of cylinder 1 HR data during operation with different EGR levels and at 5% fuel perturbation. As previously mentioned, no signal was observed for the 0% perturbation case confirming the absence of cross-sensitivity from any deterministic content present in the external EGR stream. Power spectrum signals can be clearly observed as perturbation is introduced into the injected fuel quantity and the signal frequency