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# Retard to the Limit: Closed-Loop COVIMEP Control for Aggressive Exhaust Heating

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Abstract: During cold-starts, diesel engines equipped with aftertreatment systems typically use combustion phasing retard to increase exhaust gas enthalpy to hasten catalyst light-off, resulting in lower tailpipe emissions. Although later combustion phasing can help achieve faster catalyst light-off, combustion variability increases which can physically manifest as vibration and erratic engine behavior. To achieve faster catalyst light-off while remaining within combustion variability constraints, the premise of closed-loop control of Coefficient of Variation of IMEP (COVIMEP) to a target value using feedback from an in-cylinder pressure sensor has been explored. COVIMEP controllers have been designed using a model and validated via simulation and experiment at steady-state. The simulation and experimental results indicate that closed-loop COVIMEP control is a viable technique for retarding combustion phasing to the combustion variability limit at steady-state conditions.



*Keywords:* Internal combustion engines, Automotive control, Aftertreatment light-off, Diesel

## 1. INTRODUCTION

Stringent fuel economy and emission standards for on-road diesel engines have led to the usage of exhaust aftertreatment systems. Although the incorporated catalysts are effective at reducing hydrocarbon, oxides of nitrogen, and particulate matter emissions upon reaching temperatures near 200 degrees C, these emissions pass through the exhaust system mostly untreated during cold-starts when the catalysts are below light-off temperatures. Production engines typically employ a catalyst heating mode when the catalyst temperatures are below their operating range, which prioritizes increasing exhaust gas enthalpy to get the catalysts operational as quickly as possible and minimizing feed gas emissions since they will be untreated by the aftertreatment system (Kurtz et al., 2017). Analysis of emission test data shows that a majority of tailpipe emissions are created at the beginning of the cycle, implying that faster light-off of the aftertreatment system could help reduce overall cycle emissions (Johnson et al., 2017).

A conventional strategy to increase exhaust gas enthalpy is combustion phasing retard, where engine actuators are adjusted to cause the fuel to burn later into the expansion stroke. Feedback controllers have been presented in literature that focus on closed-loop control of combustion phasing to achieve improved fuel economy and emissions, but rarely for exhaust heating optimization (Saracino et al., 2015). A potential explanation is that combustion phasing retard can induce combustion variability which if not carefully managed can result in emission, noise, and vibration issues. This paper explores the premise of using feedback from a cylinder pressure sensor to control combustion variability to a target quantity via combustion phasing retard to get the most exhaust heating for a given acceptable variability level. The premise of using statistical models to enhance controller performance for stochastic systems is well-documented (Kalman filter), but little literature is available concerning the usage of statistics such as standard deviation as a feedback parameter for control. Thus, the main control challenges include the dynamics of using windowed statistics for feedback, and the effect combustion phasing retard has on both combustion variability (COVIMEP) and engine cylinder torque (IMEP), illustrated below in Figure 1.

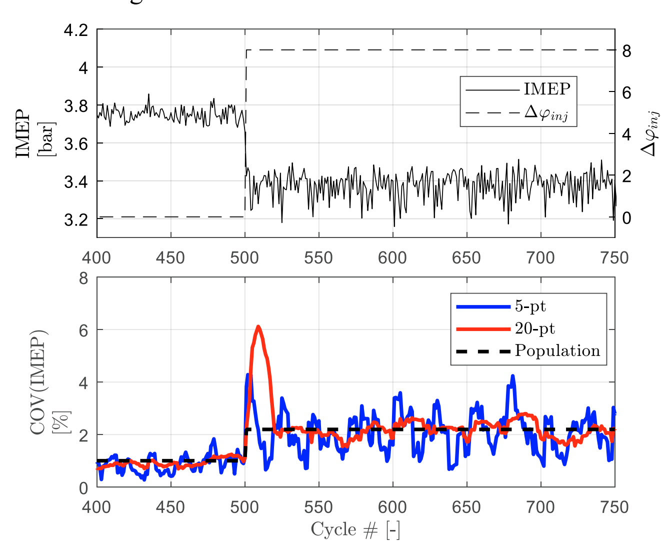


Fig. 1. Experimental combustion data at two injection retard points. Upper subplot shows the effect of injection retard on engine cylinder torque (IMEP). Lower subplot shows the effect of injection retard ($\Delta\varphi_{inj}$) on combustion variability (COVIMEP) and the effect of window size on the statistical feedback, notably the peaks induced by a change in IMEP illustrating the transient benefit of having a smaller window.

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This paper is organized as follows: Section 2 provides background on diesel engine combustion, cylinder pressure sensors, and previous modeling work. Section 3 explains the controller design process, simulation results, and experimental results for a single-cylinder control approach. Section 4 explores the opportunities and challenges created by having multiple cylinder pressure sensors in the engine. Section 5 summarizes the work and outlines next steps.

## 2. BACKGROUND

Background on diesel engine combustion control, cylinder pressure sensors, and previous modelling work are provided to inform later sections of the paper.

### *2.1 Diesel Engine Control*

Calibration and control of diesel engines is focused on meeting consumer horsepower and torque requirements while complying with emissions, vibration and harshness, and durability limits. Parameters like injection timing and quantities, boost pressure, and EGR rate are controlled based on a customer's requested torque/speed (power) using the various actuators available. Diesel engines rely on autoignition to initiate combustion, where the elevated temperature and pressure in the cylinder are used to cause a certain portion of the fuel to combust without an ignition source (premixed burn), and the rest of it to burn as it mixes with the remaining air in the cylinder (diffusion burn). The crank angle location and duration during which combustion occurs can be controlled via injection timing, where earlier/later injection timings promote earlier/later combustion in the cycle (Heywood, 1988).

The usage of in-cylinder pressure sensors allows for the measurement of cylinder pressure, $p_{cyl}$, as a function of crankshaft position, $\theta$. Using engine geometry and other data, is it possible to perform detailed analysis of engine combustion on a cylinder basis. Fundamental to the work presented in this paper is the value Indicated Mean Effective Pressure (IMEP) which quantifies the amount of torque produced by a cylinder. It is calculated by integrating the pressure-volume trace of the cylinder, shown in Eqn. 1 below:

$$IMEP = \int_{\theta=-360°}^{\theta=360°} p_{cyl}(\theta)dV(\theta). \quad (1)$$

The rate and duration of combustion can be estimated using cylinder heat release models, with the most basic models using the difference between the actual cylinder pressure and an isentropic compression model to estimate the amount of energy generated by combustion on a crank-angle degree basis. This rate of heat release curve can be integrated to estimate how combustion is phased in the cylinder. A common metric to track combustion phasing is CA50, the crank angle at which 50% of the fuel for a given cycle has burned. Modeling and experiments show that a CA50 of about 10 degrees after top dead center (aTDC) is desirable for best fuel efficiency (Klimstra, 1985). Phasing combustion earlier results in the piston needing to compress against higher pressures and higher peak gas temperatures increasing heat transfer losses, causing a reduction in net work. Phasing combustion later reduces peak cylinder pressures, causing lower levels of expansion work which results in higher exhaust gas enthalpies at exhaust valve opening (EVO).

During catalyst light-off operation, diesel engines typically retard injection timing and add injections during the expansion stroke to phase combustion later, resulting in later CA50 values, higher exhaust gas enthalpies, and higher levels of combustion variability. Combustion variability is typically quantified at steady-state operation using the Coefficient of Variance of IMEP (COVIMEP), the ratio of the standard deviation of IMEP values to the mean of IMEP values. Although the standard deviation of IMEP could be used to evaluate combustion variability, it can be deceptive from an analysis perspective because a standard deviation of 10 N·m is ±10% at a mean of 100 N·m, but ±1% at a mean of 1000 N·m.

### *2.2 Cylinder Pressure Sensors and Analysis*

Cylinder pressure sensors have been investigated for usage in closed-loop combustion control since the 1950s (Draper et al. 1951). The ability to measure cylinder pressure, coupled with knowledge about engine volume, cylinder wall temperatures, and other parameters allow for the calculation and/or modeling of cylinder torques, heat release rates, pollutant formation, amongst other parameters. Publications have demonstrated the ability to control IMEP, MFB50, and max rate of heat release simultaneously in real-time on diesel engines in laboratory settings (Chung et al., 2017).

Implementation of these sensors in production applications has been historically limited by cost, reliability, and the physical placement restrictions in the engine. Advances in sensor technology and packaging, coupled with more stringent emission and diagnostic requirements, have led to OEM's adapting cylinder pressure sensors in some consumer engines. Volkswagen has implemented pressure sensing glow plugs (PSGs) on their 1.4, 1.6, and 2.0- liter diesel engines (BorgWarner, 2014).

### *2.3 Control-Oriented Modeling*

In Bieniek et. al (2018), a Ford 6.7L V8 Powerstroke diesel engine instrumented with cylinder pressure transducers in each cylinder was used to characterize and model combustion variability behaviour at a single operating condition at a fixed coolant temperature of 20 degrees C to mimic a cold-start. The low speed and load condition (1200RPM/2.5 bar BMEP) was selected because combustion variability due to combustion phasing retard is known to be problematic, especially at cold-start coolant temperatures.

The work showed that cylinder IMEP data behaves like a random normal Gaussian variable at the combustion variability levels of interest (< 2.5% COVIMEP). Injection timing and fuel quantity sweeps were conducted to build a combustion variability model which was validated against the experimental data. The model structure, shown in Figure 2, was implemented in Simulink and used to study the open loop behaviour of COVIMEP and IMEP. It was found that the windowed statistics of COVIMEP hover about the population statistics regardless of window-size, although a larger window reduces the variability in the statistics at steady-state, desirable