

Cylinder-to-Cylinder Variations in Power Production in a Dual Fuel Internal Combustion Engine Leveraging Late Intake Valve Closings

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ABSTRACT

Advanced internal combustion engines, although generally more efficient than conventional combustion engines, often encounter limitations in multi-cylinder applications due to variations in the combustion process. This study leverages experimental data from an inline 6-cylinder heavy-duty dual fuel engine equipped with a fully-flexible variable intake valve actuation system to study cylinder-to-cylinder variations in power production. The engine is operated with late intake valve closure timings in a dual-fuel combustion mode featuring a port-injection and a direct-injection fueling system in order to improve fuel efficiency and engine performance.

Experimental results show increased cylinder-to-cylinder variation in IMEP as IVC timing moves from 570°ATDC to 610°ATDC, indicating an increasingly uneven fuel distribution between cylinders. These observations along with engine simulation models developed using GT-Power have been used to better understand the distribution of the port-injected fuel across cylinders under various operating conditions. This study revealed that the fuel distribution across cylinders in this dual fuel application is significantly affected by changes in the effective compression ratio as determined by the intake valve close timing as well as the design of the intake system (specifically the length of the intake runners). Late intake valve closures allow a portion of the trapped air and port injected fuel to flow back out of the cylinders into the intake manifold. The fuel that is pushed back in the intake manifold is then unevenly redistributed across the cylinders largely due to the dominating direction of the flow in the intake manifold. Experimental and simulation results discussing the impact of operating parameters on the fuel distribution are presented.

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INTRODUCTION

Combustion variability is a common problem in advanced combustion modes. While advanced combustion modes including low temperature combustion (LTC) strategies can provide high efficiencies, the utilization of exhaust gas recirculation, fuels of differing reactivities, as well as early fuel injection timings can introduce high variability in the quantity and composition of the trapped mass consequently leading to variations in the combustion process [1,2]. Cycle-to-cycle and cylinder-to-cylinder variations of the combustion process are observed as differences in combustion phasing, heat release rates, and peak pressure, as well as the indicated mean effective pressure (IMEP). These variations in the combustion process have been found to have three primary causes 1) variation in gas motion in the cylinder during combustion; 2) variation in the amounts of fuel, air, and recycled exhaust gas trapped in the cylinder each cycle; and 3) variation in the mixing process of the composition within the cylinder [3]. Although cycle-to-cycle variations pose significant challenges in advanced combustion engines, the scope of this work is limited to the investigation of combustion variations across cylinders.

Prior efforts have explored the driving factors of these variations and have investigated methods for improving combustion stability by strategically choosing particular operating parameters. For example, a study by Gong et. al [4] investigated the effects of injection and ignition timings, engine speed, and load on the cycle-by-cycle combustion variation of a direct-injection spark ignition (DISI) engine fueled with methanol. Their work showed that a specific fuel injection and ignition timing reduced combustion variability by promoting even mixture composition distribution. Additionally, an increase in engine load resulted in lower cyclic variations in IMEP and similarly, an increase in engine speed resulted in lower COV, which is explained by an increase of swirl intensity that forms a more uniform mixture concentration distribution. Selim [2] also investigated different parameters that affect cyclic variability and engine noise in a dual fuel engine. These parameters included the type of gaseous fuel, engine speed, load, and compression ratio, as well as fuel mass and injection timing. His findings also showed that optimal settings of the mentioned parameters can help reduce cycle-to-cycle variation and reduce combustion noise. In a study on a dual fuel multi-cylinder engine, Iv Bouchet et. al. [5] identified uneven

distribution of the port-injected fuel and significant cylinder imbalances due to the common inlet plenum and the pressure pulsations, especially during valve overlap.

In this study, experimental testing on a heavy-duty multi-cylinder engine reveal that introducing late intake valve closing (LIVC) along with a dual fuel combustion technique can lead to significant cylinder-to-cylinder variations of the combustion process. LIVC is used to control trapped in-cylinder charge mass and subsequently the peak compression pressure and temperature. Additionally, dual-fuel strategy allows the control of fuel reactivity and helps improve combustion efficiency. Despite the benefits of LIVC and dual-fuel strategy, combining these two techniques resulted in efficiency losses due to the variability of the combustion process across cylinders.

Dual fuel combustion concepts were developed as a strategy to control combustion timing and extend the load limits in LTC operations [6]. The dual fuel combustion strategy uses two fuels with different reactivities in order to adjust the overall fuel reactivity levels based on operating conditions, thereby controlling the combustion timing. Furthermore, by port-injecting the low reactivity fuel and direct injecting the high reactivity fuel, in-cylinder reactivity stratification can be improved resulting in more optimal combustion durations and acceptable pressure rise rates, a primary load-limiting factor for many HCCI-type (homogenous charge compression ignition) combustion strategies [7,8]. The benefits of the dual fuel engine in terms of performance and emission have been demonstrated on single cylinder engines [7,8], as well as multi-cylinder engines [9,10,11,12,13].

Furthermore, improvements in fuel efficiency and reductions in emissions have also been achieved by implementing late intake valve closing (LIVC) strategies. LIVC has been shown to improve fuel efficiency by reducing pumping losses [14]. By closing the intake valves after conventional timing during the compression stroke, the effective compression ratios and consequently peak compression pressures and temperatures are reduced [6]. The impact of LIVC on emissions has also been well studied. Nevin et al. [15] incorporated a hydraulically actuated variable IVC system onto a single cylinder diesel engine and this study revealed that late IVC resulted in a 90% NO_x reduction at high speed and intermediate load with constant airflow and no EGR. With the addition of late IVC, less EGR is required to achieve the same NO_x emissions, while CO and PM were reduced by nearly 70%. He et al. [16] also experimentally investigated the feasibility of using late IVC to improve the performance and emissions of a diesel engine with a fully flexible valve actuation system. They found that late IVC reduces approximately 25-50% NO_x emissions and more than 95% PM at some operating conditions. The reduction in particulates is due to the longer ignition delay and a subsequent reduction in local fuel rich combustion zones; whereas the reduction in NO_x is attributed to low combustion pressure and temperatures-both consequences of delaying the intake valve closing [16,17,18].

This study explores the combination of these two techniques, dual-fuel combustion and LIVC, which have been implemented on a heavy-duty engine to meet the standards of the SuperTruck program focused on demonstrating 50% brake thermal efficiency on a heavy duty engine and the establishment of a pathway to 55% brake thermal

efficiency [19]. In this work, the variations in combustion across cylinders stemming from the use of dual fuel and LIVC is investigated. LIVC operations were observed to exhibit significant cylinder-to-cylinder variations of up to 8% in peak pressure, up to 13% in IMEP, and up to 8% in combustion work (the cylinder-to-cylinder variations are calculated as the ratio of the standard deviation to the mean across the six cylinders). These variations are indicative of uneven distribution of fuel across the cylinders. This study seeks to understand the underlying causes for the observed fuel distribution problem in an effort to address this challenge on stock engine architectures.

This study leverages experimental data and a simulation model of the gas exchange process developed using GT-Power to investigate the main factors affecting the fuel distribution. In the following sections, the engine used for this study is described in Experimental Setup followed by the description of the GT-Power model in Model Development. Analysis of the experimentally observed variations in key metric combustion parameters during IVC modulation will be given prior to a discussion of the simulation study undertaken to explore the root causes for the experimentally observed trends. Concluding remarks and a discussion of future work will follow at the end.

EXPERIMENTAL SETUP

The experimental investigation of cylinder-to-cylinder variations was conducted using data collected from a modified 2010 Navistar MaxxForce 13 heavy-duty engine, also used in [13,20-21]. The engine specifications are given in Table 1. As shown in Figure 1, the engine features an air system configured for high EGR delivery, utilizing two-stage turbocharging (with interstage cooling) and a dual-pass EGR cooler with high and low temperature stages.

The engine employs a fully flexible intake valve actuation system developed by Jacobs Vehicle Systems [22], which uses a lost-motion mechanism to control the length of the intake valve events. To enable dual-fuel operation, the engine has separate direct-injection and port-injection fuel delivery systems. The direct-injection system is used for the high reactivity fuel and a port fuel injection (PFI) system is used for the low reactivity fuel. The high reactivity fuel used is ultra-low sulfur diesel and the low reactivity fuel investigated is compressed natural gas (CNG). PFI timing in the experiments are prior to intake valve opening, and therefore against a closed intake valve. A set of two prototype ECUs are used to control the 12 CNG injectors (each ECU controlling a set of six injectors, one injector per cylinder), in conjunction with an OEM development ECU for the diesel injectors. Cylinder-to-cylinder balancing is not actively engaged for the study - all cylinders are receiving the same set fuel command.

For these tests, the engine cooling system and air system restrictions were tuned to be representative of the conditions encountered in production vehicles. Each cylinder was equipped with a Kistler 6125B pressure transducer which supplied pressure measurements at a resolution of 0.1°C_A. Fuel flow was measured using Micro Motion CMFS010 Coriolis-type flow meters with a measurement accuracy of $\pm 0.1\%$.

Table 1. Engine Specification

Displacement Volume	12.4 L
Number of Cylinders	6
Stroke	166 mm
Bore	126 mm
Connecting Rod	251 mm
Compression Ratio	17
Diesel Fuel System	2200 bar common rail
Air System	2-stage turbocharger (variable vanes on the high pressure turbine)

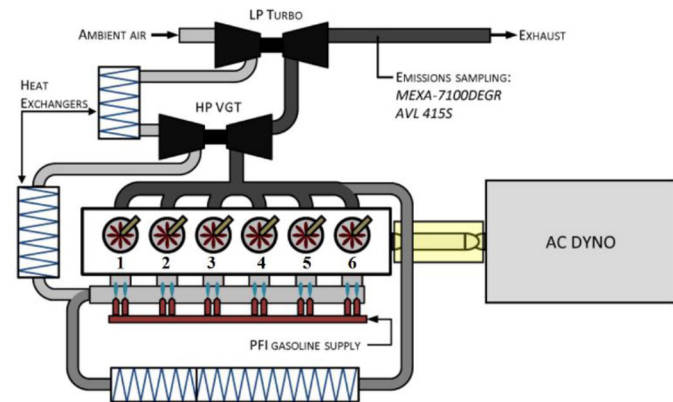


Figure 1. Schematic of Navistar MaxxForce 13 heavy-duty compression ignition engine test bed. [6]

MODEL DEVELOPMENT

While the experimental setup allows for accurate measurement of engine performance and emissions including combustion metrics, a simulation model was also developed to allow the gas exchange process to be more thoroughly investigated. The model used for the simulation studies of the cylinder-to-cylinder variations was built using GT-Power and is illustrated in Figure 2. The model is an inline 6-cylinder compression ignition engine that includes the cylinders connected to the intake manifold through the intake ports and intake runners, and the fuel injection systems connected to the cylinders (direct injection) and the intake ports (port-injection). Further details about GT-Power engine models and the other components in the model (Figure 2) can be found in [23].

The engine geometric dimensions and piping dimensions (including distances from cylinders to inlet of intake manifold) were adjusted to best match the experimental setup and the effect of the turbocharger and EGR loop were simulated by dictating the inlet conditions (pressure, temperature, and composition) that matched experimental results. This model also uses a mass flow controller at the inlet of the manifold to set the charge mass flow rate to that of the experiments. The settings of the inlet conditions, as well as the mass flow controller (a PID-like regulator), assure that the air handling performance of the engine are accurately depicted by the model.

In part of the investigation, additional fuel injectors were added directly in the intake manifold to investigate how the fuel in the manifold is distributed across cylinders. Fuel flow monitors were

added at each intake valve and at the intersections of the manifold and intake runners to allow fuel distribution to be closely examined. The model is used to investigate the gas exchange process, specifically the distribution of the fuel in the intake manifold and across the cylinders. Alternatively, the accurate depiction of the combustion process (start of combustion, combustion duration, heat release rates, etc.) is outside the scope of this study. As such, a simplified combustion model is used for the study. The GT-Power model uses a DI-Jet combustion model with default calibration settings. Further details about the combustion model can be found in [23].

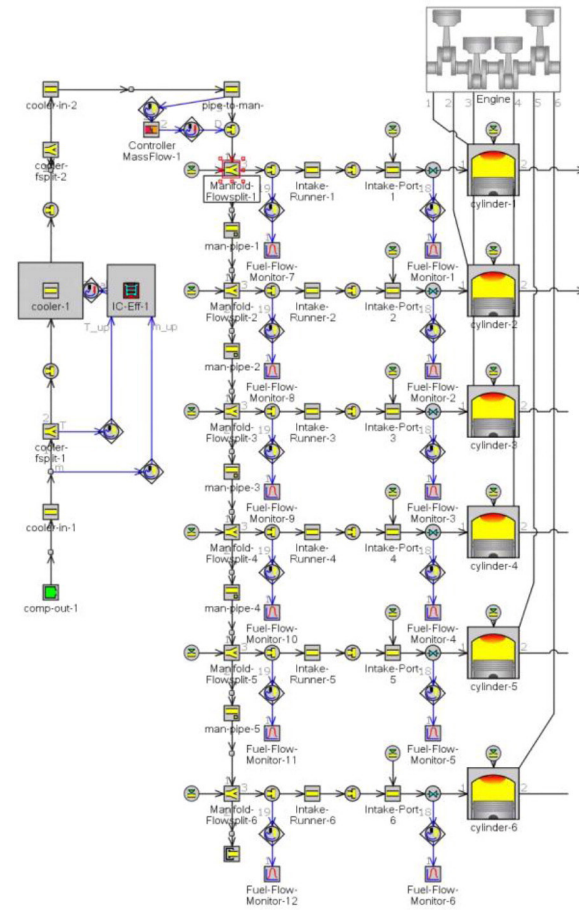


Figure 2. Diagram of simulation model developed using GT-Power.

RESULTS AND DISCUSSION- EXPERIMENTAL OBSERVATION

The effect of IVC timing on combustion was investigated experimentally to determine its impact on cylinder-to-cylinder variations in a dual fuel combustion modes. The operating points investigated represent an IVC sweep from 570° after top dead center (ATDC) to 620° ATDC at an engine speed of 1200 RPM and a brake mean effective pressure (BMEP) of 16.5 bar. The engine operating condition for this study is representative of a higher load cruise condition for a class 8 on-highway truck. Combustion variations are analyzed by examining differences in IMEP, peak pressure, as well as differences in combustion and compression work stemming from changes in IVC timing.