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Controlled End-Gas Autoignition Effect on Pollutant Emissions of Ultra-High Efficiency Heavy-Duty Natural Gas Engine

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Abstract

Heavy-duty on-highway natural gas (NG) engines present a promising alternative to diesel engines for reducing greenhouse gas emissions and harmful pollutants, provided their limitations—such as knock and misfire—are addressed to achieve diesel-like efficiencies. This study examines the impact of induced controlled end-gas autoignition (C-EGAI) on pollutant emissions in a high-efficiency, stoichiometric, spark-ignited (SI) natural gas engine. C-EGAI is employed as a combustion control strategy to enhance efficiency. Experiments were conducted using a single-cylinder heavy-duty engine designed to replicate the operation of an on-highway multi-cylinder engine. Exhaust gas recirculation (EGR) tests were carried out with a custom EGR system that simulates a high-pressure EGR loop, covering rates from 0% to 35%. A newly developed high compression ratio piston design was implemented to improve brake thermal efficiency (BTE) and mitigate knock tendencies. Measurements were taken under varying EGR rates and indicated mean effective pressures (IMEP). The results demonstrate that achieving C-EGAI conditions correlates with low engine-out emissions of nitrogen oxides (NOx), total hydrocarbons (THC), volatile organic compounds (VOC), and carbon monoxide (CO). These emissions were observed during high-load operation while attaining diesel-like BTE levels up to of 46%, using an EGR rate of 29.4%, and with f-EGAI of 28.5%.

Keywords

Heavy-Duty Engine, Natural Gas, Auto-Ignition, Knock

1. Introduction

Usage of energy from the transportation sector indicates that the heavy-duty

transportation sector moves > 80% of freight use and >25% of all domestic fuel consumed per year in the United States. By 2050, global energy usage is projected to increase by nearly 50% with respect to 2020 data [1]. This energy consumption growth motivates the continuous study on the impact of combustion emissions on the environment and human health, and the need to diversify the energy mix [2].

The last decade has seen a large increase in electric, fuel cell, and non-fossil fuel powered vehicles market share as alternative solutions for the fossil fuel associated emissions in the transportation sector. These alternative options continue improving with new battery technologies that could increase the efficiency and life span of electrified vehicles, allowing them to mitigate short term and aim to eliminate long term tailpipe emissions [3]. Achieving this will improve the overall carbon balance as more renewable energy sources increase their share as electricity sources [2]. These promising alternatives will not penetrate the same in all transportation sectors. The world's transportation fleet will still be primarily powered by ICEs in the foreseeable future, as it is projected that ICEs will account for approximately 40% of the energy demand [4]. This scenario shows that diesel fuel demand will increase by up to 85% as the transportation sector will see growth by 75%. To achieve the mitigation of climate change and the health effects associated with pollutants by 2050, the study and development of current and innovative technologies around ICEs is paramount [5]. Key areas like alternative and cleaner fuels, improved overall thermal efficiency, ultra-low emissions, specialized combustion modes, and hybrid-powertrains are required and expected to continue to be developed [6].

The heavy-duty transportation sector uses diesel fuel Compression Ignition (CI) engines mainly due to the lower operating cost, higher fuel efficiency and higher durability than spark ignition engines [7] [8]. Alternative powertrains face a greater challenge in these sectors due to the high energy density, ease of transport, storage, and handling of conventional fuels for ICEs. Petroleum-based fuels like diesel are affected by decreasing crude oil reserves and the political unstable scenarios that affect the final price of the fuel. On the other hand, NG is a fuel widely available in the US and, partly due to the implementation of hydraulic fracking technique, NG has emerged as a natural alternative for short-term substitution to traditional CI diesel engines. NG is lower in cost, produces close to zero particulate matter, and is lower in CO_2 emissions due to a lower carbon to hydrogen ratio inherent to fuel composition, mainly methane (CH_4). This results in low-cost aftertreatment systems to meet emission regulations, lowering the operative costs for the end user during the engine life cycle [9] [10].

NG ICEs must increase Brake Thermal Efficiency (BTE) to competitive in the medium- and heavy-duty transportation sector. High compression ratios (CR) are needed as the gap with diesel counterparts is one of the main tradeoffs in BTE. This requires improved combustion control of Spark Ignited (SI) homogeneous NG-Air mixtures to allow for these high CR, increased boost pressures, and high Exhaust Gas Recirculation (EGR) levels. Knock is one of the main limitations for

spark ignition engines operating under high-torque conditions, while misfire is the main problem during highly diluted operating conditions. The ability to operate closer to the knock limit will define the efficiency limitation of the engine [8] [11]. Another important aspect is the variability in fuel composition for NG and its effect on combustion characteristics. Wide regional variances of fuel composition make high-performance engines difficult to optimize for the US market due to differences in fuel reactivity [12]. The metric used to quantify the reactivity of NG, Methane Number (MN), is not standardized as is the Octane Number for gasoline. The variation in natural gas MN ranges from 68 to 96 in the US [13].

Controlled End-Gas Autoignition (C-EGAI) has been proposed as a viable technique to improve combustion control [14] [15] to mitigate the effects of varying NG compositions while allowing the use of high boost pressures and high EGR rates, with the consequent increase in overall BTE. The novelty of this approach is the control of the fraction of energy participating in the autoignition event, called fractional end-gas autoignition (f-EGAI) [16]. This is carried out by cycle-by-cycle ignition timing adjustments instead of setting a fixed spark timing or crank angle at 50% mass burned fraction (CA50). This approach has enabled the increase of the Cooperative Fuel Research (CFR) engine Indicated Thermal Efficiency (ITE) by 20.3% (3.6 efficiency points) [17] and enabled heavy-duty (HD) SI NG engines to achieve Diesel-like efficiencies [12].

The work presented in this paper is part of the U.S. Department of Energy project "Expanding the Knock/Emissions/Misfire Limits for the Realization of Ultra-Low Emissions, High Efficiency Heavy Duty Natural Gas Engines". During the earlier phases of this work, experiments were conducted using a Rapid Compression Machine (RCM) and a CFR engine to study the effects of variations in natural gas fuel reactivity [10] [13]. These efforts also included chemical mechanism optimization and computational fluid dynamics (CFD) modeling aimed at optimizing the combustion chamber design. [17]. Additionally, an innovative method to detect the presence of EGAI and determine its onset location (or crank angle) has been successfully developed, especially in the light/low EGAI levels that are important for a Controlled EGAI (C-EGAI) operation [16].

The project phase described in this paper corresponds to the testing of a Single-Cylinder Heavy-Duty Stoichiometric SI NG Engine operated under C-EGAI conditions with high EGR dilution rates. The focus is on the Cummins 15-liter heavy-duty engine platform, which has a baseline diesel BTE of 44% at peak torque. Single-cylinder engines (SCE) have been the main research tools used to reduce emissions and improve performance and fuel consumption from ICEs. In this case, a production engine was modified to have combustion process in just one cylinder. This strategy is less time-consuming and costly than a dedicated, custom single cylinder engine [11].

2. Methods/Experimental

Tests were carried out using a single cylinder heavy-duty engine developed to sim-

ulate the operation of an on-highway multi-cylinder engine. This engine is based on a production Cummins ISX15 diesel block, modified to operate as a single cylinder. Standard bore and stroke are kept (137 × 169 mm) for a displacement of 2.5 liter on the firing cylinder. A CFD improved shape flat bowl piston was installed with a compression ratio of 13.3:1 to improve brake thermal efficiency while reducing knock tendency designed by CFD optimization described by Bestel [18]. Exhaust gas recirculation (EGR) is used with a custom EGR system that simulates a high pressure EGR loop with rates from 0 to 35% [19]. The experimental measurements were performed with variable EGR rate, IMEP, and location of 50% of mass burned (CA50). A detailed description of the test cell can be found in [20].

The engine is controlled using a Woodward Large Engine Control Module (LECM) which performs a cycle-based analysis of the pressure trace, heat release, and mass fraction in real-time [21]. This allows the system to adjust the ignition timing to achieve conditions of C-EGAI, obtaining increased BTE. The test cell is also capable of controlling the air/fuel ratio, EGR rates, load, and engine speed [15]. The fuel flow is measured using a Bronkhorst Coriolis flow meter. Continuous sampling of exhaust gas concentration measurements for CO, CO_2, NOx, O_2, and THC from a Siemens 5-gas Analyzer and formaldehyde, speciated hydrocarbons up to C_3, NO, and NO_2 measured with an MKS FTIR spectrometer are available during the engine operation. The test was conducted using pipeline natural gas with 74 methane number and LHV 47,100 kJ/kg, using the MWM calculator [22].

The cylinder head was machined to install a cylinder pressure transducer (AVL QC34C), the intake and exhaust manifolds were machined to install high speed Kistler piezo resistive intake (Type 4007D) and water-cooled exhaust (Type 4049B) pressure transducers. These sensors allow for more accurate three pressure analysis (TPA) for 1-D and 3-D model validation for (CFD) and GT-Power models of the engine. These sensors are paired to a high-speed LabView based sampling system that uses a 3600 samples per revolution encoder, allowing for a 0.1 deg sampling resolution.

Performance metrics based on combustion pressure data include IMEP, Peak Pressure Coefficient of Variance (COV), IMEP COV, CA50, Start of Combustion, Heat Release and Knock Index.

Engine Test Procedure

Tests were carried out at steady state, keeping general engine parameters unvaried while the ignition timing was adjusted to induce EGAI. The main objective is to expose conditions of non-EGAI, mild EGAI and high EGAI combustion (0 to 5%, 5% to 15% and more than 15% respectively). Engine out emissions and general engine performance parameters are evaluated for the different EGAI induced on the combustion. **Table 1** outlines the operating conditions considered and **Table 2** shows the average NG composition used for the Cummins ISX15 SCE testing [23].

Table 1. Tested cummins ISX15 engine operating conditions.

Parameter	Value	Unit
CR	13.3:1	Ratio
Engine Speed	1200	RPM
IMEP	18 - 20	bar
CA50	5.5 - 14	deg. aTDC
EGR	13- 30	%
Intake Manifold Temp (IMT)	33-35	˚C
Intake Manifold Pressure (IMP)	2.0 - 2.32	bar
Exhaust Manifold Pressure (EMP)	2.2 - 2.5	bar

Table 2. NG molar composition used during the Cummins ISX15 engine testing.

Species	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_6H_{14}	N_2	CO_2
Percentage	86.60%	10.63%	1.90%	0.39%	0.10%	0.02%	0.36%	1.69%

Performance Metrics

A LabVIEW-based algorithm also quantifies knock. This method takes the pressure data to calculate the high frequencies of pressure oscillations caused by the knock event and correlates them to EGAI. A fast Fourier transform (FFT) is applied to this data to obtain the power spectrum of the signal. Detailed description over this knock estimation method can be found in the work of Fosudo *et al.* [24].

The fractional EGAI (f-EGAI) metric is used considering the fraction of the total energy released that participated in the EGAI event. This metric was developed by Zdanowicz *et al.* [14]. For detailed description of the calculation of f-EGAI can be found in the work of Bestel *et al.* [16] and [25].

The estimation of the fraction of exhaust gas recirculated into the intake is calculated using the ration of mass flow of exhaust gas over the total mass flow into the cylinder, air, fuel and recirculated exhaust mass. Detailed description of the calibration process of the instrumentation used to estimation of mass flow of exhaust gas is presented in previous work of the authors [20].

Equation (1). Mass flow of recirculated exhaust gases.

$$EGR = \frac{\dot{m}_{egr}}{\dot{m}_{egr} + \dot{m}_{air} + \dot{m}_{fuel}}$$

3. Results and Discussion

C-EGAI

Achieving conditions of C-EGAI allowed for the utilization of high EGR at and high PP without inducing uncontrollable knock. **Figure 1** shows the onset of EGAI on the apparent heat release trace for a case with peak BTE of 46% using

EGR ratio of 29.4%.

This condition was achieved with f-EGAI of 28.5%. Peak cylinder pressure was 144 bar. IMEP was 19.92 bar, and the estimated BP was 43.36 kW [25].

Heat release profile shows the onset of the EGAI between 6 and 10 deg ATDC, which increases the efficiency as more fuel is burned completely in the combustion chamber at a faster rate. Pressure traces show good combustion stability, which is validated by the COV of IMEP of 0.52% and the COV of peak pressure of 3.52%.

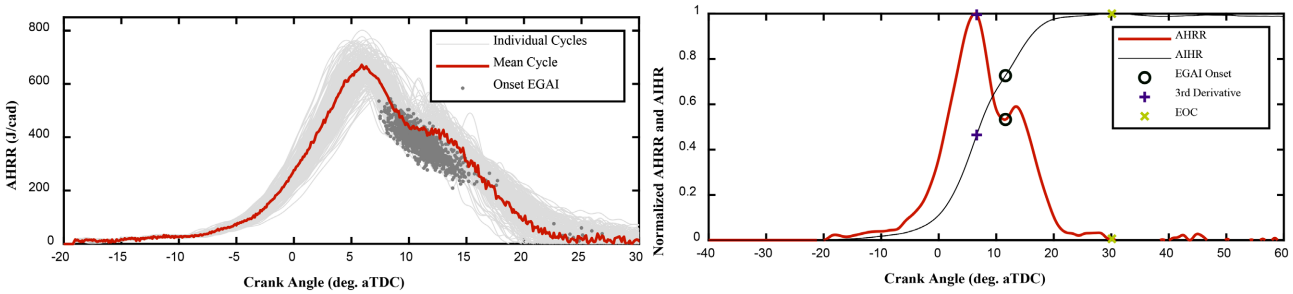

Figure 1. Apparent Hear Release Rate vs Crank Angle (left) and Normalized Apparent Heat Release Rate vs Crank Angle (right) best brake thermal efficiency condition achieved. Engine operating conditions: 1200 RPM, $\varphi = 1$, EGR rate 30%, IMP 2.3 bar, CA50 6 deg aTDC.

Combustion characteristics

EGAI is the key to achieving BTE improvements for the conditions evaluated in this work. **Figure 2** present the BTE with respect to the calculated f-EGAI. The addition of EGR into the fresh mixture allows the use of early CA50 while keeping the engine below the knock threshold for the engine. It is possible to induce EGAI in a greater fraction for the cases with higher content of EGR. A CA50 of 10 was the minimum combustion advance necessary to induce measurable EGAI, which corresponded to a f-EAGI of 0.05. Lower values of f-EGAI are difficult to quantify with the methodology used, so they are not considered EGAI combustion [16]. The effect of f-EGAI on BTE is evident on **Figure 2**, as a linear increasing behavior

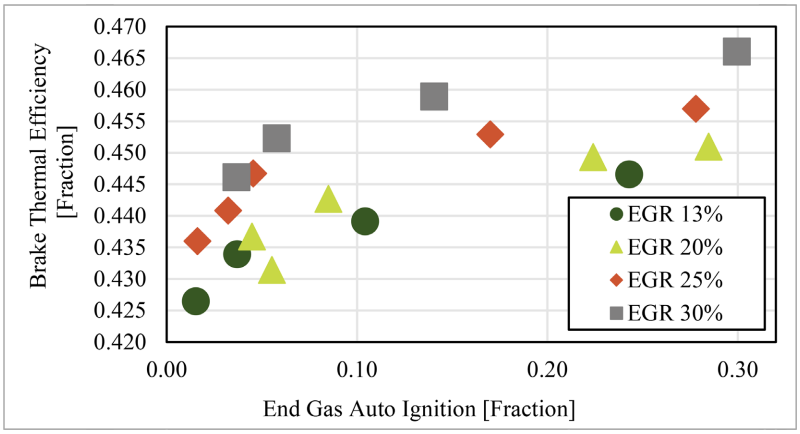

Figure 2. Fraction end gas auto ignition vs brake thermal efficiency. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

is present for each EGR rate.

Cycle by cycle pressure trace plots indicate the level of combustion stability. The parameter defined as threshold for acceptable combustion stability is the IMEP Coefficient of Variance (IMEP COV). Values below 3% for IMEP COV are considered acceptable. Figure 3 show these metrics for all the cases tested. Earlier CA50 always showed the best BTE results and this correlates with COV values below 3% for all cases.

Engine Performance

Figure 4 shows brake thermal efficiency (BTE) for all cases tested with respect to CA50. The BTE increases with earlier CA50 from an average of ~0.5% for each 2 ˚CA of advance, achieving a peak value of 46% for the case with 30% EGR rate at 6 ˚CA ATDC CA50. This improvement is expected as early CA50 moves the peak pressure closer to TDC, resulting in more efficient conditions to convert cylinder pressure into effective work at the crankshaft. Half of the conditions presented are above 44% BTE, which is the base reference efficiency for this ISX15 diesel engine.

Figure 5 presents IMEP results for the conditions tested, where an inverse

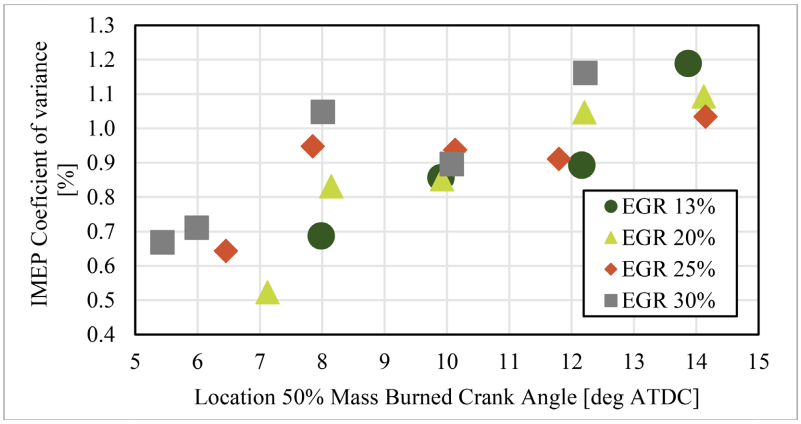

Figure 3. Location 50% mass burned crank angle vs IMEP coefficient of variance. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

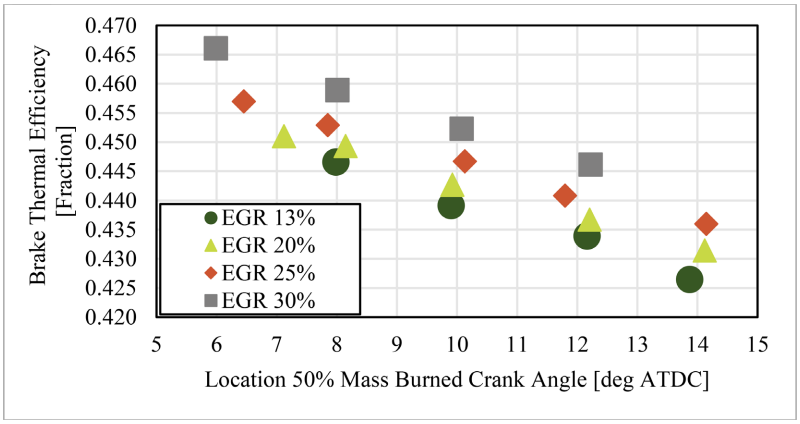

Figure 4. Location 50% mass burned crank angle vs brake thermal efficiency for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

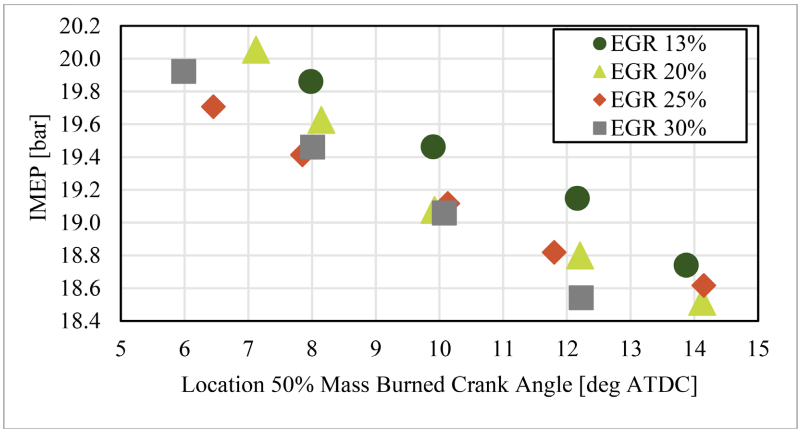

Figure 5. Location 50% mass burned crank angle vs indicated mean effective pressure for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

linear correlation of CA50 and IMEP is observed for all EGR rate cases. The highest IMEP was found at 20% EGR rate with the next closest values at 13% and 30%. These cases show up to $2\%_{pts}$ difference in BTE. This is explained as the IMP was held constant and the more aggressive timing used produced more power, hence, the engine was operating more efficiently.

Figures 6-9 show engine-out emissions normalized by brake power conditions tested with respect to the f-EGAI. Several distinguishable trends are observed related to the EGR substitution rate.

Figure 6 shows brake specific Nitrogen Oxide (NOx) emissions for different EGR rates used with respect to f-EGAI. The NOx chemistry is governed primarily by the post combustion local in-cylinder temperatures leading to increased NOx emissions as peak temperatures increase. For each EGR rate tested, there is a linear increase in NOx formation with more f-EGA (from previous section high BTE was found as earlier timing was used and more f-EGA achieved). This indicates that the in-cylinder temperatures increased as earlier timing was used but decreased for every increment on EGR added for all the scenarios studied.

Figure 7 shows brake specific Total Hydrocarbons (THC) over the range of conditions tested. THC measurements include Non-methane (NMHC) and non-ethane (NMNEHC) HCs which are important because their reactivity and potential to promote o-zone. CH_4 emission is important as is a potent greenhouse gas, about 25 times the warming potential of CO_2. The THC emissions were quantified using Siemens 600 series Fidamat Analyzer and normalized by brake power. As shown, the THC emissions decreased with more f-EGAI which produces higher BTE and BP, as faster and more complete combustion is achieved [8]. The addition of EGR shows an important influence on THC emissions, as 30% EGR cases had almost 60% higher THC emissions. However, for the higher EGR rate cases, the ignition timing and consequent BTE achieved are more influential on THC emissions; for the 30% EGR cases, the difference between the highest and lowest value represents a 60% reduction.

CO was also measured and normalized as shown in **Figure 8**. CO emissions

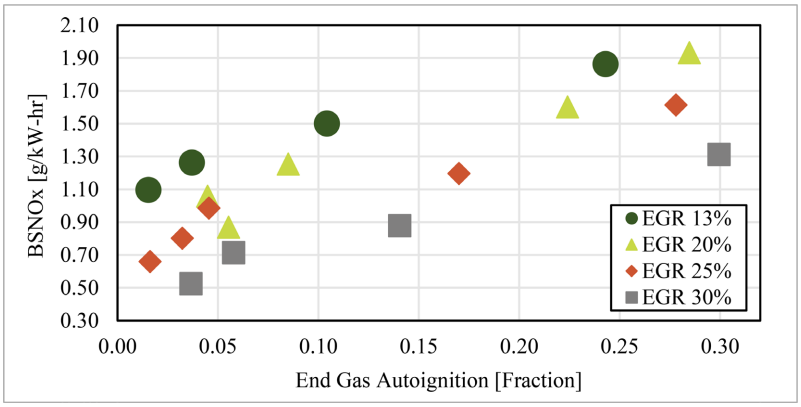

Figure 6. Location 50% mass burned crank angle vs brake specific NOx emission mission for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

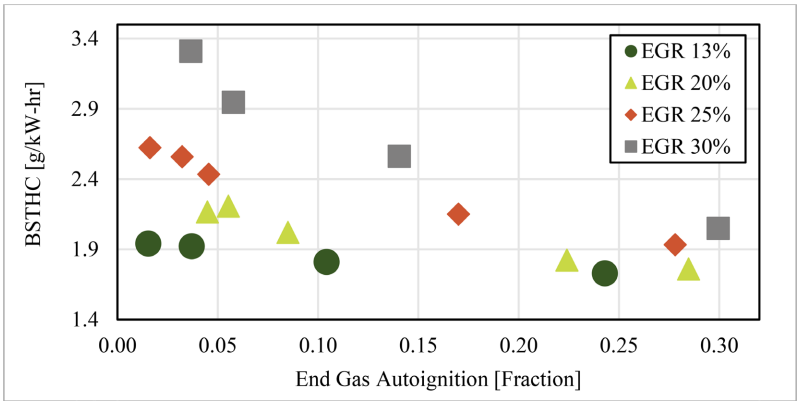

Figure 7. Fraction end gas auto ignition vs brake specific THC emission for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

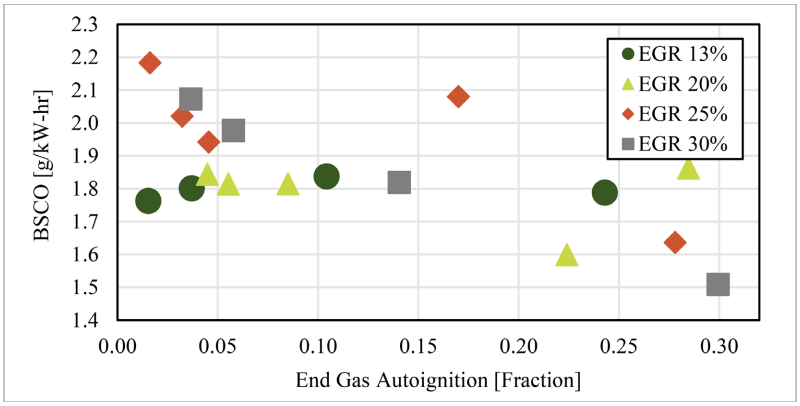

Figure 8. Fraction end gas auto ignition vs brake specific CO emission for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

indicate a loss in chemical energy, as CO chemistry is primarily dominated by the equivalence ratio and extent of fuel oxidation. In general, CO decreases as the ignition timing is advanced to achieve higher f-EGAI, which is the case for the highest EGR cases tested, 25 and 30%. The 20% EGR case tends to hold the same trend without being linearly related to the efficiency increments associated to advanced

timing, but the lower EGR case has an almost constant behavior. Slightly higher CO values were measured as more EGR was used, always within a range of 0.8 g/bkW-hr variation.

Non-methane, non-ethane hydrocarbons (NMNEHC) known as Volatile Organic Compounds (VOC) were also measured using the FTIR spectrometer. Measurements of normalized VOC are shown in Figure 9 as a function of BTE. The trend encountered shows that for the mid f-EGAI cases (10% to 20%) results in lower VOC emissions, indicating more complete combustion, and an increase for the cases with the highest f-EGAI induced (>20%) to values that are closer to the cases below the spectrum of C-EGAI (<10% f-EGAI). In the same way, a higher EGR rate produces higher VOC emissions. This is similar to the behavior of THC emissions. When more exhaust gases are recirculated, a minor increase in VOC emissions is observed. In all tested cases, the measurement is below 1 g/bkW-hr.

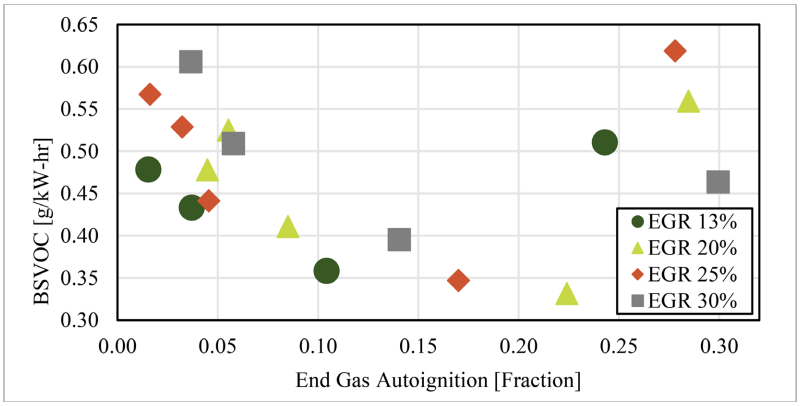

Figure 9. Fraction end gas auto ignition vs brake specific VOC emission for all EGR substitution rates. Engine operating conditions: 1200 RPM, $\varphi = 1$, IMP 2.2 bar.

4. Conclusions

In this work, experiments were conducted on a single-cylinder 2.5-liter heavy-duty engine at steady-state engine operating conditions with different EGR substitution rates and ignition timing targets. The experiment results showed that:

- Improvements in BTE were found operating the engine with higher EGR rates and early CA50s.
- C-EGAI was achieved for high-load engine conditions, using advanced combustion controls with a high-accuracy in-cylinder sensor.
- Stable combustion was achieved even for the best BTE cases, using IMEP COV as metric to define the stability threshold.
- Ultra-low Nox emissions were measured under the conditions evaluated. The trends follow the expected behavior of lower NOx emissions for higher EGR ratios. Higher f-EGAI indicated lower NOx emission.
- VOC emissions for the conditions evaluated in this work presented values under 1g/kW-hr, with variations that land under the sensibility of the instrumen-

tation, due to the low concentration in the sample.

- The test conducted demonstrates the potential of NG engines as an alternative to the traditional commercial diesel counterpart, with relatively low pollutant emissions and equal if not better thermal efficiency. This, added to the relatively low cost of components and maintenance and the availability of the NG on the US market as a locally sourced fuel, presents a great alternative for the short and mid-term needs of heavy-duty transportation powertrain solutions.
- Multiple test conditions achieved BTE values above the pre-defined target of 44%. The best BTE condition of 46% was found using EGR rate of 29.4%. This condition was achieved with f-EGAI of 28.5%. The peak cylinder pressure was 144 bar. IMEP was 19.9 bar, and the estimated BP was 43.4 kW.

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Author Contributions

Juan Felipe Rodriguez Rueda: Test design, execution, data analysis, graphing and document writing. Daniel Olsen: Test design, Data analysis, document review. Bret Windom: Data analysis, document writing and review. Nestor Rojas: Data analysis, document writing and review

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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