CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

High Frequency Corona Discharge Ignition System Demonstration

Gavin Newsom, Governor

March 2021| CEC-500-2021-015

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ACKNOWLEDGEMENTS

The authors thank the California Energy Commission and Southern California Gas Company for the opportunity to test an advanced ignition system on this advanced engine application. Special thanks to BorgWarner Beru for their contributions to the project.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

High Frequency Corona Discharge Ignition System Demonstration is the final report for the High Frequency Corona Discharge Ignition System Demonstration project (Grant Number PIR-14-010) conducted by Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Gas Technology Institute, Westport Fuel Systems, Inc., and BorgWarner Beru demonstrated the enhanced combustion performance that is possible with an advanced engine and ignition technology. The specially designed engine (Efficiency Spark Ignition) includes cylinder heads designed to deliver high turbulent kinetic energy by tumble flow motion. The engine advancements provided improvements in engine performance when using the baseline ignition system as well as the advanced ignition system. It is expected that both ignition systems would meet California Air Resources Board optional low oxides of nitrogen certification of 0.02 grams per brake horsepower-hour. The effect on carbon dioxide emissions is even more compelling, meeting all project targets. Testing results showed levels that would meet expected United States Environmental Protection Agency regulations through model year 2027.

Keywords: California Energy Commission, Gas Technology Institute (GTI), Westport Fuel Systems, Inc. (Westport), BorgWarner Beru (BorgWarner), High Efficiency Spark Ignited (HESI), EcoFlash, Corona Discharge, natural gas engine, advanced ignition system

Please use the following citation for this report:

Draper, Rob (Westport), Rod Beazley (Westport), and Ted Barnes (GTI). 2021. *High Frequency Corona Discharge Ignition System Demonstration*. California Energy Commission. Publication Number: CEC-500-2021-015.

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EXECUTIVE SUMMARY

Introduction

Over the past decades, California established energy goals to move away from traditional fossil fuels and transition to cleaner alternative fuels such as renewable natural gas. Under the Energy Policy Act of 1992, natural gas vehicles are recognized as alternative fuel vehicles which contains lower carbon intensity and operates at lower fuel economy compared to diesel. Current commercial natural gas engines are limited in their ability to maximize fuel economy and reduce emissions due to limitations of existing ignition systems. The ignition characteristics of natural gas as a fuel present issues and opportunities for engine manufacturers working to meet tighter emission standards, achieve higher fuel economies, increase engine performance, and extend maintenance intervals. Advanced, high-energy ignition systems are needed to overcome the challenges of igniting natural gas under high boost pressures with heavy exhaust gas recirculation for medium and heavy-duty natural gas engines.

Project Purpose

The project team of Gas Technology Institute (GTI), Westport Fuel Systems, Inc., and BorgWarner Beru demonstrated an advanced engine and ignition technology (corona ignition) to improve emissions, performance, and fuel economy over traditional designs. A corona discharge is defined as an electrical discharge from the ionization of a fluid surrounding a conductor that is electrically energized. BorgWarner testing compares their corona ignition technology, the EcoFlash, with the traditional spark plug ignition. Previous testing in gasoline engines validated that increasing the spark area reduces ignition delay and enhances the early ignition process, stabilizes main combustion, and reduces some throttling/pumping losses.

Prior to this research project, BorgWarner had developed and demonstrated the benefits of EcoFlash on gasoline engines with these results:

- Increased exhaust gas recirculation tolerance up to 40 percent – extra exhaust gas recirculation displaces air and reduces pumping losses at certain conditions as well as reduces oxides of nitrogen (NOx) and greenhouse gas emissions.
- Enhanced high-load combustion stability with high levels of exhaust gas recirculation, which gives better knock resistance, higher boost pressures — 45 pounds per square inch (psig) and high brake mean effective pressure capability, an effective way for comparing the performance of an engine of one type to another — at least 360 psig with appropriate turbocharging methods.
- Enhanced ignitability at very high in-cylinder pressures associated with very high brake mean effective pressure.

Project Approach

This project focused on demonstrating EcoFlash in an advanced medium-duty natural gas engine to collect detailed ignition and combustion data and measure the benefits by comparing it to a conventional spark plug, also known as a transistor coil ignition. Westport's advanced demonstration engine has capabilities to vary key characteristics (such as boost pressure, high brake mean effective pressure, and exhaust gas recirculation percentages) to optimize system performance at their test facility. The general technical approach for the full project was driven by the two major areas of work: (1) baseline assessment of the conventional spark plug, and (2) assessment of the EcoFlash corona discharge ignition system.

The project team assembled an engine built specifically for ignition testing and installed it at Westport's facility in Plymouth, Michigan. After the base engine had undergone basic mechanical and thermal development work with a transistor coil ignition system, the researchers installed the EcoFlash system, including the additional instrumentation for tracking the ignition event. The basic technical approach was to determine the relationship between the ignition event and the heat release profile for the transistor coil ignition system and the corona discharge system.

Initially, the researchers tested the engine with a conventional transistor coil ignition system, measuring key data on the combustion and ignition system behavior, acquiring a wide range of in-cylinder and engine out exhaust data. Preliminary base engine development was conducted over a standardized matrix, broadly encompassing the engine characterization.

Project Results

Westport's advanced high efficiency spark ignited engine and the BorgWarner High Frequency Corona Discharge Ignition technology will allow for dramatic emissions, performance, and fuel economy improvements in natural gas engines over traditional ignition systems. These engine advancements improved engine performance when using the baseline ignition system. To date, the engine has shown best performance with 13:1 compression ratio piston design, reaching more than 38 percent brake thermal efficiency.

Technology and Knowledge Transfer

The first step in disseminating the knowledge gained on this project will include publishing the findings with the Energy Commission's publicly accessible reports. These reports will detail the technologies that were studied as well as the results of the testing.

Industry suppliers and equipment providers are also a key component to the transferring of the technologies to the commercial market. The key partners for this project have been BorgWarner BERU, a Tier 1 supplier of ignition equipment to the auto industry, and Isuzu Technical Center of America. BorgWarner supplied the advanced ignition system for this project, and they have the capabilities to commercialize the technology at significant scale through their existing distribution system and engine partners. They have supported the project and results through their equipment and also through detailed engineering work to develop and optimize the system. Their past research on this technology has proven several benefits for its use on gasoline fueled engines. Future commercialization of the advanced ignition technology would be pursued by BorgWarner.

The technology development and results have also been shared with Isuzu as one of their engine platforms was the basis for the test engine on this project. Isuzu is an extremely valuable commercialization partner as their established manufacturing capabilities and distribution network would allow for large scale of adoption in the marketplace.

Benefits to California

The developed technology will provide an increase in fuel economy of 5 percent over current state-of-the-art natural gas engines. For a market size of 4,200 Class 7/8 natural gas vehicles driven over a five year period, assuming the vehicles operate in an urban drive cycle with an average fuel economy of 4 miles/diesel gallon equivalent, drive 30,000 miles annually and pay $2.75 per gallon equivalent; would yield a cumulative reduction in fuel use of 3,862,500 diesel gallon equivalent. The fuel savings would be more than $10 million along with the associated energy security and environmental benefits. NOx emissions are expected to be dramatically decreased. Engine test results showed that both the transistor coil ignition system and the EcoFlash ignition system would be expected to attain the CARB optional low NOx certification standard of 0.02 g/bhp-hr. Carbon dioxide emissions are even more compelling, achieving the project goal levels of meeting the expected EPA regulations through model year 2027.

CHAPTER 1: Introduction

The project team of Gas Technology Institute (GTI), Westport Fuel Systems, Inc. (Westport), and BorgWarner Beru (BorgWarner) demonstrated an advanced engine and ignition technology to test for emissions, performance, and fuel economy improvements over traditional architectures. High Frequency Corona Discharge Ignition technology (Figure 1) has a large corona ignition region that is almost 1,000 times that of a tradition spark plug and has been shown to reduce ignition delay and enhance the early ignition process, stabilize main combustion, and reduce some throttling/pumping losses. The following enhancements have been observed in corona ignition testing with gasoline, with limited natural gas engine work completed to date, prior to this project:

- Increased exhaust gas recirculation (EGR) tolerance up to 40 percent – extra EGR displaces air and reduces pumping losses at certain conditions as well as reduces NOx and greenhouse gas emissions.
- Enhanced high-load combustion stability with high levels of EGR, which gives better knock resistance, higher boost pressures - 45 psig (3 bar-g), and high BMEP capability - at least 360 psig (25 bar-g) with appropriate turbocharging methods.
- Enhanced ignitability at very high in-cylinder pressures associated with very high BMEP.

Figure 1: BorgWarner Corona Ignition Versus Traditional Spark Plug Ignition in Air

Source: Gas Technology Institute

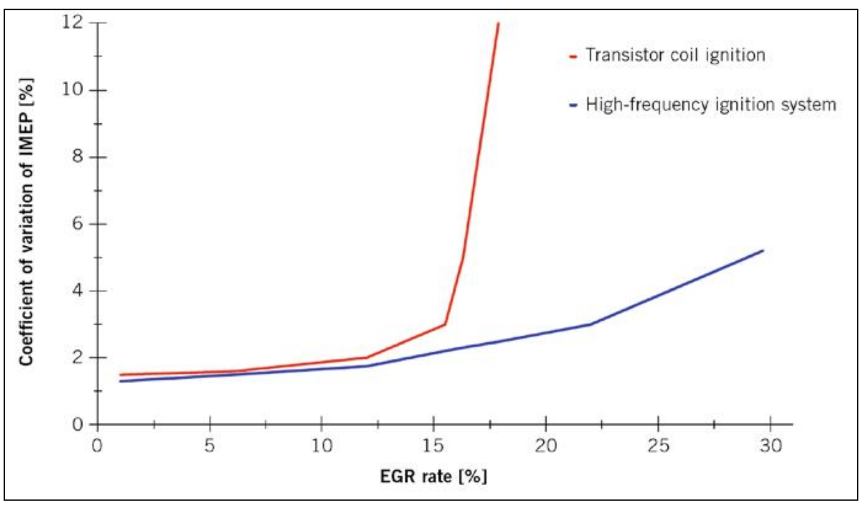
A corona discharge is an electrical discharge due to ionization of a fluid surrounding a conductor that is electrically energized. The discharge will occur when the electric field strength (that is, potential gradient) near the conductor is high enough to create some conduction, but not high enough to cause arcing to the nearby conductive surface of the cylinder head or piston. BorgWarner, a Tier 1 automotive component supplier, employs a resonant electrical circuit and a sharp metallic protrusion(s) to create high frequency alternating electric fields for corona ignition without unwanted spark formation. BorgWarner has already started developing and demonstrating the promising benefits of their corona ignition product, EcoFlash, on gasoline engines. The focus of the gasoline applications was on light-duty, European OEM, engines to improve fuel economy and service interval compared to a conventional ignition system. These applications are still in early research stages and are not part of this project.

This project focused on demonstrating EcoFlash in a medium-duty natural gas engine in order to collect detailed ignition and combustion data and measure the benefits by comparing it to a conventional spark plug, also known as a transistor coil ignition (TCI). An especially important objective was to measure the potential for further efficiency improvements in the partial-load regime. At partial-load, reduced pumping work allows for efficiency gains as long as the ignition/combustion process remains robust, as seen by stable cycle-to-cycle combustion, with high in-cylinder EGR levels. As shown in Figure 2, the EcoFlash system has shown such capability with gasoline engines.

At the highest torque conditions, large quantities of cooled EGR, approximately 20 percent to 40 percent, are also very useful in mitigating combustion knock. However, robust ignition (including adequate energy delivery, spatial distribution, and repeatability) is still needed to comfortably extend the range of engine stability with high EGR.

Another objective was in gaining an understanding of the practical limits of the corona ignition system with respect to higher cylinder pressures, which are proportional to the intake manifold boost level, while using natural gas. This is very important because new, advanced medium-duty natural gas engines will operate at higher peak cylinder pressures than present commercial engines.

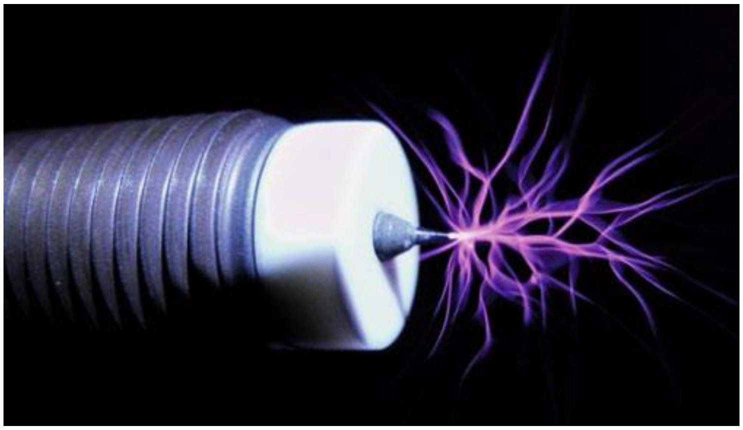
Figure 2: BorgWarner EcoFlash Ignition Data



Source: *MTZ Magazine* (January 2014, Vol. 75)

The BorgWarner EcoFlash system has been tested mostly with gasoline engines in the light-duty sector. With natural gas, we expected to see benefits for high EGR and high air boost situations due to the nature of the corona ignition system. This uses a special resonant circuit and a single electrode to create an enlarged ignition volume consisting of plasma (Figure 3).

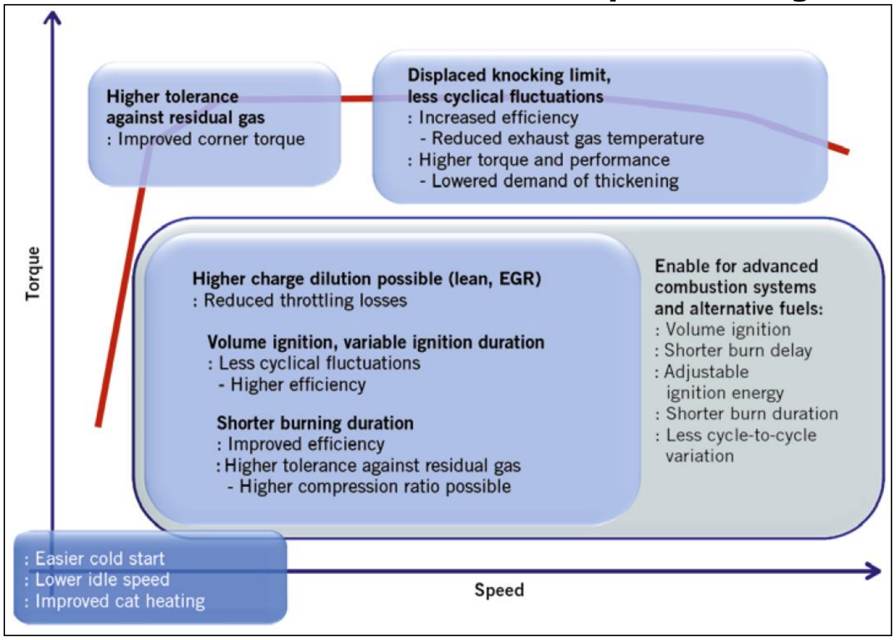
Figure 3: Corona Formation – Electrode Tip in Air



Source: *MTZ Magazine* (January 2014, Vol. 75)

Figure 4 depicts the potential benefits that could be experienced from the advancements in the developing the combustion processes using corona ignition.

Figure 4: Potential Combustion Processes Development Using Corona Ignition



Source: Gas Technology Institute

High Efficiency Spark Ignited Technology

Westport's High Efficiency Spark Ignited (HESI) technology has been developed with no constraints on the design of the combustion system. Spanning over twenty years through the design, evaluation, and testing of natural gas engines, HESI avoids the issues apparent with natural gas conversions of diesel engines. Largely due to cost and design constraints, conventional natural gas engine platforms are designed with minimum changes to the base engine. Typically, the swirl-based combustion system is not ideal for natural gas. The majority of the chamber has been put into the piston and the compression ratio is usually too large, while the resulting piston bowl geometry can lead to knock and thermal issues. Lastly, swirlflow motion is not effective at mixing gaseous fuels, which further reduced performance since the charge consists of a stratified mixture.

The HESI engine assembly process was completed at Wesport's facility in Plymouth, MI, and consists solely of HESI parts with its engine design based on a modified Isuzu four-cylinder diesel long block engine. The HESI head has been designed to deliver high turbulent kinetic energy by way of tumble flow motion and the valvetrain consists of a DOHC with cam phases. The HESI cam and idler gears then mesh up to the remaining four-cylinder diesel geartrain. The diesel bottom end provides for the durable structure needed to allow for HESI combustion at elevated peak cylinder pressure conditions.

The engine was installed in a dynamometer test cell where instrumentation was added and the appropriate fluid connections were fabricated and attached to the engine. Initial engine checkout and break-in were conducted the following month. With the engine "de-greened," engine development commenced.

Table 1 compares the major design parameters and engine ratings between a base diesel and HESI engines.

Table 1: Engine Configurations for Base Diesel Engine and HESI Engine

Configuration	Base Diesel	HESI Engine
Number of Cylinders	4	4
Stroke	125 mm	125 mm
Bore	115 mm	115 mm
Connecting Rod Length	198 mm	216.5mm
Compression ratio	16.5	13:1
Number of Valves	4	4
Fuel Lower Heating	42.8 MJ/kg	49.6 MJ/kg
Peak Cylinder Pressure	160 bar	160 bar
Maximum Torque	766 Nm @ 1600	1130 Nm @ 1400
Maximum Power	178 kW @ 2400	197 kW @ 1800

Source: Gas Technology Institute

For additional reference, Table 2 compares some of the key performance and emissions parameters of the HESI engine with the industry-leading Cummins Westport Inc. (CWI) engines.

Table 2: Engine Performance of Current State-of-the-Art Natural Gas Engines with HESI Engine for Comparison

Engine	Engine Size (L)	BMEP (bar)	Max Power (kW)	Max. Torque (Nm)	NOx (g/bhp-hr)	CO2 (g/bhp-hr)	Development Status
CWI ISX12N	11.9	20.7	298	1966	0.01	502	Production
CWI ISL G NZ	8.9	19	239	1356	0.01	465	Production
CWI ISB 6.7G	6.7	19	179	759	0.08	485	Production
Westport HESI	5.2	25	197	1130	0.01	450	Early development

Source: Gas Technology Institute

Design Method

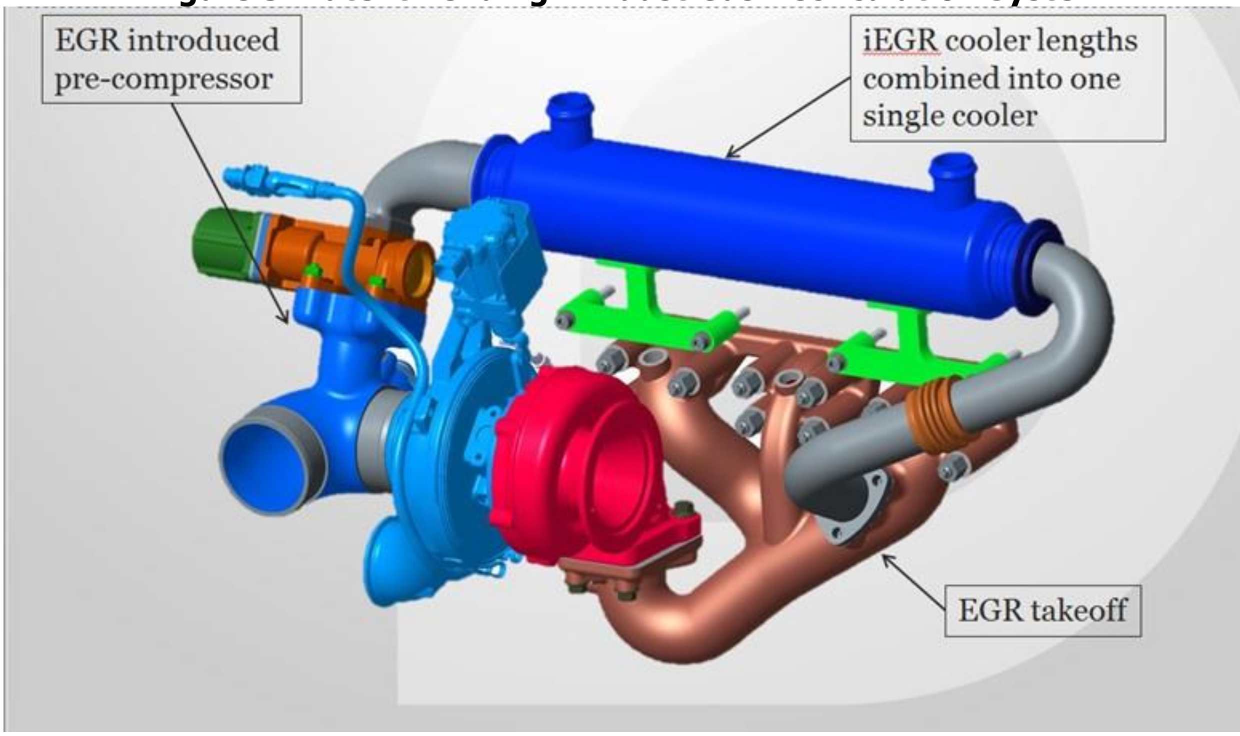
HESI technology focuses on charge motion delivery by promoting mixing during the intake stroke and generating sustained tumble flow motion in the cylinder through to the point of ignition. The intake passages are slightly inclined relative to the head deck to deliver adequate charge motion to the cylinder. The head consists of a pent roof design and the piston is made up of a shallow dish to maintain in-cylinder tumble flow motion. By removing the piston bowl from the combustion chamber, the volume to surface area ratio is maximized and the piston assembly mass is reduced by 20 percent. Sharing the combustion volume between the head and piston allows for uniform heat dissipation away from the flame front. In taking mass out the piston assembly, the connecting rod can be lengthened to decrease frictional side loading with the cylinder bore. The entire combustion chamber is optimized to take advantage of the positive properties of natural gas, allowing for operation at elevated loads over the base diesel engine capabilities.

To accommodate the higher heat released from natural gas versus diesel fuel, the head water-jacket is designed to work in conjunction with the base engine block reservoir while allowing for adequate surface area to cool the top of the fire deck from the added thermal loading due to spark ignition. The ports have been sized appropriately for generating high tumble flow motion. Port fuel injection (PFI) features are incorporated into the port design to deliver fuel to the charge. The fuel is supplied by a common rail.

The HESI valvetrain, which consists of a dual overhead cam (DOHC) rocker arm actuation mechanism that is driven from a centrally mounted idler gear that is added to the base engine geartrain. To allow for optimal timing during development testing, cam phasers are added to the DOHC.

Another feature of the gas exchange system is to allow for elevated levels of EGR, which has been employed using a patent pending system. Exhaust gas is taken pre-turbine and fed back into the turbo compressor (Figure 5). The high pressure EGR system has been developed in conjunction with a variable nozzle turbocharger (VNT) to lower exhaust gas temperatures to further reduce nitrous oxide (NOx) emissions. As such, a new EGR cooler has been designed and packaged in the same space as the diesel envelope. To minimize part proliferation, all other ancillary systems are carried over from the base diesel engine.

Figure 5: Patent Pending Exhaust Gas Recirculation System



Source: Gas Technology Institute

Ignition System Technology Overview

Natural gas engines are limited in their ability to maximize fuel economy and reduce emissions because of the limitations of existing ignition systems. The ignition characteristics of natural gas present issues and opportunities for engine manufacturers working to meet tighter emission standards, achieve higher fuel economies, increase engine performance, and extend maintenance intervals. Advanced, high-energy ignition systems are needed to overcome the challenges of igniting natural gas under high boost pressures with heavy EGR for medium and heavy-duty natural gas engines.

Current medium and heavy-duty natural gas engines (that is, CWI model ISLG) are typically spark-ignited, turbocharged with boost pressures of approximately 15 psig (1 bar-g) and BMEP of 275 psig (19 bar-g). These engines utilize a three-way catalyst and EGR between 0 and 20 percent resulting in a significantly cleaner tailpipe emissions profile than earlier generation diesel engines; however, exhibit approximately 15 percent lower fuel economy in similar drive cycles. The lower fuel economy is largely due to spark-ignited engines using lower compression ratios (CR≈11:1) than compression-ignited engines (CR≈17:1) and also partial-load throttling. Throttling is a simple way, in spark-ignited stoichiometric (or lean-burn) engines, to control the air-to-fuel ratio. It can be used to modulate airflow below 100 percent torque at a given speed. However, this typically causes some pumping losses (parasitic losses due to work during the intake and exhaust stroke) and reduces engine net efficiency. Historically, in contrast, diesel cycle engines are not throttled and ideally have nearly zero pumping losses when ignoring slight pressure drops due to frictional losses in the flow path.

Currently, the high frequency ignition corona discharge technology is transitioning from alpha-level prototypes, on test benches and in engine cells, to beta-level prototypes. Newer prototypes are expected to improve the energy efficiency in the DC to high frequency circuitry. The newer design will also have more advanced communication interface features. The technology has demonstrated faster initial burn rates from the start of ignition and better EGR tolerance in gasoline engines. For these reasons, the project team believes this to be a most promising technology for future ignition work with advanced natural gas engines.

The corona itself is a non-thermal plasma and the gas temperature is much lower than the thermal plasma that forms in a traditional spark plug using TCI. Preliminary experience with light-duty gasoline engines has so far lead researchers to expect electrode life expectancy greater than 60,000 miles or greater than 150 million ignition events.

Previous research by BorgWarner, and other groups, with corona ignition on advanced gasoline direct injection engines have shown these systems have significant advantages. However, research on medium duty, highly boosted, natural gas engines using corona discharge is relatively new. Some research on low-speed stationary natural gas engines has begun which could lead to power generation applications. Likely, the risk area for the corona discharge ignition feasibility is at the very highest EGR levels (20-40 percent) and very high boost (up to 45 psig [3 bar-g]) required for the increased BMEP levels. As the EGR level increases, the tendency to see misfire or flame extinction increase. At the highest boost levels, the ignition volume decreases and tendency for misfire due to inhomogeneity of the air/fuel/EGR mixture also increases.

The corona discharge system is not a "plug and play" system because a review of expected firing pressures and the cylinder head/piston/igniter geometry is required to assure the corona formation will not run into unforeseen challenges. The physics of these tradeoffs are very well understood by BorgWarner, however. Using Westport's natural gas engine dynamics experience and BorgWarner's expertise in the corona system has allowed the system to be optimized for even the most challenging conditions.

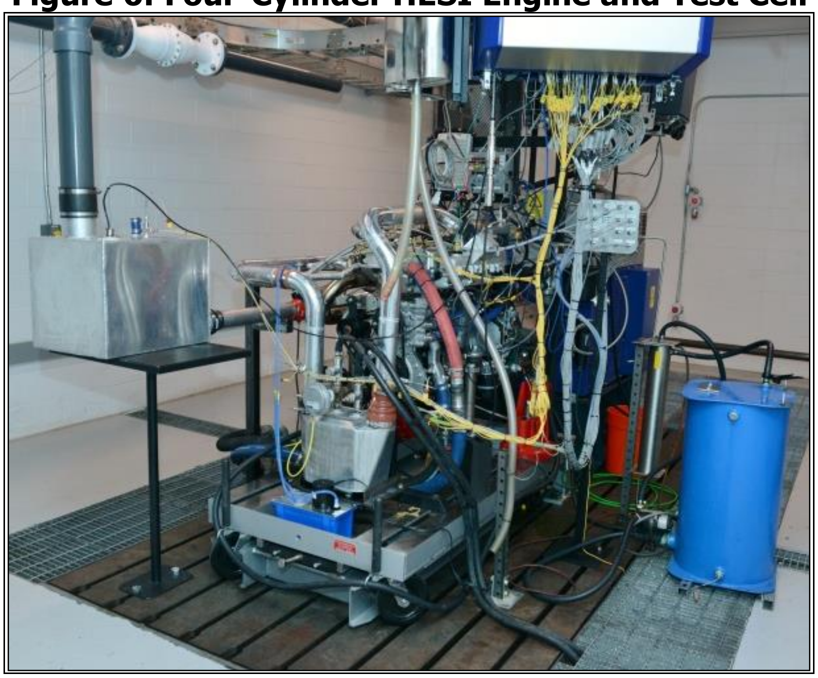
CHAPTER 2: High Frequency Ignition System Testing

Technical Approach

As discussed in Chapter 1, the general technical approach for the full project is driven by the two major areas of work: (1) baseline assessment of the conventional spark plug, also known as a transistor coil ignition (TCI) system and (2) assessment of the EcoFlash corona discharge ignition system.

A purpose-built engine for ignition testing was assembled and installed in a test cell in Westport's Plymouth, MI facility. After the base engine had undergone basic mechanical and thermal development work with a TCI system, the EcoFlash system was installed, including the additional instrumentation for tracking the ignition event. This effort was performed in collaboration with BorgWarner application engineering. The base engine has been designed to accommodate in-cylinder combustion process instrumentation (including pressure sensing and calculated heat release), but the EcoFlash system required additional voltage and current sensing. The basic technical approach was to determine the relationship between the ignition event and the heat release profile for the TCI system and the corona discharge system. For reference, the traditional TCI system tested throughout HESI engine development consisted of the BorgWarner Plug Top Ignition Coil with electronic driver and Champion regular class industrial spark plugs, similar to what is currently used in production natural gas engines (Figure 6).

Figure 6: Four-Cylinder HESI Engine and Test Cell



Source: Gas Technology Institute

The core research engine is capable of running at 360 psig (25 bar-g) BMEP at maximum torque conditions, as well as processing 20 percent EGR. Initially, the engine was tested with a conventional TCI system, measuring key data on the combustion and ignition system behavior, acquiring a wide range of in-cylinder and engine out exhaust data. Preliminary base engine development was conducted over a standardized matrix, broadly encompassing the entire engine map in accordance with the supplemental emissions test (SET) cycle 13-mode engine characterization.

At the conclusion of base engine development, a smaller subset of the 13-mode test conditions was used for detailed engine performance survey with the TCI and EcoFlash systems. An important part of the 13-mode testing is to define any ignition system limits with respect to EGR level and engine boost. If detected, any engine conditions that display ignition limitations will be a good candidate for the subset. Additionally, the subset of engine conditions will also explore the relative boost capability of the TCI system versus the corona discharge system. As boost is progressively increased, within limits of the turbocharger, combustion stability will be examined for each ignition system.

Combustion stability was quantified by mapping the coefficient of variation of indicated mean effective pressure (COV_{IMEP}) in the engine. The lowest normalized value of the indicated mean effective pressure (LNV_{IMEP}) will indicate misfires and partial burning cycles. Here, the mean indicated mean effective pressure is normalized by the lowest indicated mean effective pressure in the sample set. Hence, the high-speed cylinder pressure data will be used to calculate each ignition systems heat release profile as well as quantify combustion stability, providing sufficient data to form a comparative basis.

The TCI system is roughly using a fixed value of 100 mJ per ignition event and the spark timing can be easily advanced. In comparison, the corona discharge system will have flexibility at each specific engine condition (speed, manifold pressure, firing pressure) to optimize ignition in terms of energy quantity, duration, and timing. After spark energy/timing optimization, both the TCI and corona discharge system were run over multiple steady-state emission cycles. The program goal for supplemental engine test (SET) cycle, 13-mode emissions was two-fold:

- Obtain measured NOx emissions levels that are in line with the California Air Resources Board optional low NOx standard of 0.02 g/bhp-hr (0.027 g/kW-hr) with a passive three-way catalyst.
- Achieve the minimum projected EPA Phase 2 vocational vehicle CO_2 standard for model year 2027 of 424 g/bhp-hr.

It is also important to emphasize what was not in the scope for the technical approach for this project. This project did not involve the steps for final commercialization of the product including any major redesign of the corona ignition electronic circuitry, a detailed failure modes and effects analysis of the ignition system, or transient engine emissions work with a three-way catalyst for controls tuning or final deterioration factor assessment.

Experimental Method

The baseline engine conditions were established for the TCI system and were described in detail in the Task 2 – *Baseline Ignition System Report*. Following the baseline testing, the EcoFlash ignition system was installed. BorgWarner was on-site to perform the initial setup and ensure that the system operates as expected. Initial testing of the EcoFlash system focused on the SET cycle conditions listed in Table 3. These conditions served as a basis from which EGR and ignition were further tuned to maximize engine operation. This time-consuming portion of testing also incorporates emissions tradeoffs.

Table 3: Engine Conditions Tested Across the SET Cycle

Test Number	Speed rev/min	Torque Nm	Throttle %	Ignition Timing bTDCF	EGR Valve Setpoint %	Exhaust Cam Phaser degree	Intake Cam Phaser degree
1	1330	244	21	2	28	57.8	59.3
2	1330	560	37	4	18	60.3	59.2
3	1330	859	49	4	20	59.2	55.5
4	1330	1099	54	3.5	14	62.5	59.0
5	1700	264	21	6	22	57.9	60.0
6	1700	481	33	6	24	60.5	59.8
7	1700	770	47	8	24	62.6	59.8
8	1700	1042	57	8	20	65.6	60.0
9	2070	222	20	8	20	61.0	61.7
10	2070	453	43	6	24	60.9	60.9
11	2070	663	53	4	24	64.5	61.0
12	2070	899	59	8	18	63.6	61.0

Source: Gas Technology Institute

After testing the EcoFlash at elevated engine loads, it was found that the supply (that is, buck) voltage needed to be increased to attain the target torque at low speed. After a series of software iterations from BorgWarner, the buck voltage was increased from 120V to the maximum supply voltage of 180V. Operation of the EcoFlash ignition system with the 180V buck voltage significantly improved the repeatability of the system, while allowing for operation at elevated engine loads. It is worth noting that the EcoFlash ignition system was never able to repeatedly run at the engine operating condition established as the A100 point in the SET cycle, which was plagued by considerable misfire.

Aside from the A100 point, operation of the four-cylinder HESI engine with the EcoFlash ignition system largely resembled that of the TCI system. For switching between ignition systems, the test cell was prepared with both sets of ignition cables, making for straightforward transitions. All EcoFlash ignition testing was run with identical base engine hardware, component settings, and natural restrictions.

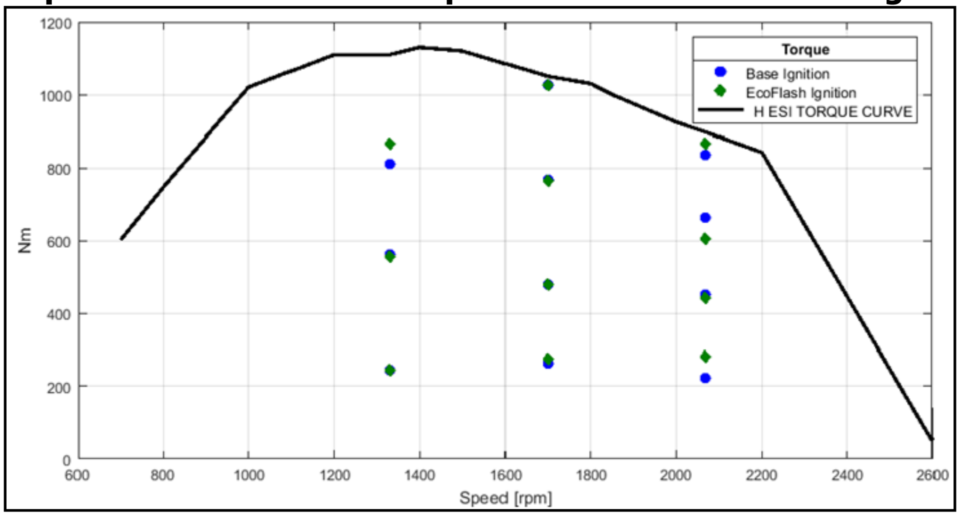
In running at its maximum supply voltage, the EcoFlash ignition system could operate at conditions near 20 percent EGR at low load, while reaching 25 bar BMEP at high load. It is worth noting that at the highest engine load, the EcoFlash ignition system allowed for operation over 39 percent brake thermal efficiency.

Measured Performance

The following information is a selection of some of the key results that were included in the *Baseline Ignition System Report* and *High Frequency Ignition System Report*. Testing of the EcoFlash ignition system focused on the same SET cycle conditions laid out by TCI testing.

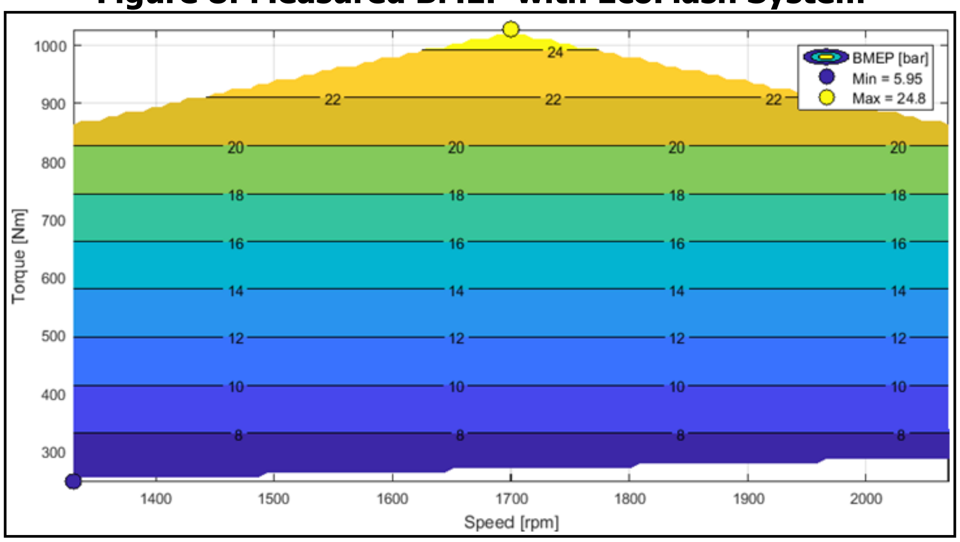
Figure 7 compares the torque attained for each of the different modes with both ignition systems. The EcoFlash ignition system was able to achieve torque within 2.5 percent of the targets at the B100 and C100 conditions, with the rest of the modes being in good agreement with the base ignition system. Figure 8 shows the BMEP contours for the EcoFlash ignition system. Again, the four-cylinder HESI engine is able to produce engine loads over 20 bar BMEP across the speed range shown, reaching 25 bar BMEP at 1700 RPM.

Figure 7: Comparison of Measured Torque with TCI and EcoFlash Ignition Systems



Source: Gas Technology Institute

Figure 8: Measured BMEP with EcoFlash System



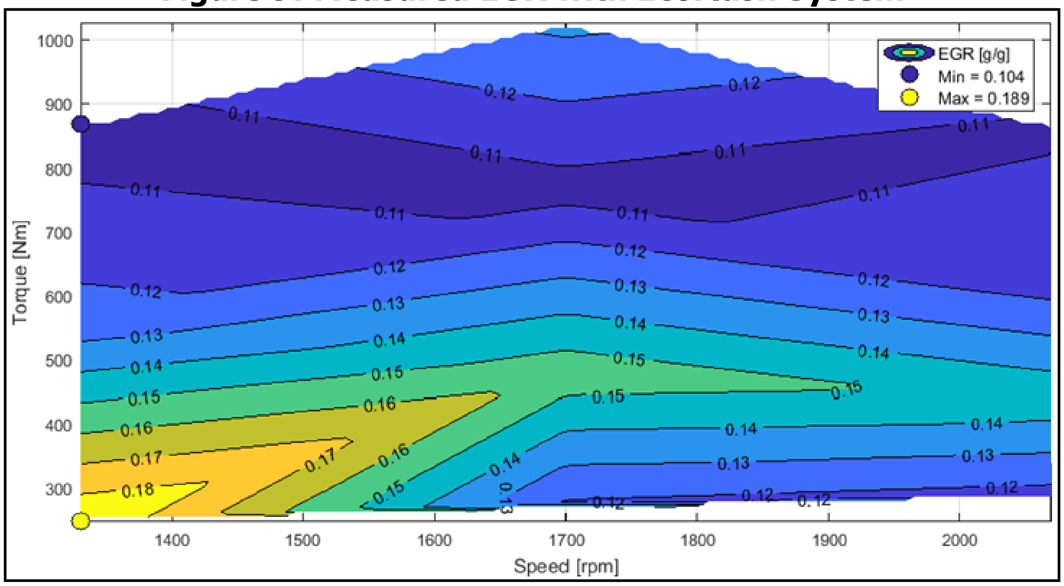
Source: Gas Technology Institute

While most engine parameters were held constant between the two ignition systems, EGR was allowed to fluctuate at modes that are more EGR tolerant. From Figure 9, the EGR contours are more consistent with speed. The EcoFlash ignition system performed better with less EGR at the B75 condition, running 5 percent less EGR than the TCI engine. Conversely, the A25 condition was able to tolerate 19 percent EGR with the EcoFlash system, whereas the TCI system ran better with 12 percent at this condition. Upon further comparison, there are six conditions that exhibited similar EGR tolerance, as listed below:

- 1330 RPM, 550 Nm with 13 percent EGR
- 1700 RPM, 270 Nm with 12 percent EGR
- 1700 RPM, 480 Nm with 15 percent EGR
- 1700 RPM, 1025 Nm with 13 percent EGR, at 25 bar BMEP
- 2070 RPM, 280 Nm with 12 percent EGR
- 2070 RPM, 450 Nm with 14 percent EGR

These six conditions are candidates for comparing high-speed cylinder pressure data to better compare the abilities of the two ignition systems.

Figure 9: Measured EGR with EcoFlash System

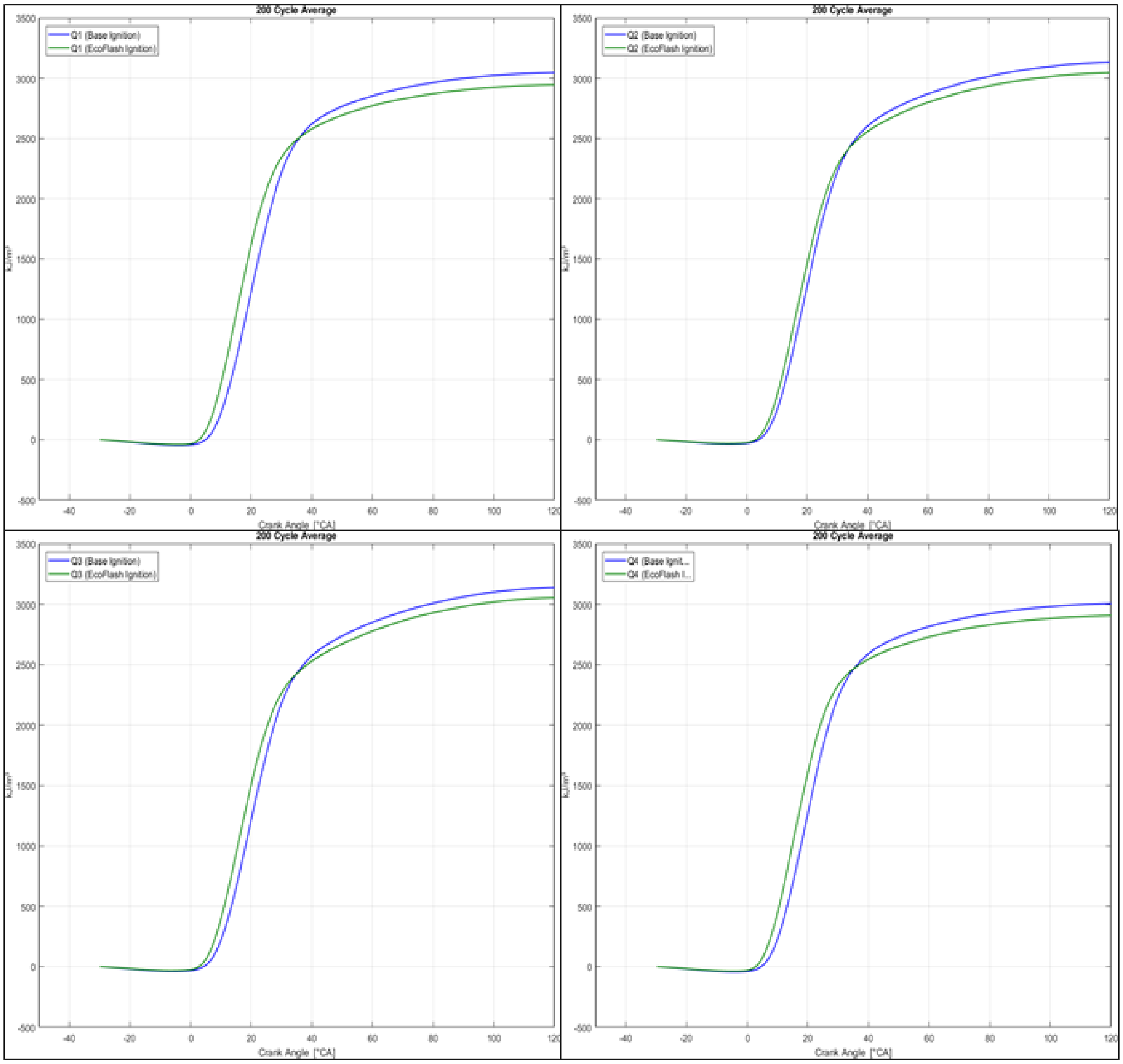


Source: Gas Technology Institute

In looking further at the six conditions that have similar EGR levels, the high-speed data that was collected during this testing should detect differences between the ignition kernel, ensuing heat release characteristics, and repeatability across the 200-cycle measurements.

At the A50 point in the SET cycle, shown in Figure 10, EcoFlash (green) ignition is 2° before the base ignition system (blue). The ensuing heat release profiles show very similar slopes across all cylinders for both ignition systems. The heat release even shows the same taper at the end of combustion.

Figure 10: Comparison of Calculated Heat Release at A25 Condition



Source: Gas Technology Institute

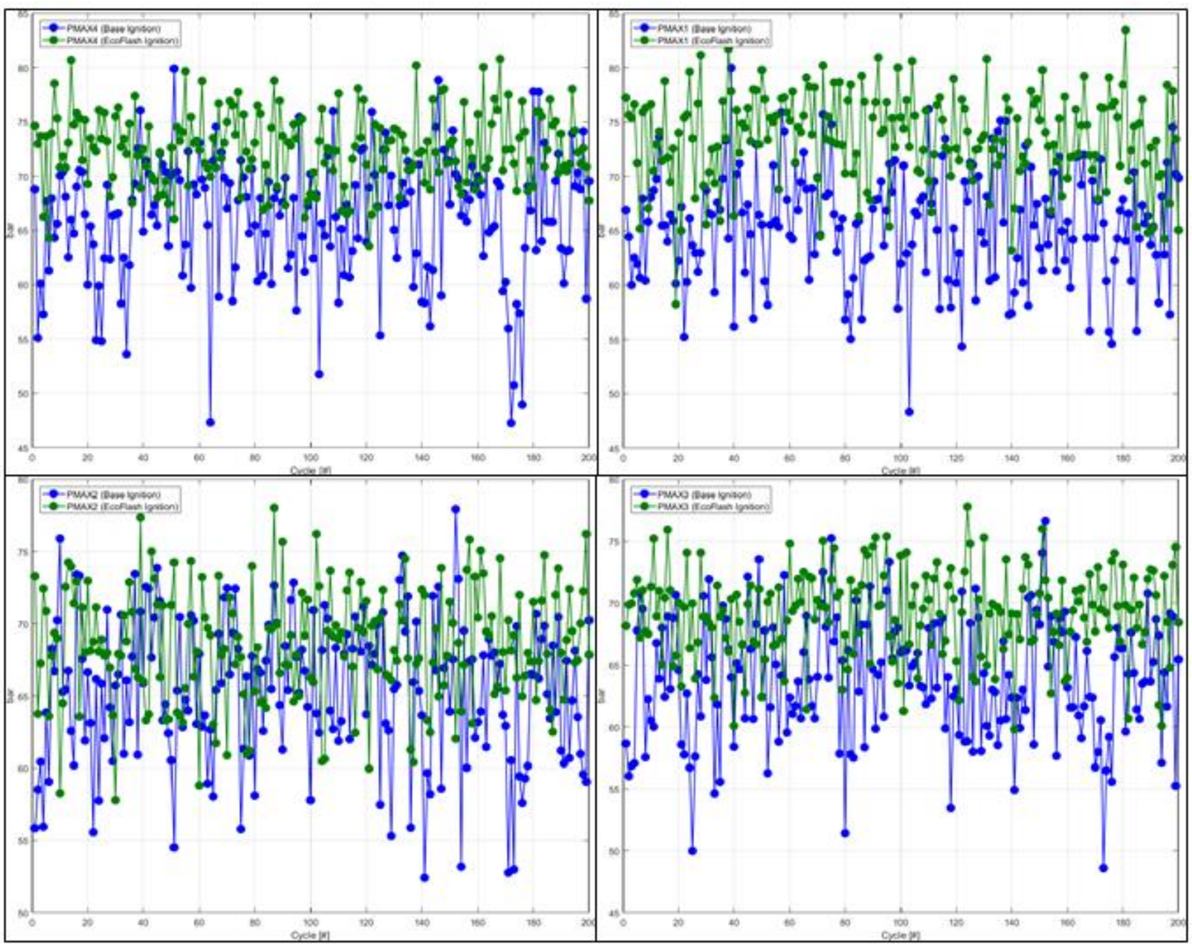
Variation in maximum cylinder pressure has been plotted in Figure 11 over the 200-cycle measurement. Table 4 lists statics of the maximum cylinder pressure measurements. It is noticeable in Figure 11 that the EcoFlash is higher on average, which is confirmed in the statics by having a mean of maximum cylinder pressure ranging from 3-8 bar higher than the TCI system. Additionally, the variation of maximum cylinder pressure is considerably less with the EcoFlash ignition system, having 5-15 bar less variation across each of the cylinders.

Table 4: Maximum Cylinder Pressure Statistics at A25 Condition

Location	Unit	Mean	Standard Deviation	Minimum	Maximum	Variation
PMAX1 (Base Ignition)	bar	65.48	5.15	48.31	79.98	31.67
PMAX1 (EcoFlash Ignition)	bar	73.54	4.15	58.23	83.46	25.23
PMAX2 (Base Ignition)	bar	65.43	4.95	52.40	77.95	25.55
PMAX2 (EcoFlash Ignition)	bar	68.45	4.00	57.79	78.04	20.25
PMAX3 (Base Ignition)	bar	63.85	4.95	48.57	76.66	28.08
PMAX3 (EcoFlash Ignition)	bar	69.13	3.56	59.79	77.81	18.01
PMAX4 (Base Ignition)	bar	66.06	5.78	47.25	79.90	32.65
PMAX4 (EcoFlash Ignition)	bar	72.61	3.33	63.54	80.80	17.26

Source: Gas Technology Institute

Figure 11: Measured Maximum Cylinder Pressure at A25 Condition

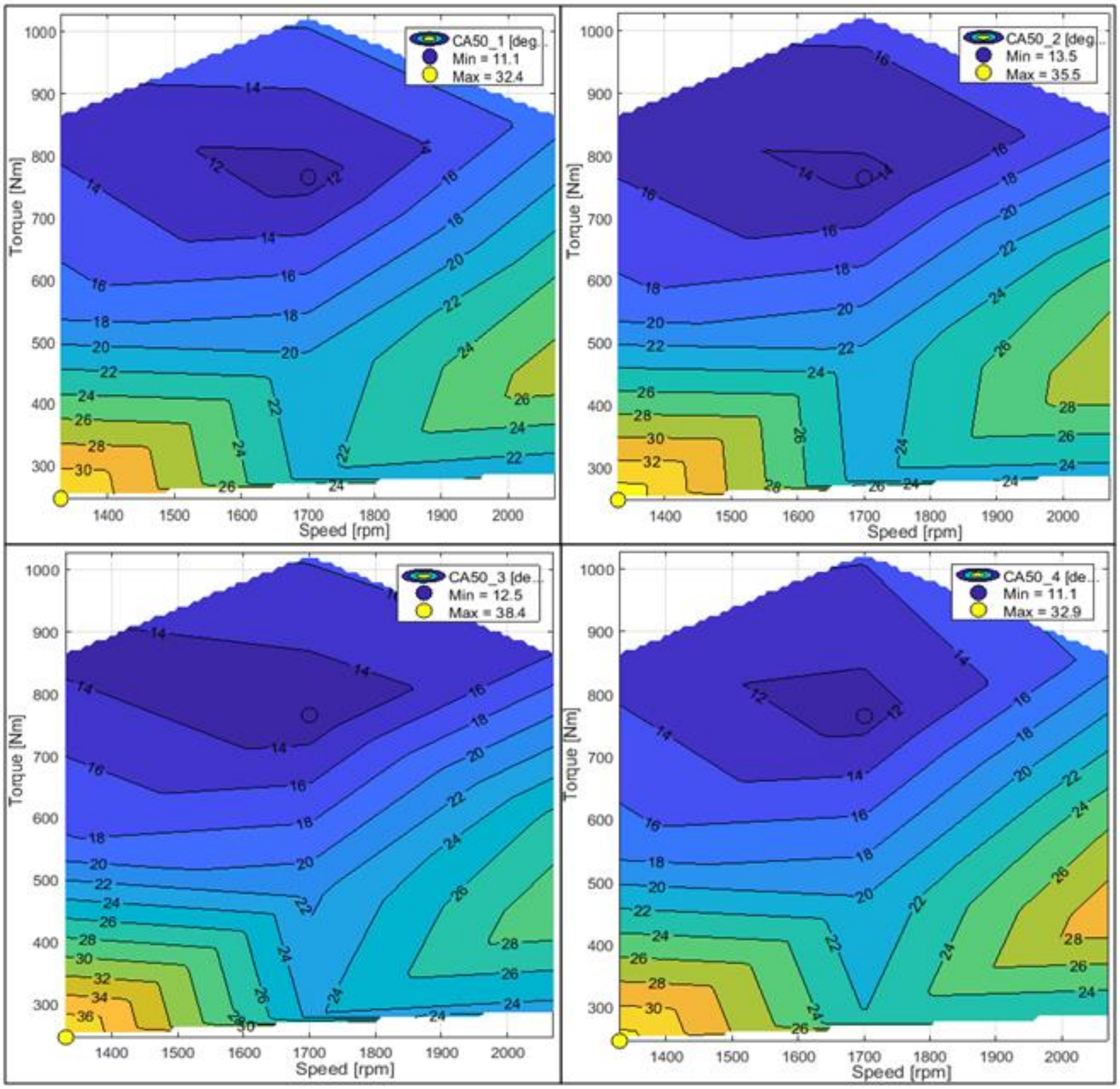


Source: Gas Technology Institute

CA50 describes the crank angle at which 50 percent of the heat from combustion has been released. Average CA50 over the SET cycle is shown in

Figure 12 for the EcoFlash system. As expected, the 19 percent EGR at the A25 point, in the SET cycle, stretches the maximum CA50 for each cylinder over the rest of the map, ranging from 32-38 degrees. The minimum CA50 occurs at the B75 condition, whereas it was the B100 condition for the TCI ignition system.

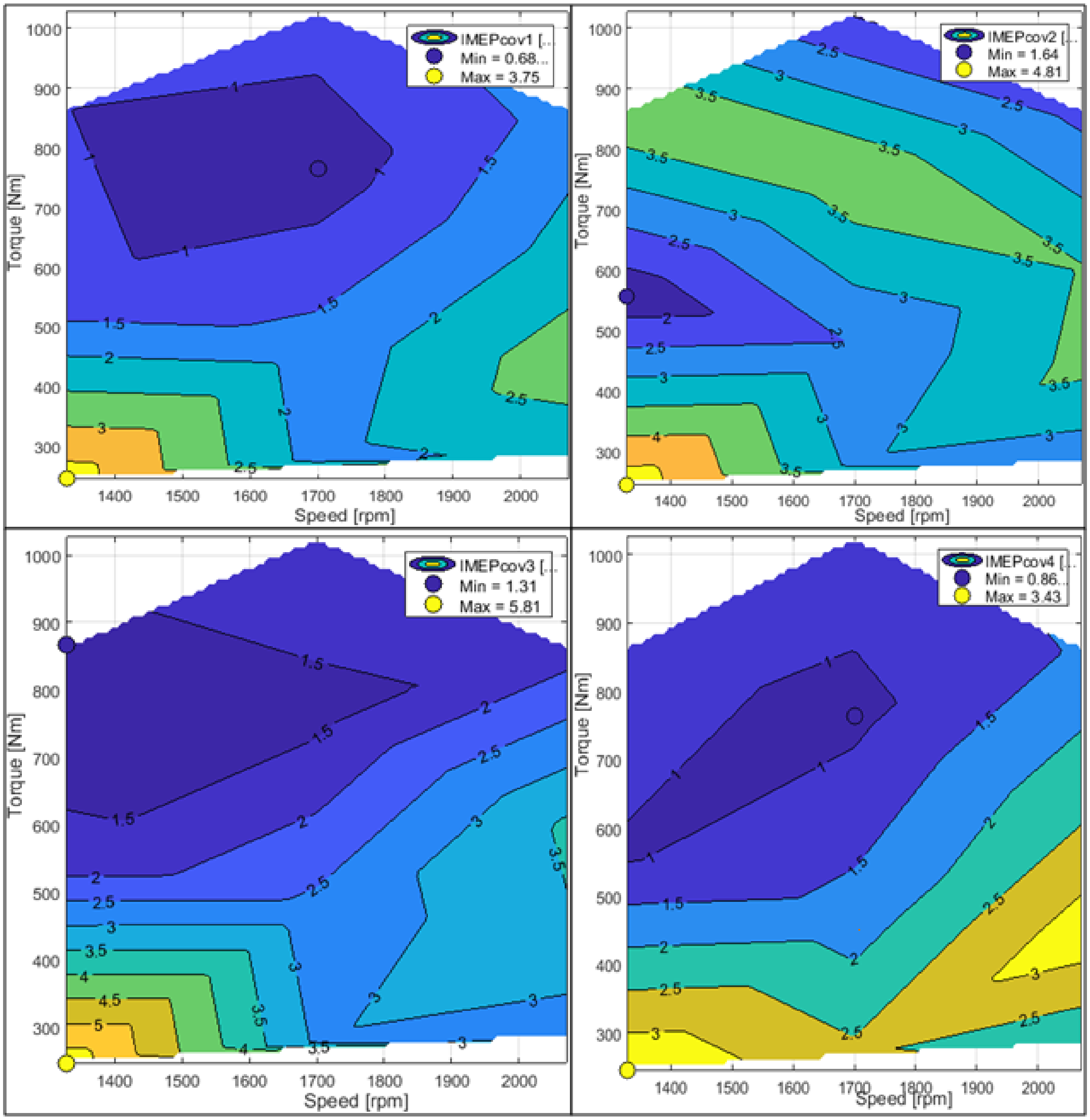
Figure 12: Measured CA50 with EcoFlash System



Source: Gas Technology Institute

As expected, the COV_{IMEP} is largely effected by the high amount of EGR at work in the cylinder at the A25 point on the EcoFlash map in Figure 13. At the other conditions, the EcoFlash system shows less variation than the TCI system, keeping all other points below 4 percent target. As a point of interest, Cylinder 3 has a significant portion of the map above 3 percent, while Cylinder 4 has the maximum COV_{IMEP} approaching 6 percent.

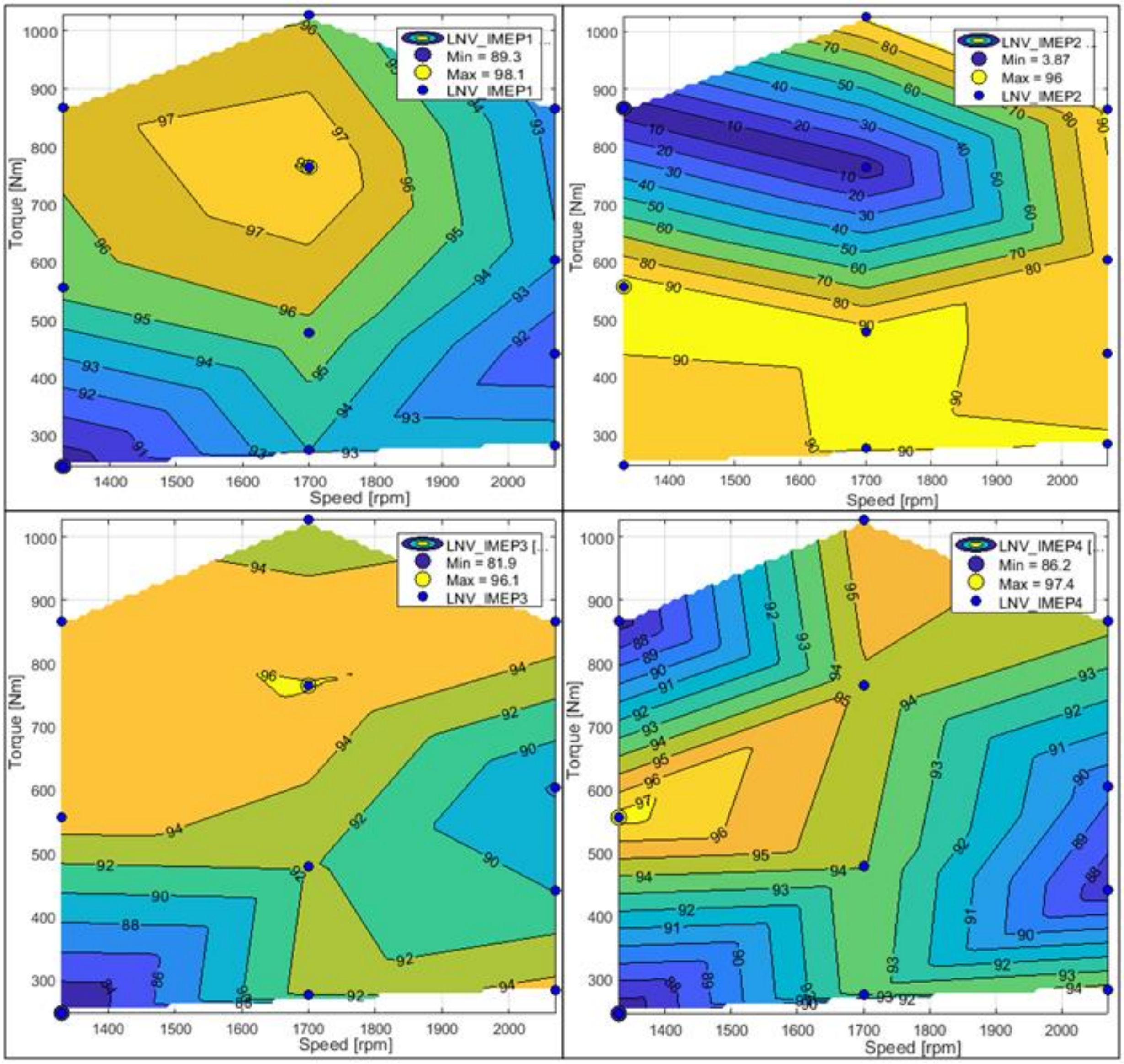
Figure 13: Measured COV_{IMEP} with EcoFlash System



Source: Gas Technology Institute

Figure 14 compares LNV_{IMEP} across the engine with the EcoFlash ignition system. In contrast to the TCI system, there are multiple spots on Cylinder 2 that are right at the point of misfire (A75 and B75). However, the other three cylinders are actually burning at a higher quality than the TCI system, with a minimum LNV_{IMEP} of 82 in Cylinders 1, 3, and 4. Interestingly, Cylinders 1 and 4 are able to process 19 percent EGR at the A25 condition without misfire.

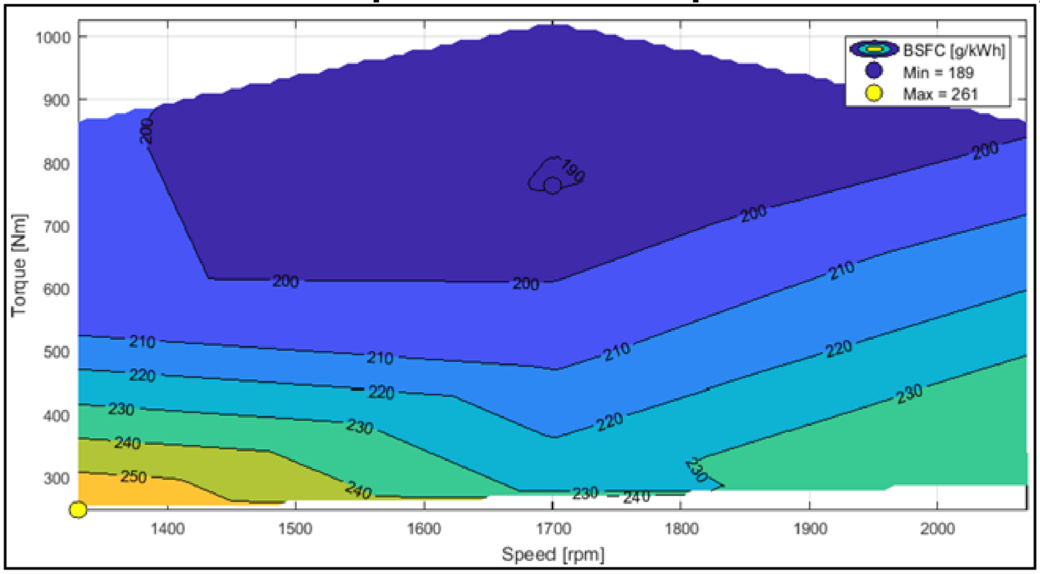
Figure 14: Measured LNV_{IMEP} with EcoFlash System



Source: Gas Technology Institute

In terms of fuel consumption, the EcoFlash ignition system performs at a similar level as the TCI system. As shown in Figure 15, the top half of the SET cycle remains under 210 g/kW-hr, reaching a minimum brake specific fuel consumption (BSFC) of 189 g/kW-hr at the 25 bar BMEP point. On the other end of the map, the maximum BSFC occurs at the A25 condition, reaching 261 g/kW-hr. Overall, the EcoFlash system is within 4 g/kW-hr at all points on the map compared to the TCI system.

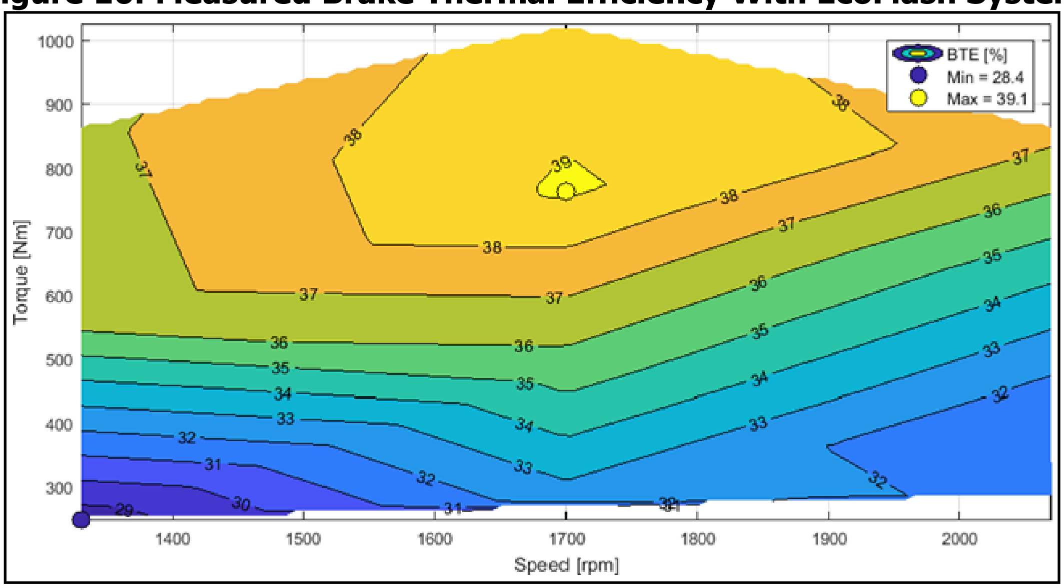
Figure 15: Measured Brake Specific Fuel Consumption with EcoFlash System



Source: Gas Technology Institute

As expected from the similarity in BSFC, the EcoFlash ignition system brake thermal efficiency (BTE) map in Figure 16 is nearly identical to the TCI map under similar conditions. As shown, the EcoFlash ignition system reaches 39 percent BTE at the B75 condition, with the B100 condition coming in at 38 percent. The rest of the map is within 1 percent of the TCI map.

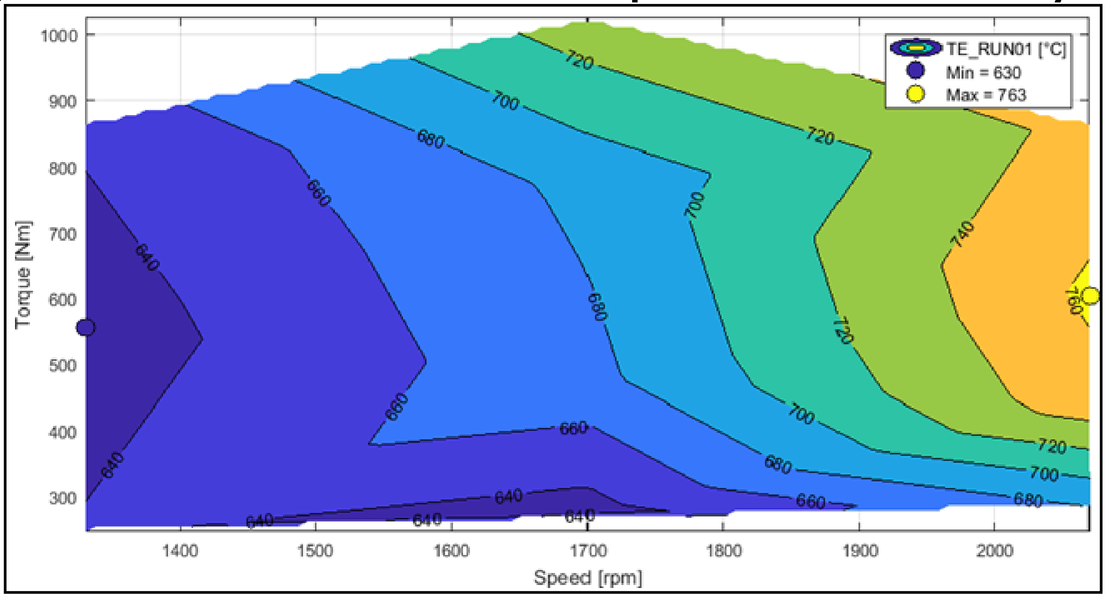
Figure 16: Measured Brake Thermal Efficiency With EcoFlash System



Source: Gas Technology Institute

The exhaust temperatures from the EcoFlash ignition system shown in Figure 17 show some variation compared TCI system. The maximum exhaust temperature comes in just over the limit, reaching 763°C at the C75 condition with the EcoFlash system, versus 745°C at this same condition with the TCI system. Additionally, the minimum exhaust temperature comes in at 630°C at the A25 condition, which is 66°C hotter than the same condition with the TCI system.

Figure 17: Measured Exhaust Runner Temperatures With EcoFlash System



Source: Gas Technology Institute

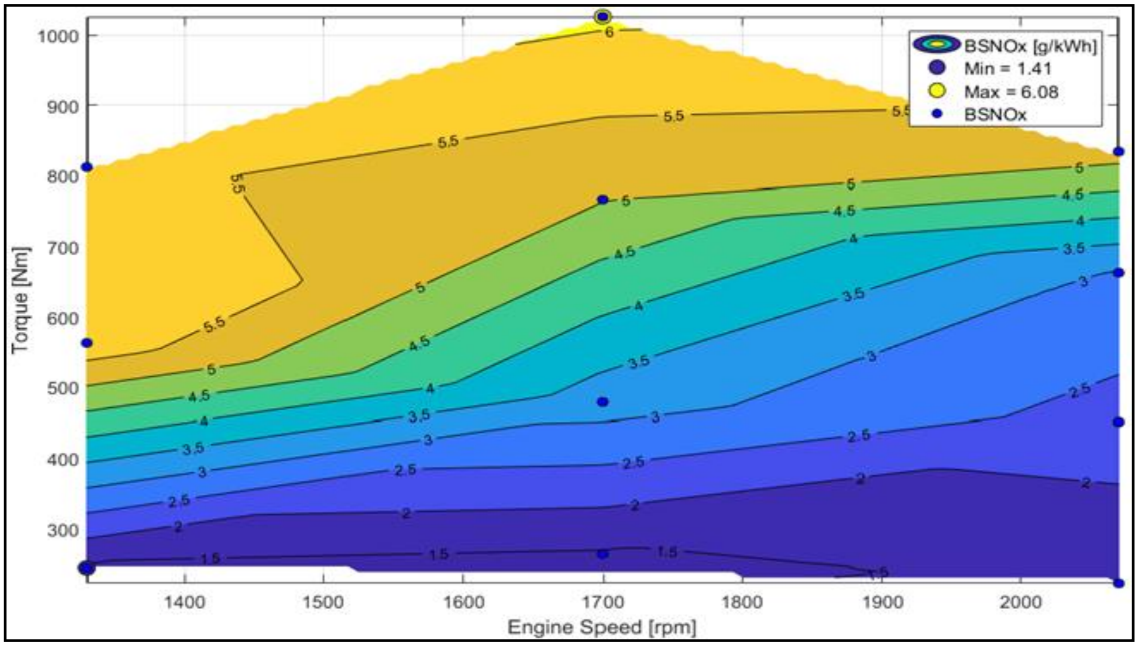
Emissions Testing

With engine and combustion performance quantified, the focus of four-cylinder HESI engine development shifted to emissions testing. In comparing emissions across the SET cycle modes that could be attained by both ignition systems, brake specific NOx (BSNOx) and CO_2 maps were created. In Figure 18 and Figure 19, the TCI system tends to run 0.5-1.0 g/kw-hr lower than the EcoFlash below 500 Nm. Above 500 Nm, the TCI system shows considerably lower BSNOx emissions despite having similar exhaust temperatures.

In testing across the SET cycle, the weighted engine out BSNOx should be near 2.0 g/bhp-hr (2.7 g/kw-hr) in order for the catalyst to meet the CARB optional low NOx standard of 0.02 g/bhp-hr. With the heaviest weighting occurring at the idle condition, there are still high exhaust temperatures that allow the system to maintain low NOx emissions. Next in line are the B group of modes, having weighing factors between 9-10 percent of the cycle. The BSNOx maps for both ignition systems gradually increase from 2 g/kw-hr (1.5 g/bhp-hr) up to 6–7 g/kw-hr (4.5-5.2 g/bhp-hr) at 1700 RPM.

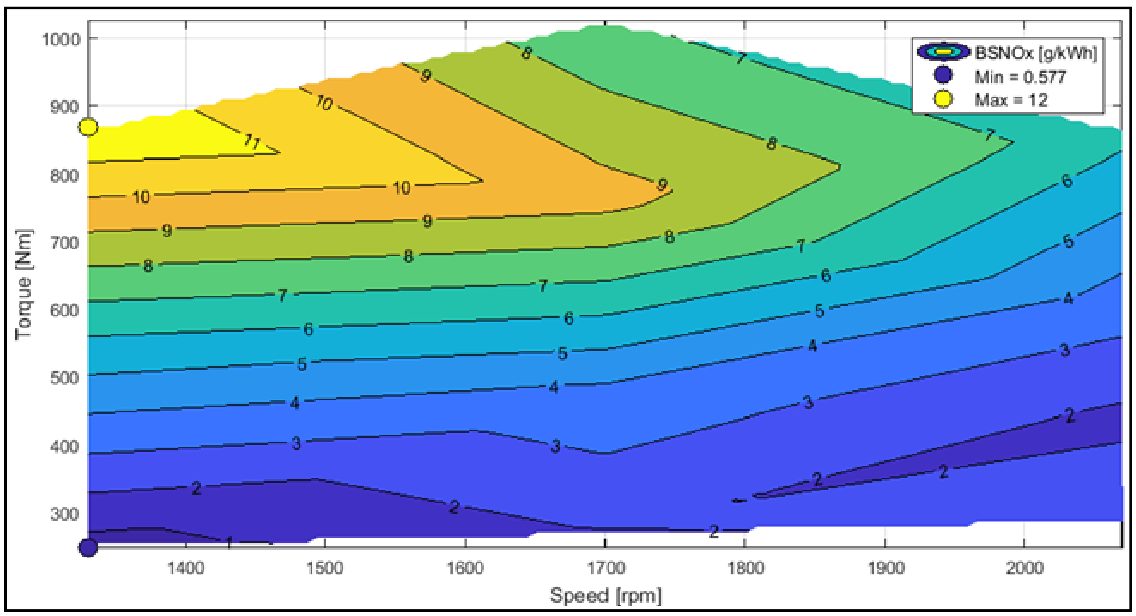
Furthermore, five of the lower six modes on both ignition system maps have engine out BSNOx at or below the 2.7 g/kw-hr level, making up 35 percent of the set cycle weighing. When idle condition is included, these modes account for nearly half of the cycle being at or below the engine out target. With the catalyst operating with 98-99 percent effectiveness, there is a good chance that both ignition systems will attain CARB optional low NOx standard of 0.02 g/bhp-hr.

Figure 18: Measured Brake Specific Nitrogen Oxides with Transistor Coil Ignition System



Source: Gas Technology Institute

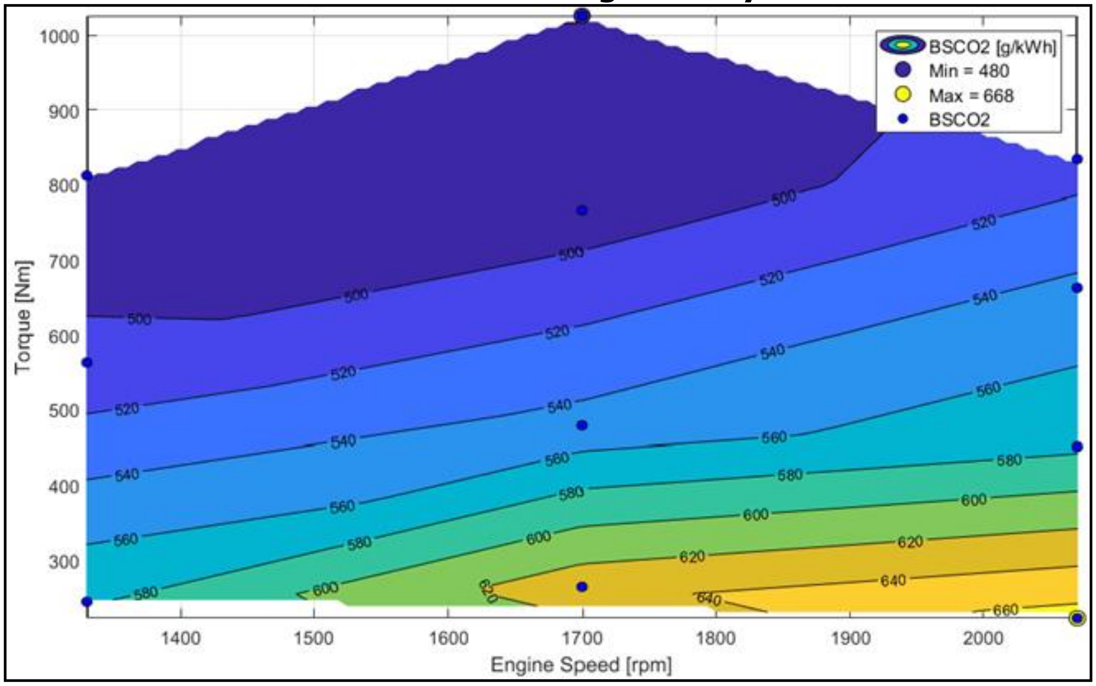
Figure 19: Measured Brake Specific Nitrogen Oxides with EcoFlash System



Source: Gas Technology Institute

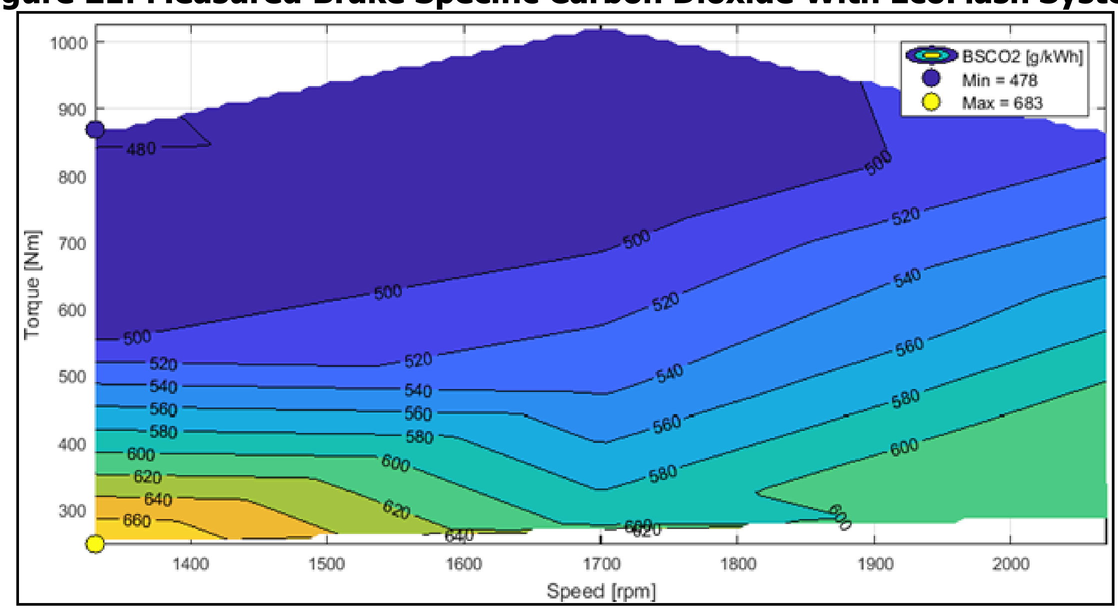
In terms of CO_2 emissions, both maps show good agreement at high load. As shown in Figure 20 and Figure 21, the $BSCO_2$ maps are nearly identical above 400 Nm. At the A25 condition, there is nearly 14 percent more CO_2 with the EcoFlash ignition system, which is also running 10 percent hotter than the TCI system. Conversely, the C25 condition has 10 percent lower CO_2 emissions with EcoFlash, despite having similar exhaust temperatures as the TCI system.

Figure 20: Measured Brake Specific Carbon Dioxide with Transistor Coil Ignition System



Source: Gas Technology Institute

Figure 21: Measured Brake Specific Carbon Dioxide With EcoFlash System



Source: Gas Technology Institute

CHAPTER 3: Conclusions

The information above comprises the research performed on the advanced HESI engine with a conventional spark plug, also known as a transistor coil ignition, and the high-frequency EcoFlash ignition system by BorgWarner. As discussed previously, the specially designed engine includes cylinder heads designed to deliver high turbulent kinetic energy by way of tumble flow motion and a diesel bottom end provides for the durable structure needed to allow for HESI combustion at elevated peak cylinder pressure conditions. These engine advancements have allowed for dramatic improvements in engine performance when utilizing the baseline ignition system. To date, the HESI engine has shown best performance with the 13:1 compression ratio piston design, reaching over 38 percent brake thermal efficiency while operating at BMEP over 25 bar.

For switching between ignition systems, the test cell was prepared with both sets of ignition cables, making for straightforward transitions. All EcoFlash ignition testing was run with identical base engine hardware, component settings, and natural restrictions. As shown in the data above, the operation of the four-cylinder HESI engine with the EcoFlash ignition system largely resembled that of the TCI system. In running at its maximum supply voltage, the EcoFlash ignition system could operate at conditions near 20 percent EGR at low load, while reaching 25 bar BMEP at high load. It is worth noting that at the highest engine load, the EcoFlash ignition system allowed for operation over 39 percent BTE.

Based on the results of the brake specific quantities, the combustion process of the four-cylinder HESI engine is robust enough that it is not dependent on the type of ignition system. From a combustion performance perspective, both sets of data have random cycles during the 200-cycle measurement that are burning under the design targets. Regardless, these events are not significant enough to affect the overall response of the engine, which is illustrated by the fact that this prototype engine is operating near the pre-test target of 40 percent BTE.

In terms of fuel consumption, the EcoFlash ignition system performs at a similar level as the TCI system. As shown above, the top half of the SET cycle remains under 210 g/kW-hr, reaching a minimum BSFC of 189 g/kW-hr at the 25 bar BMEP point. Overall, the EcoFlash system is within 4 g/kW-hr at all points on the map compared to the TCI system.

Emissions data, for both ignition systems, were presented in this report as well. When evaluating tailpipe emissions, there are additional benefits of using CNG as the fuel beyond the inherent reduced carbon content. The additional heat releases allow the engine to run hotter than a diesel, which is advantageous for warming up the after-treatment system quickly. Idle condition typically runs hot enough to supply 350°C turbine temperatures, which will allow the catalyst to work effectively during warm up. Once hot, the catalyst supplier has good confidence in cleaning up 98-99 percent of the NOx coming out of the engine so it is expected that both ignition systems would attain CARB optional low NOx certification of 0.02 g/bhp-hr. This has been further validated by preliminary testing on the four-cylinder HESI engine.

CO_2 emissions are even more compelling. More than 75 percent of the $BSCO_2$ maps are below 570 g/kw-hr (425 g/bhp-hr). With the pretest target being 424 g/bhp-hr on the SET cycle, there is adequate room to further trade off CO_2 for fuel economy while still meeting the target, which is based on expected EPA regulations through model year 2027.

To be clear, these exceptional project results show the excellent performance characteristics of the HESI engine and not a lack of performance of the advanced emission system. This research and testing have allowed for significant advancements in the understanding of the HESI engine performance as well as the EcoFlash ignition system. It has continued the optimization of the engine and ignition systems and will allow for them to continue to progress toward commercialization.

LIST OF ACRONYMS

Term	Definition
BMEP	Brake mean effective pressure
BTE	Brake thermal efficiency
CEC	California Energy Commission
CARB	California Air Resources Board
CO2	Carbon dioxide
COVIMEP	Coefficient of variation of indicated mean effective pressure
CR	Compression ratio
DGE	Diesel gallon equivalent
DOHC	Dual overhead cam
EPIC	Electric Program Investment Charge
EGR	Exhaust gas recirculation
GTI	Gas Technology Institute
g/bhp-hr	Grams per brake horse power hour
HESI	High Efficiency Spark Ignition engine
LNVIMEP	Lowest normalized value of the indicated mean effective pressure
mJ	Millijoules
NOx	Nitrogen Oxides
P	Port fuel injection
psig	Pounds per square inch
SET	Supplemental emissions test cycle - 13-mode engine characterization
TCI	Transistor coil ignition
VNT	Variable nozzle turbocharger