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Selective Interrupt and Control: An Open ECU Alternative

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Abstract

To enable the evaluation of off-calibration powertrain operation, a selective interrupt and control (SIC) test capability was developed as part of an EPA evaluation of a 1.6 L EcoBoost® engine. A control and data acquisition device sits between the stock powertrain controller and the engine; the device selectively passes through or modifies control signals while also simulating feedback signals. This paper describes the development process of SIC that enabled a test engineer to command off-calibration setpoints for intake and exhaust cam phasing as well as ignition timing without the need for an open ECU duplicating the stock calibration.

Results are presented demonstrating the impact of ignition timing and cam phasing on engine efficiency. When coupled with combustion analysis and crank-domain data acquisition, this test configuration provides a complete picture of powertrain performance. Future applications of SIC could enable evaluating the impact of cam phasing on trapped residuals, examining knock tolerance, or studying the impact of splitting direct fuel injection into multiple pulses - all on a stock powertrain platform.

Introduction

The light-duty greenhouse gas regulation for model years (MY) 2017-2025 will require a midterm evaluation (MTE) of the standards for MY 2022-2025 to consider technology developments since the rule making. This MTE will result in maintaining or changing the standards [1]. As part of this MTE, the EPA developed the Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool, a physics-based, forward-looking, full vehicle model used to predict fuel economy and vehicle emissions [2]. To validate ALPHA, the EPA evaluated several powertrain platforms through chassis and engine dynamometer testing.

Southwest Research Institute® (SwRI®) developed the Rapid Prototyping Electronic Control System (RPECS®) in the early 1990’s to support engine research and development. Selective Interrupt and Control (SIC) was realized as the combination of data-acquisition and control, and allowed for the off-calibration evaluation of a stock powertrain installed in a test cell.

To support and validate the EPA’s ALPHA tool, testing of OEM powertrains on- and off-calibration was necessary. Traditional methods of generating this type of data would require either OEM support [4] or reverse engineering of the control logic and calibration and development of a test ECU [5]. Given the lack of manufacturer support and need for open ECU functionality, a SIC system was designed, implemented, and tested to adjust ignition timing and camshaft phasing (both for intake and exhaust) to examine the impact on efficiency, emissions, and performance.

This paper will first present the technical background of tethered benchmarking, RPECS, and SIC. This background will be followed by two case studies of the implementation of SIC, ignition timing and cam phasing. Each case study includes the development process, methodology, and problems solved. Finally, results from the complete SIC implementation on the 1.6 L EcoBoost will be presented and future applications of SIC discussed.

Technical Background

This section describes topics necessary for a reader to understand the case studies presented in this paper.

Tethered Engine Benchmarking

The engine was installed into the test cell, plumbed into test cell systems (cooling, exhaust), instrumented (thermocouples, pressure, emissions), and connected to a dynamometer. The stock engine control unit (ECU) was installed near the engine in-cell and the stock engine harness was connected. A custom breakout boards (BOBs) was employed that utilized the stock ECU connector and a custom printed circuit board (PCB) to break out every ECU pin. A stock engine harness was cut to form a pigtail which was then soldered into one set of connections on the BOB. The stock engine harness was connected to the BOB ECU connector and the ECU was connected to the pigtail already soldered to the BOB. Additional connections were available on the BOB that allowed a data acquisition (DAQ) system to directly monitor and, if necessary, interrupt and control any signal on the ECU connector. An RPECS harness was constructed and soldered to the BOB - this harness monitored sensors and actuators on the engine.

Vehicle schematics were studied and a power distribution system was designed that replicated in-vehicle power distribution with a series of relays, fuse blocks, battery box, and power supply. This solution prevented control unit fault codes, while also allowing safe control of the engine in the event of an emergency stop.

The vehicle of interest was parked next to the test cell and still equipped with the engine of interest. A separate crate engine was installed in the test cell for evaluation which allowed flexibility in test sequencing (e.g. if a problem had been discovered in the test cell, the vehicle could be untethered and tested on-road or on a chassis dynamometer). A second BOB was installed in the stock vehicle with the body-side harness connected to the stock ECU connector. The BOB in the vehicle connected only the necessary body and transmission signals to the BOB in the test cell via a custom wire harness which was run through a port in the test cell wall.

This tether methodology significantly reduced the time, complexity, and effort required to satisfy the error detection algorithms in the stock ECU, allowing replication of in-vehicle performance. Traditionally, this process has involved evaluating all body and transmission signals and then replicating them in the test cell. With this method, only a handful of signals need be evaluated and replicated. This process also allows installation of the transmission into the test cell with the engine.

Selective Interrupt and Control

Selective Interrupt and Control is a test methodology. SIC focused on selectively interrupting and controlling stock powertrain actuators in a manner such that the control unit (e.g. ECU) did not produce faults or de-rate engine performance. This was accomplished by simulating and feeding signals into a control unit, providing "fake" actuators for the control unit, and controlling actuators with RPECS and associated driver hardware. The goal was to be as minimally invasive as possible:

- Interrupt only the necessary signals
- Provide for easily switching between stock and SIC configuration, including provisions for complete return to stock
- Prevent generation of control unit fault codes
- Utilize control unit calibration and strategy as much as possible
- Provide reasonable safeguards

FIGURE 1 RPECS in standard configuration

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As discussed in the implementation sections for ignition timing and cam phasing control, this process focused on iteratively developing small portions of the SIC system. The first phase attempted to insert RPECS as a pass-through device between the stock control unit and the actuator under development, leaving the control setpoint unchanged. Successive stages implemented functionality in self-contained, easily tested pieces.

Rapid Prototyping Electronic Control System

RPECS (Figure 1) is a ruggedized hardware platform for data acquisition and engine control. RPECS has a powerful single-board computer (SBC) running a real-time operating system, an analog input card, two controller area network (CAN) channels, and two field programmable gate arrays (FPGAs).

Case Studies

This section presents two case studies of the implementation of SIC, ignition timing and cam phasing, on a 2013 Ford Escape 1.6 L EcoBoost engine (Table 1), hereafter referred to as the device under test (DUT). Each case study describes the design concept, implementation, and problems solved.

TABLE 1 DUT specifications [3]

Vehicle	2013 Ford Escape
Engine	1.6 L EcoBoost®
Rated Power	132.7 kW @ 5700 RPM
Rated Torque	249.5 Nm @ 2500 RPM
Engine features	Turbocharged, direct-injected, dual independent cam phasers

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SIC Ignition Timing

Concept The DUT utilized coil-on-plug (COP) ignition drivers with simple low-voltage control signals. The override concept was simple: monitor the stock command with RPECS, interrupt the ignition command signal, and feed a command signal from RPECS into the COP. RPECS was already monitoring the stock command signal as part of the data acquisition configuration, calculating commanded ignition dwell and start/stop angle.

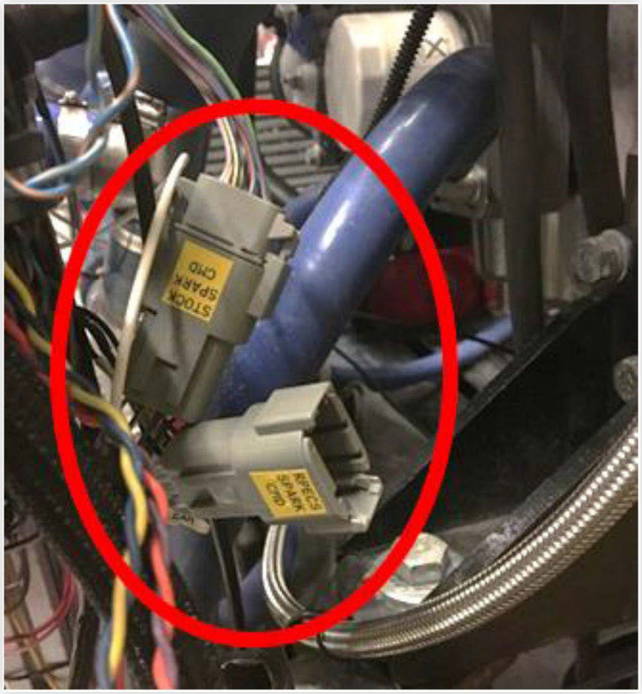
This concept was implemented in two phases:

1. Attempt to insert RPECS between the stock ECU and COP ("pass-through"), passing the command signal from the ECU through the FPGA and back out without modifying the commanded position. This phase was used to demonstrate viability of the concept.
2. Modify the ignition control signal, generating ignition timing based on input from the test engineer via an ATI VISION, an industry standard calibration software package. Dwell could be manually controlled by the test engineer or set to match the dwell of the stock signal from the previous engine cycle (default mode).

Implementation

Phase I. Phase I primarily consisted of wiring harness modifications with the goal of the SIC installation being completely reversible. To accomplish this goal, the harness was built with two female connectors, labeled "stock spark cmd" and "RPECS spark cmd" (Figure 2), and one male connector to select between each mode. When configured for SIC, each cylinder's stock ignition command signal was passed to the RPECS digital input for measurement and the command signal to the COP was sent from the RPECS digital output. Additionally, the SIC connector included a compensation circuit between the ECU and RPECS, the reason for which is explained in the section Problems Solved.

FIGURE 2 Wiring harness modifications for ignition SIC



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No RPECS application software was written; the only modification to the RPECS configuration was to pass the measured ignition signal through the FPGA from the input to the output.

This configuration was tested and demonstrated to function without producing fault codes in the ECU.

Phase II. Phase II of implementation added user-configurable ignition timing. There were no wiring harness modifications necessary in this phase; all changes were implemented in the FPGA and application software.

The application software performed numerous tasks:

- Limit the user command between configurable minimum and maximum values
- Calculate ignition dwell start position based on desired dwell time, engine speed, and desired ignition timing (dwell end position)
- Switch between stock and override mode
- Implement knock protection strategy

To prevent the entry of unreasonable ignition timing values, limits were implemented in software; however, these limits do not stop the operator from entering valid values that may cause damage to the engine (e.g. severely advanced timing within the positive limit). As the nature of SIC is to exercise the engine outside of normal operating conditions, care must be taken when modifying ignition timing. A discussion of the knock protection strategy implemented during this phase is presented in Problems Solved.

The position of the ignition dwell start command was calculated from the current engine speed and the desired dwell time. The desired dwell time was set to match the measured dwell time commanded by the ECU for the previous engine cycle. By utilizing the stock dwell, COP performance was nearly identical to stock performance while also eliminating the need to develop dwell tables for various engine operating parameters (e.g. battery state of charge, ambient temperature, engine speed, etc.).

One potential hazard in switching between pass-through and override mode is unintended premature ignition firing. If a mode switch occurred in which the previous command was high and the new command is low, the COP would discharge. For this reason, the mode switch command was updated at a specific location that accounts for adequate ignition timing range and dwell time. Additionally, the mode switch command is only accepted if engine position tracking is fully synchronized and the application is not in safe mode. If the application software crashes, the FPGA will enter safe mode.

The test engineer controlled the SIC system through ATI VISION, Figure 3 shows the dashboard developed for SIC ignition timing.

- Current engine speed and stock ignition timing were displayed
- The user could toggle between stock and override mode with a single button

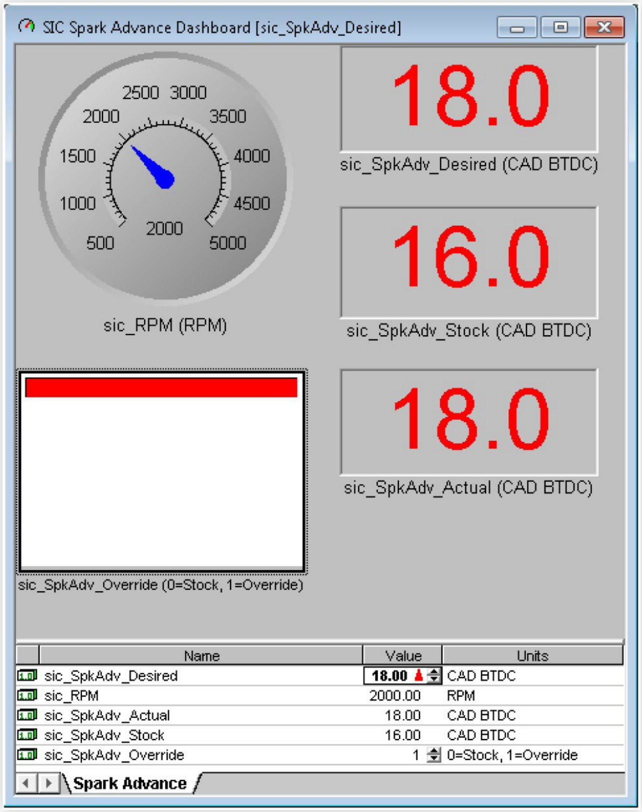
- The desired ignition timing is entered via keyboard
- The ignition timing command sent to the COP is displayed (“sic_SpkAdv_Actual”) and will match either the desired or actual value depending on the state of the override button

Problems Solved

COP Fault Detection Circuitry. The ECU continuously performed diagnostic health monitoring on the COP modules to detect common electrical failures (e.g. short to ground, short to supply). During the first phase of development, the SIC wiring harness connected the ECU control signals to the digital input conditioning circuitry only. In this configuration, the ECU generated a fault code indicating COP failure. An oscilloscope was used to compare the stock and SIC control signals, and the difference in voltage levels was immediately obvious. The SIC harness was modified to include a compensation circuit (Figure 4) and, after clearing the fault code in the ECU, the pass-through test was repeated and no fault code was produced by the new configuration.

Knock Protection. In manually overriding the ignition timing command, the stock knock protection strategy was bypassed. However, as the test engineer had full control of ignition timing and would be intentionally modifying the command to values near the knock threshold, knock protection was necessary. Initial solutions suggested included:

FIGURE 3 VISION interface for ignition timing SIC demonstrating override mode



Name	Value	Units
sic_SpkAdv_Desired	18.00	CAD BTDC
sic_RPM	2000.00	RPM
sic_SpkAdv_Actual	18.00	CAD BTDC
sic_SpkAdv_Stock	16.00	CAD BTDC
sic_SpkAdv_Override	1	0=Stock, 1=Override

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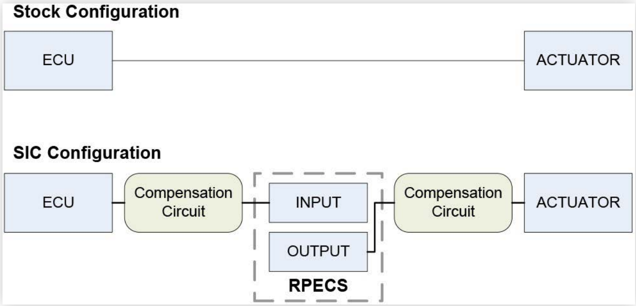
FIGURE 4 Diagram of ignition timing SIC wiring



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- Add a fully redundant knock detection system
- Utilize the stock knock sensor and add knock detection hardware and software
- Utilize the combustion analysis system knock detection

However, it soon became apparent that the stock knock detection and correction strategy could be utilized by comparing the real-time, measured stock ignition command to the command saved at the time SIC mode was enabled, reverting to stock control whenever the difference exceeded a user-defined threshold. This strategy was implemented in the RPECS application and tested at the same point that had produced knock. The strategy was successful; the stock ECU retarded ignition timing in response to knock and, at the user-defined threshold, RPECS reverted to pass-through mode and knock abated[1].

Future SIC applications of ignition timing could easily include more advanced knock protection strategies, including use of the other options outlined above. Additionally, the user input could be limited to a moving window, i.e. a narrower window based on the present ECU ignition command when switching from stock to SIC mode.

SIC Cam Phasing

Concept After successfully developing and testing SIC for ignition timing, SIC for cam phasing was requested by the client. During the concept development phase, the initial approach considered was interrupting the camshaft phaser control. This was logically similar to the ignition timing adjustments but came with additional complications:

- Additional hardware was required to drive the cam phaser (one low-side driver per phaser)
- Calibration of cam phaser control
- Simulation of tracking signal back to ECU that matches expected cam position

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[1] The number of cycles between when the ECU first started to noticeably retard ignition timing and when override mode was disabled was not measured; however, the comparison is performed per-cycle and the threshold was set to 5 CAD, so depending on how aggressively the stock knock strategy retards timing the estimated number of cycles is 2 to 3.

The first and second points were not technically challenging but would require tuning effort. The third point was also not deemed particularly technical challenging, but overall this solution seemed inelegant and overly complicated. Then, a new concept was proposed: interrupt the cam position signal and send simulated tracking signals to the ECU but with an error in the signal such that the ECU "corrects" the cam to the position desired. This solution eliminated the need for additional hardware, as the stock ECU would provide the driver, and the need for tuning cam phaser control, as this solution utilized the stock/OEM cam phaser control strategy in the ECU.

It was decided that this methodology would first be tested on the intake cam, as the exhaust cam involved the additional complexity of controlling fuel rail pressure via the high-pressure fuel pump (HPFP).

The core concept behind SIC for cam phasing is to send a cam position feedback signal into the ECU that contains a fixed offset relative to the actual feedback signal. When first introduced into the feedback signal, this fixed offset appears to the ECU as an error in cam phase; the ECU will phase the cam in the opposite direction of the offset to "correct" the cam phase to the ECU's desired position. Because the offset is fixed relative to actual cam position, the ECU will have phased the cam by a user-desired amount, resulting in a new cam phase position that matches the user's desired cam phase.

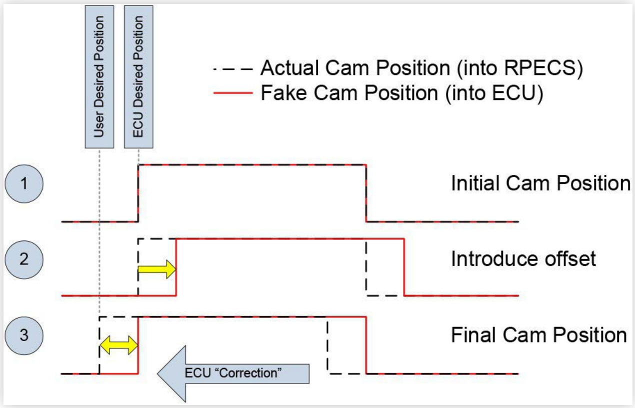
As Figure 5 illustrates:

1. Initially the user is commanding no offset; the actual cam position and fake cam position match
2. The user commands an offset, represented by the yellow arrow; this offset is applied to the fake cam position (the cam position signal seen by the ECU)
3. The ECU "corrects" the fake cam position by phasing the cam the opposite direction of the offset, represented by the yellow arrow. Because this offset is fixed relative to the actual cam position, the ECU "correction" phases the real cam by the offset amount.

This concept was implemented in three phases:

1. Insert RPECS between the ECU and intake cam position sensor (pass-through)
2. Implement cam phasing SIC on the intake cam, demonstrating the viability of the concept.
3. Implement cam phasing SIC on the exhaust cam

FIGURE 5 Graphical representation of fixed-offset cam phase concept



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Implementation

Phase I. The first phase was pass-through; insert RPECS between the cam position sensor and the ECU and pass the cam position sensor signal through RPECS without modifying it.

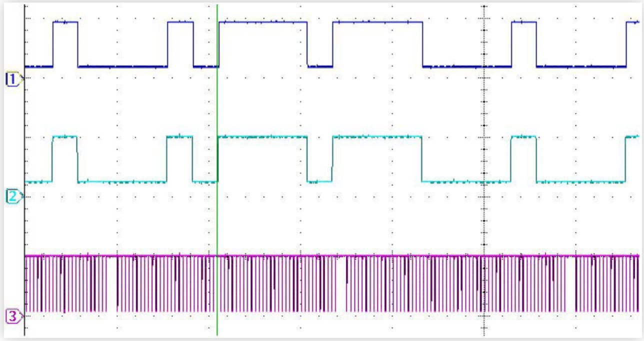
The intake cam phasing SIC harness used the ignition timing SIC harness as a model; a pair of matching connectors were labeled "stock" and "SIC", with the "stock" harness completely reverting any SIC modifications. The final SIC harness contained a compensation circuit between the cam position sensor and RPECS digital input and a compensation circuit between the digital output and the ECU cam position sensor input. The FPGA was reconfigured to pass the cam position signal through from input to output. This configuration eliminated fault codes encountered during initial development, the discussion of which is discussed in Problems Solved.

Phase II. Phase II focused on the development of the application software and FPGA configuration necessary to generate a phase-able simulated cam signal. This development targeted the intake cam only thereby avoiding the complexity associated with the HPFP driven by the exhaust cam. No wiring or hardware changes were necessary in this phase.

The FPGA module developed was constructed based on the engine position tracking information presented in Figure 6. This module contained a number of advanced algorithms designed to prevent ECU fault codes for implausible cam states. The application software provided the interface between the user and the simulation module, sending desired mode and phase offset. The final VISION interface is discussed in Phase III.

Phase III. The ECU controlled the high-pressure fuel pump in the crank angle domain, taking into consideration the position of the exhaust cam when calculating solenoid actuation start/stop angles. Phase III implemented cam phasing SIC on the exhaust cam; however, as the exhaust cam drives the HPFP, the HPFP was also controlled as a side-effect.

FIGURE 6 Oscilloscope screenshot of engine position signals



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This phase included numerous wiring harness modifications. The exhaust cam was configured in the same manner described in Phase I. The ECU drives the HPFP solenoid with a peak-and-hold strategy; as such, additional hardware was necessary. SwRI developed the Direct Injection BOT™ (DIBOT™) to control direct injectors and associated fuel system components such as HPFPs. The DIBOT was selected to drive the HPFP and configured with the profile displayed in Figure 7. To prevent fault codes, the ECU HPFP control signals were rerouted to a spare HPFP. These wiring changes were restricted to a single connector which allowed simple transitions between stock and SIC modes.

The same simulated cam module developed in Phase II was applied to the exhaust cam. A new module to simulate the HPFP command was developed and used to control the DIBOT output. The FPGA was configured to monitor the HPFP control signals ("FMV_HI" and "FMV_LO" in Figure 7) and calculate the HPFP command start/stop angles. The measured stock command was used by the HPFP simulation module, along with numerous other inputs, to generate a compensated HPFP command which controlled the HPFP on the engine. This strategy proved successful during testing - after start-up, HPFP SIC had no noticeable impact on line pressure control.

A VISION interface was developed to provide user control of cam phase SIC. The dashboard (Figure 8) reported measured fuel rail pressure as well as desired and actual cam phase, per cam. A single toggle button per cam switched between stock and SIC mode, and the user entered the desired offset via the keyboard. The VISION project also contained the ignition timing SIC dashboard which include engine speed.

Problems Solved

Cam Position Sensor Fault Detection Circuitry. Connecting RPECS directly to the cam position sensor was initially unsuccessful - the measured value was always low during engine operation. It was theorized that the ECU contained some conditioning circuit on the cam position input, so a compensation circuit was added to the SIC harness and subsequent testing demonstrated that this solved the problem.

FIGURE 7 Oscilloscope screenshot of HPFP current profile and conditioned high/low control signals

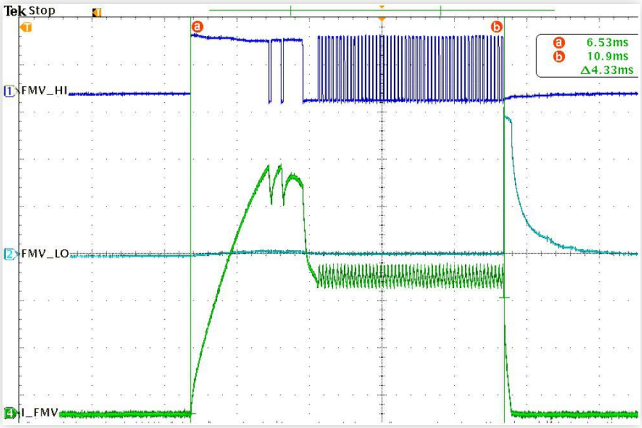

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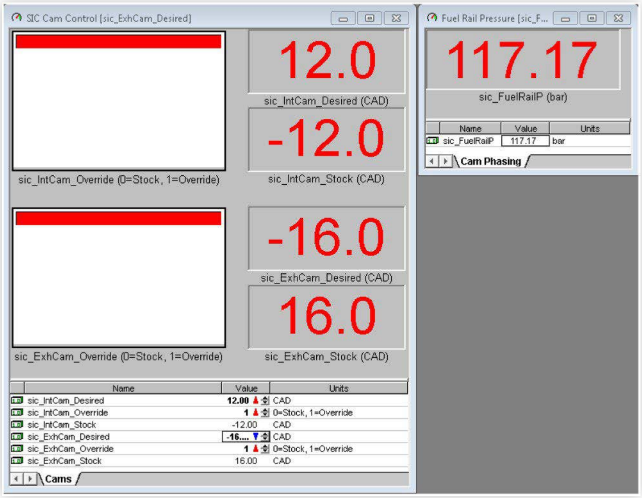
FIGURE 8 Dashboard developed for controlling SIC cams



SIC Cam Control [sic_ExhCam_Desired]

sic_IntCam_Override (0=Stock, 1=Override)

12.0 sic_IntCam_Desired (CAD)

-12.0 sic_IntCam_Stock (CAD)

sic_ExhCam_Override (0=Stock, 1=Override)

-16.0 sic_ExhCam_Desired (CAD)

16.0 sic_ExhCam_Stock (CAD)

Name	Value	Units
sic_IntCam_Desired	12.00	CAD
sic_IntCam_Override	1	0=Stock, 1=Override
sic_IntCam_Stock	-12.00	CAD
sic_ExhCam_Desired	-16....	CAD
sic_ExhCam_Override	1	0=Stock, 1=Override
sic_ExhCam_Stock	16.00	CAD

Cams

Fuel Rail Pressure [sic_F...

117.17 sic_FuelRailP (bar)

Name	Value	Units
sic_FuelRailP	117.17	bar

Cam Phasing

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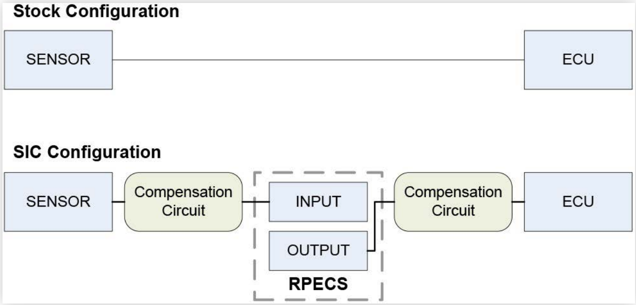
FIGURE 9 Final wiring configuration for cam position sensor SIC



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Connecting RPECS directly to the ECU was also initially unsuccessful; a fault code for "failed cam position sensor" was reported. On an oscilloscope, the stock cam position signal was compared to the simulated cam position signal and a difference in voltage levels was apparent. A compensation circuit was added to the harness and the fault code was eliminated. The final cam wiring configuration is shown in Figure 9.

Test Results

Testing was performed at the EPA's National Vehicle Fuel Emissions Laboratory (NVFEL) in Ann Arbor, MI to examine the impact of ignition timing and cam phasing on thermal efficiency and engine performance for a fixed user input (pedal position). The Ford 1.6 L EcoBoost engine was installed in a test cell (Figure 10) and outfitted with RPECS and SIC as detailed earlier in this paper. The engine was outfitted with Kistler 6052 cylinder pressure transducers in all four cylinders, thermocouples, and pressure transducers placed in the intake and exhaust path. Additionally, the engine's stock sensors for temperature and pressure in the intake and exhaust along with coolant and oil temperature were recorded

FIGURE 10 Ford 1.6 L EcoBoost engine installed at EPA test facility

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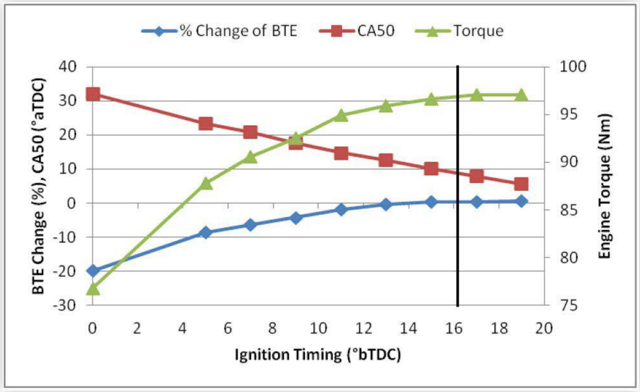
FIGURE 11 Relative percentage change of BTE, CA50 and engine torque versus ignition timing for the 1.6 L EcoBoost engine at 2000 RPM and 20% throttle. Black line represents stock ignition timing.



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using RPECS. Coolant temperature was controlled to 90 °C and manifold temperature was controlled to 35 °C. Combustion analysis was done using A&D's Phoenix combustion analysis system. The exhaust of the engine was sampled using a Horiba MEXA.

Figure 11 shows how adjusting ignition timing from the base value of 16 °bTDC (black line) affected CA50, BTE, and engine torque at 2000 RPM and 20% throttle. Only ignition timing was adjusted and all other engine parameters (injection timing and pressure, cam position, etc.) were under the control of the ECU. As ignition timing was advanced from the base timing, BTE was unchanged; however, torque increased. Retarding CA50 resulted in a maximum manifold pressure drop of 0.8 kPa and a maximum exhaust temperature increase of 60 °C. It appears that the stock engine calibration has ignition timing that is not at maximum brake torque (MBT) and that additional performance may be possible at certain areas of the engine operating range.

FIGURE 12 Relative percentage change of BTE, CA50 and engine torque versus exhaust cam phase for the 1.6 L EcoBoost engine at 2000 RPM and 20% throttle intake cam held at the base position. Black line indicates stock performance. Black line represents stock exhaust cam phase.

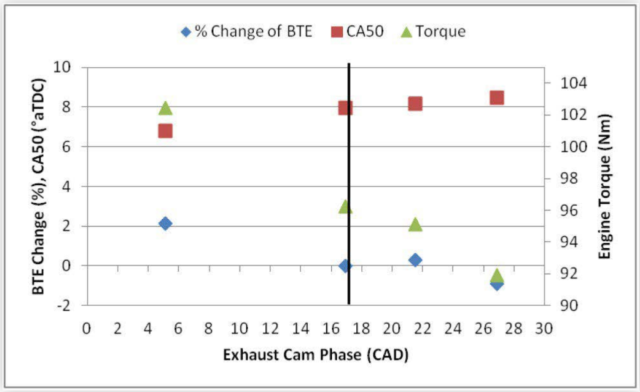

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Figure 12 shows some of the results of using SIC to change the position of the exhaust cam and examine the effect on engine torque and BTE. As the exhaust cam is advanced and the amount of valve overlap increases, engine torque increases and BTE increases. Conversely, as the exhaust cam is retarded further and the amount of valve overlap decreases, engine torque decreases and BTE drops.

Additional testing must be performed to examine the impact on emissions and BTE while keeping engine load constant rather than throttle position constant.

Summary and Conclusions

SIC has been successfully implemented on the Ford 1.6 L EcoBoost engine to assist the EPA in validation of the ALPHA model. In this paper the development process, methodology, problems encountered and solved while implementing SIC for ignition timing and cam phasing were presented. The impact to changes in ignition timing and cam phasing at one engine speed with a fixed throttle position was presented. Test results indicate that ignition timing at certain points of the operating map may not be at true MBT. Preliminary test results from adjusting exhaust cam phasing show that slight improvements in torque or BTE are possible from the base engine calibration; however, further examination of the exhaust emissions and combustion stability is necessary. Additionally, all testing was performed at steady-state so the impact of calibration changes on transient performance, drivability or emissions is unknown.

Future work will entail expanding SIC capability to include modification of injection count (add or remove injections), injector current profile, timing, and fuel rail pressure all without adjusting fuel quantity. With full engine control capability, various cold-start strategies could be developed on production engines to lower emissions with minimal impact to fuel economy. SIC would allow the implementation of different hardware (ignition coils, injector, etc.) or even the addition of hardware (port fuel injection (PFI) to a GDI system, cooled EGR, etc.). With the additional control functionality a test engineer could perform investigations and trade-off studies with existing engine hardware, for example examining the impact of trapped residuals on engine efficiency and combustion stability.

Disclaimer

The statements and opinions expressed in this paper are solely those of the authors, and do not represent the official position of the Environmental Protection Agency. The mention of trade names, products, and organizations does not constitute endorsement or recommendation for use.

References

1. U.S. Environmental Protection Agency and Department of Transportation, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: Final Rule," *Federal Register* 77(199), 15 Oct 2012.
2. Lee, B., Lee, S., Cherry, J., Neam, A. et al., "Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool," SAE Technical Paper 2013-01-0808, 2013, doi:10.4271/2013-01-0808.
3. Ford Motor Company, "2013 All-New Escape," http://www.ford.com/services/assets/Brochure?make=Ford&model=Escape&year=2013, accessed Sept 2017.
4. Kocsis, M., Briggs, T., and Anderson, G., "The Impact of Lubricant Volatility, Viscosity and Detergent Chemistry on Low Speed Pre-Ignition Behavior," *SAE Int. J. Engines* 10(3), 2017, doi:10.4271/2017-01-0685.
5. Raahede, C., Lewander, M., and Gabrielsson, P., "Ultra-Clean Transient Operation of a Compression Ignition Engine Fuelled with Upgraded Hydrous Bioethanol," SAE Technical Paper 2012-01-0859, 2012, doi:10.4271/2012-01-0859.

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Definitions/Abbreviations

ALPHA - Advanced Light-Duty Powertrain and Hybrid Analysis
BOB - Breakout board
BTDC - Before top dead center
BTE - Brake thermal efficiency
CAD - Crank angle degree
CAN - Controller area network
COP - Coil on plug
DAQ - Data acquisition
DIBOT - Direct Injection BOT
DUT - Device under test
ECU - Engine control unit
EGR - Exhaust gas recirculation
EPA - Environmental Protection Agency
FPGA - Field-programmable gate array
GDI - Gasoline direct injection
HDL - Hardware description language
HPFP - High pressure fuel pump
MBT - Maximum brake torque
MTE - Midterm evaluation
MY - Model year
NVFEL - National Vehicle Fuel Emissions Laboratory
OEM - Original equipment manufacturer
PCB - Printed circuit board
PFI - Port fuel injection
RPECS - Rapid Prototyping Electronic Control System
SBC - Single board computer
SIC - Selective interrupt and control
SwRI - Southwest Research Institute
TDC - Top dead center
Verilog - A popular HDL

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