CRC Report No. CM-138-19

Development of a Revised Engine Based Test for Determining the Effect of Spark Ignition Fuel Properties on Combustion and Vehicle Driveability

September 2021

COORDINATING RESEARCH COUNCIL, INC.

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Report FEV315393

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Development of a Revised Engine Based Test for Determining the Effect of Spark Ignition Fuel Properties on Combustion and Vehicle Driveability

Abstract

The objective of Project CM-138-19 is to take a more fundamental approach toward measuring the in-cylinder combustion instability that is the root cause of poor vehicle driveability resulting from fuel volatility properties. CRC would like to determine whether fuels of differing compositions and physical characteristics (e.g., Driveability Index) can be distinguished from vehicle performance differences using an instrumented engine in a vehicle on an all-weather chassis dynamometer. The previous study CM-138-15-2 used instrumented vehicles with in-cylinder flush mount combustion pressure sensors that provided captured combustion data that distinguished differing test fuel effects on combustion and subsequent vehicle driveability. The captured data also adds insight into modern gasoline engine reaction to high DI fuels with and without ethanol blending. Included in the study were fuels with a Driveability Index above the maximum specifications contained within the ASTM-D4814 standard. The purpose of this study is to test and establish the use of spark plug combustion pressure sensors instead of flush mount combustion sensors to reduce vehicle instrumentation complexity and cost in future studies. After conducting testing and analysis on a 2020 European Mazda 3 with an advanced high compression ratio SkyActiv-X 2.0L gasoline engine the data supports that spark plug type combustion sensors compare well with flush mount combustion sensors and are a good potential alternative to flush mount in-cylinder sensors. However, this engine was able to cope well with all high DI test fuels and did not render any distinctive combustion instability and subsequent driveabilty degradation between fuels. Therefore, a comparison between the instrumented combustion sensors measuring poor combustion events caused by fuels was not rendered.

I. Introduction

This study adds to the previous study CM-138-15-2 and investigates the feasibility and effectiveness of using Kistler spark plug combustion measurement transducers (in this case model number 6115C) instead of flush mount combustion pressure sensors that require a machined bore through the engine's cylinder head(s) into the combustion chamber(s). The machined installed flush mount pressure sensors had been used in the previous study where they were able to distinguish the combustion effects of different test fuels. However, the complexity of installing the flush mount sensors in modern engines requires technical expertise in engine disassembly and precise machining capabilities to drill into the cylinder head and install the flush mount combustion sensors. This complex operation sometimes requires a spare engine cylinder head, with section cuts, scans, and careful measurements in order to machine a bore into the intended cylinder head on a multi axis machining mill. The vehicle powertrain and engine often must be removed from the vehicle and engine disassembled and after machining the cylinder head and installing the flush mount combustion sensors the engine must be carefully reassembled and installed in the vehicle. This complex procedure can be time intensive and technically complex and will vary from vehicle to vehicle according to engine design and packaging configuration. Further, a new cylinder head, gaskets, etc. must be purchased to replace those used in testing. For these reasons, this study looked at using spark plug combustion sensors instead of the flush mount combustion sensors. The spark plug sensors are made by instrumentation suppliers like Kistler and can be readily installed in place of the OEM spark plug with no adverse effects to engine operation. These spark plug combustion sensors measure combustion pressure and subsequent parameters so that the effects of experimental fuels on engine combustion and subsequent vehicle performance and driveability can be captured and analyzed. Using the spark plug sensors can significantly reduce technical complexity, engine instrumentation lead time, and costs while still capturing accurate combustion data that can be effectively used for CRC performance and driveability studies.

II. Test Vehicle and Instrumentation Overview

The vehicle tested for this study was a European model 2020 Mazda 3 SkyActiv-X vehicle. This vehicle features Mazda's novel high compression ratio 2.0L gasoline engine with spark-controlled compression ignition (SPCCI) capability and a 24 Volt Mild Hybrid system with a belt starter generator. The vehicle was previously instrumented and tested as part of USCAR's engine benchmark research consortium and this consortium agreed to let CRC conduct fuels testing on this vehicle with the instrumentation carried over. This was also the case in the previous vehicles tested as part of the earlier study CM-138-15-2.

Notable features of this vehicle's powertrain are listed below:

- 2.0L 4 cylinder with 24-volt mild hybrid system. Start/Stop Capable
- Belt driven Integrated Starter Generator (ISG)
- Spark Controlled Compression Ignition (SPCCI)
- Compression ratio of 16.3:1
- Belt driven roots-compressor with electric actuation at low engine RPMs
- OEM in-cylinder pressure transducers for combustion feedback to Mazda ECU
- 600 bar common rail high pressure fuel injection with 10-hole injectors
- External EGR with cooler
- Gasoline Particulate Filter (GPF)
- Six speed automatic transmission equipped with an electric oil pump
- Engine only rated for European Spec. 95 RON E10 gasoline fuel
- Vehicle only available in Europe and certified to Euro 6d Emission Compliance

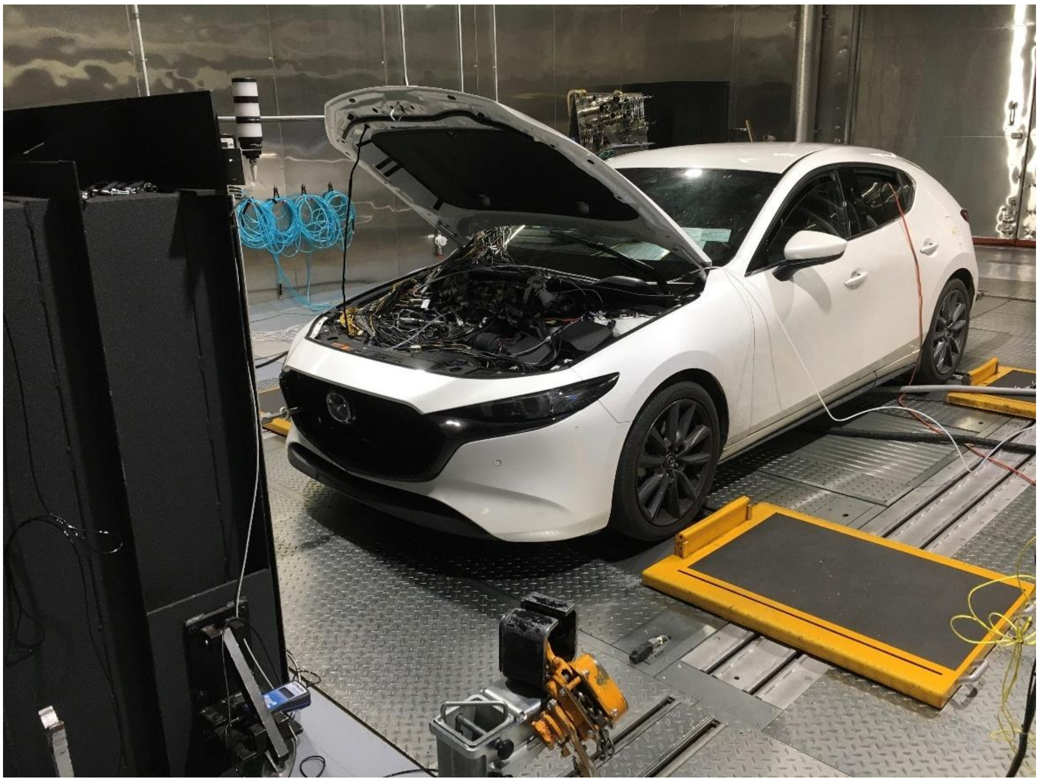

Figure 1. Mazda 3 SkyActivX Vehicle at FEV Test Facility

For the CRC testing additional instrumentation and vehicle modification was required. This included:

- Fuel tank quick drain (at lowest tank collection point)
- Low pressure fuel system quick drain connection
- High pressure fuel system quick drain connection
- Cylinder 1 and 2 spark plug combustion sensor procurement and installation.

The purpose of this study is to investigate how well spark plug sensors, sourced from Kistler, compare to the flush mount in-cylinder sensors that were used in the previous study CM-138-15-2, also sourced from Kistler. These spark plug sensors are Kistler 6115C sensors and were made custom as the original spark plugs were noted to be indexed or angled in a particular degree inside the combustion chamber. It is critical to install the spark plug combustion sensors in the same orientation as the original spark plugs in order to not adversely alter the combustion system. Therefore, the spark plug sensor supplier had to custom manufacture these sensors so that the spark plug sensor threads matched the original spark plug threads and hence had the same install angle at the plug electrode ground-strap inside the combustion chamber. Leadtime for these custom sensors was 10 weeks and cost approx. 10,000 USD in total.

Figure 2. Spark Plug Sensor (left) Original Mazda Spark Plug (Right)

Detailed in the previous report CM-138-15-2 is the addition of fuel tank drainage fittings at the lowest collection point to facilitate thorough and quick test fuel drains and evacuation with an auxiliary vacuum fuel pump.

Additionally, the under hood low-pressure and high-pressure fuel lines on the vehicle were previously instrumented with discrete pressure sensor instrumentation and quick connect fittings were added to also attach an auxiliary vacuum fuel pump to drain fuel at these points.


Figure 3. Under view of vehicle Fuel Tank quick drain setup on lowest collection point of tank

For this study the following instrumented and monitored signals are considered important for driveability fuels testing and understanding the effects of fuels on the engine management control system.

- In-cylinder pressure transducers for combustion measurements (all cylinders, 1-4) (Discrete Instrumentation)
- Spark plug combustion sensors (cylinders 1&2) (Discrete Instrumentation)
- Fuel injection timing and duration all cylinders (degrees crank angle ATDC) (Discrete Instrumentation)
- Ignition timing all cylinders (Degrees crank angle ATDC) (Discrete Instrumentation and only Cylinder 1 available on OBDII CAN Bus)
- Fuel Pressure (DI system and low pressure supply system) (Bar) (Discrete and available on OBD CAN Bus)

- Ambient air temperature (°C) (Discrete and available on OBD CAN Bus)
- Engine coolant in/out temperature (°C) (Discrete and available on OBD CAN Bus)
- Engine oil sump temperature (°C) (Discrete Instrumentation only)
- Exhaust Turbine Inlet/Outlet and Catalyst temperatures (°C) (Discrete Instrumentation only)
- Ambient air pressure (kPa Absolute) (Discrete and available on OBD CAN Bus)
- Intake manifold pressure (kPa Absolute) (Discrete and available on OBD CAN Bus)
- Stand-alone exhaust air fuel measurement (Wideband O2 sensor installed next to OEM O2 sensor) (reported unit is Lambda) (Discrete Instrumentation)
- Accelerator Pedal position (%) (Discrete and available on OBD CAN Bus)
- Throttle position (% Open) (Discrete and available on OBD CAN Bus)
- OBD-II CAN measurements:
    - Short/Long-term Fuel Trims (if available at acceptable update rates) (%)
    - Commanded EGR%
    - Transmission Gear State

III. **Fuel Drain and Test Prep Procedure**

In the previous study, CM-138-15-2, a fuel drain and test prep procedure was developed by FEV and again used in this study. Based on the findings and recommendations from the previous study it was decided to incorporate a fueling adaptation reset in between initial test fuel introduction and the FTP74 baseline test to avoid potential carry over adaptions from previous test fuels and initial test fuel introduction/fill and engine start up. This step involves disconnecting the vehicle battery for over 1 hour and clearing stored diagnostic data with a scan tool. In FEV's experience this resets the fueling adaptions stored in the engine management system, as these adaptions are typically stored in the controller's volatile memory. This added step also serves to avoid carry over fueling adaptations from previous test fuels and eliminates the previous study's method of using normal available gas station pump fuel to reset engine management fuel adaptives in-between test fuels. Incorporation of this added step serves to make testing multiple test fuels more time efficient and engine management system reset more consistent.

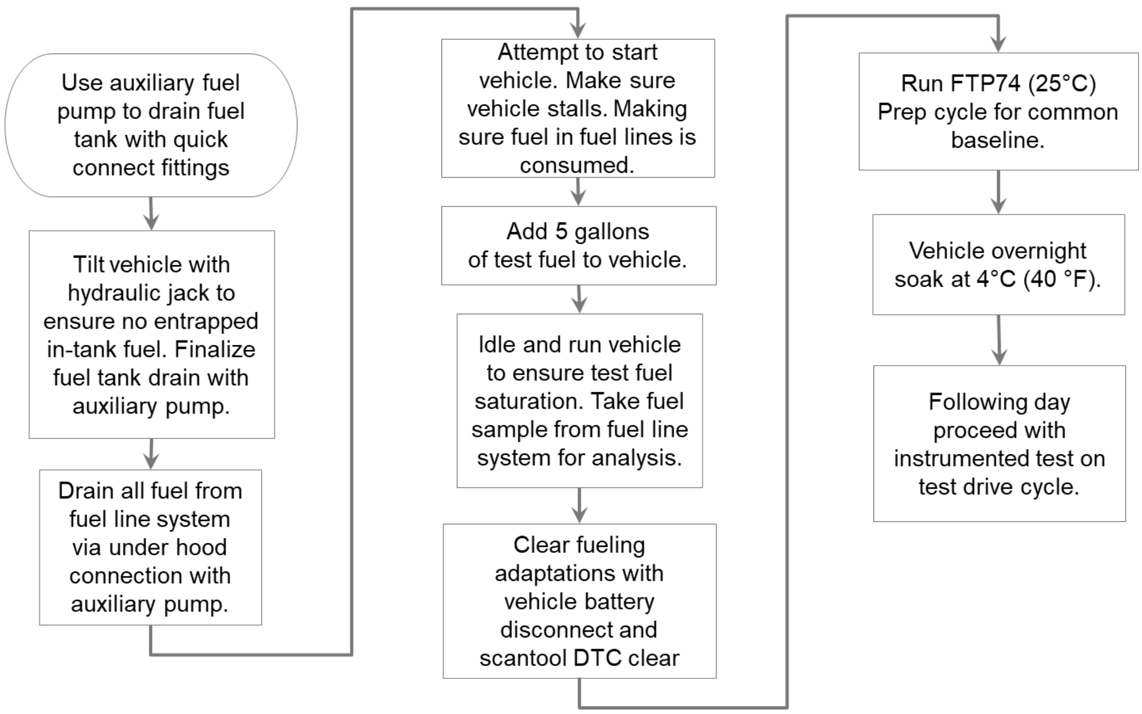

Figure 4. Revised Fuel Drain and Test Prep Procedure with Engine Management system reset incorporated

IV. **Test Fuels**

The test fuels used were carried over from the previous study and original fuel inspection sheets can be found in Appendix A. The fuels used had varying compositions and volatility properties and the objective of these studies are to characterize the effects of these fuels on vehicle engine combustion and supporting engine parameters. As part of the fuel drain and test prep procedure a sample of test fuel (1000cc) was drawn from the low-pressure fuel line connection after initial test fuel introduction and prior to FTP74 baseline drive cycle. This test fuel sample is sent out for fuel distillation analysis to verify the fuel drain. The results of the analysis and verifications are shown in Figure 5 below, full analysis results are in Appendix D. The results reconfirm the fuel drain procedure effectiveness as the distillation curves from the samples agree with the original fuel inspection distillation curves.

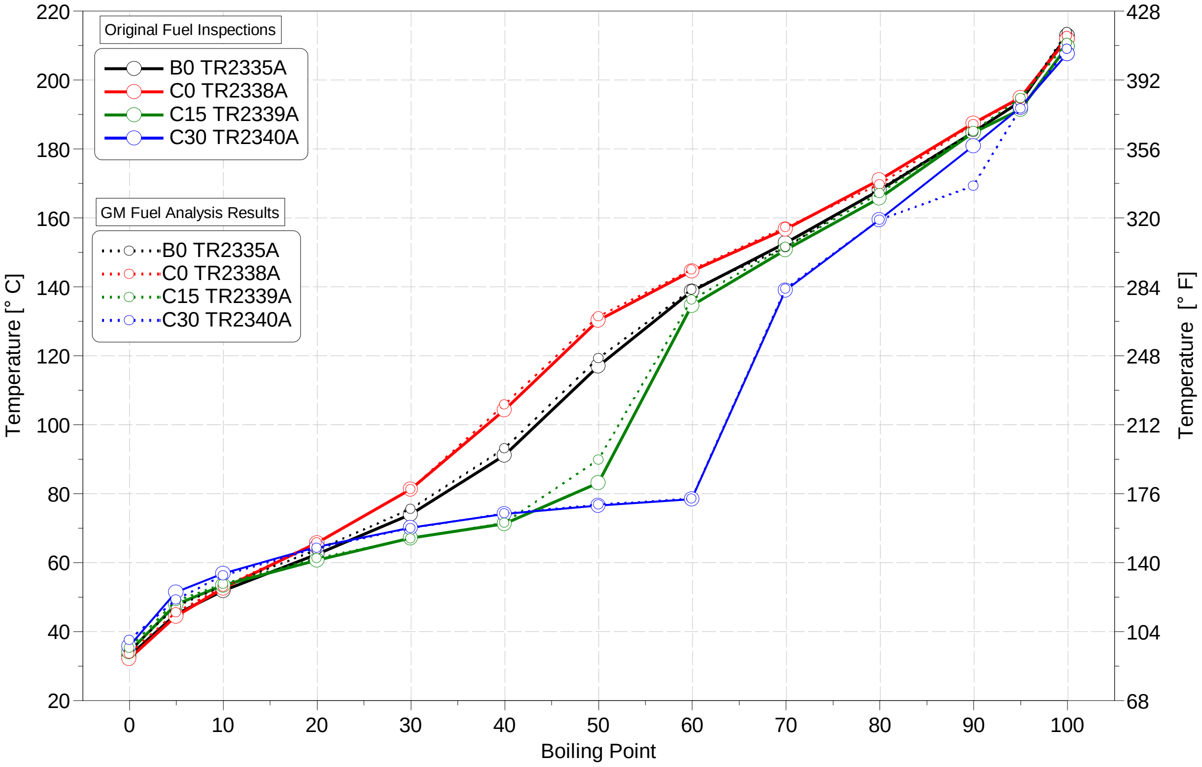

Figure 5. Test Fuel Samples Distillation Analysis Comparison with original fuel inspection distillations

V. **Drive cycle**

The drive cycle used was the FEV modified CRC drive cycle that was developed in the previous study. This cycle was used following the results from the previous study, which showed that having a more aggressive and repeatable drive cycle renders more consistent fuel induced driveability degradation that can be captured by instrumentation and subsequently analyzed.

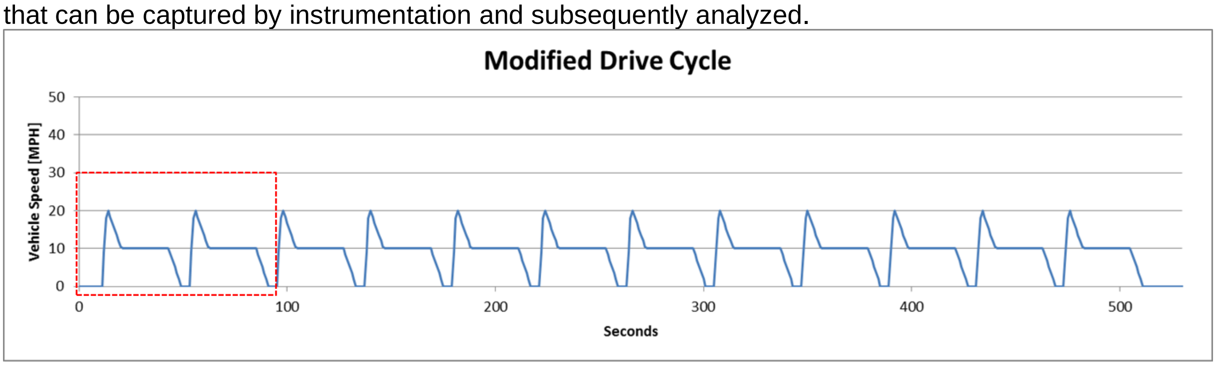

Figure 6. FEV Modified CRC Drive Cycle

VI. Spark Plug Sensor Install and Verification

Once the instrumented vehicle and spark plug combustion sensors were available in January 2021 the sensors were installed on cylinders 1 and 2 and configured in the combustion analysis system. On-road testing was then conducted with Tier III E10 87 AKI octane fuel in the vehicle. Once general agreement was confirmed between the in-cylinder flush mount sensors and the spark plug combustion sensors, an on-road full load (wide open throttle) 0-60 mph run was done to subject the spark plug sensors and combustion system to worst case scenario conditions and conditions similar to the upcoming FEV modified CRC drive cycle (aggressive accelerations). Figure 7 below shows the captured data from these sensors during the on-road full load verification testing.

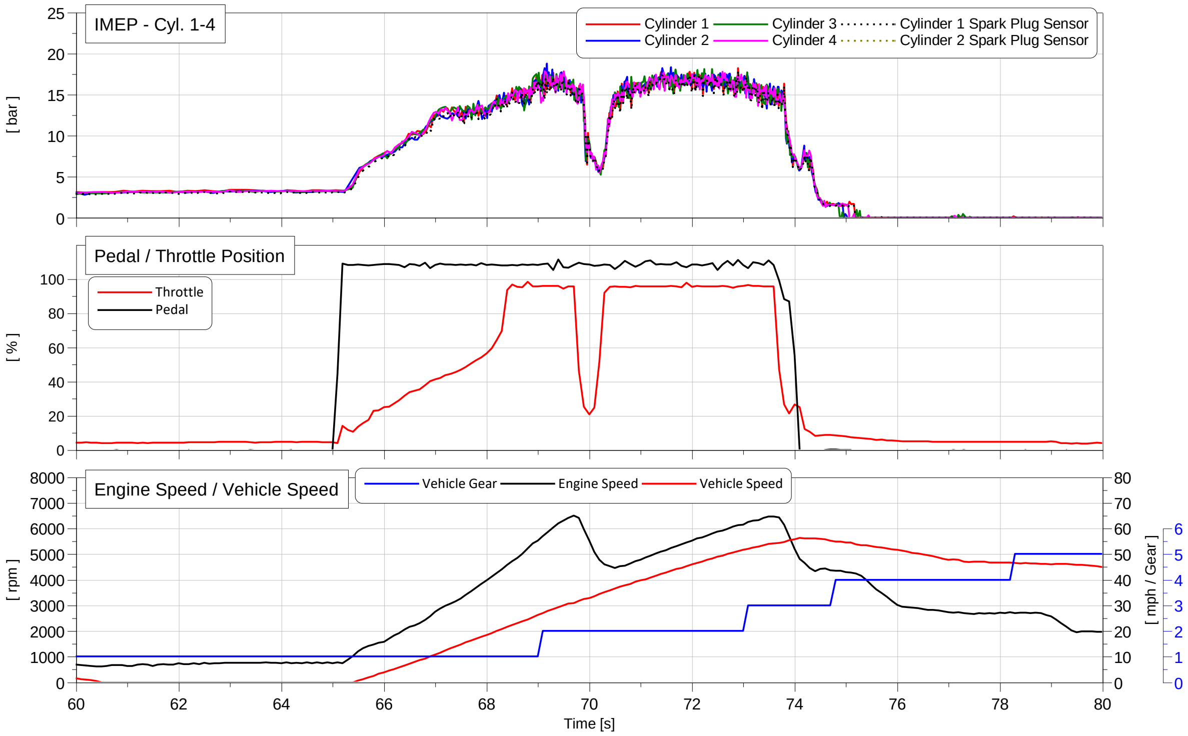

Figure 7. Full Load on road acceleration combustion IMEP data captured with combustion sensors

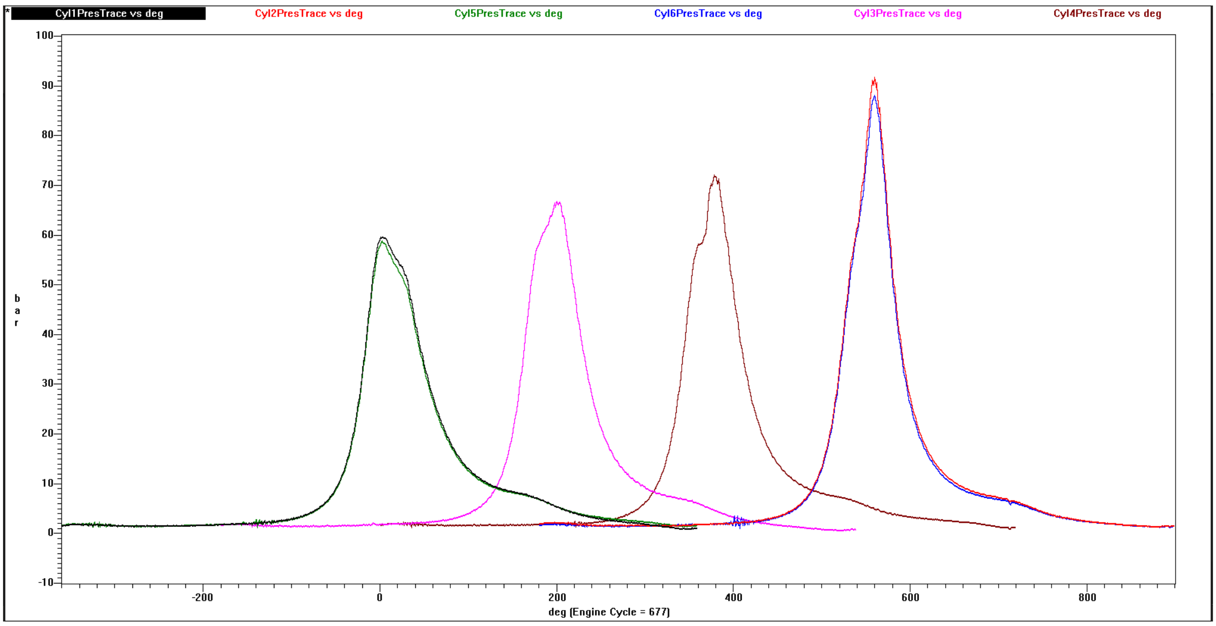

Figure 8. Full Load In-cylinder pressure measurements (Firing order 1-3-4-2)

The data shown in Figure 8 above shows good agreement between the in-cylinder flush mounted combustion sensors and the spark plug sensors at high combustion pressure levels and even combustion knock conditions, rendered by the lower 87 AKI octane fuel. The green trace on cylinder 1 is the spark plug sensor trace and the blue trace on cylinder 2 is the spark plug sensor trace, firing order of engine is 1-3-4-2. Shown in Figure 8 is a knock event on cylinder 2, evident by a sudden rise and higher peak pressure. During this knock event the spark plug combustion sensor readings show general agreement with the in cylinder flush mount sensor.

It was also concluded that the spark plug combustion sensors do not inadvertently alter the engine combustion system as the combustion data shows no significant differences or misfire/knock differences between cylinders 1 and 2 which have the spark plug combustion sensors and cylinders 3 and 4 which do not, Figure 9 below. Note how knock events occur across all cylinders and are not isolated to cylinders 1 and 2 which have the spark plug combustion sensors.

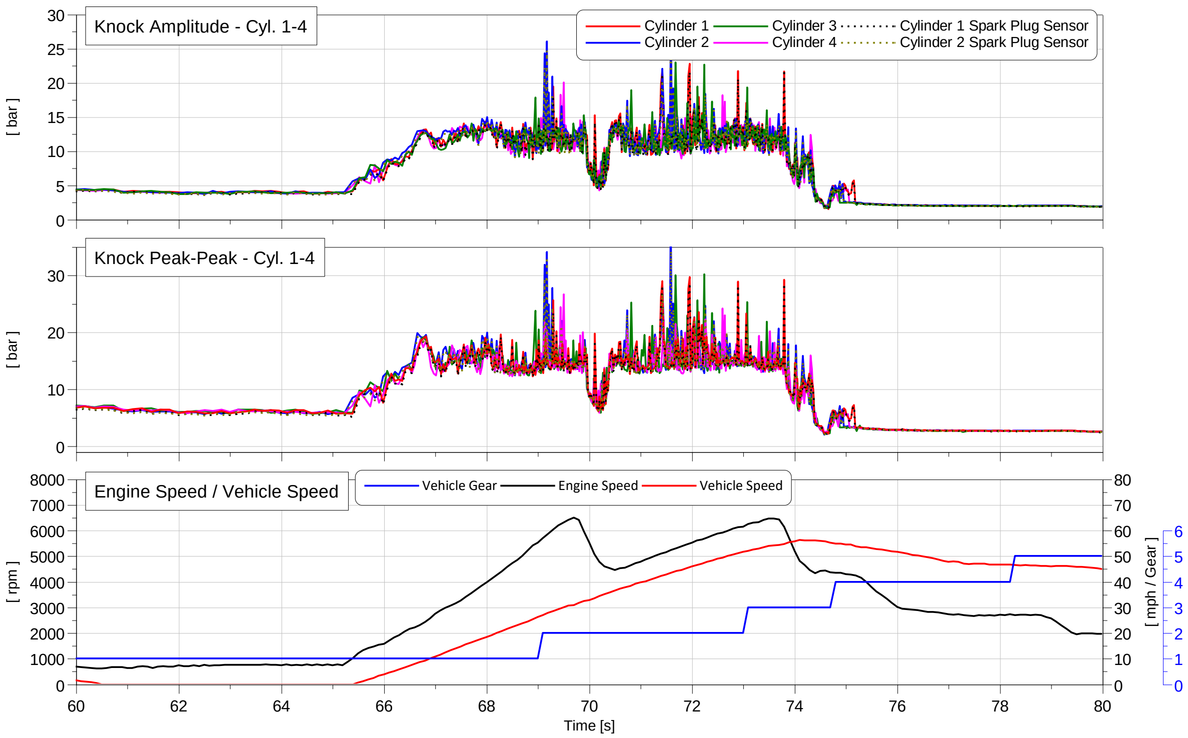

Figure 9. On road full load testing combustion knock parameter captured measurements.

Additional analysis, shown in Figure 10, on combustion CA50 (50% mass fraction burn location) on a later drive cycle also did not show a significant burn differences between cylinders, reconfirming that there is no inadvertent alteration to the combustion system due to the introduction of the spark plug sensors on cylinders 1 and 2.

	Spark Plug Sensor Cylinder 1	Spark Plug Sensor Cylinder 2	In cylinder sensor Cylinder 1	In cylinder sensor Cylinder 2	In cylinder sensor Cylinder 3	In cylinder sensor Cylinder 4
minimum............	-359.5	-359.5	-359.5	-359.5	-359.5	-359.5
maximum............	112.5	87.5	142.5	129.5	100.5	151.5
arith. mean........	8.33653	8.67273	7.96354	8.60796	7.43259	7.67163
mean deviation.....	38.6377	39.1852	39.1379	39.5863	39.9486	40.464
variance...........	6078.24	6201.73	6171.91	6249.74	6360.98	6479.89
standard deviation.	77.9631	78.751	78.5615	79.0553	79.7558	80.4978

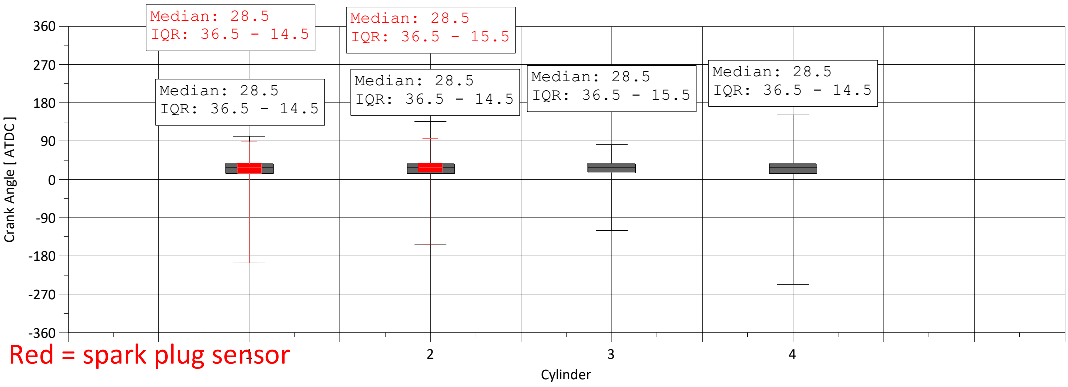

Figure 10. Combustion CA50 Distribution Plot across FEV modified CRC drive cycle

Additionally, after the test program was complete, combustion pressure sensor correlations were made and show consistent agreement between the in-cylinder flush mount sensors and spark plug combustion sensors. When plotted against each other, the flush mount pressure sensors and spark plug pressure sensors have a high correlation result and for combustion IMEP (Indicated Mean Effective Pressure) a 0.99 correlation is measured. IMEP is the primary combustion metric used in this type of driveability study as it will indicate poor combustion events and misfires that will impact driveability. Hence the agreement and high correlation are evidence that for the purpose of driveability studies the spark plug combustion sensors are a good alternative to the in cylinder flush mount combustion sensors. Full correlation study results can be found in Appendix B.

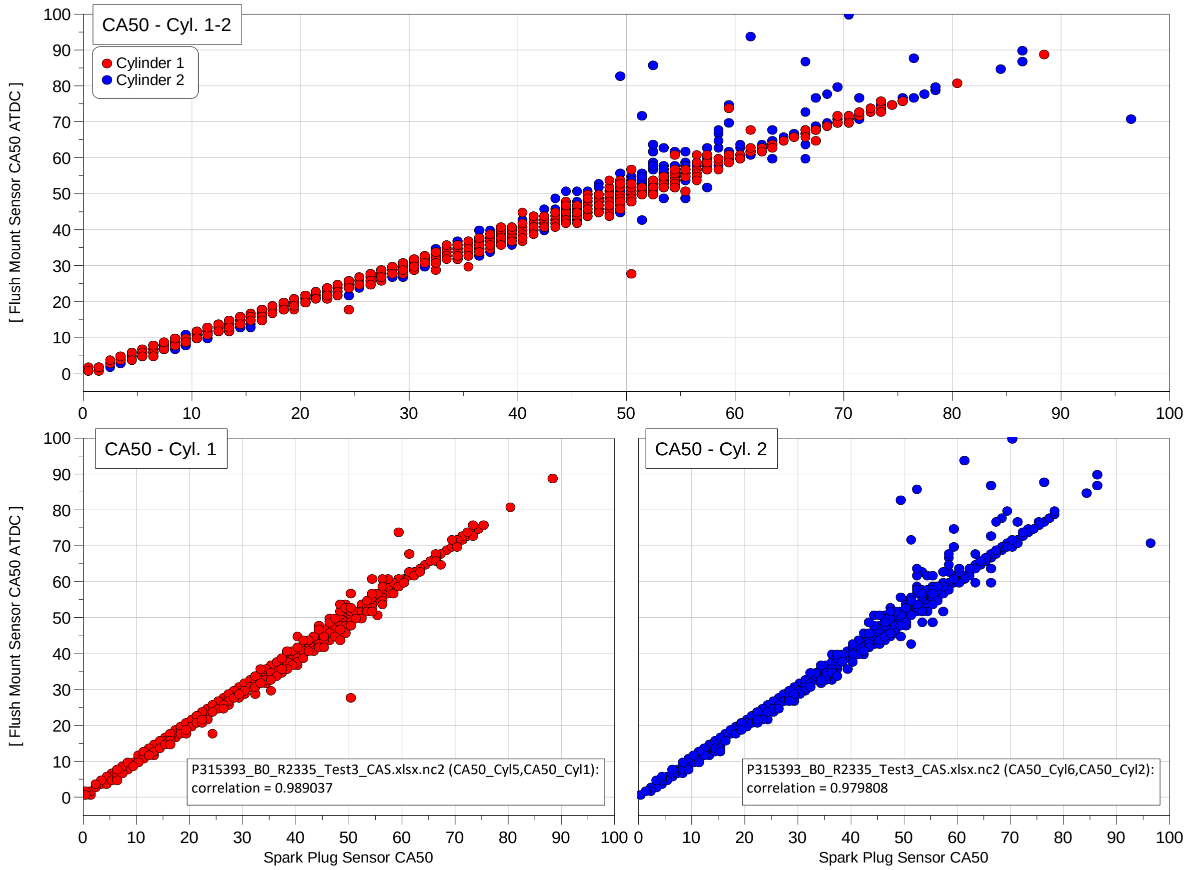

Figure 11. CA50 Combustion sensor correlation

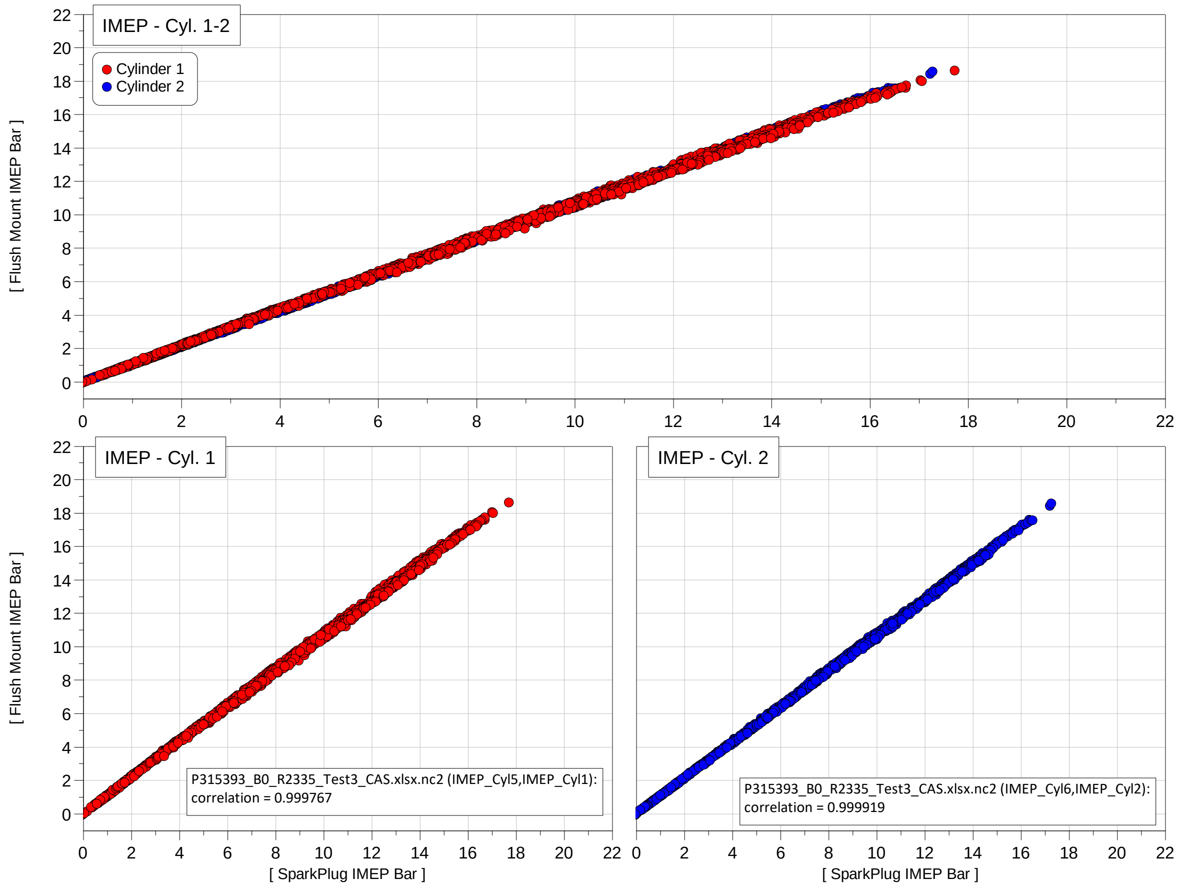

Figure 12. IMEP combustion sensor correlation

VII. **Drive Cycle Test Data Analysis**

a. B0 TR2335A Test Fuel Drive Cycle Analysis and Results

Repeating the test fuel sequence of the previous study, the first fuel that was tested on the instrumented Mazda vehicle was B0 TR2335A fuel. Overall results show that the vehicle was able to handle this test fuel with no issues and did not display any subjective driver nor instrumentation measured degradation of driveability. Figure 13 below shows the first test cold start driveaway; IMEP is stable and responsive to accelerator pedal input providing good driveability to the vehicle. Engine crank and start up times were less than 1 second, which is similar to normal start up times on manufacturer recommended fuel (95 RON European Spec. Fuel).

From these initial tests on B0 TR2335A the engine management system calibration strategy was characterized and noted. Some notable observations are:

- Short term fuel trims became active between 7-8 seconds after engine start up indicating start of closed loop air/fuel control and O2 sensor activation, Figure 15.
- Fuel rail pressure to centrally mounted direct fuel injectors was measured at maximum rated 600 bar during the cold start catalyst heating phase, Figure 16.
- Cold start open loop air/fuel lambda measurements indicated a target lambda of 0.9, Figure 15.
- Electromechanical swirl valves in the intake manifold runners were actively controlled and engaged during the cold start, Figure 17, adding swirl motion to the air entering the combustion chamber for better air fuel mixture and subsequent combustion.

Of significant interest was the fuel rail pressure supplied to the centrally mounted direct fuel injectors. The fuel system is unique in that it is capable of very high fuel pressures and uses the maximum rated pressure (600 Bar) during the initial cold start, idle, and catalyst heating phase. This fuel pressure is much higher than other gasoline direct injection engines. These very high fuel injection pressures help to promote fuel atomization and air mixture inside the combustion chamber as noted by Mazda technical literature “28th Aachen Colloquium Automobile and Engine Technology 2019 MAZDA SKYACTIV-X 2.0L Gasoline Engine”.

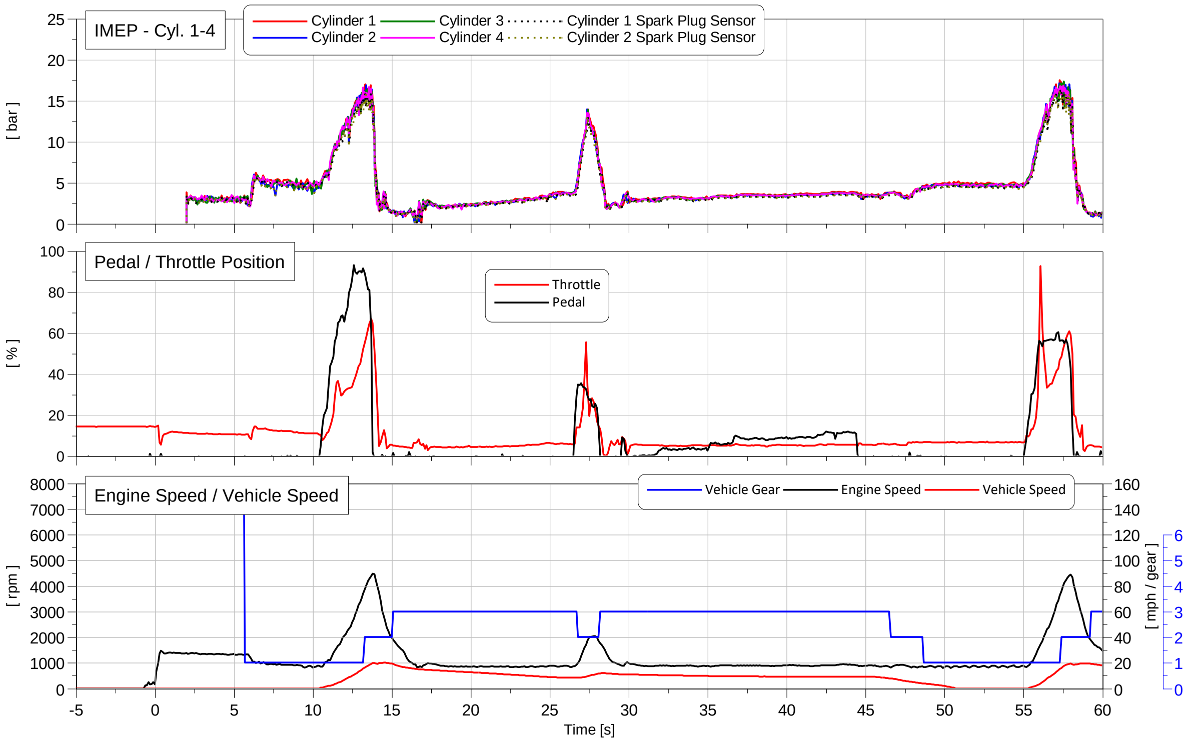

Figure 13. B0 TR2335A Test 1 cold start and initial drive away

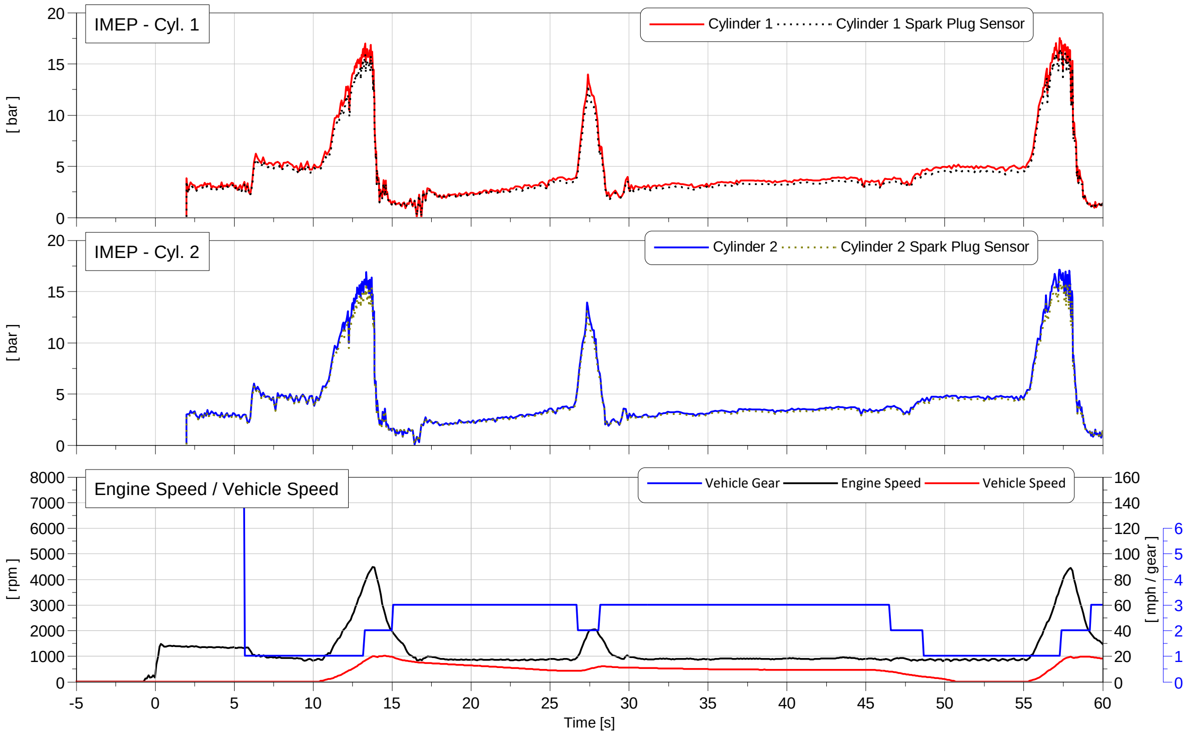

Figure 14. B0 TR2335A Test 1 cold start and initial drive away Cylinder 1 and 2 Compare

Figure 15. B0 TR2335A Test 1 Fuel Trim and Lambda measurements

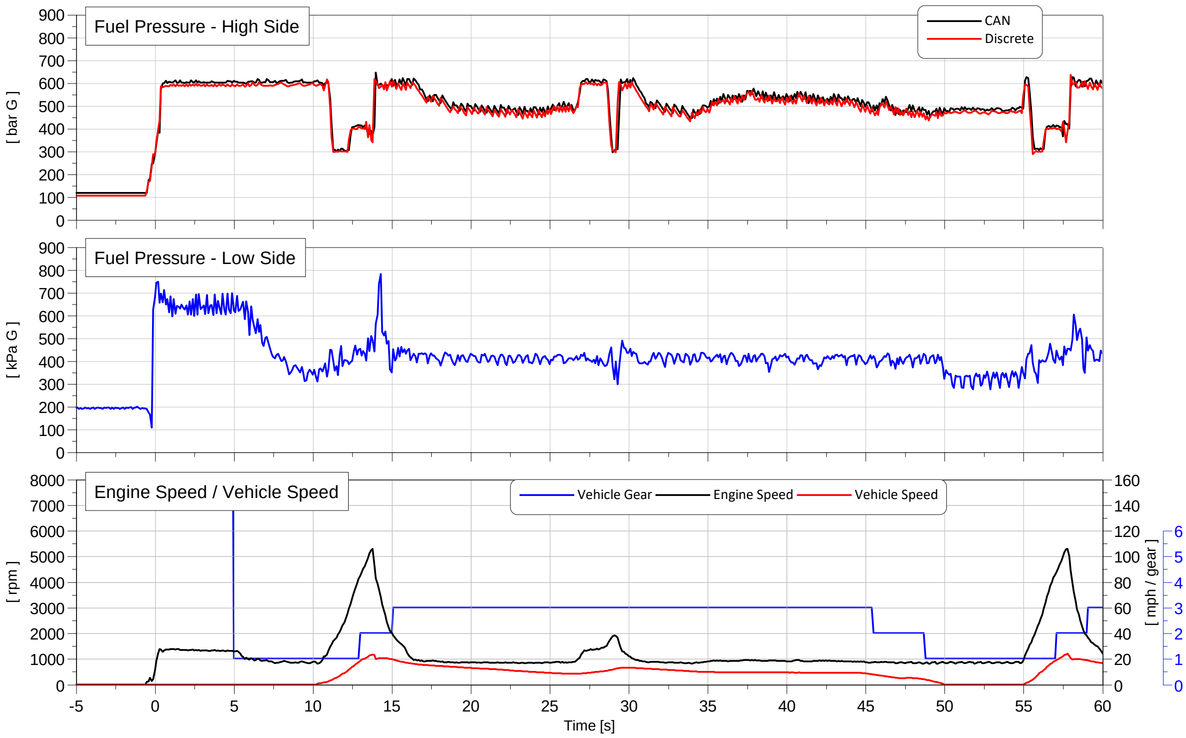

Figure 16. B0 TR2335A Test 1 Fuel Pressures

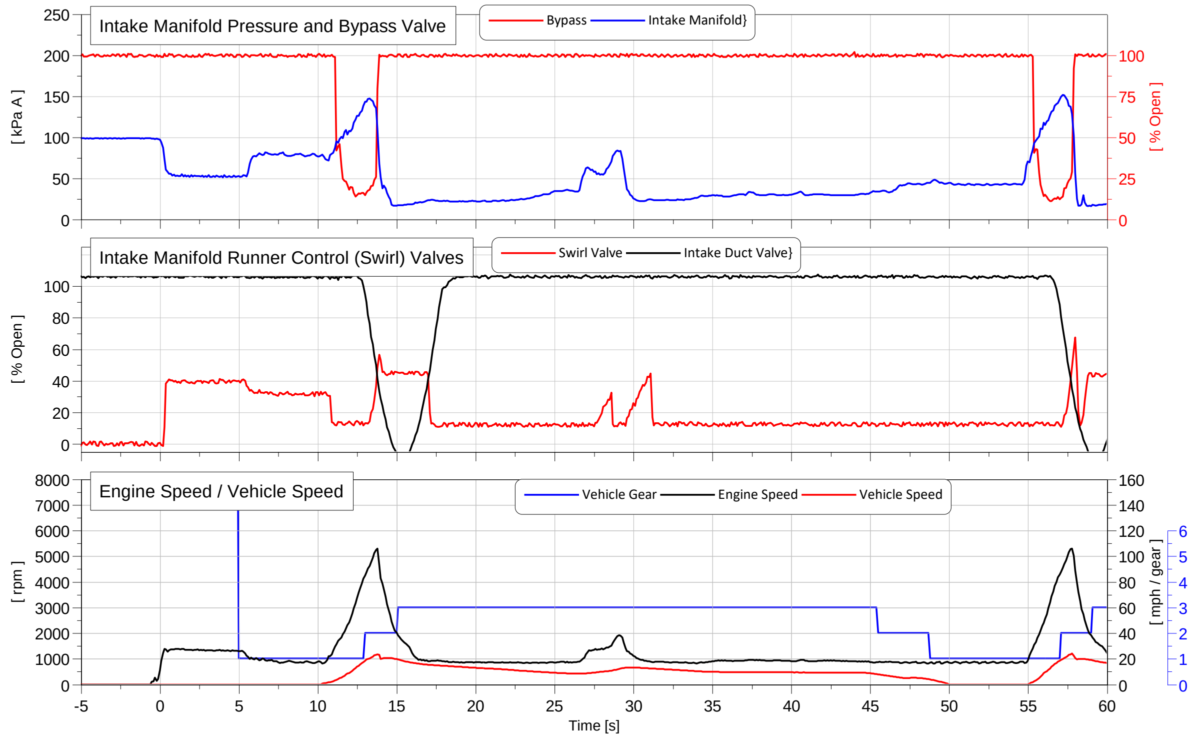

Figure 17. B0 TR2335A Test 1 Swirl Valve Control (middle plot)

It was observed and measured that for B0 TR2335A test fuel all three test iterations showed no driveability degradation as measured subjectively by the driver or objectively by the instrumentation. All test iteration combustion IMEP and accelerator plots are available in Appendix C. The engine management system cold start strategy and characteristics were noted and remained consistent across B0 TR2335A tests. They would be compared to results from later tests with the other test fuels. The engine management system's indication of closed loop air/fuel control, fuel injection strategy, fuel rail pressures, and ignition timing for catalyst heating were useful in understanding how the vehicle was reacting to test fuels.

For these three initial tests on B0 TR2335A fuel the spark plug sensors showed good agreement with the flush mount sensors for all the tests as shown in IMEP measurements in Figure 13 and 14. It was concluded that B0 TR2338A fuel did not cause the engine any combustion instability or concurrent driveability issues.

b. <u>C0 TR2338A Test Fuel Drive Cycle Analysis and Results</u>

Following B0 TR2335A test fuel, the vehicle fuel was drained using the developed drain and test prep procedure outlined in Figure 4 and C0 TR2338A test fuel was introduced.

Similar results were obtained for C0 TR2338A test fuel with the vehicle having no issues driving and coping with the high DI hydrocarbon C0 TR2338A test fuel. During the first test on C0 fuel no significant driveability degradation was measured, Figure 19 below, or had any noted subjective driver feedback. Again, engine start up times, and combustion stability was similar to B0 TR2335A testing.

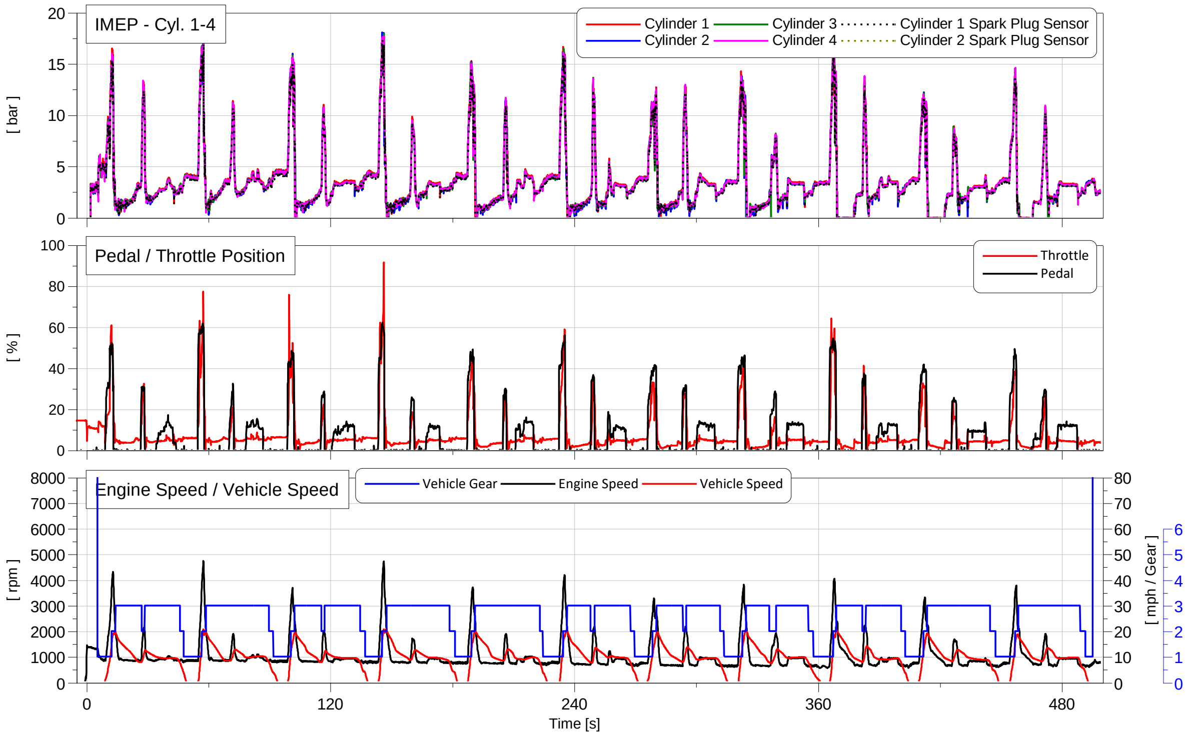

Figure 18. C0 TR2338A Test 1 entire drive cycle combustion IMEP overview

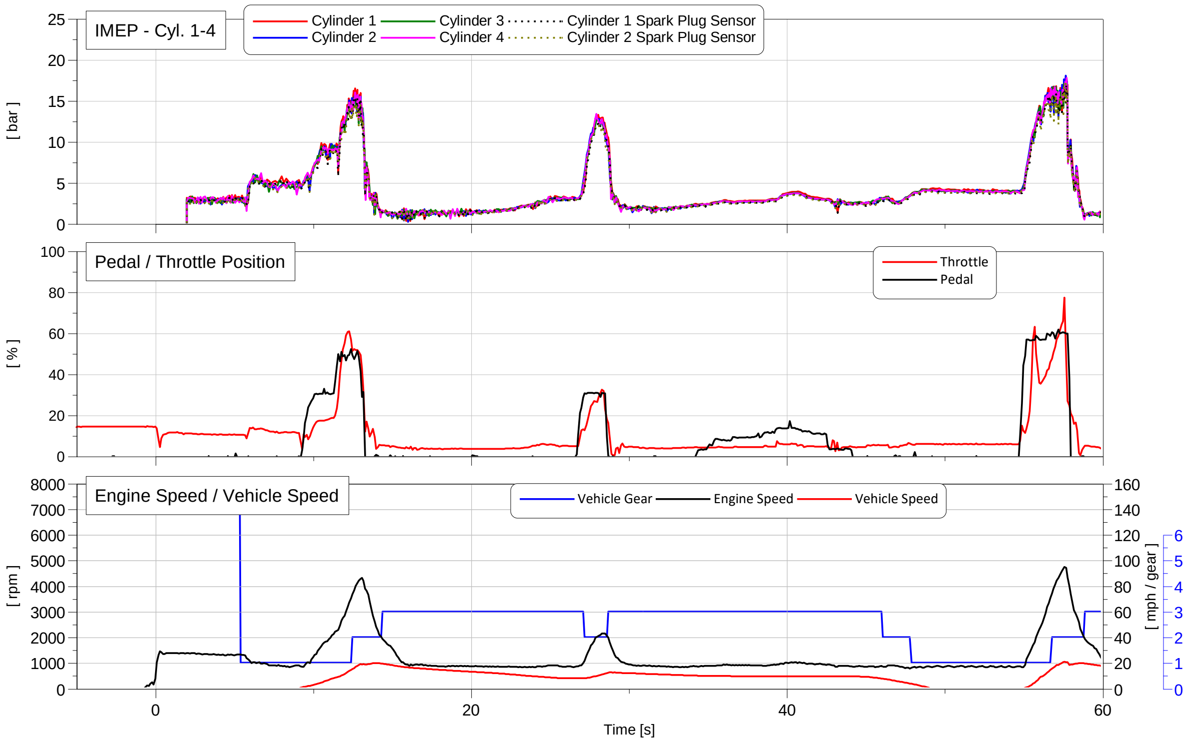

Figure 19. C0 TR2338A Test 1 combustion IMEP cold start initial drive away close up

The same cold start controls were observed in the instrumented data with consistent fueling, ignition and air path control strategies between B0 and C0 fuels indicating no notable controls adaptions being implemented.

After the three iterative tests on C0 TR2338A fuel it was decided, as a precaution, to check on all spark plugs for any signs of fouling or carbon build up from poor combustion events or rich air fuel conditions. This precaution is taken after the findings in the previous study which showed that the spark plugs could potentially become fouled as a result of a high DI fuels testing which can cause poor combustion events that in turn cause spark plug fouling and compound driveability degradation.

In agreement with the measured combustion data for B0 TR2335 and C0 TR2338A fuel which measured no significant poor combustion events, such as misfires, or prolonged rich air/fuel control the spark plugs were noted to not have any significant carbon build up or signs of fouling, Figure 20. Nonetheless, they were lightly cleaned and reinstalled.

Overall conclusions for C0 TR2338A fuel was that the vehicle did not react adversely to the fuel and experience any driveability degradation and that there was no significant difference in comparison to B0 TR2335A.

Figure 20. Spark plug inspection following C0 TR2338A Testing

c. <u>CE15 TR2339A Test Fuel Drive Cycle Analysis and Results</u>

The next test fuel was CE15 TR2339A fuel which is C0 TR2338A fuel splash blended with 15% ethanol by volume. This vehicle is only rated for E10 or 10% ethanol blended gasoline fuel. Similar to the previous two fuels this fuel did not produce any driveability degradation on the vehicle either subjectively or with objective instrumented measurements for all three iterative tests. Figure 21 shows the first test combustion IMEP stable and responsive to driver accelerator pedal input. However, it was noted that fueling during open loop cold start was leaner than with previous fuels and that once closed loop air/fuel control was reached, the fuel trim corrections indicated that the engine management system was reacting to the ethanol blended fuel and was compensating for lean conditions resulting from it. Figure 22 shows the differences in cold start Lambda between CE15 TR2339A fuel and C0 TR2338A fuel. It is noted that CE15 cold start open loop fueling (first 0-7 seconds) is leaner and that once fuel trim corrections are enabled (closed loop operation) CE15 short term fuel trims are positive, indicating a correction of lean air fuel conditions, Figure 22. This open loop delay in fueling corrections is a result of the OEM O2 sensor warm up and activation time and is common for gasoline engines.

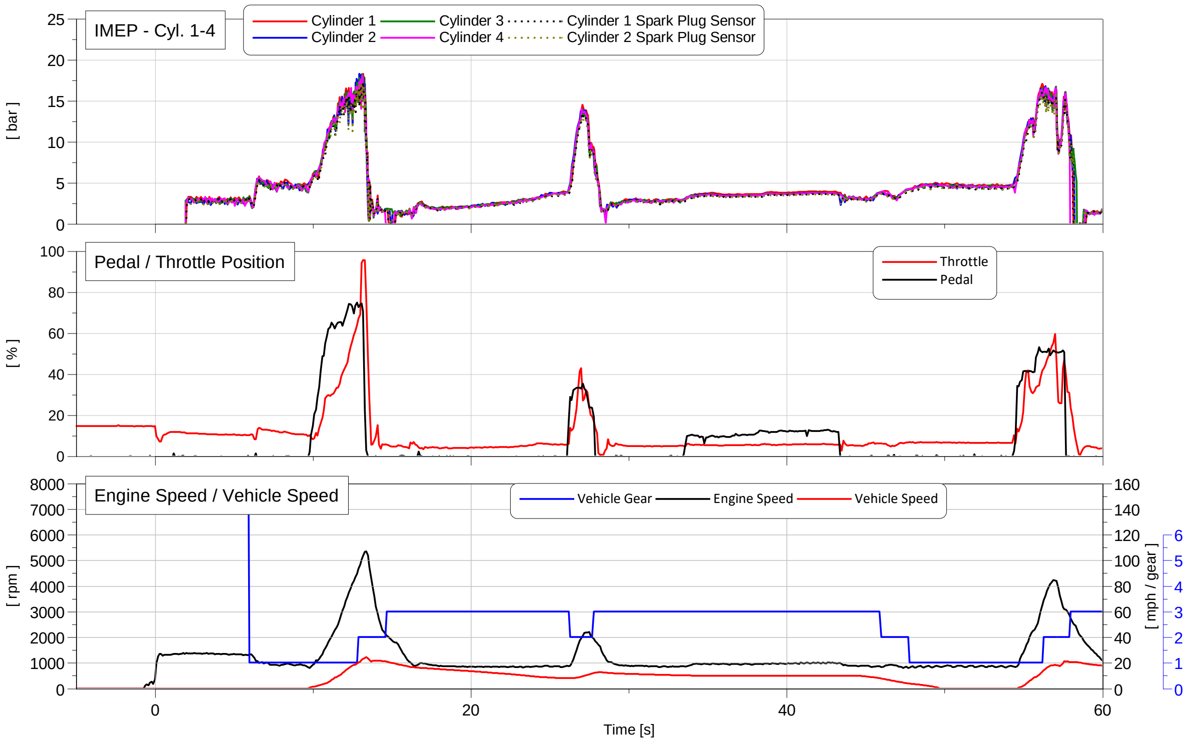

Figure 21. CE15 TR2339A Test 1 Cold start Drive away

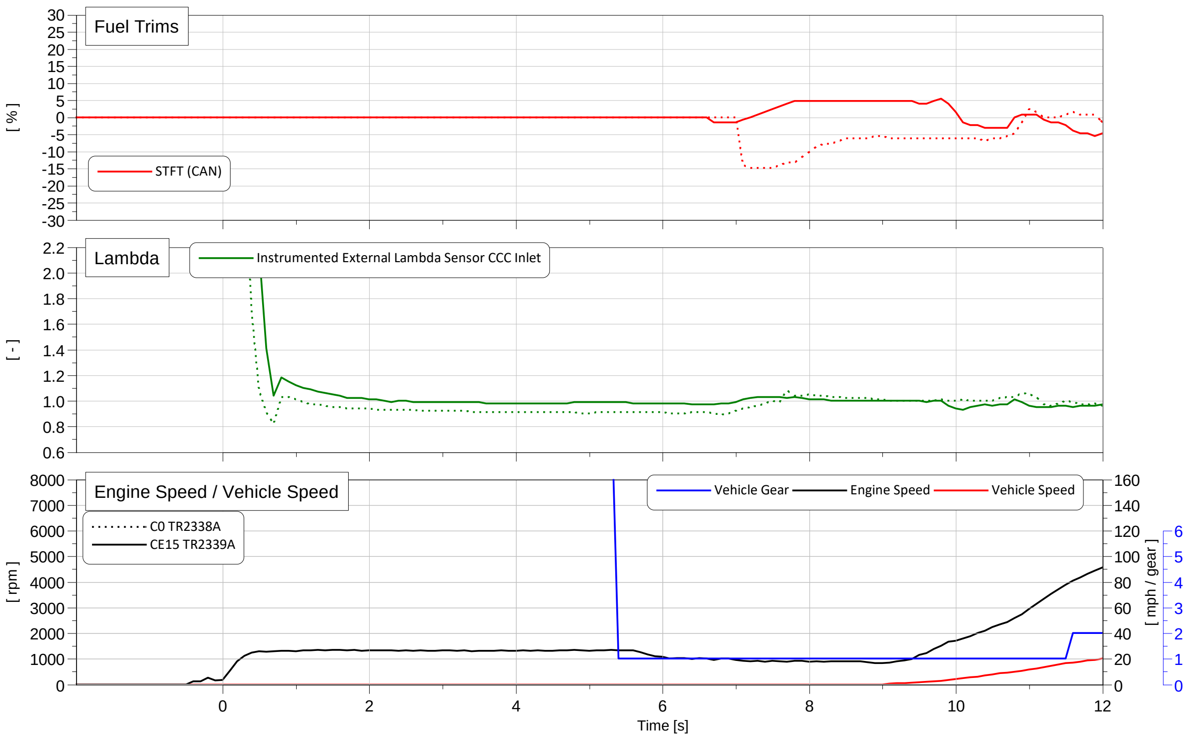

Figure 22. CE15 TR2339A cold start air/fuel Lambda measurement comparison to C0 TR2338A

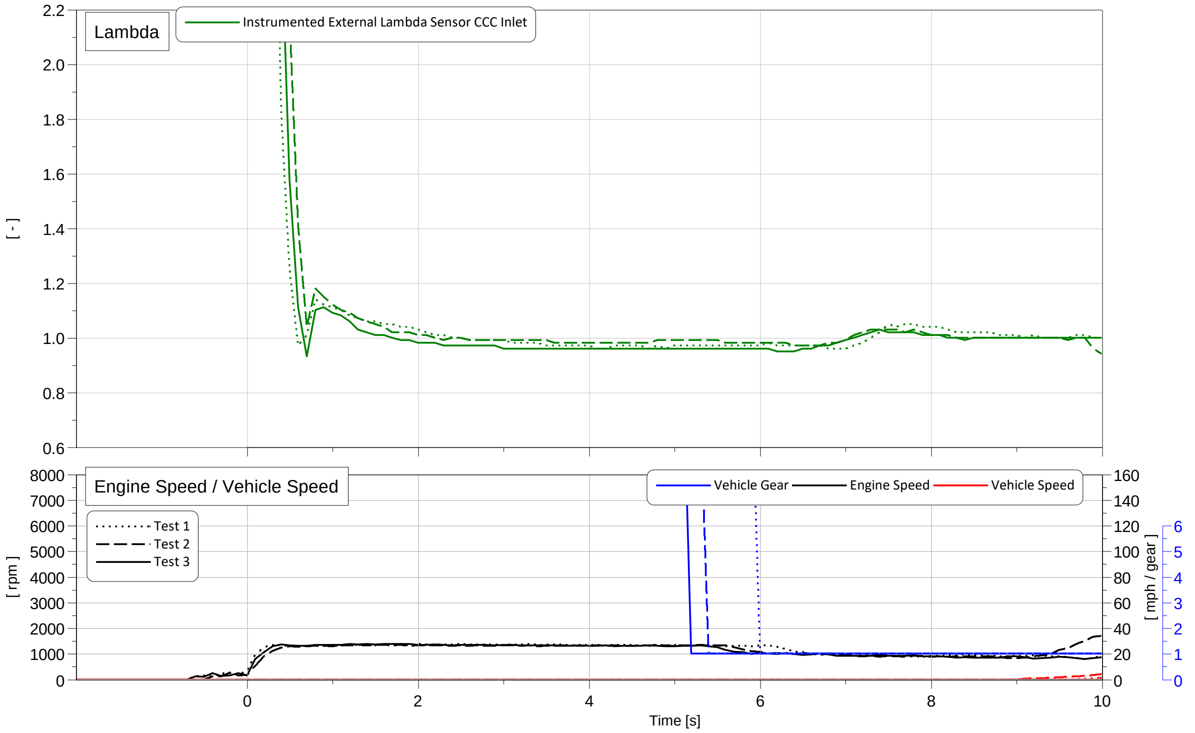

Figure 23. CE15 TR2339A All three-test cold start air fuel lambda comparison

By the third and final test on CE15 there was still no notable degradation of driveability and it was observed that the cold start open loop fueling was richer indicating that the engine management implementing and storing adaptations to the open loop cold start fueling to compensate for the ethanol blended fuel. Figure 23 above shows an overlay of air/fuel Lambda for all three tests on CE15 TR2339A fuel. It is observed how the third and final test iteration has an air/fuel lambda that is richer and closer to that observed on the base blend stock and hydrocarbon fuel C0 TR2338A (0.9 Lambda).

d. <u>CE30 TR2340A Test Fuel Drive Cycle Analysis and Results</u>

The final fuel was CE30 TR2340A fuel or a 30% volume splash blended ethanol fuel. The first test resulted in no measurable or subjective driveability degradation as shown in Figure 24. Engine start up time was less than 1 second, consistent with all other fuels testing, and the cold start up idle and shift to drive was stable as made visible in the IMEP data in Figure 24 and 25. This is comparable to the rest of the test fuels and does not show any significant driveability differences in comparison. The drive away also produced consistent and linear IMEP engine output that becomes power and torque at the wheel and is felt by the driver as adequate and linear or proportional vehicle response.

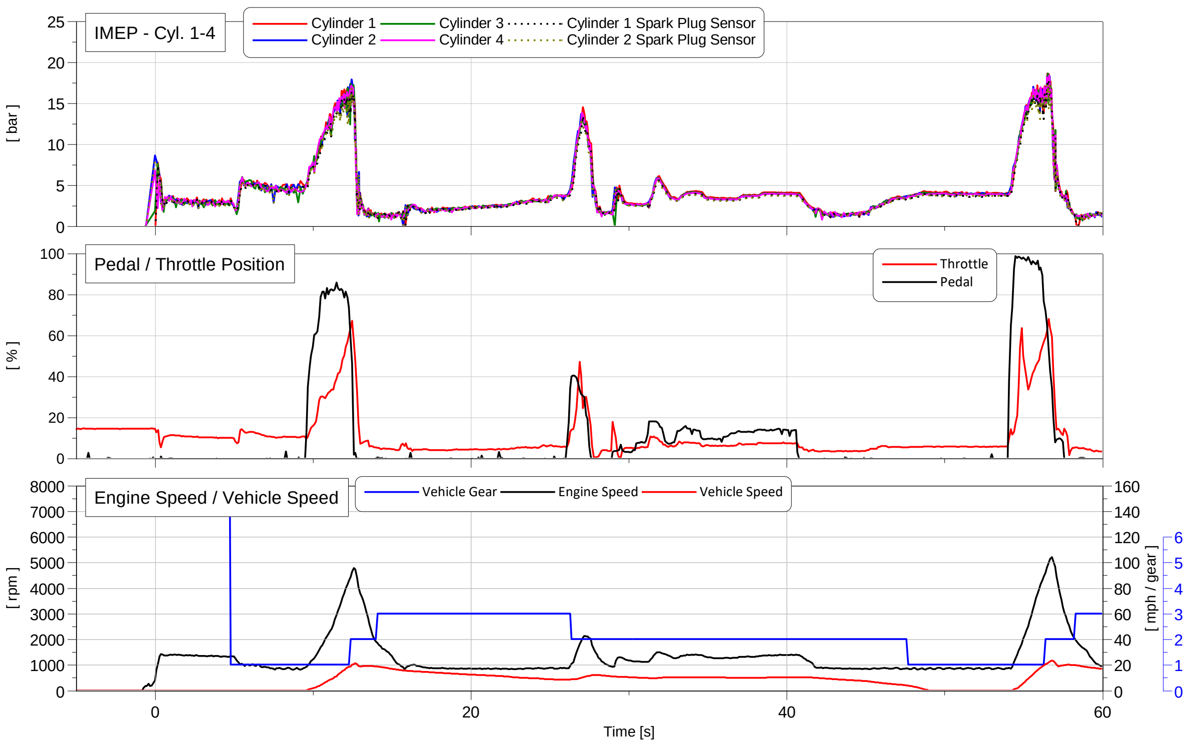

Figure 24. CE30 TR2340A Test 1 Cold Start and Drive Away

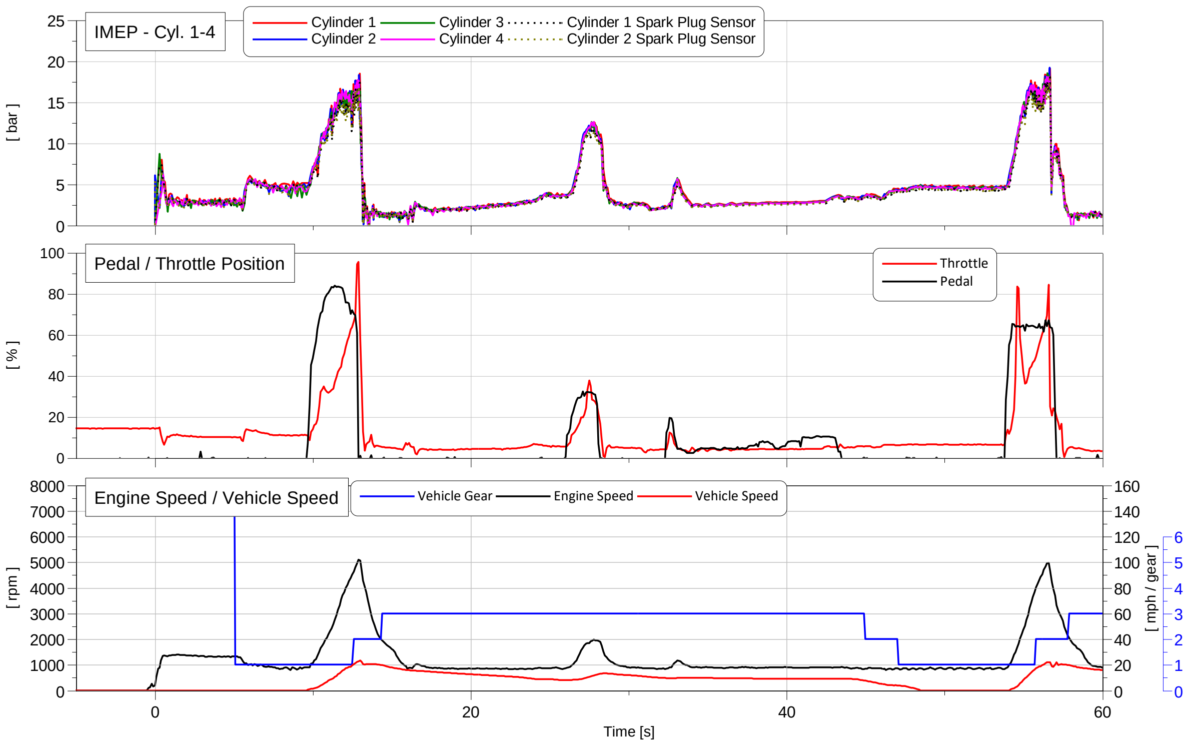

Figure 25. Third test CE30 TR2340A Cold Start and Drive away

The engine management system showed significant long-term fuel trim corrections in response to the 30% ethanol blended fuel, a fuel for which the vehicle is not designed for. This indicates that the engine management system is correcting for lean air/fuel conditions caused by the ethanol blended fuel. A consistent and positive Long-Term Fuel Trim was observed early in the first CE30 test, evidence for carry over adaption from the baseline drive cycle at 75°F. Figure 26 below shows the first CRC drive cycle test at 40°F conducted on CE30 and the resulting high positive Long-Term Fuel Trims (LTFT).

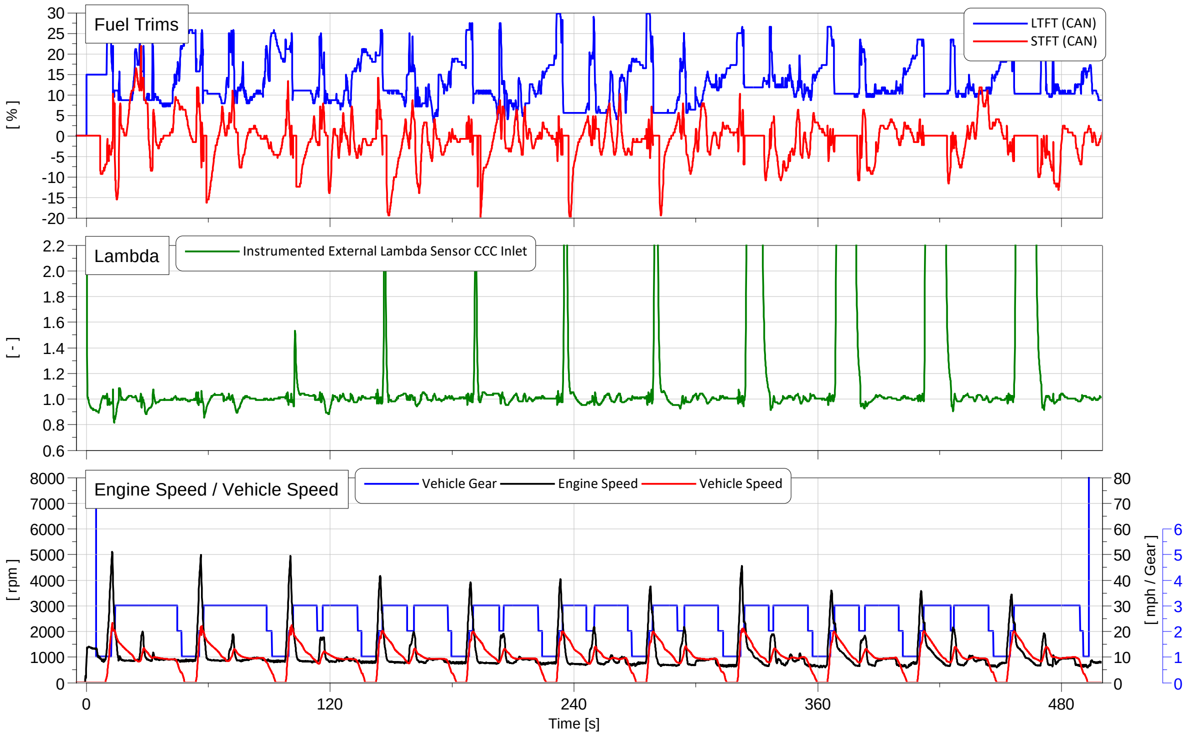

Figure 26. CE30 TR2340A Fuel Test 1 Fuel Trim and Lambda Overview

A comparison of Long-Term fuel trim adaptions across CE15 TR2339A and CE30 TR2340A fuels shows by the third test that the engine management system is compensating for the ethanol content at double the test cycle Long-Term fuel trim averaged correction percentage with CE30 compared to CE15 (+12.36% vs. +6.94%) which agrees with the ethanol content volume difference, Figure 27. This comparison is done on the third test as this is when the engine management system has had two previous tests and a baseline cycle to adapt and store Long-Term fuel trim corrections. The Long-Term fuel trim is averaged across the drive cycle for the third test giving a representative Long-Term fuel trim correction for that test fuel.

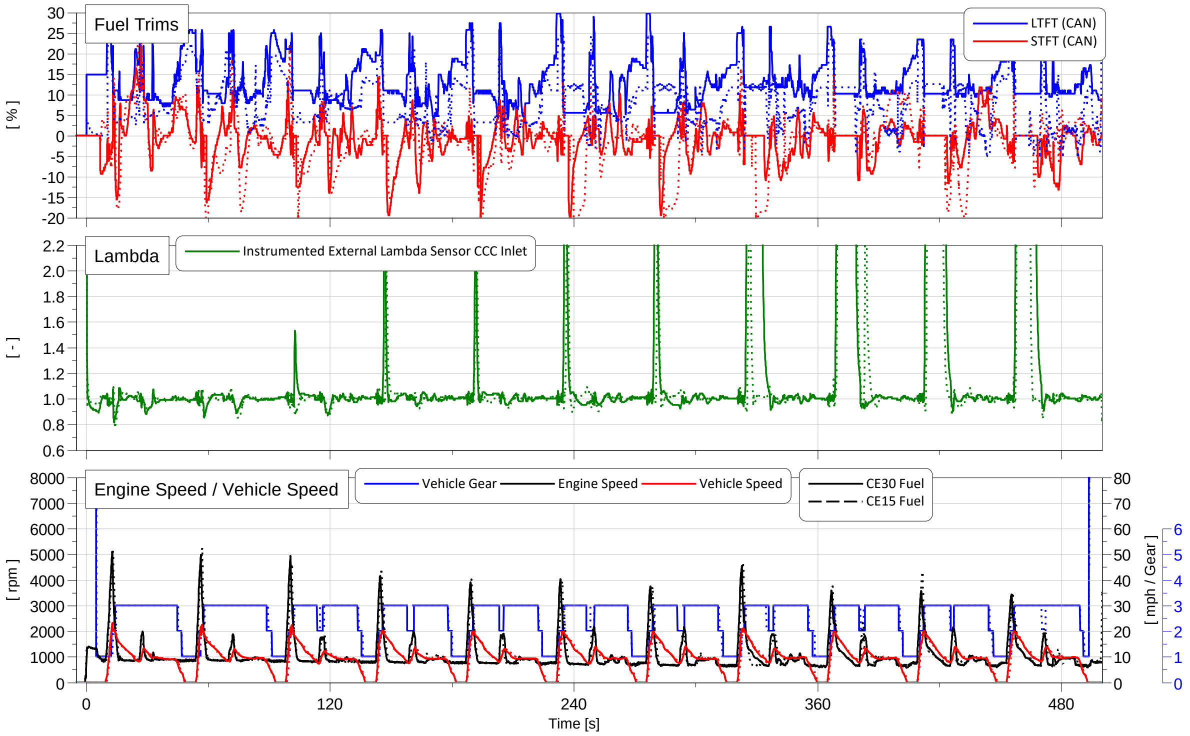

Figure 27. Third Test Iteration Fuel Trim Comparison across CE15 TR2339A and CE30 TR2340A Fuel

For comparison purposes Figure 28 below shows the fuel trim comparisons across CE30 TR2340A and C0 TR2338A fuel on the first CRC drive cycle test when the vehicle is first reacting to the fuels at 40 °F ambient and vehicle soak temperature. The base blend stock hydrocarbon fuel, C0 TR2338A, has a resulting drive cycle averaged Long-Term fuel trim of +0.24% while CE30 TR2340A fuel has an averaged Long-Term fuel trim correction of +11%, Figure 28.

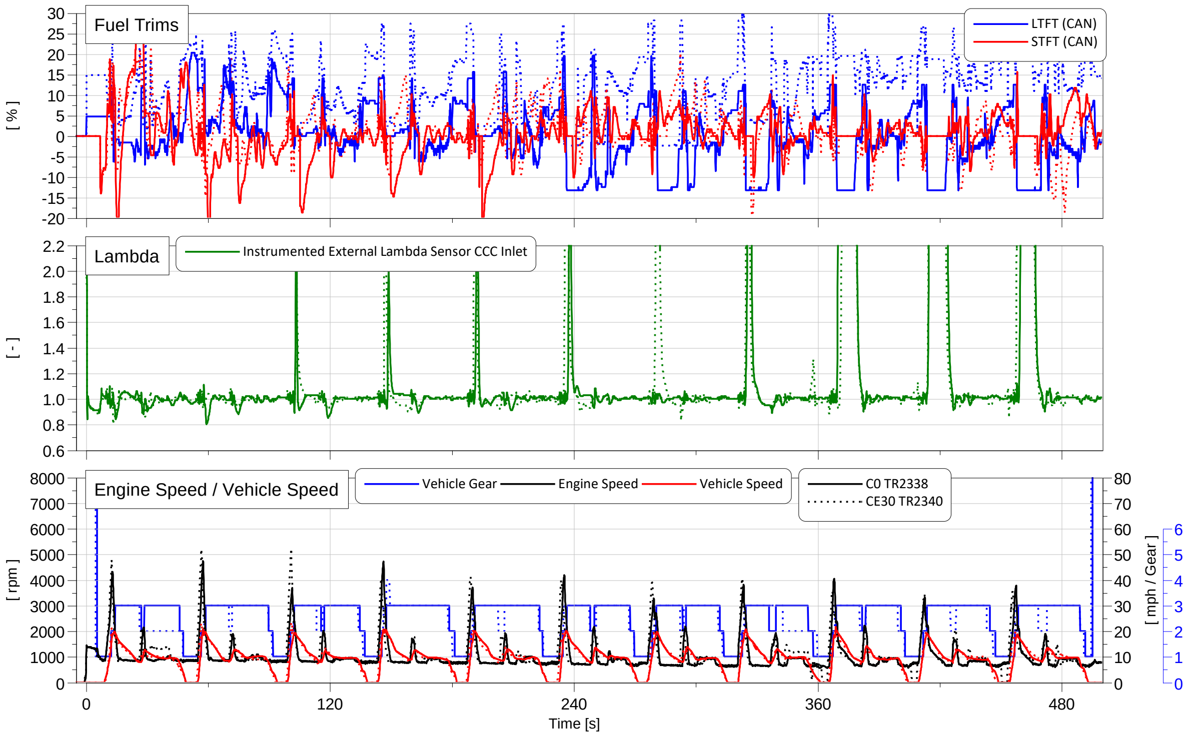

Figure 28. CE30 TR2340A Fuel Trim Comparison to Blend stock Fuel C0 TR2338A

Cold start fueling on the first CE30 TR2340A test was anticipated to have lean conditions similar to CE15 TR2339A due to the high ethanol content but the measured CE30 TR2340 cold start air/fuel Lambda was not lean and was similar to B0 TR2335A and C0 TR2338A test fuels tested earlier, Figure 29 below. This can be attributed to carryover Long-Term fuel trim adaptions from the baseline prep FTP74 drive cycle ran at 75°F prior to the 40°F CRC drive cycle. It is noted that only CE15 TR2339A cold start open loop fueling (0-8 seconds) had an en-leanment effect caused by the ethanol blended fuel. This can be attributed to variation in the stored fueling adaptions as measured by the stored Long-Term fuel trims at the start of the first CRC drive cycle test at 40°F. The CE30 test fuel was able to adapt and store fueling corrections during the FTP74 baseline prep cycle ran at 75°F a day prior to cold soak storage and CRC test cycle testing. During cold start open loop fueling the stored Long-Term fuel trim value for CE30 TR2340A is at +15% compared to 0% for CE15 TR2339A fuel. The CE15 test did not have a stored Long-Term fuel trim adaption from the baseline prep cycle, Figure 29. This indicates some variation in the engine controller’s ability to adapt and store fueling corrections to combustion stoichiometry with the ethanol blended fuels.

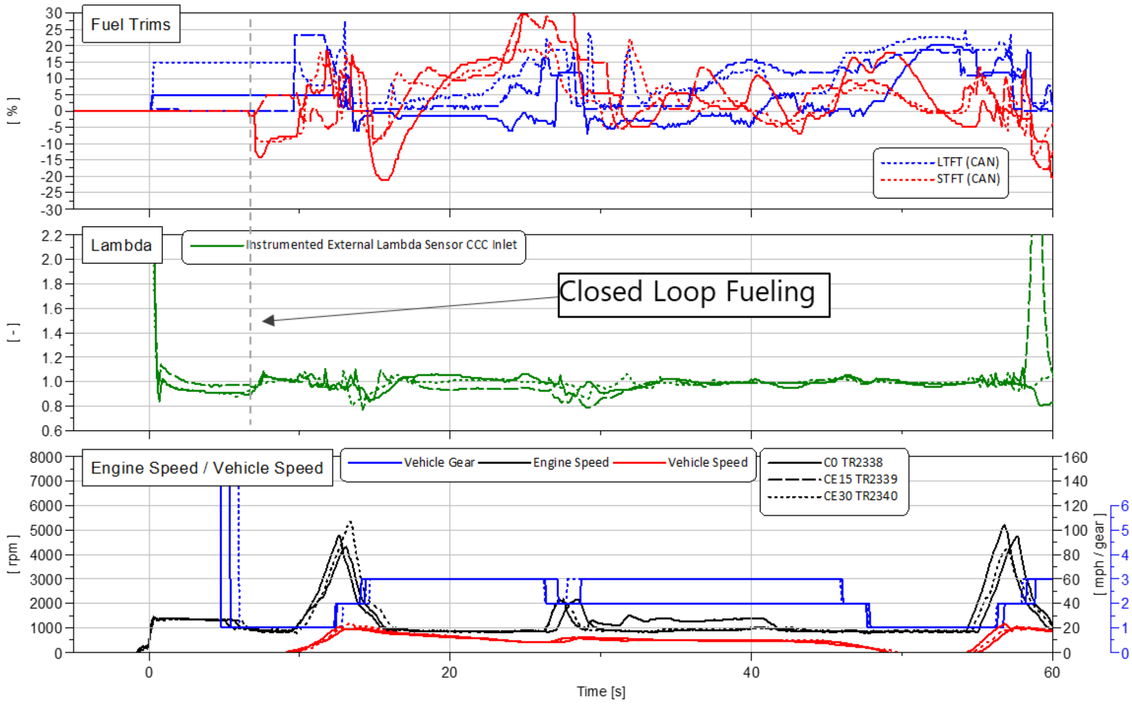

Figure 29. Cold start Air/Fuel Lambda Measurement Test 1 Comparisons across C0 TR2338 based fuels

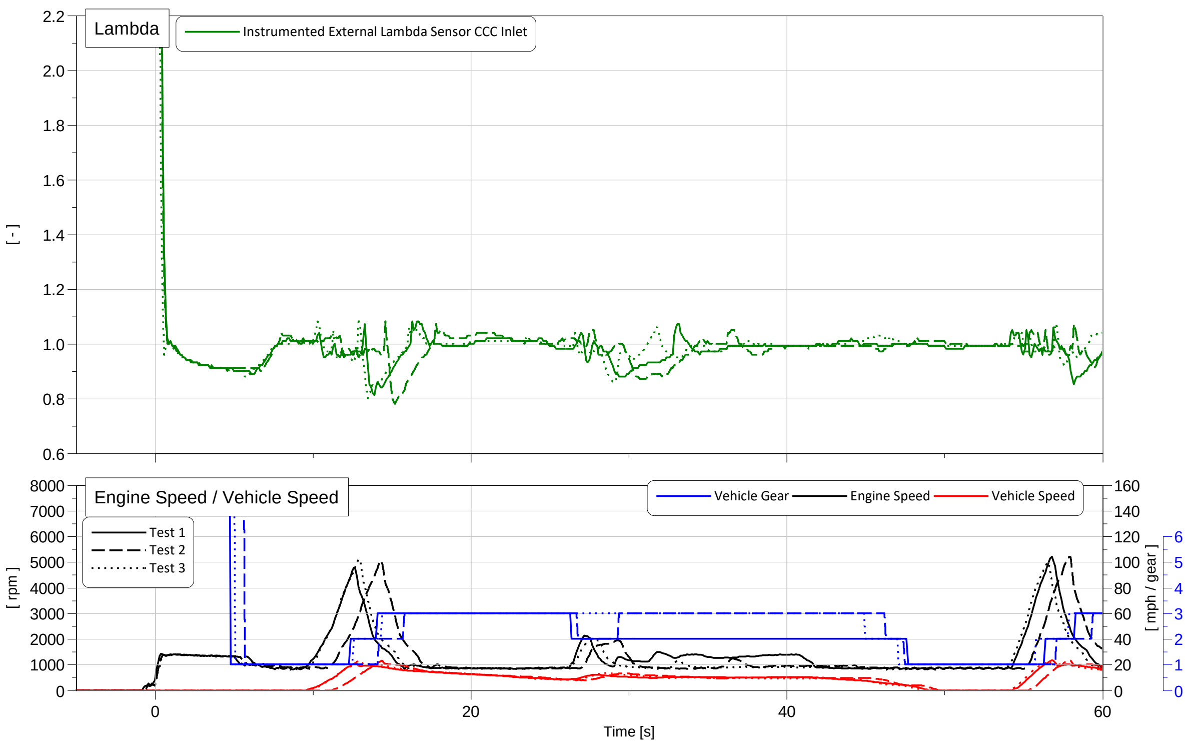

Figure 30. CE30 TR2340A Cold start Air/Fuel Lambda Measurements all three-test iteration comparison

Figure 30 above shows consistent cold start air/fuel lambda across all three test iterations conducted on CE30TR2340A fuel, further suggesting that the engine management system was well adapted to the CE30 TR2340A test fuel by the start of the 1st cold test at 40 °F.

In summary for CE30 TR2340A fuels testing the Mazda vehicle did not display any combustion instability or driveability degradation but there were significant long-term fuel trim corrections in reaction to the high ethanol content of the fuel. A closer look at the baseline prep FTP74 cycle ran at 75°F between CE30 and CE15 fuel shows that CE30 cold start open loop fueling is lean while CE15 fuel is not, circled in Figure 31 below. This indicates that the engine management system was able to store and implement Long-Term fuel trim corrections from the lean CE30 cold start during the baseline prep for the following CRC drive cycle testing conducted at 40°F.

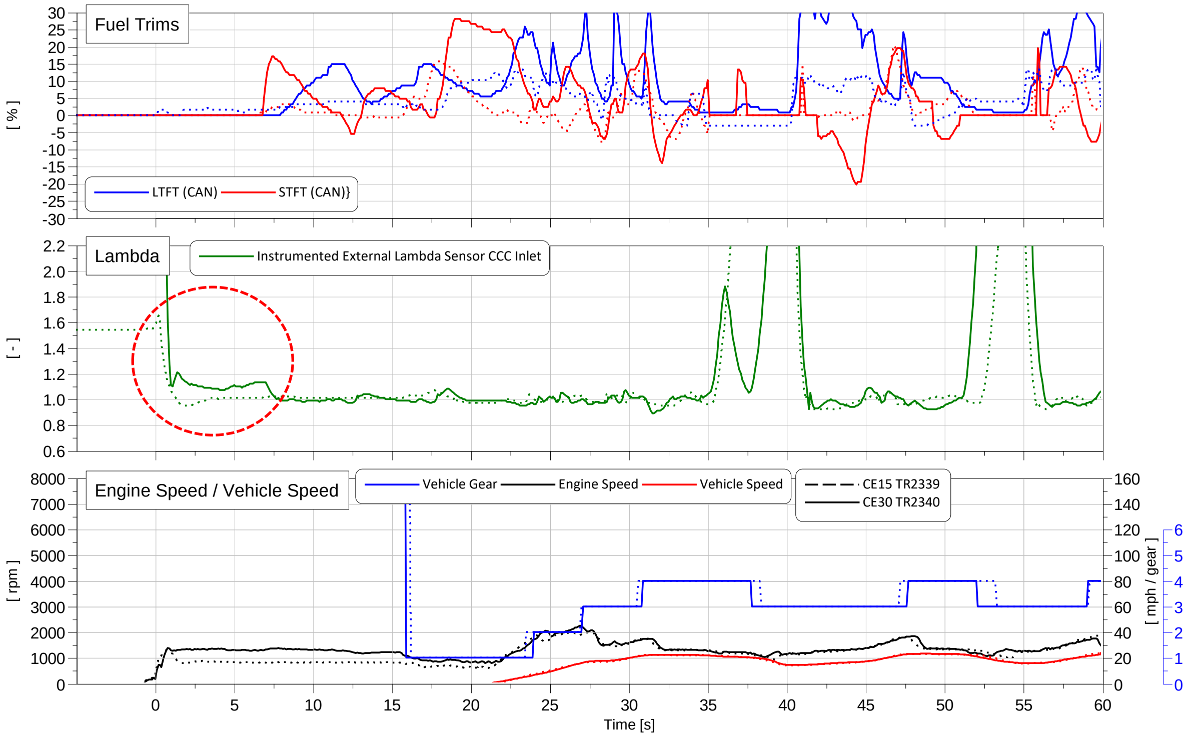

Figure 31. CE30 TR240A and CE15TR2339A Baseline FTP74 Prep Cold Start Lambda Comparison

VIII. **Summary and Conclusions**

This study was done to supplement the previous study CM-138-15-2 and determine the feasibility and accuracy of spark plug combustion pressure sensors as a replacement for the previously used in-cylinder flush mount pressure sensors. The results suggest that for the purposes of driveability and vehicle performance evaluation the spark plug combustion sensors can be a good alternative to the more complex and higher cost flush mount in-cylinder pressure sensors. This vehicle application had unique engine features and did not render any combustion instability or driveability degradation across all test fuels, something not encountered with previous vehicles. Subsequently, a comparison of combustion readings with fuel induced combustion instability was not captured and compared. Although the data supports that both combustion sensors compare well with each other, testing with another vehicle that features more common engine technologies may render a better comparison of fuel induced combustion instability and driveability degradation between the two instrumented combustion sensors (flush mount and spark plug type).

CRC high DI fuels testing on the European Spec. 2020 Mazda 3 SkyActivX 2.0L Gasoline vehicle provided insight into the resilience this engine has to all of the high DI CRC test fuels. In the previous study which looked at three USDM mass market vehicles with more conventional gasoline engine powertrains, all vehicles exhibited some level of driveability degradation caused by the test fuels. This vehicle proved to be largely unaffected by the test fuels as evidenced by the consistent engine start up times of less than 1 second, stable combustion at cold start idle, no recorded misfires for any of the test fuels or high IMEP variation, consistent and steady combustion IMEP in response to driver accelerator pedal input during the cold start drive away and all subsequent operation for the rest of the drive cycle.

It is theorized and supported by published Mazda technical literature that the unique combustion system of the Mazda engine which features centrally mounted direct injectors with very high fuel rail pressures (600 bar) coupled with the engaged swirl flaps in the intake manifold runners render very good fuel atomization, air fuel mixture and subsequent combustion. This may make the engine very resilient to high DI volatility test fuels. It is also worth mentioning that the engine features its own in cylinder combustion sensors that provide combustion information to the Mazda engine management system. FEV North America did not instrument and or alter these sensors as a precaution because they may be highly sensitive to alteration and instrumenting them might have affected their resolution and signal information. It may be that these sensors are primarily for knock detection and knock suppression strategy due to the high compression ratio of the engine and its strong tendency to knock. The engine does not have conventional knock sensors featured in other gasoline engines, and therefore must use the in-cylinder pressure sensors for knock detection and suppression. Having these sensors may also help this engine cope with varying test fuels but this is not certain. The measured and analyzed test data primarily shows fueling adaptations from the Long-Term Fuel Trims in reaction to the ethanol blended fuels and the resulting change in combustion stoichiometry. This would be stored information gathered from the engine’s primary oxygen sensor. There were not any other engine management control differences detected between the test fuels.

The comparisons between the instrumented spark plug pressure sensors and in-cylinder flush mount sensors show good agreement. However, on this application that rendered no significant combustion instability and driveability degradation, a comparison of fuel induced combustion degradation was not possible in this study.

IX. Recommendations

This study allowed for a detailed examination of the European 2020 Mazda 3 SkyActivX gasoline vehicle and its reaction to neat and ethanol blended CRC high DI test fuels. The study also showed that the spark plug combustion sensors provide results very similar to in-cylinder flush mount combustion sensors. Although the data between combustion sensors compares well there was no fuel induced combustion instability that caused driveability degradation and a more conclusive study may be merited with another vehicle application that will exhibit fuel induced driveability degradation and allow for comparisons across sensors with poor combustion events caused by the test fuels.

The advantages of using the spark plug sensors for future studies are that it will make machining and replacing the cylinder head(s) unnecessary hence making vehicle instrumentation/restoration much easier and less costly. Although spark plug transducer instrumentation and complexity will vary according to vehicle application this may be a favorable approach for future CRC fuels performance studies. The following is a reduced list of instrumented, modified systems, and measured signals that are important for this type of fuels performance study using the spark plug sensors. Many of the time based data acquisition measurements can be captured via the OBDII CAN Bus with the exception of exhaust air fuel measurement, which requires a standalone unit that can be warmed up and operational prior to engine start, however CAN Bus update rates may limit measurement resolution. It is important to note that this list may vary slightly depending on vehicle application:

Combustion Analysis System with Crank angle Encoder (1 deg resolution)

- Spark plug combustion sensors (all cylinders)
- Fuel injection timing and duration all cylinders (degrees crank angle ATDC)
- Ignition timing all cylinders (Degrees crank angle ATDC)

Time based Data acquisition system with discrete measurements to include:

- Fuel Pressure (DI system and low pressure supply system) (Bar/kPa)
- Ambient air temperature (°C)
- Engine coolant in/out temperature (°C)
- Engine oil sump temperature (°C)
- Exhaust Turbine Inlet/Outlet and Catalyst temperatures (°C)
- Ambient air pressure (kPa Absolute)

- Intake manifold pressure (kPa Absolute)
- Stand-alone exhaust air fuel measurement (Wideband O2 sensors installed next to OEM O2 sensor) (reported unit is Lambda) (must be discrete instrumentation to capture cold start air fuel measurement while OEM sensor is not warmed up).
- Accelerator Pedal position (%)
- Throttle position (% Open)
- Fuel Tank Quick Drain at lowest collection point. May require two with saddle tank design. (vehicle modification)
- Low pressure fuel line quick drain (vehicle modification)
- High pressure fuel line quick drain (vehicle modification)
- OBD-II CAN measurements (exclusively):
  - Short/Long-term Fuel Trims (%)
  - Target Air/Fuel Ratio
  - Commanded EGR% (if applicable)
  - Transmission Gear State

X. **Acknowledgements**

This program would like to thank the following contributors for all their hard work and participation:

- CRC CM-138-19 Members and Panel
- Coleman Jones
- Veronica Akers and General Motors Fuel Analysis Team
- FEV North America Vehicle Development Center Team
- Frank Richardson

XI. **References**

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2.) Eiji, Nakai, et al. *MAZDA SKYACTIV-X 2.0L Gasoline Engine* . 28th Aachen Colloquium Automobile and Engine Technology 2019, 2019.

3.) Mazda Motor Corporation. (2019). METHOD FOR PREDICTING KNOCK ,METHOD FOR SUPRESSING KNOCK , AND ENGINE SYSTEM (U.S. Patent No. 16 / 253,795). U.S. Patent and Trademark Office.

Definitions/Abbreviations

AKI – Anti Knock Index

ATDC- After Top Dead Center

CA50 – Combustion 50% Mass Fraction Burn Location

CAN – Controller Area Network

CRC – Coordinating Research Council

DI – ASTM 4814D Fuel Driveability Index

DTC – Diagnostic Trouble Code

E10 – 10% Ethanol by volume gasoline fuel blend

ECU – Engine Control Unit

EGR – Exhaust Gas Recirculation

Fouling – Excessive carbon and soot build up on spark plug electrode tip causing improper spark arc

FTP74 – U.S. Federal Emissions Drive Cycle Segment

GPF – Gasoline Particulate Filter

IMEP – Indicated Mean Effective Pressure (combustion parameter)

ISG – Integrated Starter Generator

Lambda – Air Fuel Ratio as a function of Stoichiometric Ratio (1.0 = Stoichiometric ratio)

LTFT – Long-term Fuel Trims

OEM – Original Equipment Manufacturer

O2 – Oxygen

OBD – On Board Diagnostic (system)

RON – Research Octane Number

STFT – Short Term Fuel Trims

SPCCI – Spark Controlled Compression Ignition

USCAR – United States Council for Automotive Research

USDM – United States Domestic Market

Appendix

Appendix A: Fuel Inspection Sheets

Table A-1
2016-18 CRC Study E0 Fuels Resupply Reblended Fuels

Fuel Code			B0TR2335A				
Laboratory			Gage	Chevron	MPC	BP	Average
Property	ASTM Test Method	Units					
API Gravity@60°F	D1298/D287	API	52.8	51.4	52.3	52.5	52.2
Density @ 15°C		kg/L	0.7679	0.7735	0.7698	0.7689	0.8
Research Octane Number	D2699	RON	96.6	96.4	96.1	90.9	95.0
Motor Octane Number	D2700	MON	85.2	85.0	84.7	80.7	83.9
Antiknock Index, (R+M)/2	D2699/D2700	AKI	90.90	90.7	90.4	85.80	89.5
Sensitivity							
Ethanol Content	D5599	vol %	0	0	0	0	0.0
DVPE Vapor Pressure	D5191	psi	8.43	8.1	8.25	8.17	8.2
Temperature V/L=20 (TVL20)	D5188	°F				144.8	144.8
Temperature V/L=20 (TVL20) Calculated	D4814						
Sulfur Content	D2622/D7039	ppm		<5			
FIA (uncorrected)	D1319						
Saturates		vol %	50.10	52.80		51.40	51.4
Aromatics		vol %	39.50	36.90		41.00	39.1
Olefins		vol %	10.4	10.00		0	6.8
FIA (corrected for oxygenates)	D1319						
Saturates		vol %					
Aromatics		vol %					
Olefins		vol %					
Benzene	D3606	vol %					
D86 Distillation	D86						
Initial Boiling Point		°F	91.8	90.3	90.8	90.1	90.8
5% Evaporated		°F	114.5	111.2		112.5	112.7
10% Evaporated		°F	126	124.2	125.4	124.0	124.9
20% Evaporated		°F	144.2	142.9	145.3	143.7	144.0
30% Evaporated		°F	164.5	164.5	165.8	164.4	164.8
40% Evaporated		°F	195.1	195.1	196.6	196.2	195.8
50% Evaporated		°F	240.9	240.8	244	243.6	242.3
60% Evaporated		°F	280.4	280.0	282.8	281.7	281.2
70% Evaporated		°F	305.9	305.3	308	306.3	306.4
80% Evaporated		°F	334.5	333.0	334.2	334.3	334.0
90% Evaporated		°F	364.9	363.7	365	364.3	364.5
95% Evaporated		°F	379.8	379.1	381.5	381.3	380.4
Final Boiling Point		°F	411.7	416.1	415.7	415.9	414.9
Recovered		vol %	97.5	96.7	97.9	97.5	97.4
Residue		vol %	1.1	1.1	0.9	1.1	1.1
Loss		vol %	1.4	2.2		1.4	1.7
Driveability Index Uncorrected	D4814	°F	1276.7	1272.4	1285.0	1281.1	1278.8

Table A-1 Cont'd.
2016-18 CRC Study E0 Fuels Resupply Reblended Fuels

Fuel Code			C0 TR2338A				
Laboratory			Gage	Chevron	MPC	BP	Average
Property	ASTM Test Method	Units					
API Gravity@60°F	D1298/D287	API	53.4	52.3	53.2	53.4	53.1
Density @ 15°C		kg/L	0.7653	0.7700	0.7661	0.7652	0.767
Research Octane Number	D2699	RON	97.0	96.4	95.9	92.8	95.5
Motor Octane Number	D2700	MON	86.3	85.3	85.3	82.1	84.8
Antiknock Index, (R+M)/2	D2699/D2700	AKI	91.70	90.9	90.6	87.40	90.1
Sensitivity							
Ethanol Content	D5599	vol %	0	0	0	0	0.0
DVPE Vapor Pressure	D5191	psi	8.43	8.0	8.24	8.12	8.2
Temperature V/L=20 (TVL20)	D5188	°F		147.1		149.7	148.4
Temperature V/L=20 (TVL20) Calculated	D4814						
Sulfur Content	D2622/D7039	ppm		<5			
FIA (uncorrected)	D1319						
Saturates		vol %	59.00	60.00		55.90	58.3
Aromatics		vol %	34.90	31.90		36.00	34.3
Olefins		vol %	6.1	8.10		3.8	6.0
FIA (corrected for oxygenates)	D1319						
Saturates		vol %					
Aromatics		vol %					
Olefins		vol %					
Benzene	D3606	vol %					
D86 Distillation	D86						
Initial Boiling Point		°F	91.4	89.4	89.1	87.7	89.4
5% Evaporated		°F	113	109.0		113.0	111.7
10% Evaporated		°F	127.1	124.8	126.2	126.5	126.2
20% Evaporated		°F	150.1	148.2	150.4	150.4	149.8
30% Evaporated		°F	178	176.5	178.1	179.4	178.0
40% Evaporated		°F	219	216.6	220	221.6	219.3
50% Evaporated		°F	265.1	263.9	267.1	268.2	266.1
60% Evaporated		°F	291.3	289.8	293	292.9	291.8
70% Evaporated		°F	313.3	313.0	313.5	315.4	313.8
80% Evaporated		°F	339.7	338.5	339	340.1	339.3
90% Evaporated		°F	370	368.4	369	368.5	369.0
95% Evaporated		°F	382.4	381.8	382.2	382.6	382.3
Final Boiling Point		°F	412.8	411.1	413.2	414.7	413.0
Recovered		vol %	97.3	96.5	98	97.9	97.4
Residue		vol %	1.1	1.1	0.7	1.1	1.0
Loss		vol %	1.6	2.4	1.3	1.0	1.6
Driveability Index Uncorrected	D4814	°F	1356.0	1347.3	1360.0	1362.9	1356.5

Table A-1 Cont'd.
2016-18 CRC Study E15 Fuels Resupply Reblended Fuels

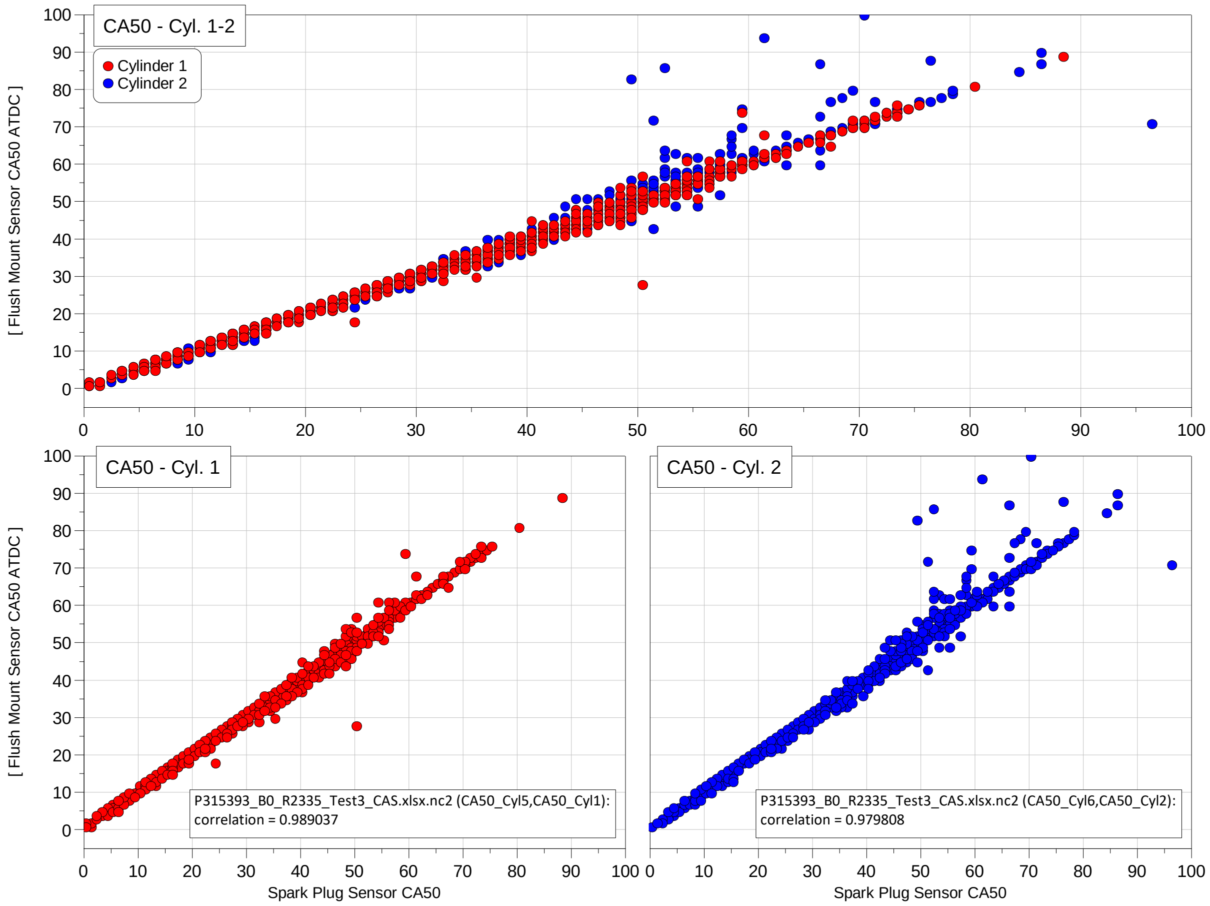
Fuel Code			CE15 TR2339A				
Laboratory			Gage	Chevron	MPC	BP	Average
Property	ASTM Test Method	Units					
API Gravity@60°F	D1298/D287	API	52.3	51.3	52.4	52.6	52.15
Density @ 15°C	D1298/D287	kg/L	0.7698	0.7739	0.7694	0.7684	0.7704
Research Octane Number	D2699	RON	100.6	100.4	100.5	97.9	99.9
Motor Octane Number	D2700	MON	87.6	87.7	87.6	84.2	86.8
Antiknock Index, (R+M)/2	D2699/D2700	AKI	94.1	94.1	94	91	93.3
Sensitivity	D2699/D2700						
Ethanol Content	D5599	vol %	15.08	15.28	14.1	15.2	14.9150
DVPE Vapor Pressure	D5191	psi	9.17	9.0	9.13	9.15	9.1125
Temperature V/L=20 (TVL20)	D5188	°F		131.8		132.2	132.0
Temperature V/L=20 (TVL20) Calculated	D4814			134.8			
Sulfur Content	D2622/D7039	ppm		<5			
FIA/DHA (uncorrected)	D1319/D6849						
Saturates		vol %					
Aromatics		vol %					
Olefins		vol %					
FIA (corrected for oxygenates)/DHA	D1319/D6849						
Saturates		vol %		51.5		49.2	50.4
Aromatics		vol %		26.3		30.9	28.6
Olefins		vol %		6.5		1.3	3.9
Benzene	D3606	vol %					
D86 Distillation	D86						
Initial Boiling Point		°F	95	93.2	93.6	90.3	93.0
5% Evaporated		°F	118.3	115.8		118.8	117.6
10% Evaporated		°F	128.3	125.8	128.7	128.8	127.9
20% Evaporated		°F	140.8	138.6	142.2	141.9	140.9
30% Evaporated		°F	150.8	149.5	152.2	152.0	151.1
40% Evaporated		°F	159.6	159.7		160.7	160.0
50% Evaporated		°F	182	176.1	179.1	187.6	181.2
60% Evaporated		°F	275.3	270.2		276.4	274.0
70% Evaporated		°F	302.1	303.4	303.1	303.4	303.0
80% Evaporated		°F	329.7	329.4		330.8	330.0
90% Evaporated		°F	363.1	363.9	364.5	364.6	364.0
95% Evaporated		°F	380.5	380	381.4	380.6	380.6
Final Boiling Point		°F	406.4	410	409.4	410.7	409.1
Recovered		vol %	97.2	96.8	97.9	98.0	97.5
Residue		vol %	1.1	1.1	0.8	1.1	1.0
Loss		vol %	1.7	2.1	1.3	0.9	1.5
Driveability Index Uncorrected	D4814	°F	1101.6	1080.9	1095	1120.6	1099.5

Table A-1 Cont'd.
2016-18 CRC Study E30 Fuels Resupply Reblended Fuels

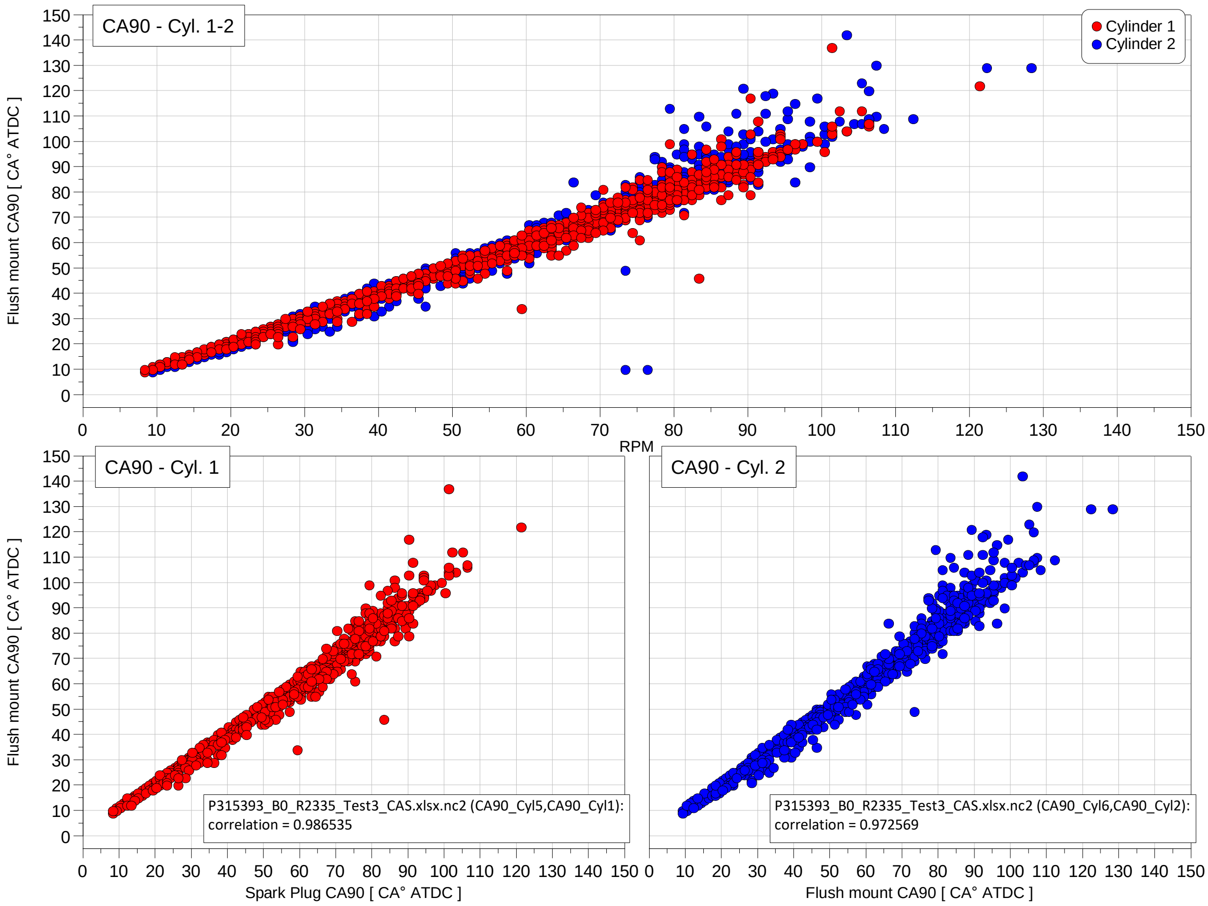
Fuel Code			CE30 TR2340A				
Laboratory			Gage	Chevron	MPC	BP	Average
Property	ASTM Test Method	Units					
API Gravity@60°F	D1298/D287	API	50.8	50.8	51.6	51.7	51.23
Density @ 15°C	D1298/D287	kg/L	0.776	0.776	0.773	0.7720	0.7743
Research Octane Number	D2699	RON		102.8	102.3	101.1	102.1
Motor Octane Number	D2700	MON		88.4	89.2	84.4	87.3
Antiknock Index, (R+M)/2	D2699/D2700	AKI		95.6	95.8	93	94.7
Sensitivity	D2699/D2700						
Ethanol Content	D5599	vol %	30.3	28.8	26.7	33.0	29.7
DVPE Vapor Pressure	D5191	psi	8.8	8.3	8.9	8.80	8.7
Temperature V/L=20 (TVL20)	D5188	°F		133.5		134.0	133.8
Temperature V/L=20 (TVL20) Calculated	D4814						
Sulfur Content	D2622/D7039	ppm					
FIA/DHA (uncorrected)	D1319/D6849						
Saturates		vol %					
Aromatics		vol %					
Olefins		vol %					
FIA (corrected for oxygenates)/DHA	D1319/D6849						
Saturates		vol %		43.6		45.4	44.5
Aromatics		vol %		21.4		27.4	24.4
Olefins		vol %		5.6		0.0	2.8
Benzene	D3606	vol %				0.0	0.0
D86 Distillation	D86						
Initial Boiling Point		°F	96.8		96.1	94.6	95.8
5% Evaporated		°F	125.1			123.5	124.3
10% Evaporated		°F	134.8		133.3	134.1	134.1
20% Evaporated		°F	147.7		147.9	148.0	147.9
30% Evaporated		°F	157.6		158.2	158.1	158.0
40% Evaporated		°F	164.9			165.4	165.2
50% Evaporated		°F	169.3		169.8	169.5	169.5
60% Evaporated		°F	172.5			173.3	172.9
70% Evaporated		°F	281.3		282	282.0	281.8
80% Evaporated		°F	317.9			319.3	318.6
90% Evaporated		°F	357.2		356.6	357.3	357.0
95% Evaporated		°F	376.8		377.8	376.7	377.1
Final Boiling Point		°F	403		406.7	406.4	405.4
Recovered		vol %	97.7		97.9	98.1	97.9
Residue		vol %	1.1		0.9	1.1	1.0
Loss		vol %	1.2		1.2	0.8	1.1
Driveability Index Uncorrected	D4814	°F	1067.3		1066	1067.0	1066.8

Appendix B: Combustion Instrumentation Sensor Correlation

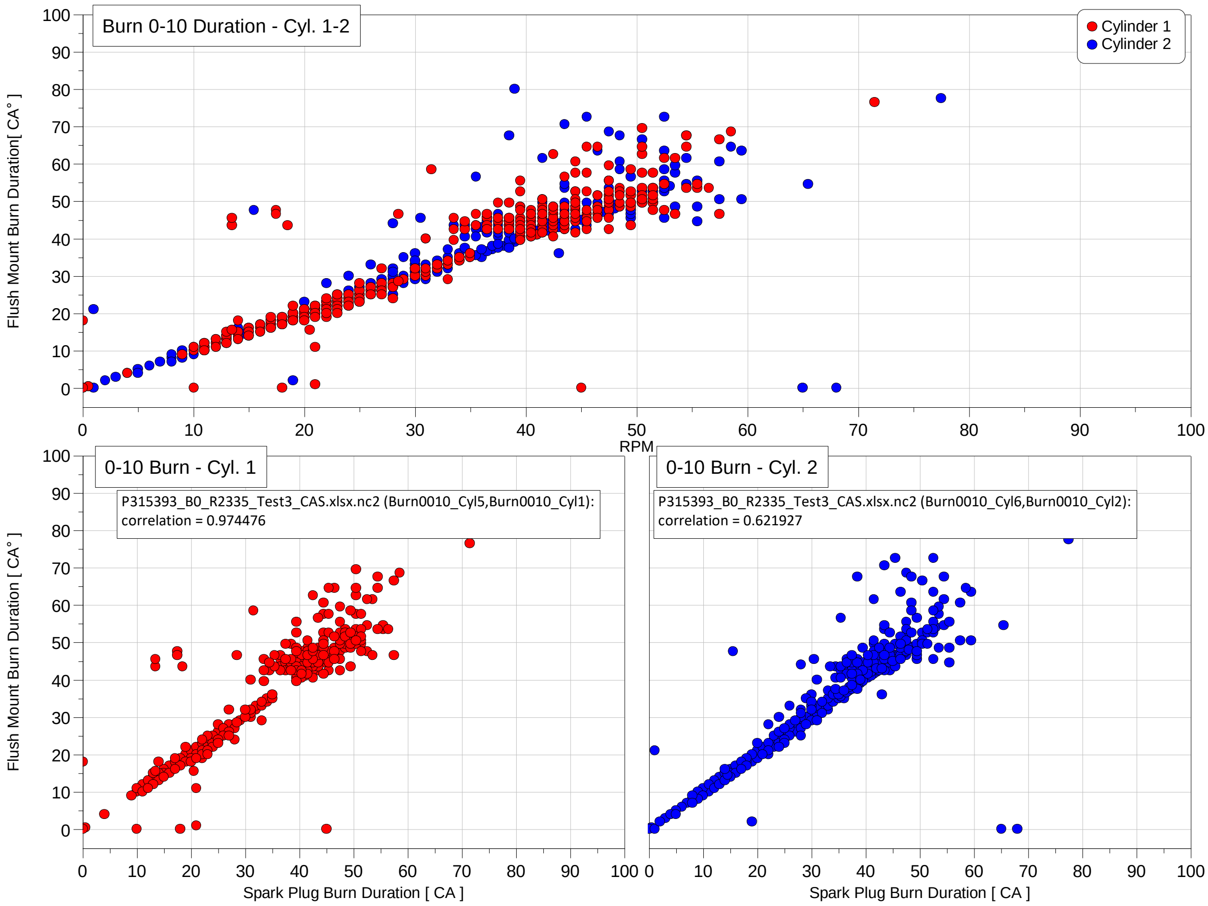
1.) Combustion CA50 Correlation



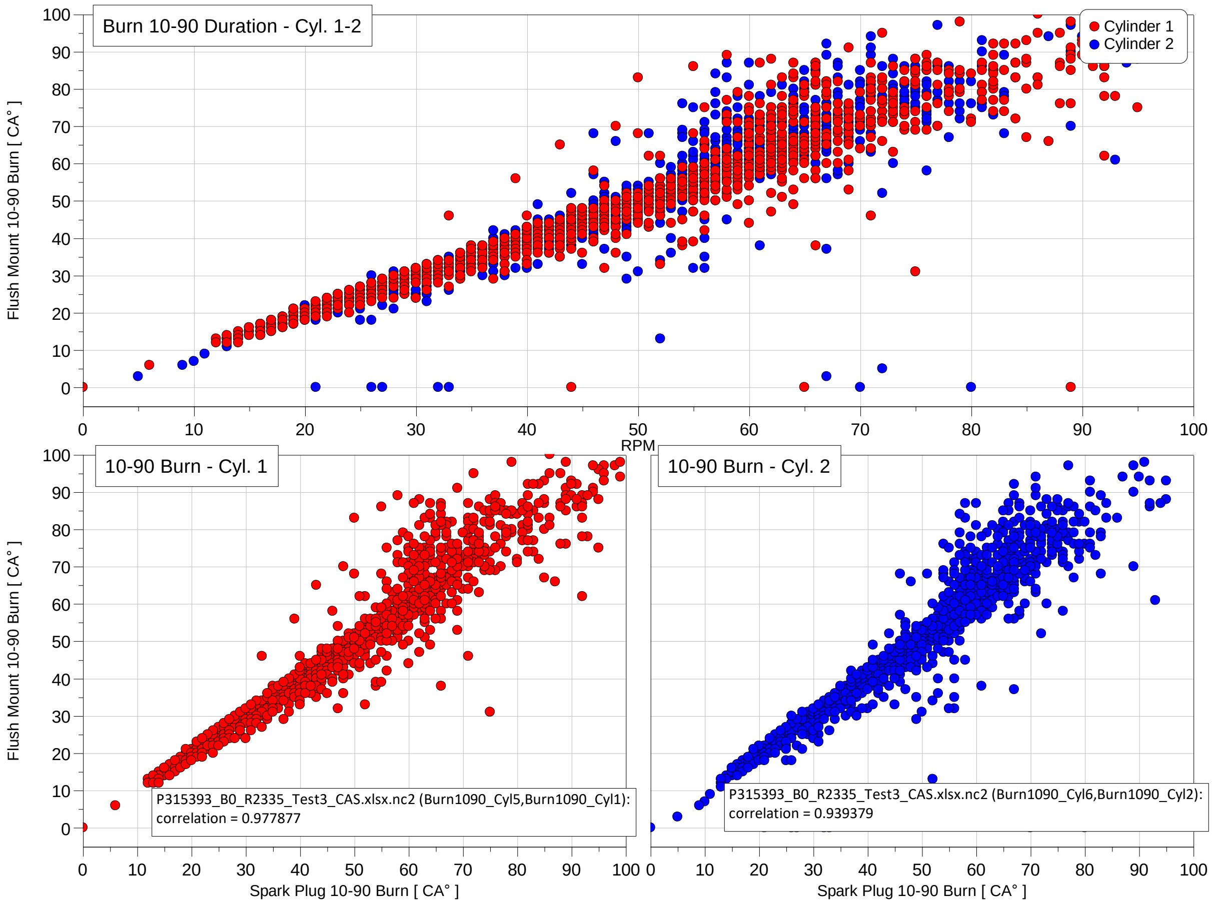
2.) Combustion CA90 Correlation



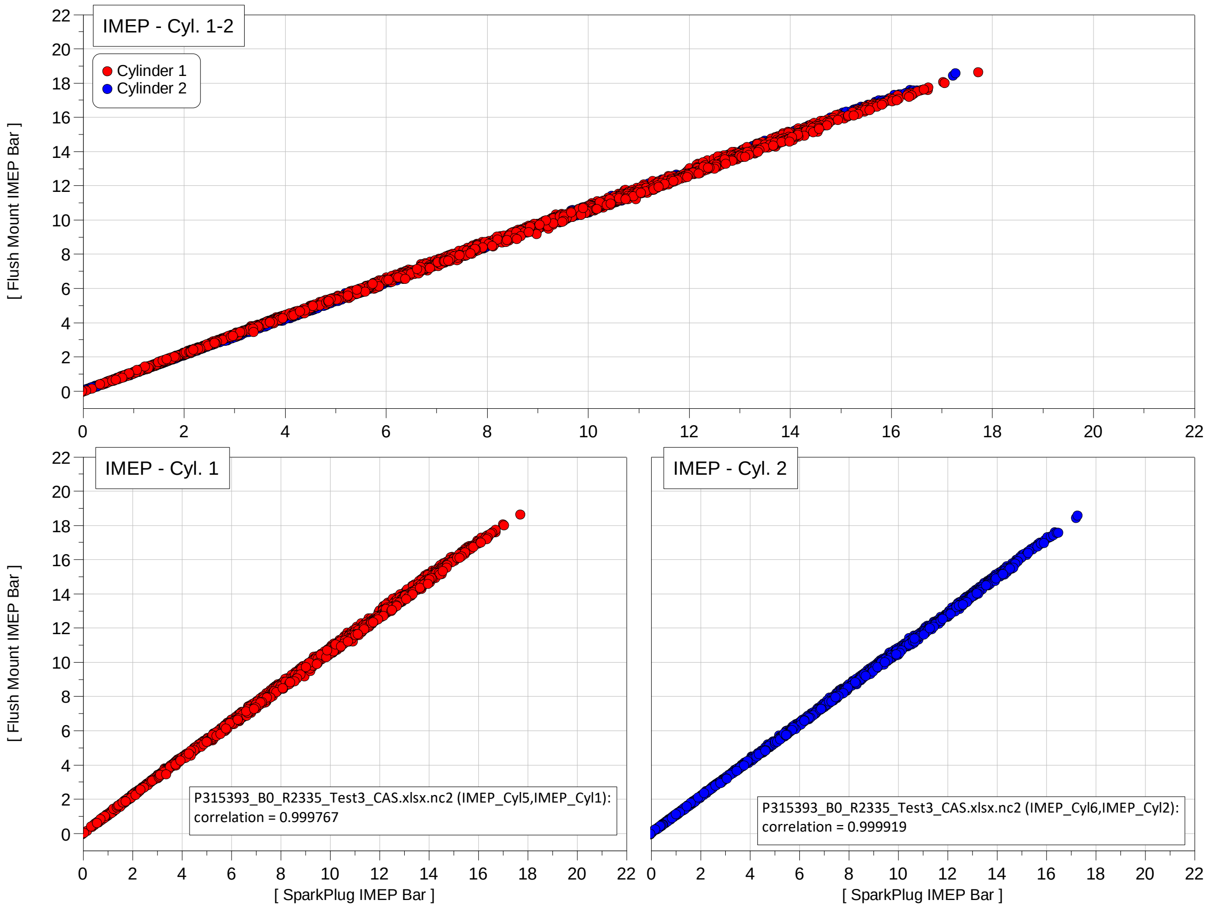
3.) Combustion Burn 0-10 Duration Correlation



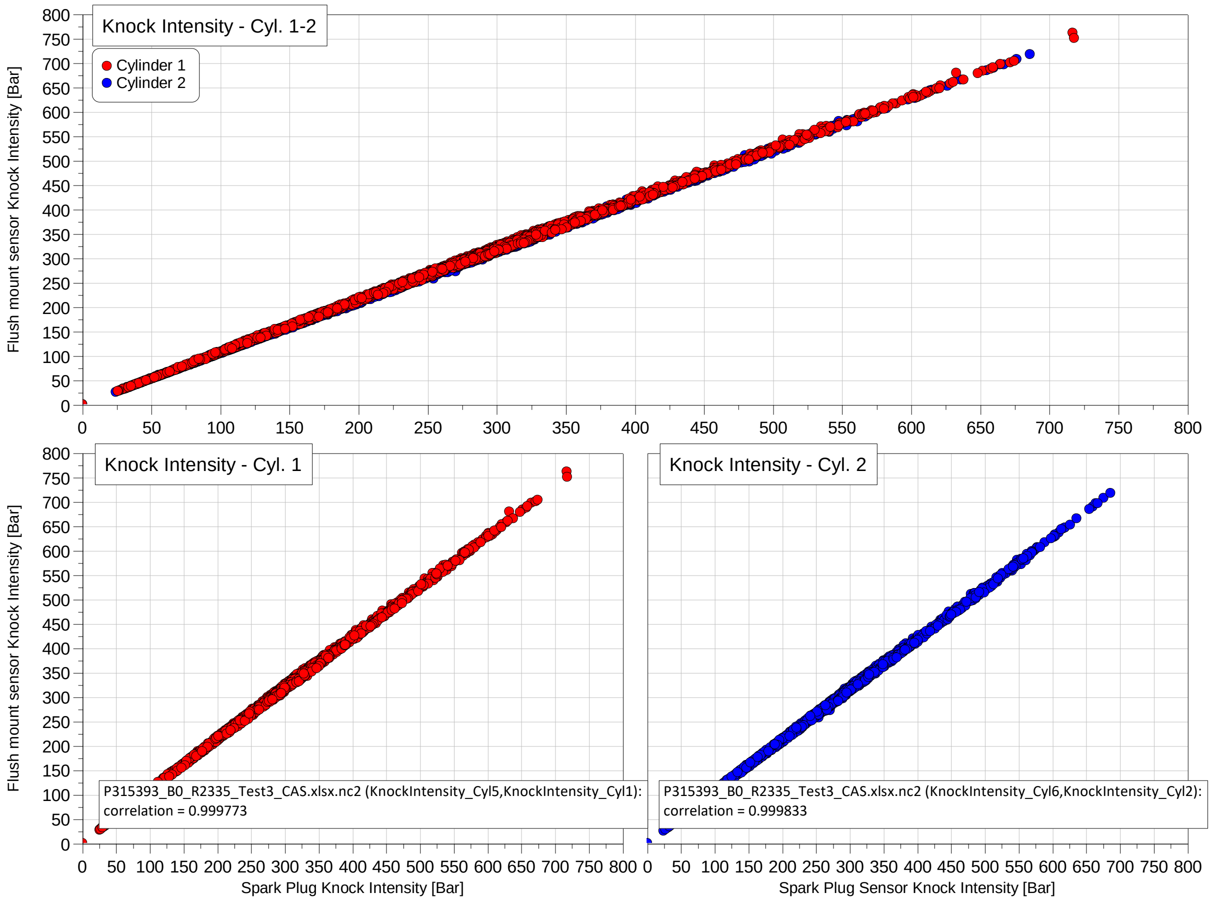
4.) Combustion Burn 10-90 Duration Correlation



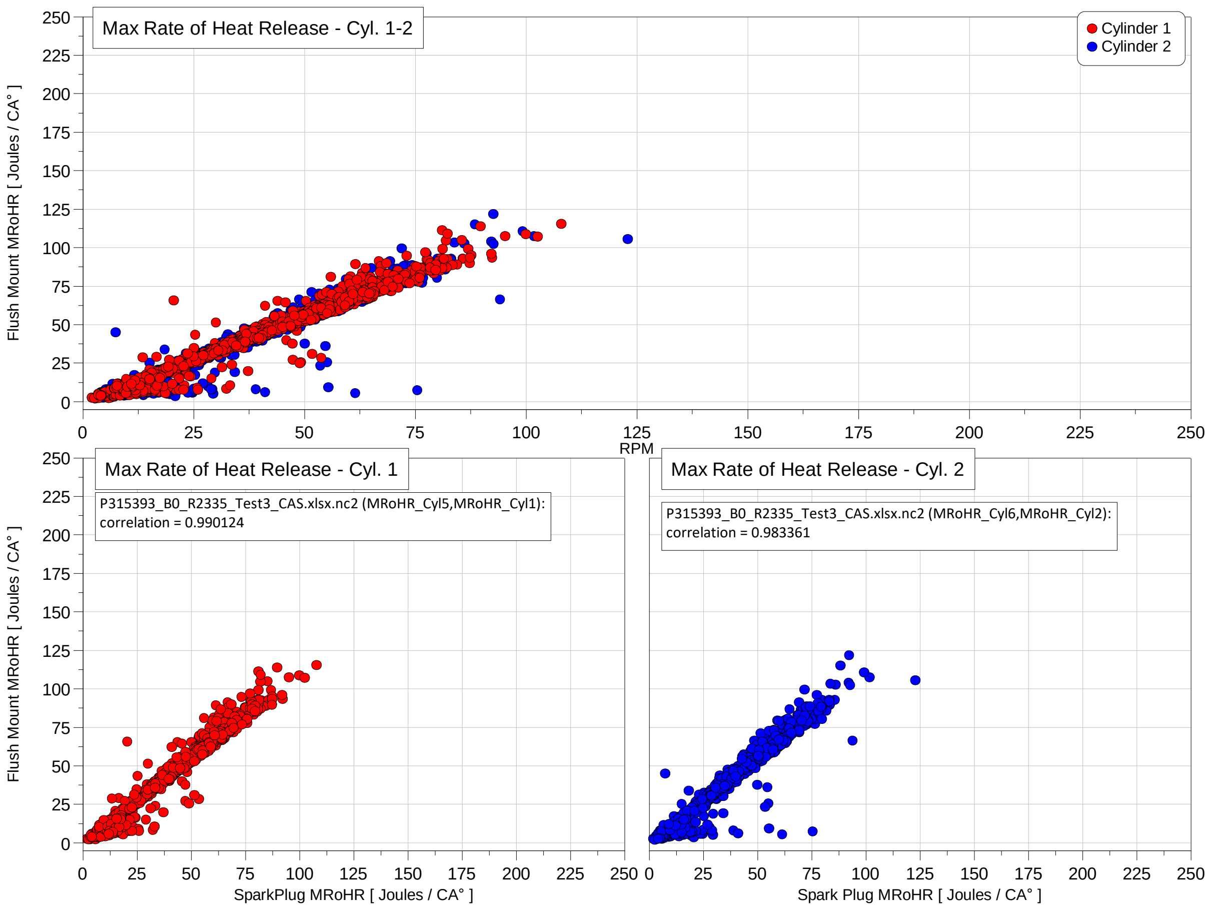
5.) Combustion IMEP Correlation



6.) Combustion Knock Intensity Correlation

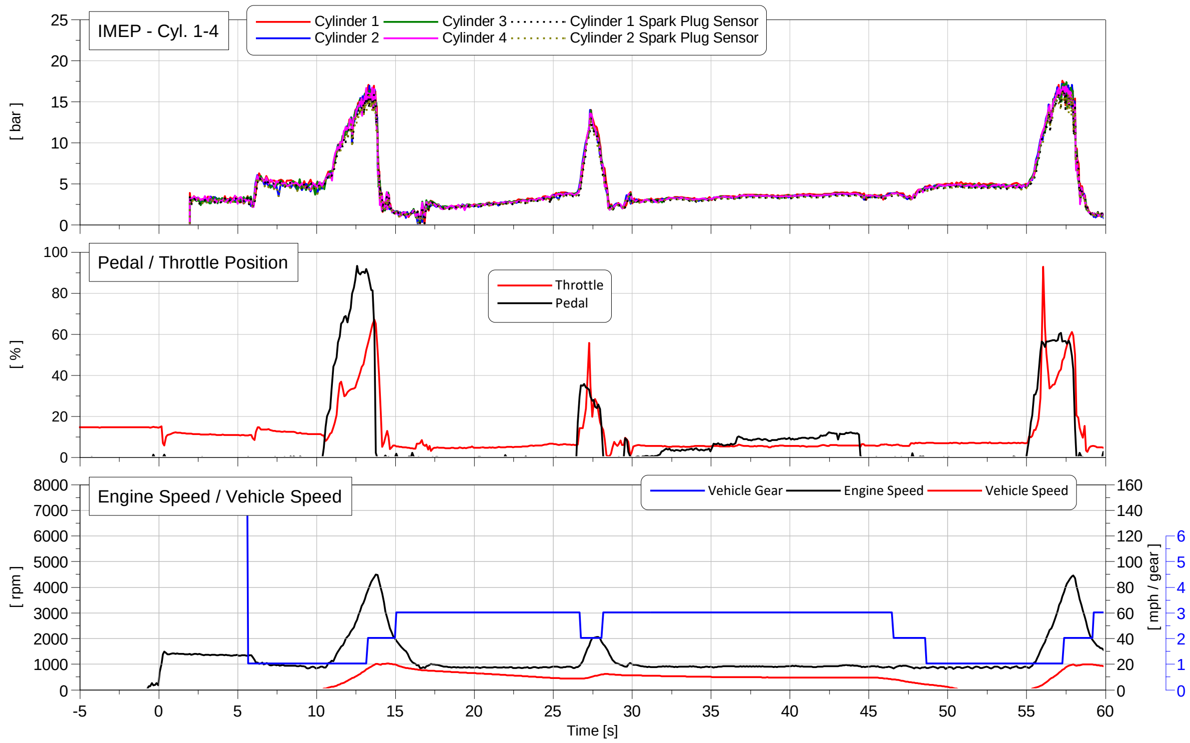


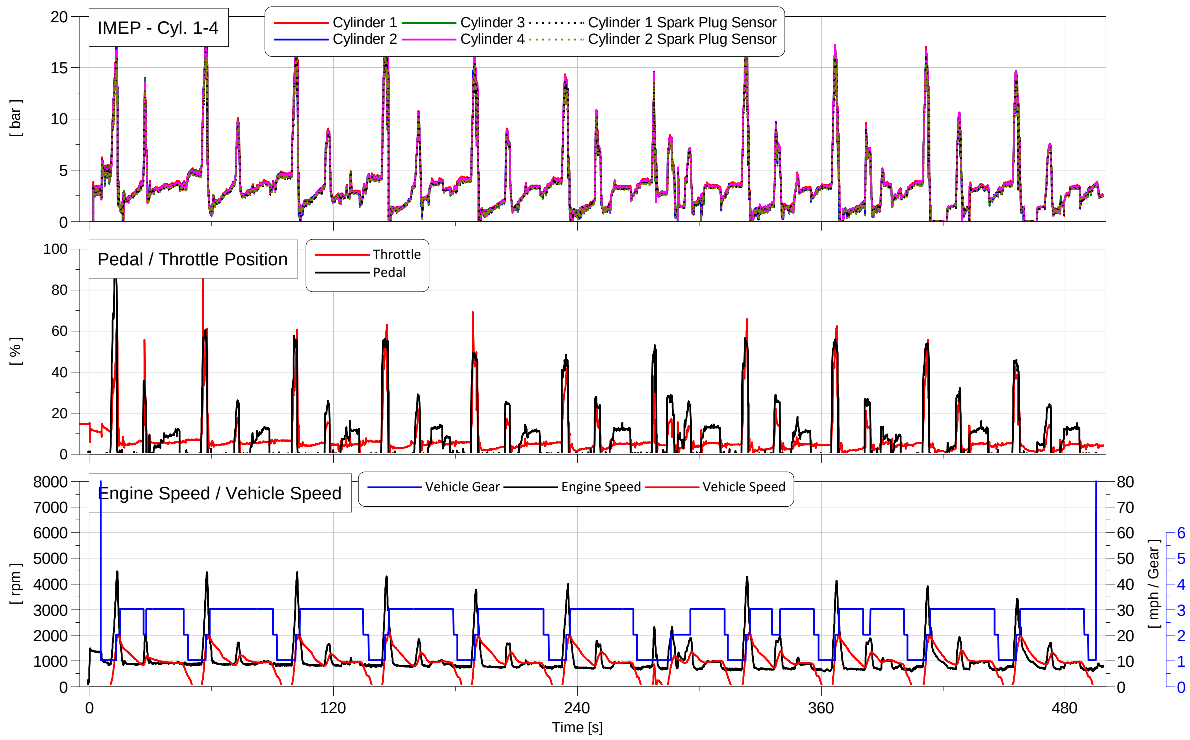
7.) Combustion Max Rate of Heat Release Correlation



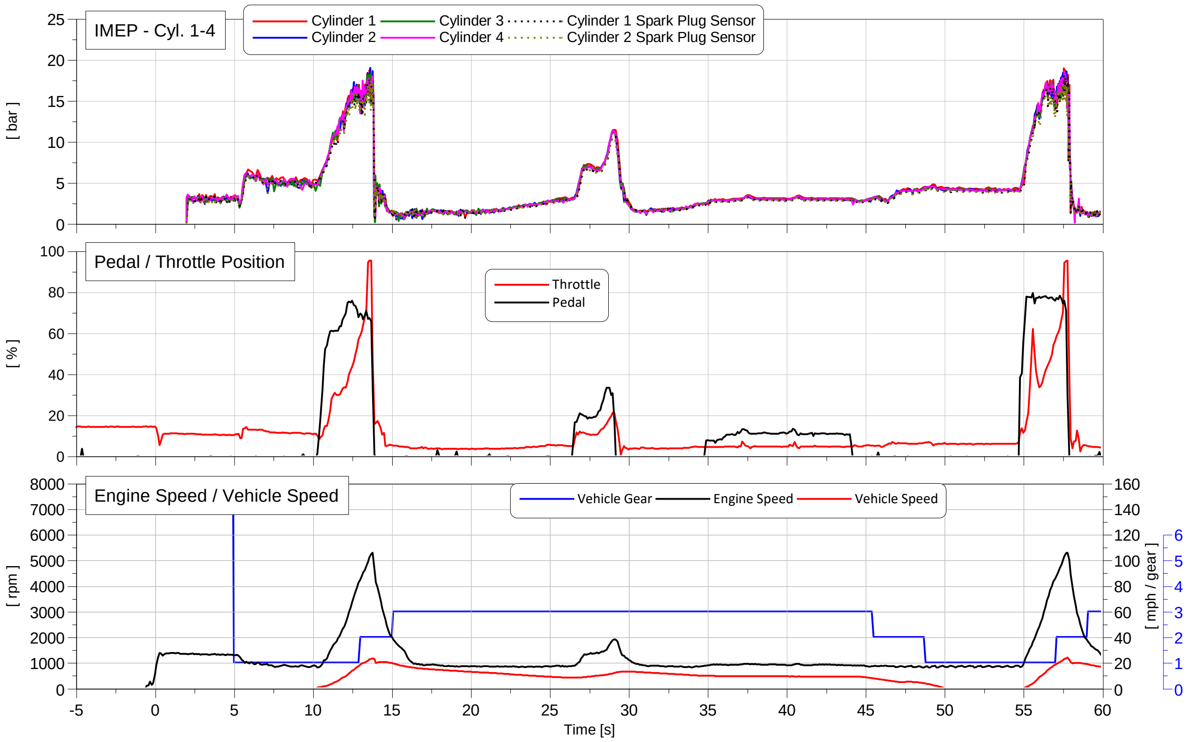
Appendix C. IMEP and Accelerator Pedal Driveability Plots

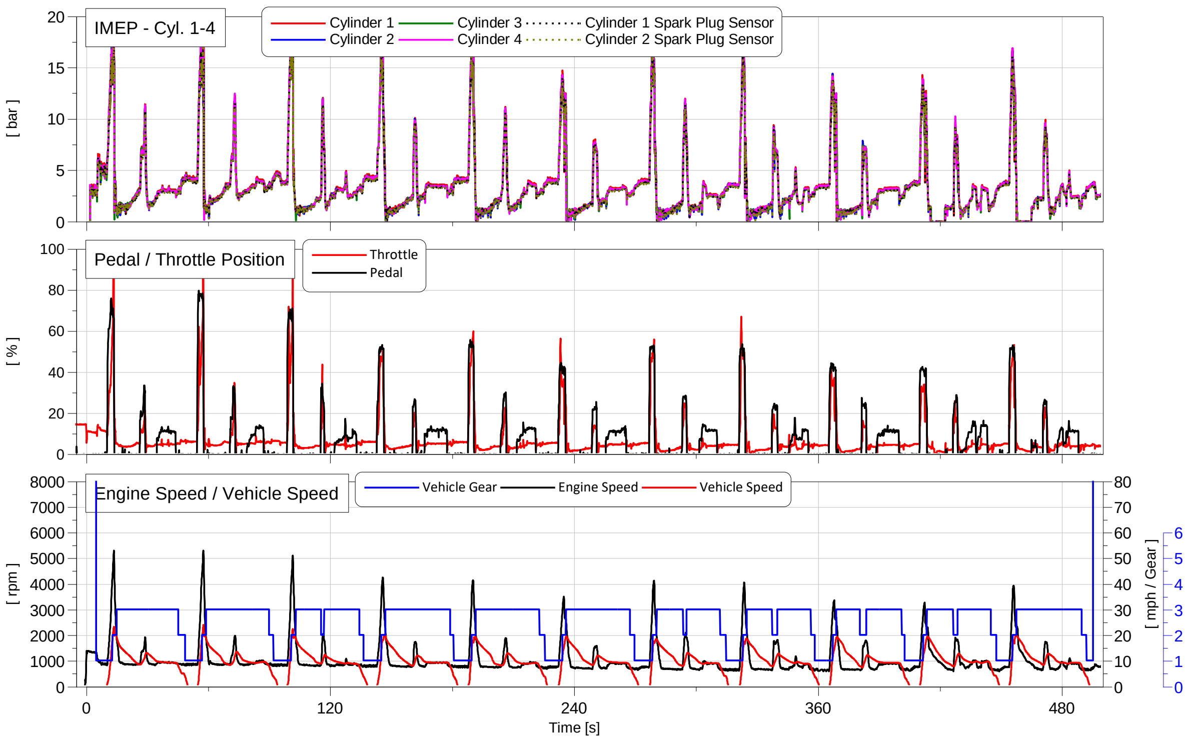
1.) B0 TR2335A Test 1



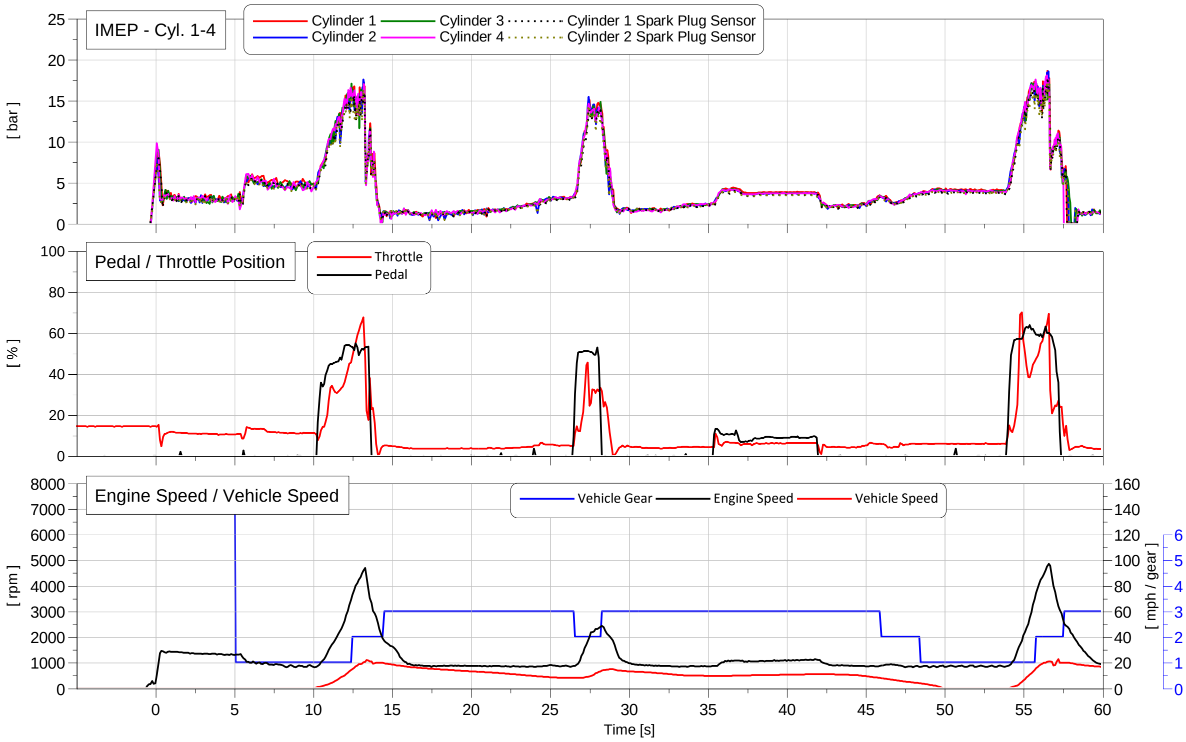


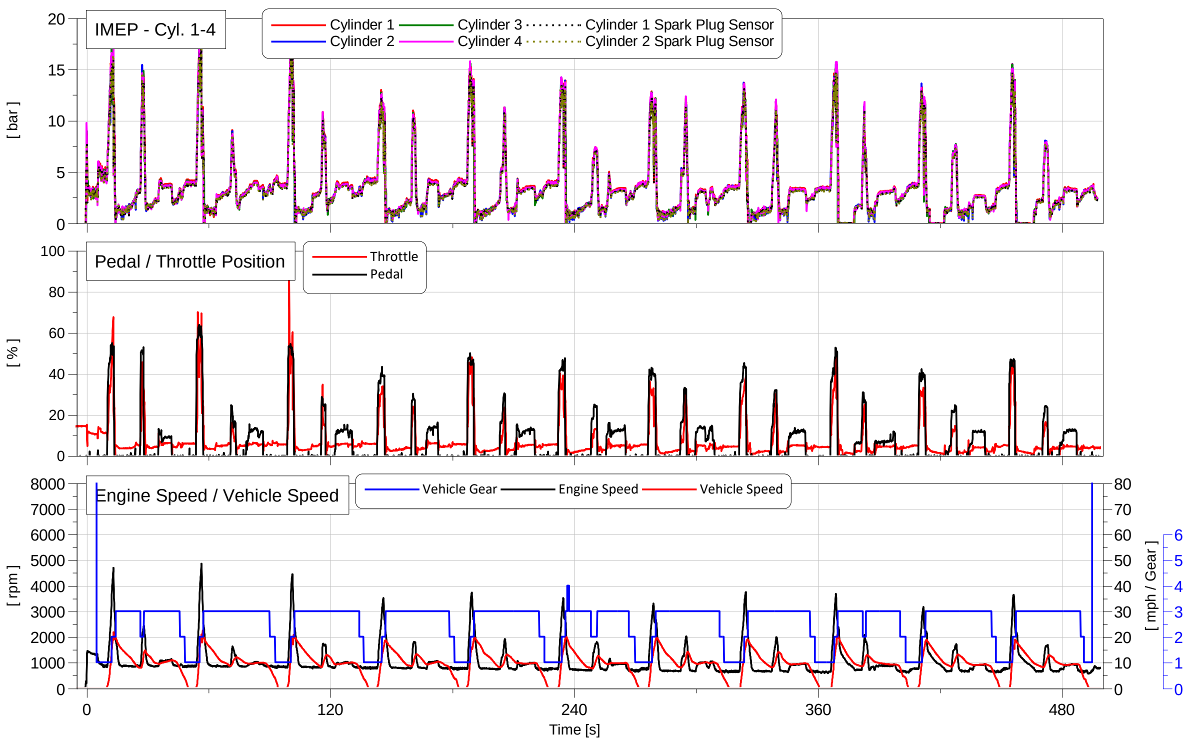
2.) B0 TR2335A Test 2



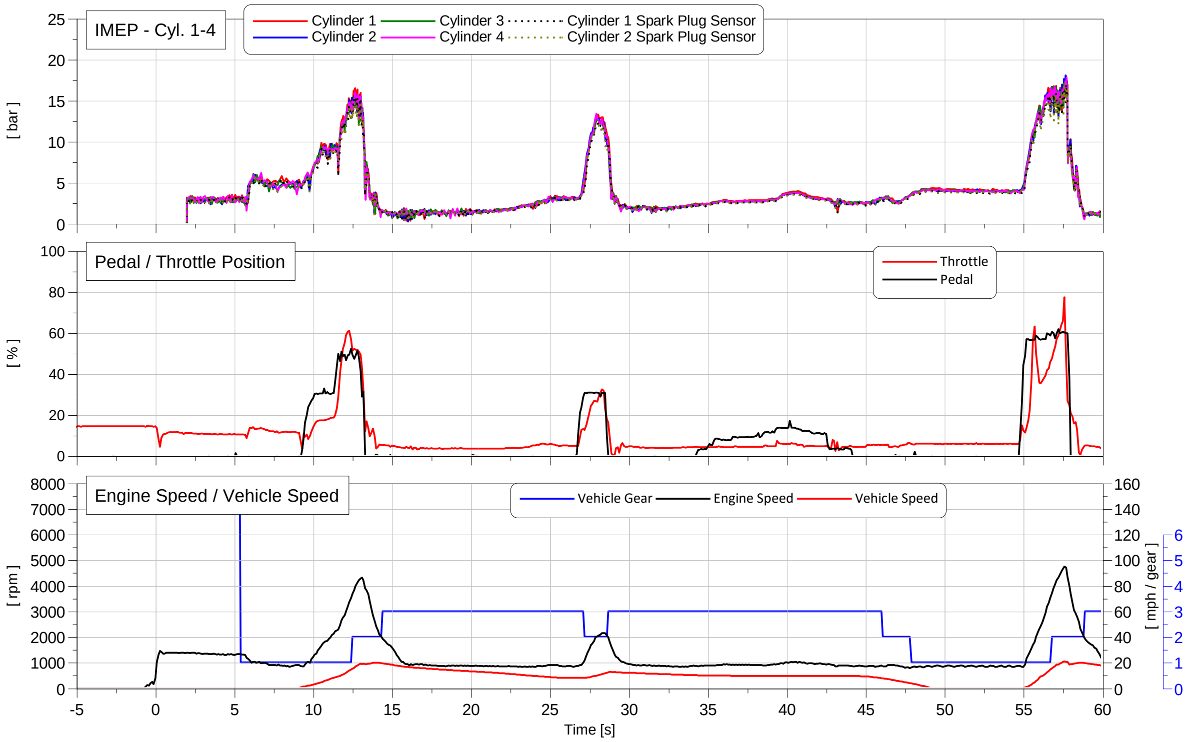


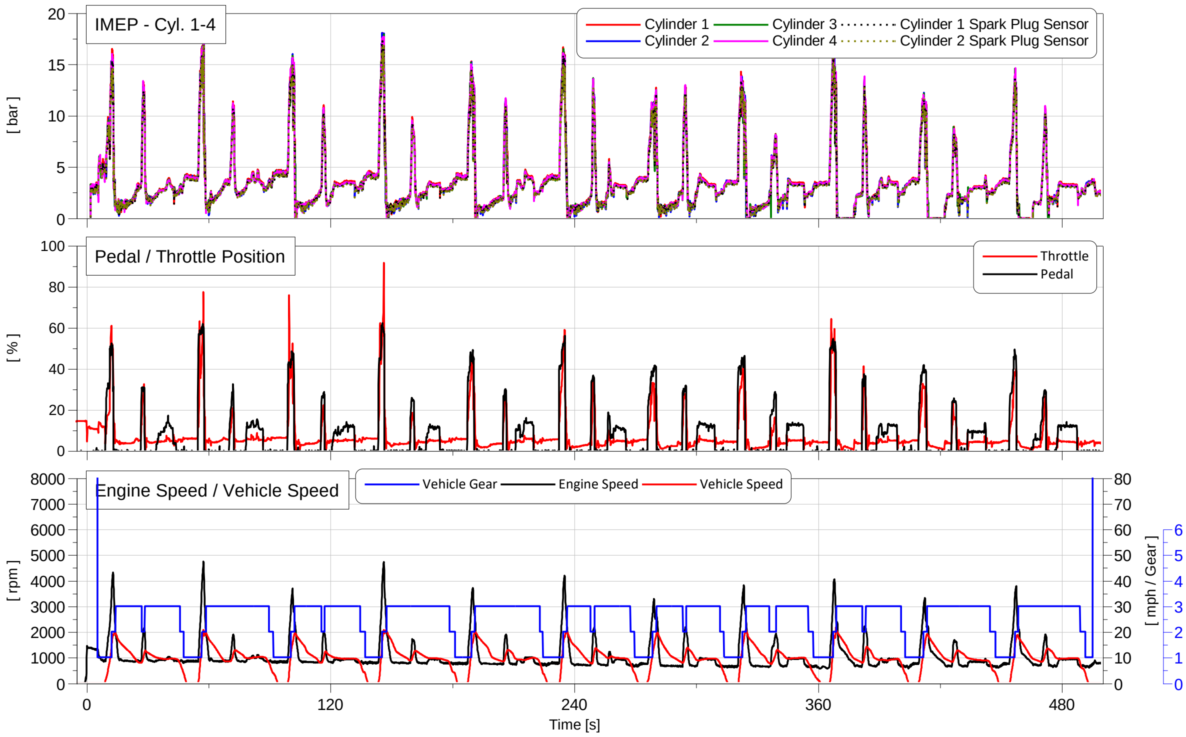
3.) B0 TR2335A Test 3



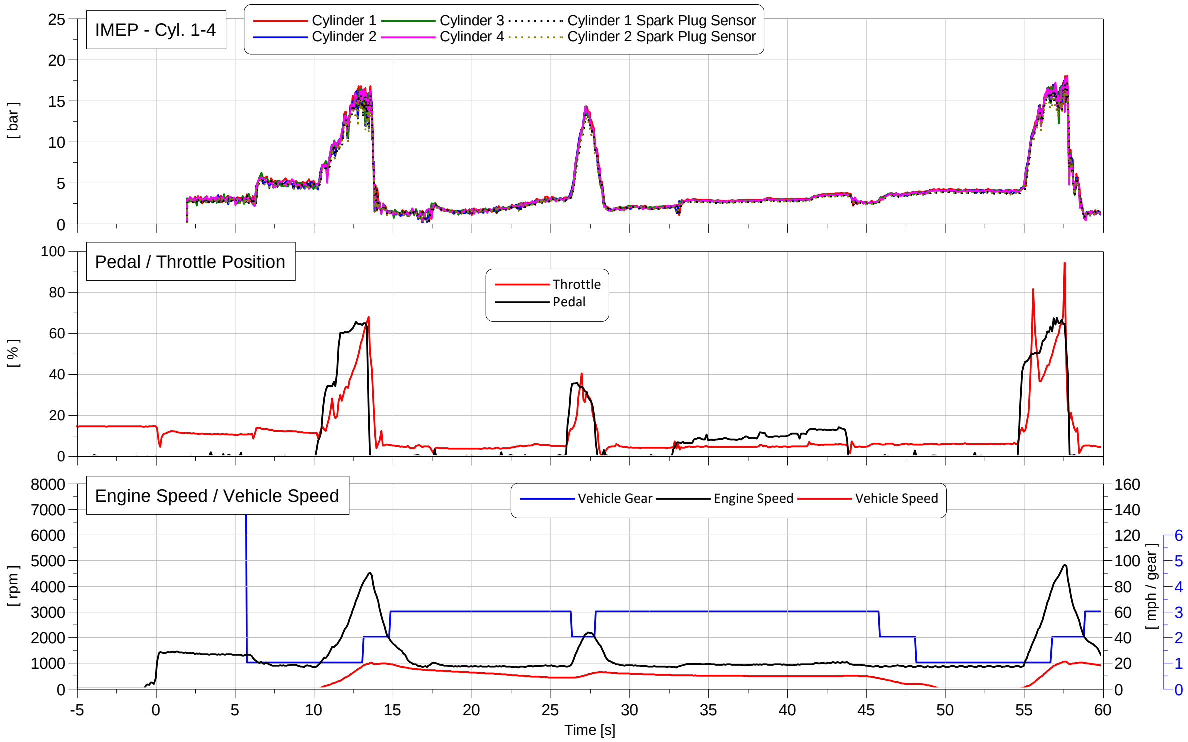


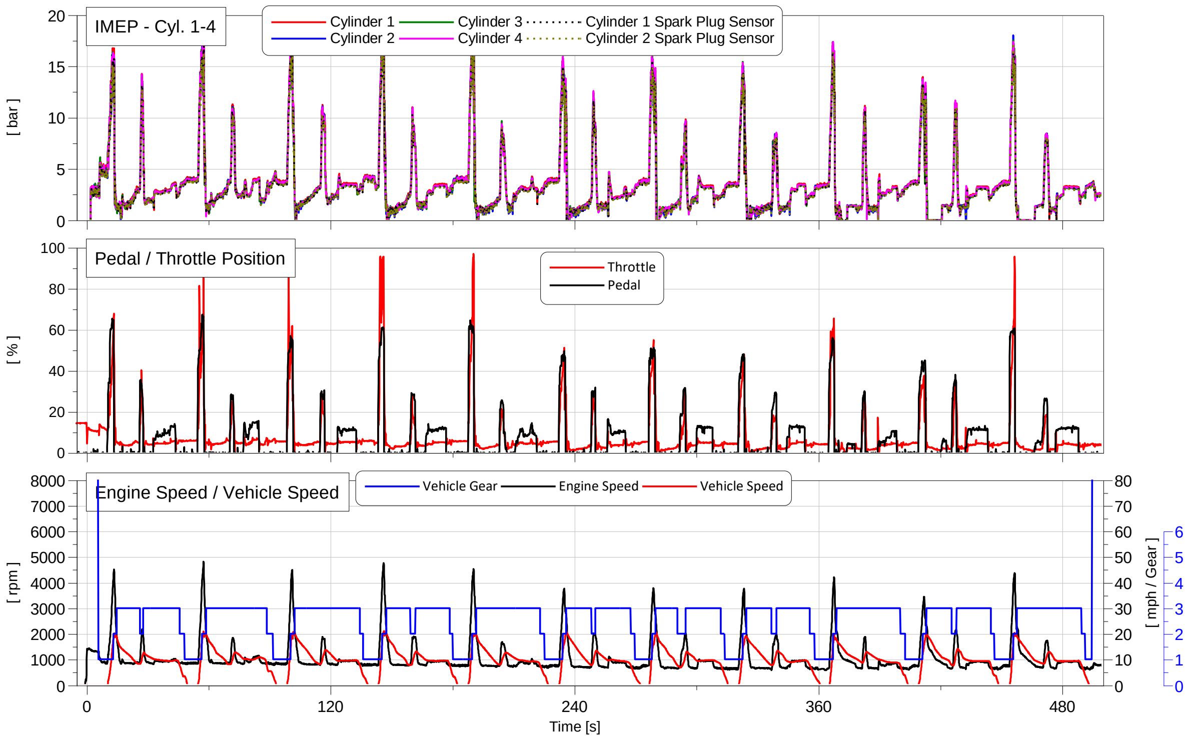
4.) C0 TR2338A Test 1



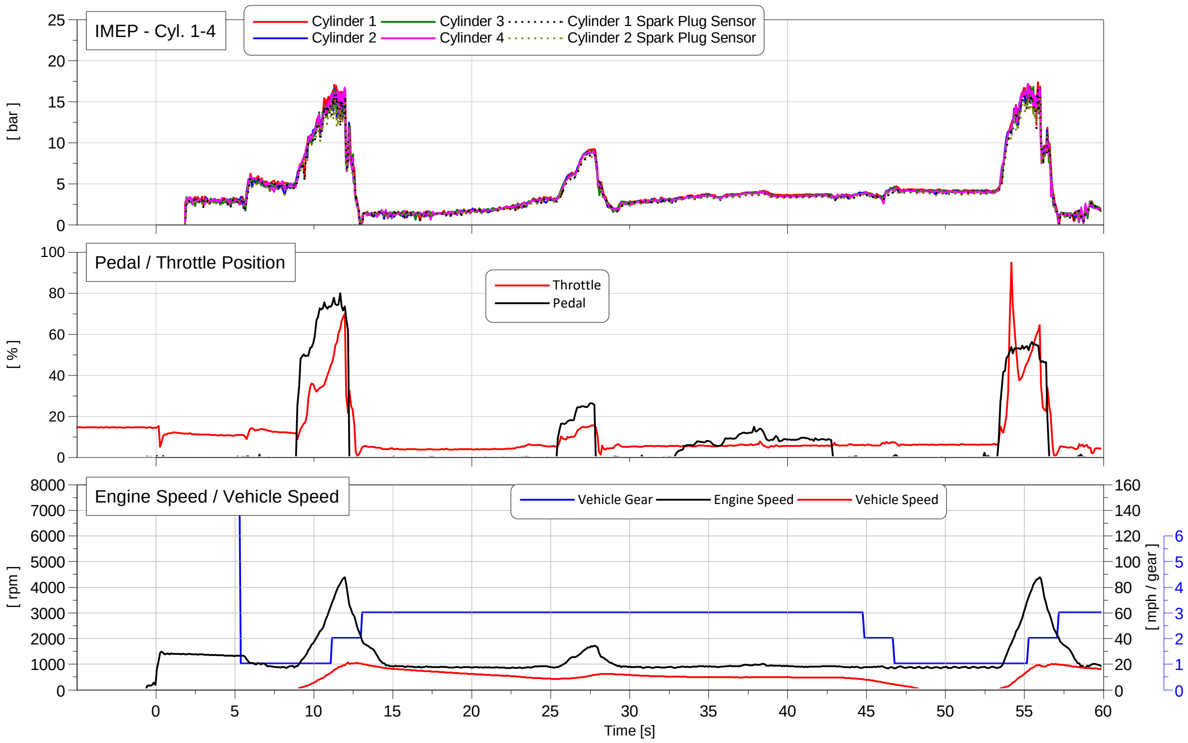


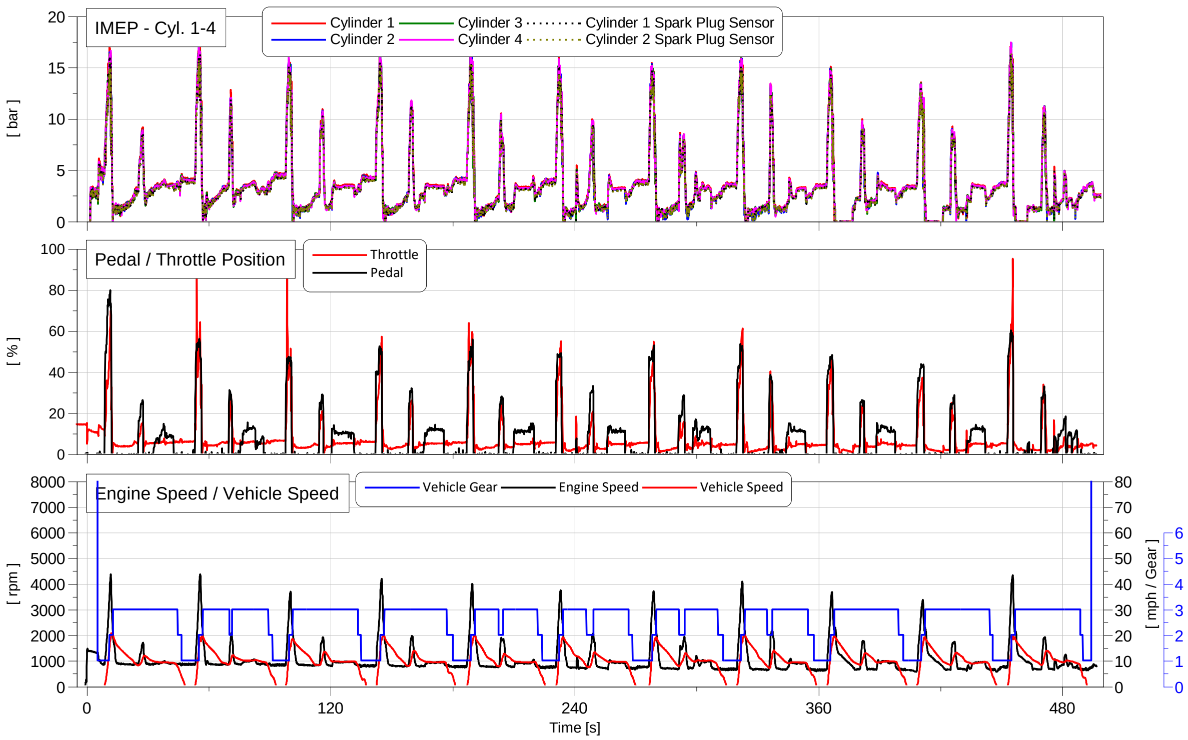
5.) C0 TR2338A Test 2



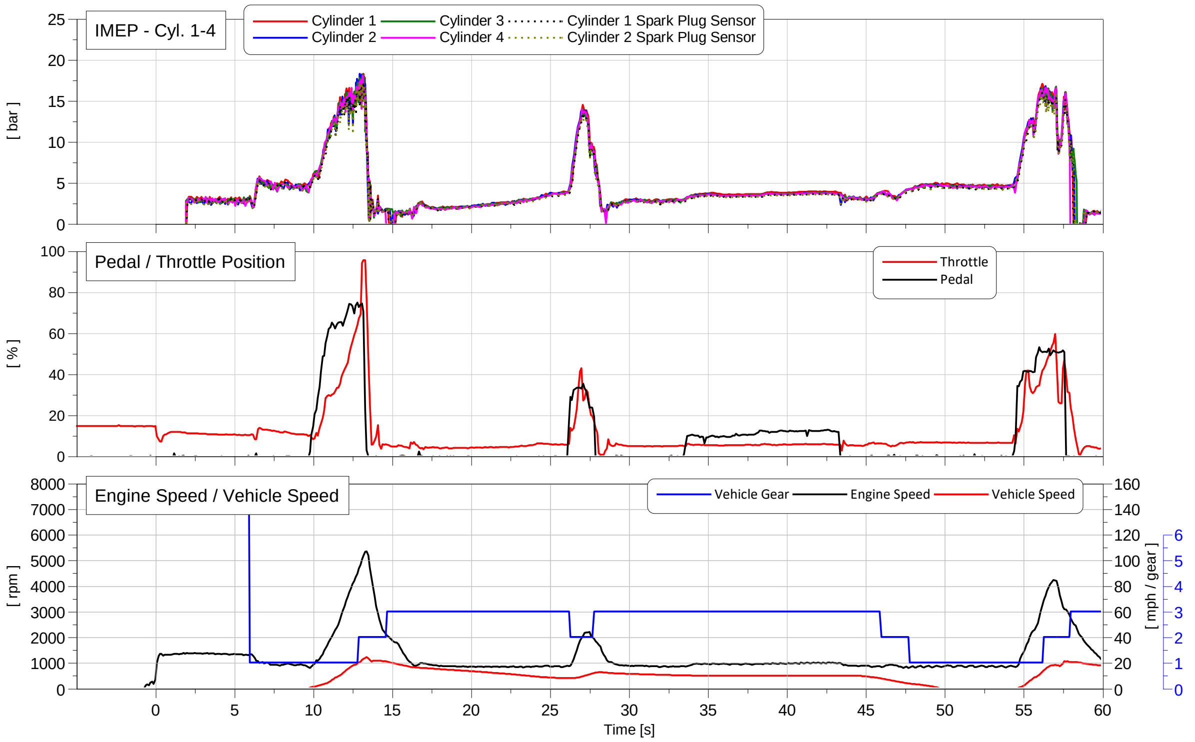


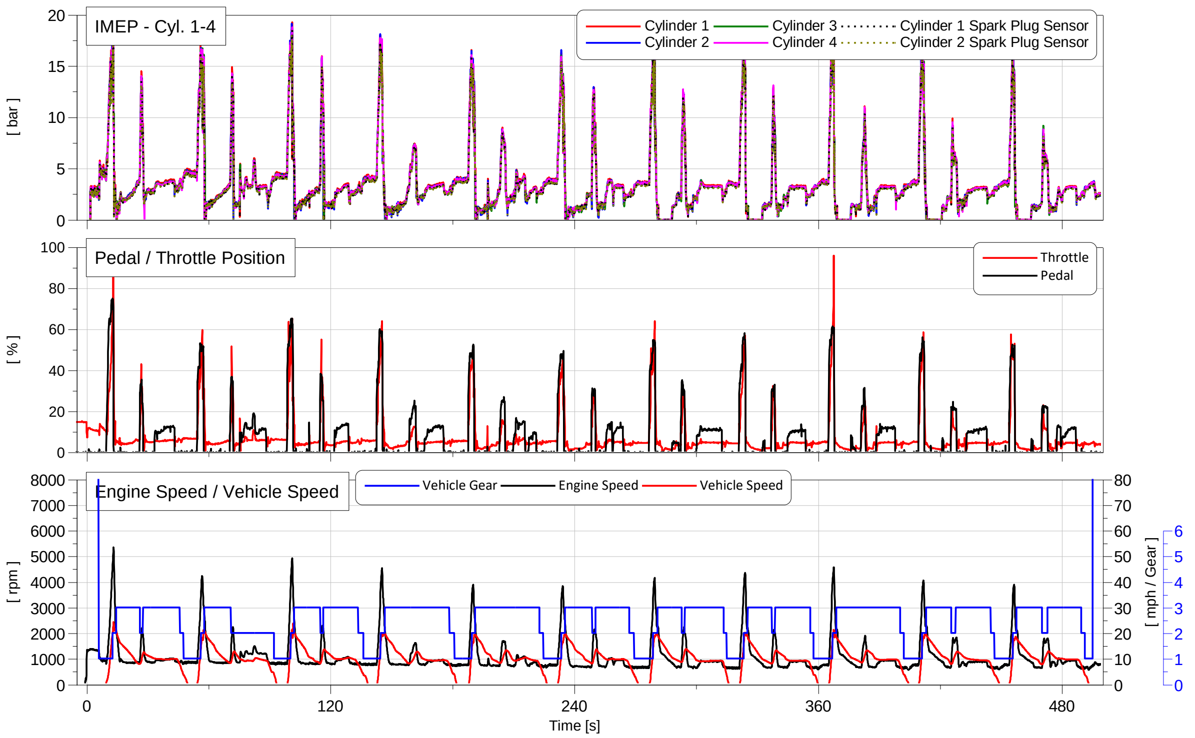
6.) C0 TR2338A Test 3



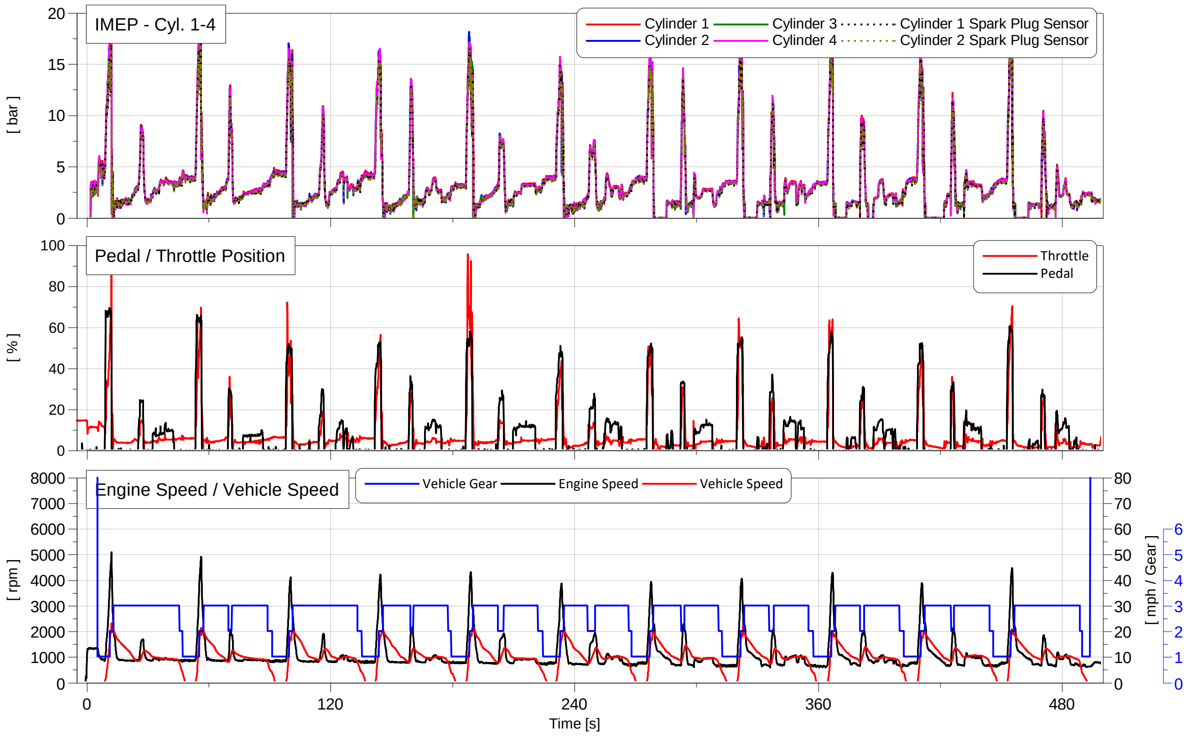


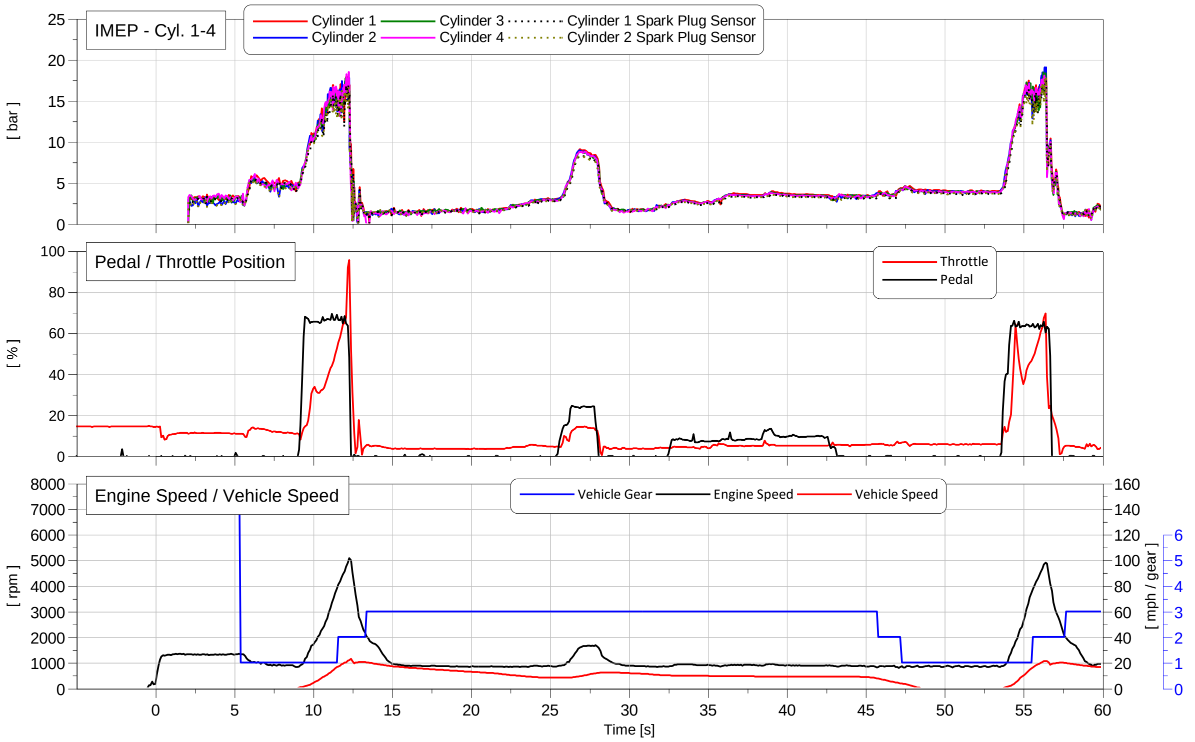
7.) CE15 TR2339A Test 1



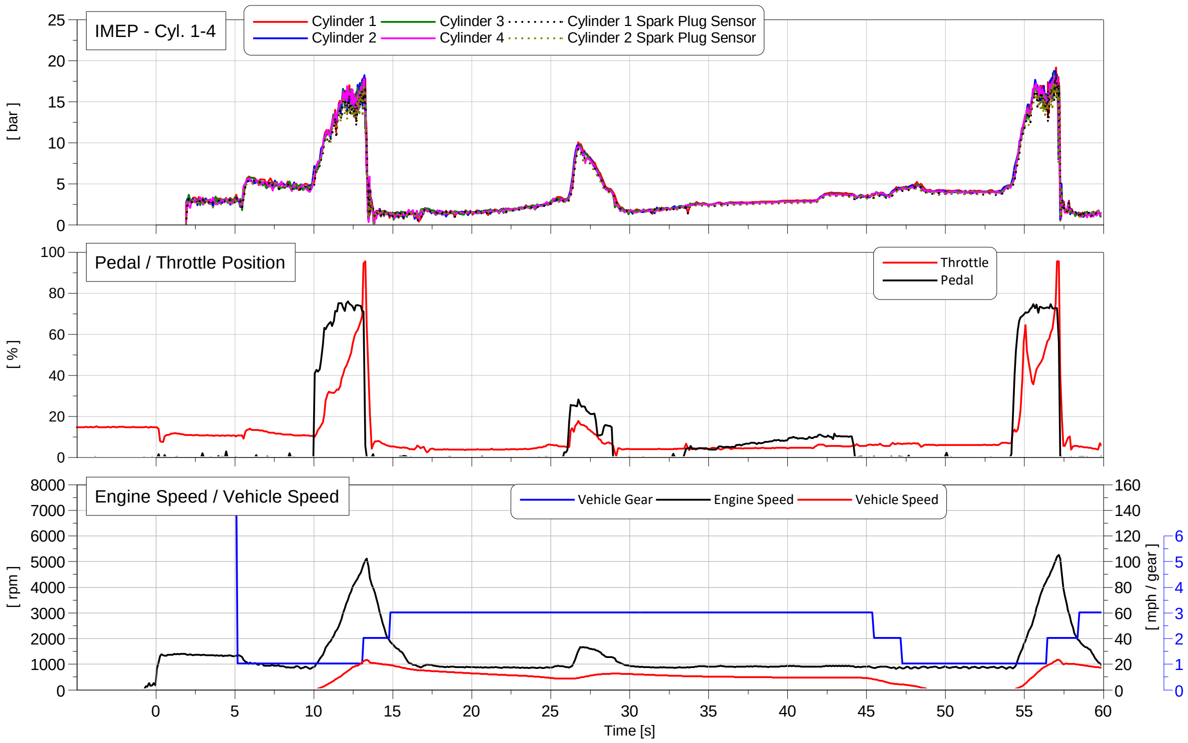


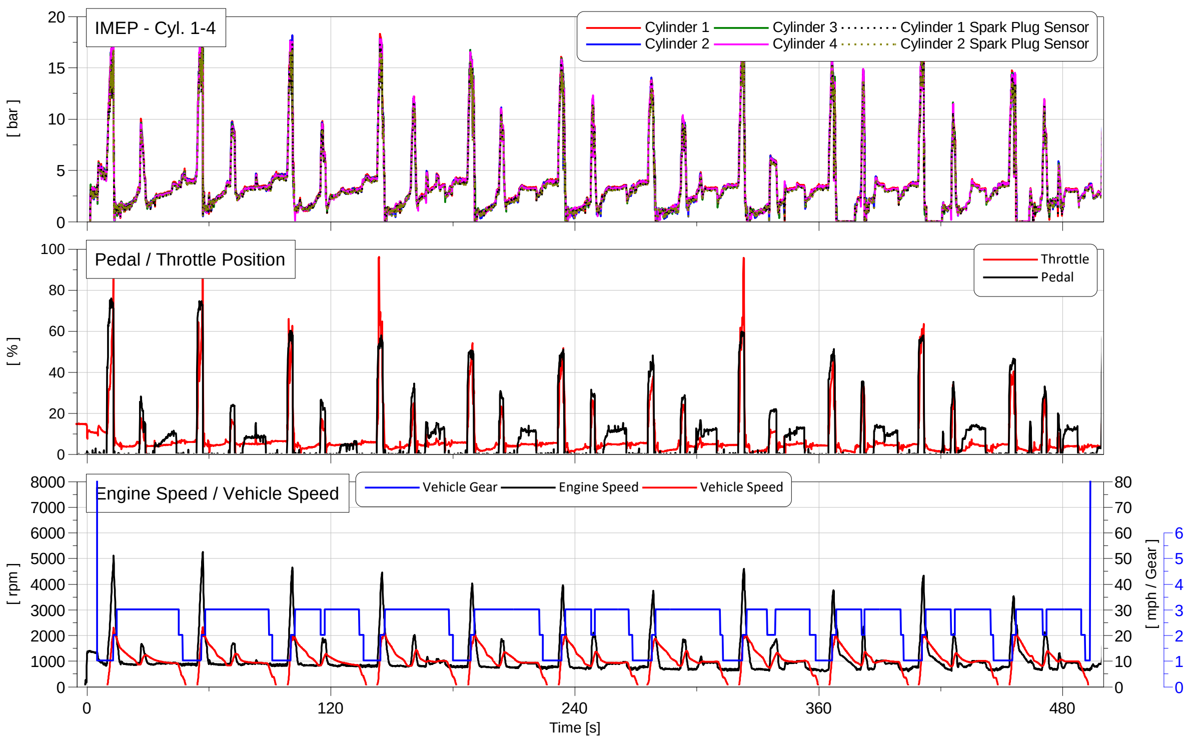
8.) CE15 TR2339A Test 2



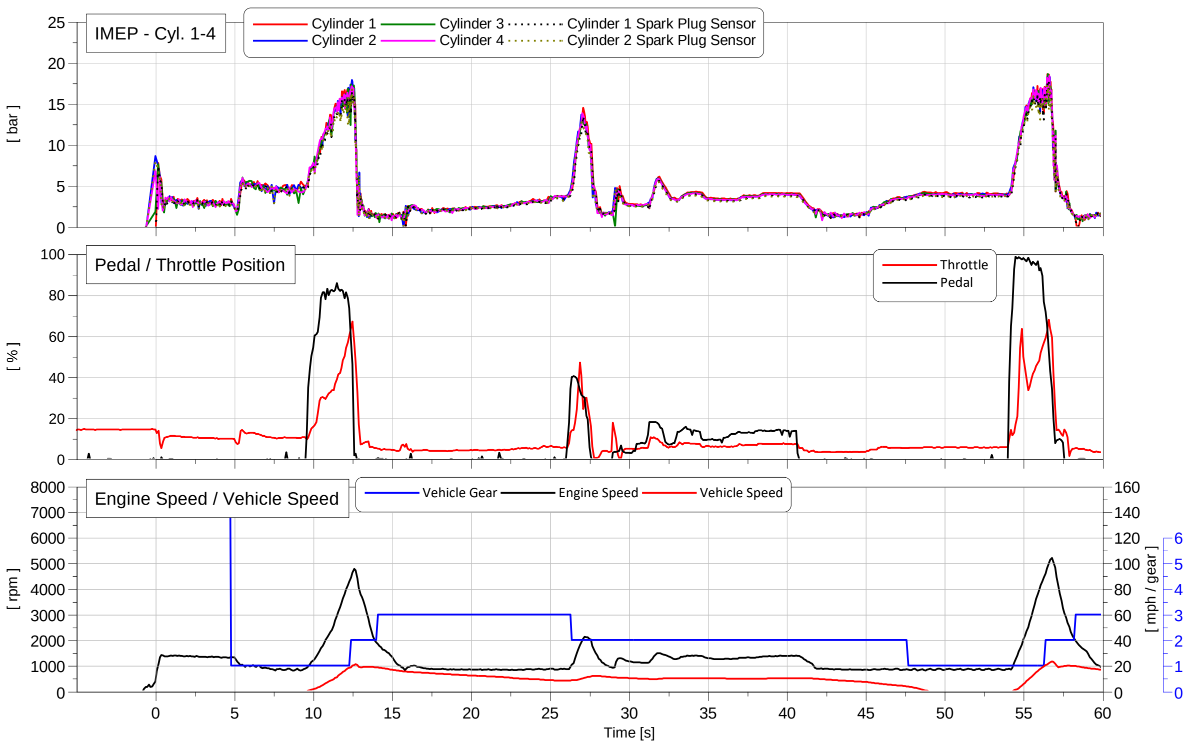


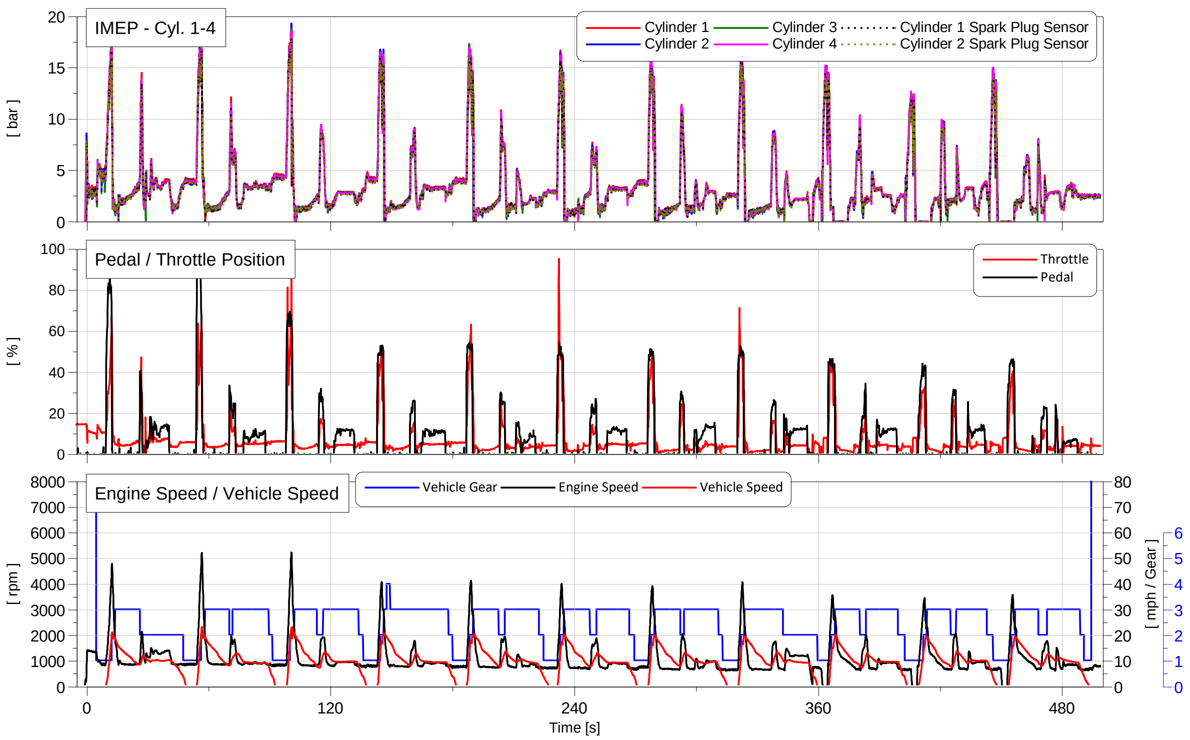
9.) CE15 TR2339A Test 3



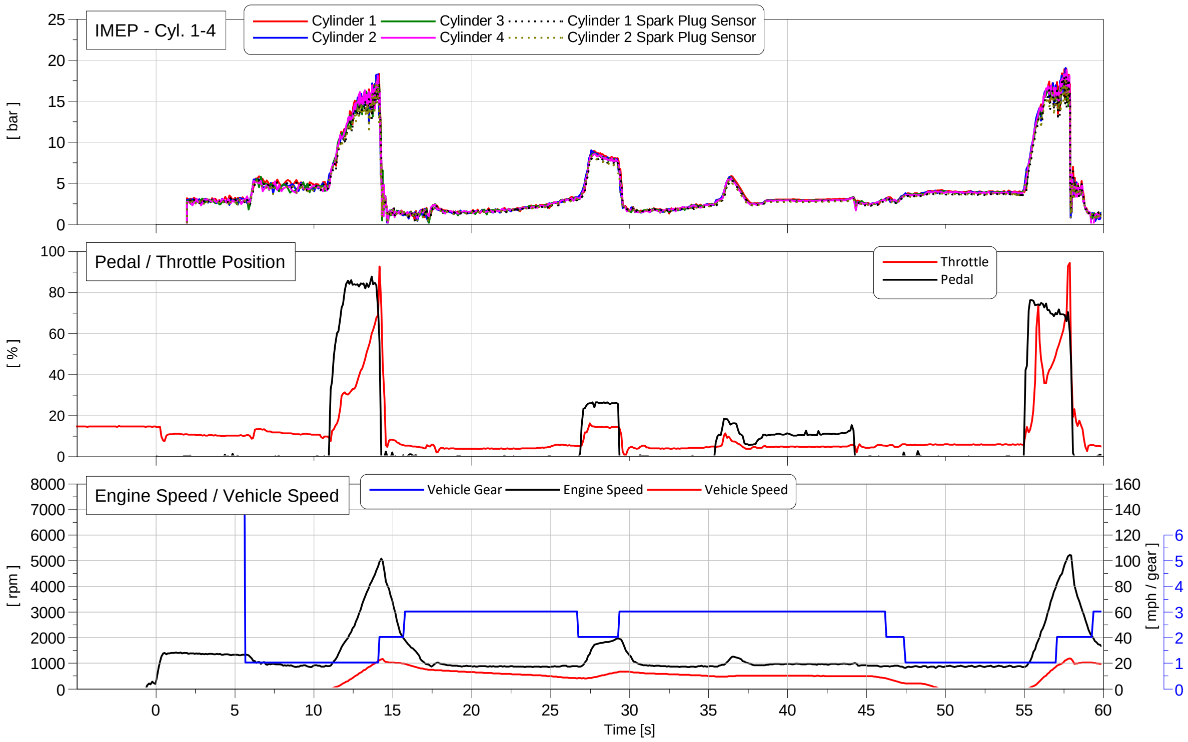


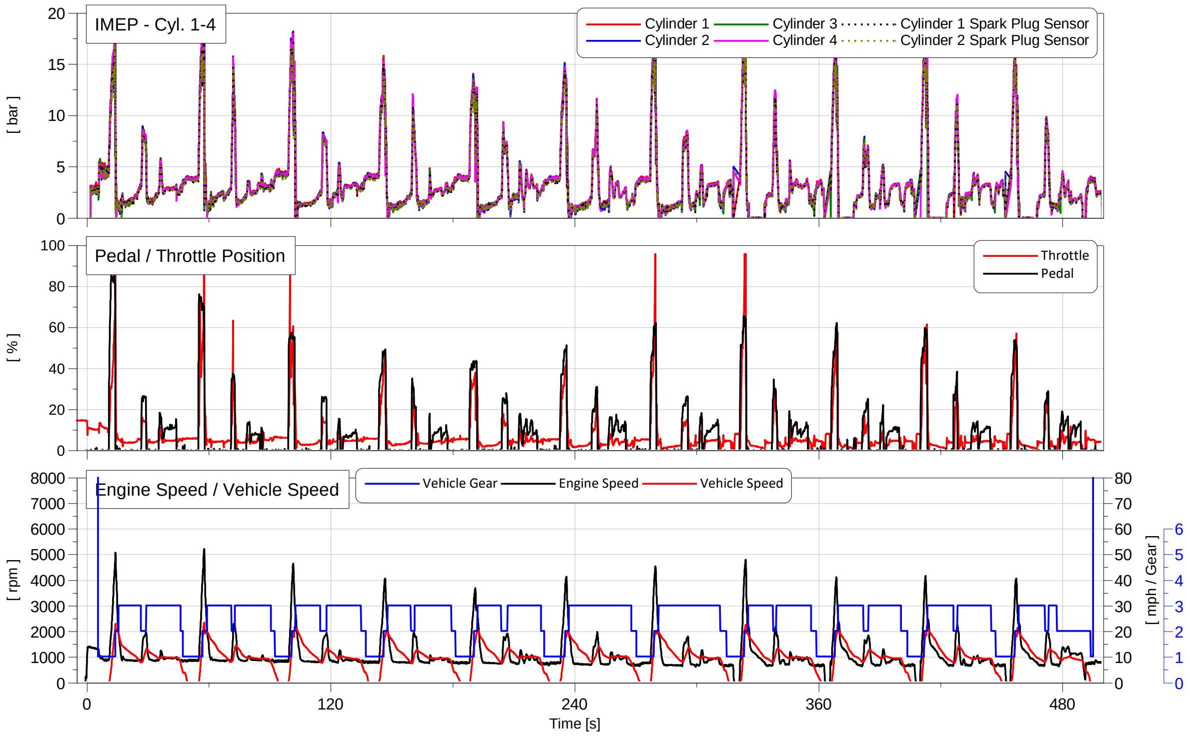
10.) CE30 TR2340A Test 1



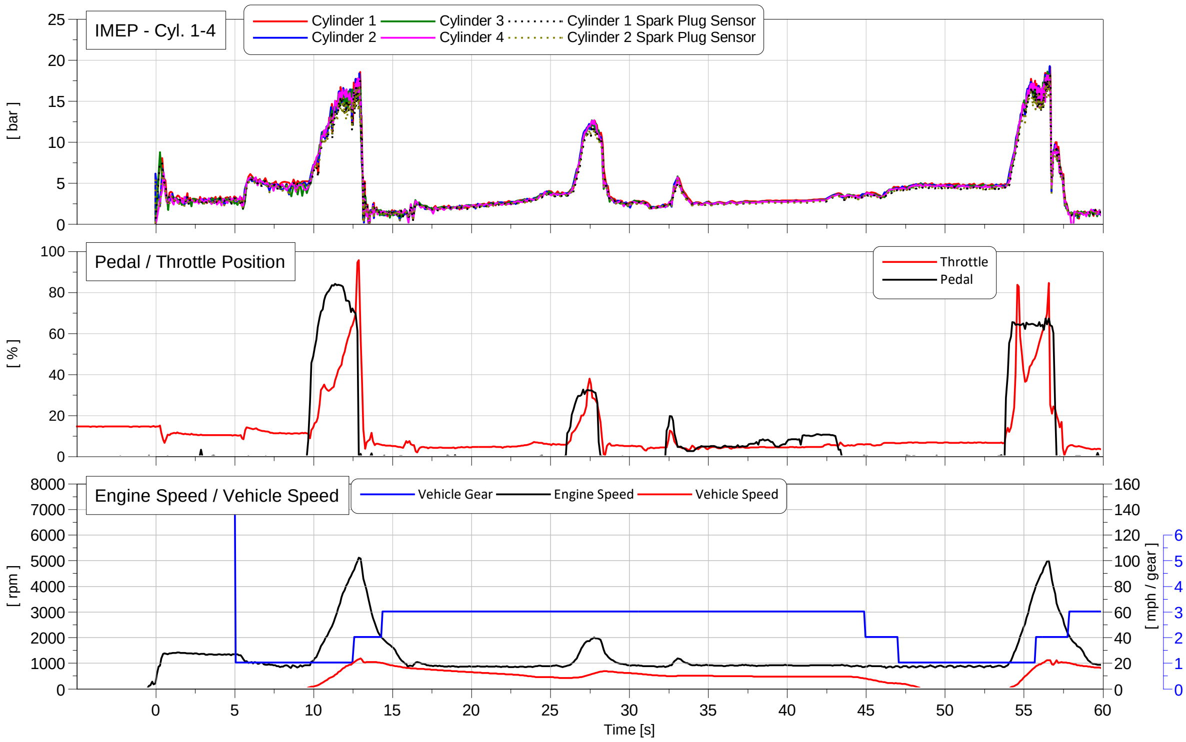


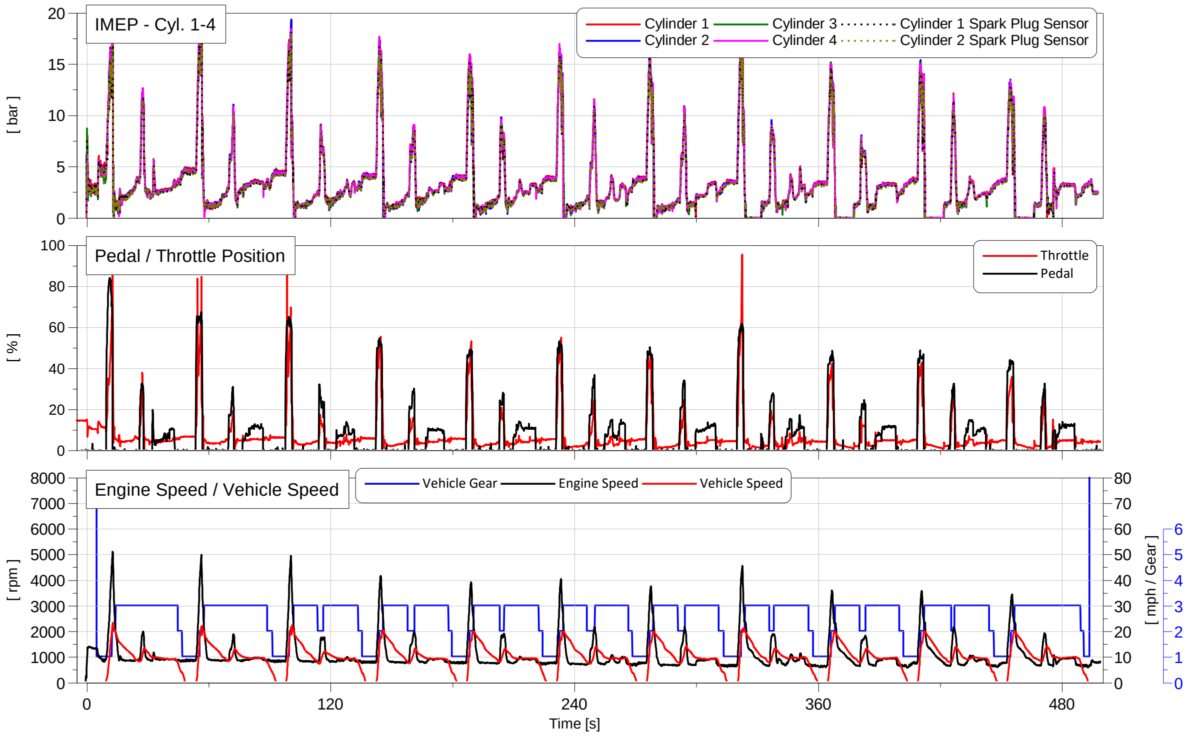
11.) CE30 TR2340A Test 2





12.) CE30 TR2340A Test 3





Appendix D. GM Test Fuel Sample Inspections and Analysis

(Fuel sample taken from vehicle fuel rail after fuel drain and test fuel refill)

		Sample	TR2335A-B0	TR2338-C0	CE15 TR2339A	CE30 TR2340
ASTM	Description	Date	2/15/2021	3/3/2021	3/9/2021	4/12/2021
D4815	Ethanol (lv%)	vol. %	0.2	0	14.7	28.6
D86	IBP	deg. C	34.0	33.3	35.0	37.3
D86	5% Evaporated	deg. C	47.0	45.3	48.7	49.1
D86	10% Evaporated	deg. C	53.1	52.8	53.6	56.0
D86	20% Evaporated	deg. C	63.5	65.6	61.0	64.1
D86	30% Evaporated	deg. C	75.3	81.1	66.8	69.8
D86	40% Evaporated	deg. C	92.9	105.6	71.3	74.1
D86	50% Evaporated	deg. C	119.1	131.2	89.6	76.6
D86	60% Evaporated	deg. C	139.0	144.8	136.1	78.3
D86	70% Evaporated	deg. C	151.2	157.1	151.3	139.2
D86	80% Evaporated	deg. C	168.2	169.5	166.9	159.2
D86	90% Evaporated	deg. C	184.7	186.9	185.0	169.1
D86	95% Evaporated	deg. C	193.3	194.3	194.5	191.5
D86	FBP	deg. C	213.7	212.5	210.5	208.8
D86	Recovery	vol. %	98.5	97.7	97.9	96.3
D86	Residue	vol. %	1.1	1.1	1.1	1.1
D86	Loss	vol. %	0.4	1.2	1.0	2.6
D5191	Vapor Pressure, ASTM	psi	8.29	8.3	9.2	8.9
D4052	Sp. Grav at 60F		0.7699	0.7656	0.769	0.7727