

2013 Ford 1.6L EcoBoost Engine Tested with Tier 2 Fuel – NCAT Test Report



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**Test:** 2013 Ford 1.6L EcoBoost Engine Tested with Tier 2 Fuel – NCAT Test Report

**Program:** Light-Duty Greenhouse Gas Test Program

**Project:** Mid Term Evaluation (MTE) Engine Benchmarking

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# Purpose of Test

The purpose of this test is to characterize the performance of a 2013 Ford EcoBoost 1.6L engine, in particular to generate fuel map data that may be used in the ALPHA model. During the course of this testing, test methods for use in characterizations of future engines were also developed.

# Definitions

|  |  |
| --- | --- |
| Fuel map | Engine operating map that displays contours of brake specific fuel consumption (in g/kWh) on a grid of engine speeds (RPM) and engine torques (Nm). |
| Coefficient of Variation (COV) | A measure of variability defined as the ratio of standard deviation to mean (σ/μ) |
| Protection mode | An engine operation mode where the ECU retards ignition timing, limits load and/or runs excess fuel (λ<1) due to exhaust temperature limits being reached |

# 

# Description of Test Article

The engine used in this project was a 2013 Ford EcoBoost 1.6L, which is a direct-injection gasoline engine from a Ford Escape vehicle. Table 1 summarizes information that describes the vehicle and engine used in this test program.

**Table 1: Summary of Vehicle and Engine Identification Information**

|  |  |
| --- | --- |
| Vehicle (MY, Make, Model) | 2013 Ford Escape |
| Vehicle Identification Number | 1FMCU0GX3DUC49410 |
| Engine (displacement, name) | 1.6 L EcoBoost |
| Rated Power | 180 Hp @ 5700 RPM |
| Rated Torque | 240 Nm @ 1600-5000 RPM |
| Recommended Fuel | Regular unleaded |
| Engine Features of Interest for MTE | turbocharged, spray-guided direct-injection |

# Test Site

This test was performed in National Center for Advanced Technology (NCAT) Test Cell 9, but the procedure is applicable in various NCAT test cells using iTest controls and RPECS data collection.

# Test Cell Capabilities

The following instrumentation, listed in Table 2, exists in Test Cell 9 although not all instrumentation listed may have been utilized during this testing.

**Table 2: Instrumentation in NCAT Test Cell 9**

|  |  |  |
| --- | --- | --- |
| Instrument Name | Purpose/Measurement Capabilities | Manufacturer |
| Dynamometer | Motoring and absorbing AC dyno | Meidensha |
| Torque Sensor | Measures engine torque | HBM |
| CVS dilution tunnel | Exhaust flow system | EPA |
| Coriolis fuel meter | Measures fuel flow rate | Micromotion |
| Laminar flow element | Measures air flow rate | Merriman |
| Methane cutter | Removes methane | Horiba |
| Emissions bench | Raw and dilute exhaust gases:  CO, THC, NOx, CH4, CO2 | MEXA |

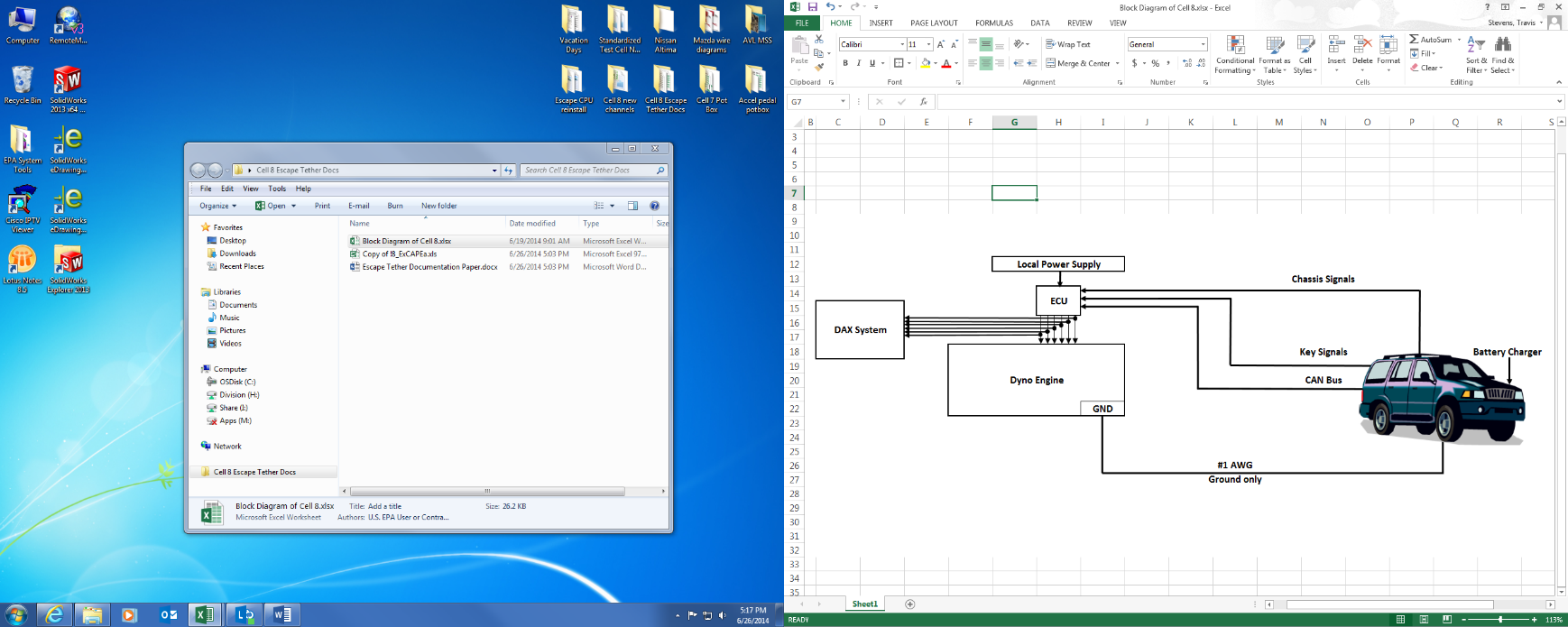
# Data Collection Systems

Test cell data acquisition and dynamometer control are performed by iTest, a data acquisition system developed by A&D Technology, Inc. Test cell data including temperatures, pressures, speed and torque are logged by iTest. Engine and transmission ECU inputs and outputs are measured using the Rapid Prototyping Engine Control System (RPECS), a hardware/software package for engine control and supplemental data acquisition developed by Southwest Research Institute (SwRI). RPECS data is logged by iTest via an Ethernet connection and combined into a single output file. The engine control and data acquisition software packages are summarized below in Table 3.

**Table 3: Engine Control and Data Acquisition Systems**

|  |  |  |  |
| --- | --- | --- | --- |
| **System** | **Developer** | **Description** | **Data Rate** |
| iTest | A&D Technology Inc., Ann Arbor, MI | Test cell automation hardware and software system that controls the dynamometer and some engine controls; collects test cell data; master data logger. | 10-100 Hz |
| MATLAB | MathWorks, Natick, MA | Software used for development of data processing algorithms for transient testing | -- |
| RPECS | Southwest Research Institute, San Antonio, TX | Crank angle based engine control and data acquisition system that collects ECU analog and CAN data, TCU analog and CAN data, and controls torque converter lock up solenoid. | 1/engine cycle |

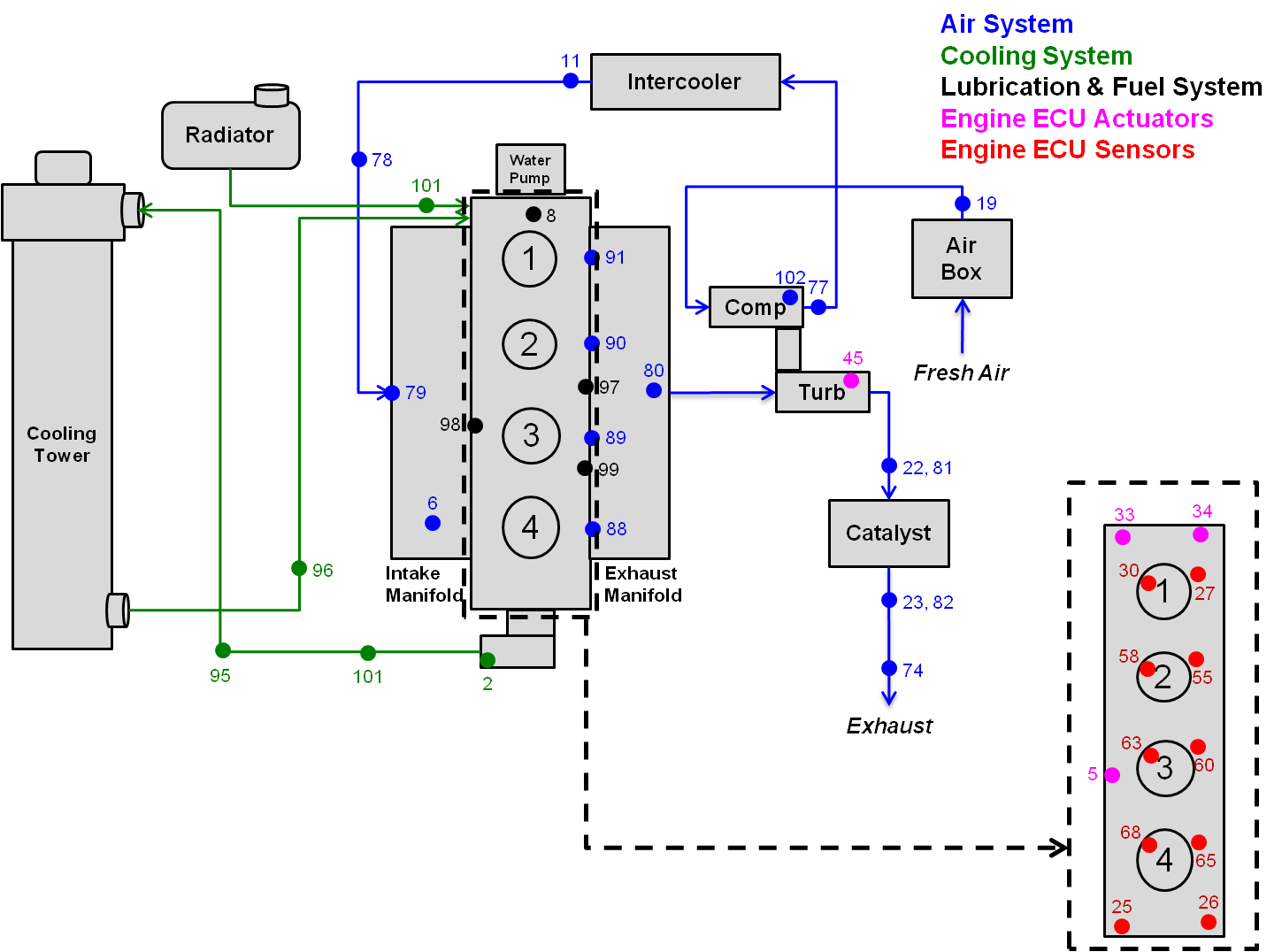
**Vehicle Tethering**

****The objective of this benchmarking was to characterize the engine while operating in an engine dynamometer test cell as though the engine were operating in the vehicle. The ECU in today’s vehicles requires communication with other control modules to monitor the entire vehicle’s operation (security, entry, key on, dashboard signals, etc.). Because the ECU needs signals from these modules to operate, the signals need to be extended into the test cell so the ECU can send and receive signals indicating correct vehicle operation. For this benchmark testing, the wiring harnesses were lengthened connecting the ECU in the test cell to the rest of the vehicle. As a result, the engine located in the dynamometer cell was then tethered to its vehicle chassis located outside the cell. The ECU signals were monitored by the data acquisition system. Figure 1 illustrates the tethered wiring harness.

**Figure 1. Vehicle and Engine Tethered Wiring Harness**

# Engine Setup

Figure 2 illustrates the engine setup and sensor location in the dynamometer test cell. The engine sensor locations of the systems being monitored are indicated on the diagram corresponding to the system colors. A description of the monitored systems is also provided in the upper right corner of the figure.



**Figure 2: Testing Schematic with Engine Sensor Locations & Monitored Systems**

# Engine Systems

The stock engine systems were used with the addition of instrumentation as follows:

1. *Intake:* Stock airbox and plumbing with a laminar flow element (LFE) connected to airbox inlet.
2. *Charge air cooling*: Stock tubing and intercooler; stock intercooler was sandwiched to a chilled water heat exchanger with fans; fan speed and chilled water temperature controlled stock intercooler air outlet temperature; this type of intercooler system maintains the stock air flow characteristics of the vehicle system with stable temperature control.
3. *Exhaust*: Turbocharger outlet connected to stock catalyst and emissions tunnel via 2-inch diameter tubing; emission tunnel pressure controlled to Patm +/- 1.2 kPa per the CFR.
4. *Cooling system*: Stock cooling system but the radiator was replaced with a cooling tower; stock engine thermostat controlled engine coolant temperature; cooling tower controlled to 85 °C by the test cell control system.
5. *Oil system*: Stock oil cooler connected to a chilled water system and controlled to 90 °C by the test cell control system.
6. *Front End Accessory Drive (FEAD)*: Stock drive belt and pulley FEAD system.
7. *Alternator*: Modified output by removing the field coils for no electrical.
8. *Flywheel and housing*: Stock manual flywheel with aluminum adapter plate connected to the driveshaft; generic SAE 6 flywheel housing with an adapter plate connected to the engine.

**Intercooler Temperature Control**

During testing, engine temperatures were maintained to a level representative of real-world use, where the engine would be cooled by airflow into the engine compartment as vehicle speed increases. On-road testing of a European Ford Focus, which contained an identical EcoBoost engine, identified 30-40 °C as the target intercooler air temperature range for the engine. In the test cell, air charge temperature was thus maintained between 30-40 °C by using the stock intercooler attached to a water-to-air cooler and fans.

# Test Methodology

## Test Fuel

The primary properties of the Tier 2 fuel used in this test program are shown in Table 4 below. A detailed summary of the fuel analysis performed and results measured for the Tier 2 fuel utilized in the test program can be found in the file: *6- NVFEL Fuel Analysis Report 25278.pdf*.

**Table 4. Fuel Properties for FTAG 25278**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter Description | Test Fuel Specifications  (40 CFR §86.113-04) | Reference Procedure | Measured Results | Units |
| Research Octane (optional) | 93 (minimum) | ASTM D2699; ASTM D2700 | 96.6 | RON |
| Octane Sensitivity (optional) | 7.5 | ASTM D2699; ASTM D2700 | 7.7 | RON-MON |
| Hydrocarbon Composition (vol %) | | | | |
| Olefins | 10% Maximum | ASTM D1319 | 0.6 | Vol % |
| Aromatics | 35% Maximum | ASTM D1319 | 30.6 | Vol % |
| Total Sulfur, wt.% | 0.0015-0.008 | ASTM D2622 | 39.6 | ppm |
| Dry Vapor Pressure Equivalent, psi (kPa) | 8.7–9.2 (60.0-63.4) | ASTM D5191 | 8.95 | psi |
| The following are provided for Reference Only and are not specified in the CFR | | | | |
| Antiknock | None | N/A | 92.75 | (RON+MON)/2 |
| Net Heating Value | None | ASTM D3338 | 18447 | BTU/lb |
| None | N/A | 42.9 | MJ/kg |
| Alcohol Content | None | ASTM D5599 | 0.00 | Vol % |
| Carbon Content | None | ASTM D3343 | 0.86640 | Weight Fraction |

# Quality Procedures

This test program is covered by the Light-Duty Greenhouse Gas Test Program: Evaluating Potential Future Vehicle Technologies Quality Assurance Project Plan (QAPP).

# Engine Safeties

Table 5 lists the limits that exist for several engine parameters. These variables were monitored to ensure component durability and operator safety.

**Table 5: Engine Safety Limits**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Test Parameter Name** | **Units** | **Minimum** | **Maximum** |
| Oil Pressure |  | kPag | 175 |  |
| Coolant Temperature | Coolant Temp | oC |  | 120 |
| Engine Speed | Speed | RPM |  | 6500 |

# Pre-Conditioning and Common Mode Check

Before testing began, the engine was warmed up. The engine was considered “warm” when the fuel flow rate and exhaust temperatures stabilized and the coolant and oil temperatures were a minimum of 90 oC and 80 oC respectfully. A common mode, run with the parameters given in Table 6, was repeated at the beginning of each test to expose any potential inconsistencies that could indicate equipment wear or improper instrument calibration. For each common mode, the parameters in Table 7 were examined to check for any deviation from the norm.

**Table 6: Common Mode Test Conditions and Criteria for Achieving “Warmed” State**

|  |  |  |
| --- | --- | --- |
| Parameter | Test Parameter Name | Condition |
| Engine Speed Setting | Speed | 2000 RPM |
| Pedal Command Setting |  | 30% |
| Coolant Temperature Criteria | Coolant Temp | 90 oC min |
| Oil Temperature Criteria | Oil Sump Temp | 80 oC min |

**Table 7: Common Mode Test Parameters**

|  |  |  |
| --- | --- | --- |
| Parameter | Test Parameter Name | Unit |
| Brake Mean Effective Pressure | BMEP | Bar |
| Thermal Efficiency | BTE | % |
| Intake Manifold Pressure | Intake Manifold Press | kPa |

# Data Set Definition

The data logged included torque, fuel flow, emissions, temperatures, pressures, in-cylinder pressure and OBD/epid CAN data. The steady-state data were recorded by the iTest data acquisition system. Each steady-state mode was logged to a single output file.

The final data set containing the engine mapping test parameters is provided in the test data file: *4- 2013 Ford 1.6L EcoBoost Engine Tier 2 Fuel - Test Data.xlsx*. The data set includes a list of the test parameters along with the variable name, description, and calibration status. Variables that are listed “Reference Only” are not calibrated to a standard but are recorded to verify the correct operation of the engine to ensure the engine and ECU are operating without any faults or a check engine light. NCAT’s test data processor also uses this data set to produce the test data plots provided in the file: *5- 2013 Ford 1.6L EcoBoost Engine Tier 2 Fuel - Test Data Plots.pdf.*

# Test Data Points

The test data points for this engine map were intended to cover the engine’s torque and speed range rated values listed in Table 1. The steady state testing was conducted by operating the engine at a fixed speed and setting the engine load with the pedal (accelerator) input from iTest.

Each engine mapping data point was established by setting the engine’s speed with the dyno and then nominal torque value was requested by setting the pedal to a position from 0 to 100%. Once the engine torque value at that data point stabilized, the data was then recorded. The speed values were selected in 200-250 rpm increments at the lower engine speeds and 500 rpm increments at higher engine speeds. The pedal inputs range from 0 to 100% and were incremented to gradually increase load until the engine torque reaches the next higher load point.

The engine mapping process incremented through the torque column starting with the engine’s lowest speed in the map. Once the load range was completed for a specific engine speed by increasing the pedal position from 0% to 100%, the engine speed was then increased to the next predetermined speed and the process was repeated. The zero pedal (0%) point for each speed setting established the minimum torque value utilized in the construction of the full engine map. The torque and speed values measured for this engine are shown in Figure 3, note the speed points were limited to not exceed 4500 rpm.

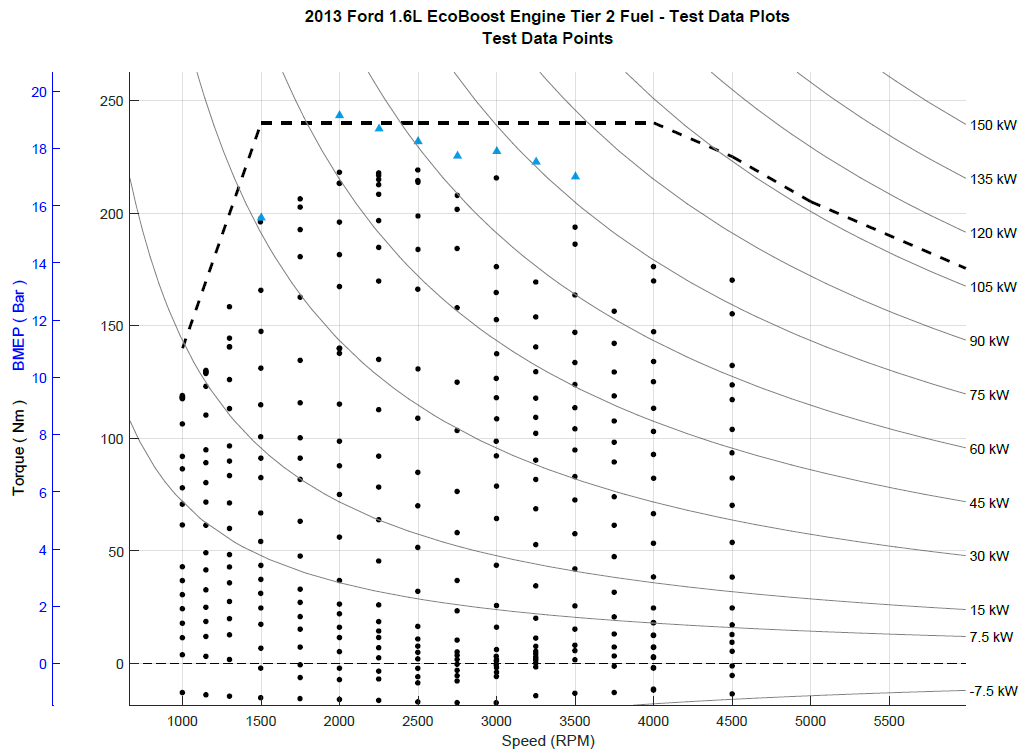


Figure 3. Test Data Points

# Data Collection Procedure

The engine with its associated ECU controller is subject to OEM-specific protection modes that are not controllable in the test cell. These protection modes may limit operation of the engine, particularly at higher loads where engine temperatures can reach critical thresholds.

To account for the protection modes, two test procedures, were followed. The first procedure was used to obtain low-load (below ~70% maximum rated torque) steady-state data points on the fuel map where the engine protection modes were not engaged. The second procedure, incorporating a step-change transient, was used to obtain high-load data points when the engine experiences variable behavior due to its protection strategies.

**Test Procedure**

The engine and vehicle were tested in the engine dyno cell with a tethered wire harness as described previously. The speed of the engine was controlled by the dyno speed set point. The load of the engine was controlled by the ECU which was set by the vehicle pedal input. The pedal input signal was generated by disconnecting the vehicle’s pedal and replacing it with an iTest controller. The transmission PRNDL was set in the neutral position to allow for starter cranking, starting and setting desired engine load.

The procedure for starting up and shutting down the test cell is outlined in the file: *3b- 2013 Ford 1.6L EcoBoost Engine - Test Cell 9 Startup & Shutdown Procedure.docx*. This procedure describes how to activate and operate the test cell components required to run the engine. This procedure was developed during the installation of the engine and associated hardware needed for testing prior to conducting any recorded engine mapping and testing. This procedure ensures the correct start up and shutdown of the engine, the vehicle, and the test cell equipment for the engine to operate as expected in the test cell.

**Low-Load Data Points Procedure**

For each engine speed, the procedure stepped through an array of torques and records data. The engine speed was then incremented by 250 rpm and the torque array repeated. At each speed and torque combination a set of stability criteria were applied prior to logging the point for 10 seconds. Stability was determined by fuel flow, torque, & turbocharger turbine inlet temperature.

**High-Load Data Points Procedure**

A step-change procedure was applied to obtain high-load data. In real-world driving, the engine will not remain at wide open throttle (WOT) for more than a few seconds, and drivers are unlikely to be interested in achieving steady-state under high load conditions. For this fuel map, it was of interest to obtain a quasi-steady-state value for these high load points that represented the engine’s performance at a given pedal command.

At high-load conditions (typically ≥70% of rated torque), when the ECU is in protection mode, the engine was set to a desired speed at 10 Nm. The data logger was triggered on and the engine was stepped to the desired torque. The log ran for a total of 20 seconds and then the engine was brought back to the cool down mode of 1500 rpm and 10 Nm. The engine was then cooled down before stepping to the next point. The transient nature of the collected data was accounted for in the post processing of these points.

# Data Set Processing

The iTest data collection system logs each single mode at 10 hz for 10 seconds and the data is subsequently averaged and written to the data file. The variable list also includes statistical information for selected variables such as standard deviation, coefficient of variation, minimum and maximum. Also within iTest, certain parameters are calculated as described below.

**Low-Load Data Post-Processing**

The low-load data are stable over the entire log. Brake specific fuel consumption (BSFC) in g/kWh was calculated according to the equation below using values obtained from iTest.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | |  |
|  | | | |
| Where: | |  | |

Brake thermal efficiency (BTE) was calculated using the known heating value of the test fuel.

Where: Net Heating Value of the fuel is provided in Table 4

After BSFC and thermal efficiency were calculated, the mean, standard deviation, and COV of the time-series were calculated for each field. All variables in each test were averaged, which resulted in a single value for each variable.

**High-Load Data Post-Processing**

Typically, when benchmarking an engine, steady-state operation allows for the straightforward measurement of fuel consumption either by a fuel flow meter or by exhaust emissions. NCAT generally uses a fuel flow meter when benchmarking engines. Due to transport lag and other time delays, these two measurement techniques are unable to accurately quantify the amounts of fuel consumed over short periods of engine operation. Consequently, NCAT uses a third technique that uses fuel injector data to measure how much fuel is consumed.

By capturing detailed measurements of fuel injector pulse duration and fuel rail pressure during steady state testing, an injector calibration can be constructed to then estimate fuel consumption. For improved accuracy, the fuel rail pressure is measured via a high-speed data acquisition system synchronously with the crankshaft to minimize the distortion caused by rapid fluctuations in pressure. The textbox shown in Figure 4 labeled “Injector Fuel Flow Correlation” explains the method of injector fuel flow correlation that was developed for this testing

The relationship between fuel rail pressure, injection duration and injected fuel quantity for a single injection event follows from the classic orifice equation and is shown in the equation below.

|  |
| --- |
|  |

Where: = injected fuel quantity (mg)

= High pressure fuel rail pressure (MPa)

= Injector open duration (ms)

The calibration constants m (slope) and b (offset) can be determined via linear regression. Figure 4 below provides an example of the relationship using data obtained during testing.

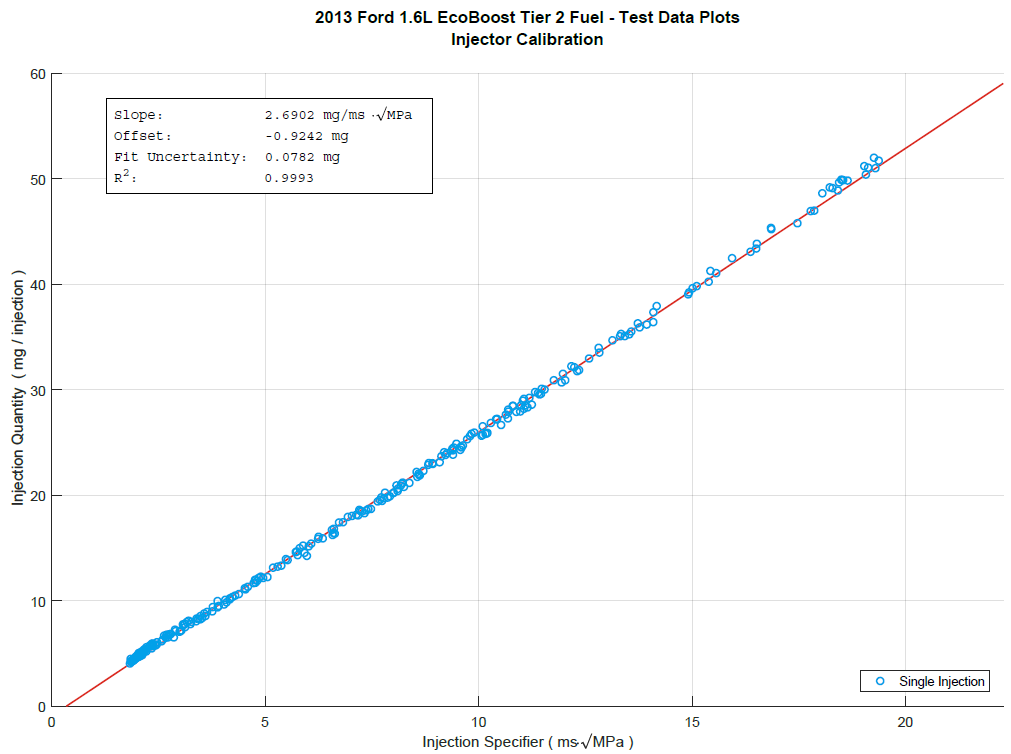


Figure 4. Fuel Flow Correlation

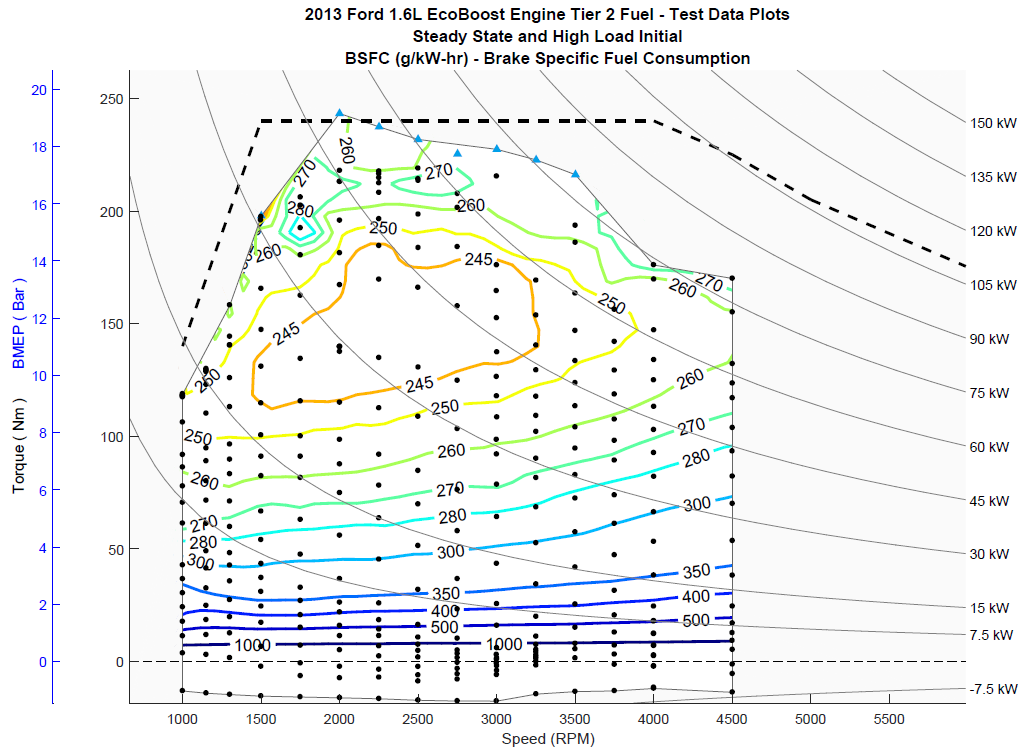
# Data Quality Control

A test parameter subset of data focused on engine efficiency was extracted from the iTest data log for review. Descriptions for the test parameter list are provided in the test data set for reference. The data set is analyzed for outlier data based on the statistical data included in the iTest data logger file. In addition, the data set is plotted and reviewed using an NCAT developed contour plotting routine. During these reviews, any outliers may be removed as needed based upon the discretion of the internal review team.

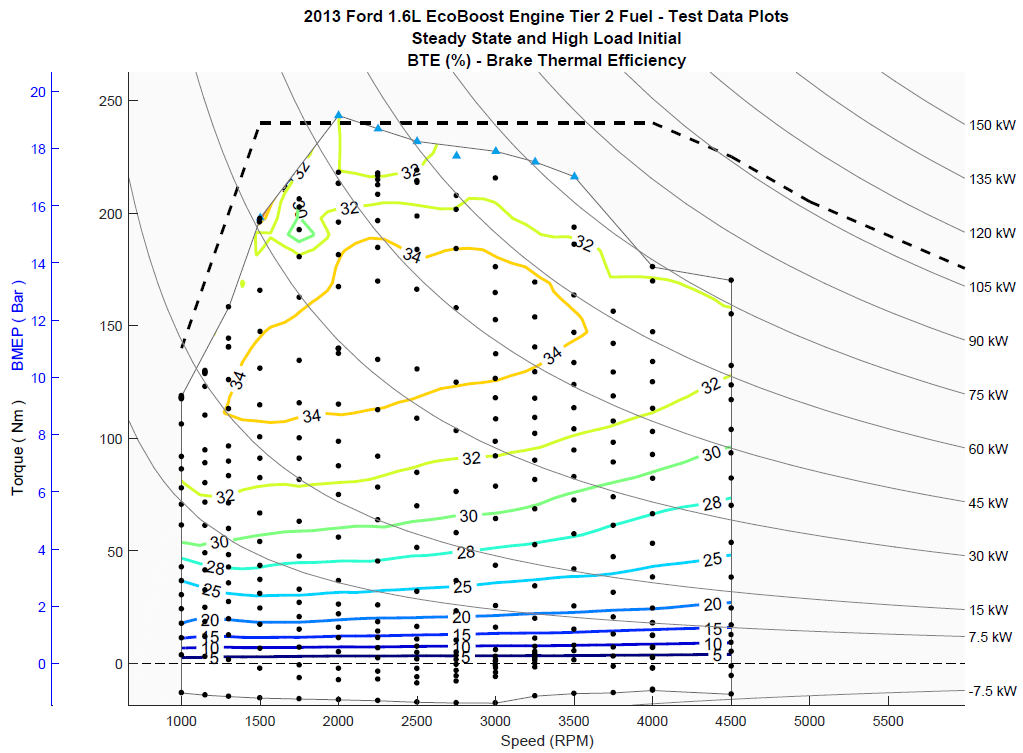
# Results

The final test data set containing the engine mapping test parameters is provided in the file: *4- 2013 Ford EcoBoost 1.6L Engine Tier 2 Fuel - Test Data.xlsx.* The average torque, speed, and fuel flow measurements were used to determine a grid and generate fuel contour maps for Brake Specific Fuel Consumption (BSFC), shown in Figure 5, and Brake Thermal Efficiency (BTE), shown in Figure 6.

The black dots in the figures above indicate the speed/load points at which steady state data were included in the contour. The dashed line indicates the rated torque/power points as advertised by the manufacturer [1]. Contour maps for additional test data measurements are provided in the file *5- 2013 Ford 1.6L EcoBoost Engine Tier 2 Fuel – Test Data Plots.pdf.*



**Figure 5. BSFC**



**Figure 6. BTE**

# Uncertainty

Sensor/Signal Uncertainties

The uncertainties of the signals [u(signal)] in the data set can be based on (a) the uncertainty associated with the calibration standard, (b) the uncertainty of the sensor calibration [u(calibration)], and (c) the uncertainty of the signal during operation [u(operation)]. The uncertainty associated with the calibration standard is assumed to be negligible when compared to other uncertainties and thus this uncertainty is not considered for this calculation.

To determine the uncertainty of the sensor calibration, past calibration records were assessed and the difference between the standard and measured quantities were used to calculate uncertainty, resulting in an uncertainty of 0.532 rpm for the dynamometer speed, 0.176 Nm for the torque signal, and 0.0109 grams per second for the fuel flow. To determine the uncertainty of the signal during operation, the standard deviations for each signal were calculated from the testing data for each mode. This standard deviation was then used to calculate the operational uncertainty as:

Where n is the number of data points in a mode. The total signal uncertainty was then calculated as shown in Table 8.

**Table 8: Standard Uncertainties for Signals**

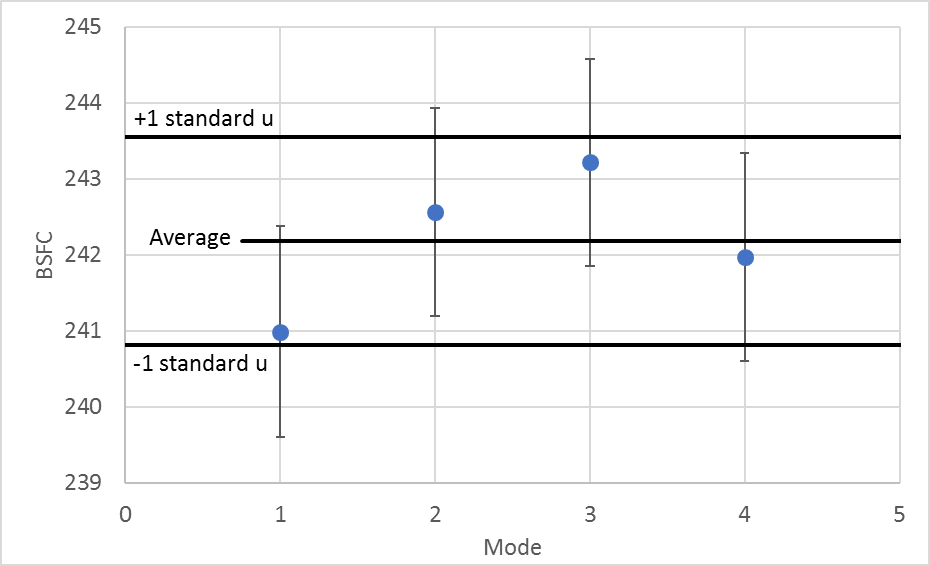
|  |  |  |  |
| --- | --- | --- | --- |
| Signal | u(calibration) | u(operation) | u(signal) |
| Speed (rpm) | 0.532 | */n* | Sqrt[0.283 + (*/n*)] |
| Torque (Nm) | 0.176 | */n* | Sqrt[0.0309 + (*/n*)] |
| Fuel (g/sec) | 0.0109 | */n* | Sqrt[0.0001188 + (*/n*)] |

Uncertainty of BSFC

The total uncertainty for BSFC is thus calculated by:

or

As a check, the uncertainty of repeated modes in the data set were examined. The data included four modes taken at approximately 2000rpm and 139 Nm; at this point the BSFC uncertainty is approximately 1.37 g/kW-hour. All four modes fall within +/- 1 standard uncertainty from the mean, indicating that the uncertainty calculation is likely reflective of the actual uncertainty.



**Figure 8. BSFC Uncertainty for Repeated Modes**

Uncertainty of BTE

The derivation of the uncertainty of thermal efficiency is similar, but with the inclusion of the uncertainty of the fuel heating value. Assuming *u(HV)* = 10 BTU/lb,

Standard uncertainties are analogous to standard deviations, such that it would be expected that, for a given set of data, the “true” value of a parameter would fall within +/-1*uc* for 68% of the data points, the “true” value of a parameter would fall within +/-2*uc* for 95% of the data points, and the “true” value of a parameter would fall within +/-3*uc* for 99.7% of the data points. The calculated uncertainty for both the BSFC and BTE measurements are shown in Figures 8 and 9.

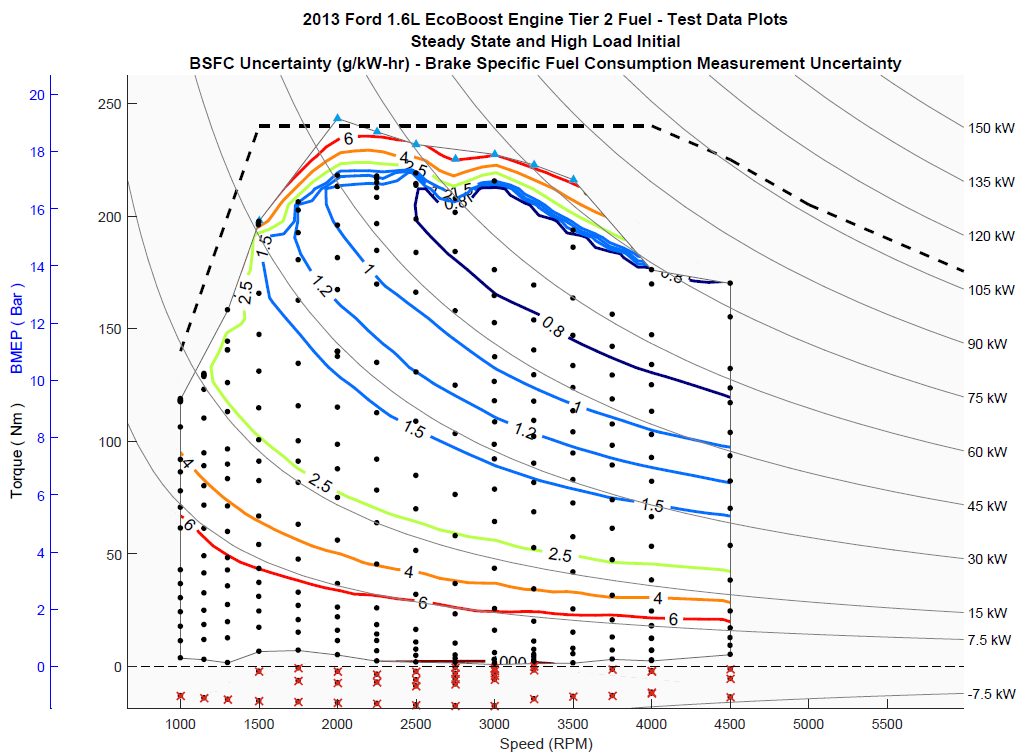
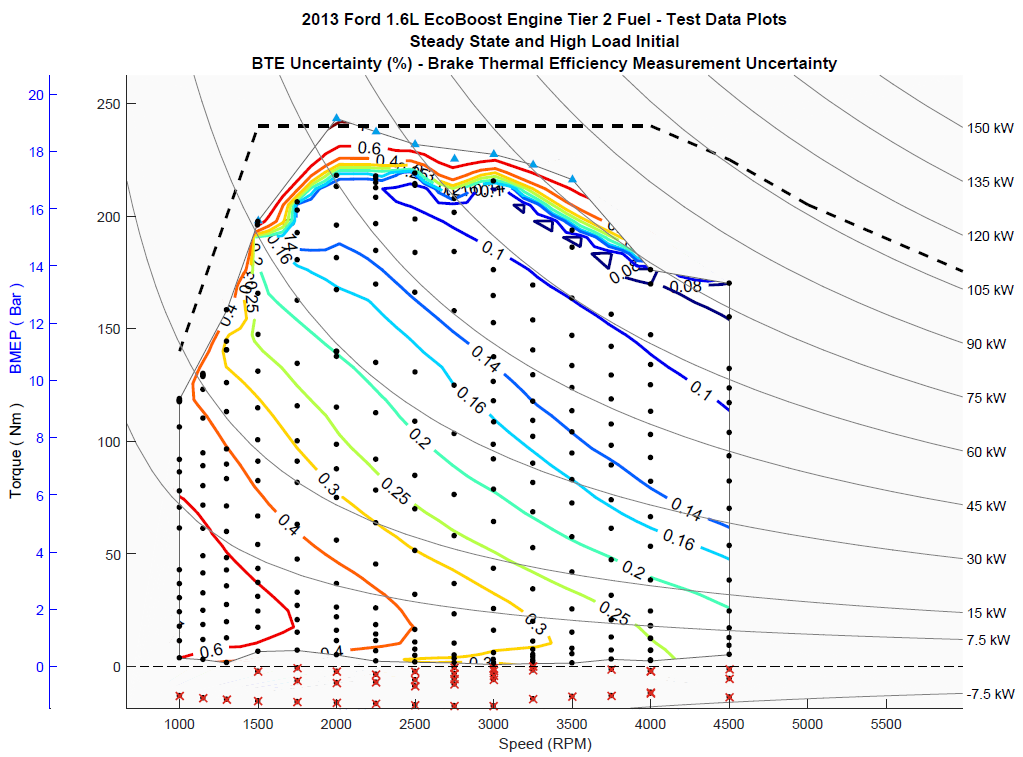


Figure 9. BSFC Uncertainty



**Figure 10. BTE Uncertainty**

# References

[1] Stuhldreher, M., Schenk, C., Brakora, J., Hawkins, D. et al., "Downsized Boosted Engine Benchmarking and Results," SAE Technical Paper 2015-01-1266, 2015, doi:10.4271/2015-01-1266.