

2018 Mazda 2.5L Skyactiv-G Engine Tested with Tier 3 Fuel – NCAT Test Report

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# Purpose of Test

The purpose of this test is to characterize the performance of a 2018 Mazda 2.5L Skyactiv-G engine and generate fuel map data that may be used in the ALPHA full vehicle simulation model.

# 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) |
| 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 |
| ALPHA | Advanced Light-Duty Powertrain and Hybrid Analysis tool |

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# Description of Test Article

The engine used in this testing was a 2018 Mazda6 2.5L Skyactiv-G with cylinder deactivation and Variable Valve Timing (VVT). 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) | 2018 Mazda6 Sport |
| Vehicle Identification Number | JM1GL1UMXJ1303453 |
| Engine (displacement, name) | 2.5-liter Skyactiv-G |
| Rated Power | 187 hp @ 6000 RPM |
| Rated Torque | 186 lb-ft @ 4000 RPM |
| Recommended Fuel | Regular unleaded gasoline |
| Engine Features of Interest | • DOHC 16-valve 4-cylinder  • Variable Valve Timing (VVT)  • Cylinder Deactivation  • Chain driven dual overhead cams  • Direct Coil-on-plug electronic ignition |

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# Test Site

This test was performed in National Center for Advanced Technology (NCAT) Test Cell 8, but the procedure is applicable to any NCAT test cells using iTest controls and RPECS data collection.

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# Test Cell Capabilities

The following instrumentation, listed in Table 2, exists in Test Cell 8 although not all instrumentation listed may have been utilized during this testing.

**Table 2: Instrumentation in NCAT Test Cell 8**

|  |  |  |
| --- | --- | --- |
| Equipment / Instrument Name | Purpose/Measurement Capabilities | Manufacturer |
| Dynamometer | Absorb torque from engine and provide motoring torque to engine | Meidensha Corp.,  Tokyo, Japan |
| Torque Sensor | Measures torque | HBM GmbH,  Darmstadt, Germany |
| CVS Dilution Tunnel | Exhaust flow system | EPA |
| Coriolis Fuel Meter | Measures fuel flow rate | Emerson Micro Motion,  St. Louis, MO |
| Laminar Flow Element | Measures air flow rate | Meriam Process Technologies, Cleveland, OH |

# Data Collection Systems

Test cell data acquisition and dynamometer control were performed by iTest, a software package developed by A&D Technology, Inc. RPECS-IV (Rapid Prototyping Electronic Control System - IV) is a supplemental data acquisition software developed by Southwest Research Institute (SwRI) which directly measures and streams ECU input/output (I/O) along with test cell data to iTest. Temperatures, pressures, and test cell data were also sent from iTest to RPECS via CAN. The engine control and analysis systems are summarized 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 engine control unit (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 to connect (tether) the ECU in the test cell to the rest of the 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 Wire Harness**

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# Engine Setup

In the test setup for this testing. the engine is coupled to the dynamometer via the drive shaft.  Utilizing this test method minimizes the engine accessory loads and removing the alternator does not provide any output electrical load.  The only possible accessory loads are from the serpentine belts, water pump, idler pulleys, and alternator pulley and bearings. Figure 2 illustrates the engine configuration and sensor location in the dynamometer test cell. The sensor colors shown in the upper left corner of the figure indicate which systems are monitored.

Chart

Description automatically generated

**Figure 2: Schematic of Dynamometer Test Cell and the Engine Sensor Locations Corresponding to the Identified Systems**

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

* *Intake:* The stock air box and plumbing were used.
* *Exhaust:* The stock exhaust system was used including catalyst and mufflers (the figure only shows one muffler). The exhaust system outlet was connected to the constant volume sampling (CVS) dilution tunnel via 2-inch diameter tubing. CVS pressure was controlled to approximately Patm +/- 1.2 kPa, which is a variation of pressure below the required limits specified within the U.S. Code of Federal Regulations for chassis dynamometer testing.
* *Cooling system:* The stock cooling system was used, but the radiator was replaced with a cooling tower. The stock engine thermostat and electric water pump were used to control engine coolant temperature. The chassis was tested before the engine was benchmark tested and the engine coolant temperatures were observed for these tests and used as a guide for the coolant temperature set point. The cooling tower was controlled to 85°C by the test cell control system.
* *Oil system:* The engine oil was cooled by adding a sandwich oil filter manifold which allows oil to be routed to an external heat exchanger. This heat exchanger was connected to a chilled water system and controlled to 90°C by the test cell control system.
* *Alternator*: No alternator was used.
* *Front End Accessory Drive (FEAD):* The serpentine belt for the water pump was left on for this testing while the belt for the alternator was removed.

# Test Methodology

## Test Fuel

The primary properties of the Tier 3 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 3 fuel utilized in the test program can be found in the file: *6– NVFEL* *Fuel Analysis Report 28637.pdf*.

**Table 4. Fuel Properties for FTAG 28637**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter Description | Test Fuel Specifications  (Tier 3) | Reference Procedure | Measured Results | Units |
| Antiknock Index | 87.0-88.4 (minimum) | ASTM D2699; ASTM D2700 | 87.85 | (RON+MON)/2 |
| Sensitivity | 7.5 (minimum) | ASTM D2699; ASTM D2700 | 8.3 | RON-MON |
| Olefins | 4.0-10.0 | ASTM D6550 | 7.8 | mass % |
| Total Aromatic Hydrocarbons | 21.0-25.0 | ASTM D5769 | 22.40 | volume % |
| Sulfur | 8.0-11.0 | ASTM D2622, D5453 or D7039 | 8.30 | ppm |
| Dry Vapor Pressure Equivalent, psi (kPa) | 8.7–9.2 (60.0-63.4) | ASTM D5191 | 8.99, 8.97 | kPa (psi) |
| Ethanol | 9.4-10.2 | ASTM D4815 or D5599 | 9.60 | volume % |
| The following are provided for Reference Only and are not specified in the Regulations | | | | |
| Density | None | ASTM D4052 | 0.74899 | g/cm3 |
| Net Heating Value | None | ASTM D3338 | 17894.00 | BTU/lb |
| None | N/A | 41.62 | MJ/kg |
| Carbon Content | None | ASTM D5291 | 82.53 | wt % |

# 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 | 100 |  |
| Coolant Temperature | Coolant Temp | oC |  | 110 |
| Engine Speed | Speed | RPM |  | 6500 |

# Pre-Conditioning and Common Mode Check

Before collecting operating map data, 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 respectively. 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.

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

|  |  |  |
| --- | --- | --- |
| Parameter | Test Parameter Name | Condition |
| Engine Speed Setting | Speed | 2500 RPM |
| Pedal Command Setting |  | 30% |
| Coolant Temperature Criteria | Coolant Temp | 90 oC |
| Oil Temperature Criteria | Oil Sump Temp | 80 oC |

**Test Cell Procedures**

The procedure for starting up and shutting down the test cell is outlined in the file: *3b- 2018 Mazda 2.5L Skyactiv-G - Test Cell 8 Startup & Shutdown Procedure.* 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.

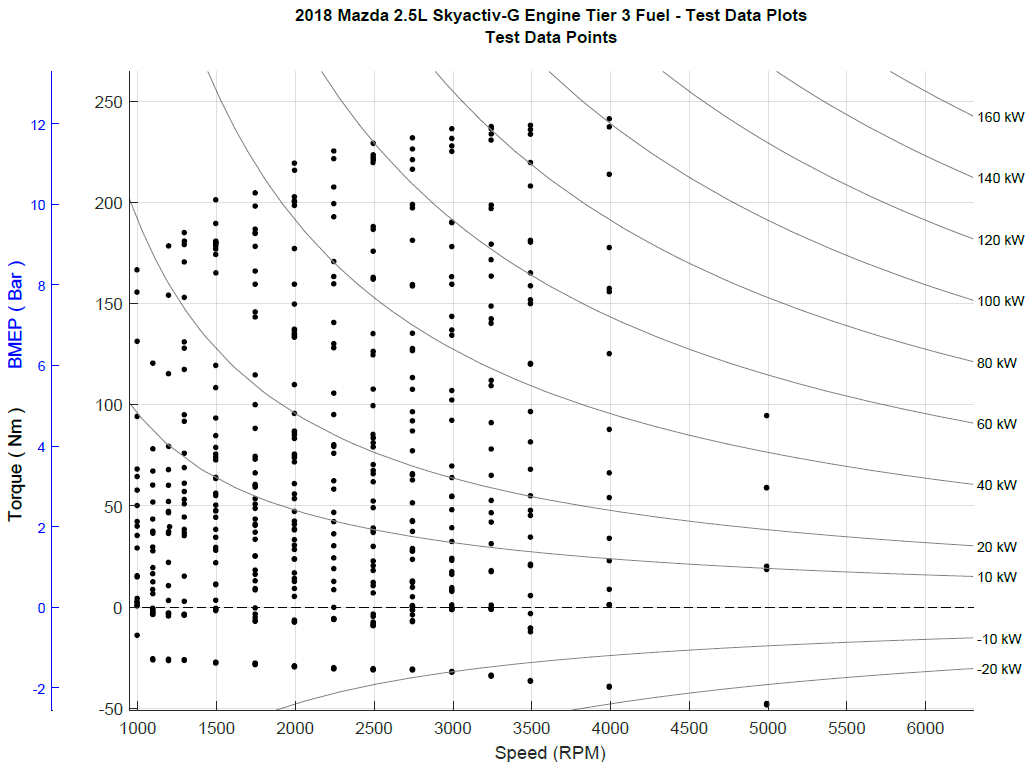
# Test Data Collection

The test data points for this engine map covered the torque and speed range of the engine according to the Test Data Points shown in Figure 3. 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 100-200 rpm increments at the lower engine speeds and 250 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 torque and speed values measured for this engine are shown in Figure 3.

The zero pedal (0%) point for each speed setting established the minimum torque value utilized in the construction of the full engine map. The setup as described previously, with the engine coupled to the dynamometer via the drive shaft in the test cell, precludes the engine from running below 1000 rpm due to the driveline going into torsional resonance. To operate the engine and collect data at idle, a clutch and flywheel were installed on the engine that could be disengaged for starting and idle speeds. The clutch was actuated remotely by a hydraulic throw-out bearing and pneumatic actuator which was controlled by iTest to enable the engine to run at idle speeds (600 to 700 rpm) and collect data without any driveline inertia.



**Figure 3. Test Data Points**

# Data Set Definition

The data logged during testing 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- 2018 Mazda 2.5L Skyactiv-G Engine Tier 3 Fuel - Test Data*. 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- 2018 Mazda 2.5L Skyactiv-G Engine Tier 3 Fuel - Test Data Plots.*

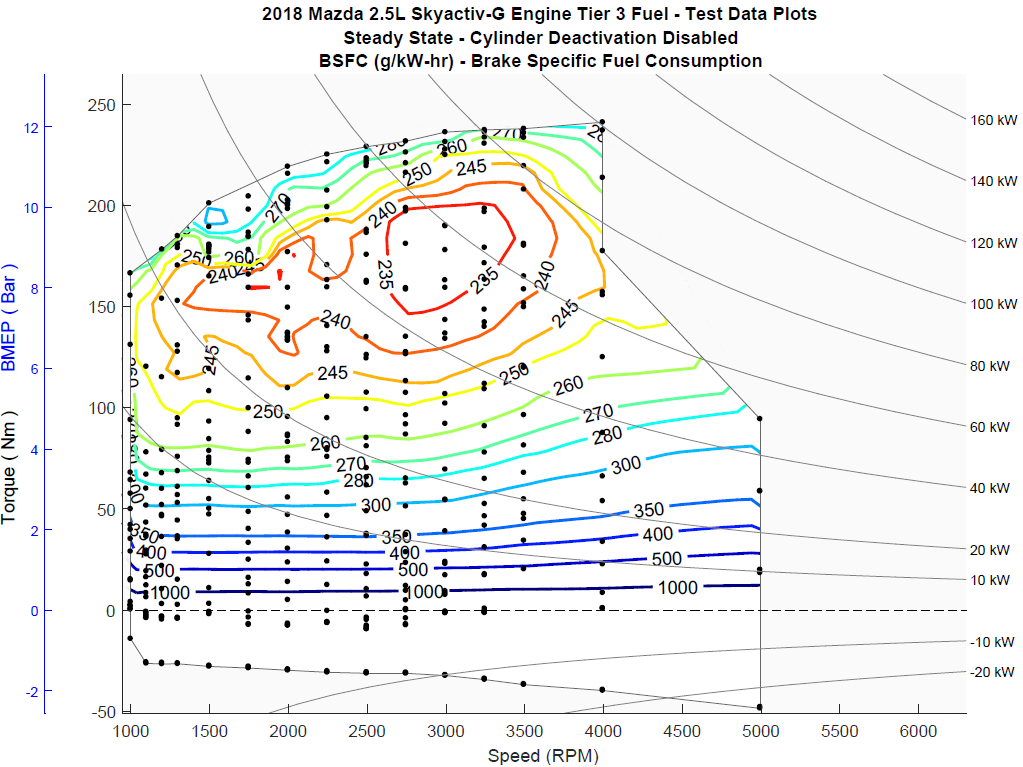
# Data Quality Control

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.

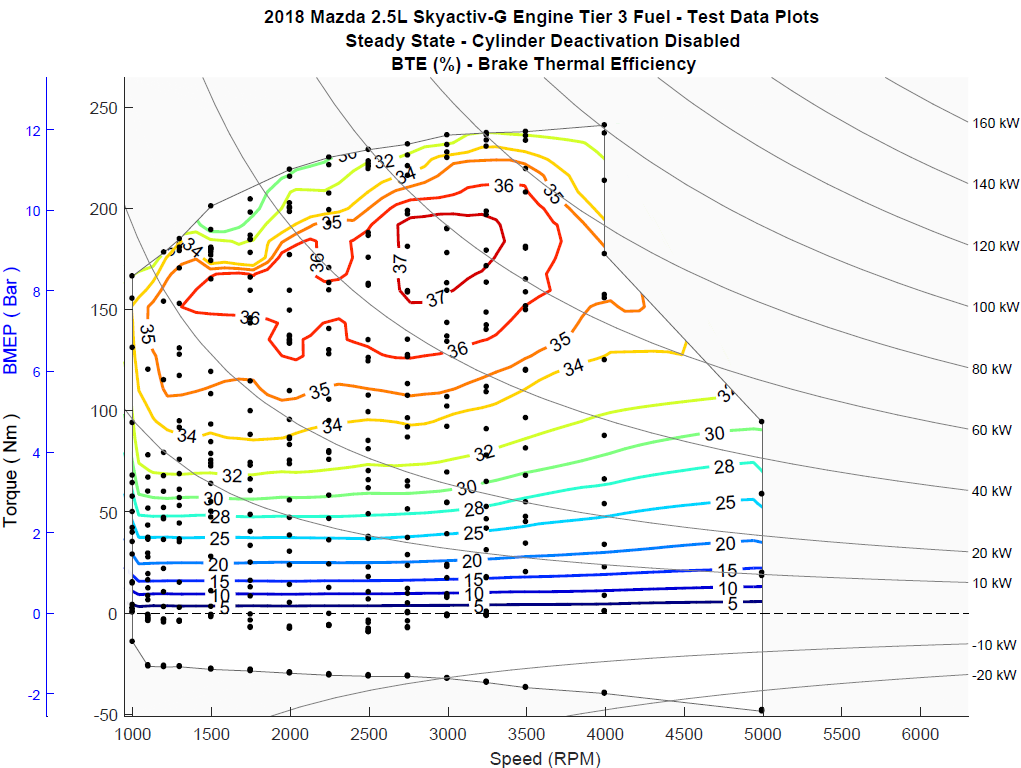
# Fuel Consumption Results

The final test data set containing the engine mapping test parameters is provided in the file: *4-2018 Mazda 2.5L Skyactiv-G Engine Tier 3 Fuel - Test Data*. The Mazda 2.5L Skyactiv-G engine uses cylinder deactivation to improve thermal efficiency by reducing pumping losses during low-load operation by deactivating cylinders 1 and 4 simultaneously. Note for this testing, mapping was completed both with and without cylinder deactivation.

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 4, and Brake Thermal Efficiency (BTE), shown in Figure 5. These plots represent the engine mapping results without the cylinder deactivation feature enabled. The black dots in the figures above indicate the speed/load points at which steady state data were acquired. Additional contour maps for the test data measurements with the cylinder deactivation operation both enabled and disabled are provided in *5- 2018 Mazda 2.5L Skyactiv-G Engine Tier 3 Fuel - Test Data Plots.pdf.*

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**Figure 4. 2018 Mazda 2.5L Skyactiv-G – BSFC (g/kW-hr) Cylinder Deactivation Disabled**



**Figure 5. 2018 Mazda 2.5L Skyactiv-G – BTE (%) Cylinder Deactivation Disabled**

**Effects of Cylinder Deactivation**

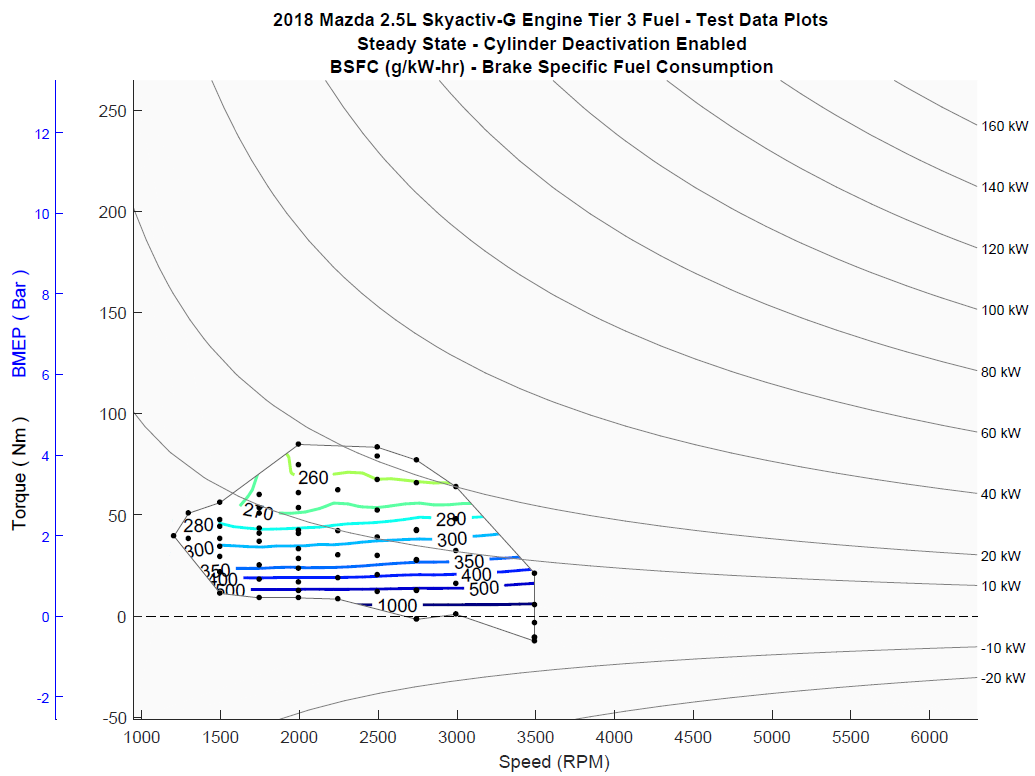
The 2.5L Skyactiv-G engine uses cylinder deactivation to improve thermal efficiency by reducing pumping losses during low-load operation. The cylinder deactivation method deactivates cylinders 1 and 4 simultaneously as determined by the RPECS data acquisition system used during testing. The RPECS monitored and recorded the fuel injector voltage and CAN bus ePID signals using crank-angle based sampling.

An example data set recorded at 2000 rpm is shown in Figure 6 which illustrates the effect of cylinder deactivation on thermal efficiency. The data clearly shows how cylinder deactivation increases BTE. As an example, near 2.0 BMEP the BTE increased from 25.3% to 30.1%, resulting in around a 19% increase in thermal efficiency.

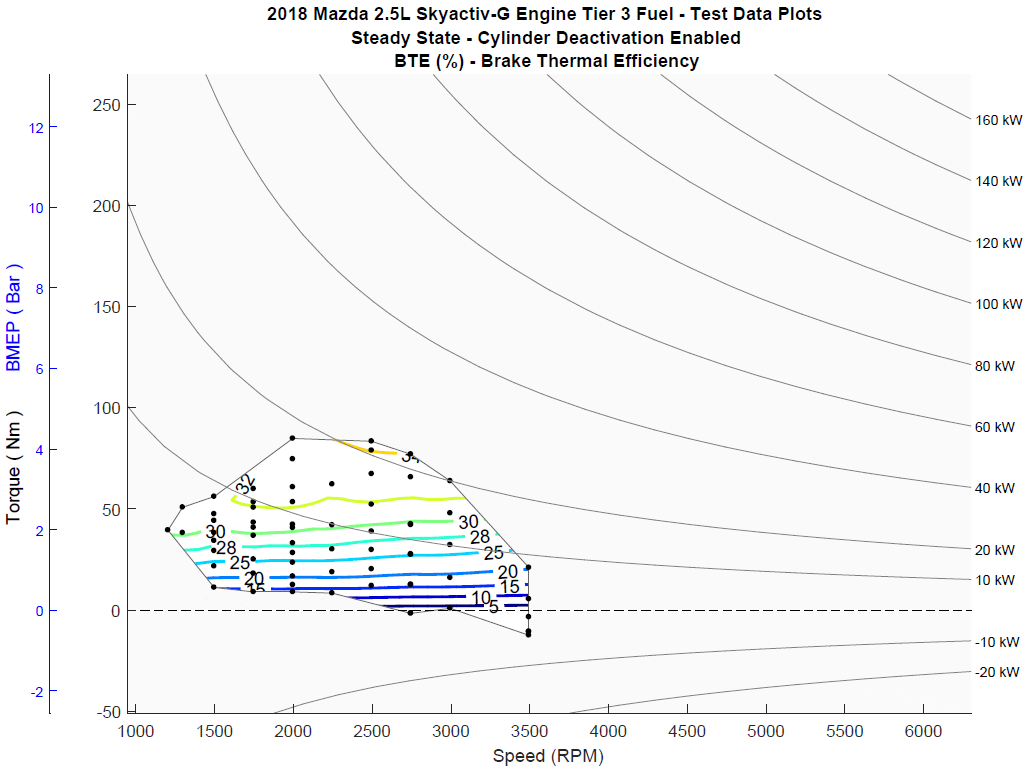


**Figure 6. Cylinder Deactivation Effect on BTE at 2000 rpm   
while operating on Tier 2 Fuel**

The final BSFC and BTE maps for the engine with cylinder deactivation are shown below in Figures 7 and 8. Only the region where cylinder deactivation was enabled as permitted by the ECU are shown in the figures below. The *4- 2018 Mazda 2.5L Skyactiv-G Engine Tier 3 Fuel – Test Data.xlsx* also provides an indication of the status of cylinder deactivation in the data set.



**Figure 7. 2018 Mazda 2.5L - BSFC (g/kW-hr) With Cylinder Deactivation Enabled**

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**Figure 8. 2018 Mazda 2.5L - BTE (%) With Cylinder Deactivation Enabled**

# 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 1.3354 rpm for the dynamometer speed, 0.0186 Nm for the torque signal, and 0.0009 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 7.

**Table 7: Standard Uncertainties for Signals**

|  |  |  |  |
| --- | --- | --- | --- |
| Signal | u(calibration) | u(operation) | u(signal) |
| Speed (rpm) | 1.3354 | */n* | Sqrt[0.283 + (*/n*)] |
| Torque (Nm) | 0.0186 | */n* | Sqrt[0.0309 + (*/n*)] |
| Fuel (g/sec) | 0.0009 | */n* | Sqrt[0.0001188 + (*/n*)] |

Uncertainty of BSFC

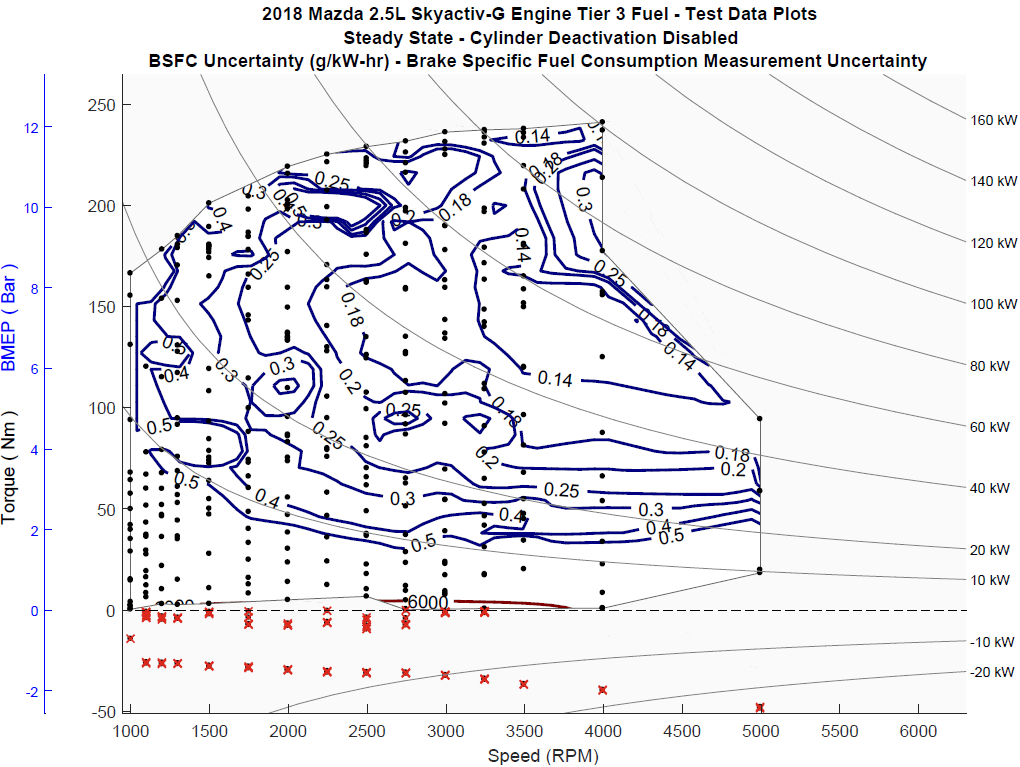
The total uncertainty for BSFC is thus calculated by:

or

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 9 and 10. The red Xs shown on the figures indicate speed/load points where negative torque data existed that could not be used in calculating the uncertainty.



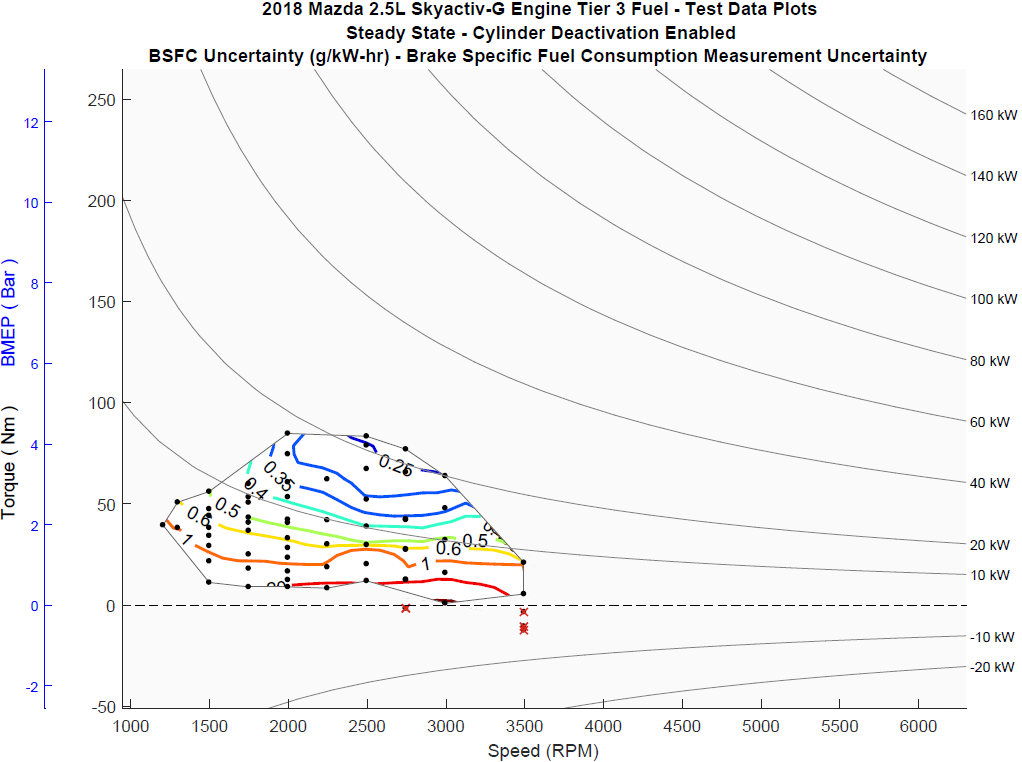
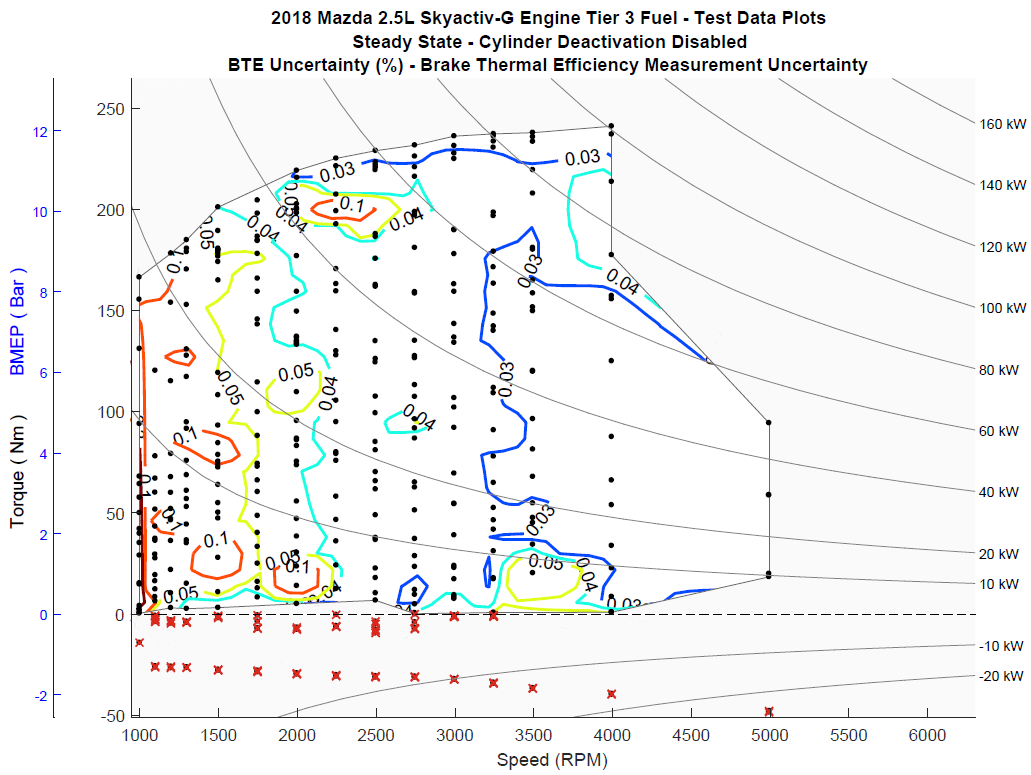
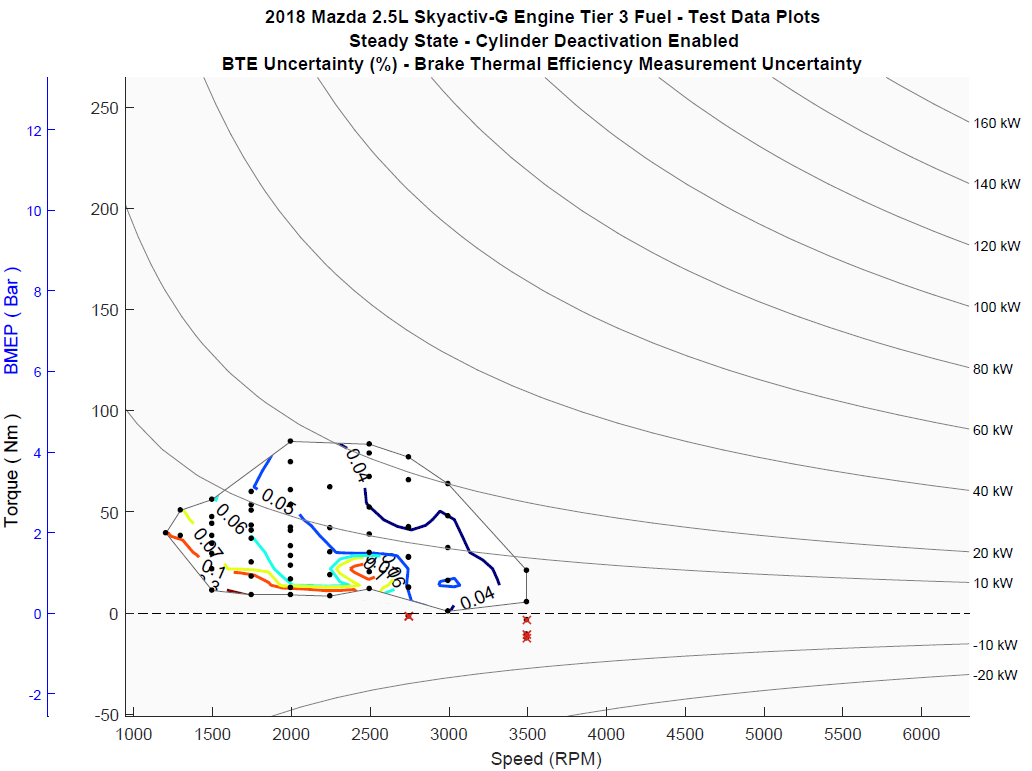


Figure 9. BSFC Uncertainty





**Figure 10. BTE Uncertainty**