

2014 Mazda 2.0L SKYACTIV-G Engine Tested with Tier 2 Test Fuel – NCAT Test Report

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**NCAT – National Center for Advanced Technology**

*National Vehicle and Fuel Emissions Laboratory* – *Office of Transportation and Air Quality*

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**Test:** 2014 Mazda 2.0L SKYACTIV-G Engine Tested with Tier 2 Test 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 was to characterize the performance of a 2014 Mazda SKYACTIV-G 2.0L engine on Tier 2 certification fuel to generate fuel map data that could be used in the ALPHA model.

# Definitions

|  |  |
| --- | --- |
| Fuel Map | Engine operating map that displays contours of brake specific fuel consumption (in g/kWh) on a grid of engine speeds (in RPM) and engine torques (in Nm). |
| Coefficient of Variation (COV) | A measure of variability defined as the ratio of standard deviation to mean (σ/μ) |
| Steady-State Data Point | A single data point generated by averaging 10 seconds of stable, continuous data collection |

# Description of Test Article

The engine used in this project was a 2014 Mazda SKYACTIV-G 2.0L which is a naturally aspirated direct-injection gasoline engine. The engine was tethered to a vehicle located outside of the test cell to make use of the stock engine and vehicle controllers. Table 1 summarizes information that details the vehicle and engine used in this test program.

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

|  |  |
| --- | --- |
| Vehicle (MY, Make, Model) | 2014 Mazda3 |
| Vehicle Identification Number | JM1BM1U79E1189422 |
| Engine Family | ETKXV02.05BA |
| Certification Level | Tier 2 Bin 5 |
| EPA Vehicle ID | GHGMAZman |
| Engine (Displacement, Name) | 2.0L SKYACTIV-G |
| Rated Power | 115 kW @ 6000 rpm |
| Rated Torque | 203 Nm @ 4000 rpm |
| Recommended Fuel | Regular unleaded |
| Engine Features of Interest for MTE | 13:1 CR, Atkinson cycle, Direct-Injection, Dual Cam Phasers |
|  |  |

# Test Site

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

# Test Cell Capabilities

Test Cell 8 was equipped with the instrumentation listed in Table 2.

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

|  |  |  |
| --- | --- | --- |
| Instrument Name | Purpose/Measurement Capabilities | Manufacturer |
| Dynamometer | Engine Speed, Torque | Meidensha |
| Coriolis Fuel Meter | Fuel Flow Rate | Micromotion |
| Laminar Flow Element | Air Flow Rate | Merriman |

# Data Collection Systems

Test cell data acquisition and dynamometer control were performed by iTest, a software package developed by A&D Technology, Inc. RPECS, a supplemental data acquisition system developed by Southwest Research Institute (SwRI), directly measured and logged ECU inputs and outputs along with test cell data. Temperatures, pressures, and test cell data were sent from iTest to RPECS. The engine control and analysis systems are summarized in Table 3.

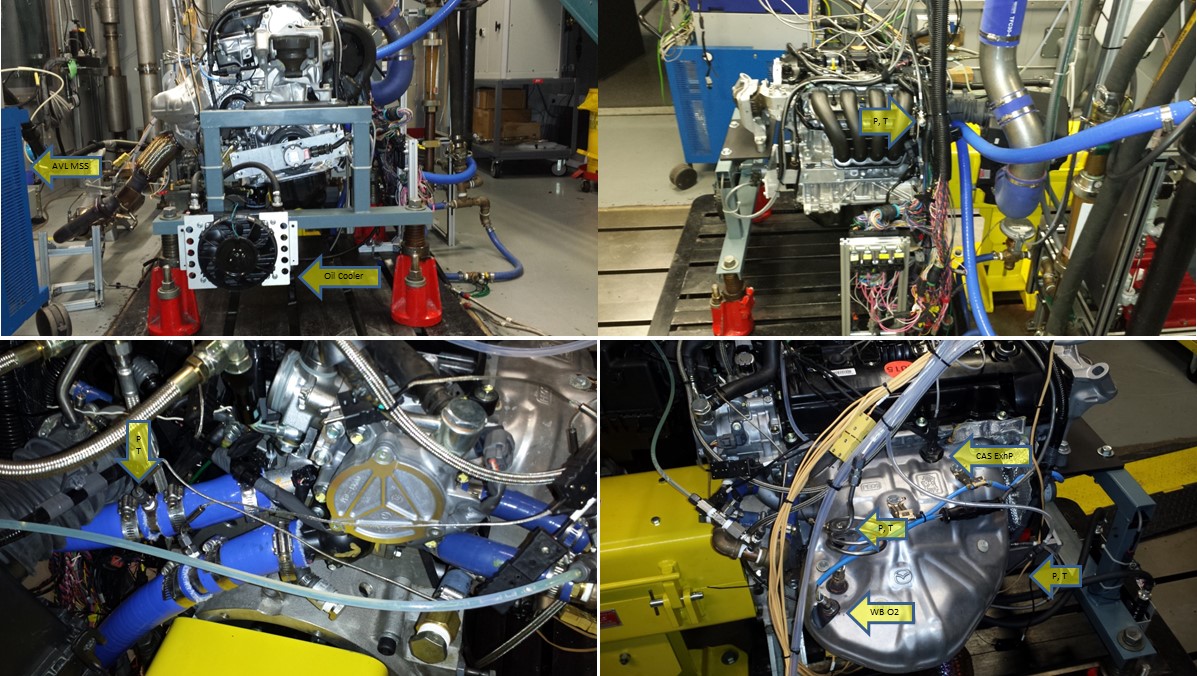
**Table 3. Engine Control and Analysis Systems**

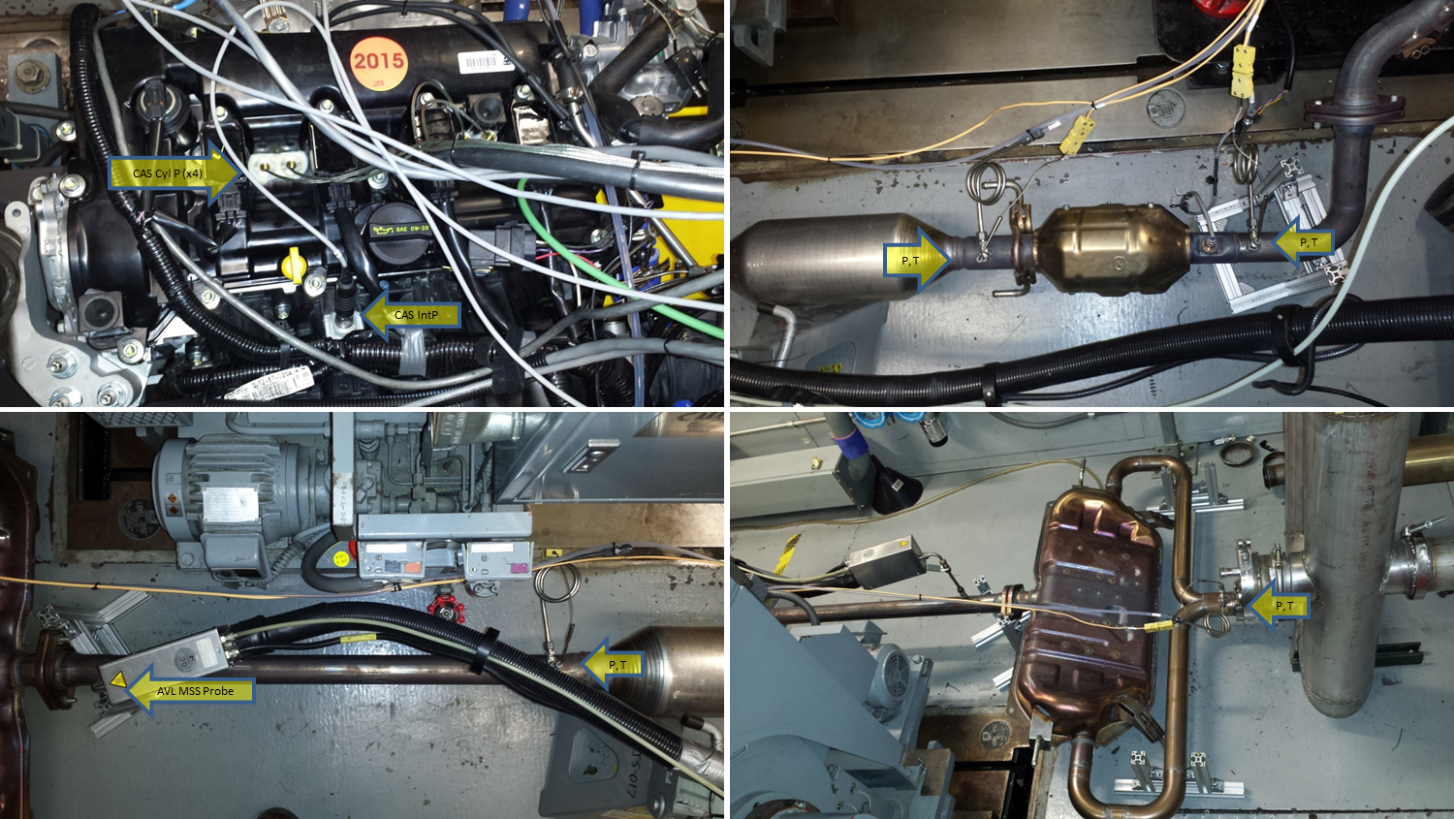
|  |  |  |  |
| --- | --- | --- | --- |
| System | Developer | Description | Data Rate |
| iTest | A&D Technology, Inc. | Controls dyno | 10 Hz |
| RPECS | Southwest Research Institute | Collects: ECU I/O, ECU CAN, iTestMaster data logger | 1/engine cycle |

# 

# Engine Setup

The actual sensor locations and monitors utilized in Test Cell 8 are shown in the photographs provided in Figure 1. Figure 2 is provided as an illustration of the overall engine setup.

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**Figure 1. Test Cell Configuration with Engine Sensor Locations**



**Figure 2. Schematic of Setup & Monitored Systems**

# Engine Systems

1. Intake: Stock airbox and plumbing with laminar flow element (LFE) connected to airbox inlet.
2. Exhaust: Mazda3 factory system with a muffler and underfloor catalyst; emission tunnel pressure controlled to Patm ± 1.2 kPa.
3. Cooling System: Stock cooling system except the radiator replaced with a cooling tower; stock engine thermostat to control engine coolant temperature; cooling tower outlet controlled to 85 °C by iTest.
4. Oil System: Air to oil cooler connected to a fan set to turn on at 92 °C.
5. FEAD: Modified so only the water pump was driven.
6. Flywheel and Housing: Stock manual flywheel with an aluminum adapter plate connected to the dynamometer driveshaft; generic SAE 6 flywheel housing with an adapter plate connected to the engine.

# Test Methodology

## Test Fuel

The primary properties of the 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 23945.pdf*.

**Table 4. Fuel Properties for FTAG 23945**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter Description | Test Fuel Specifications (40 CFR §86.113-04) | Reference Procedure | Measured Results | Units |
| Research Octane (optional) | 93 (minimum) | ASTM D2699; ASTM D2700 | 97.1 | RON |
| Octane Sensitivity (optional) | 7.5 | ASTM D2699; ASTM D2700 | 8.9 | RON-MON |
| Hydrocarbon Composition (vol %) | | | | |
| Olefins | 10% Maximum | ASTM D1319 | 2.0 | Vol % |
| Aromatics | 35% Maximum | ASTM D1319 | 33.51 | Vol % |
| Total Sulfur, wt.% | 0.0015-0.008 | ASTM D2622 | 38.5 | ppm |
| Dry Vapor Pressure Equivalent, psi (kPa) | 8.7–9.2 (60.0-63.4) | ASTM D5191 | 9.17 | psi |
| The following are provided for Reference Only and are not specified in the CFR | | | | |
| Antiknock | None | N/A | 92.65 | (RON+MON)/2 |
| Net Heating Value | None | ASTM D3338 | 18438 | BTU/lb |
| None | N/A | 42.887 | MJ/kg |
| Alcohol Content | None | ASTM D5599 | 0.00 | Vol % |
| Carbon Content | None | ASTM D3343 | 0.86678 | 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 Description | Test Parameter Name | Units | Minimum | Maximum |
| Oil Pressure | Oil Press | kPag | 100 |  |
| Coolant Temperature | Coolant Temp | oC |  | 120 |
| Engine Speed | Speed | rpm |  | 6000 |

# Pre-Conditioning and Common Mode Check

Before testing began, the engine was warmed up. The engine was considered “warm” when the coolant and oil temperatures reached 87 oC. A common mode, run with the parameters given in Table 6, was repeated randomly during each test to expose 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 Description | Test Parameter Name | Condition |
| Engine Speed Setting | Speed | 2000 rpm |
| Torque Command Setting | Torque | 45 Nm (~2.5 bar BMEP) |
| Coolant Temperature Criteria | Coolant Temp | >87 oC |
| Oil Temperature Criteria | Oil Sump Temp | >85 oC |

**Table 7. Common Mode Test Parameters**

|  |  |  |
| --- | --- | --- |
| Parameter Description | Test Parameter Name | Units |
| Brake Mean Effective Pressure | BMEP | bar |
| Thermal Efficiency | BTE | % |
| Intake Manifold Pressure | Intake Manifold Press | kPa |

# Data Set Definition

Data were logged once per engine cycle by RPECS and a new output file was generated for each test point. Post-processing was required to create the fuel map’s single data points from the cycle data. The final test data set containing the engine mapping test parameters can be found in: *4– 2014 Mazda 2.0L SKYACTIV-G Engine Tier 2 Fuel – Test Data.xlsx.*

# Test Data Points

The test points for this engine map covered the torque and speed range of the engine as indicated in Figure 3. Data points were measured in 250 rpm or less increments at lower engine speeds and 500 rpm increments at higher engine speeds. Operators limited the test points to not exceed 4500 rpm. Additional points were run to capture loads near idle speed.

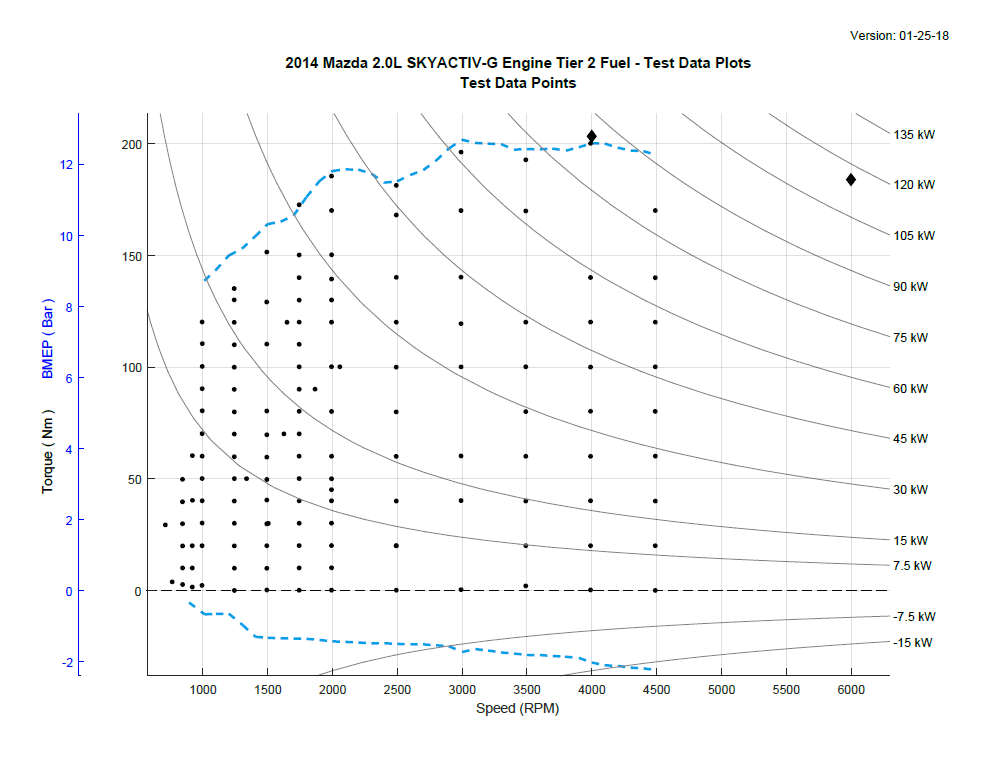


Figure 3. Test Data Points

# Data Collection Procedure

The following procedure was used to collect continuous stable data that was used to generate steady-state points on the fuel map. The data point collection order was randomized prior to the test. The dynamometer controlled engine speed and the engine throttle controlled to a torque target at all points, including idle. 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, and exhaust temperature. RPECS logged data from iTest, the engine, and the engine controller.

# Data Set Processing

A single data file was generated by RPECS for each speed/load point on the engine map. A single data point was created by averaging the crank angle data in each file.

# Data Processing

Brake specific fuel consumption (BSFC) in g/kW-hr was calculated according to the equation below using the values obtained from iTest.

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

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

Where: Net Heating Value of the fuel is provided in Table 4 (MJ/kg)

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

# WOT and Motoring Curves

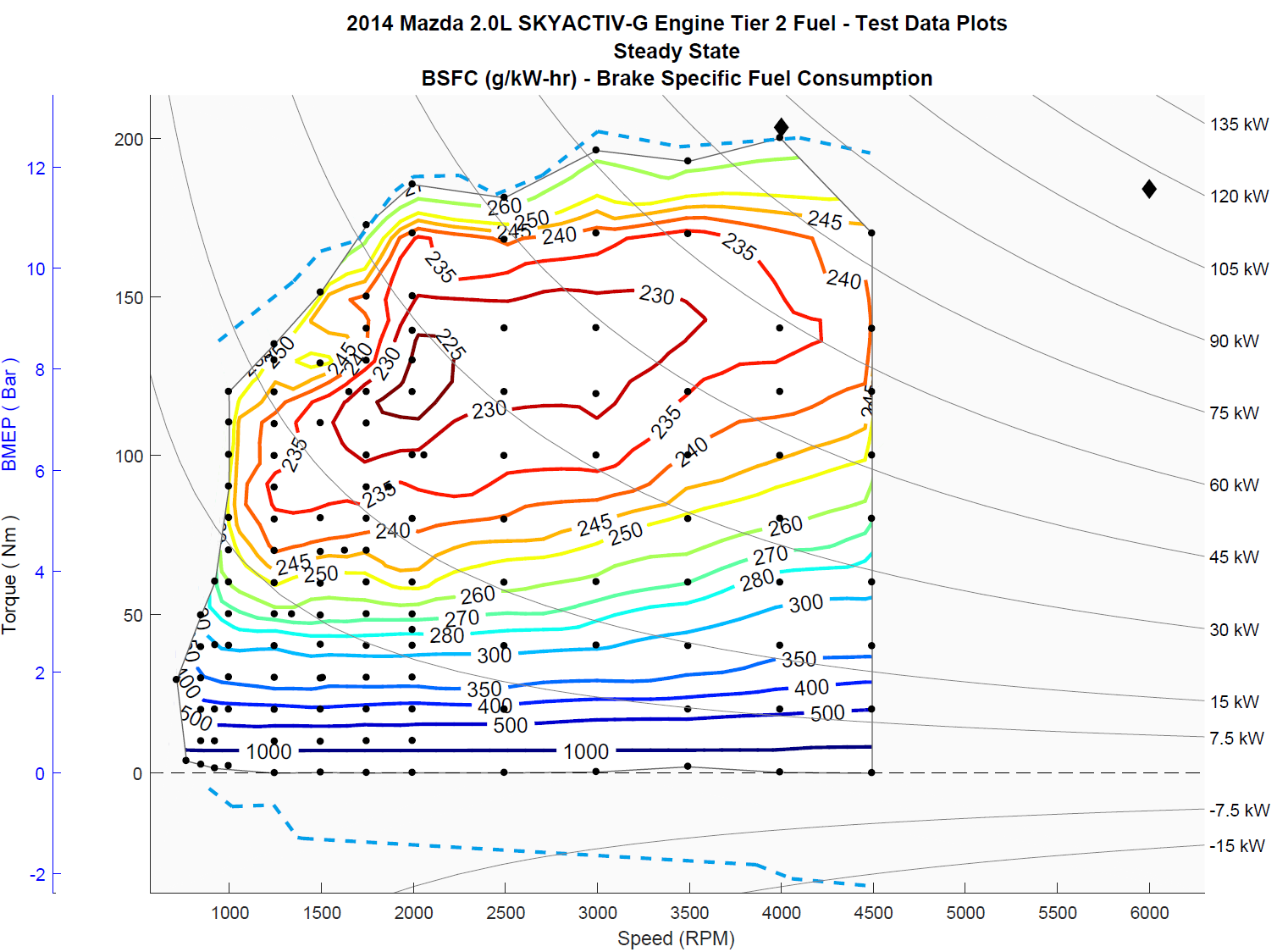
The wide open throttle (WOT) curve was generated by sweeping the dynamometer from 800 rpm to 4500 rpm at 40 rpm/s as shown in Figure 3. The motoring curve was generated with 0% throttle at a rate of 10 rpm/s from 800 rpm to 4500 rpm. Near 1300 rpm in the motoring curve, the engine turned off fueling which resulted in a sharp drop in torque. The WOT curve matched the steady state points used to generate the performance maps and was very near the manufacturer reported peak torque and power points as shown in Figures 4 and 5.

# 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 a 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 was provided in the file: *4- 2014 Mazda 2.0L SKYACTIV-G 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 4, and Brake Thermal Efficiency (BTE), shown in Figure 5.



**Figure 4. 2014 Mazda3 (US) 2.0L – BSFC (g/kW-hr)**

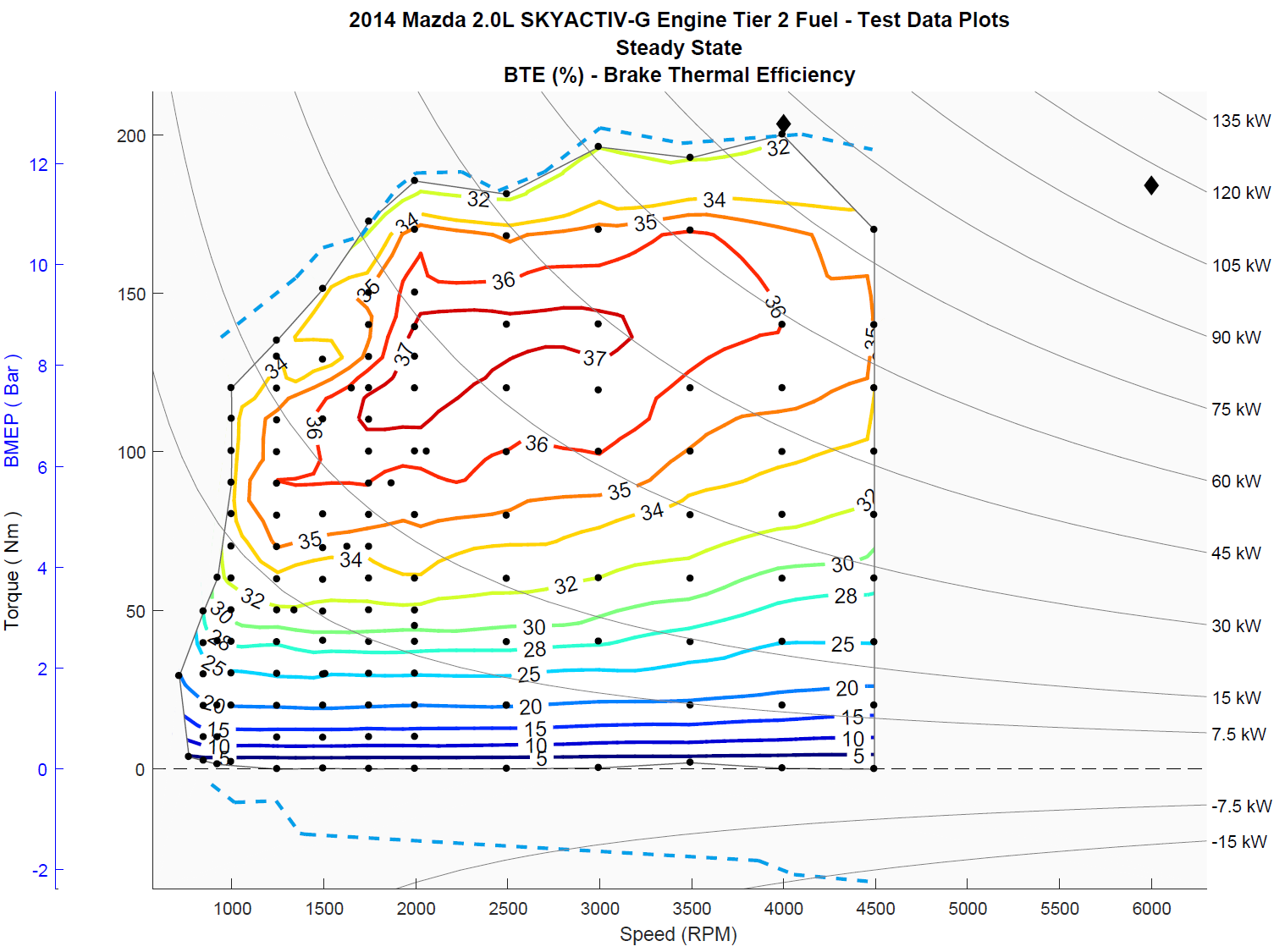


Figure 5. 2014 Mazda3 (US) 2.0L – BTE (%)

The black dots in the figures above indicate the speed/load points at which steady state data were included in the contour. The black diamonds indicate the rated torque/power points as advertised by the manufacturer [1]. Light blue dashed lines indicate speed/load points selected to represent maximum or minimum engine torque. Additional contour maps for all of the test data measurements are provided in *5- 2014 Mazda 2.0L SKYACTIV-G Engine Tier 2 Fuel – Test Data Plots.pdf.*

[1] http://www.mazdausa.com/MusaWeb/musa2/pdf/specs/specs\_M3S.pdf

# Uncertainty

Sensor/signal uncertainties

The uncertainties of the signals [u(signal)] in the data set were calculated based on (a) the uncertainty associated with the calibration standard [u(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 was assumed to be negligible when compared to other uncertainties, and thus this uncertainty was ignored for the 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. To determine the uncertainty of the signal during operation, the standard deviations for each signal were calculated from the testing data and the average was used to calculate the variance of the mean, and thus the uncertainty,

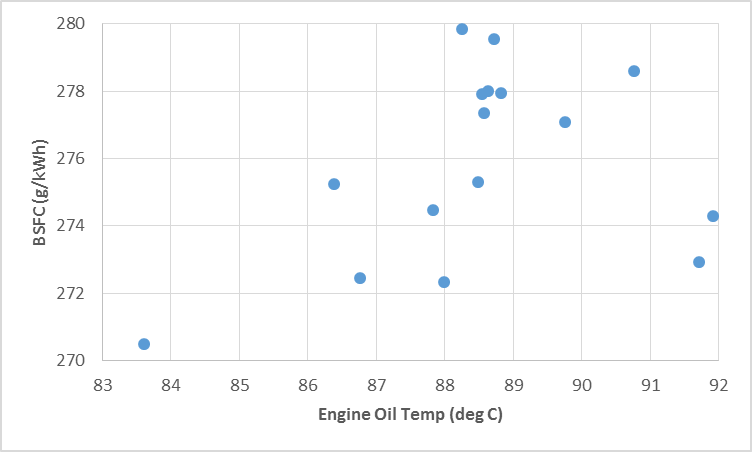
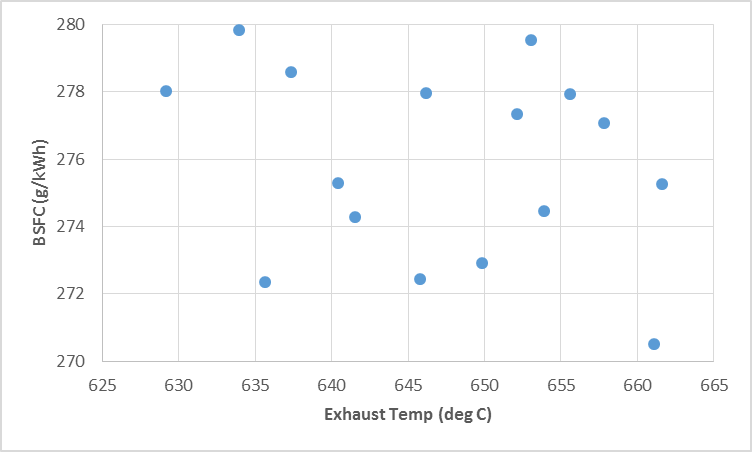
Where n is the number of data points in a mode. Assuming n = 70 (a minimum number), the standard uncertainty for each signal is given in Table 8.

**Table 8. Standard Uncertainties for Signals**

|  |  |  |  |
| --- | --- | --- | --- |
| Signal | u(calibration) | u(operation) | u(signal) |
| Temperature (oC) | 0.549 | 0.225 | 0.593 |
| Pressure (kPa) | 0.321 | 0.0053 | 0.321 |
| Speed (rpm) | 1.183 | 0.178 | 1.197 |
| Torque (Nm) | 0.0808 | 0.137 | 0.159 |
| Fuel (g/s) | 0.00640 | 0.00365 | 0.00737 |

Testing uncertainty

In addition to the uncertainties associated with each signal, there may be an overall uncertainty associated with the repeatability of the testing procedure and the engine operation. To estimate this uncertainty, common mode data taken during earlier testing (reference the section “Pre-Conditioning and Common Mode Check”) were examined. The common mode data showed little correlation of engine BSFC with either oil temperature (a reasonable proxy for test procedure uncertainty) or exhaust temperature (a reasonable proxy for engine operation) as indicated in Figure 6. As a result, testing uncertainty was considered to have minimal impact on the overall uncertainty and only the uncertainty of the sensors was utilized.

**Figure 6. BSFC versus Engine Oil Temperature & Exhaust Temperature**

Uncertainty of BSFC

The total uncertainty for BSFC was calculated by:

or

where, from above,

*uc*(*q*) = 0.00640 g/s *uc*(*T*) = 0.0808 Nm *uc*(*ω*) = 1.183 rpm

*σ*(*q*) = 0.0305 g/s *σ*(*T*) = 1.147 Nm *σ*(*ω*) = 1.493 rpm

*n* = number of points in mode = *ω*/12

Uncertainty of BTE

The derivation of the uncertainty of thermal efficiency was similar. The uncertainty in measurement of the fuel heating value was assumed to be small compared to other uncertainties. Assuming *u(HV)* = 10 BTU/lb,

Standard uncertainties (including the uncertainty of the BSFC) 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 7 and 8.

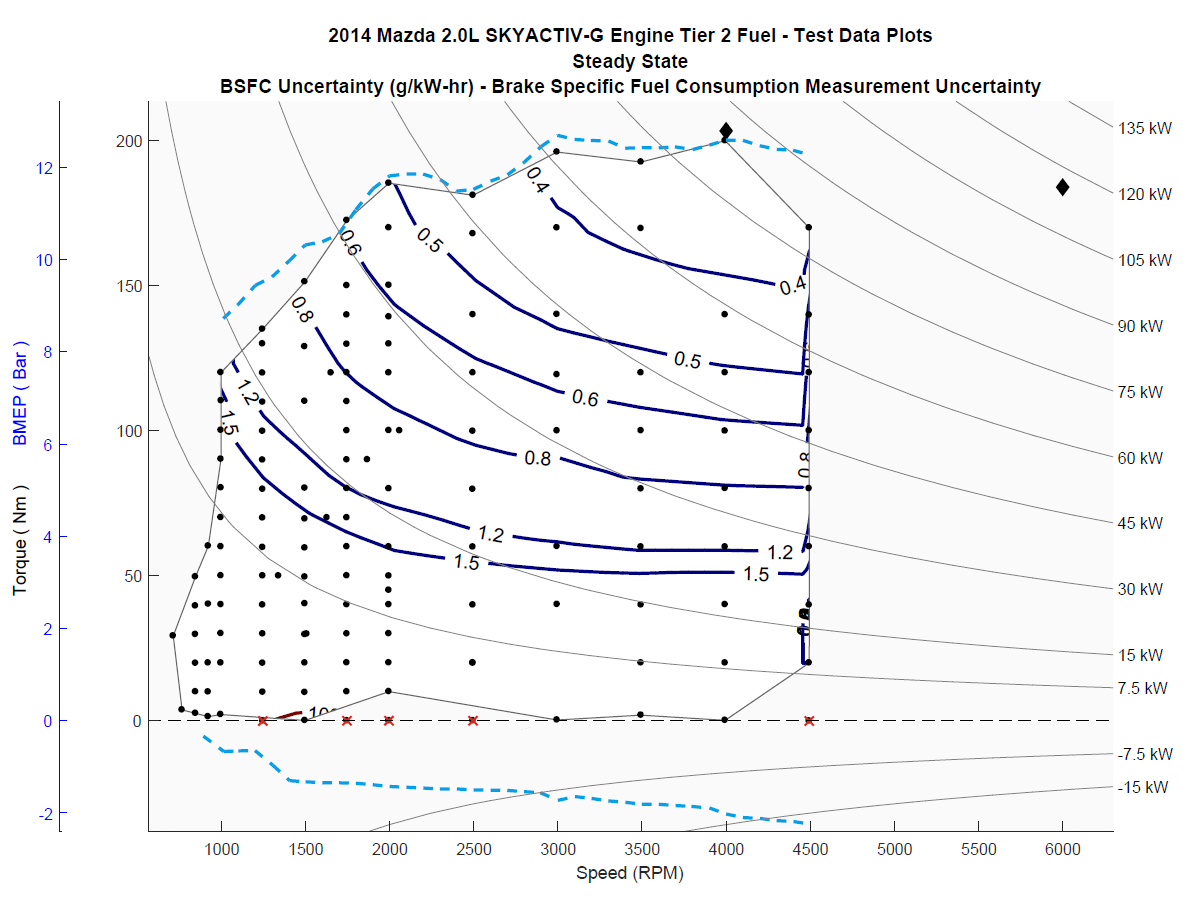
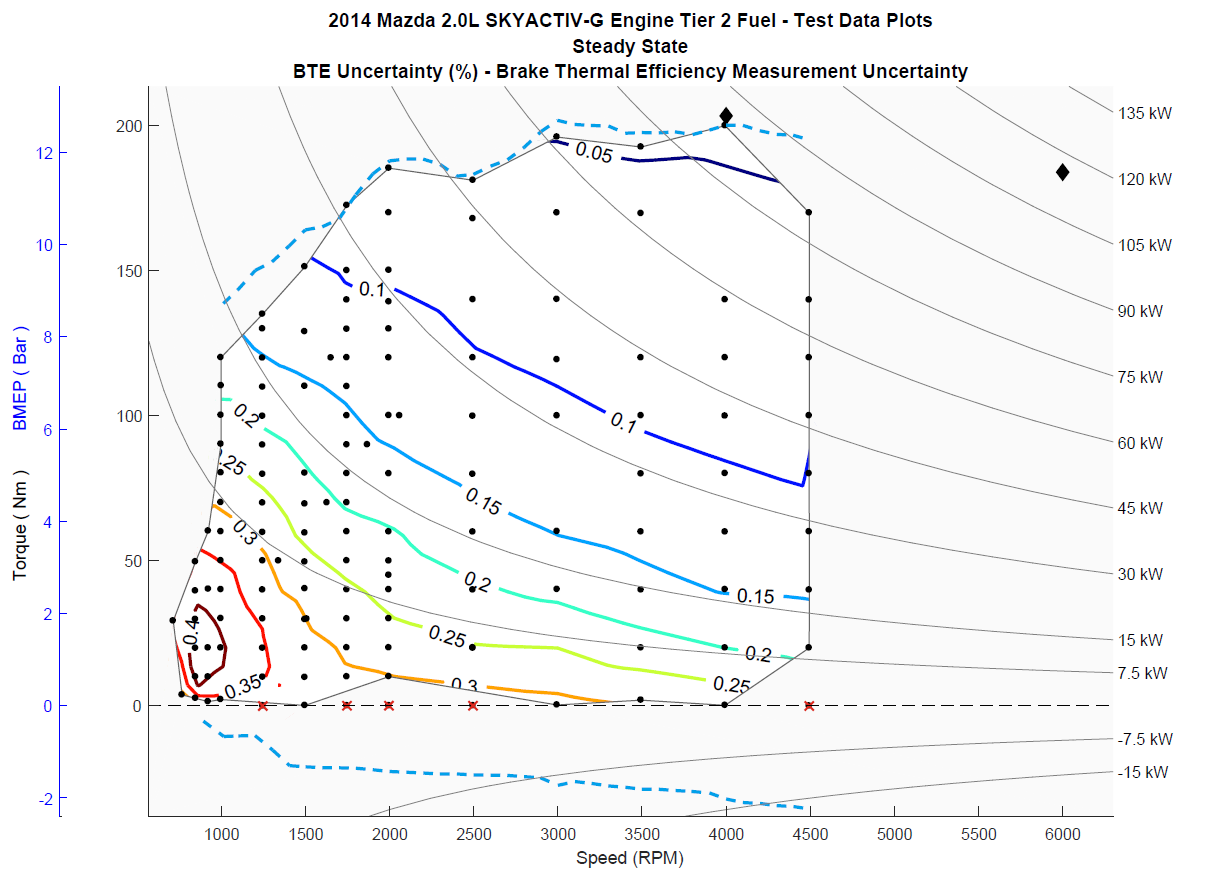


Figure 7. BSFC Uncertainty



**Figure 8. BTE Uncertainty**

# Discussion and Data Usage

The intent of this test was to establish a baseline to characterize the performance of the 2014 Mazda SKYACTIV-G 2.0L engine on Tier 2 E0 fuel by running a full suite of tests including both steady state maps and torque curves.

In general, the engine operation and fuel consumption data produced in this testing are robust and can be used for any purpose. As shown in Figures 7 and 8, the uncertainty of very low-load points increases, particularly below 50 Nm, for the 2.0L SKYACTIV-G engine. This effect is expected and will have a negligible effect on fuel economy calculations over a representative cycle.