Performance Evaluation of a 2014 Mazda3's 2.0L SKYACTIV® Engine with Tier 2 Test Fuel

June 28, 2016

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Version: 16-06-28

NCAT – National Center for Advanced Technology

National Vehicle and Fuel Emissions Laboratory – Office of Transportation and Air Quality
U.S. Environmental Protection Agency

TEST:	Performance Evaluation of a 2014 Mazda3's 2.0L SKYACTIV® Engine with Tier 2 Test Fuel
PROGRAM:	NCAT/ASD Light-Duty Greenhouse Gas Test Program
PROJECT:	MTE Engine Benchmarking
PROJECT ENGINEERS:	Charles Schenk

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PURPOSE OF TEST

The purpose of this test is to characterize the performance of a 2014 Mazda SKYACTIV® 2.0L engine on Tier 2 certification fuel to generate fuel map data that may be used in the ALPHA model.

SUPPORTING DOCUMENTATION

This data packet contains the following files:

2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Test Data.xlsx	Data collected during engine testing for all points tested; including speed, load, fuel flow and calculated BMEP, BSFC & BTE values; additional temperature and pressure parameters are also included for reference
2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Contour Plots.pdf	Contour plots of the measured variables in the core data set
FTAG 23945 Fuel Analysis Report.pdf	Analysis report of the fuel properties

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® 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 identifies the system 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®
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, VVT, Direct-Injection

TEST SITE

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

Test Cell Capabilities

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

Table 2: Instrumentation in NCAT Test Cell 8

Instrument Name	Purpose/Measurement Capabilities	Manufacturer
Dynamometer	Engine speed, torque, power	Meidensha
CVS dilution tunnel	Dilution, exhaust flow	EPA
Coriolis fuel meter	Fuel flow rate	Micromotion
Laminar flow element	Air flow rate	Merriman
Micro Soot Sensor	Dry Particulate	AVL
Emissions bench	Raw and dilute exhaust gases: CO, THC, NOx, CH4, CO2	MEXA

Data Collection Systems

Test cell data acquisition and dynamometer control were performed by iTest, a software package developed by A&D Technology, Inc. Combustion data was analyzed by the MTS Combustion Analysis System (CAS). RPECS-IV is supplemental data acquisition software developed by Southwest Research Institute (SwRI). RPECS directly measures and logs ECU I/O along with test cell data. Temperatures, pressures, and test cell data were sent from iTest to RPECS via CAN.

Combustion summary data from CAS were also sent to RPECS via iTest. CAS logs were taken for selected points. Pressure transducers were installed at the intake and exhaust ports and logged by CAS to be used for the GT Power model. The engine control and analysis systems are summarized in Table 3.

Table 3: Engine Control and Analysis Systems

System	Developer	Description	Data Rate
CAN	Engine OEM	Collects/monitors ECU output	variable
iTest	A&D Technology, Inc.	Controls dyno	10 Hz
CAS	MTS Systems Corporation	Combustion analyzer	3600/rev
RPECS	Southwest Research Institute	Collects data Master data logger	1/engine cycle

Engine Setup

Figure 1 illustrates the engine setup and sensor location in Test Cell 8. 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 lower left corner of the figure.

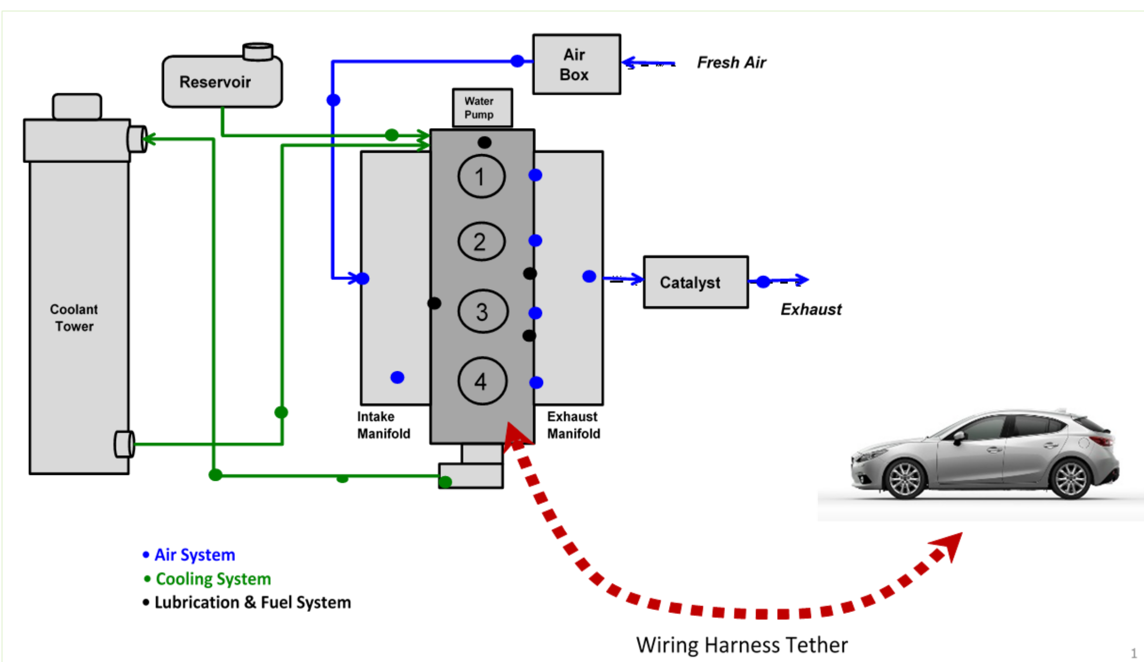

Figure 1: Schematic of Test Cell with Engine Sensor Locations & Monitored Systems

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 was used. Emission tunnel pressure was controlled to P_{atm} +/- 1.2 kPa.
3. Cooling System: Stock cooling system except the radiator which was replaced with a cooling tower. Stock engine thermostat was used to control engine coolant temperature and the cooling tower outlet was controlled to 85 °C by iTest.
4. Oil System: Air to oil cooler was connected to a fan set to turn on at 92 °C.
5. FEAD: Only the water pump was driven.
6. Flywheel and Housing: Engine used a stock manual flywheel with an aluminum adapter plate connected to the dynamometer driveshaft. Flywheel housing is generic SAE 6 with adapter plate to connect to 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: *FTAG 23945 Fuel Analysis Report.pdf*.

Table 4: Fuel Properties for FTAG 23945

Parameter Description	Measured Results	Units
Antiknock	92.65	AKI
Net Heating Value	18438.07	BTU/lb
Alcohol Content	0.00	%

Quality Procedures

This test program is covered by the LD GHG 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	kPa_g	100	
Coolant Temperature	Coolant Temp	^oC		120
Engine Speed	Speed	rpm		6000

Pre-Conditioning and Common Mode Check

Before testing began, the engine was allowed to warm 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 at the beginning of 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 was logged once per engine cycle by RPECS and a new output file was generated for each test point. The data log period is described in the Data Collection Procedure section. Post-processing was required to create the fuel map's single data points from the cycle data. The final core data set containing the engine mapping test parameters is provided in the file: *2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Test Data.xlsx.*

Test Data Points

The test points for this engine map covered the torque and speed range of the engine according to the rated values in Table 1. 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. The test points for this engine map covered the torque and speed range of the engine shown in Figure 2. Additional points were run to capture loads near idle speed.

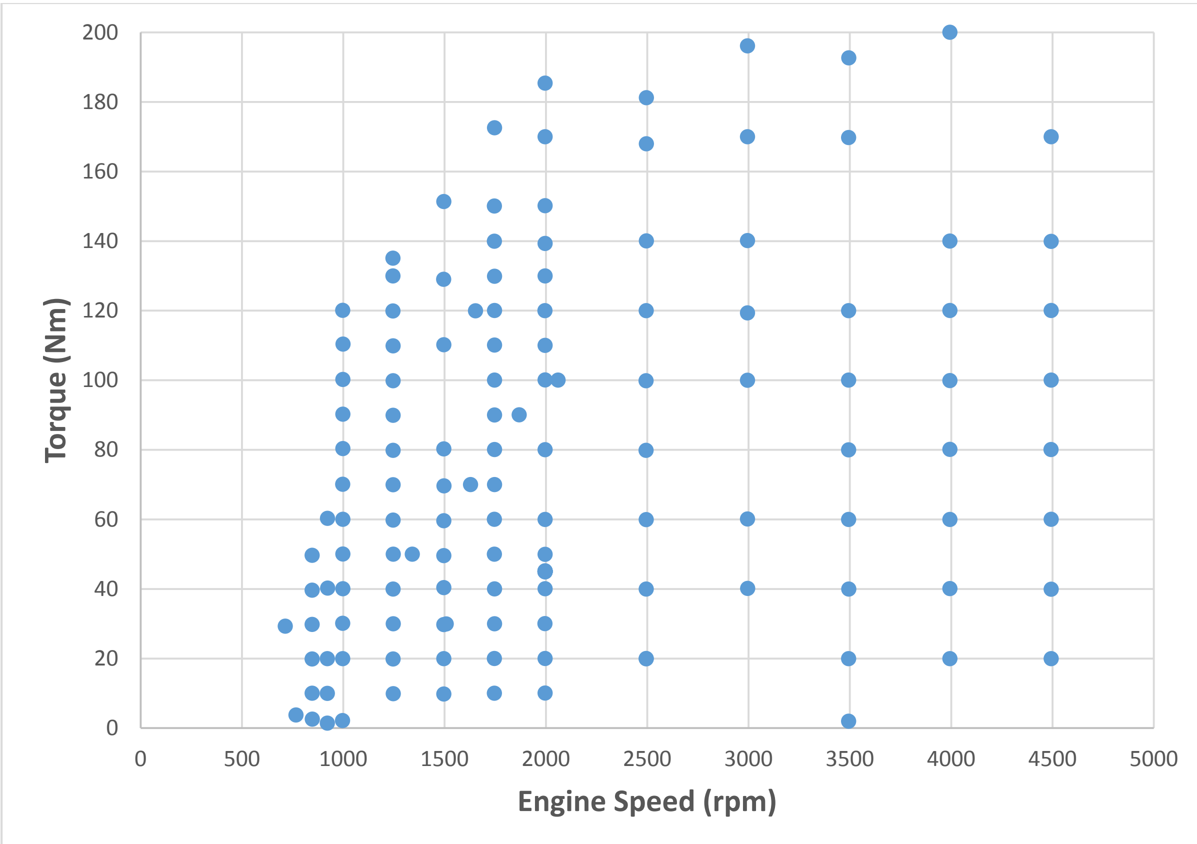

Figure 2. Test Data Points

DATA COLLECTION PROCEDURE

The following procedure is used to collect continuous stable data that can be used to generate steady-state points on the fuel map. The data points were randomized prior to the test. At each speed and torque combination a set of stability criteria are applied prior to logging the point for 10 seconds. Stability is determined by fuel flow, torque and exhaust temperature. RPECS logs data from iTest, CAS, the engine and the engine controller.

DATA SET PROCESSING

A single time-series data file was generated by RPECS for each speed/load point on the engine map, by averaging each data collected over the 10-second mode length.

Data Processing

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

$$\text{BSFC} = \frac{\text{Fuel Flow}}{\text{Torque} * \text{Speed} * \left(\frac{2\pi}{60}\right)} 3.6 * 10^6$$

Where: Fuel Flow = fuel flow rate measured by iTest (g/s)
Torque = engine torque measured by iTest (Nm)
Speed = engine speed (rev/minute)

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

$$\text{BTE} = \frac{\text{Torque} * \text{Speed} * \left(\frac{2\pi}{60}\right)}{\text{Fuel Flow} * \text{Net Heating Value} * 1000}$$

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.

Data Quality Control

A core test data is extracted from the data logger file and includes test parameters selected to provide valuable information when evaluating engine performance. Descriptions for the test parameter list are provided in the core test data set for reference. The core data set is analyzed for outlier data based on the statistical data included in the data logger file. In addition, the core data set is plotted and reviewed using a MATLAB-based SwRI 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 core data set containing the engine mapping test parameters is provided in the file: *2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core 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 3, and Brake Thermal Efficiency (BTE), shown in Figure 4.

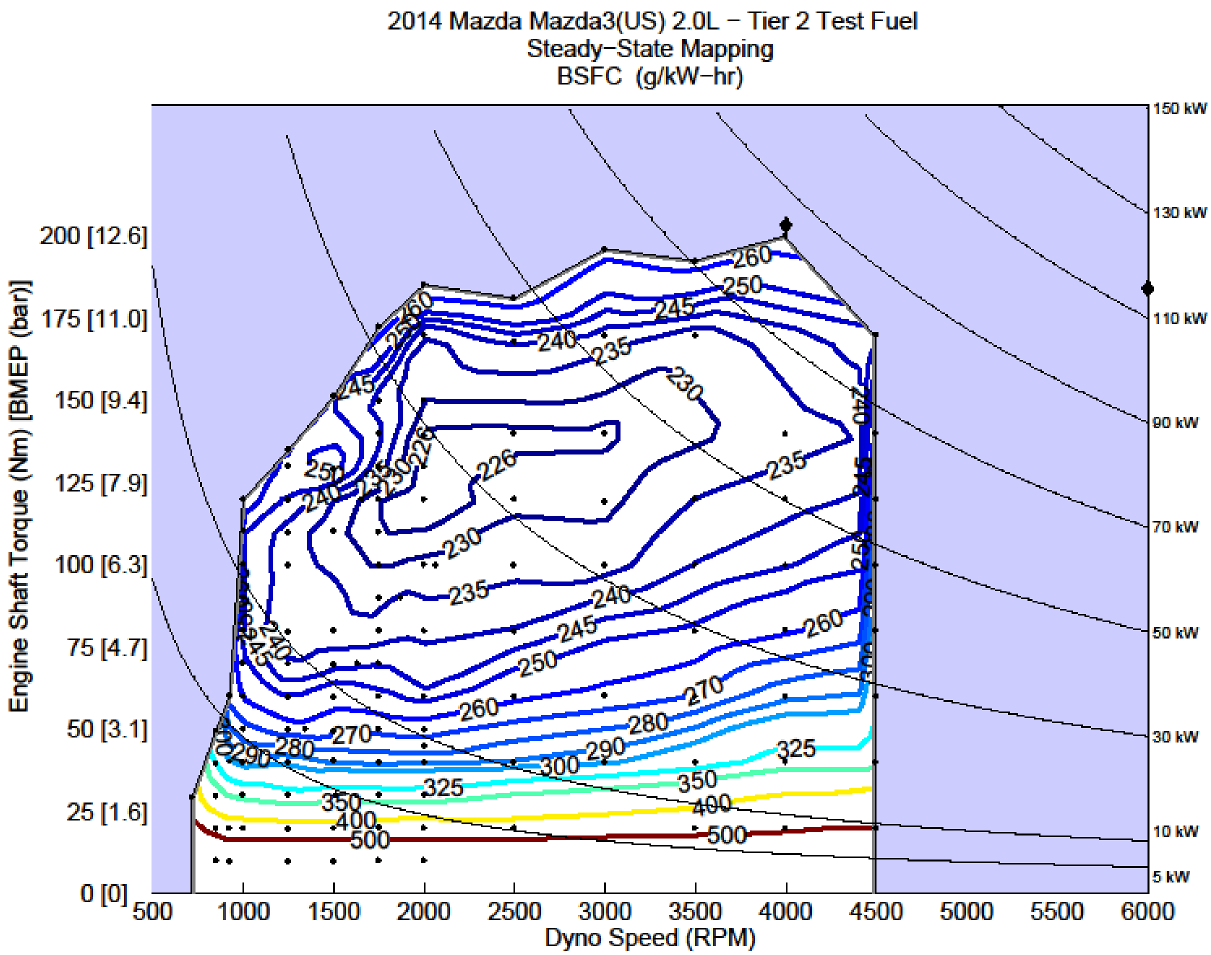

Figure 3. 2014 Mazda3 (US) 2.0L – BSFC (g/kW-hr)

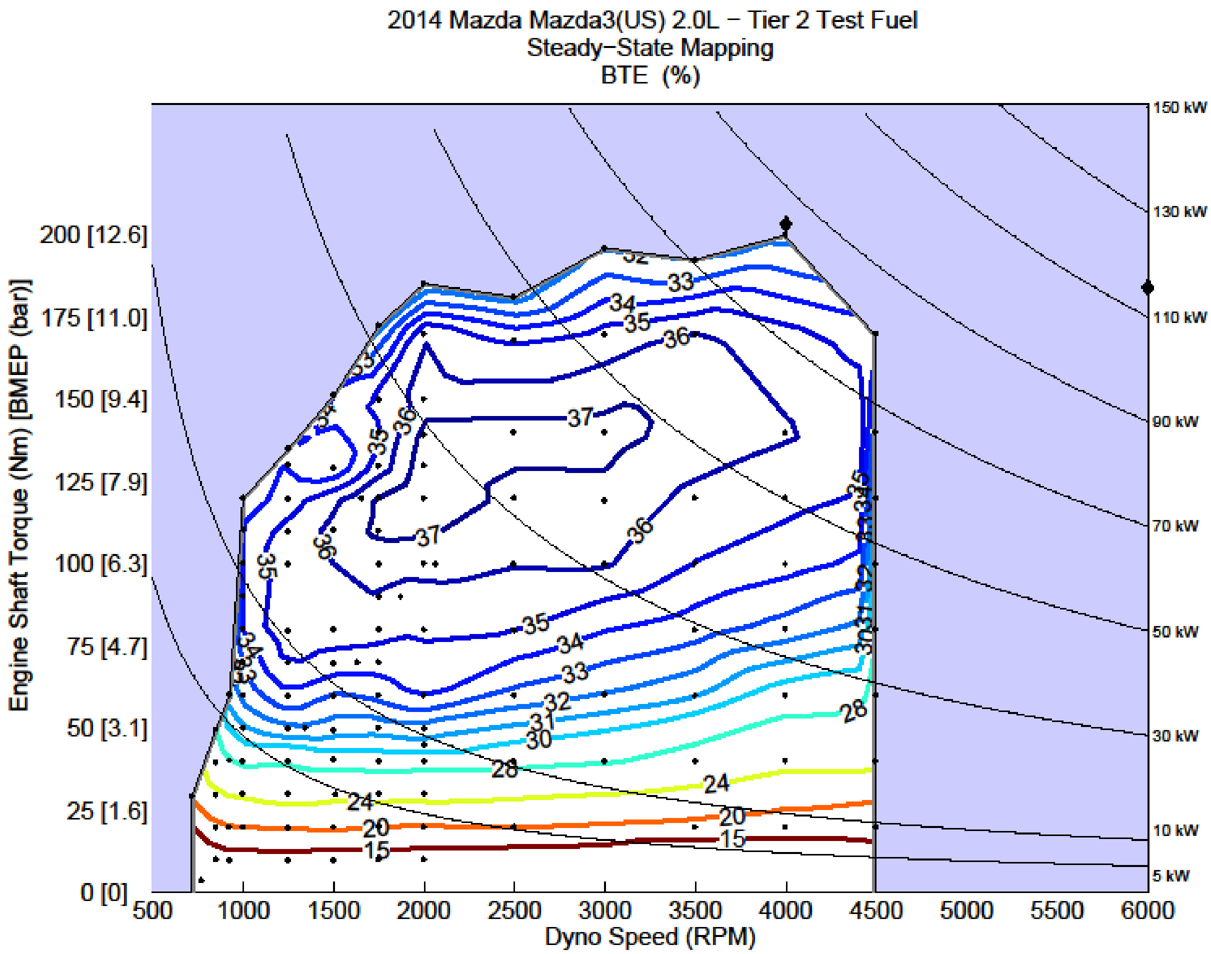

Figure 4. 2014 Mazda3 (US) 2.0L – BTE (%)

The black dots in the figures above indicate the speed/load points at which steady state data were acquired. The black diamonds indicate the rated torque/power points as advertised by the manufacturer [1]. Additional contour maps for all of the core test data measurements are provided in *2014 Mazda 2.0L Skyactiv 13-1 Tier 2 Fuel - Core Contour Plots.pdf.*

In these contour plots, individual data points may have been ignored or inserted, using the internal review team's best engineering judgment, to correct irregularities in the visual presentation of the contour lines. Test data is analyzed by reviewing the standard deviation and coefficient of variation of the measured results to statistically determine whether data may or may not be considered.

[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 are 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 is assumed to be negligible when compared to other uncertainties, and thus this uncertainty is 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,

$$u = {}^{\sigma}/_{\sqrt{n}}$$

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 5. As a result, testing uncertainty was considered to have minimal impact on the overall uncertainty and only the uncertainty of the sensors was utilized.

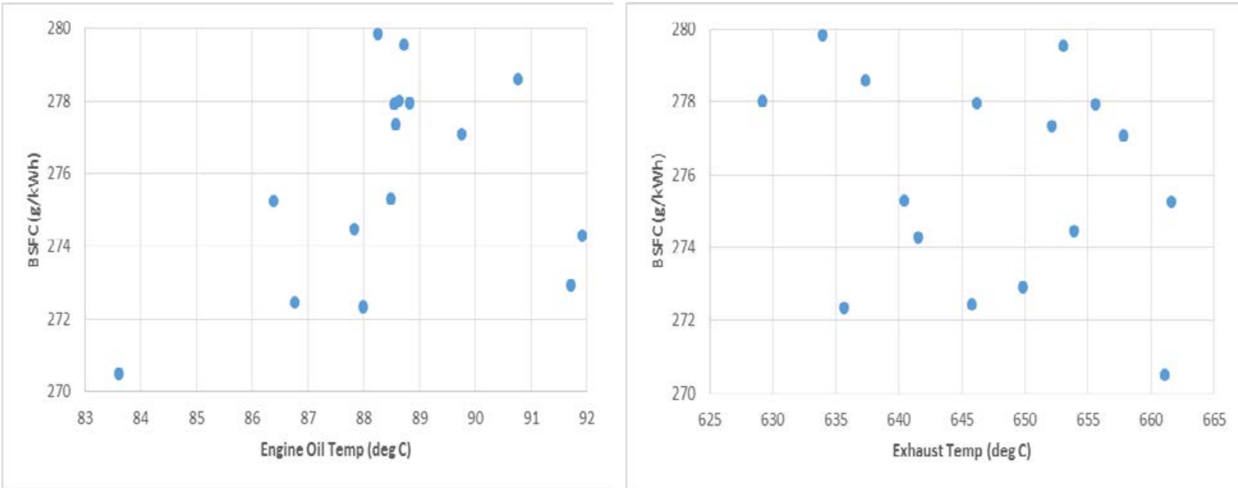

Figure 5. BSFC versus Engine Oil Temperature & Exhaust Temperature

<u>Uncertainty of BSFC</u>

The total uncertainty for BSFC is calculated by:

$$u(BSFC) = \sqrt{\left(\frac{\partial BSFC}{\partial q}\right)^2 [u(q)]^2 + \left(\frac{\partial BSFC}{\partial T}\right)^2 [u(T)]^2 + \left(\frac{\partial BSFC}{\partial \omega}\right)^2 [u(\omega)]^2}$$

or

$$u(BSFC) = BSFC\sqrt{\left[\frac{u_c(q)^2 + [\sigma(q)/n]^2}{q^2} + \frac{u_c(T)^2 + [\sigma(T)/n]^2}{T^2} + \frac{u_c(\omega)^2 + [\sigma(\omega)/n]^2}{\omega^2}\right]}$$

where, from above,

$u_c(q)$ = 0.00640 g/s $\quad$ $u_c(T)$ = 0.0808 Nm $\quad$ $u_c(\omega)$ = 1.183 rpm

$\sigma(q)$ = 0.0305 g/s $\quad$ $\sigma(T)$ = 1.147 Nm $\quad$ $\sigma(\omega)$ = 1.493 rpm

n = number of points in mode = $\omega/12$

<u>Uncertainty of BTE</u>

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

$$u(EFF) = EFF\sqrt{\left[\frac{u_c(q)^2 + [\sigma(q)/n]^2}{q^2} + \frac{u_c(T)^2 + [\sigma(T)/n]^2}{T^2} + \frac{u_c(\omega)^2 + [\sigma(\omega)/n]^2}{\omega^2} + 3.1 * 10^{-7}\right]}$$

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 +/-1u_c for 68% of the data points, the "true" value of a parameter would fall within +/-2u_c for 95% of the data points, and the "true" value of a parameter would fall within +/-3u_c for 99.7% of the data points. The calculated uncertainty for both the BSFC and BTE measurements are shown in Figures 6 and 7.

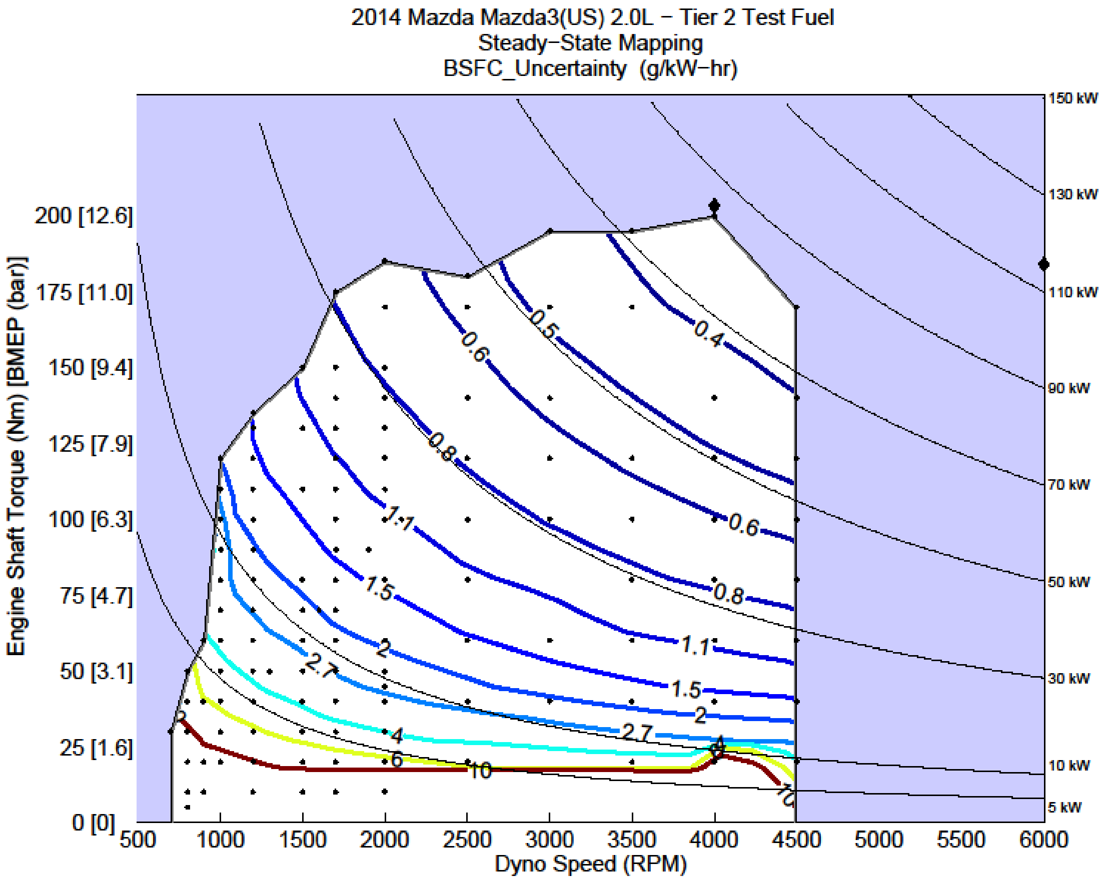

Figure 6. BSFC Uncertainty

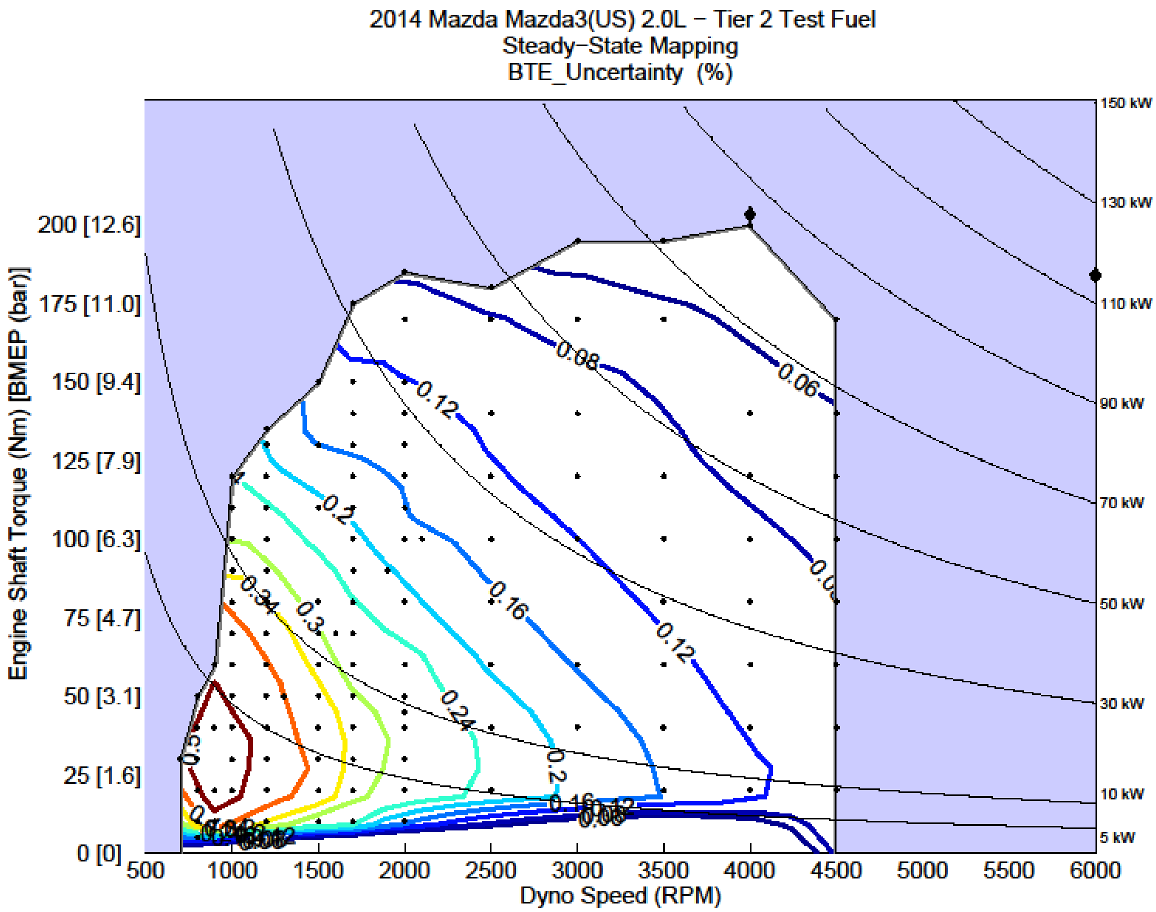

Figure 7. BTE Uncertainty

Discussion and Data Usage

The intent of this test was to establish a baseline to characterize the performance of the 2014 Mazda(3) SKYACTIV® 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 6 & 7, the uncertainty of very low-load points increases, particularly below 50 Nm, for the 2.0L SKYACTIV® engine. This effect is expected & will likely have a negligible effect on fuel economy calculations over a representative cycle.