



Downsized Boosted Engine Benchmarking and Results

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Abstract

Light-duty vehicle greenhouse gas (GHG) and fuel economy (FE) standards for MYs 2012-2025 are requiring vehicle powertrains to become much more efficient. One key technology strategy that vehicle manufacturers are using to help comply with GHG and FE standards is to replace naturally aspirated engines with smaller displacement "downsized" boosted engines. In order to understand and measure the effects of this technology, the Environmental Protection Agency (EPA) benchmarked a 2013 Ford Escape with an EcoBoost® 1.6L engine.

This paper describes a "tethered" engine dyno benchmarking method used to develop a fuel efficiency map for the 1.6L EcoBoost® engine. The engine was mounted in a dyno test cell and tethered with a lengthened engine wire harness to a complete 2013 Ford Escape vehicle outside the test cell. This method allowed engine mapping with the stock ECU and calibrations. Data collected included torque, fuel flow, emissions, temperatures, pressures, in-cylinder pressure, and OBD/epid can data.

Introduction/Background

During the development of the light-duty GHG standards for the years 2017-2025 [1], EPA utilized a 2011 light-duty vehicle simulation study from the global engineering consulting firm, Ricardo, Inc. This study provided a round of full-scale vehicle simulations to predict the effectiveness of future advanced technologies.

The 2017-2025 LD GHG rule required that a comprehensive advanced technology review, known as the midterm evaluation, be performed to assess any potential changes to the cost and the effectiveness of advanced technologies available to manufacturers. In preparation for this evaluation, EPA is planning to use a full vehicle simulation model, called the Advanced Light-duty Powertrain and

Hybrid Analysis Tool (ALPHA)[2], to supplement and expand upon the previous study used during the Federal rulemaking. ALPHA will be used to confirm and update, where necessary, efficiency data from the previous study, such as the latest efficiencies of advanced downsized turbo and naturally aspirated engines. It may also be used to understand effectiveness contributions from advanced technologies not considered during the original Federal rulemaking, such as continuously variable transmissions (CVTs) and clean diesel engines.

To simulate drive cycle performance, the ALPHA model requires various vehicle parameters as inputs, including vehicle inertia and road loads, and component efficiencies and operations. The benchmarking study described in this paper uses an engine dyno test cell in order to measure the efficiency of an engine for input to the ALPHA model. This paper describes EPA's "tethered" engine dyno benchmarking method which used a 1.6L EcoBoost® engine mounted in a dyno test cell and tethered with a lengthened engine wire harness to a complete 2013 Ford Escape vehicle outside the test cell. This method allowed engine mapping with the stock ECU and calibrations.

It should be noted that our complete benchmarking work on the 2013 Ford Escape included vehicle chassis testing to characterize the engine and transmission operation prior to engine dyno testing. However, the chassis testing results are outside of the scope of this paper.

Description of Test Article

The engine used in this project was a 2013 Ford Escape 1.6 liter EcoBoost®, which is a turbocharged direct-injection gasoline engine. The engine was tethered to its vehicle located outside of the test cell to make use of the stock engine and vehicle controllers. [Table 1](#) summarizes information that identifies the vehicle system used in this test program.

Table 1. Summary of vehicle and engine identification information

Vehicle (MY, Make, Model)	2013 Ford Escape
VIN	1FMCU0GX3DUC49410
Engine (displacement, name)	1.6 L EcoBoost®
Rated Power	180 Hp @ 5700 RPM
Rated Torque	240 Nm @ 1600-5000 RPM
Fuel requirement	87 octane AKI
Emission level	Tier 2 bin 4
Engine features of interest	turbocharged, spray-guided direct-injection

Test Site

This test was performed in a light duty engine dyno test cell located at the National Vehicle Fuels and Emissions Laboratory (NVFEL) in Ann Arbor Michigan. The test cell equipment and instrumentation is listed in [Table 2](#).

Table 2. Test cell Equipment and Instrumentation

Instrument Name	Purpose/Measurement Capabilities	Manufacturer
Dynamometer (AC)	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
Emissions bench	Raw and dilute exhaust gases: CO, THC, NOx, CH4, CO2	Horiba MEXA

Vehicle Tether Information

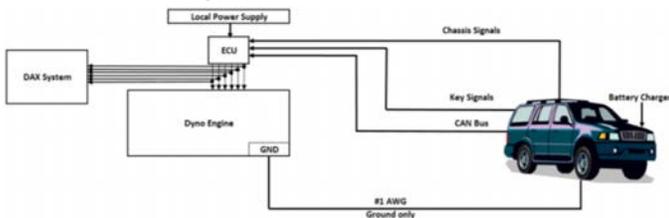


Figure 1. Vehicle and engine tethered wire harness

In modern cars, the engine control unit (ECU) is no longer the main computer. The ECU also requires communication with the body control module (BCM) to be able to monitor the entire vehicles operation (security, entry, key on, dash board signals, etc.). Because the ECU needs signals from the BCM to operate, the BCM signals need to be extended to the test cell ECU, so that the ECU will receive signals indicating correct vehicle operation. For our benchmarking testing, the wire lengthened, so that the engine in the dynamometer cell could be tethered to its vehicle chassis located outside the cell.

[Figure 1](#) illustrates the tethered wire harness. Wires were tapped into for all of the signals from the ECU to the engine so that the signal could either be monitored or fed, depending on what was needed for that particular sensor or actuator.

Engine Setup

[Figure 2](#) illustrates the engine setup and sensor location in the dyno test cell. The sensor colors shown in the upper right corner of the figure indicate which systems are monitored. The sensor numbers on the diagram refer only to our specific internal test cell setup.

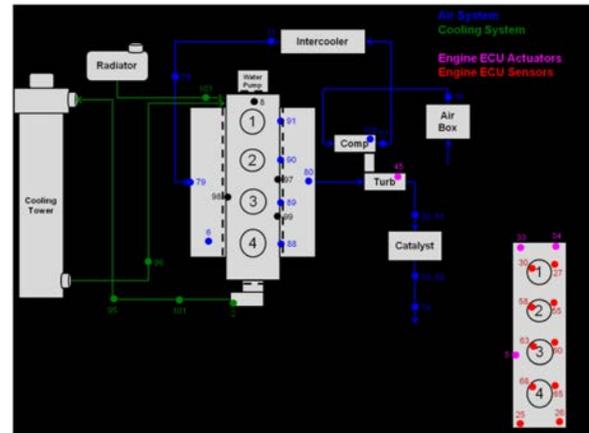


Figure 2. This was done to assure that the pressure drops through the charge air system is the same as the vehicle

Engine Systems

To install the engine in the cell, the stock portions of various engine systems were used, to the extent possible, but were connected with the control and sensing systems in the test cell.

- Intake:** The stock airbox and plumbing was used with laminar flow element (LFE) connected to airbox inlet.
- Charge air cooling:** Stock *Escape EcoBoost* tubing and intercooler were used. The stock intercooler was sandwiched to a chilled water heat exchanger with fans. Fan speed and chilled water temperature were used to control the stock intercooler air outlet temperature. This type of intercooler system maintains the stock air flow characteristics of the vehicle system with stable temperature control.
- Exhaust:** The stock exhaust system was used in the test cell and connected to the exhaust emission tunnel system to ensure the correct exhaust system backpressure. Emission tunnel pressure was controlled to $P^{atm} \pm 1.2$ kPa per the Code of Federal Regulations (CFR).
- Cooling system:** The stock cooling system was used, but with the radiator replaced with a cooling tower. The stock engine thermostat is used to control engine coolant temperature. The cooling tower is controlled to 85 C by the test cell control system.
- Oil system:** The stock oil cooler is connected to a chilled water system and controlled to 90 C by the test cell control system.
- FEAD:** The stock belt and pulley FEAD system was used.

7. **Alternator:** The alternator was modified for no electrical output by removing the field coils. This was done to map the engine without any alternator electrical load.
8. **Flywheel and housing:** The stock manual flywheel with aluminum adapter plate was connected to the driveshaft. The flywheel housing was a generic SAE 6 with adapter plate to connect to the engine.

Intercooler Temperature Control

During our engine dyno testing, engine temperatures were maintained to a level representative of real-world dynamic use, where the engine is cooled by increasing airflow into the engine compartment as vehicle speed increases. It was difficult to obtain typical engine intercooler outlet temperatures on the chassis dyno in the lab due to the limitations of road-speed fan operation. Instead, real-world on-the-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 engine test cell, air charge temperature was maintained at 30 to 40 C by using the stock intercooler sandwiched to a water to air cooler and fans.

Fuel

All testing was run using LEV III regular gasoline. See [Table 3](#) for the fuel specifications.

Table 3. Test cell fuel

Name	CARB LEV III regular
Octane	87 AKI
Ethanol	10%
Net heating value	17963 BTU/lb (41.78 kJ/g)

Fuel Mapping Test Points

The test points to map the fuel efficiency of this engine map covered the torque and speed range of the engine according to the rated values in [Table 1](#). These test points included engine speeds from 1000-3500 rpm in 250 rpm increments, and speeds up to 5500 rpm in 500 rpm increments.

Engine torques ranged from 0-30 Nm in 5 Nm increments and up to 240 Nm in 10 Nm increments. Fewer data points were needed at higher engine speeds so operators limited the number of test points above 4000 rpm. The data mapping points are shown in [Figure 4](#).

Data Set Definition

The data logged included torque, fuel flow, emissions, temperatures, pressures, in-cylinder pressure, and OBD/epid can data. Much of the data were logged once per engine cycle by the data acquisition system and a new output file was generated for each test point. Post-processing (described in later sections) was required to create the fuel map's single data points from the continuous data.

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.

Low-Load Data Points Procedure

For each engine speed, the procedure steps through an array of torques and records data. The engine speed is then incremented by 250 rpm and the torque array is repeated. 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 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 is of interest to obtain a quasi-steady-state value for these high load points that is representative of the engine's performance at a given pedal command.

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

Data Set Post-Processing

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 [Equation 1](#), using values obtained from data acquisition system.

$$BSFC = \frac{q_m}{P} = \frac{q_m}{\tau\omega \left(\frac{2\pi}{60}\right)} 3.6 * 10^6$$

Equation 1. BSFC Calculation for low-load points

Where:

q_m = fuel flow rate measured by flow meter (g/s)

P = engine power (W)

τ = engine torque measured by torque sensor (Nm)

ω = engine speed (rad/s)

Thermal efficiency was calculated according to [Equation 2](#) using the known heating value of the test fuel.

$$\eta_{th} = \frac{\tau \omega \left(\frac{2\pi}{60} \right)}{q_m h_v * 1000}$$

Equation 2. Thermal Efficiency Calculation

Where: h_v , Heating value of test fuel (kJ/g)

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

Due to engine behavior during testing, the high-load test data can alternate between multiple operating conditions within a single test. This behavior prohibits simply calculating the mean for the entire time-series. Instead, a stabilization detection algorithm was utilized to isolate points of stable engine operation and calculate a mean strictly for that duration. The employed algorithm calculated slope (via least-squares) and variance for a moving window of 25 points centered around each data point. While slope and variance remained below 5%, the operation was deemed stable. When 5 or more consecutive exceedances occurred, the operation was deemed unstable.

For the high-load data, the measured fuel flow rate significantly lagged the actual fuel flow, which, given the dynamic nature of the data collection procedure, made the previous post-processing strategy unworkable. An alternative fuel flow rate value was calculated based on injector duration and fuel rail pressure. The alternative fuel flow rate value, shown in [Equation 3](#), was used to calculate BSFC, again in g/kWh.

$$BSFC = \frac{q_m}{P} = \frac{q_m}{\tau \omega \left(\frac{2\pi}{60} \right)} 3.6 * 10^6$$

Equation 3. BSFC Calculation for high-load points

The alternative fuel flow rate value, q_{mcorr} , was developed based on the fuel flow correlation shown in [Figure 3](#). A second order polynomial regression with $R^2=0.9984$ was developed for fuel flow: injector duration * engine speed * sqrt(rail pressure). The slight curvature seen in [Figure 3](#) is likely due to the assumption that the pressure differential across the injector nozzle is constant when it is not. It is a function primarily of boost pressure since the injection occurs when the piston is near bottom dead center.

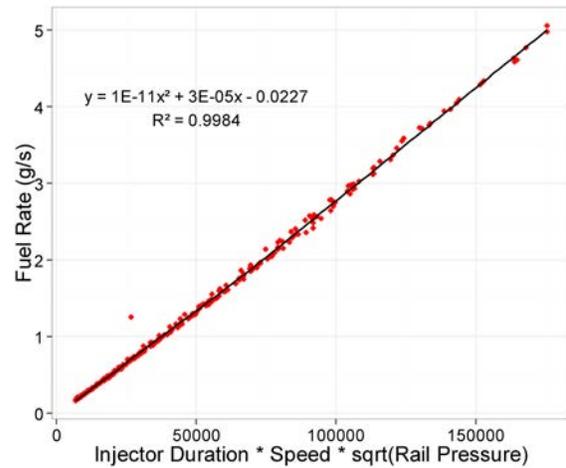


Figure 3. Fuel Flow Correlation

The corrected fuel flow quadratic function was...

$$q_{mcorr} = InjDur (ms) * \omega * \sqrt{FuelrailPressure (bar)}$$

Where:

$$q_m = 1.3 * 10^{-11} * q_{mcorr}^2 + 2.6 * 10^{-5} * q_{mcorr} - 0.0227$$

Thermal efficiency for the high-load tests was calculated the same as the low-load tests using [Equation 2](#).

Data Quality Assurance (QA)

[Figure 4](#) shows the speed and torque of the completed engine tests; the color of each point denotes whether the low load or high load test procedure was used to characterize the engine operation at that location.

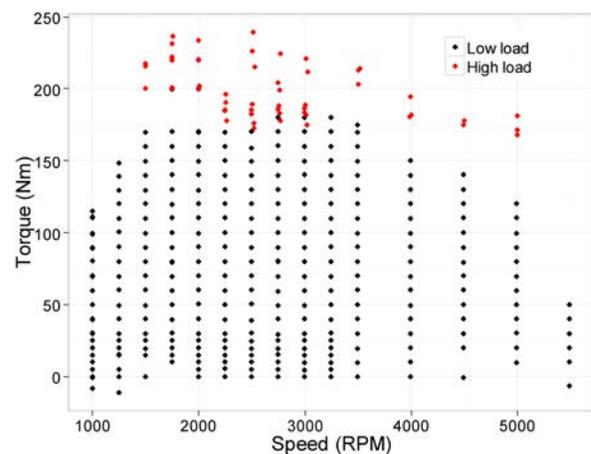


Figure 4. Engine test points, taken with the low-load procedure (black) or high-load procedure (red)

In a final QA step, any field where COV was greater than 10% was truncated from that test. For example, if COV(fuel rate) was greater than 10%, the fuel rate value would be removed from that test and BSFC would not be calculated. These points were presumed to exhibit engine and test cell behavior too unsteady to produce reliable data for the final dataset. This was typically an issue at very light loads (<10 Nm) where the dyno controller was not able to maintain a steady load.

Mapping Results

The average torque, speed, and fuel flow points were used to generate a fuel map, for BSFC (Figure 5) and efficiency (Figure 6). The torque and engine speeds were used to determine a grid, and the calculated BSFC and thermal efficiency values were used to generate contours of fuel consumption. The interpolation of irregularly spaced data across a 2d grid was performed in the R language using the `interp()` function within the `Aikman` package, a commercially available plotting software. The contour maps were drawn using the `filled.contour()` method.

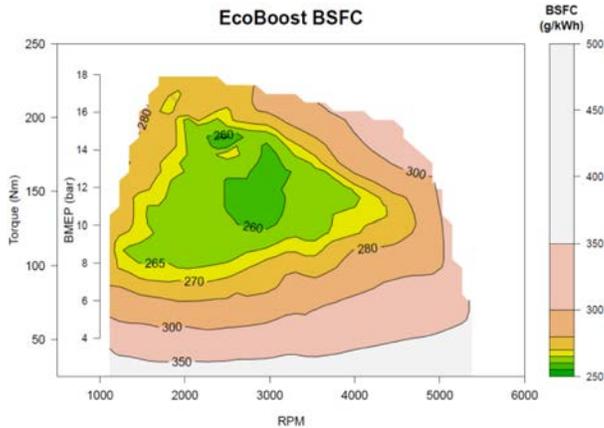


Figure 5. EcoBoost® BSFC (g/kWh)

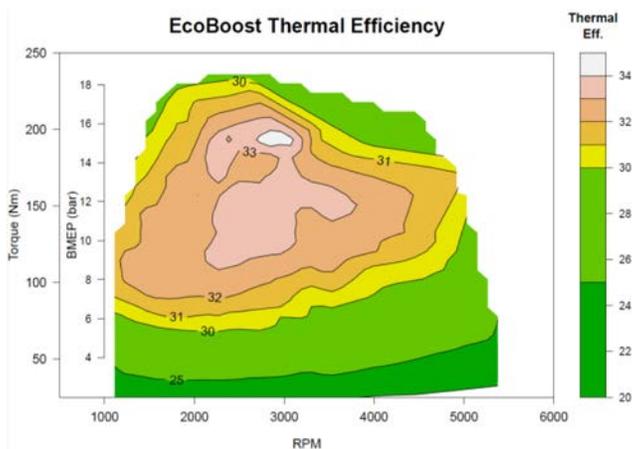


Figure 6. EcoBoost® Thermal Efficiency

Uncertainty

For each data point, the standard uncertainty in the measured BSFC was calculated as a function of the uncertainties of the measured signals and the uncertainty in the repeatability of the testing procedure. 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 $\pm 1u$ for 68% of the data points.

The uncertainties of the signals in the data set were calculated based on the uncertainty of the signal during operation, and the uncertainty of the sensor calibration. The uncertainty associated with the calibration standard is assumed to be negligible when compared to other uncertainties. The standard uncertainty for each signal is given in Table 8.

Table 8. Standard uncertainties for signals

Signal	$u(\text{calibration})$	$u(\text{operation})$	Total $u(\text{signal})$
Speed (rpm)	0.55	0.039	0.55
Torque (Nm)	0.49	0.069	0.49
Fuel (g/sec)	0.00274	0.0043	0.0049

For the high torque modes, the COV of the fuel flow correlation (Figure 2) was used to calculate the uncertainty of the fuel flow. For high pulse widths (e.g., in the “high torque” range where the correlation is used), the COV of the data is about 2%. This is well above the other uncertainties associated with this signal.

In addition to the uncertainties associated with each signal, there is an overall uncertainty associated with the repeatability of the testing procedure and the engine operation. To estimate this uncertainty, the variation of BSFC among a set of common modes was examined. The variation in the common modes was most tightly correlated with variation in coolant temperature and exhaust temperature. These temperatures can be considered as reasonable proxies for test procedure uncertainty (control of coolant temperature) and engine operation uncertainty (exhaust temperature) and the effect of each on BSFC was estimated. In the engine map data, the standard deviation of the coolant temperature was found to be 1.73 degrees C, which corresponds to 1.38 g/kWh BSFC, and the standard deviation of exhaust temperatures was estimated as 3.00 degrees C, which corresponds to 0.30 g/kWh BSFC, for an overall uncertainty associated with the repeatability of the testing procedure and the engine operation of 1.414 g/kWh BSFC.

The total standard uncertainty was calculated for each test point based on the combined uncertainties from the signals and the engine operation, as shown in Equation 4.

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

Equation 4. BSFC Uncertainty Calculation

For the low torque points, the individual uncertainties are, from above,

$$u(q) = 0.0049 \text{ g/sec fuel flow}$$

$$u(T) = 0.49 \text{ Nm torque}$$

$$u(\omega) = 0.55 \text{ rpm}$$

$$u_e(BSFC) = 1.414 \text{ g/kWh}$$

For the high torque points, the quantity $\frac{u(q)}{q}$ is 2%, with the remaining parameters the same.

A map of the standard uncertainty of the BSFC is given in [Figure 7](#).

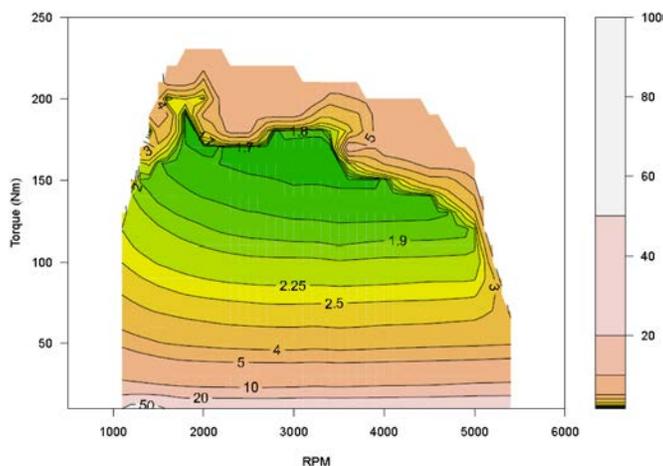


Figure 7. EcoBoost® BSFC Uncertainty

Summary/Conclusions

The test method of mapping an engine by tethering a vehicle to an engine in an engine dyno cell has been demonstrated. Particular care was taken to verify that the stock ECU was allowed to operate the engine through the entire speed/load map. Set up details such as ensuring proper intercooler temperature and electrical signal integrity through the extended wiring harness are key factors in assuring correct engine ECU controls.

In general, the engine operation and fuel consumption data produced in this testing are robust, and can be used for any purpose, as seen by the overall low BSFC uncertainties seen in [Figure 7](#). The BSFC uncertainty of very low-load points increases, but this effect is to be expected as the uncertainty at low load is dominated by the 0.49 Nm uncertainty of the torque itself (see [Eq. 4](#)). The higher uncertainty at low load is inherent in any engine test results, and will likely have a negligible effect on fuel usage modeling, as the fuel consumption at extremely low loads makes up a negligible portion of standard drive cycles.

It should be noted that, due to the greater uncertainty of the fuel measurement, the uncertainty of the BSFC calculation in the “high load” regime is substantially greater than the uncertainty of adjacent “low load” points. This can be seen clearly in [Figure 7](#), where the “high load” points above 180-200 Nm (see [Figure 4](#)) have an uncertainty of 5-7 g/kWh (around 2% of the calculated BSFC value), while adjacent points under 180-200 Nm have an uncertainty of less than 2 g/kWh. However, this effect is again to be expected and will likely have a negligible effect on fuel economy calculations over the FTP and HWFET cycles, which rarely require operation at these higher loads. Even with more aggressive cycles such as the US06, the moderate amount of operation at high torques and the roughly 2% ceiling on uncertainty will still provide robust fuel economy modeling results.

Work is underway to use this engine data as input to the ALPHA model to predict vehicle chassis fuel economy.

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Definitions/Abbreviations

GHG - green house gas

ALPHA - Advanced Light-duty Powertrain and Hybrid Analysis Tool

ECU - engine control unit

BCU - body control unit

FE - fuel economy

LD - light duty

OBD - onboard diagnostics

COV - coefficient of variation

BSFC - brake specific fuel consumption

CFR - Code of Federal Regulations

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