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Fuel Efficiency Mapping of a 2014 6-Cylinder GM EcoTec 4.3L Engine with Cylinder Deactivation

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Mark Stuhldreher
EPA Office of Mobile Sources

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Abstract

As part of the midterm evaluation of the 2022-2025 light-duty GHG emissions rule, the Environmental Protection Agency (EPA) has been evaluating fuel efficiency data from tests on newer model engines and vehicles. The data is used as inputs to an EPA vehicle simulation model created to estimate greenhouse gas (GHG) emissions from light-duty vehicles. The Advanced Light Duty Powertrain and Hybrid Analysis (ALPHA) model is a physics-based, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies and showing realistic vehicle behavior and auditing of all internal energy flows in the model.

Under the new light-duty fuel economy standards vehicle powertrains must become significantly more efficient. Cylinder deactivation engine technology is capable of deactivating one or more of its combustion cylinders when not needed to meet power demand. In order to understand and measure the efficiency effects of this technology, the EPA benchmarked a 2014 Chevrolet Silverado with a 6-cylinder 4.3L LV3® engine, capable of lowering its displacement from six to four cylinders.

EPA's complete benchmarking study of this vehicle included both chassis testing and engine dyno testing to measure the vehicle and engine efficiencies. This paper describes the test method and results for the engine dyno portion of the benchmarking. The test method involves installing the engine in an engine dyno test cell with the engine wiring harness tethered to its vehicle parked outside the test cell. This technique enables the engine to be mapped using the stock ECU and calibrations along with all the safety checks including those coupled to vehicle sensors. The data measured included torque, fuel flow, emissions, temperatures, pressures, incylinder pressure, and OBD/epid CAN bus data. The benchmarking test results include engine fuel consumption maps showing the effects of cylinder deactivation technology.

Introduction/Background

During the development of the light-duty GHG standards for the years 2022-2025 [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. For the midterm 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, if necessary, update efficiency data from the previous study, to include the latest efficiencies of advanced downsized turbo and naturally aspirated engines. ALPHA will also be used to understand effectiveness contributions from advanced technologies not considered during the original Federal rulemaking, such as continuously variable transmissions (CVTs) and Atkinson-cycle naturally aspirated engines.

To simulate drive cycle performance, the ALPHA model requires various vehicle parameters as inputs, including vehicle inertia and road loads, component efficiencies, and vehicle operation data. 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 Chevrolet 4.3L LV3® engine mounted in a dyno test cell and tethered with a lengthened engine wiring harness to a complete 2014 Chevrolet Silverado vehicle outside the test cell. This method allowed engine mapping to be conducted using the stock ECU and calibrations.

Our complete benchmarking work on the 2014 Chevrolet Silverado included vehicle chassis testing to characterize the engine and transmission operation prior to engine dyno testing. EPA plans to use the complete vehicle data set to validate the ALPHA model against the 2014 Silverado. However, most of the chassis testing results that are needed to support the validation are outside the scope of this paper.

Description of Test Article

The engine used in this project was a 2014 Chevrolet Silverado 4.3 liter LV3®, which is a naturally aspirated, 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)	2014 Chevrolet Silverado
VIN	1GCNCPEH2EZ171727
Engine (displacement, name)	4.3 L LV3®
Rated Power	285 hp (213 kw) @ 5300 RPM
Rated Torque	305 lb.-ft (413 Nm) @ 3900 RPM
Fuel requirement	87 octane AKI
Emision level	Bin 4 emissions
Engine features of interest	☐ Direct injection ☐ Cylinder deactivation ☐ Continuously variable valve timing. Pushrod, single cam.

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.

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 CAN and data was combined into a single output file. The engine control software packages are summarized in Table 3.

Table 2. Test Cell Equipment and Instrumentation

Instrument Name	Purpose/Measurement Capabilities	Manufacturer
RPECS	Data acquisition. Crank angle sampling	Southwest Research Institute
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	Dilute tailpipe exhaust gases: CO, THC, NOx, CH_4, CO_2.	Horiba MEXA

Table 3. Engine Control and Analysis Software

Software	Developer	Description	Data Rate
CAN	Engine OEM	Collects/monitors ECU output	variable
iTest	A&D Technology, Inc.	Controls dyno Collects test cell data	10 hz
CAS	MTS Systems Corporation	Combustion analyzer	720/rev
RPECS final	Southwest Research Institute	Commands pedal Collects supplemental data Master data logger	1/cycle

Vehicle Tether Information

In modern cars, the engine control unit (ECU) 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 the ECU will receive signals indicating correct vehicle operation. For our benchmarking testing, the wiring harnesses connecting the ECU to the rest of the vehicle were lengthened, so the engine in the dynamometer cell could be tethered to its vehicle chassis located outside the cell. Figure 1 illustrates the tethered wiring harness. Wires were tapped into for all of the signals from the ECU to the engine so the signal could either be monitored or fed, depending on what was needed for that particular sensor or actuator.

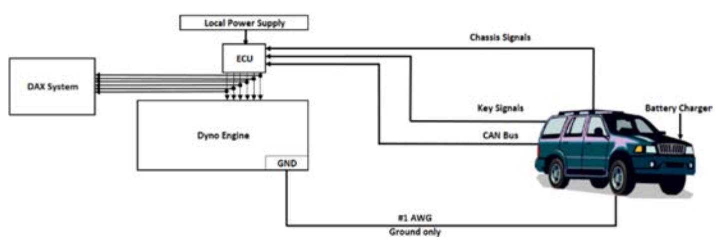

Figure 1. Vehicle and Engine Tethered Wire Harness

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.

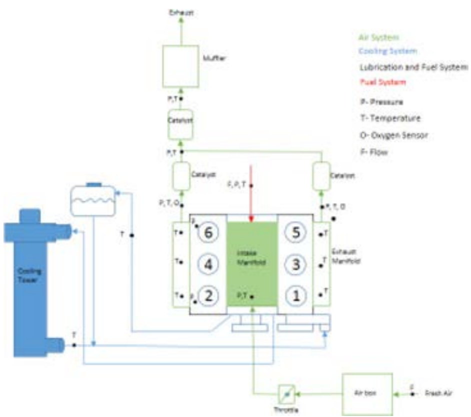

Figure 2. Schematic of Dyno Test Cell and the 4.3L LV3® Engine Sensor Locations Corresponding to the Identified Systems

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.

1. **Intake**: The stock air box and plumbing was used with laminar flow element (LFE) connected to air box inlet.
2. **Exhaust**: The stock exhaust system was used including catalyst and mufflers. The exhaust system outlet connected to the emissions tunnel via 2 inch diameter tubing. Emission tunnel pressure was controlled to P^{atm} +/- 1.2 kPa per the CFR.
3. **Cooling system**: The stock cooling system was used, but with the radiator replaced with a cooling tower. The stock engine thermostat was used to control engine coolant temperature. The cooling tower was controlled to 85 C by the test cell control system.
4. **Oil system**: The stock oil cooler was connected to a chilled water system and controlled to 90 C by the test cell control system.
5. **FEAD**: The stock belt and pulley FEAD system was used.
6. **Alternator**: The alternator was modified for no electrical output by removing the field coils.
7. **Flywheel and housing**: The stock manual flywheel with aluminum adapter plate was connected to the driveshaft. The flywheel housing was a fabricated housing with mounting pads for rear mounts.

Fuel

The engine tests were performed with two fuels. E10 88 octane and E0 92 octane. See Table 4 for the fuels specifications.

Table 4. Test Cell Fuels

Name	CARB LEV III regular	Tier 2
Octane (AKI)	88	92
Ethanol (%)	10	0
Net Heating Value (BTU/lb)	17963	18439

Fuel Mapping Test Points

The test points to map the fuel efficiency of this engine 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 3.

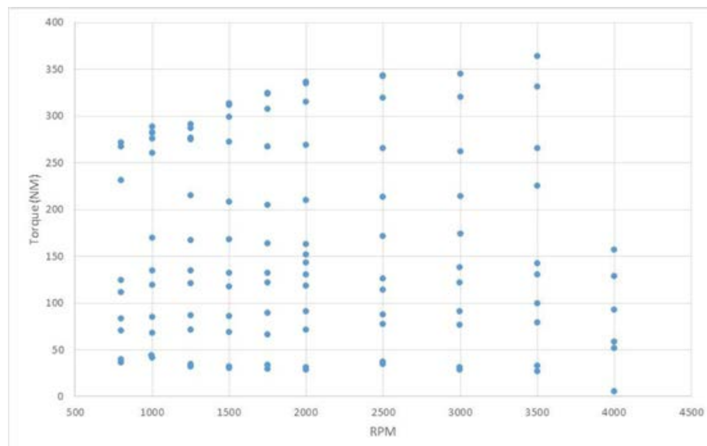

Figure 3. Engine Test Points

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 was 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

For each engine speed, the procedure steps through an array of torque values and records the 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, and torque.

Operational Test Procedure

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

Data Set Post-Processing

The data is 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)

Brake Thermal Efficiency (BTE) 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.

Data Quality Assurance (QA)

Figure 3 shows the speed and torque of the completed engine tests.

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.

Base Operation Mapping Results

The average torque, speed and fuel flow points shown in Figure 3 were used to generate a base contour map for brake thermal efficiency. Mapping was done with and without cylinder deactivation. Figure 4 illustrates the BTE without cylinder deactivation enabled. Mapping results with cylinder deactivation enabled are described in the next sections.

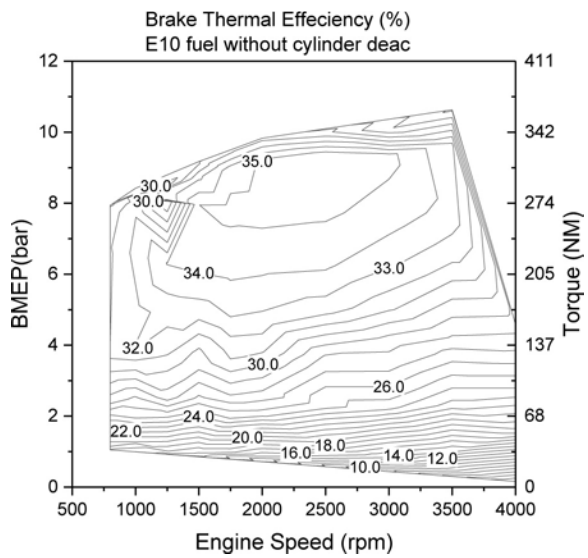

Figure 4. 4.3L Brake Thermal Efficiency, E10 fuel, without Cylinder Deactivation

Cylinder Deactivation during Chassis Cycle and Engine Dynamometer Testing

Cylinder deactivation was observed during the chassis testing over the FTP (bag 1&2 only) and Highway fuel economy test cycles. Engine data was collected every engine cycle and logged to RPECS. Each point on the graph represents one engine cycle.

Cylinder deactivation was also observed during the engine dynamometer testing as shown in Figure 7.

Cylinder deactivation occurs in the region determined by the boxed, labeled zones shown in Figures 5 and 6, bounded by the max and min speed and load observed during cycle testing. Figure 5 shows cylinder deactivation operation over bag 1 & 2 of the FTP cycle, while Figure 6 shows cylinder deactivation operation over the highway fuel economy test cycle. Even though cylinder deactivation can occur in this speed and load range, it does not occur for every operating point during the drive cycles.

Zone 1 is the entire area in which cylinder deactivation can occur, as determined during the steady state engine dynamometer testing. When the engine was tested in the engine dyno cell, cylinder deactivation was enabled or disabled by using the GM Multiple Diagnostic Interface service/scan tool. This tool allowed the user to control cylinder deactivation, which enabled the ability to map steady state points with and without cylinder deactivation. When the vehicle was tested on the chassis dyno, cylinder deactivation was controlled by the ECU.

Cylinder deactivation was observed to be limited by the engine ECU in the lower speed and load ranges of the engine map. Figure 7 shows the area of cylinder deactivation explored by EPA during steady state engine dynamometer testing. It should be noted that the engine is capable of running in deactivation mode below 1000 rpm as observed in Figures 5 & 6. However, EPA did not collect that data in its initial test program, but plans to gather the data in a follow-up test program on the engine and transmission.

Zone 2 is a subset representing cylinder deactivation observed during the cycle test, to compare with the deactivation zone allowed by the GM scan tool during dynamometer testing. Zone 3 provides an example of the one of the highest percentage areas of deactivation observed.

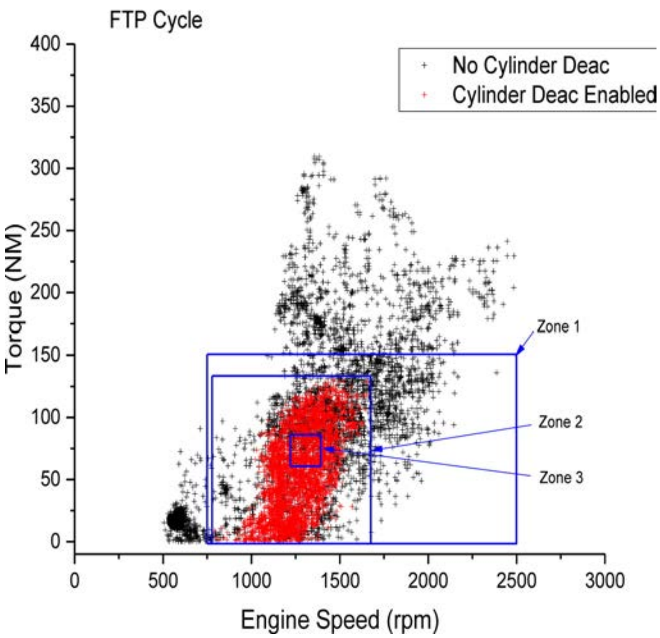

Figure 5. FTP Cycle Test Data

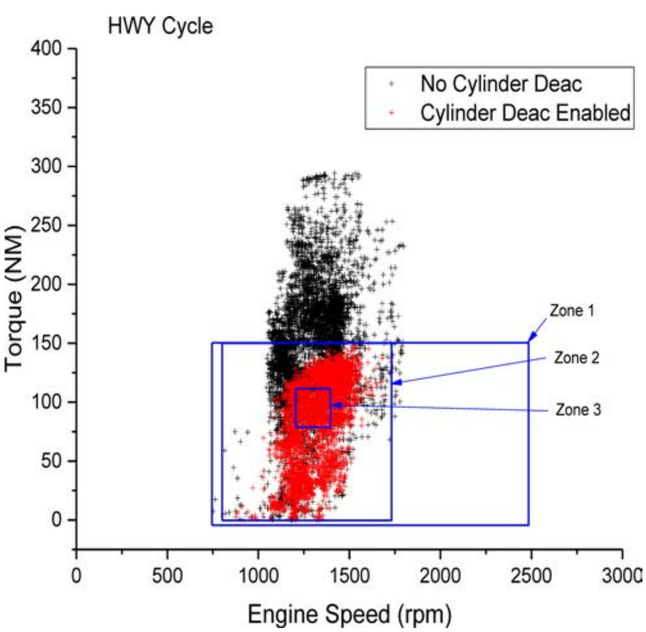

Figure 6. HWY Cycle Test Data

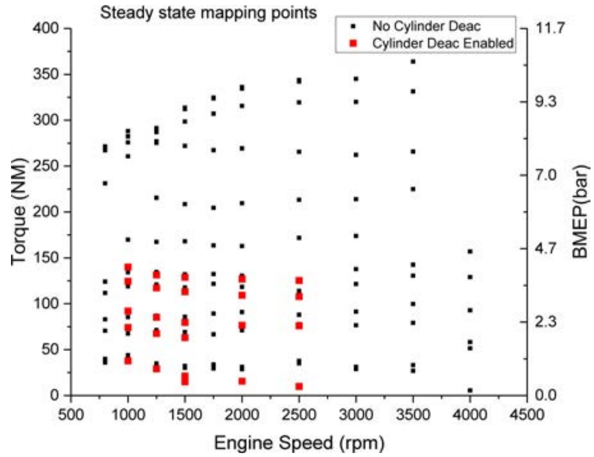

Figure 7. Steady State Engine Dynamometer Data Points with Cylinder Deactivation

The cylinder deactivation % was then calculated by the number of cylinder deactivation enabled points (engine cycles) divided by the total number of points within the region of cylinder deactivation shown in the table below.

Table 5. Cylinder Deactivation Percentage (engine cycles) by Zone

Cycle/Test	Speed/Load window	% Cylinder Deac
FTP bag 1 & 2 Total	All	40.3%
FTP bag 1 & 2 Zone 1	0-2500 rpm, 0-150 NM	46.2%
FTP bag 1 & 2 Zone 2	790-1660 rpm, 0-132 NM	63.5%
FTP bag 1 & 2 Zone 3	1180-1360 rpm, 55-84 NM	73.6%
HWY Cycle Total	All	43.6%
Hwy Zone 1	0-2500 rpm, 0-150 NM	59.5%
Hwy Zone 2	800-1740 rpm, 0-150 NM	61.7%
Hwy Zone 3	1200-1400 rpm, 80-112 NM	70.5%

Effects of Cylinder Deactivation on Brake Thermal Efficiency

The 4.3L LV3® engine uses cylinder deactivation to improve efficiency by reducing pumping losses during low-load operation. Figure 9 is an example engine dynamometer data set of the effect of cylinder deactivation on thermal efficiency at 1250 rpm. This data shows that cylinder deactivation increases BTE. For example, an individual BMEP point increased BTE 27.5 to 30.6, resulting in an 11% increase in efficiency.

The 4.3L cylinder deactivation method deactivates cylinders 3 and 6 simultaneously as detected by the RPECS data acquisition system. The RPECS monitors and records the fuel injector voltage and CAN bus epid signals on crank angle based sampling. The engine was also instrumented with incylinder Kistler pressure transducers on cylinders 1 and 3.

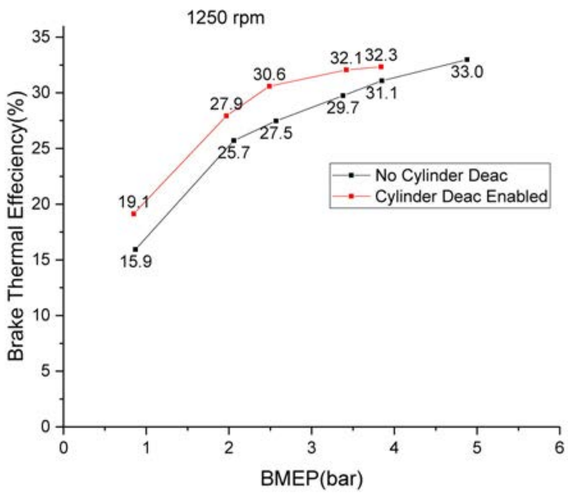

Figure 8. Cylinder Deactivation Effect on BTE at 1250 rpm

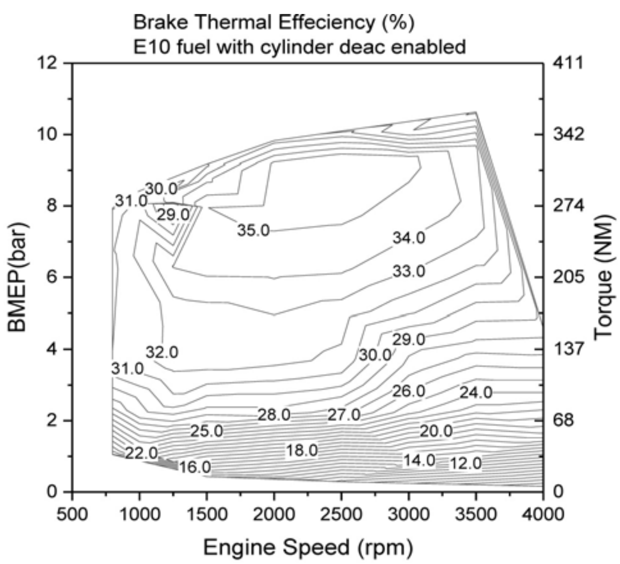

Figure 9. 4.3L Brake Thermal Efficiency, E10 fuel, with Cylinder Deactivation

Effects of Fuels on Efficiency

The 4.3L LV3 engine was tested with two different fuels. 88 octane E10 and 92 octane E0. See Table 4 for the specific fuel specifications.

The steady state mapping was repeated for each fuel. The engine and ECU were prep run with each fuel in order for the ECU to actively adjust to the change in octane and alcohol content. This procedure consisted of running the engine at medium to high loads for an extended period of time.

The fuel system on the vehicle does contain a fuel sensor which detects % alcohol. This epid value can be read by the GM service scan tool. This sensor was relocated into the test cell to sense the test fuel going into the engine.

The steady state mapping results do not show any significant brake thermal efficiency differences between the two fuels. This is illustrated by comparing the BTE map results of the two fuels shown in Figures 4 and 10. In addition, Figure 11 is an example data set at 2000 rpm showing the minimal effect of the two different fuels on BTE.

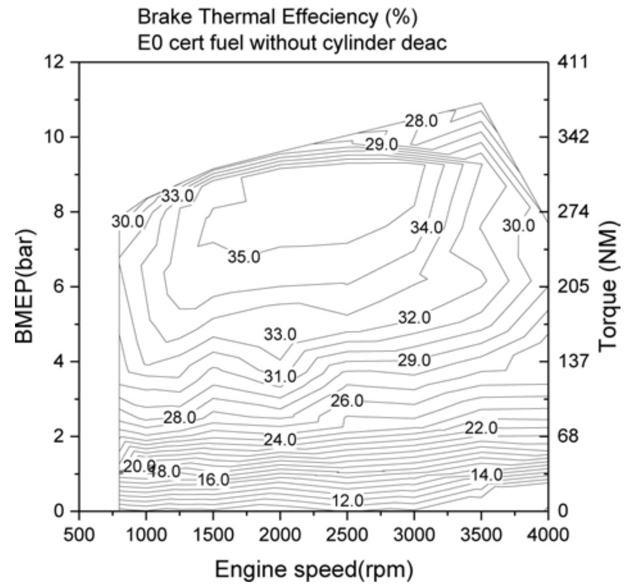

Figure 10. 4.3L Brake Thermal Efficiency, E0 fuel, without Cylinder Deactivation

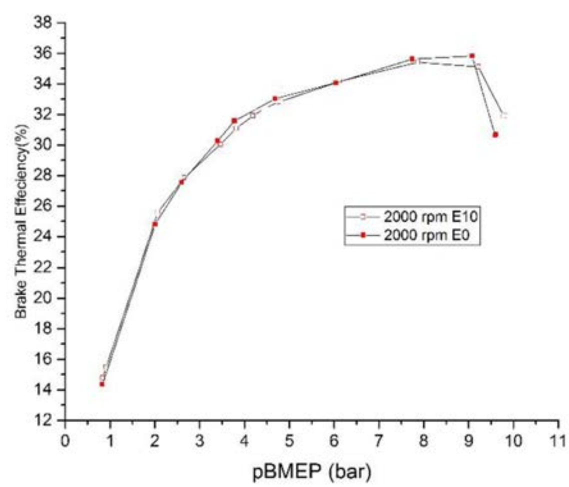

Figure 11. Different Fuels Effect on BTE at 2000 rpm

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 simulate real vehicle driving conditions in order for the engine ECU controls to work like a driven vehicle. Set up details such as electrical signal integrity are key factors in the engine ECU controls.

The benchmarking test results include engine fuel consumption maps showing the effects of cylinder deactivation technology. Cylinder deactivation was controlled by the ECU to occur in the low to medium speed and load points. The engine efficiency increased by up to 11% through the use of cylinder deactivation.

The steady state maps show the benefit of cylinder deactivation to BTE. The vehicle chassis testing shows the speed and load range of cylinder deactivation as well as the frequency it is enabled. The vehicle cycle data shows that cylinder deactivation is used in about 40% of the engine cycles over bag 1 and 2 of the FTP cycle and about 44% of the engine cycle over the HWY cycle. As a result, even though the engine may be in the speed and load range for cylinder deactivation, there are restrictions. The application of the steady state data to the ALPHA simulations must consider these restrictions.

The engine was tested with two different fuels to demonstrate the effect on BTE. The fuels with properties 88 octane E10 (Lev III) and 92 octane E0 (Tier 2) were tested and showed minimal change in BTE.

In general, the engine operation and fuel consumption data produced in this testing are robust, and can be used for any purpose. In support of the of the midterm evaluation of the 2022-2025 light-duty GHG emissions rule, the engine data is intended to be used as inputs to the ALPHA model to predict vehicle chassis fuel economy.

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Contact Information

Mark Stuhldreher
National Center for Advanced Technology
US EPA - National Vehicle and Fuels Emissions Laboratory
734-214-4922
Stuhldreher.mark@epa.gov

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Definitions/Abbreviations

BTE - Brake Thermal Efficiency

GHG - Greenhouse 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

EPA - Environmental Protection Agency

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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