Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine

2016-01-1007
Published 04/05/2016

Benjamin Ellies, Charles Schenk, and Paul Dekraker
US Environmental Protection Agency

CITATION: Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, doi:10.4271/2016-01-1007.

Abstract

As part of its technology assessment for the upcoming midterm evaluation (MTE) of the 2022-2025 Light-Duty Vehicle Greenhouse Gas (LD GHG) emissions standards, EPA has been benchmarking engines and transmissions to generate inputs for use in its Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) model, a physics-based, forward-looking, full vehicle computer simulation tool. One of the most efficient engines today, a 2.0L Mazda SkyActiv engine, is of particular interest due to its high geometric compression ratio and use of an Atkinson cycle. EPA benchmarked the 2.0L SkyActiv at its National Vehicle and Fuel Emissions laboratory.

EPA then incorporated ALPHA into an engine dynamometer control system so that vehicle chassis testing could be simulated with a hardware-in-the-loop (HIL) approach. In order to model the behavior of current and future vehicles, an algorithm was developed to dynamically generate transmission shift logic from a set of user-defined parameters, a cost function (e.g., engine fuel consumption) and vehicle performance during simulation.

This paper first presents the results of EPA's benchmarking of a Mazda 2.0L 13:1 CR SkyActiv engine. It then details the implementation of the SkyActiv 2.0L engine in an HIL test bed to represent chassis testing of an advanced vehicle configuration, which includes assumptions for a future high-efficiency transmission and reduced vehicle road loads. The engine was operated over simulated EPA city and highway test cycles to assess the greenhouse gas (GHG) emissions performance in the context of EPA's LD GHG standards through year 2025.

Introduction

In 2012, EPA and NHTSA promulgated a final rulemaking to set light-duty vehicle greenhouse gas emissions standards for vehicles sold for model years 2017-2025 [1]. This rulemaking included a commitment by both agencies to perform a Mid-Term Evaluation (MTE) to review progress toward the standards. As part of EPA's technology review to support the MTE, EPA has been conducting a series of engine benchmarking and development activities at its National Vehicle Fuel and Emissions Laboratory in Ann Arbor, MI.

Since the original rulemaking, several technologies have seen improvements, and additional technologies not considered in the Agencies' original technical analysis have recently come to market. One such technology is the implementation of a high expansion ratio Atkinson cycle outside of hybrid electric applications.

The original Atkinson cycle is nothing new - James Atkinson first patented the concept in 1882 - and has been researched for decades as a means of increasing thermal efficiency [2,3,4]. Despite this interest, variations of the Atkinson engine with earlier fixed mechanical valvetrain designs had seen limited applicability in practice. However, the concept has seen renewed interest with the onset of variable valvetrains over the past decade. While a high compression ratio (CR) provides higher overall combustion efficiency, the propensity for knock limits the compression ratio at which traditional Otto-cycle engines can operate. Typically, compression ratios above 12:1 are rare for naturally-aspirated, Ottocycle engines. However, with modern variable valvetrains multiple strategies, e.g., using late intake valve closing (LIVC), serve to reduce the "effective" compression ratio while preserving a high geometric ratio for the expansion stroke of an engine. This approach still provides significant efficiency gains while protecting the engine against knock. At high loads GDI suppresses knock and allows good peak BMEP. While Toyota has utilized an Atkinson-cycle engine in its Prius hybrid for several years [5], there were no commercial examples of vehicles powered exclusively with an Atkinson cycle engine until Mazda's SkyActiv engines went into production in 2012.

As part of the technology assessment for the MTE, the EPA is interested in analyzing the effectiveness of new technologies, such as the SkyActiv engine. This paper is organized into three major sections. First, the benchmarking of the 2.0L SkyActiv is described, with key findings unique to this engine architecture (including a brief section on the SkyActiv's sensitivity to test fuel octane). Then EPA's hardware-in-the-loop (HIL) model is presented as a method for simulating vehicle emissions and fuel economy drive cycles in an engine dynamometer test cell. Finally, HIL cycle test data for the 2.0L SkyActiv engine in a virtual future vehicle is presented and discussed in the context of 2025 GHG emissions standards.

Engine Benchmarking

Engine Description

The naturally aspirated direct-injection 2014 Mazda SkyActiv 2.0L used in the Mazda3 is the subject of this benchmarking. Table 1 summarizes the engine specifications.

This engine was chosen for benchmarking because it uses a late intake valve closing (LIVC) Atkinson cycle. This allows the use of a high 13:1 geometric compression ratio on 87 AKI gasoline. The LIVC is achieved with an electric intake cam phaser that allows 75 degrees of advance from a base IVC position of 58 degrees BTDC. A conventional hydraulic exhaust phaser has 45 degrees of retard from a base EVC position of 14 degrees ATDC of the exhaust stroke. Additional details on the SkyActiv architecture are available from Mazda press materials [6].

Table 1. Mazda SkyActiv 2.0L specifications

Displaced volume	1998 cc
Stroke	91.2 mm
Bore	83.5 mm
Rated power	115 kW @ 6000 RPM
Rated torque	203 Nm @ 4000 RPM
Compression ratio	13.0:1
Peak fuel rail pressure	200 bar

Test Setup

This engine was benchmarked at EPA's National Vehicle and Fuel Emissions Laboratory in an engine dynamometer test cell. A picture of the test setup is shown in Figure 1. The engine was first run on LEVIII-compliant certification fuel which has a 7 psi vapor pressure and 88 AKI. This fuel is similar to Tier 3 fuel with the exception of the vapor pressure which is required to be 9 psi to meet Tier 3 certification. It was then tested on Tier 2 certification fuel (93 AKI) to assess effects of higher octane fuel on engine operation and efficiency. The test fuel properties are summarized in Table 2. Similar to other recent EPA engine benchmarking programs, this engine was run with its ECU tethered to a vehicle located outside of the test cell. Additional details of this test setup, including instrumentation, are consistent with other EPA benchmarking programs [7].

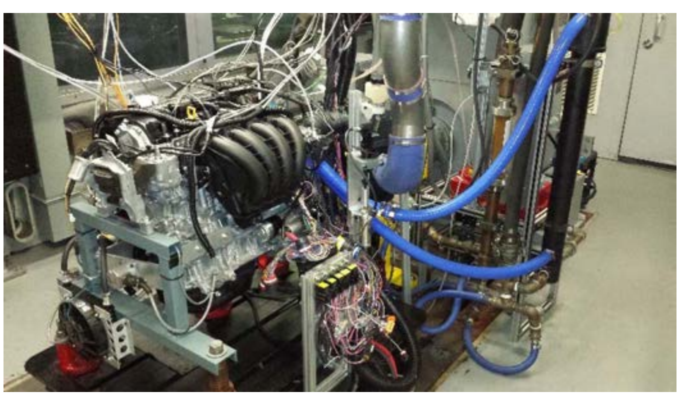

Figure 1. SkyActiv Engine in Test Cell

Table 2. Measured test fuel properties

	LEV III regular	Tier 2 Certification
AKI (RON+MON)/2	88.1	92.6
Ethanol content (% vol) D5599	9.6	0.0
Vapor pressure (psi) D5191	7.0	9.2
Net Heating Value (BTU/lb) D240	17955	18438
Density (g/cm3) D4052	0.7502	0.7430

Benchmarking

A steady state map consisting of over two hundred test points between idle (750 rpm) and 4500 rpm were taken. The brake thermal efficiency (BTE) of these points are given in the map shown in Figure 2. The engine exceeds 36% BTE over a broad range of operation. There is also a small region that exceeds 37% BTE. These are very impressive efficiencies for a production gasoline engine. Figure 3 shows that the SkyActiv engine has better peak BTE than any of the referenced engines including the Ricardo predictions for a 2020 engine (described in the Technical Support Document for the LD GHG rule) [8].

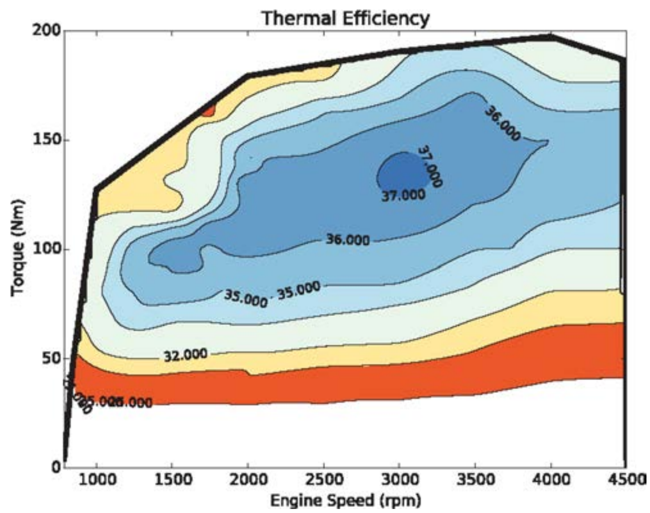

Figure 2. Brake thermal efficiency with 88 AKI LEV III gasoline

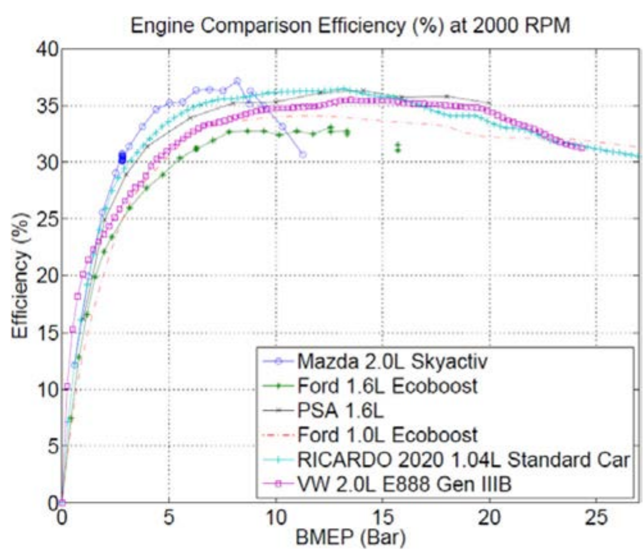

Figure 3. BTE comparison

Key Observations

The efficiency of this engine was achieved by minimizing losses and effectively increasing the expansion ratio through the LIVC Atkinson cycle. The efficiency methods that were observed directly in this testing were the oil pressure and air pumping controls. This engine had very low oil pressure at low speed and light loads. Oil pressure was less than 160 kPa in the map area below 3500 rpm and 120 Nm. At higher speeds and loads the oil pressure switched to a more typical pressure (over 320 kPa depending on speed and oil temperature). While oil pressure alone is not a direct indicator of work, it is likely that this stepped pressure control was done to reduce oil pumping losses.

Minimizing air pumping loss was achieved in part through LIVC Atkinson cycle. This method leaves the intake valve open for part of the compression stroke, reducing the use of the throttle. The intake valves are held open while the cylinder volume decreases as the piston moves toward TDC. When the desired intake charge mass is reached, the intake valve is closed. The manifold pressure can be held near atmospheric (Figure 4) and very little work is done on the charge mass until the valves are closed and compression starts. This reduces the work required to pump air across the throttle.

However, there are limitations under which conditions this can be done. At light loads (<75 Nm) some compression needs to be preserved for reliable ignition. This limits how close to TDC the intake valves can be closed. In this condition the intake throttle is also used to lower the manifold pressure as would be done in a conventional engine. At high loads the IVC is advanced away from TDC and Atkinson operation so that the cylinder traps the maximum air charge for good power density.

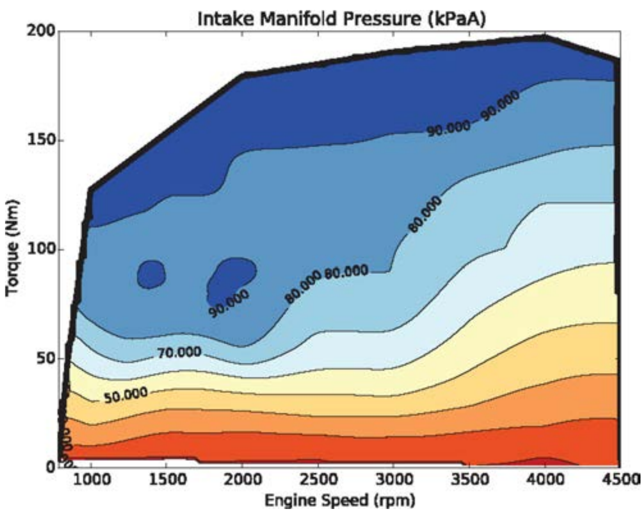

Figure 4. Intake manifold pressure (kPaA)

The use of LIVC reduces the effective compression ratio (Figure 5) while maintaining the geometric expansion ratio. This reduces compression work which is also a loss. Figure 5 shows an effective compression ratio as low as 5:1 up to 11:1. The 5:1 effective compression ratio is the result of IVC at 63 degrees BTDC (Figure 6). This minimizes the compression and pumping work while maintaining the 13:1 expansion stroke which helps thermal efficiency. Another benefit of lower effective compression ratio is that it decreases in-cylinder temperature and knock. The engine was not observed to knock audibly during this test program.

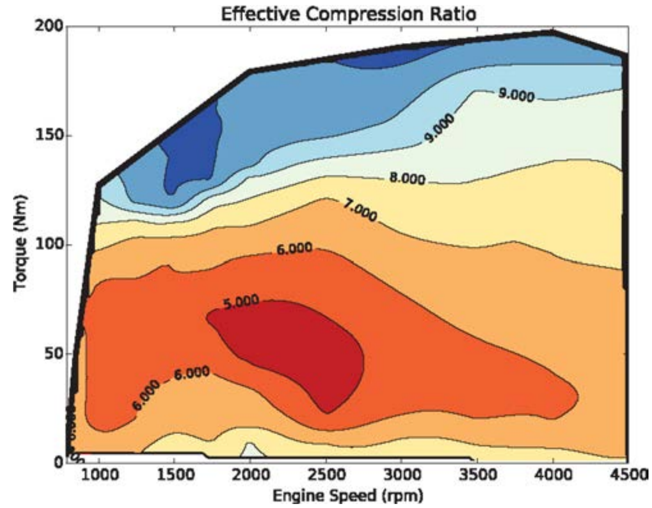

Figure 5. Effective compression ratio due to LIVC

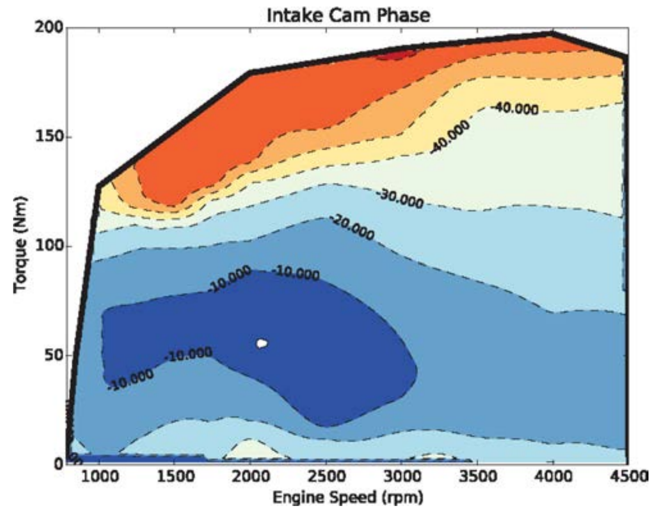

Figure 6. Intake cam retard from base position (58 deg BTDC IVC)

To investigate if there was more efficiency to be gained from higher octane, the engine was mapped again using 93 AKI Tier 2 (E0) certification gasoline, with specifications shown in Table 2. Other than fuel type, the test setup and procedures were identical to those that produced the map with 88 AKI LEV III gasoline (Figure 2).

Figure 7 shows the BTE results when the engine was run using 93 AKI Tier 2 gasoline. The 36% and 37% areas are larger than with 88 AKI fuel (Figure 2). However, Figure 8 shows that the difference in BTE between the two maps is generally near 0 where the engine was not knock limited. The largest differences (~3% BTE, in light blue) are along the low speed torque curve where the higher AKI allows as much as 5 degrees spark advance for better combustion phasing and efficiency. The engine was equipped with a knock sensor that could be observed as spark timing differences between the two fuels. Figure 8 largely reflects the effects of the knock retard and enrichment from the lower AKI. The spark timing was not substantially different over most of the engine map which implies that MBT could be achieved with the 88 AKI fuel.

These efficiency maps indicate that the real-world benefit to running higher octane fuel would be difficult to quantify for most users. The octane benefit is near zero where most driving occurs and would probably not provide a good value given the higher price for premium gasoline. This result is consistent with the 87 AKI fuel recommendation for the engine.

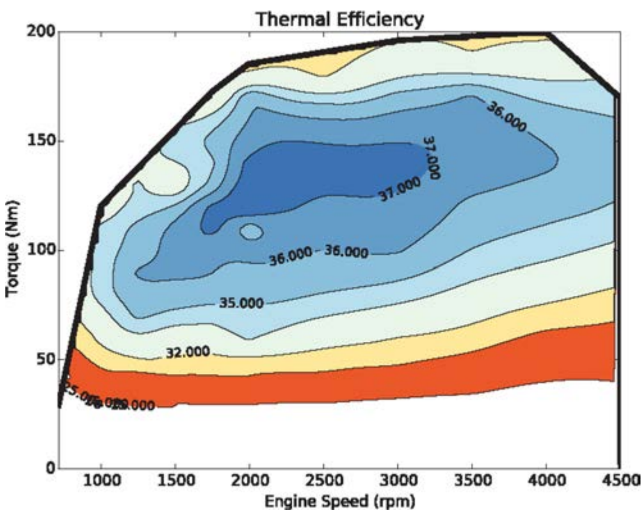

Figure 7. Brake thermal efficiency with 93 AKI Tier 2 certification fuel

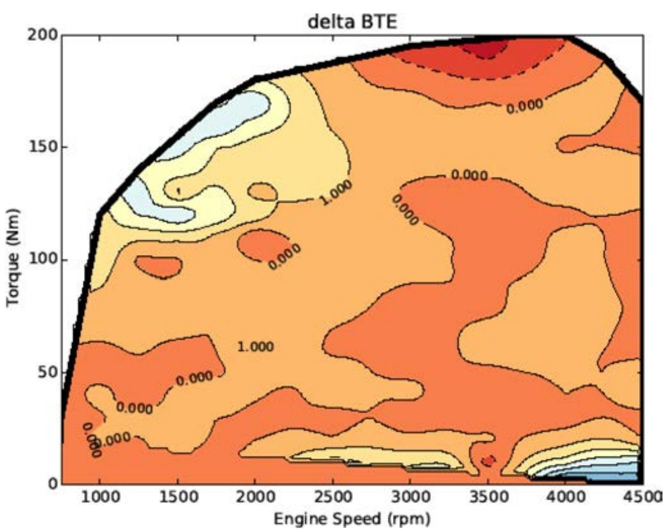

Figure 8. BTE difference, 93 - 88 AKI BTE

In the LD GHG rulemaking analysis, the Agencies predicted Atkinson cycle engines would be used primarily in hybrid vehicles to meet the 2025 fuel economy standards. Downsized turbocharged engines were seen as the primary path for non-hybrid vehicles. The benchmarking data from this engine shows efficiencies that are competitive with that of downsized turbocharged engines, and presents another potential technology path toward meeting the future fuel economy standards. To evaluate this potential, the engine was run in a HIL test bed with modeled future vehicles.

Cycle-Testing the Engine in a HIL Configuration

Description of ALPHA

EPA's Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created to estimate greenhouse gas (GHG) emissions from light-duty vehicles [9]. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of all internal energy flows in the model. ALPHA was developed in Matlab/Simulink and is capable of being converted into a standalone executable file. Substantial effort has been made to validate ALPHA against chassis test data of various vehicles. Its primary aim is to support the MTE of the upcoming 2022-2025 light duty GHG standards. ALPHA has been used to conduct a number of sensitivity analyses and futuring exercises.

Since ALPHA is capable of simulating the behavior of road loads and the vehicle powertrain components downstream of the engine, it was decided to incorporate the ALPHA simulator into the engine test cell in a hardware-in-the-loop configuration (VSIM). VSIM allows the engine to be run dynamically in the same way it would be in the vehicle, and fuel consumption can be measured over any drive cycle.

Development of VSIM

In ALPHA, torques and inertias flow downstream from the engine to the wheels where the resulting speed is calculated and propagated back up through the drivetrain. When the simulated vehicle is cruising this approach matches well with the test cell. The engine torque (measured via an inline torque meter) is passed to the model which calculates a new speed set point for the next time interval in the model. This approach, however, proved unstable when operating near idle as both the engine and dynamometer were attempting to control speed. To stabilize operation the dynamometer was switched to torque control mode near idle utilizing the loads calculated by ALPHA. This created a discontinuity when switching back to speed controls due to the engine speed integrator within ALPHA winding up at idle. The discontinuity was mitigated by implementing a PID control that would drive the speed in the model to match the speed of the dynamometer when operating in torque mode.

The ALPHAshift algorithm [10] is the primary gear selection routine employed for VSIM as it provides an optimal shift map with minimal tuning. Its application to this hardware-in-the-loop setup required some additional modifications. ALPHAshift utilizes the engine torque and speed to determine the fuel-optimized gear after applying constraints for speeds and torque reserve. Using the engine torque measured via the inline torque meter proved problematic as it would report torques lower than what the engine was producing during accelerations: this resulted in earlier upshifts in VSIM than were seen in the equivalent ALPHA model. The torque input to ALPHAshift was replaced by an estimate of engine torque as a function of engine speed and accelerator pedal position. This data was collected from the steady state mapping data.

A simple transmission thermal model also had to be developed for VSIM. Most prior ALPHA simulations had been conducted assuming a warm transmission and engine, then applying a correction factor for cold starts. However, VSIM utilized the power loss in the transmission as well as heat transfer to the engine and ambient temperature. Transmission temperature data had been collected during chassis testing that was used to calibrate the VSIM heat transfer coefficients to approximate the warmup observed in the vehicle.

Validation of VSIM to Chassis Test Data

With the VSIM model built, it was first necessary to validate VSIM to vehicle test data. Chassis test data on a 2014 Mazda3 was completed in September 2014 and included continuously logged data from the vehicle CAN bus. Key data recorded included engine speed, transmission gear, percent engine load, and fuel charge per cylinder. To make a direct correlation, the percent engine load and fuel charge were also recorded over the CAN bus of the tethered test cell engine during VSIM testing. Other engine parameters were logged directly from the engine test cell.

Consistent with those used for the LD GHG rules, both the FTP and HWFE test schedules were simulated in the VSIM test bed. Emissions data were sampled continuously (via a Horiba emissions analyzer) over the test cycles and integrated for each phase. A carbon balance was then calculated from the integrated emissions for CO, HC and CO2 emissions to determine fuel economy for each test phase. Total fuel was compared to integrated fuel flow from the fuel flow meter. Both of these values reconciled with the integrated fuel flow as reported by the engine over the CAN bus.

The 2014 Mazda3 vehicle parameters were included in VSIM/engine baseline testing over the FTP and HWFE EPA certification test cycles. Initial testing showed good correlation between actual vehicle transmission gear and the modeled gear in VSIM. Transmission gear data for Bag 2 of the FTP test cycle is presented in Figure 9 for both the real 2014 Mazda3 tested in the chassis dynamometer test cell and the VSIM representation of that vehicle in the engine test cell. With minor exceptions, the gear shift pattern is consistent between the VSIM and the vehicle test data. Vehicle speed is included for reference in the top part of the figure.

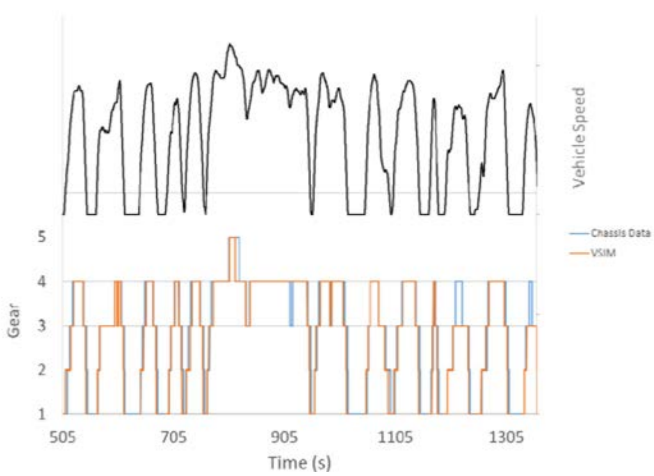

Figure 9. Gear Comparison, FTP Bag 2

Initially, differences were observed in calculated fuel flow (a surrogate for load), most apparent during the early (cold) idle periods of the FTP test. As the test progressed, this difference decreased considerably. It was hypothesized that this load difference was due to increased accessory load during the cold transient phase. A modification was made to the VSIM model to account for this difference. The final model reflects these changes and now shows a good correlation in all three phases of the FTP test.

Figures 10 and 11 show a comparison of cumulative fuel consumption over an FTP and HWFE test for both the tested 2014 Mazda3, and the VSIM representation of the 2.0L SkyActiv in the test cell.

For the 2014 Mazda3 and futured vehicle configurations (described later), three tests were run to account for any test-to-test variability. Table 3 shows a comparison of test results between the vehicle test data and the VSIM test data for the 2014 Mazda3. As was observed for future vehicle configurations, the test-to-test variability for the baseline configuration is much smaller than is typically seen on traditional driver-operated vehicle chassis testing.

Overall, the engine loads, speeds, and gear behavior are similar. This, as well as the resulting fuel consumption over the test cycles was sufficient to give confidence that the VSIM model accurately simulates the 2014 Mazda3 in the engine dynamometer.

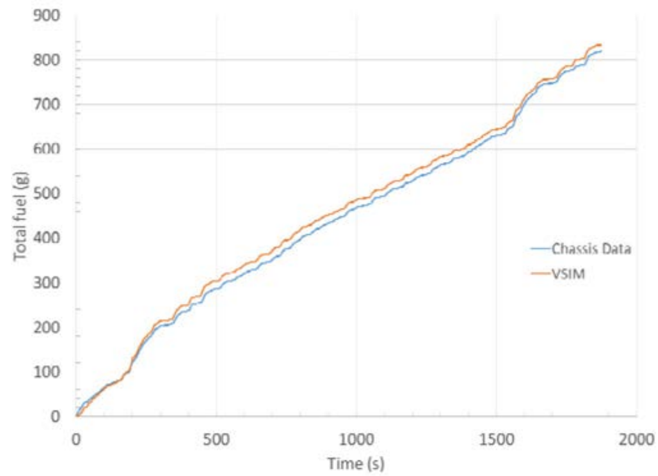

Figure 10. Cumulative Fuel Consumption over FTP Test Cycle

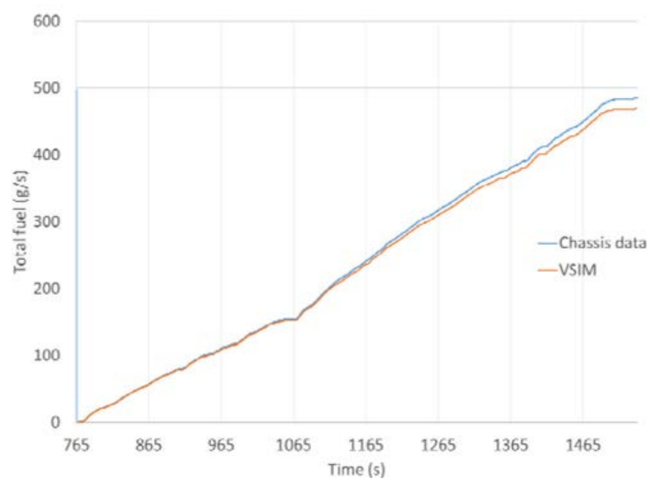

Figure 11. Cumulative Fuel Consumption over HWFE Test Cycle

Table 3. Comparison of VSIM Results to Certification Test Data for the 2014 Mazda3

	Bag 1	Bag 2	Bag 3	FTP	HWFE
Test 1	35.0	36.5	42.8	37.7	58.5
Test 2	35.0	36.6	42.8	37.8	58.8
Test 3	35.5	36.9	42.7	38.1	58.6
Average	**35.2**	**36.7**	**42.8**	**37.9**	**58.6**
Cert data	**35.1**	**37.9**	**43.1**	**38.6**	**56.9**
% error	0%	-3%	-1%	-2%	3%

Testing a Future Vehicle in the HIL Test Bed

With EPA's new capability to perform a HIL test, the next step taken was to explore the use of this tool to evaluate the CO2-reducing potential of future vehicle technology combinations. In a parallel analysis using ALPHA, EPA simulated the use of best-available technologies into a future vehicle [11].

For this example analysis, which goes a step beyond pure vehicle simulation through modeling, EPA chose to combine the SkyActiv engine described in this paper in its VSIM setup with a future technology package. The goal of this exercise was to estimate CO2 emissions from a hypothetical future mid-sized car.

Description of Futuring Process

In testing a future vehicle configuration, it was important to maintain the same power/weight ratio of the tested SkyActiv engine in the baseline vehicle (Mazda3). Because weight reduction is assumed to be applied to the future vehicle, it was more convenient to assume a *larger* future vehicle with weight reduction so that the final test weight (and hence power/weight ratio) was similar to the baseline vehicle test weight. In this way, the test engine would be appropriately sized for both the baseline and larger future vehicle.

The basis for the 2025 vehicles were the road load test target coefficients for the 2008 Mazda6 which were selected from EPA's certification test car list database [12]. These coefficients represent a quadratic function that characterizes the resistive road loads as a function of speed on the chassis dynamometer. Initially, the road load curves of ten high-volume 2008 model year midsize cars were analyzed. The Mazda6 represented the median road load curve for this cohort of vehicles.

Two levels of road load reductions were tested for the future midsize car. In total, 10% weight reduction was applied to the "L1" configuration of the future vehicle, as well as a 20% reduction in both rolling resistance and aerodynamic drag. These levels are consistent with EPA's assumptions for expected reductions in vehicle road loads in 2025 (from the 2008 model year reference) for the LD GHG rule [13]. As a sensitivity analysis, additional road load reductions were applied to an "L2" vehicle. In the L2 configuration, 15% weight reduction was applied, along with a 25% reduction of aerodynamic drag and a 30% reduction of rolling resistance (compared to the 2008 Mazda6 road loads).

Road loads for a vehicle (F_{RL}) can also be represented as a combination of rolling resistance, aerodynamic drag and gravity (in the case of a vehicle going up a grade). Because no grades are included in EPA drive cycle testing, this equation simplifies to:

$$F_{RL} = F_{rolling} + F_{aero} = (C_{rr}mg) + \frac{1}{2}C_d A\rho v^2 \tag{1}$$

where:

C_{rr} is the rolling resistance coefficient;

mg = vehicle weight;

C_dA is the aerodynamic drag coefficient C_d, multiplied by A, the frontal area of the vehicle (m^2);

ρ is the density of air;

v is the vehicle velocity (m/s)

A quadratic curve fit was used to approximate CdA and the rolling resistance coefficient (RRC) for the baseline 2008 Mazda6. From these coefficients, a 20% reduction was applied to both the CdA and the RRC for the midsize car L1. Likewise, a 25% reduction and 30% reduction were applied to CdA and RRC, respectively, for the midsize car L2. From these new terms, new ABC coefficients were empirically determined to best fit a road load curve expected with the new test weight, CdA and RRC.

Table 4 shows both of the vehicle test coefficients, as well as approximated CRR and CdA which were used to develop the test coefficients for the 2025 midsize cars.

Table 4. Road Load Coefficients Comparison of 2025 Vehicles to 2008 Mazda6

	2008 Mazda6	2025 Midsize Car L1	2025 Midsize Car L2
ETW	3625	3250	3125
A (lb)	29.7	24.3	22.5
B (lb/mph)	0.3810	0.0279	0.1622
C (lb/mph^2)	0.01811	0.01765	0.01456
CRR	0.0089	0.0071	0.0062
CdA (m^2)	0.76	0.60	0.57

Figure 13 shows the road load curves for the 2008 Mazda6 and the L1 and L2 configurations for the 2025 midsize car.

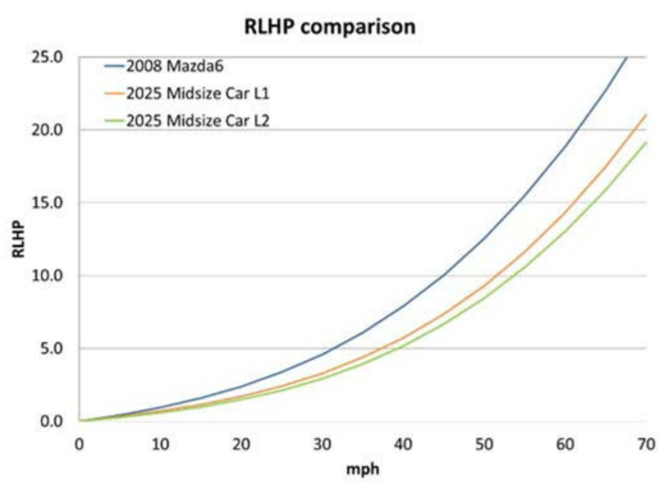

Figure 12. Road Load Curves for 2008 Mazda6 and 2025 Midsize Cars

Table 5. VSIM Vehicle and Transmission Parameters for Baseline and Future Vehicles

	2014 Mazda3 (baseline vehicle)	2025 Midsize Car L1	2025 Midsize Car L2
ETW	3250	3250	3125
A (lb)	20.4	24.3	22.5
B (lb/mph)	0.2116	0.0279	0.1622
C (lb/mph^2)	0.01822	0.01765	0.01456
Footprint (ft^2)	45.3	48	48
gears	6	8	8
ratios	3.552	5.501	5.501
	2.022	3.473	3.473
	1.452	2.200	2.200
	1.000	1.737	1.737
	0.708	1.326	1.326
	0.599	1.000	1.000
	n/a	0.817	0.817
	n/a	0.632	0.632
total span	5.9	8.7	8.7
final drive	3.59	2.89	2.89

The vehicle footprint for the 2025 midsize cars are assumed to be equivalent to the average of today's midsize cars (approximately 48 ft^2).

A new 8-speed transmission (representing transmission design and improvements expected by year 2025) was implemented into the VSIM parameters for the 2025 midsize car. The future transmission, based on ZF's second-generation 8HP50, includes additional expected reductions in spin and pump losses based on strategies outlined in the literature [14]. The losses were also scaled to match the torque output of the SkyActiv 2.0l, which is substantially lower than the capacity of the 8HP50. Key vehicle and transmission parameters for both the 2014 Mazda3 and the 2025 midsize cars are summarized in Table 5.

Test Summary

Test data for the 2.0L Mazda SkyActiv engine as simulated in a hypothetical 2025 midsize car is presented in Table 6 and Table 7. It is expected that most manufacturer's will employ a stop-start (idle-off) strategy as part of their plans to meet the LD GHG standards, and therefore it was decided to include stop-start in the technology package for this test program. Because the engine test cell was not configured to operate in this manner, a simple adjustment was made to the test results by subtracting the idle fuel consumed for each phase of the FTP test. It was assumed that stop-start would be enabled for idle after 300 seconds into Bag 1 of the FTP and thereafter, and for hot restarts, after 120 seconds of operation. Idle consumption adjustments are included in the test summary data in Table 6 and Table 7. Three tests were shown for each configuration, with the averaged results shown in each table.

Table 6. Test Data for the 2.0L Mazda SkyActiv Engine as Simulated in a 2025 Midsize Car, L1 configuration (FTP total reflects bag-weighting).

	Total Fuel (g)	Idle Fuel (g)	Adjusted Fuel (g)	FE (mpg)	g/mi CO2
Bag 1	247.3	4.3	242.9	41.3	215.0
Bag 2	278.3	18.4	259.9	41.5	214.3
Bag 3	230.4	9.4	220.9	47.5	186.9
FTP (total)	257.9	12.8	245.1	**43.0**	**206.7**
HWFE				**64.5**	**137.7**
Combined				**50.6**	**175.6**

Table 7. Test Data for the 2.0L Mazda SkyActiv Engine as Simulated in a 2025 Midsize Car, L2 configuration.

	Total Fuel (g)	Idle Fuel (g)	Adjusted Fuel (g)	FE (mpg)	g/mi CO2
Bag 1	241.7	3.9	237.8	42.2	210.4
Bag 2	269.0	17.6	251.4	42.8	207.5
Bag 3	214.3	9.0	205.4	48.9	181.8
FTP (total)	247.6	12.2	235.4	**44.3**	**200.8**
HWFE				**67.1**	**132.4**
Combined				**52.3**	**170.0**

As tested, the L1 configuration resulted in a combined FTP and HWFE fuel economy of 50.6 mpg (which translating into 176 g/mi of CO2). The L2 configuration resulted in a combined FTP and HWFE fuel economy of 52.3 mpg (or 170 g/mi of CO2).

GHG Compliance Levels and Adjustments

Figure 14 (from the LD GHG rule) [1] shows the nominal GHG compliance levels for 2025 cars, prior to credit adjustments. Based on the assumed footprint of 48 ft^2 for this 2025 midsize car, the vehicle would have to emit less than 154 g/mi CO2 over the combined FTP and HWFE test cycles to be in compliance.

For discussion purposes, it is anticipated that manufacturers will use up to 18.8 g/mi of A/C credits for passenger cars in meeting the 2022-2025 standards. Off-cycle credits are yet another strategy to bridge the gap between vehicle test cycle performance and GHG standards, although they are not assumed in this analysis. With the inclusion of only A/C credits, it may suggest a target range for this 2025 midsize car of 154-173 g/mi.

The simulated cycle test data for the 2025 midsize car, powered by the 2014 Mazda SkyActiv 2.0L engine, suggests the potential to meet these compliance levels even with some present-day production engines. It is not unreasonable to assume continued advances in engine efficiency over the next 10 years, which bodes well for the potential to meet these compliance levels with engine-powered vehicles.

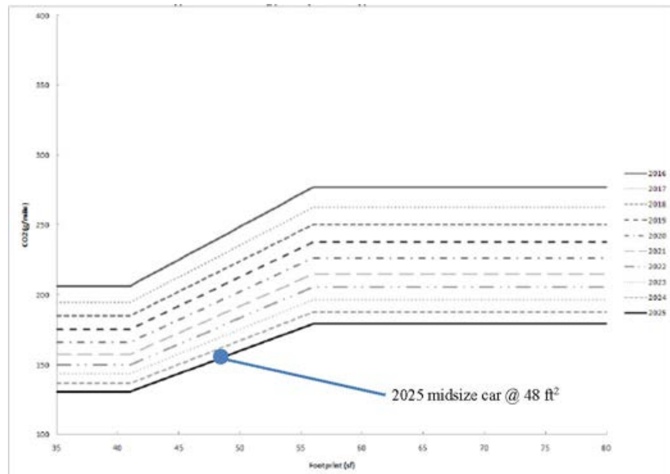

Figure 13. GHG Emissions Standards for Passenger Vehicles, By Year

Discussion

A Mazda 2.0L SkyActiv engine was benchmarked. VSIM, an EPA hardware-in-the-loop model, was developed to run virtual chassis test cycles in an engine dyno. It was validated and then used to simulate a hypothetical future vehicle and evaluated in the context of 2025 LD GHG standards. Test results showed that - given the underlying analytical assumptions applied in this example - this future vehicle with the existing SkyActiv production engine could approach the 2025 LD GHG standard for a midsize car, assuming the inclusion of some A/C credits.

Future Work

Future work may employ the same test strategy for other engines under review for EPA's Midterm Evaluation program. These may include a Miller cycle engine or one with a cooled EGR system. Additional VSIM development incorporating more detailed simulation of accessory loads and battery management strategies is also planned. EPA also has plans to compare VSIM results with ALPHA model results as another way to cross-validate EPA's analytical tools.

References

1. US EPA, DOT/NHTSA, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards" http://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf, Oct. 2012

2. Luria, D., Taitel, Y., and Stotter, A., "The Otto-Atkinson Engine - A New Concept in Automotive Economy," SAE Technical Paper 820352, 1982, doi:10.4271/820352.
3. Wan, Y. and Du, A., "Reducing Part Load Pumping Loss and Improving Thermal Efficiency through High Compression Ratio Over-Expanded Cycle," SAE Technical Paper 2013-01-1744, 2013, doi: 10.4271/2013-01-1744.
4. Wan, Y. and Du, A., "Reducing Part Load Pumping Loss and Improving Thermal Efficiency through High Compression Ratio Over-Expanded Cycle," SAE Technical Paper 2013-01-1744, 2013, doi:10.4271/2013-01-1744.
5. Kawamoto, N., Naiki, K., Kawai, T., Shikida, T. et al., "Development of New 1.8-Liter Engine for Hybrid Vehicles," SAE Technical Paper 2009-01-1061, 2009, doi:10.4271/2009-01-1061.
6. Mazda Motor Corporation, "MAZDA'S INNOVATIVE SKYACTIV TECHNOLOGIES MAKE U.S. DEBUT", April 21, 2011, http://www.mazdausamedia.com/index.php?s=31676&item=967#assets_67:125272, accessed Sep 2015.
7. Stuhldreher, M., Schenk, C., Brakora, J., Hawkins, D. et al., "Downsized Boosted Engine Benchmarking and Results," SAE Technical Paper 2015-01-1266, 2015, doi:10.4271/2015-01-1266.
8. US EPA, DOT/NHTSA, "Joint Technical Support Document: Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards" www.epa.gov/otaq/climate/regulations/420r10901.pdf, Aug. 2012
9. Lee, B., Lee, S., Cherry, J., Neam, A. et al., "Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool," SAE Technical Paper 2013-01-0808, 2013, doi:10.4271/2013-01-0808.
10. Newman, K., Kargul, J., and Barba, D., "Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation," *SAE Int. J. Engines* 8(3):1417-1427, 2015, doi:10.4271/2015-01-1142.
11. Kargul, J., Moskalik, A., Barba, D., Dekraker, P., et al., "Estimating GHG Reduction from Combinations of Current Best-Available and Future Powertrain and Vehicle Technologies for a Midsized Car Using EPA's ALPHA Model," SAE Technical Paper 16PFL-0745, 2015.
12. US EPA, Test Car List Data, http://www3.epa.gov/otaq/tcldata.htm, accessed October, 2015.
13. US EPA, "Regulatory Impact Analysis: Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards" (Table 3.5-25) http://www3.epa.gov/otaq/climate/documents/420r12016.pdf, Aug. 2012
14. Greiner, J., Grumbach, M., Dick, A., and Sasse, C., "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE Technical Paper 2015-01-1087, 2015, doi:10.4271/2015-01-1087.

Contact Information

Benjamin Ellies
Transportation and Climate Division
US EPA - Office of Transportation & Air Quality
ellies.ben@epa.gov

Definitions/Abbreviations

AKI - Anti-knock index, (RON+MON)/2

ALPHA - Advanced Light-Duty Powertrain and Hybrid Analysis

ATDC - After top dead center

BMEP - Brake mean effective pressure

BTDC - Before top dead center

BTE - Brake thermal efficiency

CdA - Aerodynamic drag coefficient multiplied by vehicle frontal area (m^2)

CAN - Controller area network

ECU - Engine control unit

EPA - Environmental Protection Agency

ETW - Equivalent test weight, roughly curb weight (dry) + 300 lbs

FTP - Federal test procedure; in this paper, a 3-bag LA4

GDI - Gasoline direct injection

GHG - Greenhouse gas

HIL - Hardware-in-the-loop

HWFE - Highway fuel economy test procedure

IVC - Intake valve close

LD - Light duty

LIVC - Late intake valve close

MTE - Midterm Evaluation

NHTSA - National Highway Traffic Safety Administration

RRC - Rolling resistance coefficient

TAR - Technical Assessment Report

TDC - Top dead center

VSIM - Virtual simulation

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.

ISSN 0148-7191

http://papers.sae.org/2016-01-1007