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Laboratory Testing of a 2016 Mazda CX-9 2.5T I4 SkyActiv With a 6-Speed Transmission

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16. Abstract

The vehicle benchmarked in this report is a 2016 Mazda CX-9 with a 2.5L I4 "SkyActiv" turbocharged engine and a 6-speed automatic transmission. This vehicle provides favorable fuel economy results while providing significant vehicle performance. The focus of the benchmark is to understand the use of the critical powertrain components and their impact on the vehicle efficiency. The vehicle is instrumented to provide data to support the model development and validation in conjunction to providing the data for the analysis in the report. The vehicle is tested on a chassis dynamometer in the controlled laboratory environment across a range of certification tests. Further tests are performed to map the different powertrain components.

The analysis in this report start by providing the fuel economy and efficiency results on the certification drive cycles along with of component operation on those tests. The maximum performance envelops of the powertrain are presented. A section is devoted to specific powertrain characterization. Some off-cycle testing, such as the thermal testing of 5-cycle label fuel economy and octane fuel testing, is explored. Finally, some vehicle specific test, such as active grille shutters operation, close out the analysis.

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Definitions and Abbreviations

°C or C	degrees Celsius
° F oc F	degrees Fahrenheit
2WD	two-wheel drive
4WD	four-wheel drive
AC	air conditioning
AKI	anti-knock index
APRF	Advanced Powertrain Research Facility (Argonne)
Autonomie	Argonne full vehicle simulation software www.autonomie.net/
Argonne	Argonne National Laboratory
ASR	absolute speed change rating
AVTE	Advanced Vehicle Testing Evaluation (U.S. DOE activity)
BEV	battery electric vehicle
BTU	British thermal unit
CAN	computer area network
CAFE	Corporate Average Fuel Economy
cc	cubic centimeter
ccps	cubic centimeters per second
CEd	positive driven cycle energy
cm	centimeter
CO	carbon monoxide
CO_2	carbon dioxide
DAQ	Data acquisition system
deg	degree
DFCO	deceleration fuel cut-off
DFI	Direct fuel injected
DI	Direct Injection
DOHC	double overhead cam
DR	distance rating
EGR	exhaust gas recirculation system
EPA	U.S. Environmental Protection Agency
ER	energy rating
EER	Energy Economy Rating
FTP	Federal test procedure (EPA defined)
gps	grams per second
HC	hydrocarbon
HEV	hybrid electric vehicle
hp	horsepower
Highway	EPA certification testing: Highway dynamometer driving cycle

Hz	Hertz
inH20	inches of water
inHg	inches of mercury
kPa	kilopascal
kph	kilometer per hour
kW	kilowatt
L	liter
LA92	California unified driving schedule
Lb / lbs	pound(s)
lb-ft	foot pounds
lbm	pound-mass
LHV	lower heating value
m	meter
MBT	maximum brake torque
mg	milligrams
mpg	mile(s) per gallon
mph	miles per hour
N	Newton
NA	naturally aspirated
Nm	Newton-meters (torque)
NOx	oxides of nitrogen
PFI	Port fuel injected
RMS	root mean squared error
rpm	rotations per minute
RWD	rear wheel drive
s	second
SAE	Society of Automotive Engineers
SC03	EPA certification test (Air conditioning test)
scfm	standard cubic feet per minute
SSS	steady speed stairs
TCC	torque converter clutch
TCU	transmission control unit
UDDS	EPA certification test: urban dynamometer driving schedule
US06	EPA certification test: US06 dynamometer driving schedule
Volpe	Volpe National Transportation Systems Center
V	Volts

1. Executive summary

The National Highway Traffic Safety Administration (NHTSA) is the agency of the U.S. Department of Transportation (DOT), that sets Corporate Average Fuel Economy (CAFE) standards for passenger cars, light trucks and medium-duty passenger vehicles. NHTSA has contracted Argonne to conduct full vehicle simulation using Autonomie (www.autonomie.net/), a vehicle system simulation tool, to provide input into the CAFE model to determine minimum average fuel economy. Autonomie relies on vehicle technology assumptions for model development and validation. Argonne's Advanced Research Powertrain Facility (APRF) provides the laboratory test data that informs that technology assumptions in Autonomie. NHTSA funded Argonne's APRF to perform a benchmark of a 2016 Mazda CX-9 SUV and to provide data to Autonomie and assess the fuel saving technologies of that powertrain.

The vehicle benchmarked in this report is a 2016 Mazda CX-9 with a 2.5L I4 "SkyActiv" turbocharged engine and a 6-speed automatic transmission. This vehicle provides favorable fuel economy results while providing significant vehicle performance. The focus of the benchmark is to understand the use of the critical powertrain components and their impact on the vehicle efficiency. The vehicle is instrumented to provide data to support the model development and validation in conjunction to providing the data for the analysis in the report. The vehicle is tested on a chassis dynamometer in the controlled laboratory environment across a range of certification tests. Further tests are performed to map the different powertrain components.

The analysis in this report start by providing the fuel economy and efficiency results on the certification drive cycles along with of component operation on those tests. The maximum performance envelops of the powertrain are presented. A section is devoted to specific powertrain characterization. Some off-cycle testing, such as the thermal testing of 5-cycle label fuel economy and octane fuel testing, is explored. Finally, some vehicle specific test, such as active grille shutters operation, close out the analysis.

2. Introduction and background

2.1. Project background

Argonne is providing a benchmark report based on chassis dynamometer testing in laboratory conditions for a 2016 Mazda CX-9. In order to complete this evaluation, the Vehicle System Research Group at Argonne National Laboratory conducted vehicle testing on a chassis dynamometer at its Advanced Powertrain Research Facility (www.anl.gov/d3). The vehicle was heavily instrumented to understand powertrain operation and the impact of specific advanced vehicle technologies on fuel consumption. In addition to this report, the hundreds of available time resolved vehicle signals generated by the testing were provided to Argonne's vehicle simulation group in order to inform the refinement of Autonomie software and enable validation of the vehicle specific technologies (www.autonomie.net).

This report provides a detailed analysis of the 2016 Mazda CX-9 equipped with the 2.5L I4 Skyactiv engine and a 6-speed automatic transmission. This turbocharged I4 engine provides similar power to traditional V6 engines, but with claimed fuel efficiency benefits seen from smaller displacement engines with turbocharging.

2.2. Argonne's vehicle simulation and testing synergy

Argonne's vehicle benchmark and simulation efforts have grown in parallel since the early 2000s. The powertrain data generated from the vehicle testing in the laboratory has been used to develop component models and control strategies for simulations. The laboratory data is also used to validate the powertrain simulation results.

3. Argonne's vehicle system research capabilities

3.1. Laboratory description

Argonne National Laboratory has several research groups and facilities performing automotive research within the Center for Transportation Research. The testing and analysis in this report is performed by the Vehicle Systems Research group. The Advanced Powertrain Research Facility (APRF) provides resources for both vehicle instrumentation and testing, including two chassis dynamometer test cells. The testing for this report is performed using the APRF's 4WD chassis dynamometer test cell. This test cell is designed to handle light- to medium-duty vehicles and includes a thermal chamber that is EPA 5-cycle-capable. A vehicle speed-matching simulation fan fulfills the test regulations for the SC03 air-conditioning test. The cell also contains solar lamps to simulate real-world solar loading of 850 W/m^2. Figure 1 highlights some of the major capabilities of the test cell.

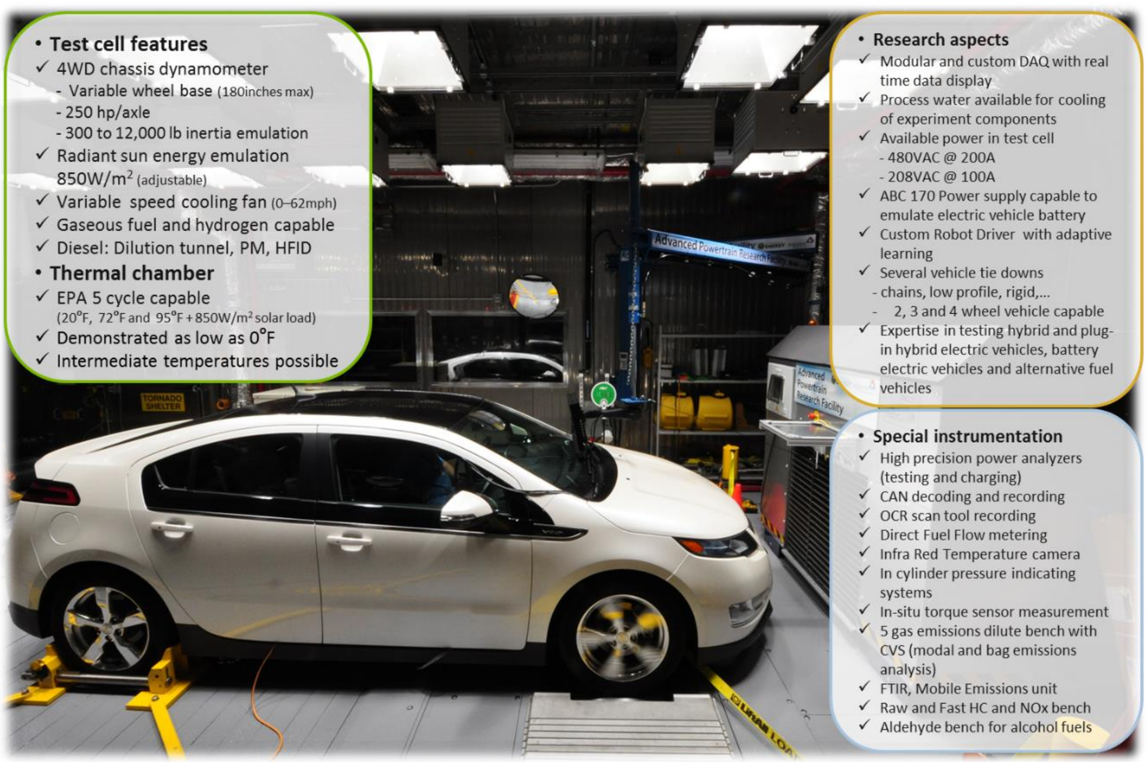

Figure 1: Major features of the 4WD chassis dynamometer and thermal chamber test cell.

The APRF is purpose-built for technology evaluations and powertrain research. Within this research-focused facility, in-depth testing of a vehicle is best facilitated by leaving that vehicle mounted on the chassis dynamometer for the duration of the testing. A testing session usually lasts from a few days to a few weeks. This approach has been found to minimize test-to-test variability inherent to vehicle re-mounting, and was applied for the test vehicle in this report. Vehicle instrumentation in the facility includes a custom fully integrated data acquisition (DAQ) system which merges and time aligns data streams from many different selectable sources such as facility sensors, dynamometer feedback, analog vehicle sensors, vehicle communication messages, emissions analyzers, fuel flow meters and many others. The test cell contains a dilute emission bench that measure the criteria emissions of total hydrocarbons (HCs), oxides of nitrogen (NOx), and carbon monoxide (CO), as well as carbon dioxide (CO_2).

A particular benefit of the custom DAQ is the ability to display real time signals from any sensor in the instrumentation. This enables targeted component mapping as the testing staff can set and verify component operating points, vary test conditions, and ensure that all relevant signals have reached stability in real time which ensures quality data for component characterization and modeling.

The Argonne staff has been benchmarking advanced technology vehicles since the 1990s. The well-refined vehicle test process starts with instrumentation and testing and ends with detailed analysis of the results. The testing staff always aims to understand the power (fuel and electric) flows between the components in the vehicle, to establish transient efficiency and usage maps for components, and to characterize the behavior of the key components of the powertrain.

3.2. Difference in purpose between certification testing and the APRF testing

The major focus of certification testing is to provide robust, repeatable vehicle evaluations to ensure fuel economy and emission compliance within the regulatory framework. The testing that Argonne performs for the U.S. Department of Energy differs from standard certification testing in two specific dimensions: (1) the depth of instrumentation; and (2) the breadth of test types and testing conditions. While standard certification testing performed by the EPA focuses on certification drive cycles fuel economy and tailpipe emissions on a very large number of cars, Argonne targets a much smaller set of vehicles (and therefore of powertrains) with the intent to characterize the components in each powertrain across a wide range of conditions.

Similar to certification testing, Argonne measures fuel consumption and tailpipe emissions at the vehicle level for specific drive cycles. The Argonne testing provides additional value with in-depth information on specific powertrain components and characterization of component operational areas, efficiencies, and performance limits (where possible). The comprehensive instrumentation approach allows the research staff to determine the powertrain behavior and how each component contributes to the powertrain system efficiency on standard drive cycles.

In addition to EPA standard certification drive cycles, the testing covers many other drive transient cycles, performance tests, and component mapping tests across a range of ambient temperatures. The performance testing typically includes maximum accelerations, passing maneuvers, and grade testing. Additionally, component mapping often includes steady state speed testing with a focus on specific component operation areas.

3.3. Differences between certification test procedures and procedures at the APRF

The Argonne testing deviates from certification testing as Argonne's goal is research fidelity rather than regulatory compliance. Based on this intent, the staff often purposefully chose to change specific aspects of the test procedures to prioritize vehicle operation in real world conditions. The next paragraphs describe some of the variations in vehicle testing which are unique to testing at the APRF.

Speed-matched fan: In order to provide results close to real world conditions, Argonne uses a fan in front of the vehicle in speed match mode and has the vehicle hood closed for all testing at any ambient temperature, unless otherwise specified. This deviates from certification testing requirements described in the Codes of Federal Regulations which requires the vehicle hood to be open and the fan to operate at a constant speed of 5,300 scfm for the standard UDDS and Highway drive cycles. Argonne has determined that there is a small, but measurable different in fuel consumption between these two vehicle configuration at 72° F and especially at 20° F and 95° F.

Emission bench set-up: The second test setup difference is that Argonne continuously runs a diluted exhaust sample through the emissions analyzers during the drive cycle testing in order to obtain modal (time resolved) emission data. Therefore, the emission bags are not sampled immediately after the end of a test phase but they are sampled at the end of a full test. Argonne has run some experiments to compare both procedures and found statistically insignificant differences in fuel consumption results. Due to this result, the staff chose to sample to emissions bags at the end of the test in order to obtain the time resolved emission data.

Figure 2 details the vehicle and equipment setup used by Argonne for chassis dynamometer testing. The major differences are explained above. The vehicle cooling setup and the emissions bench sampling are the two major differences between Argonne testing and certification testing. The 20° F testing at Argonne is performed on the same certification fuel as the 72° F and 95° F tests. Furthermore, the target road load coefficients are not readjusted for 20° F testing as they are for certification testing.

	20°F ambient temperature	72°F ambient temperature	95°F ambient temperature
Origin	▪ Cold CO and HC test	▪ UDDS, HWFET and US06	▪ SC03 test with air conditioning
Road load	▪ Listed EPA listed coefficients, unless otherwise provided ▪ Target coefficients used are listed in the summary sheet for each vehicle		
Cooling fan	▪ Vehicle Speed match mode	▪ Vehicle Speed match mode	▪ Vehicle Speed match mode
Hood position	▪ Hood down	▪ Hood down	▪ Hood down
Window position	▪ Windows closed	▪ Windows open	▪ Windows closed
Climate control	▪ Automatic mode ▪ 72°F target temp	▪ OFF	▪ Automatic mode ▪ 72°F target temp
Solar lamps	▪ OFF	▪ OFF	▪ 850 W/m² radiant solar energy
Additional notes	▪ Target road load not necessarily readjusted ▪ Cold temperature fuel not used for AVTE	▪ None	▪ None
	Valid at all temperatures • Modal and bag measurements simultaneously		

Figure 2: Vehicle test setup at Argonne

For the remainder of this report all data and test results are generated using the Argonne test setup and procedures as described in this section unless otherwise noted.

3.4. Instrumentation approach

The APRF was purpose built for automotive powertrain research and technology benchmarking. Based on that mission, the staff have developed unique expertise focused on the instrumentation of advanced technology powertrain components. This expertise includes, decoding and capture of vehicle broadcast CAN and diagnostic messages, in-situ component mapping, custom facility and the custom data acquisition system, and the development of special test procedures to produce desired high quality research results.

Figure 3 illustrates the general instrumentation of conventional vehicles. For the testing on conventional vehicles such as the 2017 Ford F-150, the testing integrates data streams from several sources. The facility data captures the test cell conditions (ambient test cell temperature and relative humidity), the dynamometer data (vehicle speed and the tractive effort) and emissions data (bag and modal bench data: HC, CO, NOx, and CO_2). The fuel consumption is measured in several different ways: (1) Carbon balance fuel economy results from the emissions bench (bag and modal) and (2) several fuel flow meters, providing both volumetric and mass measurements.

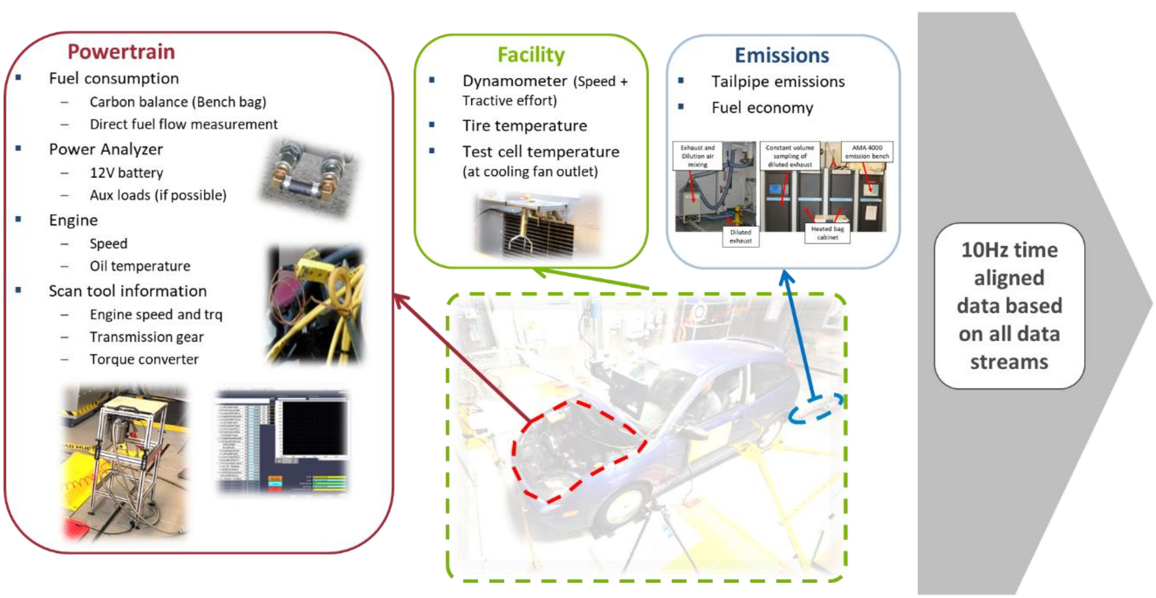

Figure 3: Overview of general instrumentation for conventional vehicle

The target drive schedule and phase information is also recorded with the results. The modal emissions data from the analyzers is the third data stream. General analog vehicle signals are part of the standard testing and typically include engine oil temperature, direct fuel flow measurements and electric power flow measurements (12V battery for conventional vehicles). The list of standard signals and data streams is shown in Table 1.

Table 1: Standard data streams collected for all vehicles tested at Argonne's Advanced Powertrain Research Facility

Facility data	Drive cycle input	Emissions data	Generic vehicle data
Dyno_Spd[mph]	Drive_Schedule_Time[s]	Dilute_CH4[mg/s]	Engine_Oil_Dipstick_Temp[C]
Dyno_TractiveForce[N]	Drive_Trace_Schedule[mph]	Dilute_NOx[mg/s]	Cabin_Temp[C]
Dyno_LoadCell[N]	Exhaust_Bag []	Dilute_COlow[mg/s]	Solar_Array_Ind_Temp[C]
DilAir_RH[%]		Dilute_COmid[mg/s]	Eng_FuelFlow_Direct[gps]
Tailpipe_Press[inH2O]		Dilute_CO2[mg/s]	Eng_FuelFlow_Direct[ccps]
Cell_Temp[C]		Dilute_HFID[mg/s]	12V Battery [V], [A] and [W]
Cell_RH[%]		Dilute_NMHC[mg/s]	
Cell_Press[inHg]		Dilute_Fuel[g/s]	
Fan_Air_Spd[mph]			
Tire_Rear_Temp[C]			
Tire_Front_Temp[C]			

A Re-Sol RS840-060 fuel measurement system is routed in the fuel line between the vehicle tank and the fuel rail. This device is suitable for all vehicles with return-less style fuel delivery systems. It is installed in-line with the vehicle fuel supply and makes use of a positive displacement flow meter to measure the volumetric flow rate of fuel consumed by the engine. The meter is able to measure flow rates between 0.3 and 60 liters per hour with an accuracy of ± 0.5 percent of the reading.

A core capability of the APRF staff is the ability to decode the vehicle and powertrain internal communication messages (CAN), which is relevant to this testing. Over the last few years, the APRF staff has developed powerful tools that enable the decoding of both broadcast and diagnostic CAN messages. These tools rely on the understanding of powertrain CAN structure, the correlation of changes in CAN messages to known scan tool or instrumentation signals, the ability to mimic scan tool message requests, and the dynamometer environment that can safely put the powertrain in specific planned scenarios to enable the decoding of certain signals. The team decoded a significant list of powertrain messages for the vehicle which are detailed in section 5.1.2.

3.5. General test plan approach for this study

The testing focus for this work is on the UDDS, the Highway and the US06 drive cycles at the 72° F ambient temperature. The test sequence includes a cold start UDDS, a hot start UDDS, a third UDDS, a Highway pair and a US06 pair. The preparation for the cold start test consists of completing a UDDS cycle at 72° F and leaving the vehicle to thermally soak at 72° F for over 12 hours. The overnight soak is done on the chassis dynamometer in the test cell since the vehicle stayed mounted on the rolls for the duration of the testing. The graph in Figure 4 shows the sequence of drive cycles executed for this testing. Note that a 10-minute soak period is held between the UDDS cycles as noted in the figure. The test sequence is repeated at least three times. The fuel economy numbers in this report are based on the test phases highlighted by the pink boxes. The phases for the US06 drive cycle are the split city and Highway phases needed to calculate the EPA 5-cycle fuel economy label.

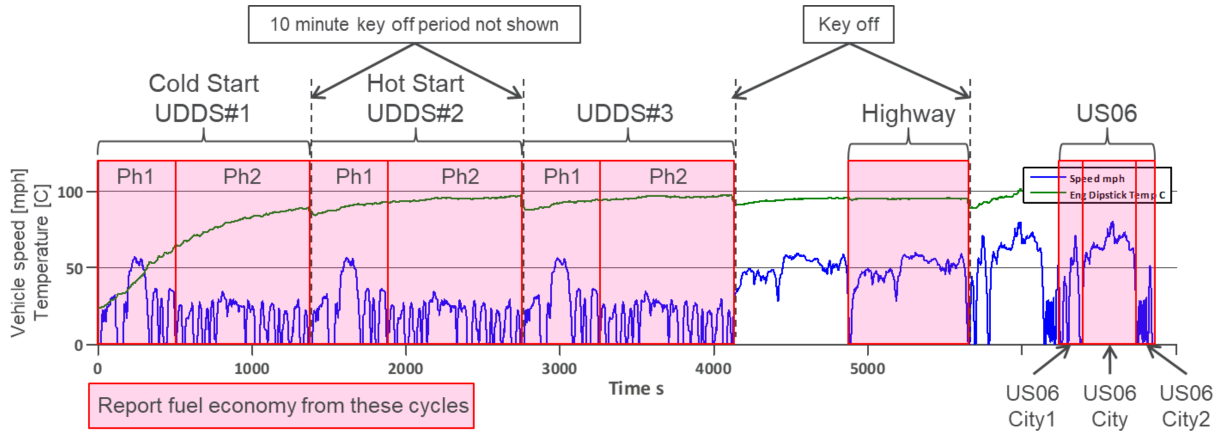

Figure 4: Daily drive cycle test sequence executed in the morning

Performance testing, component mapping and other drive cycles testing was performed in the afternoons. The performance testing includes maximum accelerations, several passing maneuvers, and steady state speed tests at different grades. The mapping focused on specific engine features and transmission shifting.

Two additional investigations were performed. The impact of premium and regular fuel on performance and fuel economy was investigated. The vehicle was also tested at 20° F and 95° F with 850 W/m^2 of solar loading on the test sequence shown in Figure 4. A detailed test plan is described in section 5.1.3

3.6. General vehicle preparation and chassis dynamometer setup

Argonne purchased a new 2016 Mazda CX-9 at a dealership. The vehicles was appropriately broken in through an on-road mileage accumulation of 4,000 miles as indicated by the vehicle odometer. The final tank of fuel during the on-road mileage accumulation was performed with certification test fuel.

The vehicle test weigh and road load coefficients are acquired from EPA (www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy). After the instrumented vehicle was mounted on the chassis dynamometer, the team performed some signal check out which served to warm up the powertrain and tires. The vehicle then completed a double Highway drive cycle (pair of Highways) as required by SAE J1263, "Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques," before engaging the vehicle loss determination procedure on the chassis dynamometer interface. The derived vehicle dyno set coefficients were accepted, saved and applied to the road load emulation. The dyno set coefficients from the vehicle loss determination are used for the remainder of the chassis dynamometer testing for the vehicle. The dynamometer road load target coefficients (target and dyno set) are provided in the specific-vehicle section 5.1.1.

3.7. Professional driver vs robot driver

Argonne has experienced dynamometer drivers who have driven test cycles on chassis rolls for decades. Argonne has also developed and refined a custom robot driver. The robot driver was first developed for plug-in hybrids and battery electric vehicles. The powertrains in these vehicles require repetitive testing over the course of very long and uninterrupted test periods (up to 18 hours for electric vehicles with large battery packs). The high repeatability of the robot driver enables a determination of very small changes in fuel consumption in comparative technology testing such as testing the effect of a specific technology through A to B testing.

Argonne developed the robot hardware as well as the software. The robot driver is composed of two oversized linear actuators. The first actuator operates the accelerator pedal and the second actuates the brake pedal. The control software is implemented directly in the APRF custom data acquisition system. Several software features – such as look ahead, gain scheduling, and active feed-forward learning – enabled the staff to fine tune the robot driver to the powertrain and certification cycles.

Argonne considered using the robot driver for this testing but ended up using the professional chassis dynamometer drivers. The decision was driven by the facts that: (1) the test period was short and the training of the robot driver requires some time, and (2) that the testing was focused on technology assessment rather than comparing specific technology changes in a vehicle (such as different fuels or two separate powertrain warm up strategies).

Additionally, Argonne calculates, prints and verifies the SAE J 2951 drive quality metrics for each test in real time.

3.8. SAE J2951 drive quality metrics

SAE J2951 "Drive Quality Evaluation for Chassis Dynamometer Testing" defines a set of parameters aimed at quantifying how close the driving speed trace followed the actual drive trace. The procedure clearly prescribes the different data processing and calculation steps to generate these parameters. Argonne staff members were actively involved in developing the drive quality metrics through mathematical concepts as well as target chassis dynamometer testing.

The J2951 metrics are the Energy rating (ER), the Distance Rating (DR), the Energy Economy Rating (EER), Absolute Speed Change Rating (ASR) and the Root Mean Squared Speed Error (RMS). The standard clearly defines how to process the 10 Hz data from the drive schedule and the measured driven speed along with the vehicle characteristics (test weight and road load) to calculate the positive driven cycle energy (CEd) that is the foundation is the J2951 energy and economy ratings. The CEd can also be used for powertrain efficiency calculations. The energy rating is the percent difference between the positive driven cycle energy to the positive drive cycle energy. The distance rating is the percent difference between the total driven distance and the drive cycle distance. The energy economy rating combines the ER and DR into an economy rating. The absolute speed change rating compares the acceleration and deceleration rates between the driven trace and the drive trace. The RMS error provides the mathematical root mean square error between the driven trace and the drive trace. Figure 5 shows a few of the drive quality metrics that resulted from a past study focused on the how these parameters change with different drivers.

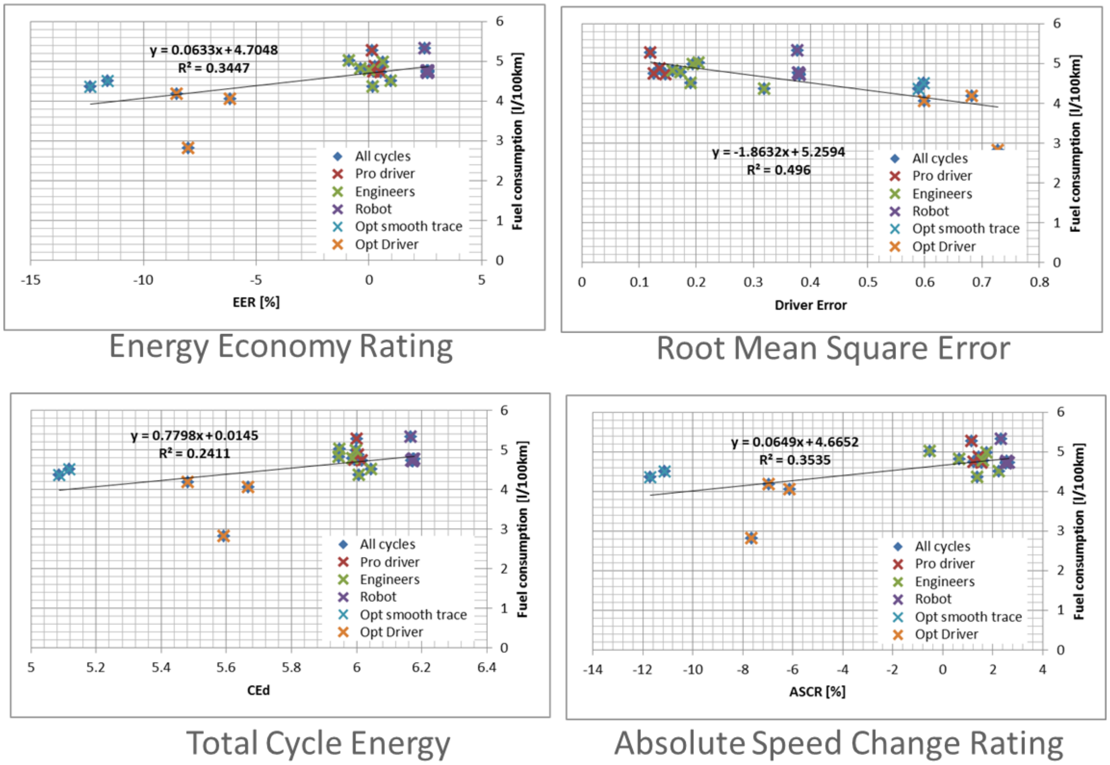

Figure 5: A few select SAE J2951 drive quality metrics from a study comparing different drivers from professional dyno drivers to the robot driver

The data in Figure 5 clearly shows that the robot driver and the professional dynamometer drivers repeat results are closely clustered into two groups. The "Engineers" label represent a range of different engineers on staff who had less experience driving on the chassis dynamometer. Clearly the professional dynamometer drivers are very repeatable. It is notable the robot and professional driver clusters are close but that they rarely overlay. Usually the professional drivers perform better on these rating or are closer to the ideal rating compared to the robot driver. This information contributed to the decision to use the professional chassis dynamometer drivers for this testing rather than the robot driver.

Finally, it is important to understand that neither SAE nor EPA has defined any targets or limits on these drive quality metrics to define "good" or valid testing versus "bad" or invalid tests. The Argonne staff uses its experience and judgement on these drive quality metrics to determine if a test was "bad" which rarely occurs. All the J2951 drive metrics are provided with each test as part of this work.

3.9. Test-to-test repeatability at Argonne's APRF

In a previous study using a conventional vehicle, Argonne determined that the fuel economy test-to-test variability on a UDDS drive cycle is 0.8 percent on cold start and 0.6 percent on a hot start with a 90 percent confidence interval in fuel consumption terms. The low test-to-test variability is achieved by: (1) keeping the vehicle mounted on the chassis dynamometer for the duration of the test period; (2) staying very consistent on the test plan and time of day to ensure consistent day-to-day thermal conditions; (3) the consistency in daily operation from a small staff in one test cell (including experienced professional dyno drivers); and (4) number of other small experimental details. Like many other test laboratories, Argonne follows a strict calibration schedule for all the measurement equipment used.

3.10. Test Fuel Specifications

EPA Tier 2 EEE certification fuel was used for the testing. The fuel was procured through Haltermann Solutions under the product code of HF0437. Table 2 provides the major specification for the Tier 2 certification fuel used. The full fuel specifications can be found in Appendix A.

Table 2: Main specifications of the EPA Tier 2 EEE fuel

Fuel Name:	**HF0437 EEE Tier 2**
Carbon weigh fraction	0.8656
Density	0.743 [g/ml]
Net heating value	18539 [BTU/lbm]
Research Octane Number	97.8
Motor Octane Number	88.7
R+M/2	93.2
Sensitivity	9.1

Premium gasoline is recommended by the manufacturer but not required. One of the goals of this assessment is to evaluate the impact of premium and regular fuel on fuel economy as well as vehicle performance. The EPA Tier 2 EEE certification fuel described above serves as a premium gasoline with its 93 AKI octane rating. The EPA Tier 3 EEE certification fuel has an 88 AKI octane rating and serves as the regular gasoline in the comparison.

Table 3 provides the major specification for the Tier 2 certification fuel used. The full fuel specifications can be found in Appendix A.

Table 3: Main specifications of the EPA Tier 3 EEE fuel

Fuel Name:	**HF2021 EEE Tier 3**
Carbon weigh fraction	0.8263
Density	0.7447 [g/ml]
Net heating value	17972 [BTU/lbm]
Research Octane Number	91.8
Motor Octane Number	84.2

Fuel Name:	HF2021 EEE Tier 3
R+M/2	88.0
Sensitivity	7.6

The Tier 2 fuel has a 3.1 percent lower energy content by mass compared to the Tier 3 fuel which does impact the volumetric fuel economy comparison. The vehicle efficiency calculations do use the actual energy content and fuel specifications.

4. 2016 Mazda CX-9 SkyActiv 2.5T

4.1. Test vehicle specifications

The 2016 Mazda CX-9 is a mid-sized three-row crossover redesigned for the 2016 model year with updated body and powertrain. With this update, a single powertrain option is made available, downsizing the prior V6 engine to a turbocharged, direct injected 4-cylinder (called "I4") engine coupled to a 6-speed automatic transmission. Vehicle service documentation lists the 2.5 liter I4 as producing 227 hp at 5,000 rpm while operating on 87 octane fuel, with power increasing to 250 hp at 5,000 rpm when 93 octane fuel is used. At either octane, torque is listed as 310 lb-ft at 2,000 rpm. The turbocharged I4 engine replaced a 3.7L V6 engine, standard for this vehicle class, producing 273 hp and 270 lb-ft of torque.

With the update, combined EPA label fuel economy for the front wheel drive model increases from 19 mpg (17 city, 24 Highway) to 24mpg (22 city, 28 Highway). The implementation of a downsized turbocharged engine in this weight class, and the improvement in fuel economy led to interest in this particular powertrain configuration and the corresponding technology assessment work. The build sheet for the test vehicle can be found in Appendix D. As a summary, Table 4 lists the technical specifications of the 2016 Mazda CX-9 test vehicle.

Table 4: Technical specification of the Mazda CX-9 test vehicle

Test vehicle	2016 Mazda CX-9 SkyActiv 2.5T with 6-speed automatic transmission
VIN	JM3TCABY0G0101103
Engine	2.5 liter Turbo, I4, DOHC 16, 227 hp @ 5,000 rpm, 87 octane, regular fuel 250 hp @ 5,000 rpm, 93 octane, premium fuel 310 lb-ft @ 2,000 rpm Compression ratio 10.5.:1 Direct Injection
Transmission	Front wheel drive (FWD) 6-speed automatic transmission 1st 3.487 2nd 1.992 3rd 1.449 4th 1.00 5th 0.707 6th 0.600 Final Drive 4.411 255/60 R18 all-season tires
Climate control	Belt-driven air conditioning compressor Waste heat heating

EPA Label Fuel Economy (mpg)	22 City / 28 Highway / 24 Combined (FWD)

4.2. Specific technology features of interest

The significant 2016 CX-9 technologies that test data can provide more insight on are the following.

- SkyActiv engine
    - General engine operation and efficiency
    - Direct injection operation
- 6-speed transmission
    - Shift strategy and torque converter operation
- Impact of octane on vehicle performance.
- Grille shutter operation

5. 2016 Mazda CX-9 test results and analysis

5.1. General observations from testing

5.1.1. Vehicle setup

Evaluation of the test vehicle occurred on a chassis dynamometer at the APRF in 2WD mode. The vehicle was tested using only the front chassis dynamometer roll in the test cell with the vehicle restrained on the chassis dynamometer using straps to located front of the vehicle, and wheel chocks on the rear wheels. Once secured, and instrumentation had been completed and verified, the team performed the vehicle coast down and vehicle loss determination.

The EPA annual certification data for vehicles was reviewed in order to determine the proper test weight and target road load coefficients. The vehicle test group and engine family were confirmed within the documentation, and the test vehicle determined to match that of the test vehicle (U.S. market at 4,500lb ETW from manufacturer). Table 5 provides the chassis dynamometer parameters used throughout the evaluation of the CX-9. Figure 6 shows a picture of the test vehicle mounted to the chassis dynamometer.

Table 5: Chassis dynamometer parameters for the Mazda CX-9 test vehicle

Test weight	4,500 [lb]	
Chassis dyno setup	2WD/FWD on rolls with traction control off	
	Target	ANL Set
Road load A term	40.443 [lb]	20.975 [lb]
Road load B term	0.2594 [lb/mph]	0.0567 [lb/mph]
Road load C term	0.0264 [lb/mph^2]	0.0263 [lb/mph^2]

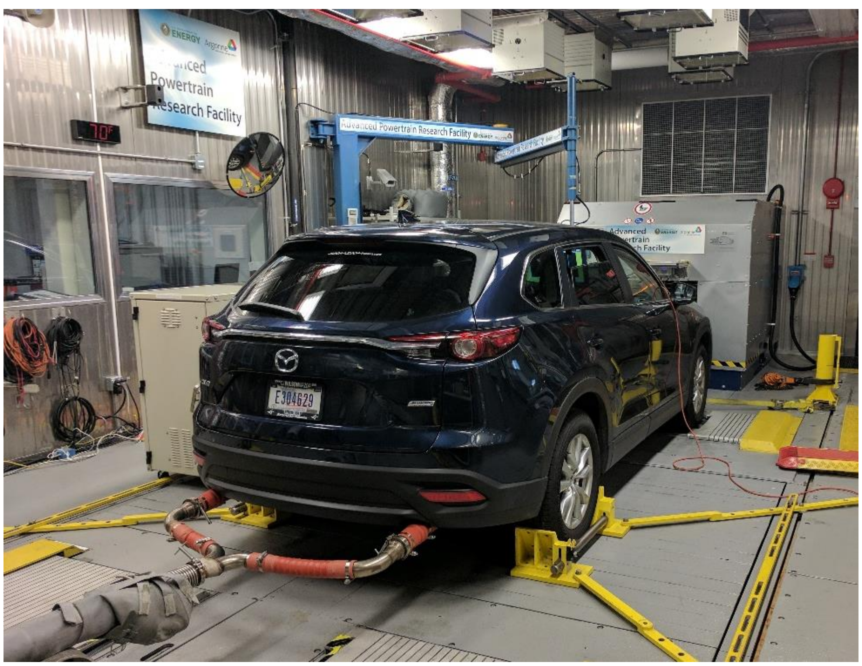

Figure 6: Mazda CX-9 test vehicle mounted to the chassis dynamometer inside of the test cell.

5.1.2. Instrumentation description

This section describes the specific instrumentation installed on the CX-9 in addition to the generic instrumentation detailed in Table 1. The additional analog signals include a thermocouple measuring the air temperature behind the radiator and a thermocouple measuring the engine bay temperature.

The following is a categorized list of important signals decoded on the vehicle communication bus.

- Driver input:
  - Accelerator pedal position (several signals)
  - Brake pedal (several signals)
  - Mode selection (normal, sport)
  - Transmission PRNDL selection
- Engine:
  - Engine speed
  - Engine torque
  - Engine intake pressure
  - Waste gate position
  - Intake air temp
  - Exhaust and intake cam angle
  - Engine oil pressure
  - Knock feedback
  - EGR sensor
  - Equivalence ratio
- Cooling system
  - Engine coolant temperature (vehicle reported)
  - Engine variable fan duty cycle
  - Grille shutter position
- Transmission
  - Transmission fluid temperature
  - Gear # desired and engaged
  - Transmission drive ratio
  - Transmission turbine speed
  - Shift in progress

This list of signals is intended to be sufficiently comprehensive to provide the modeling and simulation team with enough detail to develop models, calibrate control strategies, and to validate simulation results. The complete list of the Mazda CX-9 test vehicle signals (recorded at 10 Hz) is in Appendix B. The vehicle messages have varying degrees of accuracy depending on the need for accuracy within the powertrain control.

The 2.5L I4 SkyActiv engine provides fuel through a direct fuel injection (DI) system. Within the fuel system, a low-pressure fuel pump located at the fuel tank, which then delivers the fuel through sections of solid and flexible fuel lines to the rear of the vehicle engine bay. At this location, a flexible line routes the fuel from the body-mounted solid lines to the mechanically driven high-pressure fuel pump located at the rear of the engine. At this quick-disconnect location in the engine bay, the total fuel flow was measured using both a positive displacement fuel scale and a Coriolis fuel flow meter. Figure 7 illustrates the fuel system in the vehicle as well as the fuel flow measurement system.

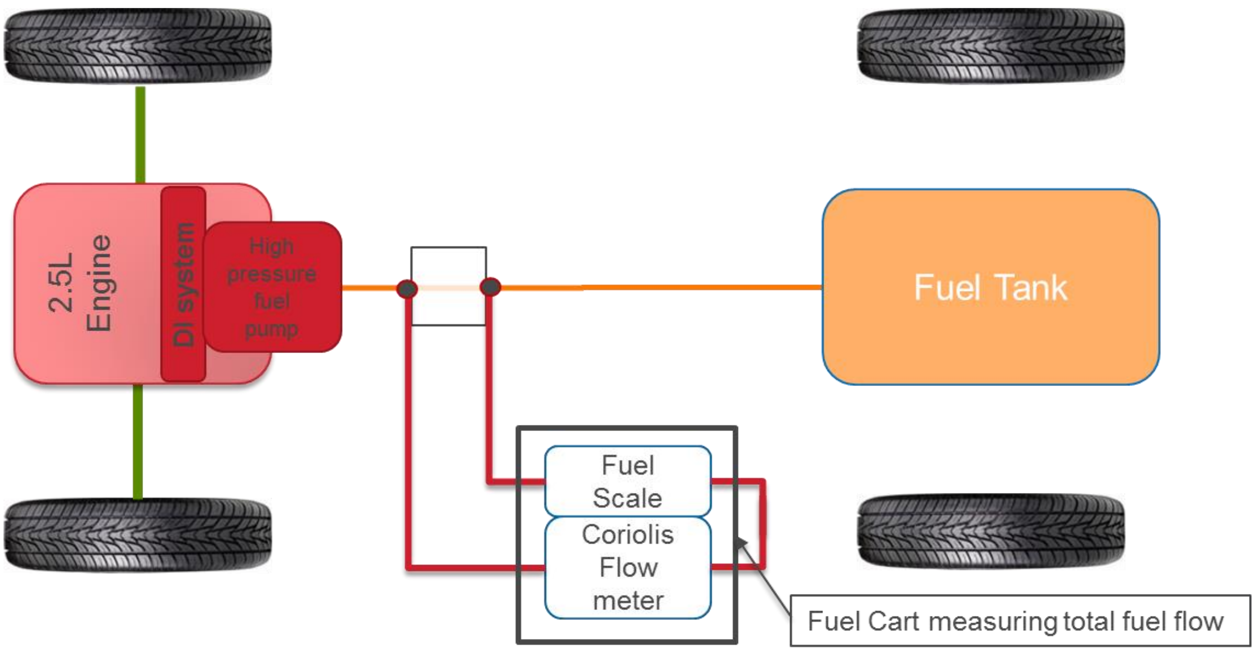

Figure 7: Fuel flow instrumentation diagram of the 2016 Mazda CX-9

5.1.3. Executed test plan

The test sequence introduced in Figure 2, consisting of series of UDDS, Highway, and US06 drive cycles, is repeated three times at the temperature of 72° F. Additional testing is performed on performance cycles and at high and low ambient temperatures. In addition the drive cycle test sequence is repeated at 72° F with Tier 3 certification fuel for the premium versus regular gasoline comparison study. Table 6 provides a summary of the tests that are executed as part of the general test plan, and a full summary of each individual test can be found in Appendix C.

Table 6: Summary of the executed general test plan

Test cycle / Test conditions	72° F	95° F + 850W/m^2	20° F	72° F Tier 3 fuel
UDDSx3 (including cold start)	3X	UDDSx2	X	3X
Highwayx2	3X		X	3X
US06x2 (4bag)	3X	US06X3	X	3X
SC03x2	N/A	3x		
Steady state speed testing 0%, 3% 6% grade				X

Test cycle / Test conditions	72° F	95° F + 850W/m^2	20° F	72° F Tier 3 fuel
Passing 0%, 3%, 6% grade	X			X
WOT'sx3	X			X

Additionally, tests are conducted to map the powertrain operation and further explore the vehicle performance. The additional testing includes the following.

- 72° F Cold start idle: to map out the idle fuel flow consumption as a function of powertrain temperature
- Engine and transmission operation mapping with a robotic driver through:
    - constant accelerator tip ins tests
    - accelerator tip ins with vehicle locked at constant speed
- Deceleration Fuel Cut Off (DFCO) mapping

The vehicle remained on the chassis dynamometer over the testing duration to ensure that vehicle loading remained consistent.

5.2. Test results and analysis

5.2.1. Brief powertrain operation overview

This section provides a brief overview of powertrain operation prior getting into more technical detail in subsequent sections. The CX-9 operates as a modern downsized turbocharged engine mated to a 6-speed transmission. Figure 8 displays the powertrain operation on a segment of the UDDS drive cycle. While the vehicle is stopped, the engine idles at 550 rpm. When the driver lets his/her foot off the brake pedal, the transmission turbine speed begins to match engine speed, and the vehicle gradually begins to launch. As the driver accelerates the transmission shifts through the gears. The transmission settles in a gear as the vehicle cruises at a constant speed. During vehicle deceleration, the fuel to the engine is zeroed in order to save fuel. This is known as Deceleration Fuel Cut Off (DFCO).

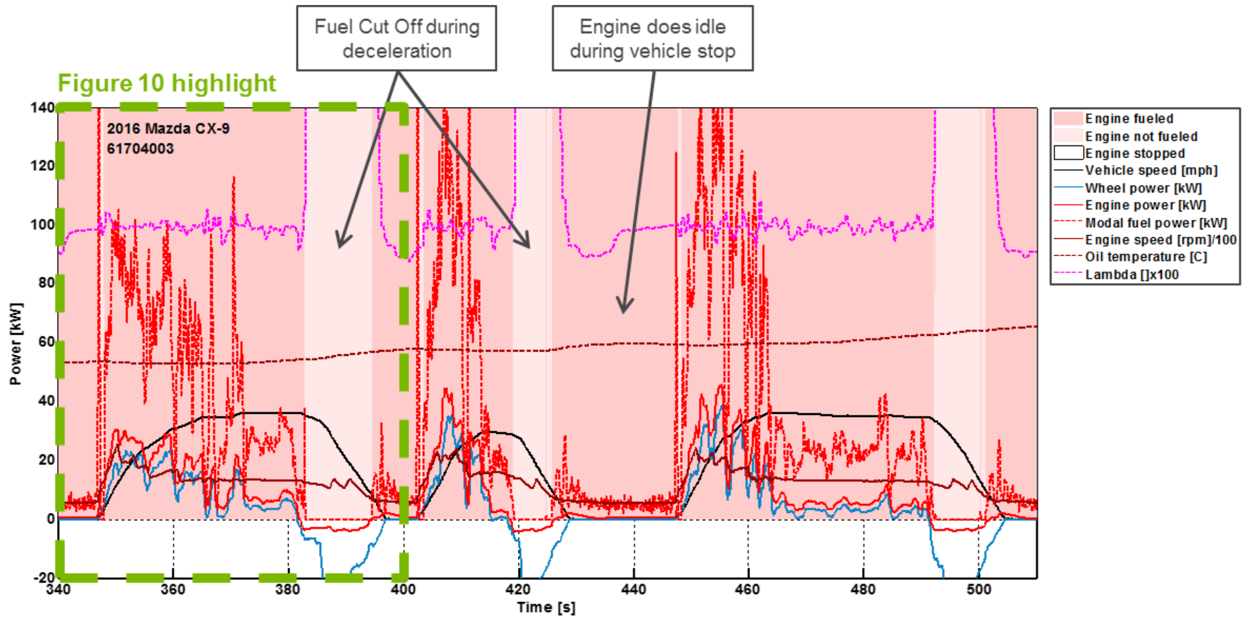

Figure 8: CX-9 powertrain operation on cold start UDDS

Figure 9 provides a closer look at the transmission shifting behavior of the test vehicle. The 6-speed transmission operates as would be expected during accelerations, shifting incrementally into higher gears. The torque converter does not fully lock on the UDDS cold start or hot start cycles. Very small amounts of torque converter slip are seen during several cycles, but in general full transmission lockup is rarely encountered. Torque converter lockup is discussed further in section 5.4.3.2.

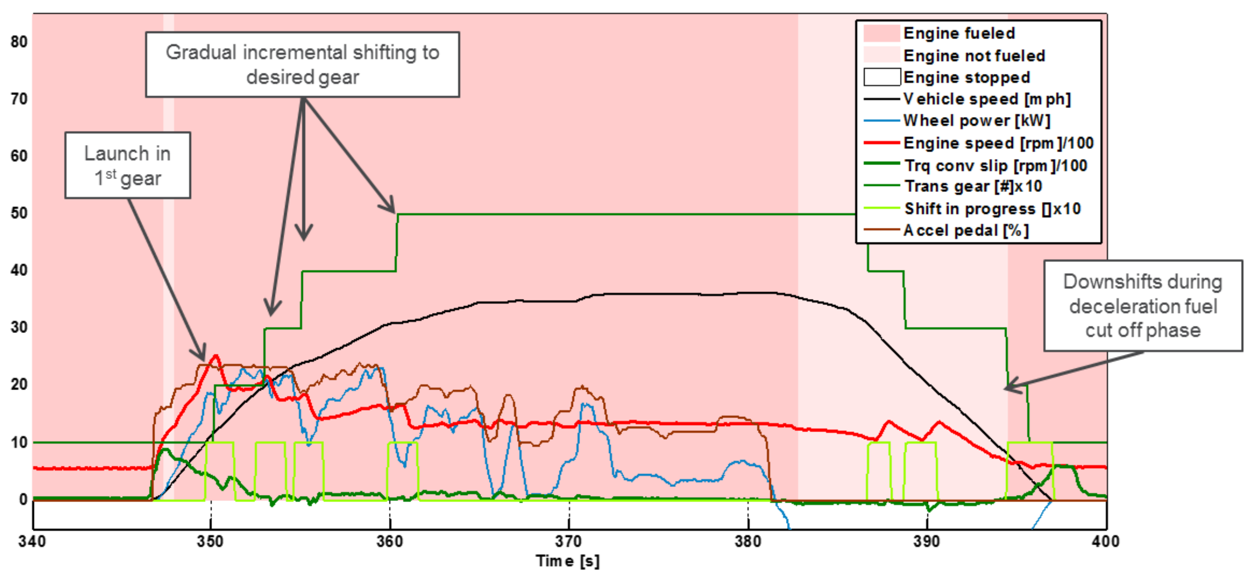

Figure 9: CX-9 shift operation on cold start UDDS

The different powertrain components and their operation, such as DFCO, torque converter operation and features are investigated in much deeper detail in section 5.4.

5.2.2. CAFE fuel economy results with comparison to label values

The fuel economy results from the testing at Argonne compare very closely to the fuel economy results published on the EPA test car list data website. The EPA publishes unadjusted fuel economy results from the manufacturer as well as their own testing results for phases 1, 2 and 3 of the UDDS as well as the Highway cycle. Figure 10 and Table 7 compare the published fuel economy results to the three test sequences completed at the APRF with the Tier 2 high octane fuel.

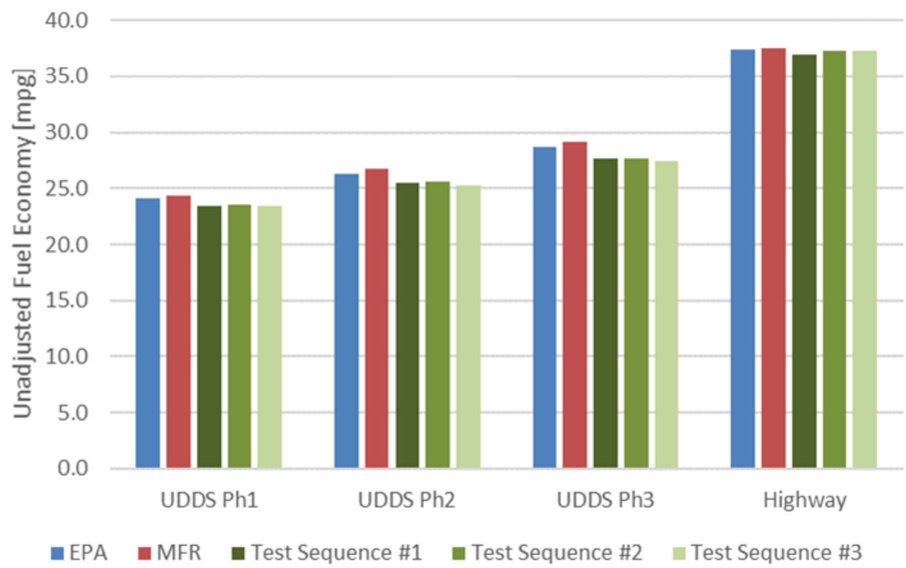

Figure 10: Raw fuel economy results for the UDDS and Highway certification cycles from EPA and Argonne

Table 7: Raw fuel economy results for the UDDS and Highway certification cycles from EPA, MFR reported, and Argonne

FE [mpg]	EPA	MFR	Repeat#1	Repeat#2	Pepeat#3	ANL average
UDDS Ph1	24.2	24.3	23.4	23.6	23.4	23.46
UDDS Ph2	26.3	26.7	25.5	25.6	25.3	25.45
UDDS Ph3	28.6	29.1	27.7	27.6	27.4	27.56
Highway	37.4	37.5	36.9	37.2	37.2	37.10

5.2.3. Fuel economy results for standard drive cycles

The fuel economy for standard drive cycles are presented in Table 8. The drive cycles include the cold start UDDS (Phase 1 and 2), the hot start UDDS (Phase 3 and 4), a third UDDS cycle, the Highway cycle, and the US06 cycle. The third UDDS cycle is not part of the certification testing, however it is performed to understand vehicle operation and fuel economy changes as the powertrain temperature reaches higher, and stable operating temperatures. Both of the Highway and US06 drive cycles are tested in phases and the fuel economy presented here is from the second cycle as described in Figure 4.

Table 8: Raw fuel economy results for drive cycle results

	Fuel economy [mpg]
UDDS #1 Cold Start	**24.45**
UDDS#1 Ph1	23.46
UDDS#1 Ph2	25.45
UDDS#2 Hot	**26.76**
UDDS#2 Ph1	27.56
UDDS#2 Ph2	26.05
Highway	**37.10**
US06	**22.40**
US06 City	15.16
US06 Highway	25.92

5.2.4. Vehicle efficiency based on SAE J2951 positive cycle energy

In order to provide a repeatable method for measuring vehicle efficiency, the SAE J2951 calculation for vehicle efficiency is used. In J2951, vehicle efficiency is calculated by dividing the positive cycle energy (CEd) by the fuel energy used over the drive cycle. Table 9 provides the calculated vehicle efficiencies for the drive cycles in each test sequence.

Table 9: Powertrain efficiencies based on J2951 positive cycle energy on the Tier 2 High octane fuel

	Test Sequence #1	Test Sequence #2	Test Sequence #3	Average
UDDS #1 Cold Start	19.2%	19.3%	19.3%	19.3%
UDDS#2 Hot Start	21.1%	21.0%	21.1%	21.1%
UDDS#3	21.3%	21.2%	21.3%	21.3%
Highway	28.8%	29.1%	29.0%	29.0%
US06	27.7%	28.2%	27.7%	27.9%

The lowest average vehicle efficiency occurs on the UDDS cycle which is typical for conventional vehicles. The UDDS cycle is a stop and go drive cycle with very mild power requirements. On the UDDS cycle the engine operates at low load with a relatively low throttle opening which increases the pumping losses. The powertrain efficiency increases by about 2 percent from the cold start cycle to the third cycle when the powertrain has reached its operating temperature. This efficiency increase is likely due to the lower friction which is a typical results of higher temperatures in all components within the powertrain.

The average powertrain efficiency is the highest on the Highway drive cycle. On this cycle no idle events are experienced, and the vehicle operates at speeds where the powertrain is more heavily loaded, resulting in higher efficiency. On the Highway cycle 6th gear is engaged over 80 percent of the time with engine speeds varying from 1,500 rpm to 1,800 rpm. This enables the vehicle to achieve almost 29 percent vehicle efficiency on the Highway cycle.

The average powertrain efficiency on the US06 drive cycle is close to 28 percent. This drive cycle requires high engine loads which results in higher engine efficiencies, but the high idle times and high dynamic driving contributes to the fact the vehicle efficiency is lower on the US06 as compared to the Highway drive cycle.

5.2.5. Break down of fuel consumption based on drive mode

This section decomposes the fuel usage of the Mazda CX-9 into basic drive modes which are: (1) the vehicle being stopped, (2) the vehicle accelerating, (3) the vehicle cruising and (4) the vehicle decelerating. The vehicle is considered stopped when the dynamometer speed is below 0.1 mph. Cruise is defined as an acceleration less than 0.05 m/s^2 for the purpose of this analysis. Figure 11 shows the contribution of these for drive modes to the fuel consumption on the certification drive cycles. Note that the total fuel used in each mode is found and divided by the total distance of the drive cycle.

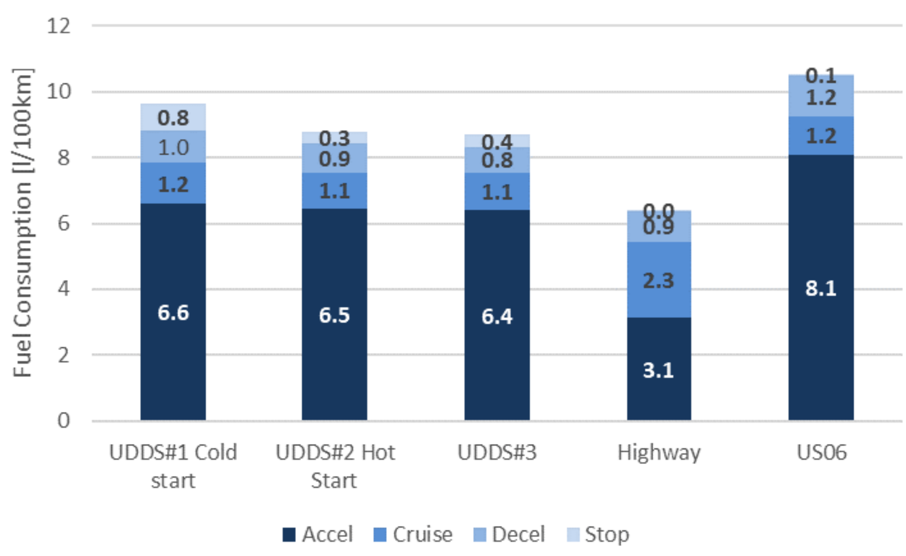

Figure 11: Drive cycle fuel consumption decomposed into drive modes

A comparison of the three UDDS cycles shows that the vehicle used more fuel in each drive mode when the powertrain was cold. More fuel is used in all four basic drive modes on the cold start test. The largest increase in fuel usage occurs during idle on the cold start test, which is more than double the fuel consumed on the hot start and third UDDS cycle. The majority of the fuel is used during.

Table 10 provides the percentage of fuel used in each drive mode for the different drive cycles. The Highway cycle has a high percentage of cruise driving compared to the other drive cycles. This relatively steady driving mode also helps increase the powertrain efficiency.

Table 10: Percentage of fuel used on drive cycles by drive mode

	Accel	Cruise	Decel	Stop
UDDS #1 Cold Start	68.6%	12.9%	10.0%	8.5%
UDDS#2 Hot Start	73.6%	12.5%	10.1%	3.9%
UDDS#3	74.0%	13.0%	8.9%	4.1%
Highway	49.1%	36.3%	14.6%	0.1%
US06	76.8%	11.0%	11.7%	0.5%

5.2.6. Cold start penalty on UDDS

This work also looks at the cold start penalty on the UDDS. The cold start penalty is defined as the additional fuel used on the cold start drive cycle as compared to the fuel used on the hot start drive cycle. This cold start penalty can be calculated by comparing phase 1 and phase 3 or by comparing the entire cold start UDDS drive cycle to the entire hot start UDDS drive cycle. Both cold start penalties are provided in Table 11.

Table 11: Cold start fuel penalty by phase and full cycle

	Test Sequence #1	Test Sequence #2	Test Sequence #3
Phase 1 vs Phase 3	18.2%	17.2%	17.0%
UDDS #1 vs UDDS #2	9.7%	8.9%	9.6%

Figure 12 compares the cold start and hot start behavior of the powertrain on the UDDS. The comparison includes fuel flow, engine speed and engine oil temperature. The difference in fuel flow is most apparent over the first 800 seconds. The increased fuel flow on the cold start cycle is a result of higher powertrain friction due to lower operating temperatures. The difference in the engine cold start behavior is most notable through the first two hills, where the engine speed is higher as the transmission operates in a lower gear. The initial engine idle is higher for the first 15 seconds of the cycle.

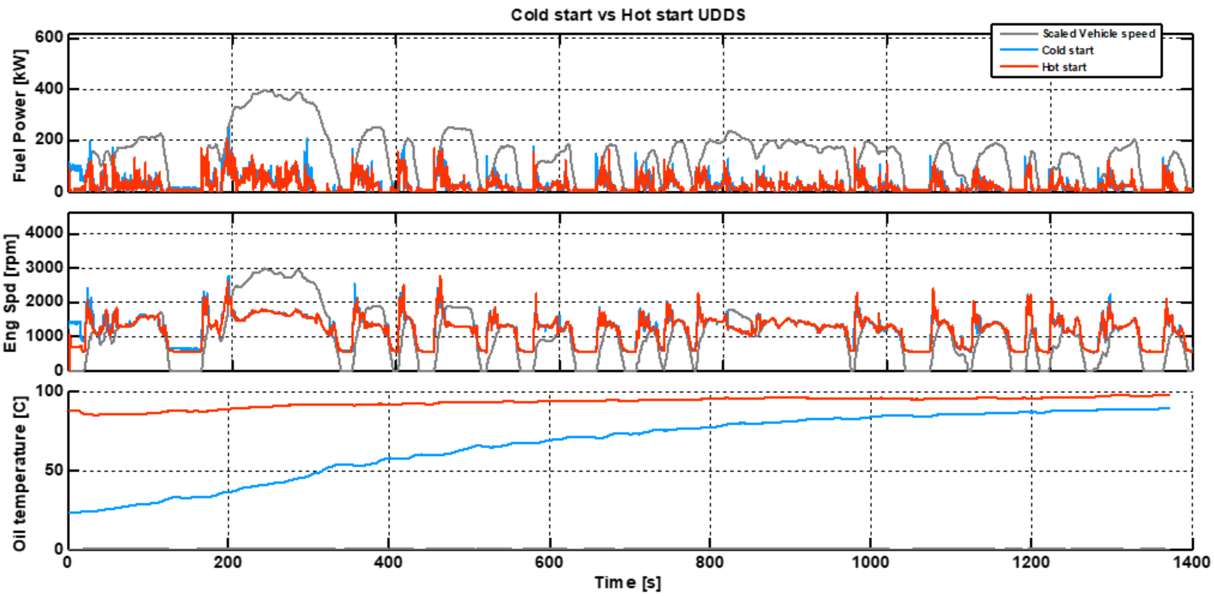

Figure 12: Comparison of powertrain operation on a cold start UDDS and a hot start UDDS

Figure 13 compares the cold start to the hot start fuel consumption by drive mode and includes a histogram of engine speeds for the cold start and hot start cycles. The elevated initial engine idle as well as the engine idle between hill one and two on the cold start test contributes to the increased fuel consumption. The powertrain also uses more fuel on the cold start cycle during the accelerations and decelerations. On average the engine speed during the cold start test is slightly higher compared to the hot start test.

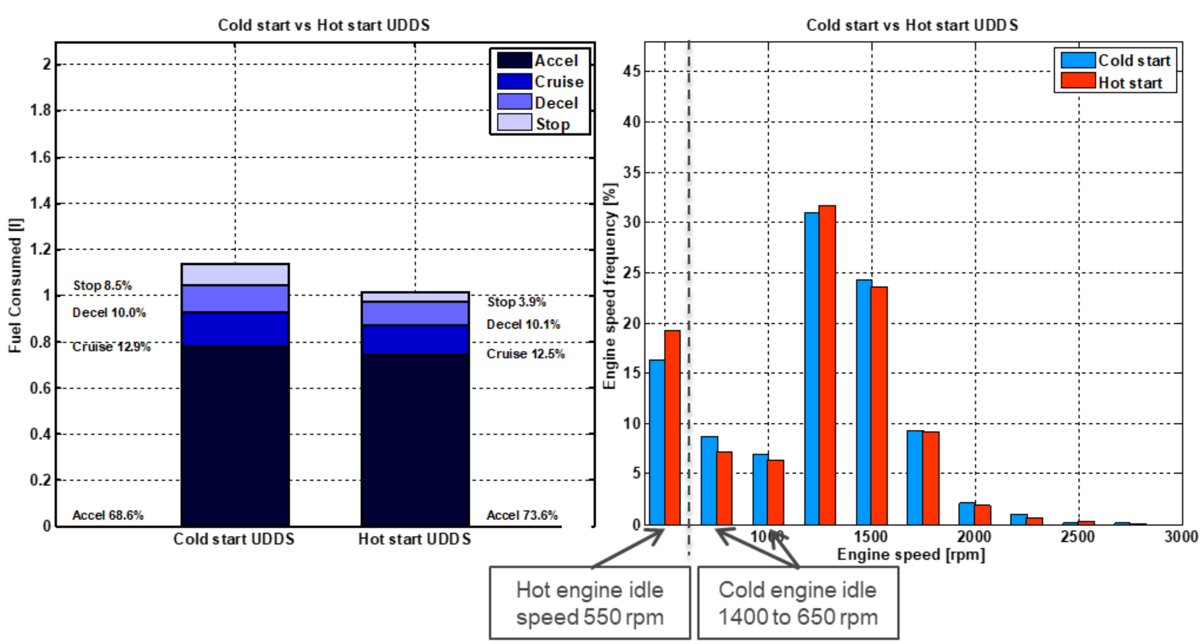

Figure 13: Fuel consumption inventory by drive mode and engine speed operation comparison between cold and hot start UDDS

5.2.7. Engine operating area on certification drive cycles

The Mazda CX-9 uses a 6-speed automatic transmission and attempts to operate the engine efficiently (at low speeds and high loads). The majority of the engine operation is below 2,000 rpm for the UDDS the Highway cycles. On the more aggressive US06 cycle, the median engine speed is around 2,000 rpm. The maximum speed on the US06 cycle is below 4,000 rpm. Figure 14 shows the engine speed histograms for the three certification cycles (UDDS, Highway, and US06).

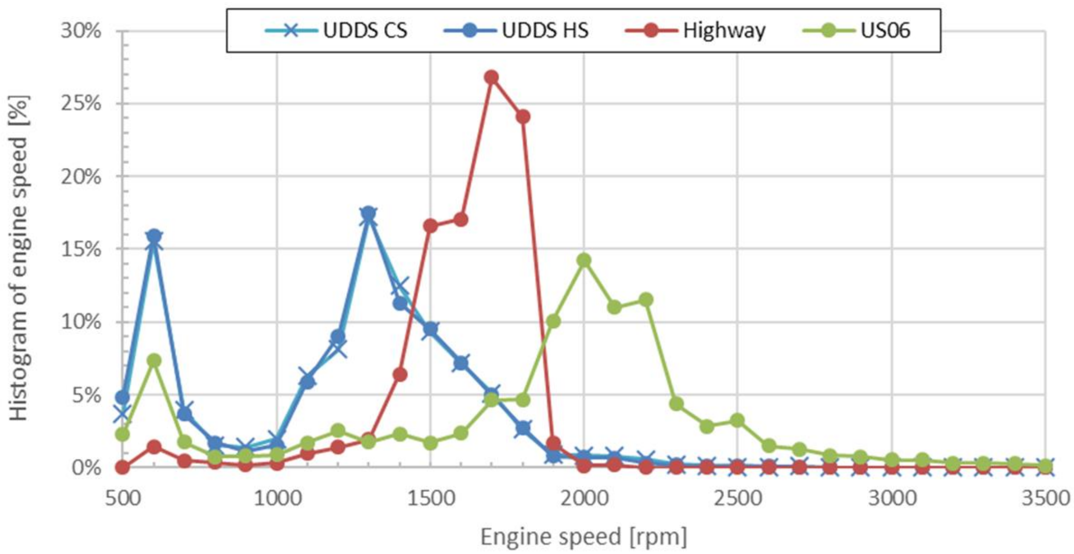

Figure 14: Engine speed histogram for certification cycles

Engine usage maps as a function of engine speed and absolute engine load are shown in Figure 15. The gray points in the graph represents all of the 10 Hz data points from the test. The black line represents the maximum engine load envelope of the test. An engine speed histogram is in the background of the figure. The color map represents the integration of fuel energy in the engine load and speed domain. This figure shows the engine usage for the three UDDS cycles, the two Highway cycles and the two US06 cycles separately.

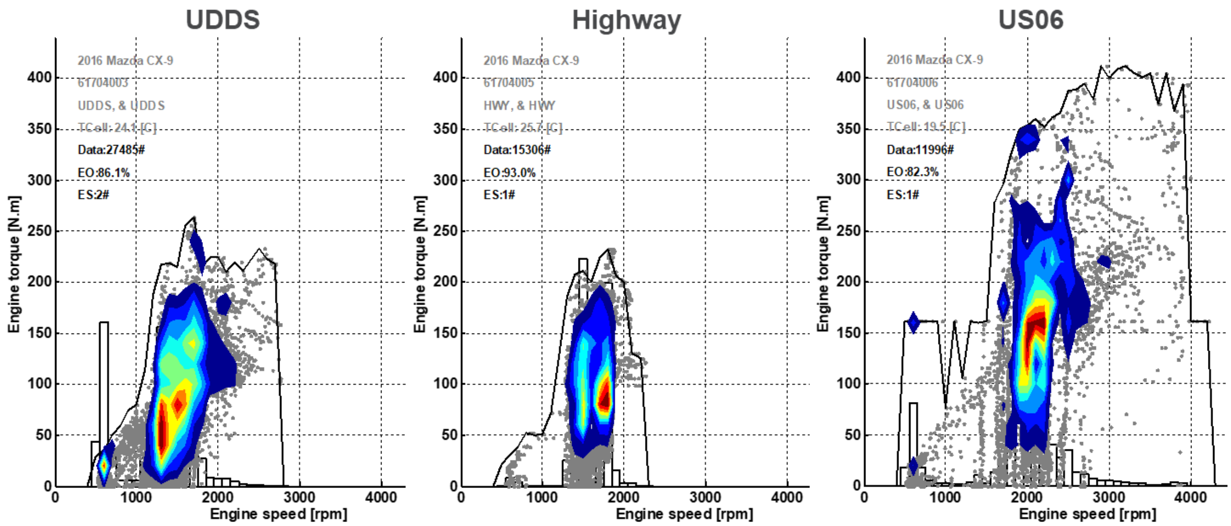

Figure 15: Engine operating area on certification drive cycles

On the UDDS cycle the engine spends most of its energy at around 1,400 rpm and 30 to 80 N.m. The colormap shows a spread as the engine accelerates through the gears. A small idle fuel flow island is visible at 500 to 600 rpm. On the Highway cycle the engine is operated narrowly between 1,500 to 1,800 rpm at an average load of 80 to 100 N.m. The operational envelop has significantly moved to higher loads on the US06, which has more aggressive accelerations and vehicle speeds up to 80 mph. In general, the engine speeds are around 2,000 to 2,200 rpm on the US06. The engine appears to have much higher torque reserves available for use on all three of these drive cycles. These higher load operating areas could be beneficial for powertrain efficiency but the engine operation is constrained by the transmission. Torque reserve for drivability might also be a consideration.

5.2.8. Transmission operation on certification drive cycles

The engine operating area is directly linked to the transmission hardware and controls strategy. Figure 16 shows the histogram of time spent in specific gears on the three certification cycles. A significant portion of time is spent in first gear on the UDDS cycle as this gear is engaged while the vehicle is stopped and during the initial vehicle lunch. On the Highway cycle 6th gear is engaged over 80 percent of the time. The gear usage is a bit more spread on the US06, but it is still dominated by the top gear which is engaged over the longer Highway segment of the US06 drive cycle.

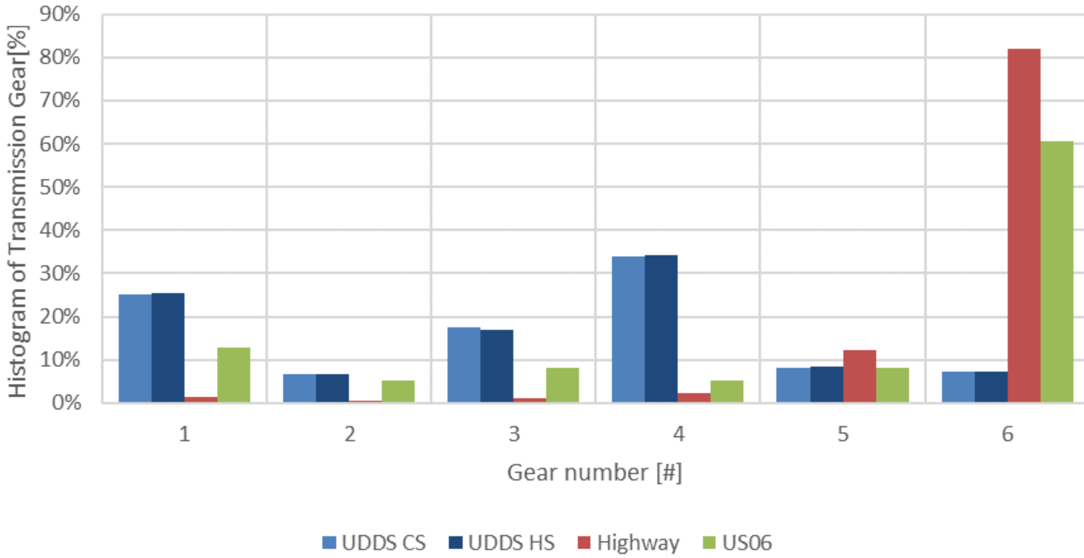

Figure 16: Histogram of gear usage on certification drive cycles

Figure 17 illustrates the gear spread of the 6-speed automatic transmission in the CX-9. The graph was assembled using the UDDS, the Highway and US06 drive cycles from the test sequence. The 6 gears are clearly visible in the figure. The upshifts at higher engine speeds and vehicle speeds are also clearly visible. Section 5.4.3.2 defines the torque converter operation in this space as well. Note that across all these drive cycles, the median engine speed is maintained between 1,300 to 2,200 rpm.

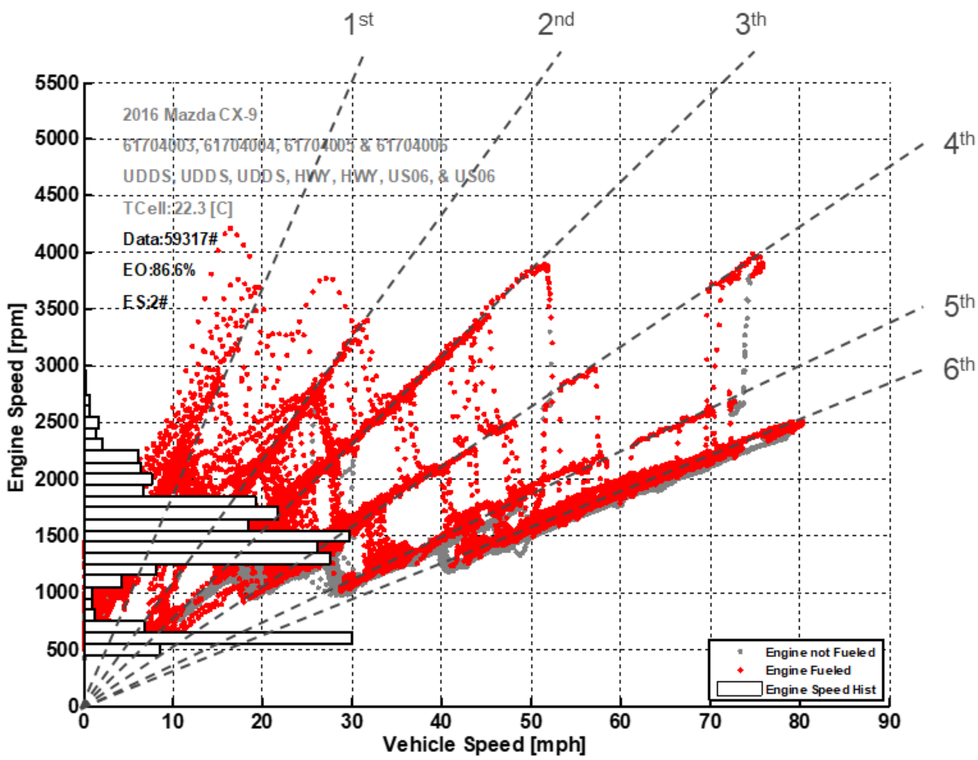

Figure 17: 6-speed transmission shift ratios and engine speed usage

Figure 18 correlates the gear up shifts to vehicle speed and accelerator pedal position. The accelerator pedal position rarely exceeds 30 percent on the UDDS and Highway cycles. A shifting trend related to vehicle speed emerges on the UDDS cycle. The Highway cycle contains relatively few shift points. The US06 data contains some higher load shift points and vehicle speeds. The Argonne staff performed some specific transmission mapping tests to further define a clear shift map. Those results are discussed in section 5.4.3.1.

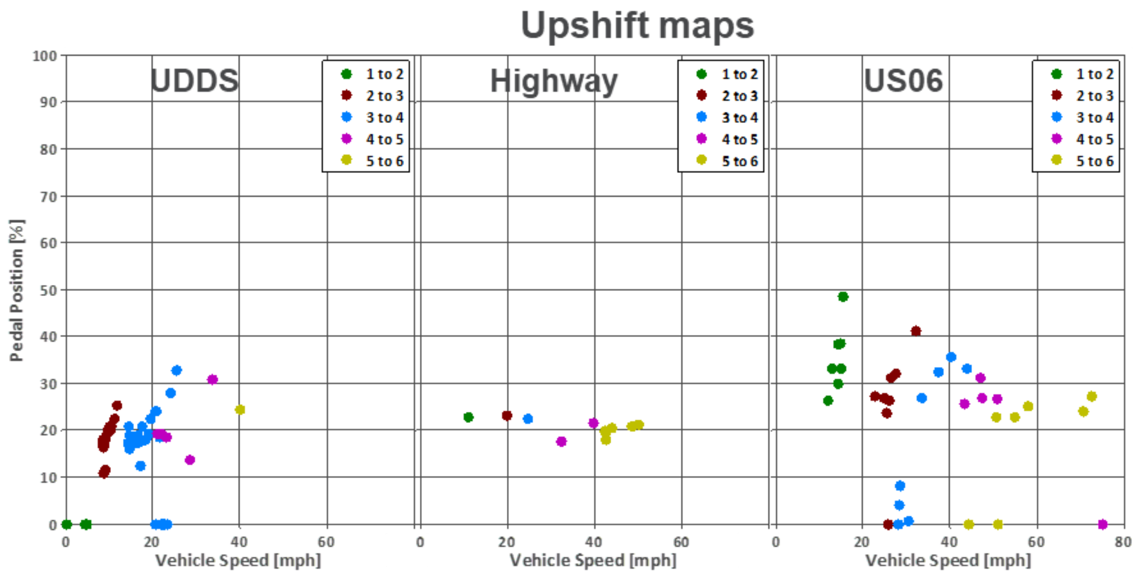

Figure 18: Transmission shift operation on certification drive cycles

Table 12 summarizes the number of upshifts per drive cycle. These number of shift events are relatively standard compared to other conventional vehicles with 6-speed automatic transmissions.

Table 12: Number of upshifts per drive cycle

# of shifts	1-2	2-3	3-4	4-5	5-6	Total
UDDS	18	18	24	5	1	66
Highway	1	1	1	2	7	12
US06	7	8	8	5	7	35

5.3. Powertrain performance test results

5.3.1. Steady state speed fuel economy

In order to characterize the performance of the CX-9 at steady speeds, a series of tests are conducted where vehicle speed is held for a set period of time, either 30 seconds or 1 minute depending on the test. The vehicle speed varies from 10 mph to 80 mph in increments of 10 mph, then the speed decreases back to 10 mph again in 10 mph increments. The fuel economy results as well as some vehicle characterization parameters are presented as an average of the results, in addition to vehicle efficiency, the power required at the wheel, and the engine speed. These results can be seen in Figure 19 for the (Tier 2 -93 AKI) fuel.

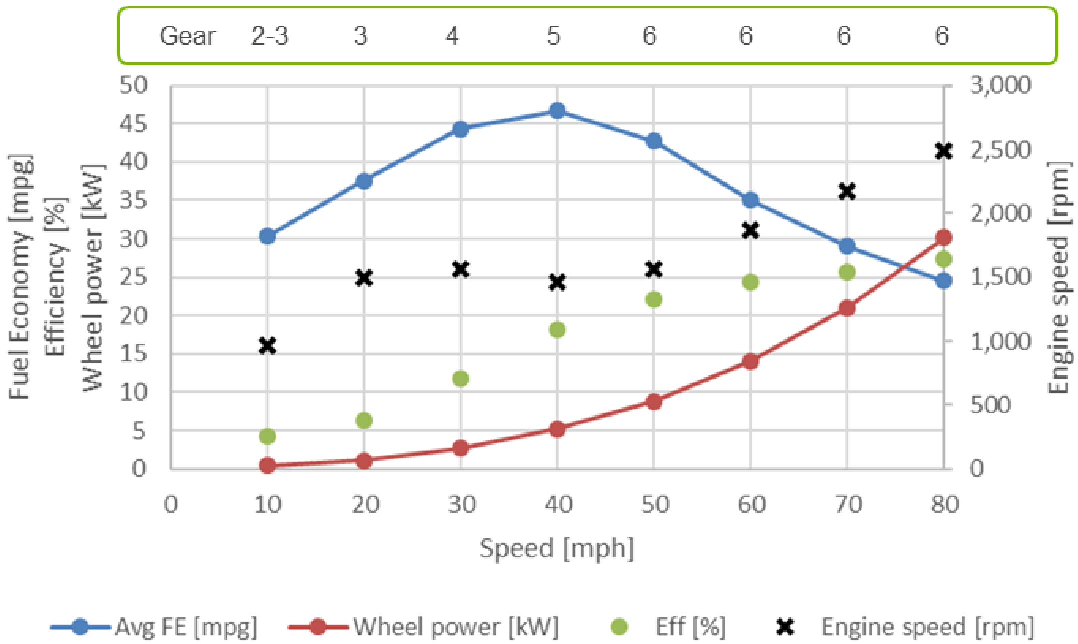

Figure 19: Steady state speed fuel economy with other powertrain measurements- high octane fuel

The highest fuel economy of about 45 mpg is achieved at a speed of 40 mph. Below the speed of 40 mph, low powertrain efficiency results in a lower resulting fuel economy. At speeds above 40 mph the increased efficiency does not offset the increased power required at the wheel to move the vehicle, mainly due to increasing aerodynamic drag. The peak efficiency of the vehicle on this cycle was found to be about 28 percent at 80 mph. The highest available gear, 6th gear, is engaged starting at 50 mph. At the speeds from 10 mph to 40 mph, the engine speed was below 1565 rpm.

5.3.2. Maximum acceleration

Maximum acceleration performance tests were performed on the chassis dynamometer. The maximum acceleration tests consist of a series of at least three accelerations at 100 percent acceleration pedal input until a maximum speed of over 80 mph. The test is performed from a rolling start to alleviate the traction issues of the tire on a smooth steel roll such as a chassis dynamometer Acceleration times are not directly comparable with those seen during on-road testing due to aforementioned traction limitation on the dyno. The acceleration times to 60 mph and 80 mph shown in Table 13.

Table 13: Maximum performance results- average of three subsequent accelerations

	Time [s]
Start-60 mph	8.0
Start-80 mph	14.4

Figure 20 shows the details of the powertrain operation during the maximum acceleration test. After the accelerator pedal is at 100 percent, the intake manifold pressure (absolute) begins to increase from approximately 30kPa. Time from full pedal input until the engine had reached atmospheric pressure varied from .5 to 1.5 seconds depending on the acceleration event. The maximum manifold pressure on the acceleration events varied between acceleration events from 220 kPa to 235 kPa. The air fuel mixture is also enriched during these events.

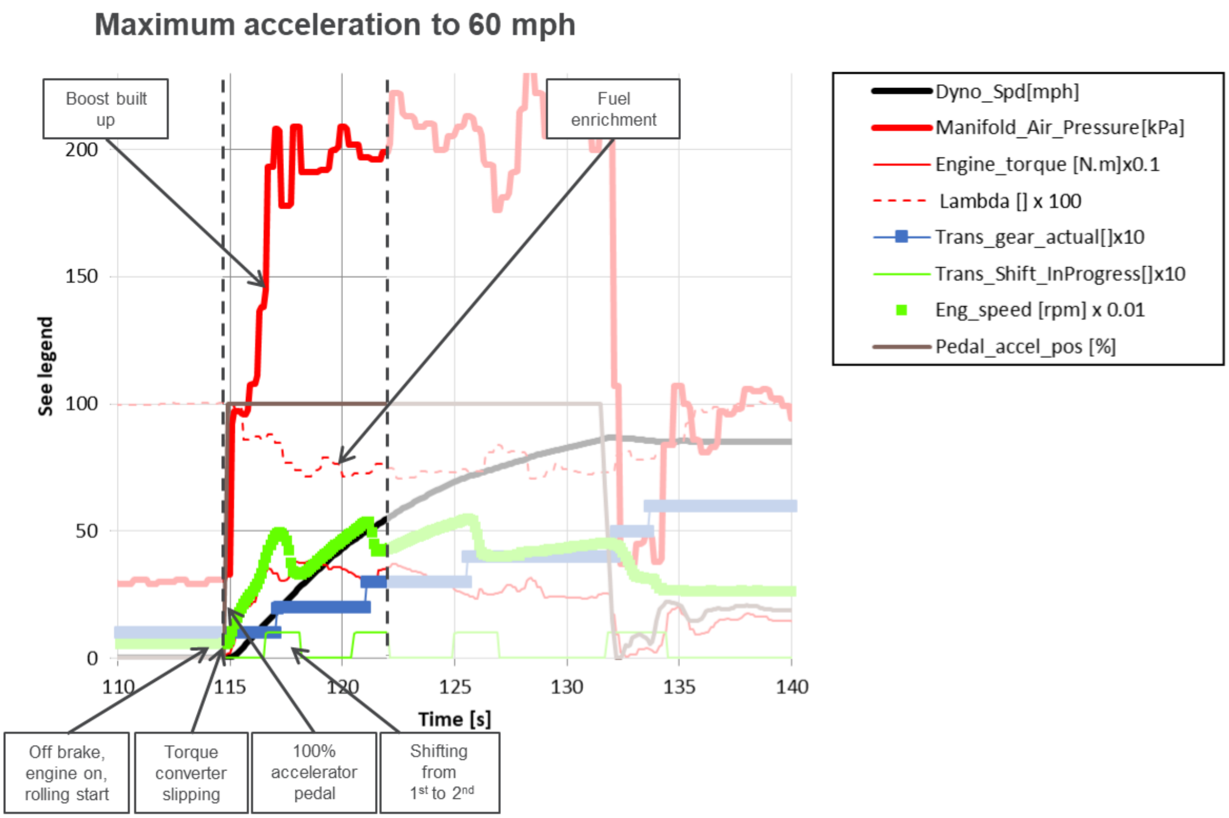

Figure 20: Powertrain operation during maximum acceleration

Transmission shifts from 1st to 2nd begin at engine speeds from 3,750-4,000 rpm with a maximum engine speed of 5050rpm. The 2nd to 3rd shift began between 5,000-5,025 rpm, with a maximum engine speed of 5,350 rpm. The 3rd to 4th gear shift begins when engine speed of approximately 5,325 rpm with a maximum speed of 5500rpm. Torque converter slip varies dependent on gear engaged. High levels of torque converter slip are seen in first gear during the initial acceleration. Following the shifts to 2nd and 3rd gear, torque converter clutch slip was found to decrease to an average of about 130rpm and 80rpm, respectively. The final gear used during the acceleration, 4th gear, continued to show that the torque converter clutch was not fully locked, with a difference between engine speed to turbine speed between 40-50rpm.

5.3.3. Passing maneuvers

Maximum performance testing also includes some typical passing maneuvers. To provide a repeatable evaluation of passing maneuvers on a dynamometer, Argonne has devised a drive cycle which includes a number of passing maneuvers. The passing maneuver drive cycle includes accelerations from 35 to 55 mph, 55 to 65 mph, 35 to 75 mph and 55 to 80 mph.

Prior to each acceleration event, the vehicle is held at a steady-state at the starting speed, then upon input from the drive trace, the driver applies 100 percent accelerator pedal until the vehicle accelerates past the final target speed. The results are then analyzed to determine the duration of time elapsed from when 100 percent pedal input is seen to when the dynamometer reaches the desired end speed. Note that as is the case with the maximum acceleration test, this test is developed to compare vehicles and analyze vehicle operation while on the dynamometer, rather than provide a comparison to on road evaluations.

Table 14 summarizes the time it takes the CX-9 to complete each passing maneuver. A plot of the powertrain details for the passing maneuver from 55 mph to 80 mph is shown in Figure 21. On this acceleration, the powertrain requires about a half second after 100 percent application of the accelerator pedal for engine manifold pressure to reach 100kPa, while a boost pressure of over 200kPa occurs after 1.3 seconds. Upon pedal input, the transmission downshifts from 6th gear to 3rd gear. Fuel enrichment occurs after manifold pressure reaches 100kPa.

Table 14: Passing maneuver performance results

	Time [s]
35-55 mph	4.0
55-65 mph	2.9
35-70 mph	7.1
55-80 mph	6.8

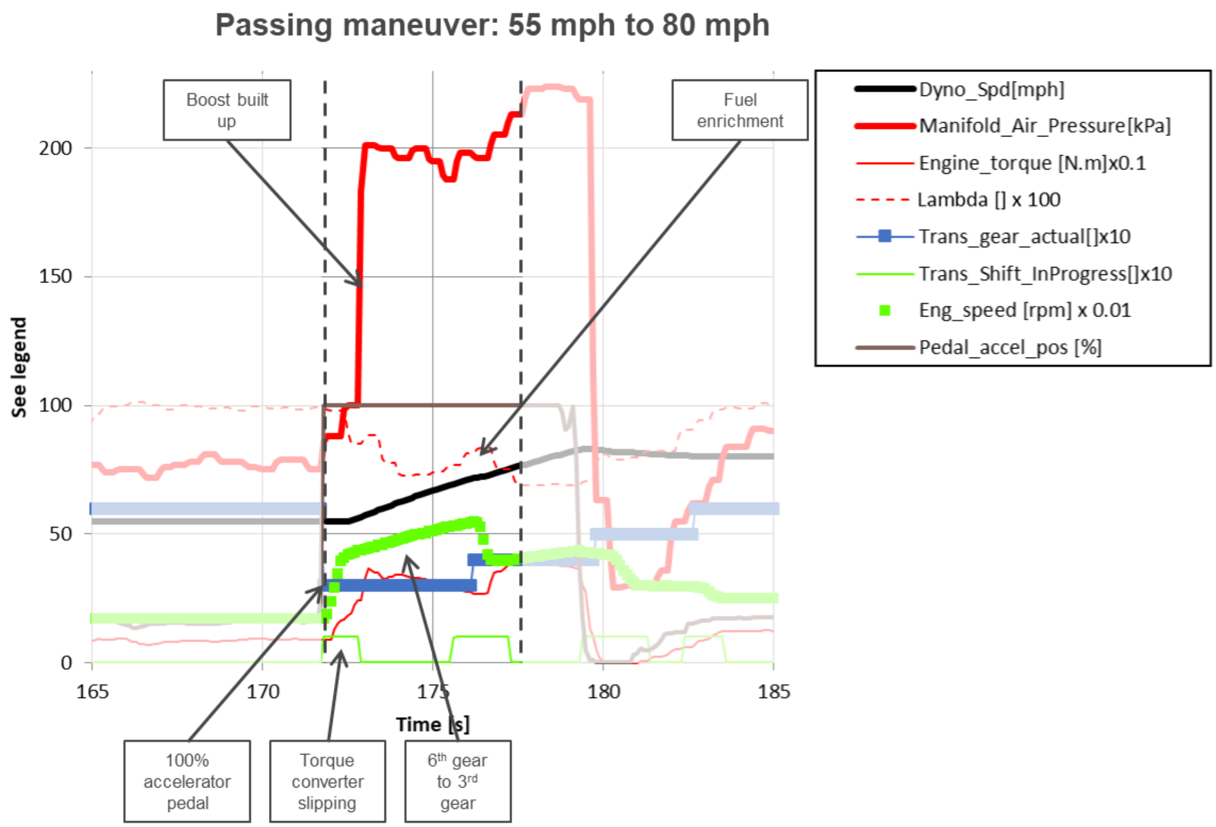

Figure 21: Powertrain operation during the 55 mph to 80 mph passing maneuver

5.4. Powertrain characterization

5.4.1. Idle fuel flow

In order to characterize engine behavior and fuel flow rate at idle, the test plan includes a 25 minute engine idle tests in cold start conditions at an ambient temperatures of 72° F. Prior to the test, the vehicle is soaked at 72° F overnight in the test cell. This idle test is performed with the transmission in Park, and the vehicle simply started and left to idle while data collection occurs.

Figure 22 shows the first several hundred seconds of the cold start engine idle test. The initial engine idle speed is 1,400 rpm which then switches to 900 rpm after 30 seconds and finally lowers to just above 600 rpm seconds. The ignition is also retarded on start up to help warm-up of the exhaust after treatment system.

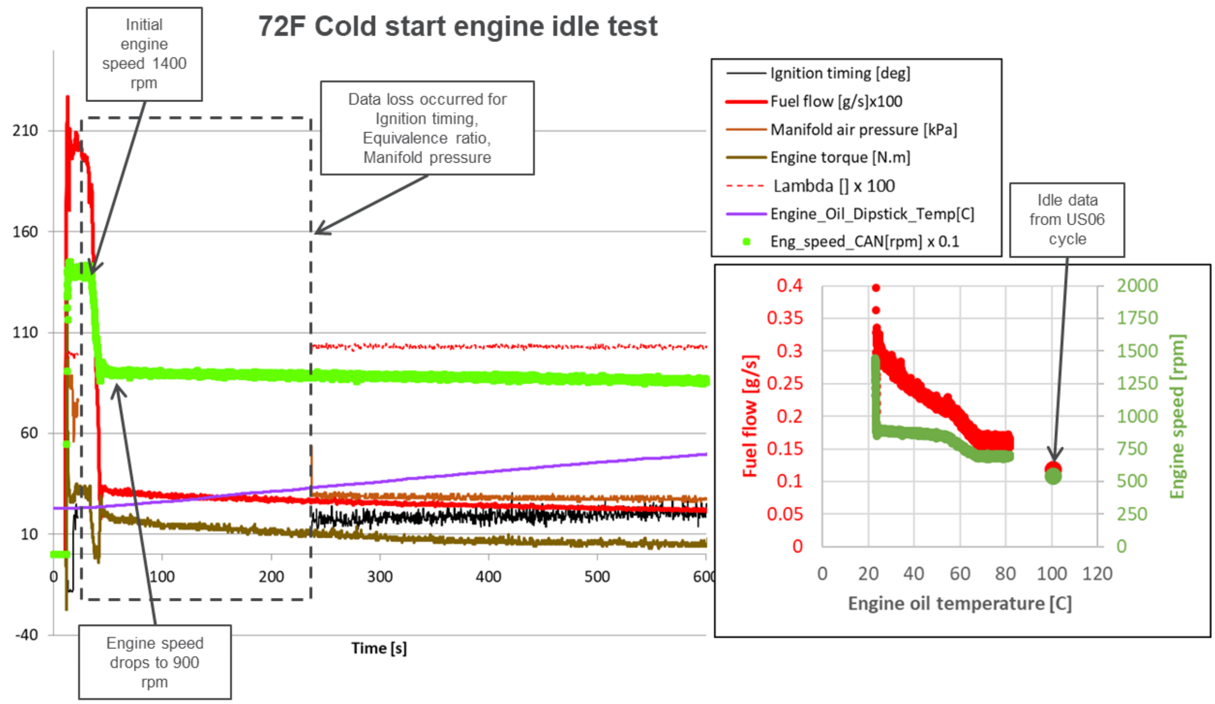

Figure 22: Analysis on a cold engine start and idle

At idle on the UDDS drive cycle, a fuel flow rate of 0.13 cc/s is found, which is equivalent to a fuel power rate of 4 kW. Figure 23 compares the idle fuel flow rates of the 2016 Mazda CX-9 to some other test vehicles in the APRF database. The CX-9 has the lowest fuel flow rate of all vehicles tested even for cars with smaller displacement engines compared to this direct injected 2.5L 4-cylinder engine. In general, DI engines have lower idle fuel flow rates on a per displacement basis.

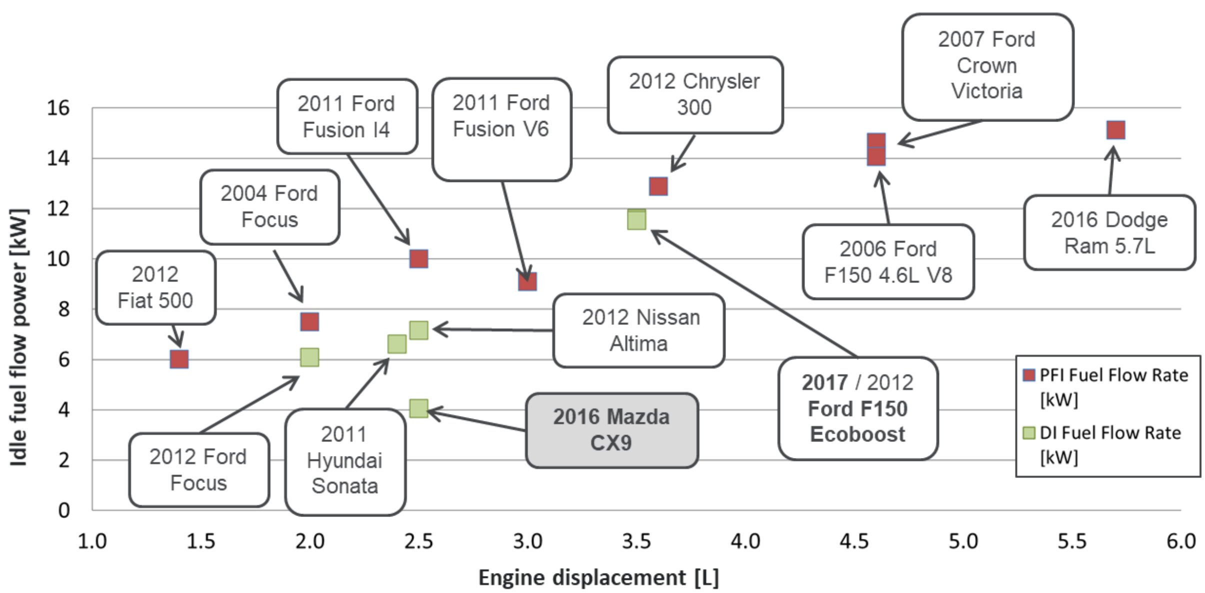

Figure 23: Idle fuel flow rate comparisons

5.4.2. Specific engine technologies

5.4.2.1. Mapping methodology

This section focuses on some engine operation parameters across the engine load and engine speed domain. The graphs in the section are built by dividing the engine load and engine speed domain into a grid by defining engine load and engine speed bins. A large data set is built by combining many drive cycles, performance tests and component mapping tests into one data structure. The resulting data structure is composed of 10 Hz time aligned data signals. Analysis software is used to distribute specific measurements or signals into the engine load and speed grid. The end result is a table with the averages values for each parameter of interest. That table results in the plot in this section.

Figure 24 to Figure 26 are developed with this method using over 480,000 data points. Data from the 72° F testing on the Tier 2 certification fuel is used. The tests for this analysis are carefully selected to span the entire engine operating envelop. The engine maximum operating envelops for the UDDS, the Highway and US06 cycles are overlaid on the figures to provide a visual guide to distinguish certification cycles from “off-cycle” operation.

5.4.2.2. Ignition timing

Figure 24 shows the spark ignition timing map for the engine. The greatest spark advance is observed at very low torque demand (low load cruise) and from 1,500 rpm to 2,800 rpm.

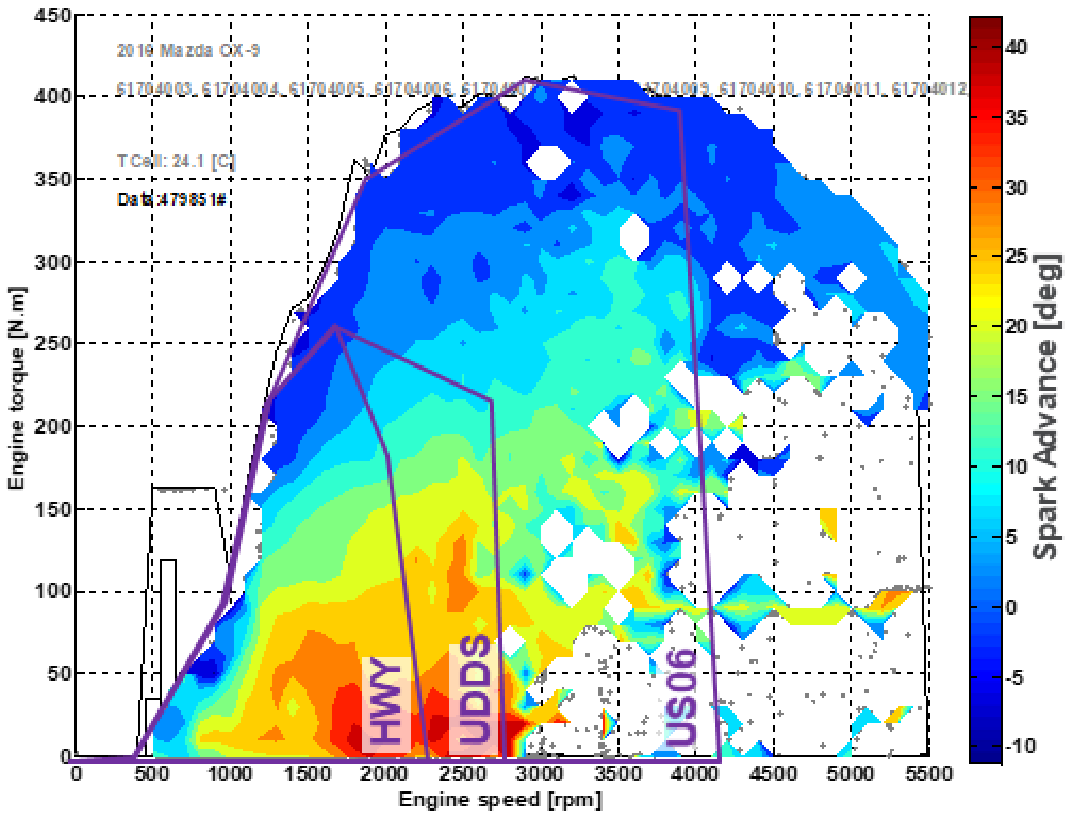

Figure 24: Spark advance map as a function of the engine speed and load

5.4.2.3. Engine boost strategy

Figure 25 shows the engine boost map. Note that the engine intake pressures on the UDDS and Highway cycles require very little boost from the turbocharger. On the US06 cycle the powertrain achieves required power by taking full advantage of the boost from the turbocharger.

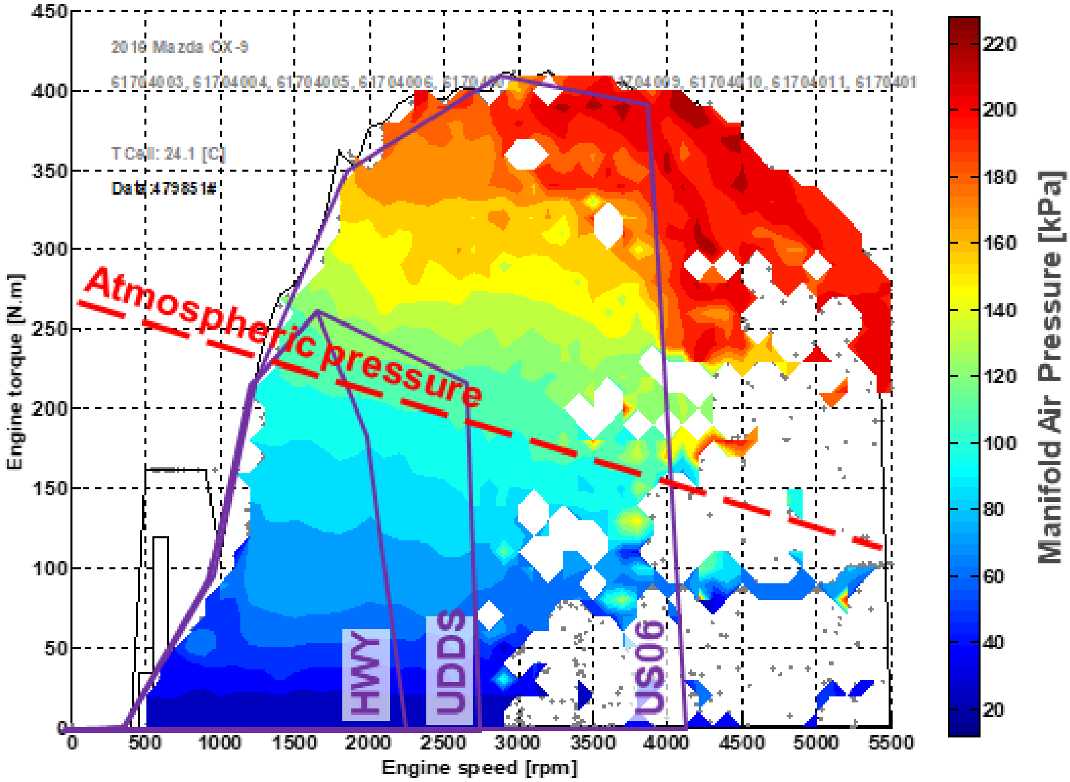

Figure 25: Manifold pressure and boost map as a function of the engine speed and load

5.4.2.4. Engine fueling map

Figure 26 provides the fuel flow map of the engine. This graph again shows the difference in power requirements between the relatively low power UDDS cycle and Highway cycle compared to the US06 cycle.

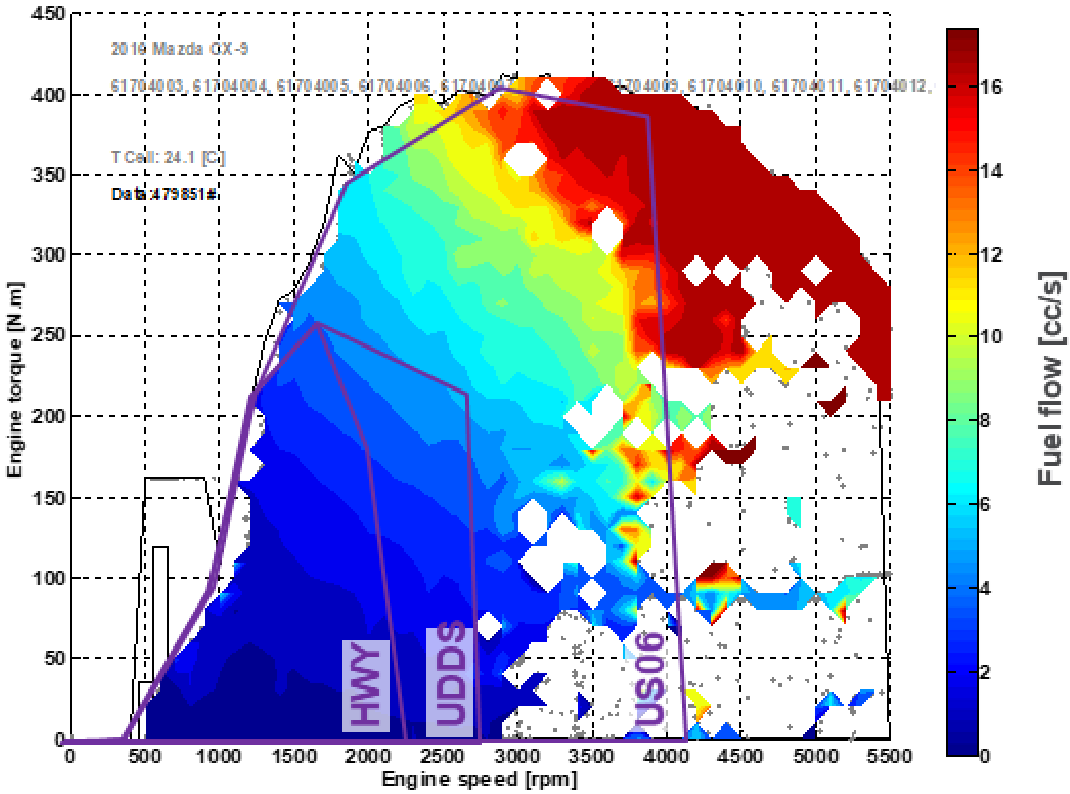

Figure 26: Fuel flow map as a function of the engine speed and load

5.4.2.5. Deceleration fuel cut off

Like other modern vehicles, the CX-9 uses a deceleration fuel cut off strategy to improve fuel economy. Recall Figure 8 and Figure 9 that show the deceleration fuel cut off mechanics as a function of time.

Figure 27 shows the deceleration fuel cut off area in the vehicle speed and tractive effort space. This data is derived from 10 Hz drive cycle data, which explains some of the noise in the data. Fuel is cut off at decelerations greater than 100N at the wheel, which translates to a deceleration rate of 0.05 m/s^2. The engine is fueled again once the vehicle speed drops below roughly 9 mph.

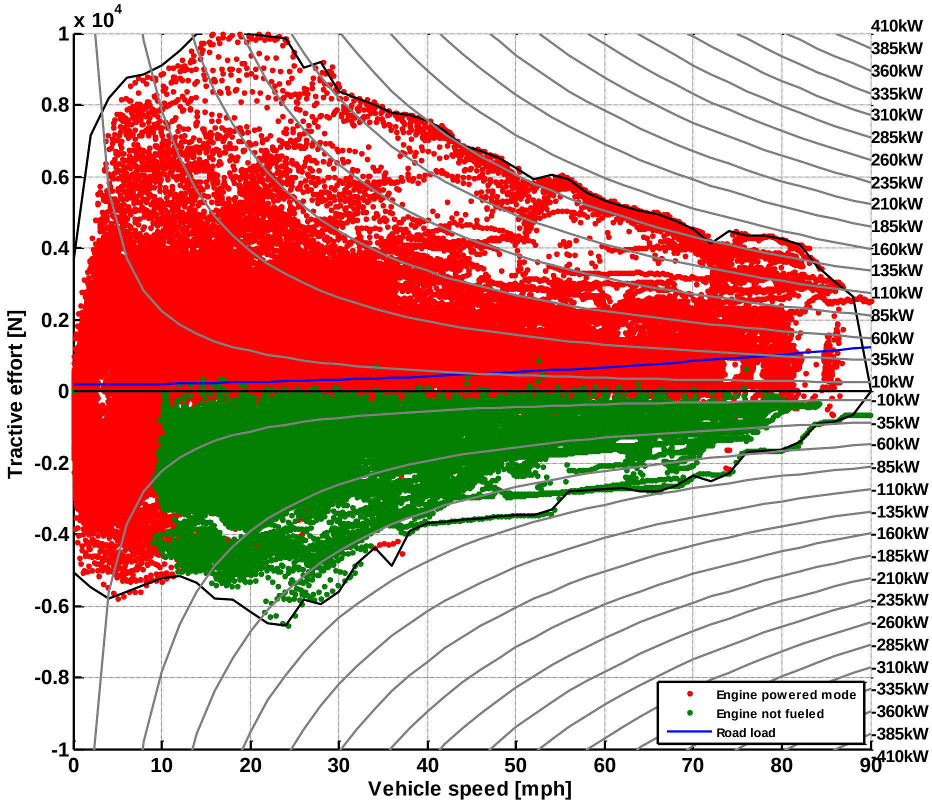

Figure 27: Deceleration fuel cut off strategy

5.4.3. Transmission operation

5.4.3.1. Shifting strategy

Since 10 Hz data from drive cycles can be a bit dynamic, a special transmission mapping test is performed to explore the shifting strategy of the 6-speed automatic transmission. The test consists of constant pedal tip-ins from zero to maximum speed for multiple pedal position between zero and 100 percent. For any pedal position which is capable of reaching 85 mph or over, the maximum speed is limited to 85 mph. The resulting upshift map from this transmission mapping test is shown in Figure 28. The map shows clear trends in the shift strategy. In the low load area represented by accelerator pedal position up to15 percent the transmission shifts as soon as possible. In the medium load area represented by accelerator pedal positions between 15 percent to 60 percent, the transmission starts to hold the gears longer to enable the engine to make enough power for the driver demand. In the high load areas represented by accelerator pedal positions above 60 percent, the transmission begins to wait until the engine has nearly reached its maximum power speed before shifting gears. However, not all gear shifts begin to occur at maximum engine power speed at the same pedal position. The 1st to 2nd gear shift is delayed to near maximum engine power speed at a pedal position of only 60 percent, the 2nd to 3rd gear shift is delayed to near maximum engine power speed at a pedal position of 70 percent, and the 3rd to 4th gear shift is delayed to near maximum engine power speed at a pedal position of 80 percent and over. The shift points for 4th to 5th and 5th to 6th gear at pedal positions above 50 percent and 35 percent, respectively, were not captured in this data due to the maximum speed set to 85mph.

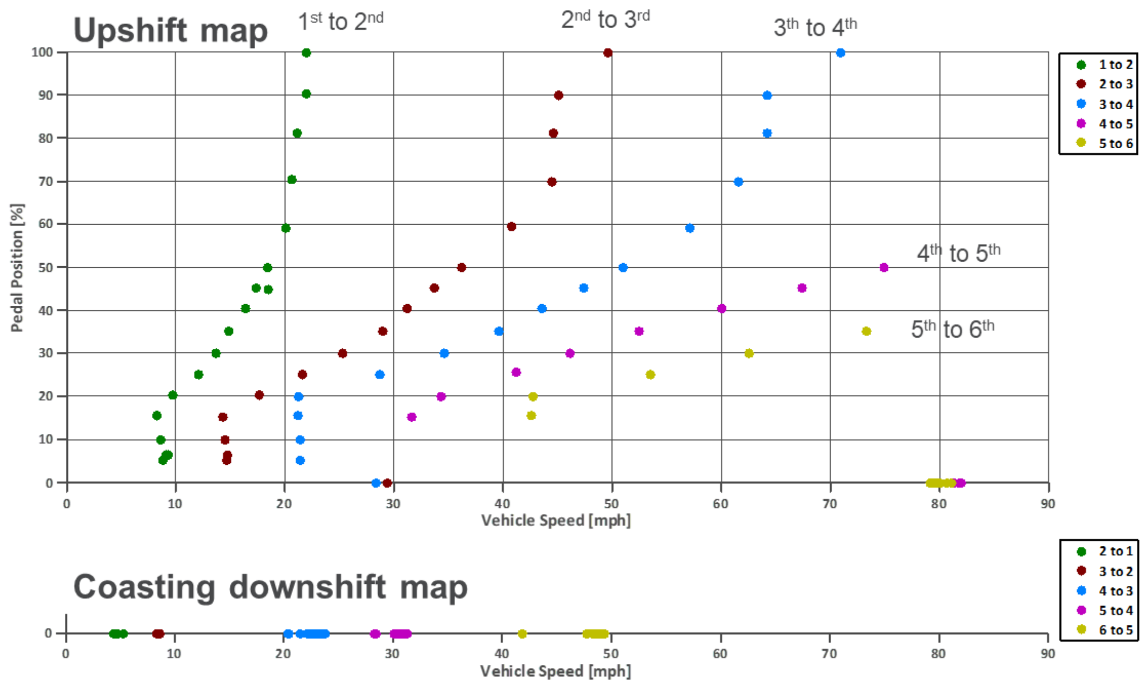

Figure 28: Shift strategy for the 6-speed automatic transmission

5.4.3.2. Torque converter locking

The torque converter clutch (TCC) of the 6-speed automatic transmission allows for a precise and smooth control of the amount of torque converter slip. Torque converter slip is defined as the difference in rotational speed between the impeller (attached to the engine crankshaft) and the turbine (attached to the transmission input shaft) of the torque converter. Three distinct operating modes for the TCC are: open, slipping, and locked. In the TCC open operation, the torque converter clutch is disengaged and allows maximum torque converter slip. In the TCC slipping operation, pressure on the TCC is controlled by the transmission controller to reduce the amount of torque converter slip. Finally, in the TCC locked operation, maximum pressure is applied to the TCC to minimize torque converter slip. For the purpose of this analysis, the TCC is defined as open when the slip speed is greater than 150 rpm, slipping when the slip speed is between 60 and 150 rpm, and locked when the slip speed is less than 60 rpm.

The TCC operation on the UDDS, Highway, and US06 drive cycles is summarized in Figure 29. The TCC is mostly open with a limited number of slipping points in 1st gear. In 2nd gear, the TCC has roughly equal open and slipping operation points, with a limited number of locked points. 3rd gear TCC operation is a majority of slipping points with a limited number of locked and open points as well. Finally, for gears 4 through 6, the TCC operation is increasingly more locked, with fewer slipping points, and almost zero open operation.

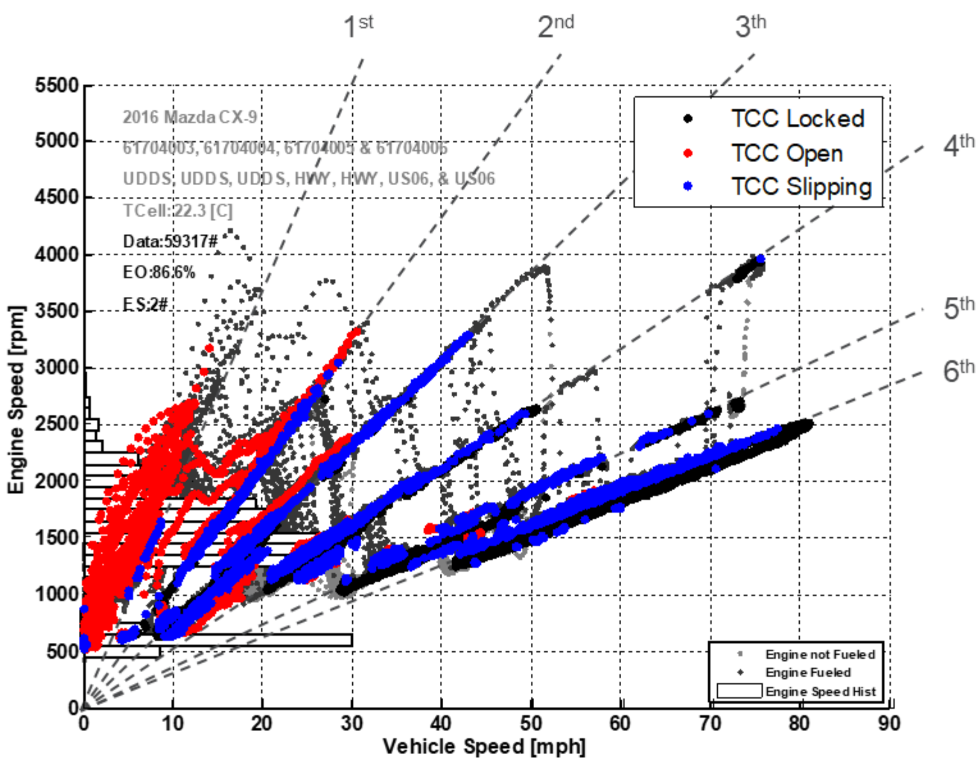

Figure 29: Torque converter operation on certification drive cycles (UDDS, Highway and US06)

The time spent in each TCC operating condition for each gear is summarized for the UDDS, Highway, and US06 cycles in Table 15, Table 16, and Table 17, respectively. The UDDS and US06 drive cycles have significant amount of TCC locked operation in first gear because the transmission is put into neutral during idle periods to allow the TCC to be locked and reduce parasitic losses due to torque converter slip, which improves idle fuel consumption. For gears 2 through 6, the ratio of TCC locked operation increases with each gear, up to nearly 100 percent for 6th gear on all drive cycles.

Table 15: Torque converter operation on UDDS (% time in mode)

Gear	TCC locked*	TCC slipping**	TCC open***
1	55.3	5.0	39.7
2	20.0	57.9	22.2
3	66.8	28.8	4.4
4	78.7	20.4	0.8
5	87.8	11.3	0.9
6	96.6	3.4	0.0
% time on cycle *TCC locked: torque converter slip < 60 rpm ** TCC slipping: torque converter slip 60-150 rpm *** TCC open: torque converter slip >150 rpm			

Table 16: Torque converter operation on Highway cycle (% time in mode)

Gear	TCC locked*	TCC slipping	TCC open
1	10.5	7.5	82.0
2	24.1	63.2	12.6
3	60.0	40.0	0.0
4	57.5	42.5	0.0
5	89.7	9.7	0.6
6	96.0	3.8	0.1
% time on cycle			

Table 17: Torque converter operation on US06 cycle (% time in mode)

Gear	TCC locked*	TCC slipping	TCC open
1	37.0	5.8	57.2
2	24.7	32.1	43.1
3	63.9	34.5	1.6
4	68.2	30.0	1.8
5	74.5	24.1	1.4
6	88.0	11.9	0.1
% time on cycle			

A map of torque converter slip vs. engine torque and engine speed is shown in Figure 30. An island of high torque converter slip occurs within 0-100 Nm of torque and 500-1,250 rpm engine speed, corresponding to launching from a stop. Aside from this island, torque converter slip is near zero for engine torque values below 100 Nm. As the engine torque increases, the amount of torque converter slip increases across the entire rpm range as well.

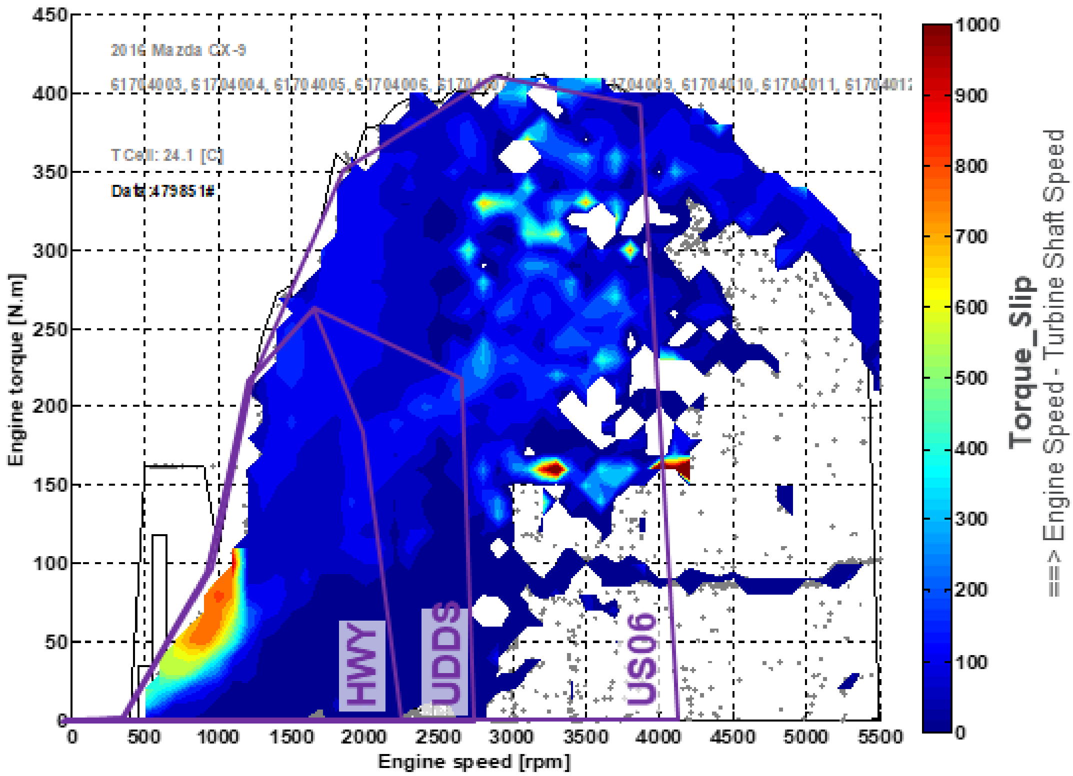

Figure 30: Map of torque converter slip vs. engine torque and engine speed

This testing did not include torque and speed measurements at the input or output of the transmission in order to determine the torque converter and gearbox efficiency. In general the torque converter efficiency is at its highest when locked and at its lowest when open. Lower gears are typically transient gears in which the vehicle accelerates and therefore the torque converter tends to be open. When the vehicle is cruising at higher speeds, it is typically cruising at relatively steady speeds which allows the powertrain to lock the torque converter to maximize the powertrain efficiency.

5.5. “5-Cycle” thermal test conditions

The UDDS cycles, the Highway cycles and the US06 cycles were also tested at 20° F and at 95° F with 850 W/m^2 of solar load, which are the two extreme temperature conditions for the EPA 5-cycle fuel economy label. Figure 31 provides the test results for all of those conditions and drive cycles.

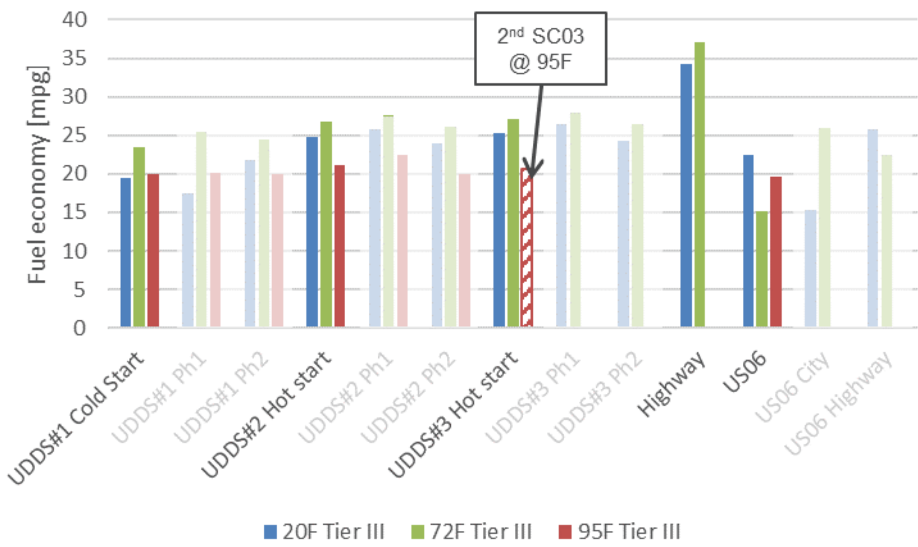

Figure 31: Raw fuel economy results for certification cycles across different temperature conditions

The fuel economy for the cold start UDDS at 20° F is decreased by 17 percent compared to the same test at 72° F, yet the fuel economy for the second urban cycle at 20° F is only 8 percent lower compared to the same test at 72° F. The powertrain has to overcome significantly increased friction losses throughout the drive train on the cold start at 20° F, but once the powertrain reaches a steady operating temperature those friction losses become less significant. The fuel economy penalty at 20° F compared to 72° F become smaller as the powertrain temperature increases.

The fuel economy at the 95° F test condition is also reduced compared to the 72° F test condition. At 95° F the fuel economy decreases by 15 percent and 21 percent for the cold start UDDS and the hot start UDDS respectively compared to the 72° F test condition. The fuel economy reduction is driven by the additional power required to operate the air conditioning system to cool down the cabin. Contrary to the cold temperature testing, this compressor load is a permanent energy penalty needed to maintain the comfort of the occupants in the vehicle. Note that for the 95° F testing, the third UDDS was replaced by a pair of SCO3 drive cycles which is the fuel economy reported in Figure 31 instead of the third UDDS cycle.

Table 18 provides the calculated vehicle efficiencies for the different ambient test conditions. The impact of the cold powertrain temperatures is apparent in the 20° F cold start efficiency. As the powertrain temperatures rise throughout the tests in the test sequence, the vehicle efficiencies at 20° F start to approach the vehicle efficiencies at 72° F ambient temperature. The impact of the auxiliary load from the air conditioning compressor at 95° F is also apparent in this table. It is noteworthy that the efficiency impact of the air conditioning compressor is lower on the high power US06 drive cycle as the ratio between the air conditioning power to the average wheel power is lower compared to the same ratio for lower power UDDS cycle.

Table 18: Powertrain efficiencies across different ambient test conditions

	20° F	72° F	95° F
UDDS #1 Cold Start	15.4%	19.3%	15.8%
UDDS#2 Hot Start	19.6%	21.1%	16.7%
UDDS#3	19.9%	21.3%	17.7%
Highway	27.3%	29.0%	
US06	27.8%	27.9%	25.0%

Figure 32 shows the engine operating areas for the cold start and hot start UDDS at each of the three ambient temperature conditions. The 72° F plot in the middle serves as the reference. At 20° F the idle fuel flow island is higher due to the larger powertrain friction at cold temperatures. It also appears that the transmission held gears slightly longer, therefore increasing the average engine speed at 20° F. At 95° F the engine idle island is also significantly increased and at slightly higher engine speed This is explained by the power needed by the belted air conditioning compressor. The overall absolute engine load envelop is increased, which is also due to the additional power required for the air conditioning compressor.

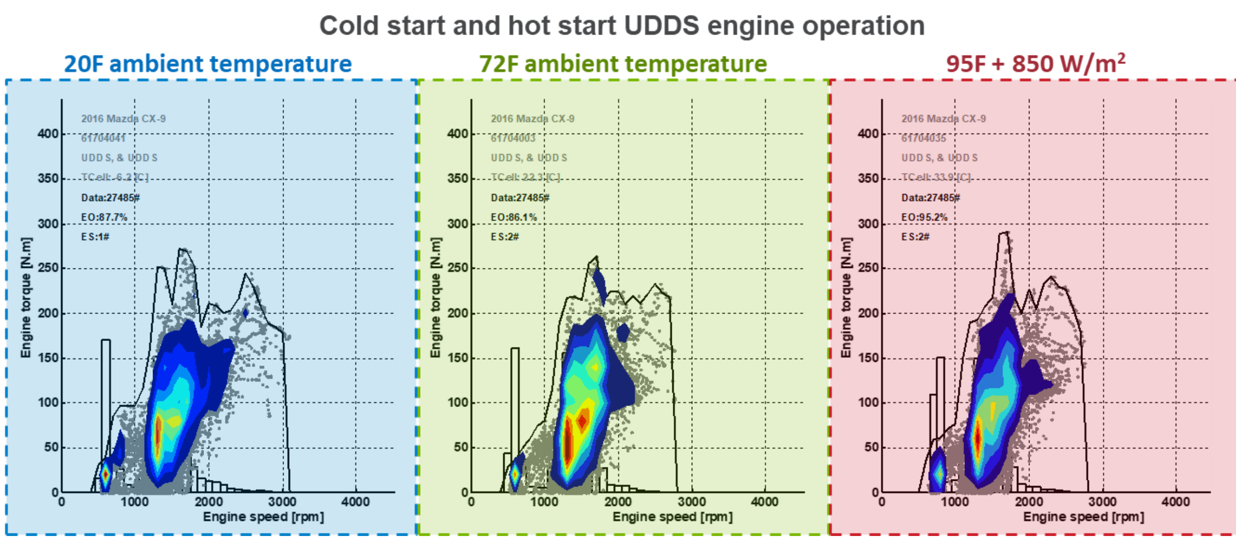

Figure 32: Engine operation on the UDDS across different temperatures

Figure 33 shows some relevant powertrain and ambient temperature profiles over the completion of the test sequence. These graphs also show the targeted 72° F cabin temperature that the climate control system tries to achieve in the 20° F and 95° F test condition.

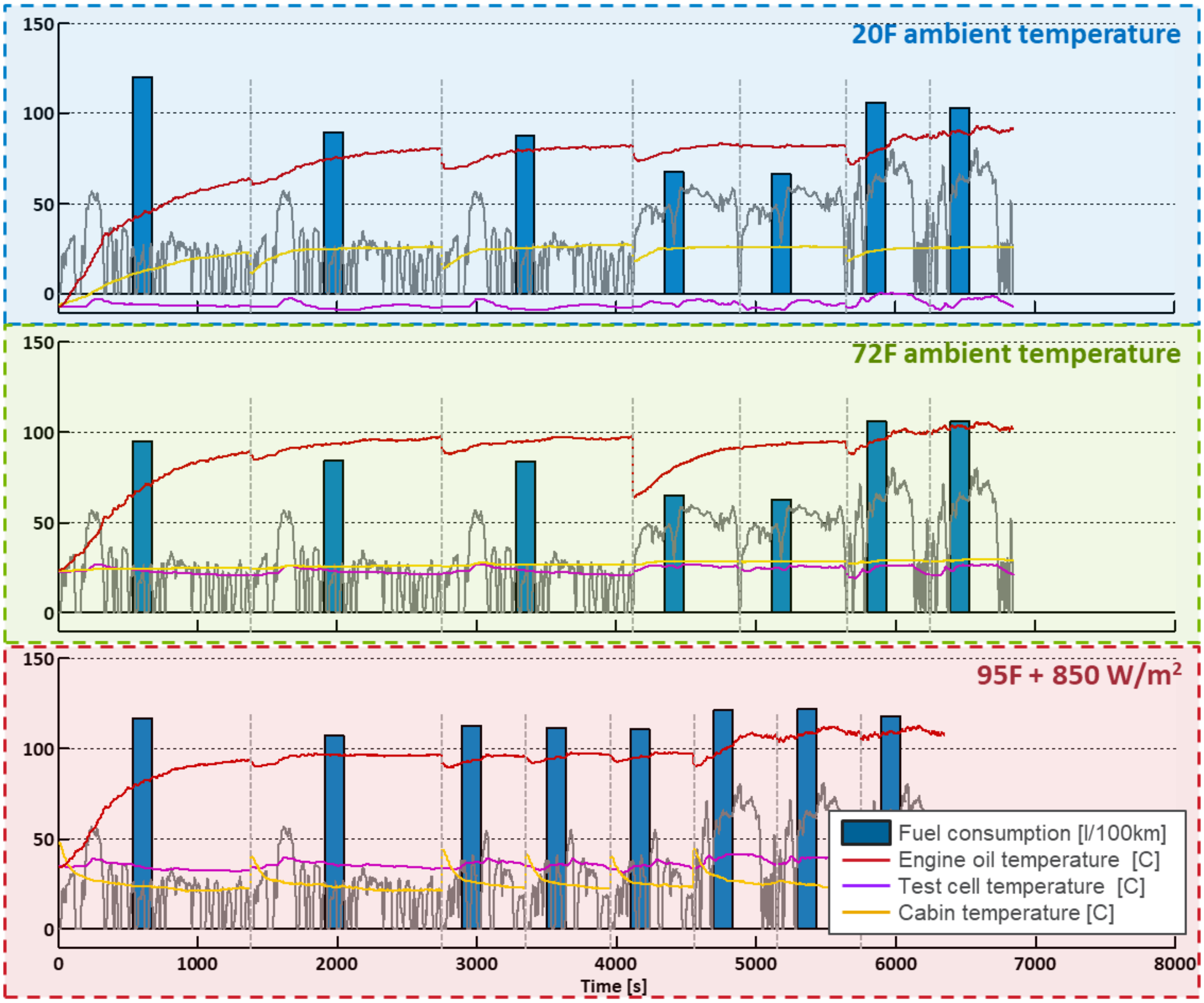

Figure 33: Powertrain and cabin temperature profits across different temperature

The engine oil temperature is representative of the powertrain temperature. For all three ambient temperature conditions the final engine oil temperature for the US06 is around 90°C to 110°C. The average powertrain temperature in the 20° F testing never rise to the average powertrain temperatures at 72° F.

5.6. 93 (Tier 2) to 88 (Tier 3) AKI octane fuel comparison

The owner's manual of the Mazda CX-9 recommends the usage of premium fuel but does not require it. Argonne tested the vehicle on Tier 2 and Tier 3 certification fuel to investigate the impact of octane rating on fuel economy and performance. The Tier 2 certification fuel has an octane rating of 93 AKI and the Tier 3 certification fuel has an octane rating of 88 AKI. The Tier 2 fuel represents the premium fuel and the Tier 3 fuel represents the regular fuel in this investigation.

Argonne drained the Tier 2 certification fuel used for the vehicle technology work presented thus far in the report and replaced it with Tier 3 certification fuel. The vehicle was then driven on mild and aggressive drive cycles to enable the engine controller to adjust ignition calibration and fuel trims to the new fuel.

After the adjustment, the test sequence of three UDDS cycles, a pair of Highway cycles and a pair of US06 cycles was repeated three times. The average drive cycle fuel economies based on the three repeats are presented and Table 19 and Figure 34. As pointed out in section 3.10, the Tier 2 fuel has a 3.1 percent lower energy content by mass compared to the Tier 3 fuel, which does impact the volumetric fuel economy comparison. The fuel economy results here are presented in terms of volumetric fuel economy based on each individual fuel. Considering that only three repeats were completed, the fuel economy results for the UDDS drive cycles, the Highway drive cycles and the US06 drive cycles between the different fuels are within test-to-test variabilities.

Table 19: Average fuel economy results for the Tier 2 and Tier 3 fuels

Avg [mpg]	Tier 2 93 AKI	Tier 3 88 AKI
UDDS #1 Cold Start	23.5	24.3
UDDS#2 Hot Start	25.4	26.3
UDDS#3	27.6	27.0
Highway	37.1	37.1
US06	22.4	22.2

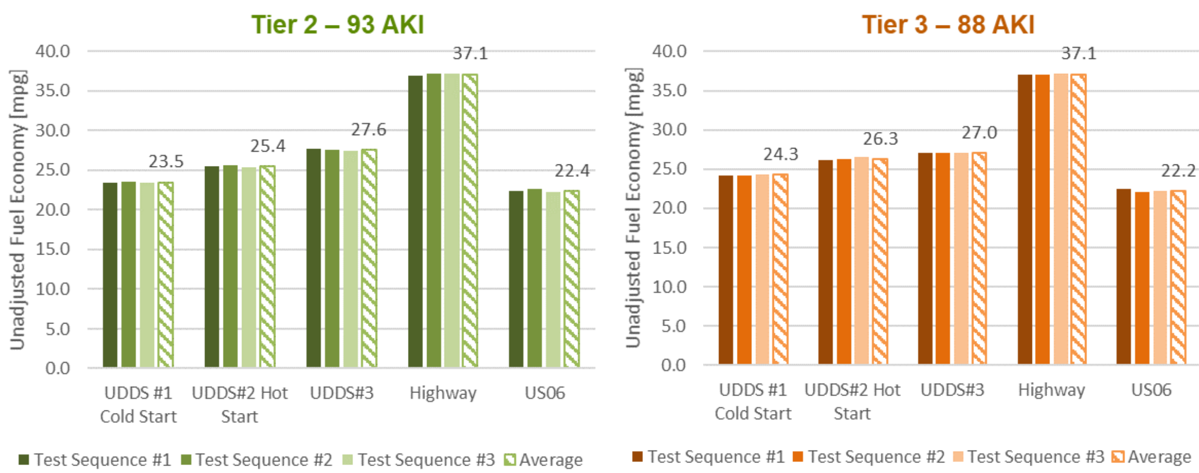

Figure 34: Drive cycle fuel economy results for the Tier 2 and Tier 3 fuels

The vehicle efficiencies calculations are based on the actual energy content of the fuels as provided in Table 2 and Table 3. The vehicle efficiencies were calculated for each drive cycle and averaged together based on the three repeats of the test sequence. They are shown for each drive cycle and test fuel in Figure 35. Again the average vehicle efficiencies for the UDDS cycle and the Highway cycle are very similar. The vehicle efficiency for the US06 has decreased by 1 percent when switching from the 93 AKI fuel to the 88 AKI fuel.

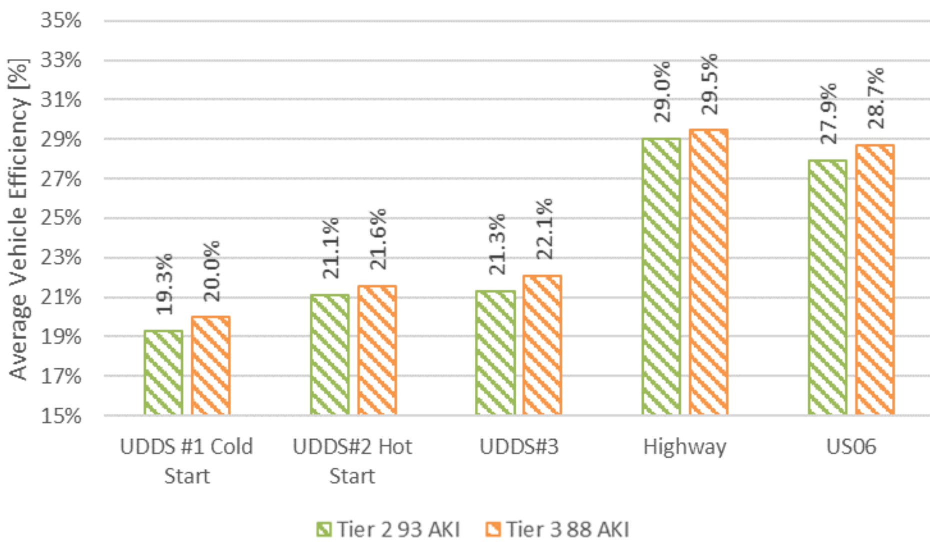

Figure 35: Average powertrain efficiencies for Tier 2 and Tier 3 fuels

Table 20 and Table 21 summarize the results from the performance testing with the different fuels. There is little difference between the two fuels on performance.

Table 20: Maximum acceleration performance results for Tier 2 and Tier 3 fuels

WOT [s]	Tier 2 93 AKI	Tier 3 88 AKI
0-60	8	7.7
0-80	13.9	14

Table 21: Passing maneuvers results for Tier 2 and Tier 3 fuels

Passing [s]	Tier 2 93 AKI	Tier 3 88 AKI
35-55	4.6	4
55-65	2.2	2.9
35-70	6.9	5.1
55-80	6.6	6.8

Figure 36 shows the ignition timing for both fuels for the UDDS, the Highway and the US06 cycles. At higher torque levels, the spark timing for the 93 AKI fuel is more advanced enabling the engine to operate closer to the maximum brake torque combustion conditions. The overall maximum torque available from the engine is almost identical between the two fuels.

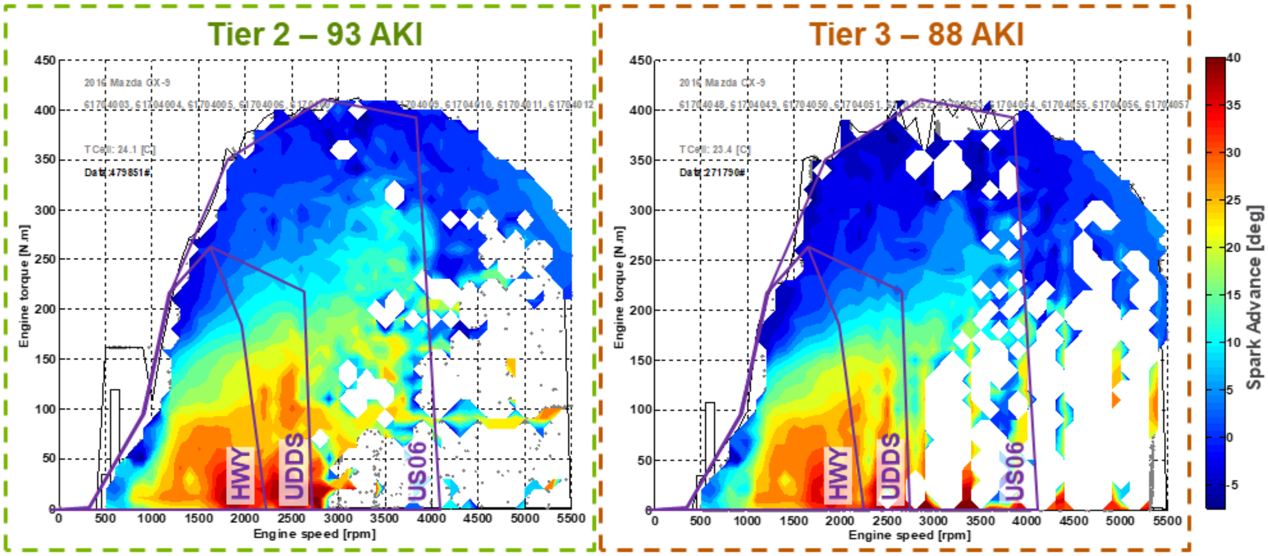

Figure 36: Spark advance comparison between Tier 2 and Tier 3 fuels

A larger impact on fuel economy and performance is expected based on the different octane ratings of the test fuels. Perhaps the adjustment for the new lower grade Tier 3 fuel was not performed effectively.

Figure 37 shows the steady state fuel economy results for the Tier 3 – 88 AKI fuel along with some powertrain characterizations. Figure 19 shows the same results for the Tier 2 – 92 AKI fuel. The fuel economy and powertrain efficiency are slightly higher for the high octane and higher energy content fuel.

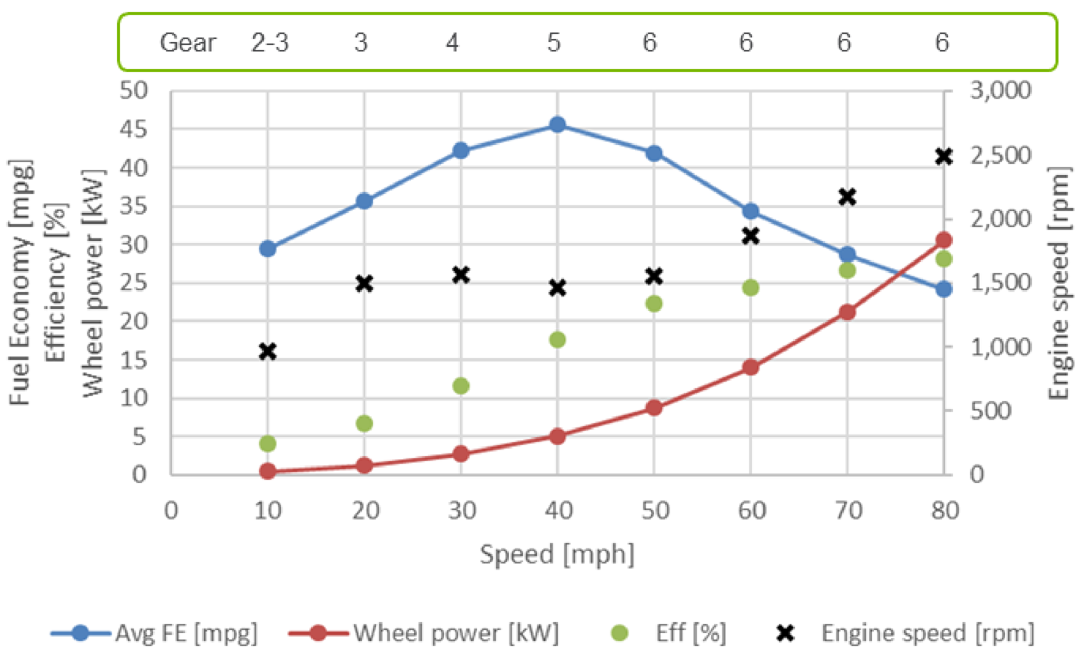

Figure 37: Steady state speed fuel economy with other powertrain measurements on Tier 3 – 88 AKI

5.7. Vehicle specific testing

5.7.1. Active Grille Shutter Operation

The 2016 Mazda CX-9 is equipped with an active grill shutter system which consists of a single array of shutters, covering a portion of the radiator and condenser behind the main grille inlet. The goal of the system is to provide improved vehicle aerodynamics while also providing adequate cooling airflow when needed.

The system operates a single array of shutters, which isolates only a section of the radiator and condenser, as seen in Figure 38. The vehicle intercooler, the lower and upper sections of the radiator and condenser are not fully affected the shutter array

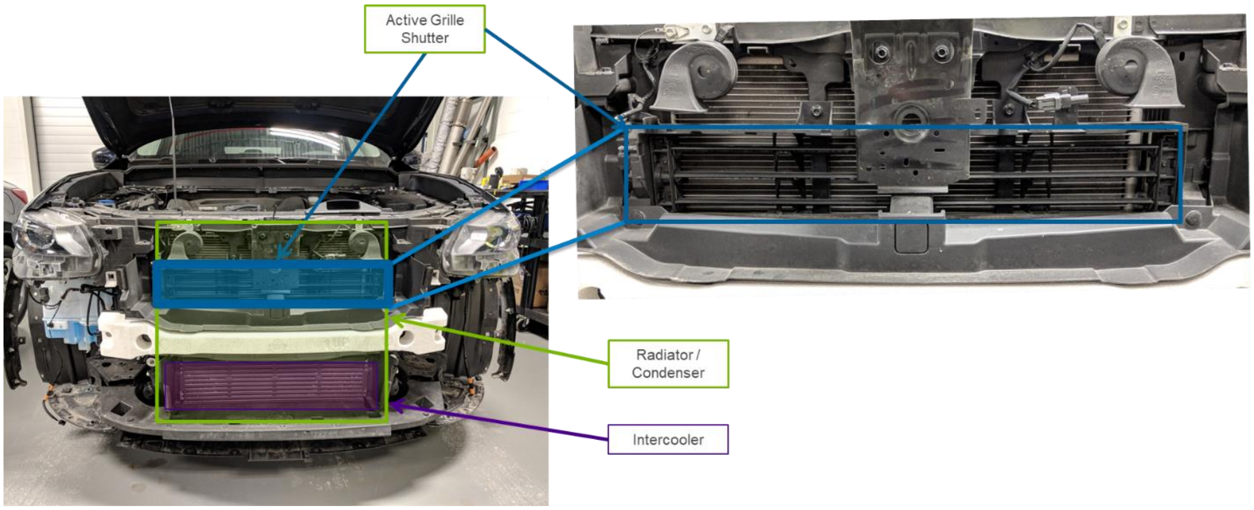

Figure 38: 2016 Mazda CX-9 active grille shutter component overview

The system has two main control states, a basic operation mode with the default set to a closed state, and a protection mode where the shutter is open to 78° angular degrees when coolant, estimated oil, or transmission fluid temperature is above a set limit. When the system is in basic operating mode, a self-test is conducted following each ignition on event to verify that the system is operating properly by cycling the shutters from a closed state of 0° angular degrees to a fully open state of 90° angular degrees. Following this self-test, the manufacturer service documentation lists the shutter operation to cycle between basic (0°) and protection mode (78°) due to vehicle speed (less than 140 kph), engine coolant temperature (less than 100° C), or air conditioning system load (A/C refrigerant pressure greater than 1.7 MPa).

To verify the system operation, diagnostic messages related to the active grille shutter system are decoded and logged during vehicle test. These messages consist of the reported actual position of the grille shutter array. With this scaling 0 percent represents a fully closed position, 86 percent represents the protection state of 78°, and 100 percent represents the fully open state of 90°.

Of interest during testing is the operation of the grille shutter system on U.S. drive cycles. Figure 39 displays shutter operation during the vehicle coast downs performed on the chassis dynamometer for the vehicle loss determination. A set of three Highway cycles are completed before the coast down section in order to bring the vehicle to thermal stability. During the Highway and coast down cycles, the grille shutter array remained closed for the duration of the test. It should be noted that the grille shutter remained closed for the duration of the Highway cycles with coastdowns, and the pair of Highway certification cycles at 72° F.

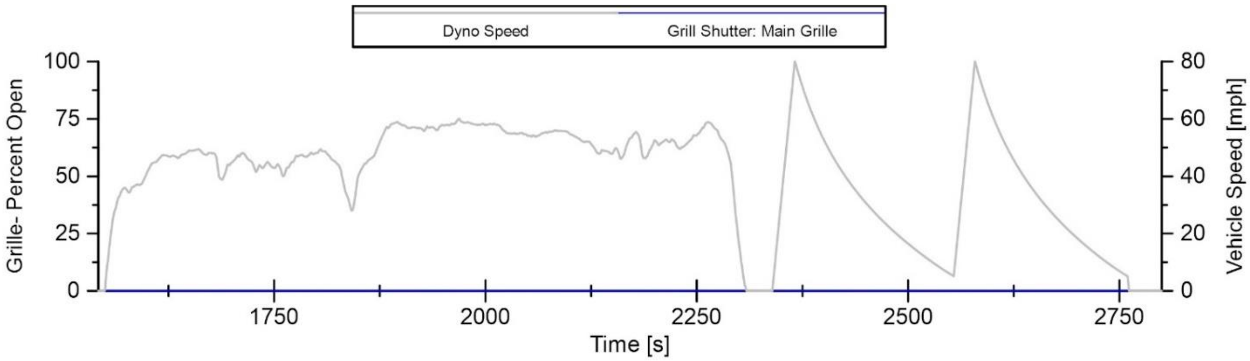

Figure 39: Grille Shutter operation on the dynamometer the third Highway coast downs cycles

An overview of the system operation on the UDDS and hot start cycle at 72° F is shown in the Figure 40. Following every key-on event, the vehicle performs a test of operation of both active grille shutters by cycling the shutters from completely close to completely open. Following that self-test, the shutter array remained closed for the duration of the first cycle. The system then can be seen to cycle during the self-check following the key on event after the 10minute soak.

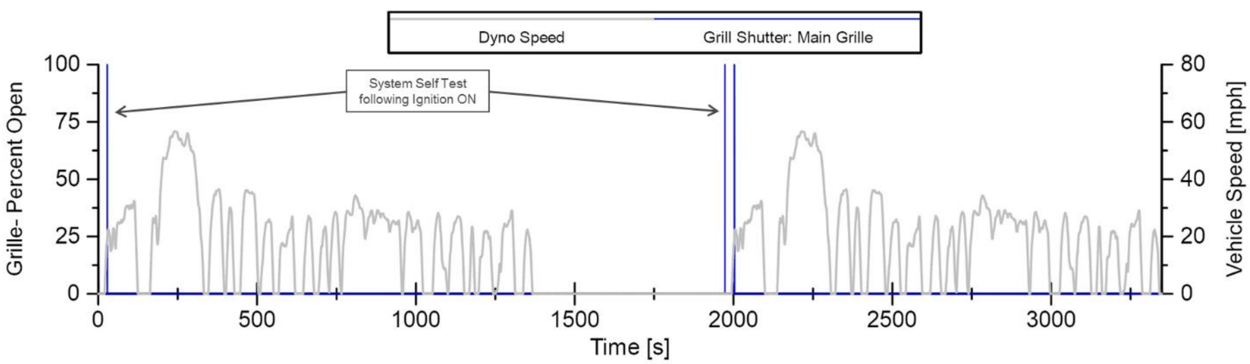

Figure 40: UDDS Cold start Grille Shutter commanded operation

On the US06 cycle at the test temperature of 72° F, the shutter system enters protection mode twice due to engine coolant temperature exceeding the 100° C setpoint. This event occurs on both the US06 prep cycle, as well the certification cycle following. In the protection state, the grille shutter opened to 86 percent, representing 78°. The engine coolant temperature and grille shutter operation can be seen in Figure 40.

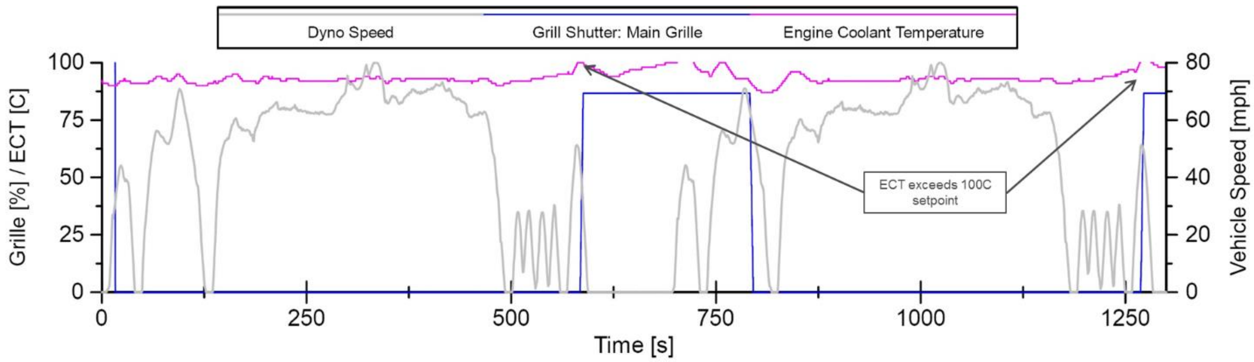

Figure 41: UDDS Hot start Grille Shutter commanded operation

The active grille shutter operation on the SC03 cycle at 95° F can be seen in in Figure 42. On this cycle the transmission fluid, estimated engine oil, and coolant temperatures do not exceed 100° C. HVAC system operation results in the A/C system pressure increasing past the 1.7 Mpa set point, at which time the active grille shutter cycled from the 86 percent to fully closed over the duration of the cycle.

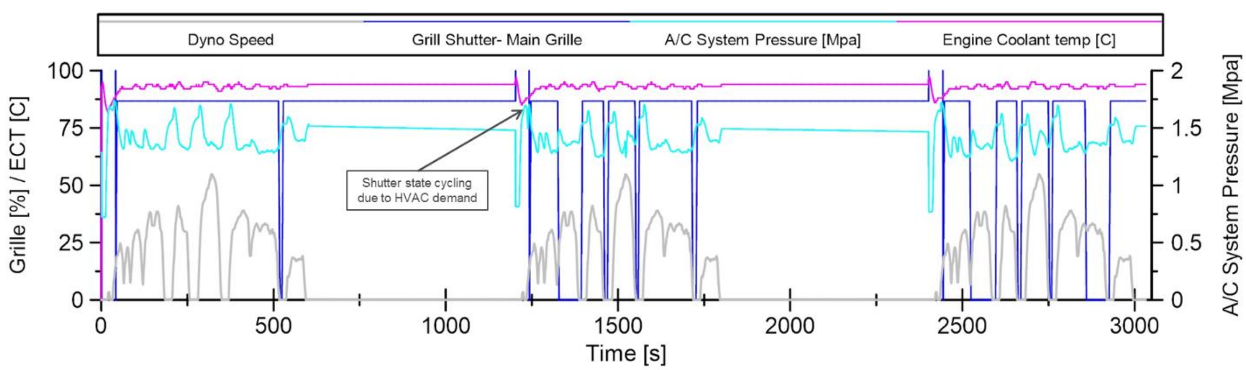

Figure 42: Active Grille Shutter commanded operation SC03 at 95F with 850W/m² solar loading

Operation on the cold start UDDS cycle at 20° F can be seen in Figure 43 below. The system remained closed over the duration of the cycle following the self test completed at each ignition on event.

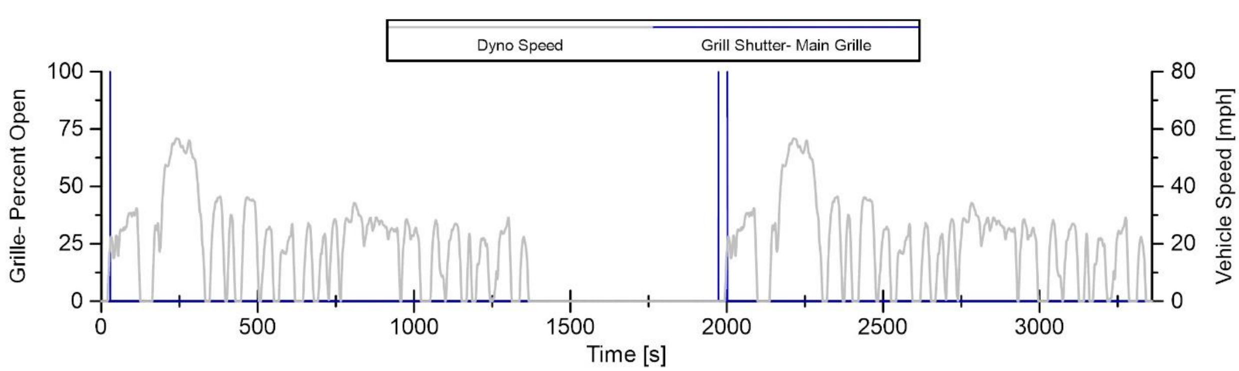

Figure 43: Active Grille Shutter Commanded Operation 20F UDDS cycle

6. Public access to the data

The 10Hz data files used for the analysis in this report are available at www.anl.gov/d3.

If the data is not available at that location please e-mail d3@anl.gov to notify Argonne.

7. Conclusion

NHTSA funded Argonne's APRF to perform a benchmark of a 2016 Mazda CX-9 SUV and to provide data to *Autonomie* and assess the fuel saving technologies of that powertrain.

The vehicle benchmarked in this report is a 2016 Mazda CX-9 with a 2.5L I4 SkyActiv engine and a 6-speed automatic transmission. This particular powertrain configuration provides favorable fuel economy results while providing significant vehicle performance. The focus of the benchmark is to understand the usage of the critical powertrain components and their impact on the vehicle efficiency. The vehicle is instrumented to provide data to support the model development and validation in conjunction to providing the data for the analysis in the report. The vehicle is tested on a chassis dynamometer in the controlled laboratory environment across a range of certification tests. Further tests are performed to map the different powertrain components.

The analysis in this report started by providing the fuel economy and efficiency results on the certification drive cycles along with of component operation on those tests. The maximum performance envelops of the powertrain were presented. A section was devoted to specific powertrain characterization. Some off-cycle testing, such as the thermal testing of 5-cycle label fuel economy and octane fuel testing, was explored. Finally, some vehicle specific test, such as the impact of active grill shutters, close out the analysis.

8. Acknowledgements:

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Finally, the authors want to acknowledge that this work would not have been possible without the entire team at the Advanced Powertrain Research Facility. Special thanks go to Mike Kern, Geoffrey Amann, and George Tsigolis.

Appendix A: Certification fuel specifications

haltermannsolutions

Product Information

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PRODUCT:	EPA TIER II EEE FEDERAL REGISTER	Batch No.:	EK2821GP10
PRODUCT CODE:	HF0437	Tank No.:	Drums
		Date:	11/29/2016

TEST	METHOD	UNITS	HALTERMANN Specs MIN	TARGET	MAX	RESULTS
Distillation - IBP	ASTM D86[2]	°F	75		95	89
5%		°F				110
10%		°F	120		135	124
20%		°F				142
30%		°F				163
40%		°F				191
50%		°F	200		230	217
60%		°F				231
70%		°F				242
80%		°F				260
90%		°F	305		325	317
95%		°F				339
Distillation - EP		°F			415	395
Recovery		vol %		Report		97.2
Residue		vol %		Report		1.1
Loss		vol %		Report		1.7
Gravity	ASTM D4052[1]	°API	58.7		61.2	59.4
Density	ASTM D4052[1]	kg/l	0.734		0.744	0.741
Reid Vapor Pressure	ASTM D5191[1]	psi	8.7		9.2	9.1
Carbon	ASTM D3343[2]	wt fraction		Report		0.8648
Carbon	ASTM D5291[2]	wt fraction		Report		0.8678
Hydrogen	ASTM D5291[2]	wt fraction		Report		0.1322
Hydrogen/Carbon ratio	ASTM D5291[2]	mole/mole		Report		1.815
Stoichiometric Air/Fuel Ratio				Report		14.533
Oxygen	ASTM D4815[2]	wt %			0.05	None Detected
Sulfur	ASTM D5453[2]	wt %	0.0025		0.0035	0.0034
Lead	ASTM D3237[2]	g/gal			0.01	None Detected
Phosphorous	ASTM D3231[2]	g/gal			0.005	None Detected
Silicon	ASTM 5184	mg/kg			4	None Detected
Composition, aromatics	ASTM D1319[2]	vol %			35	28
Composition, olefins	ASTM D1319[2]	vol %			10	1
Composition, saturates	ASTM D1319[2]	vol %		Report		72
Particulate matter	ASTM D5452[2]	mg/l			1	0
Oxidation Stability	ASTM D525[2]	minutes	240			1000+
Copper Corrosion	ASTM D130[2]				1	1a
Gum content, washed	ASTM D381[2]	mg/100mls			5	0.5
Fuel Economy Numerator/C Density	ASTM D5291[2]		2401		2441	2429
C Factor	ASTM D5291[2]			Report		0.9982
Research Octane Number	ASTM D2699[2]		96.0			96.5
Motor Octane Number	ASTM D2700[2]			Report		88.4
Sensitivity	D2699/2700[2]		7.5			8.1
Net Heating Value, btu/lb	ASTM D3338[1]	btu/lb		Report		18485
Net Heating Value, btu/lb	ASTM D240[2]	btu/lb		Report		18659
Color	VISUAL			Report		Undyed

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[2] Tested by ISO/IEC 17025 accredited subcontractor.

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Main Lab, 15600 West Hardy,Houston TX 77060

haltermannsolutions

Telephone: (800) 969-2542

Certificate of Analysis

FAX: (281) 457-1469

PRODUCT:	EPA TIER II EEE FEDERAL REGISTER	Batch No.:	FD2421GP10
PRODUCT CODE:	HF0437	Tank No.:	Drums
		Date:	4/26/2017

TEST	METHOD	UNITS	HALTERMANN Specs MIN	TARGET	MAX	RESULTS
Distillation - IBP	ASTM D86[2]	°F	75		95	88
5%		°F				110
10%		°F	120		135	123
20%		°F				141
30%		°F				161
40%		°F				188
50%		°F	200		230	216
60%		°F				230
70%		°F				241
80%		°F				258
90%		°F	305		325	316
95%		°F				340
Distillation - EP		°F			415	402
Recovery		vol %		Report		97.4
Residue		vol %		Report		1.0
Loss		vol %		Report		1.6
Gravity	ASTM D4052[1]	°API	58.7		61.2	59.0
Density	ASTM D4052[1]	kg/l	0.734		0.744	0.743
Reid Vapor Pressure	ASTM D5191[1]	psi	8.7		9.2	9.1
Carbon	ASTM D3343[2]	wt fraction		Report		0.8656
Carbon	ASTM D5291[2]	wt fraction		Report		0.8616
Hydrogen	ASTM D5291[2]	wt fraction		Report		0.1384
Hydrogen/Carbon ratio	ASTM D5291[2]	mole/mole		Report		1.914
Stoichiometric Air/Fuel Ratio				Report		14.674
Oxygen	ASTM D4815[2]	wt %			0.05	None Detected
Sulfur	ASTM D5453[2]	wt %	0.0025		0.0035	0.0029
Lead	ASTM D3237[2]	g/gal			0.01	None Detected
Phosphorous	ASTM D3231[2]	g/gal			0.005	None Detected
Silicon	ASTM 5184	mg/kg			4	None Detected
Composition, aromatics	ASTM D1319[2]	vol %			35	29
Composition, olefins	ASTM D1319[2]	vol %			10	0
Composition, saturates	ASTM D1319[2]	vol %		Report		71
Particulate matter	ASTM D5452[2]	mg/l			1	0
Oxidation Stability	ASTM D525[2]	minutes	240			1000+
Copper Corrosion	ASTM D130[2]				1	1a
Gum content, washed	ASTM D381[2]	mg/100mls			5	<0.5
Fuel Economy Numerator/C Density	ASTM D5291[2]		2401		2441	2418
C Factor	ASTM D5291[2]			Report		0.9959
Research Octane Number	ASTM D2699[2]		96.0			97.8
Motor Octane Number	ASTM D2700[2]			Report		88.7
Sensitivity	D2699/2700[2]		7.5			9.1
Net Heating Value, btu/lb	ASTM D3338[1]	btu/lb		Report		18466
Net Heating Value, btu/lb	ASTM D240[2]	btu/lb		Report		18539
Color	VISUAL			Report		Undyed

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haltermannsolutions

Telephone: (800) 969-2542 FAX: (281) 457-1469

Product Information

PRODUCT: EPA Tier 3 EEE Emission Certification Fuel, General Testing - Regular

Specification No.: HF2021

Batch No.: EH1021LT10-HW

Tank No.: Drums

Date: 9/26/2016

TEST	METHOD	UNITS	SPECIFICATIONS MIN	SPECIFICATIONS TARGET	SPECIFICATIONS MAX	RESULTS
Distillation - IBP	ASTM D86[2]	°F				94.8
5%		°F				123.0
10%		°F	120		140	130.6
20%		°F				140.0
30%		°F				147.5
40%		°F				154.1
50%		°F	190		210	200.2
60%		°F				229.3
70%		°F				253.1
80%		°F				278.4
90%		°F	315		335	318.0
95%		°F				339.4
Distillation - EP		°F	380		420	381.1
Recovery		ml		Report		98.1
Residue		ml			2.0	0.8
Loss		ml		Report		1.2
Gravity @ 60° F	ASTM D4052[1]	°API		Report		58.30
Density @ 15.56° C	ASTM D4052[1]	-		Report		0.7447
Reid Vapor Pressure EPA Equation	ASTM D5191[1]	psi	8.7		9.2	9.2
Carbon	ASTM D5291[2]	wt fraction		Report		0.8263
Hydrogen	ASTM D5291[2]	wt fraction		Report		0.1366
Hydrogen/Carbon ratio	ASTM D5291[2]	mole/mole		Report		1.970
Oxygen	ASTM D4815[2]	wt %		Report		3.71
Ethanol content	ASTM D5599-00	vol %	9.6		10.0	9.8
Total oxygentates other than ethanol	ASTM D4815[2]	vol %			0.1	None Detected
Sulfur	ASTM D5453[2]	mg/kg	8.0		11.0	10.2
Phosphorus	ASTM D3231[2]	g/l			0.0013	None Detected
Lead	ASTM D3237[2]	g/l			0.0026	None Detected
Composition, aromatics	ASTM D5769[2]	vol %	21.0		25.0	22.6
C6 aromatics (benzene)	ASTM D5769[2]	vol %	0.5		0.7	0.5
C7 aromatics (toluene)	ASTM D5769[2]	vol %	5.2		6.4	5.9
C8 aromatics	ASTM D5769[2]	vol %	5.2		6.4	5.9
C9 aromatics	ASTM D5769[2]	vol %	5.2		6.4	5.7
C10+ aromatics	ASTM D5769[2]	vol %	4.4		5.6	4.7
Composition, olefins	ASTM D6550	wt %	4.0		10.0	5.2
Oxidation Stability	ASTM D525[2]	minutes	1000			1000+
Copper Corrosion	ASTM D130[2]				1	1a
Existent gum, washed	ASTM D381[2]	mg/100mls			3.0	1.0
Existent gum, unwashed	ASTM D381[2]	mg/100mls		Report		1.0
Research Octane Number	ASTM D2699[2]			Report		91.8
Motor Octane Number	ASTM D2700[2]			Report		84.2
R+M/2	D2699/2700[2]		87.0		88.4	88.0
Sensitivity	D2699/2700[2]		7.5			7.6
Net Heat of Combustion	ASTM D240[2]	BTU/lb		Report		17972

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Appendix B: 2016 Mazda CX-90 Test Signals

The following signals were collected at 10Hz for each test.

Facility and Vehicle Signal list

Facility, dyno and cell data	Analog data from vehicle	Modal tailpipe emissions
DAQ_Time[s]	DAQ_Time[s]	AMA_Dilute_THC[mg/s]
Time[s]	Time[s]	AMA_Dilute_CH4[mg/s]
Dyno_Spd[mph]	Engine_Oil_Dipstick_Temp[C]	AMA_Dilute_NOx[mg/s]
Dyno_TractiveForce[N]	Radiator_Air_Outlet_Temp[C]	AMA_Dilute_COlow[mg/s]
Dyno_LoadCell[N]	Engine_Bay_Temp[C]	AMA_Dilute_COmid[mg/s]
Distance[mi]	Cabin_Temp[C]	AMA_Dilute_CO2[mg/s]
Dyno_Spd_Front[mph]	Cabin_Upper_Vent_Temp[C]	AMA_Dilute_HFID[mg/s]
Dyno_TractiveForce_Front[N]	Cabin_Lower_Vent_Temp[C]	AMA_Dilute_NMHC[mg/s]
Dyno_LoadCell_Front[N]	Solar_Array_Ind_Temp[C]	AMA_Dilute_Fuel[g/s]
Dyno_Spd_Rear[mph]	Eng_FuelFlow_Direct2[gps]	CVS_Volume_Flow[Nm^3/min]
Dyno_LoadCell_Rear[N]	12VBatt_Volt_Hioki_U1[V]	CVS_Pressure[hPa]
Dyno_TractiveForce_Rear[N]	12VBatt_Curr_Hioki_I1[A]	CVS_Temperature[K]
DilAir_RH[%]	12VBatt_Power_Hioki_P1[W]	CVS_Corrected_Volume_Flow[Nm^3/min]
Tailpipe_Press[inH2O]	Alternator_Curr_Hioki_I2[A]	
Cell_Temp[C]	Alternator_Power_Hioki_P2[W]	
Cell_RH[%]	Eng_FuelFlow_Direct[ccps]	
Cell_Press[inHg]	Eng_Fuel_Temp_Direct[C]	
Front_Tire_Temp[C]		
Drive_Schedule_Time[s]		
Drive_Trace_Schedule[mph]		
Exhaust_Bag		

Can Signal list

Broadcast CAN	Scantool PCM, TCM, and ABS Modules	Scantool HVAC, IC, FBCM, and EPSM Modules
Eng_coolant_temp_CAN[C]	Eng_EGR_position_desired_PCM[per]	HVAC_inside_car_temp_HVAC[C]
Eng_fuel_flow_integrated_CAN	Eng_ManifoldAir_pressure_sensor_PCM[kPa]	HVAC_outside_car_temp_sensor_HVAC[C]
Eng_speed_CAN[rpm]	Eng_fuel_trim_short_bank_1_PCM[per]	HVAC_heater_core_temp_HVAC[C]
Eng_torque_actual_CAN[Nm]	Eng_mass_air_flow_PCM[gps]	HVAC_evap_temp_sensor_HVAC[C]
Pedal_accel_pos_CAN[per]	Eng_spark_advance_PCM[deg]	HVAC_front_window_temp_HVAC[C]
Pedal_brake_switch_CAN	Eng_spd_desired_PCM[rpm]	HVAC_humidity_sensor_HVAC[per]
Pedal_kickdown_switch_CAN	Eng_throttle_relative_pos_PCM[per]	HVAC_RLS_surround_temp_HVAC[C]

Broadcast CAN	Scantool PCM, TCM, and ABS Modules	Scantool HVAC, IC, FBCM, and EPSM Modules
Trans_downshift_manual_command_CAN	Veh_barometric_pressure_PCM[kpa]	HVAC_solar_rad_sensor_left_HVAC[wpm2]
Trans_drive_ratio_CAN	Eng_equiv_ratio_b1_s1_PCM	HVAC_solar_rad_sensor_right_HVAC[wpm2]
Trans_gear_actual_CAN	Eng_fuel_trim_long_bank_1_PCM[per]	HVAC_AC_switch_HVAC
Trans_in_manual_mode_CAN	Eng_fuel_trim_long_term_b1_s2_PCM[per]	HVAC_recirc_switch_HVAC
Trans_manual_mode_CAN	Eng_load_PCM[per]	HVAC_auto_switch_HVAC
Trans_manual_mode_engaged_CAN	Eng_turbo_inlet_pressure_PCM[kpa]	HVAC_def_switch_HVAC
Trans_PRNDL_pos_CAN	Eng_boost_pressure_desired_PCM[kPa]	HVAC_dual_switch_HVAC
Trans_shift_in_progress_CAN	Eng_gen_field_current_control_duty_commanded_PCM[per]	HVAC_fan_down_switch_HVAC
Trans_upshift_manual_command_CAN	Eng_throttle_control_pos_actual_PCM[deg]	HVAC_fan_up_switch_HVAC
Veh_speed_CAN[kph]	Eng_turbo_wastegate_desired_position_PCM[per]	HVAC_off_switch_HVAC
Veh_sport_mode_CAN	Eng_turbo_wastegate_position_PCM[per]	Veh_fuel_gauge_IC[L]
Veh_traction_control_active_CAN	Eng_variable_fan_duty_cycle_PCM[per]	Veh_odometer_rolling_count_IC[m]
Veh_traction_control_off_CAN	Evap_emissions_canister_purge_valve_duty_cycle_PCM[per]	Veh_outside_air_temp_FBCM[C]
Veh_wheel_speed_FL_CAN[kph]	HVAC_ACComp_cycling_switch_PCM	Veh_power_steering_motor_current_EPSM[A]
Veh_wheel_speed_FR_CAN[kph]	HVAC_ACComp_cycling_switch_other_PCM	Veh_steering_wheel_angle_EPSM[deg]
Veh_wheel_speed_RL_CAN[kph]	HVAC_AC_pressure_sensor_PCM[kPa]	
Veh_wheel_speed_RR_CAN[kph]	Veh_active_air_shutter_actual_pos_PCM[per]	
	Eng_EGR_valve_position_PCM	
	Eng_exhaust_VVT_retard_from_max_actual_PCM[deg]	
	Eng_fuel_injection_amount_PCM[mgpercyl]	
	Eng_fuel_pulse_width_PCM	
	Eng_intake_VVT_retard_from_max_actual_PCM[deg]	
	Eng_knock_retard_PCM[deg]	
	Eng_oil_temp_estimated_PCM[C]	
	Trans_PRNDL_pos_PCM	
	Trans_electric_oil_pump_duty_cycle_TCM[per]	
	Trans_electric_oil_pump_state_TCM	
	Trans_gear_ratio_TCM	

Broadcast CAN	Scantool PCM, TCM, and ABS Modules	Scantool HVAC, IC, FBCM, and EPSM Modules
	Trans_motor_pump_speed_actual_TCM[rpm]	
	Trans_pressure_control_solenoid_current_commanded_TCM[A]	
	Trans_shift_solenoid_1_current_commanded_TCM[A]	
	Trans_shift_solenoid_2_current_commanded_TCM[A]	
	Trans_shift_solenoid_3_current_commanded_TCM[A]	
	Trans_shift_solenoid_4_current_commanded_TCM[A]	
	Trans_turbine_shaft_speed_TCM[rpm]	
	Eng_torque_actual_TCM[Nm]	
	Eng_torque_desired_TCM[Nm]	
	Trans_fluid_temp_TCM[C]	
	Trans_pressure_control_solenoid_commanded_pressure_TCM[kPa]	
	Veh_left_front_wheel_speed_ABS[kph]	
	Veh_left_rear_wheel_speed_ABS[kph]	
	Veh_right_front_wheel_speed_ABS[kph]	
	Veh_right_rear_wheel_speed_ABS[kph]	
	Veh_lateral_accel_raw_ABS[G]	
	Veh_long_acceleration_raw_ABS[G]	
	Veh_yaw_rate_raw_ABS[degps]	

Appendix C: Summary of the tests performed

Test ID [#]	Cycle	Date	Test Cell Temp [C]	Test weight [lb]	Cycle Distance [mi]	Cycle Fuel Economy [mpg] (Emiss Bag)	Fuel Economy Modal [mpg]	Fuel Economy Scale [mpg]	Test Driver	APCtime	ASCR	ASC_d	ASC_t	CE_d	CE_t	EER	ER	IWR	Fuel Heating Value [BTU/lbm]
Day 0 Coastdowns, Channel Check and Prep																			
61704001	Hwyx3, Ph 1	04/03/17	25	4500	10.23	36.4	36.4	37.28	MK	2135.68	1.93	1332.10	1306.87	9.69	9.78	-0.87	-0.93	0.25	18659.0
61704001	Hwyx3, Ph 2	04/03/17	25	4500	10.23	37.2	37.2	38.33	MK	2133.40	4.34	1363.56	1306.87	9.76	9.78	-0.19	-0.23	0.25	18659.0
61704001	Hwyx3, Ph 3	04/03/17	25	4500	10.23	37.3	37.3	38.24	MK	2130.85	5.23	1375.19	1306.87	9.75	9.78	-0.26	-0.33	0.25	18659.0
61704002	UDDS prep, Ph 1	04/03/17	23	4500	3.60	27.7	27.8	28.53	MK	2637.15	1.09	2071.29	2049.05	3.75	3.76	-0.33	-0.11	0.54	18659.0
61704002	UDDS prep, Ph 2	04/03/17	22	4500	3.85	25.8	25.9	27.57	MK	1620.79	0.59	3436.74	3416.56	3.36	3.39	-0.73	-0.87	0.67	18659.0
61704002	**UDDS prep, Ph 1+2**	04/03/17	**23**		**7.45**	**26.69**	**26.79**	**28.02**											18659.0
Day 1 Standard Cycles																			
61704003	UDDS #1, Ph 1	04/04/17	24	4500	3.59	23.4	23.4	22.98	MK/GA	2621.80	0.57	2060.76	2049.03	3.76	3.76	0.06	0.15	0.54	18659.0
61704003	UDDS #1, Ph 2	04/04/17	22	4500	3.85	25.5	25.5	26.73	MK/GA	1607.14	0.77	3442.99	3416.57	3.37	3.39	-0.35	-0.59	0.67	18659.0
61704003	**UDDS #1, Ph 1+2**	04/04/17	**23**		**7.44**	**24.42**	**24.41**	**24.78**											18659.0
61704003	UDDS #2, Ph 3	04/04/17	23	4500	3.60	27.7	27.7	28.17	MK/GA	2622.17	1.05	2070.56	2049.02	3.78	3.76	0.33	0.62	0.54	18659.0
61704003	UDDS #2, Ph 4	04/04/17	22	4500	3.87	26.1	26.0	27.51	MK/GA	1606.88	0.40	3430.10	3416.54	3.38	3.39	-0.59	-0.26	0.67	18659.0
61704003	**UDDS #2, Ph 3+4**	04/04/17	**23**		**7.47**	**26.80**	**26.80**	**27.82**											18659.0
61704004	UDDS #3, Ph 1	04/04/17	24	4500	3.59	27.9	27.9	28.61	MK	2636.12	1.27	2075.05	2049.03	3.76	3.76	0.04	0.08	0.54	18659.0
61704004	UDDS #3, Ph 2	04/04/17	22	4500	3.86	26.4	26.2	27.73	MK	1621.28	0.40	3430.42	3416.59	3.39	3.39	-0.16	-0.08	0.67	18659.0
61704004	**UDDS #3, Ph 1+2**	04/04/17	**23**		**7.46**	**27.08**	**27.00**	**28.15**											18659.0
61704005	HWY, Ph 1	04/04/17	26	4500	10.26	35.7	35.7	36.27	GA	2125.89	3.94	1358.37	1306.87	9.78	9.79	-0.15	-0.10	0.25	18659.0
61704005	HWY, Ph 2	04/04/17	25	4500	10.27	36.9	36.7	37.45	GA	2126.40	3.45	1351.93	1306.86	9.78	9.79	-0.20	-0.12	0.25	18659.0
61704006	US06x2, Ph 1	04/04/17	22	4500	1.78	14.8	15.1	14.72	GA	6039.63	0.06	2461.33	2459.77	3.53	3.53	-0.40	0.06	0.78	18659.0
61704006	US06x2, Ph 2	04/04/17	25	4500	6.25	26.0	26.3	25.97	GA	12958.76	2.82	1172.18	1139.99	8.55	8.61	-0.92	-0.67	0.30	18659.0
61704006	**US06x2, Ph 1+2**	04/04/17	**23**		**8.03**	**22.24**	**22.61**	**22.21**											18659.0
61704006	US06x2, Ph 3	04/04/17	22	4500	1.78	14.9	15.2	14.87	GA	6023.54	0.18	2464.29	2459.76	3.53	3.53	-0.18	0.16	0.78	18659.0
61704006	US06x2, Ph 4	04/04/17	26	4500	6.25	26.0	26.5	25.87	GA	12958.95	1.84	1160.99	1139.99	8.59	8.61	-0.44	-0.23	0.30	18659.0
61704006	**US06x2, Ph 3+4**	04/04/17	**24**		**8.03**	**22.32**	**22.75**	**22.22**											18659.0
61704007	UDDS Prep, Ph 1	04/04/17	22	4500	3.60	27.9	27.9	28.93	GA	2636.58	1.07	2070.92	2049.02	3.77	3.76	-0.02	0.28	0.54	18659.0
61704007	UDDS Prep, Ph 2	04/04/17	22	4500	3.88	26.2	25.9	27.97	GA	1620.41	0.78	3443.16	3416.54	3.41	3.39	0.21	0.63	0.67	18659.0
61704007	UDDS Prep, Ph 1+2	04/04/17	**22**		**7.48**	**26.99**	**26.83**	**28.42**											18659.0

Day 2 Repeat 1																			
61704008	UDDS #1, Ph 1	04/05/17	23	4500	3.60	23.6	23.6	23.31	MK	2620.99	0.41	2057.35	2049.03	3.76	3.76	-0.16	-0.03	0.54	18659.0
61704008	UDDS #1, Ph 2	04/05/17	22	4500	3.86	25.6	25.7	26.75	MK	1607.23	0.86	3445.86	3416.55	3.39	3.39	0.00	0.01	0.67	18659.0
61704008	**UDDS #1, Ph 1+2**	04/05/17	**23**		**7.46**	**24.56**	**24.63**	**24.97**											18659.0
61704008	UDDS #2, Ph 3	04/05/17	23	4500	3.59	27.6	27.8	28.47	MK	2622.37	0.81	2065.70	2049.02	3.74	3.76	-0.10	-0.26	0.54	18659.0
61704008	UDDS #2, Ph 4	04/05/17	22	4500	3.85	26.0	26.2	27.46	MK	1606.96	1.08	3453.31	3416.54	3.37	3.39	-0.37	-0.54	0.67	18659.0
61704008	**UDDS #2, Ph 3+4**	04/05/17	**23**		**7.44**	**26.76**	**26.94**	**27.94**											18659.0
61704009	UDDS #3, Ph 1	04/05/17	24	4500	3.59	28.0	28.1	28.72	GA	2636.75	-0.48	2039.22	2049.03	3.74	3.76	-0.38	-0.41	0.54	18659.0
61704009	UDDS #3, Ph 2	04/05/17	22	4500	3.86	26.2	26.0	27.68	GA	1620.63	0.25	3424.94	3416.55	3.36	3.39	-0.73	-0.81	0.67	18659.0
61704009	**UDDS #3, Ph 1+2**	04/05/17	**23**		**7.45**	**27.01**	**26.99**	**28.17**											18659.0
61704010	HWY, Ph 1	04/05/17	25	4500	10.24	36.4	36.2	36.93	GA	2125.96	6.15	1387.23	1306.87	9.71	9.79	-0.67	-0.82	0.25	18659.0
61704010	HWY, Ph 2	04/05/17	25	4500	10.25	37.2	37.0	37.61	GA	2126.41	7.77	1408.38	1306.86	9.75	9.79	-0.29	-0.37	0.25	18659.0
61704011	US06x2, Ph 1	04/05/17	21	4500	1.78	15.6	15.4	15.20	MK	6038.55	0.23	2465.34	2459.76	3.51	3.53	-0.69	-0.48	0.78	18659.0
61704011	US06x2, Ph 2	04/05/17	25	4500	6.23	26.1	26.5	25.77	MK	12957.81	1.32	1155.03	1139.96	8.58	8.61	-0.36	-0.37	0.30	18659.0
61704011	**US06x2, Ph 1+2**	04/05/17	**23**		**8.01**	**22.72**	**22.87**	**22.33**											18659.0
61704011	US06x2, Ph 3	04/05/17	22	4500	1.78	15.4	15.4	15.08	MK	6023.77	0.71	2477.33	2459.76	3.54	3.53	0.17	0.38	0.78	18659.0
61704011	US06x2, Ph 4	04/05/17	26	4500	6.23	26.0	26.5	25.77	MK	12958.48	4.05	1186.16	1139.99	8.61	8.61	0.02	-0.02	0.30	18659.0
61704011	**US06x2, Ph 3+4**	04/05/17	**24**		**8.01**	**22.60**	**22.84**	**22.27**											18659.0
61704012	Steady State Speeds 0-80-0	04/05/17	24	4500	11.55		31.6	31.99	GA	801.50	19.46	854.49	715.26	12.36	12.43	-0.44	-0.49	0.11	18659.0
61704013	55mph warm up	04/05/17	26	4500	9.22	36.4	36.2	36.66	GA	8348.31	3.26	507.78	491.74	9.54	9.45	0.50	0.90	0.07	18659.0
61704014	Steady State Speeds 0-80-0	04/05/17	22	4500	6.22		-2.6	29.25	GA	1479.64	12.34	803.50	715.26	7.01	7.08	-0.87	-0.98	0.19	18659.0
61704015	WOTs x3	04/05/17	23	4500	3.89		0.0	13.98	GA	37189.64	2.66	2340.48	2279.90	7.72	9.51	-9.19	-18.84	0.47	18659.0
61704016	Passing Manuevers at 0, 3, 6% grades	04/05/17	26	4500	9.73		0.0	13.78	GA	16422.46	17.00	3922.62	3352.80	15.17	16.50	-3.15	-8.06	0.42	18659.0
61704017	UDDS Prep, Ph 1	04/05/17	21	4500	3.59		27.6	29.20	MK	2636.92	0.64	2062.15	2049.03	3.76	3.76	0.10	0.02	0.54	18659.0
61704017	UDDS Prep, Ph 2	04/05/17	21	4500	3.85		26.2	28.36	MK	1620.75	0.69	3440.05	3416.56	3.37	3.39	-0.28	-0.47	0.67	18659.0
61704017	UDDS Prep, Ph 1+2	04/05/17	**21**		**7.44**		**26.88**	**28.76**											18659.0
Day 3 Repeat 2																			
61704018	UDDS #1, Ph 1	04/06/17	24	4500	3.59		23.2	23.09	MK	2621.50	0.60	2061.39	2049.05	3.75	3.76	-0.17	-0.15	0.54	18659.0
61704018	UDDS #1, Ph 2	04/06/17	22	4500	3.86		25.3	26.93	MK	1607.33	1.15	3455.89	3416.57	3.40	3.39	0.50	0.40	0.67	18659.0
61704018	**UDDS #1, Ph 1+2**	04/06/17	**23**		**7.45**		**24.26**	**24.93**											18659.0
61704018	UDDS #2, Ph 3	04/06/17	23	4500	3.59		27.6	28.34	MK	2622.44	1.23	2074.17	2049.03	3.77	3.76	0.28	0.31	0.54	18659.0
61704018	UDDS #2, Ph 4	04/06/17	22	4500	3.85		25.9	27.65	MK	1607.17	0.82	3444.42	3416.56	3.37	3.39	-0.48	-0.60	0.67	18659.0
61704018	**UDDS #2, Ph 3+4**	04/06/17	**23**		**7.45**		**26.69**	**27.98**											18659.0
61704019	UDDS #3, Ph 1	04/06/17	24	4500	3.59	28.0	28.0	28.88	GA	2638.77	0.86	2066.67	2049.09	3.75	3.76	-0.04	-0.13	0.54	18659.0
61704019	UDDS #3, Ph 2	04/06/17	22	4500	3.85	26.3	26.2	27.85	GA	1621.93	0.69	3440.17	3416.65	3.37	3.39	-0.29	-0.47	0.67	18659.0
61704019	**UDDS #3, Ph 1+2**	04/06/17	**23**		**7.44**	**27.08**	**27.02**	**28.34**											18659.0
61704020	HWY, Ph 1	04/06/17	25	4500	10.25	36.5	36.5	37.47	GA	2125.67	3.71	1355.34	1306.86	9.73	9.79	-0.53	-0.64	0.25	18659.0
61704020	HWY, Ph 2	04/06/17	25	4500	10.25	37.2	37.2	38.06	GA	2128.56	4.99	1372.10	1306.92	9.73	9.79	-0.53	-0.60	0.25	18659.0
61704021	US06x2, Ph 1	04/06/17	22	4500	1.78	14.8	15.1	14.69	MK	6039.52	0.11	2462.58	2459.77	3.53	3.53	-0.31	0.03	0.78	18659.0
61704021	US06x2, Ph 2	04/06/17	26	4500	6.23	25.8	26.1	25.72	MK	12960.05	4.58	1192.26	1140.02	8.57	8.61	-0.43	-0.47	0.30	18659.0
61704021	**US06x2, Ph 1+2**	04/06/17	**24**		**8.01**	**22.18**	**22.48**	**22.05**											18659.0
61704021	US06x2, Ph 3	04/06/17	23	4500	1.78	15.1	15.2	14.98	MK	6024.39	0.56	2473.59	2459.76	3.53	3.53	-0.12	0.23	0.78	18659.0
61704021	US06x2, Ph 4	04/06/17	26	4500	6.24	25.8	26.2	25.78	MK	12959.11	2.20	1165.04	1140.00	8.62	8.61	0.07	0.12	0.30	18659.0
61704021	**US06x2, Ph 3+4**	04/06/17	**24**		**8.02**	**22.26**	**22.59**	**22.23**											18659.0
61704022	55mph warm up	04/06/17	25	4500	21.04		35.2	36.33	SKULLY	0.00		1186.07	0.00	20.74	0.00				18659.0
61704023	Transmission Mapping	04/06/17	22	4500	24.53		0.0	22.93	SKULLY	0.00		12126.13	0.00	32.35	0.00				18659.0
61704024	UDDS Prep, Ph 1	04/06/17	21	4500	3.60	27.8	27.7	28.58	SKULLY	2637.74	-0.07	2047.74	2049.09	3.78	3.76	0.35	0.71	0.54	18659.0
61704024	UDDS Prep, Ph 2	04/06/17	21	4500	3.88	24.8	25.3	27.06	SKULLY	1621.04	-0.49	3399.92	3416.59	3.39	3.39	-0.59	0.04	0.67	18659.0
61704024	UDDS Prep, Ph 1+2	04/06/17	**21**		**7.49**	**26.14**	**26.39**	**27.77**											18659.0

Day 4, Repeat UDDS for 3 w/ bags on																			
61704025	UDDS #1, Ph 1	04/07/17	24	4500	3.60	23.4	23.4	23.18	MK	2620.99	0.18	2052.78	2049.03	3.76	3.76	-0.09	0.06	0.54	18659.0
61704025	UDDS #1, Ph 2	04/07/17	22	4500	3.86	25.3	25.2	26.34	MK	1607.42	1.61	3471.44	3416.58	3.41	3.39	0.69	0.74	0.67	18659.0
61704025	**UDDS #1, Ph 1+2**	04/07/17	**23**		**7.46**	**24.37**	**24.34**	**24.72**											18659.0
61704025	UDDS #2, Ph 3	04/07/17	23	4500	3.59	27.4	27.5	28.01	MK	2622.22	0.77	2064.79	2049.02	3.77	3.76	0.27	0.21	0.54	18659.0
61704025	UDDS #2, Ph 4	04/07/17	22	4500	3.86	26.1	25.9	27.25	MK	1606.92	1.20	3457.66	3416.54	3.39	3.39	0.06	0.17	0.67	18659.0
61704025	**UDDS #2, Ph 3+4**	04/07/17	**23**		**7.45**	**26.72**	**26.65**	**27.61**											18659.0
61704026	WLTP, Ph 1	04/07/17	23	4500	1.92	22.1	22.2	23.16	MK	1193.74	2.02	2039.50	1999.20	1.78	1.77	0.64	0.81	0.76	18659.0
61704026	WLTP, Ph 2	04/07/17	24	4500	2.95	27.9	28.0	28.74	MK	2347.87	0.22	1862.25	1858.10	3.04	3.04	-0.26	-0.28	0.64	18659.0
61704026	WLTP, Ph 3	04/07/17	24	4500	4.38	30.9	31.1	31.48	MK	2065.92	2.73	1671.96	1627.48	4.55	4.54	0.17	0.08	0.45	18659.0
61704026	WLTP, Ph 4	04/07/17	25	4500	5.13	27.1	26.9	26.85	MK	1836.54	1.59	1009.18	993.41	7.20	7.22	-0.33	-0.36	0.30	18659.0
61704027	WLTP, Ph 1	04/07/17	20	4500	1.92	22.5	22.5	23.65	GA	1193.64	-0.44	1990.33	1999.20	1.76	1.77	-1.00	-0.56	0.76	18659.0
61704027	WLTP, Ph 2	04/07/17	23	4500	2.95	27.7	27.8	28.44	GA	2348.14	0.34	1864.47	1858.10	3.03	3.04	-0.44	-0.40	0.64	18659.0
61704027	WLTP, Ph 3	04/07/17	25	4500	4.39	31.0	31.1	31.67	GA	2065.97	1.90	1658.46	1627.48	4.53	4.54	-0.27	-0.24	0.45	18659.0
61704027	WLTP, Ph 4	04/07/17	26	4500	5.13	27.0	26.9	26.95	GA	1836.49	1.22	1005.54	993.41	7.23	7.22	0.12	0.13	0.30	18659.0
61704028	UDDS Prep, Ph 1	04/07/17	23	4500	3.59	25.0	24.8	25.12	MK	2637.03	0.12	2051.56	2049.03	3.75	3.76	-0.13	-0.09	0.54	18659.0
61704028	UDDS Prep, Ph 2	04/07/17	22	4500	3.85	25.9	25.8	27.28	MK	1620.85	0.98	3450.03	3416.57	3.37	3.39	-0.31	-0.46	0.67	18659.0
61704028	**UDDS Prep, Ph 1+2**	04/07/17	**23**		**7.45**	**25.49**	**25.34**	**26.19**											18659.0
Day 5, Additional Repeat / Mapping																			
61704029	UDDS #1, Ph 1	04/10/17	22	4500	3.60	23.6	23.4	22.90	MK	2621.49	0.93	2068.08	2049.05	3.77	3.76	0.00	0.23	0.54	18659.0
61704029	UDDS #1, Ph 2	04/10/17	22	4500	3.86	26.0	25.8	26.89	MK	1607.53	0.41	3430.53	3416.58	3.38	3.39	-0.32	-0.24	0.67	18659.0
61704029	**UDDS #1, Ph 1+2**	04/10/17	**22**		**7.46**	**24.78**	**24.57**	**24.80**											18659.0
61704029	UDDS #2, Ph 3	04/10/17	22	4500	3.60	27.8	27.9	28.48	MK	2622.58	1.09	2071.28	2049.04	3.77	3.76	0.20	0.37	0.54	18659.0
61704029	UDDS #2, Ph 4	04/10/17	23	4500	3.87	26.3	26.1	27.39	MK	1607.17	0.77	3442.93	3416.56	3.41	3.39	0.28	0.50	0.67	18659.0
61704029	**UDDS #2, Ph 3+4**	04/10/17	**22**		**7.47**	**27.00**	**26.91**	**27.90**											18659.0
61704030	UDDS #2, Ph 1	04/10/17	20	4500	3.59	28.5	28.4	29.02	GA	2635.99	1.00	2069.42	2049.03	3.76	3.76	-0.05	0.05	0.54	18659.0
61704030	UDDS #2, Ph 2	04/10/17	20	4500	3.86	26.7	26.5	27.98	GA	1621.58	0.40	3430.41	3416.60	3.38	3.39	-0.23	-0.16	0.67	18659.0
61704030	**UDDS #2, Ph 1+2**	04/10/17		4500	**7.46**	**27.54**	**27.37**	**28.47**											18659.0
61704031	HWY, Ph 1	04/10/17	23	4500	10.26	37.5	37.3	37.74	GA	2125.78	3.22	1348.89	1306.86	9.80	9.79	0.09	0.13	0.25	18659.0
61704031	HWY, Ph 2	04/10/17	23	4500	10.26	37.9	37.9	38.26	GA	2126.31	4.42	1364.61	1306.86	9.79	9.79	-0.02	0.00	0.25	18659.0
61704032	DFCO and Engine mapping	04/10/17	24	4500	14.68		0.0	21.65	MK	0.00		7043.55	0.00	19.48	0.00				18659.0
61704033	Engine Mapping	04/10/17	19	4500	2.47	41.5	41.8	44.90	SKULLY	0.00		234.62	0.00	1.20	0.00				18659.0
61704034	UDDS Prep, Ph 1	04/10/17	26	4500	3.61	24.7	24.7	24.96	SKULLY	2636.73	2.90	2108.41	2049.03	3.80	3.76	0.57	1.13	0.54	18659.0
61704034	UDDS Prep, Ph 2	04/10/17	29	4500	3.89	22.4	22.3	23.40	SKULLY	1620.52	1.34	3462.20	3416.55	3.42	3.39	0.23	0.96	0.67	18659.0
61704034	**UDDS Prep, Ph 1+2**	04/10/17	**27**		**7.50**	**23.45**	**23.38**	**24.13**											18659.0

Day 6 - Hot testing - 95F w/ 850W/m^2 Solar

61704035	UDDS #1, Ph 1	04/11/17	36	4500	3.59	20.1	20.0	19.80	MK/GA	2620.78	0.41	2057.48	2049.02	3.75	3.76	-0.13	-0.21	0.54	18659.0
61704035	UDDS #1, Ph 2	04/11/17	33	4500	3.86	20.0	19.7	20.69	MK/GA	1607.06	1.13	3455.14	3416.58	3.38	3.39	-0.50	-0.39	0.67	18659.0
61704035	**UDDS #1, Ph 1+2**	04/11/17	**35**		**7.45**	**20.05**	**19.82**	**20.25**											18659.0
61704035	UDDS #2, Ph 3	04/11/17	37	4500	3.60	22.5	22.4	22.93	MK/GA	2622.10	0.60	2061.34	2049.01	3.78	3.76	0.35	0.47	0.54	18659.0
61704035	UDDS #2, Ph 4	04/11/17	35	4500	3.87	20.0	19.7	21.18	MK/GA	1606.90	1.40	3464.37	3416.54	3.41	3.39	0.29	0.66	0.67	18659.0
61704035	**UDDS #2, Ph 3+4**	04/11/17	**36**		**7.47**	**21.11**	**20.90**	**21.99**											18659.0
61704036	SC03x3, Ph 1	04/11/17	37	4500	3.59	20.3	20.3	20.96	GA	2572.57	0.38	2541.49	2531.91	3.75	3.75	-0.27	-0.05	0.65	18659.0
61704036	SC03x3, Ph 2	04/11/17	36	4500	3.59	20.5	20.5	21.06	GA	2566.53	0.40	2542.05	2531.89	3.74	3.75	-0.47	-0.14	0.65	18659.0
61704036	SC03x3, Ph 3	04/11/17	35	4500	3.59	20.6	20.6	21.24	GA	2570.77	0.49	2544.39	2531.90	3.75	3.75	-0.32	-0.01	0.65	18659.0
61704037	US06x3, Ph 1	04/11/17	39	4500	8.03	19.9	20.2	19.39	GA	10274.52	-0.25	3590.60	3599.74	12.10	12.14	-0.55	-0.30	0.44	18659.0
61704037	US06x3, Ph 2	04/11/17	39	4500	8.02	19.7	20.1	19.31	GA	10284.31	-0.41	3584.84	3599.72	12.09	12.14	-0.57	-0.41	0.44	18659.0
61704037	US06x3, Ph 3	04/11/17	38	4500	8.03	20.2	20.5	19.97	GA	10284.28	-0.63	3577.20	3599.72	12.09	12.14	-0.67	-0.43	0.44	18659.0
61704039	Engine Mapping	04/11/17	26	4500	33.54		0.0	11.02	SKULLY	0.00		2217.04	0.00	30.39	0.00				18659.0
61704040	UDDS Prep, Ph 1	04/11/17	-5	4500	3.60	26.6	26.4	27.00	Skully	2636.75	1.19	2073.46	2049.03	3.79	3.76	0.46	0.86	0.54	18659.0
61704040	UDDS Prep, Ph 2	04/11/17	-7	4500	3.89	24.5	24.5	26.23	Skully	1620.74	0.63	3438.12	3416.56	3.41	3.39	-0.06	0.62	0.67	18659.0
61704040	**UDDS Prep, Ph 1+2**	04/11/17	**-6**		**7.49**	**25.48**	**25.37**	**26.60**											18659.0

Day 7 - Cold testing - 20F

61704041	UDDS #1, Ph 1	04/12/17	-5	4500	3.58	17.4	17.4	16.95	MK	2620.90	0.79	2065.22	2049.02	3.74	3.76	-0.23	-0.47	0.54	18659.0
61704041	UDDS #1, Ph 2	04/12/17	-6	4500	3.85	21.8	22.0	22.94	MK	1607.12	1.75	3476.23	3416.55	3.43	3.39	1.23	1.11	0.67	18659.0
61704041	**UDDS #1, Ph 1+2**	04/12/17	**-6**		**7.44**	**19.45**	**19.49**	**19.60**											18659.0
61704041	UDDS #2, Ph 3	04/12/17	-6	4500	3.59	25.7	25.6	26.67	MK	2622.23	2.00	2089.94	2049.02	3.77	3.76	0.46	0.44	0.54	18659.0
61704041	UDDS #2, Ph 4	04/12/17	-7	4500	3.86	23.9	24.3	25.87	MK	1606.91	1.61	3471.64	3416.53	3.39	3.39	0.06	0.00	0.67	18659.0
61704041	**UDDS #2, Ph 3+4**	04/12/17	**-6**		**7.45**	**24.73**	**24.90**	**26.25**											18659.0
61704042	UDDS #3, Ph 1	04/12/17	-6	4500	3.59	26.5	26.2	27.31	GA	2636.96	1.17	2073.08	2049.04	3.77	3.76	0.41	0.28	0.54	18659.0
61704042	UDDS #3, Ph 2	04/12/17	-7	4500	3.86	24.2	24.3	26.18	GA	1620.52	1.28	3460.22	3416.54	3.38	3.39	-0.50	-0.37	0.67	18659.0
61704042	**UDDS #3, Ph 1+2**	04/12/17	**-6**		**7.45**	**25.26**	**25.20**	**26.71**											18659.0
61704043	HWY, Ph 1	04/12/17	-5	4500	10.25	33.8	33.8	34.96	GA	2125.86	5.26	1375.63	1306.87	9.74	9.79	-0.42	-0.52	0.25	18659.0
61704043	HWY, Ph 2	04/12/17	-6	4500	10.26	34.3	34.4	35.53	GA	2126.42	4.66	1367.78	1306.87	9.79	9.79	-0.04	-0.01	0.25	18659.0
61704044	US06x2, Ph 1	04/12/17	-5	4500	1.78	15.0	15.3	15.21	GA	6039.55	0.26	2466.15	2459.76	3.54	3.53	0.07	0.46	0.78	18659.0
61704044	US06x2, Ph 2	04/12/17	-1	4500	6.24	25.3	25.6	25.63	GA	12957.96	3.30	1177.57	1139.98	8.57	8.61	-0.56	-0.45	0.30	18659.0
61704044	**US06x2, Ph 1+2**	04/12/17	**-3**		**8.02**	**21.93**	**22.23**	**22.25**											18659.0
61704044	US06x2, Ph 3	04/12/17	-6	4500	1.78	15.4	15.5	15.64	GA	6023.01	0.16	2463.78	2459.74	3.53	3.53	-0.22	0.19	0.78	18659.0
61704044	US06x2, Ph 4	04/12/17	-3	4500	6.24	25.8	26.0	26.22	GA	12958.10	-0.96	1129.08	1139.98	8.55	8.61	-0.85	-0.75	0.30	18659.0
61704044	**US06x2, Ph 3+4**	04/12/17	**-5**		**8.02**	**22.45**	**22.59**	**22.80**											18659.0

Day 8 - 72F LOW OCTANE FUEL prep

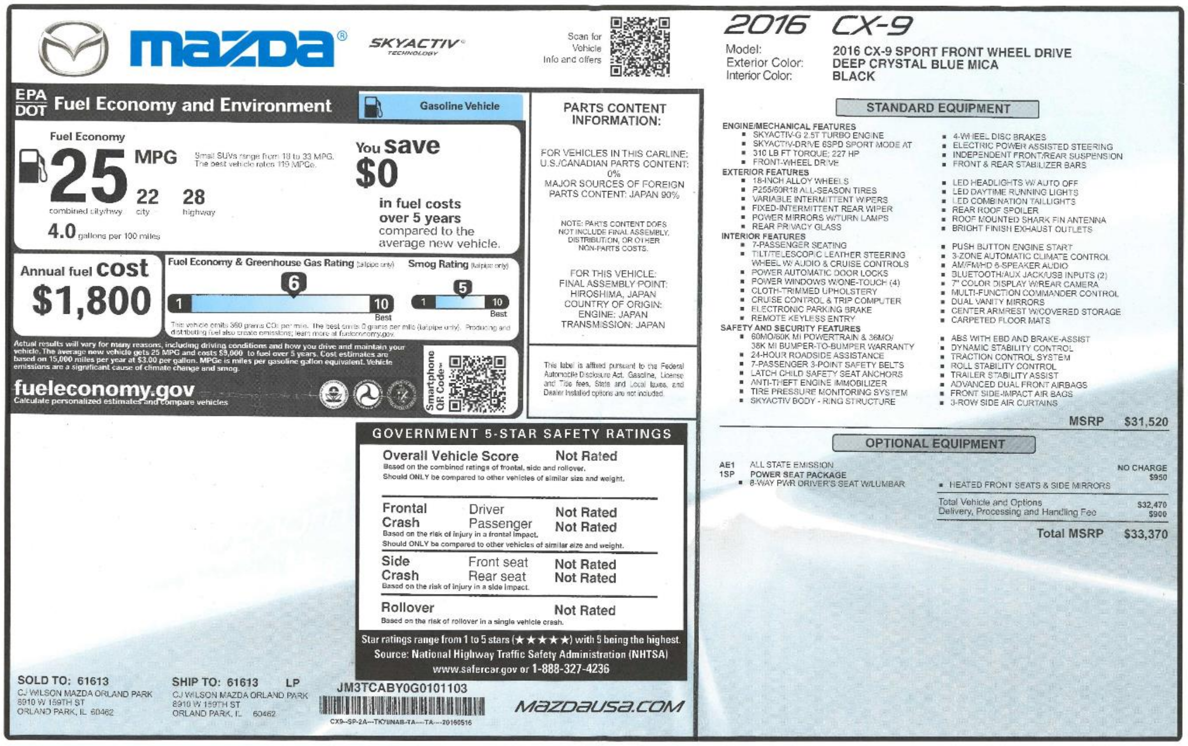
Transfer to Tier III low octane fuel

61704045	Octane Adjustment	04/13/17	25	4500	8.03	22.2	22.2	21.58	GA/MK	10276.75	0.58	3620.81	3600.06	12.18	12.14	0.06	0.29	0.44	17972.0
61704046	55mph steady state speeds	04/13/17	26	4500	9.18	37.2	37.2	37.15	MK	8348.31	9.10	536.48	491.74	9.44	9.45	-0.07	-0.12	0.07	17972.0
61704047	Steady State Speeds 0-80-0	04/13/17	23	4500	11.55	31.5	31.0	31.01	GA	801.43	17.79	842.49	715.26	12.35	12.43	-0.55	-0.61	0.11	17972.0
61704048	WOTs x3	04/13/17	23	4500	3.53		0.0	14.99	GA	37152.74	1.89	2322.92	2279.90	5.80	9.51	-31.63	-38.97	0.47	17972.0
61704049	Passing Manuevers at 0, 3, 6% grades	04/13/17	25	4500	9.37		0.0	12.75	GA	16423.02	16.42	3903.35	3352.80	15.06	16.50	-0.11	-8.72	0.42	17972.0
61704050	UDDS Prep, Ph 1	04/13/17	21	4500	3.60	27.9	27.8	28.50	MK	2636.83	1.40	2077.77	2049.03	3.77	3.76	0.25	0.41	0.54	17972.0
61704050	UDDS Prep, Ph 2	04/13/17	21	4500	3.86	25.9	25.8	26.78	MK	1620.70	0.95	3448.92	3416.56	3.41	3.39	0.50	0.57	0.67	17972.0
61704050	**UDDS Prep, Ph 1+2**	04/13/17	**21**		**7.46**	**26.81**	**26.74**	**27.58**											17972.0

Day 9 - 72F LOW OCTANE FUEL																			
61704051	UDDS #1, Ph 1	04/14/17	24	4500	3.59	23.3	23.2	22.08	MK	2627.37	1.29	2075.48	2049.14	3.79	3.76	0.69	0.75	0.54	17972.0
61704051	UDDS #1, Ph 2	04/14/17	20	4500	3.86	25.1	25.1	25.34	MK	1609.95	1.69	3474.41	3416.78	3.42	3.39	0.80	0.80	0.67	17972.0
61704051	**UDDS #1, Ph 1+2**	04/14/17	**22**		**7.45**	**24.20**	**24.15**	**23.66**											17972.0
61704051	UDDS #2, Ph 3	04/14/17	24	4500	3.59	26.7	26.8	26.73	MK	2626.36	0.33	2055.85	2049.16	3.75	3.76	-0.15	-0.29	0.54	17972.0
61704051	UDDS #2, Ph 4	04/14/17	22	4500	3.86	25.5	25.5	26.27	MK	1609.66	0.99	3450.57	3416.75	3.40	3.39	0.19	0.32	0.67	17972.0
61704051	**UDDS #2, Ph 3+4**	04/14/17	**23**		**7.45**	**26.09**	**26.12**	**26.49**											17972.0
61704052	UDDS #3, Ph 1	04/14/17	24	4500	3.60	27.9	28.0	27.92	GA	2636.93	0.15	2052.11	2049.03	3.77	3.76	-0.01	0.24	0.54	17972.0
61704052	UDDS #3, Ph 2	04/14/17	22	4500	3.87	26.3	26.0	26.60	GA	1620.71	0.71	3440.92	3416.55	3.39	3.39	-0.22	0.07	0.67	17972.0
61704052	**UDDS #3, Ph 1+2**	04/14/17	**23**		**7.47**	**27.07**	**26.92**	**27.22**											17972.0
61704053	HWY, Ph 1	04/14/17	26	4500	10.25	37.0	36.9	36.54	GA	2125.89	3.55	1353.20	1306.87	9.76	9.79	-0.30	-0.35	0.25	17972.0
61704053	HWY, Ph 2	04/14/17	25	4500	10.25	37.0	37.1	36.64	GA	2126.34	5.00	1372.21	1306.86	9.76	9.79	-0.25	-0.30	0.25	17972.0
61704054	US06x2, Ph 1	04/14/17	23	4500	1.78	15.0	15.0	14.41	GA	6039.48	0.51	2472.27	2459.76	3.54	3.53	-0.06	0.34	0.78	17972.0
61704054	US06x2, Ph 2	04/14/17	27	4500	6.24	25.6	25.7	24.74	GA	12959.42	0.76	1148.69	1140.00	8.56	8.61	-0.80	-0.65	0.30	17972.0
61704054	**US06x2, Ph 1+2**	04/14/17	**25**		**8.02**	**22.10**	**22.21**	**21.35**											17972.0
61704054	US06x2, Ph 3	04/14/17	23	4500	1.78	15.0	15.0	14.50	GA	6023.20	0.24	2465.75	2459.75	3.54	3.53	0.22	0.40	0.78	17972.0
61704054	US06x2, Ph 4	04/14/17	26	4500	6.24	26.1	26.1	25.25	GA	12958.48	-1.74	1120.10	1139.98	8.57	8.61	-0.60	-0.53	0.30	17972.0
61704054	**US06x2, Ph 3+4**	04/14/17	**25**		**8.01**	**22.42**	**22.43**	**21.69**											17972.0
Day 10 - 72F LOW OCTANE FUEL Repeat 1																			
61704055	UDDS #1, Ph 1	04/17/17	24	4500	3.60	23.1	23.0	22.26	MK	2621.17	1.11	2071.85	2049.03	3.78	3.76	0.47	0.63	0.54	17972.0
61704055	UDDS #1, Ph 2	04/17/17	22	4500	3.86	25.3	25.0	25.58	MK	1607.26	1.47	3466.74	3416.55	3.40	3.39	0.39	0.41	0.67	17972.0
61704055	**UDDS #1, Ph 1+2**	04/17/17	**23**		**7.46**	**24.20**	**23.99**	**23.86**											17972.0
61704055	UDDS #2, Ph 3	04/17/17	23	4500	3.59	26.8	26.9	26.96	MK	2622.51	1.04	2070.42	2049.03	3.76	3.76	0.13	0.08	0.54	17972.0
61704055	UDDS #2, Ph 4	04/17/17	22	4500	3.86	25.8	25.6	26.53	MK	1607.01	1.54	3468.99	3416.54	3.41	3.39	0.60	0.48	0.67	17972.0
61704055	**UDDS #2, Ph 3+4**	04/17/17	**23**		**7.44**	**26.28**	**26.20**	**26.73**											17972.0
61704056	UDDS #3, Ph 1	04/17/17	24	4500	3.59	27.8	27.9	28.07	GA	2636.78	0.34	2056.07	2049.03	3.74	3.76	-0.48	-0.43	0.54	17972.0
61704056	UDDS #3, Ph 2	04/17/17	22	4500	3.86	26.3	26.2	27.10	GA	1620.59	0.88	3446.71	3416.55	3.38	3.39	-0.50	-0.40	0.67	17972.0
61704056	**UDDS #3, Ph 1+2**	04/17/17	**23**		**7.46**	**27.01**	**26.97**	**27.56**											17972.0
61704057	HWY, Ph 1	04/17/17	25	4500	10.26	36.5	36.6	36.58	GA	2126.10	3.05	1346.74	1306.87	9.77	9.79	-0.24	-0.21	0.25	17972.0
61704057	HWY, Ph 2	04/17/17	25	4500	10.24	37.0	37.0	36.94	GA	2126.66	2.65	1341.53	1306.87	9.75	9.79	-0.30	-0.43	0.25	17972.0
61704058	US06x2, Ph 1	04/17/17	22	4500	1.78	14.4	14.7	13.98	GA	6040.23	0.00	2459.82	2459.78	3.53	3.53	-0.38	0.04	0.78	17972.0
61704058	US06x2, Ph 2	04/17/17	26	4500	6.25	25.3	25.7	24.71	GA	12961.95	2.99	1174.11	1140.06	8.63	8.61	-0.02	0.17	0.30	17972.0
61704058	**US06x2, Ph 1+2**	04/17/17	**24**		**8.03**	**21.70**	**22.02**	**21.12**											17972.0
61704058	US06x2, Ph 3	04/17/17	23	4500	1.78	14.9	15.0	14.47	GA	6024.26	-0.03	2459.05	2459.77	3.54	3.53	0.03	0.35	0.78	17972.0
61704058	US06x2, Ph 4	04/17/17	26	4500	6.24	25.7	26.1	25.09	GA	12960.60	-1.67	1121.05	1140.03	8.57	8.61	-0.61	-0.49	0.30	17972.0
61704058	**US06x2, Ph 3+4**	04/17/17	**24**		**8.02**	**22.12**	**22.39**	**21.58**											17972.0
61704059	UDDS Prep, Ph 1	04/17/17	22	4500	3.59	27.4	27.4	27.69	MK	2637.33	2.01	2090.22	2049.04	3.78	3.76	0.66	0.73	0.54	17972.0
61704059	UDDS Prep, Ph 2	04/17/17	22	4500	3.87	25.7	25.8	26.69	MK	1620.94	1.96	3483.40	3416.57	3.41	3.39	0.32	0.63	0.67	17972.0
61704059	**UDDS Prep, Ph 1+2**	04/17/17	**22**		**7.47**	**26.49**	**26.55**	**27.16**											17972.0

Day 11 - 72F LOW OCTANE FUEL Repeat 2																			
61704060	UDDS #1, Ph 1	04/18/17	23	4500	3.59	23.3	23.1	22.31	MK	2621.14	0.56	2060.54	2049.03	3.76	3.76	0.00	0.08	0.54	17972.0
61704060	UDDS #1, Ph 2	04/18/17	20	4500	3.86	25.5	25.2	25.93	MK	1607.37	1.30	3460.84	3416.56	3.41	3.39	0.47	0.49	0.67	17972.0
61704060	**UDDS #1, Ph 1+2**	04/18/17	**22**		**7.45**	**24.38**	**24.16**	**24.05**											17972.0
61704060	UDDS #2, Ph 3	04/18/17	24	4500	3.59	27.2	27.2	27.26	MK	2622.57	1.17	2072.93	2049.03	3.76	3.76	0.04	0.13	0.54	17972.0
61704060	UDDS #2, Ph 4	04/18/17	22	4500	3.87	25.9	25.8	26.56	MK	1607.09	0.76	3442.38	3416.56	3.39	3.39	-0.11	0.16	0.67	17972.0
61704060	**UDDS #2, Ph 3+4**	04/18/17	**23**		**7.46**	**26.53**	**26.45**	**26.89**											17972.0
61704061	UDDS #3, Ph 1	04/18/17	24	4500	3.60	28.2	28.1	28.18	GA	2636.75	0.49	2059.05	2049.03	3.76	3.76	-0.12	0.05	0.54	17972.0
61704061	UDDS #3, Ph 2	04/18/17	22	4500	3.87	26.1	26.0	26.93	GA	1620.66	1.24	3458.83	3416.55	3.40	3.39	-0.03	0.22	0.67	17972.0
61704061	**UDDS #3, Ph 1+2**	04/18/17	**23**		**7.47**	**27.06**	**26.98**	**27.52**											17972.0
61704062	HWY, Ph 1	04/18/17	25	4500	10.26	36.7	36.8	36.69	GA	2125.94	2.11	1334.46	1306.87	9.75	9.79	-0.43	-0.44	0.25	17972.0
61704062	HWY, Ph 2	04/18/17	25	4500	10.26	37.1	37.1	36.75	GA	2126.48	4.62	1367.19	1306.87	9.77	9.79	-0.20	-0.18	0.25	17972.0
61704063	US06x2, Ph 1	04/18/17	22	4500	1.78	14.6	14.8	14.05	GA	6038.26	0.28	2466.73	2459.76	3.55	3.53	0.08	0.54	0.78	17972.0
61704063	US06x2, Ph 2	04/18/17	26	4500	6.24	25.5	25.8	24.78	GA	12955.67	0.56	1146.31	1139.92	8.56	8.61	-0.80	-0.65	0.30	17972.0
61704063	**US06x2, Ph 1+2**	04/18/17	**24**		**8.02**	**21.86**	**22.18**	**21.19**											17972.0
61704063	US06x2, Ph 3	04/18/17	23	4500	1.77	14.9	14.9	14.30	GA	6022.85	0.78	2479.04	2459.74	3.53	3.53	-0.08	0.02	0.78	17972.0
61704063	US06x2, Ph 4	04/18/17	26	4500	6.25	25.8	26.2	25.16	GA	12956.05	-0.04	1139.52	1139.93	8.59	8.61	-0.54	-0.31	0.30	17972.0
61704063	**US06x2, Ph 3+4**	04/18/17	**25**		**8.02**	**22.20**	**22.42**	**21.54**											17972.0
61704064	Engine Mapping	04/18/17	27	4500	9.20		36.07	36.03	SKULLY	8345.54	7.06	526.45	491.74	9.49	9.45	0.20	0.37	0.07	17972.0
Day 13 - Coastdowns and further transmission mapping																			
61704066	Idle warm up	04/24/17	22	4500	0.00		0.0	0.00	SKULLY	0.00		0.00	0.00	0.00	0.00				17972.0
61704067	HWYx3 w/ coastdowns, Ph 1	04/24/17	26	4500	10.26	35.7	35.7	35.78	SKULLY	2135.74	8.21	1414.11	1306.87	9.86	9.78	0.63	0.82	0.25	17972.0
61704067	HWYx3 w/ coastdowns, Ph 2	04/24/17	25	4500	10.26	36.1	36.3	36.03	SKULLY	2133.45	8.34	1415.83	1306.87	9.86	9.78	0.64	0.83	0.25	17972.0
61704067	HWYx3 w/ coastdowns, Ph 3	04/24/17	25	4500	10.26	36.3	36.2	36.12	SKULLY	2130.96	8.41	1416.78	1306.87	9.86	9.78	0.63	0.84	0.25	17972.0
61704068	Transmission mapping- set pedal with downshifts at varying grade	04/24/17	-155	4500	33.57		23.8	23.77	Skully	0.00		3501.93	0.00	23.23	0.00				17972.0
61704069	55mph steady state speeds	04/24/17	25	4500	9.20	37.4	37.1	36.48	SKULLY	8348.31	8.99	535.95	491.74	9.49	9.45	0.21	0.37	0.07	17972.0
61704070	SSS 0-80-0 x 3, 0% grade, Ph 1	04/24/17	23	4500	6.24		28.9	27.86	SKULLY	1478.06	27.87	915.44	715.90	7.13	7.08	0.58	0.80	0.19	17972.0
61704070	SSS 0-80-0 x 3, 3% grade, Ph 2	04/24/17	23	4500	6.23		-0.1	16.25	SKULLY	1479.69	39.83	1000.18	715.26	7.18	7.08	1.31	1.53	0.19	17972.0
61704070	SSS 0-80-0 x 3, 6% grade, Ph 3	04/24/17	24	4500	6.24		0.0	10.49	SKULLY	1479.61	39.68	999.07	715.26	7.17	7.08	1.15	1.37	0.19	17972.0
Day 14 - Further transmission mapping																			
61704071	55mph steady state speeds	04/25/17	26	4500	9.20		34.8	34.69	SKULLY	8348.31	6.59	524.13	491.74	9.49	9.45	0.20	0.37	0.07	17972.0
61704072	Transmission mapping- constant speed	04/25/17	-31	4500	40.91		0.0	9.22	SKULLY	0.00		1212.98	0.00	36.56	0.00				17972.0

Appendix D: Build sheet for Mazda CX-9 test vehicle



mazda® SKYACTIV® TECHNOLOGY

Scan for Vehicle Info and offers

EPA DOT Fuel Economy and Environment — Gasoline Vehicle

Fuel Economy

25 MPG combined city/hwy — **22** city — **28** highway

Small SUVs range from 18 to 33 MPG. The best vehicle rates 119 MPGe.

4.0 gallons per 100 miles

You **save** **$0** in fuel costs over 5 years compared to the average new vehicle.

Annual fuel **cost** **$1,800**

Fuel Economy & Greenhouse Gas Rating (tailpipe only): 6 (1–10 Best)

Smog Rating (tailpipe only): 5 (1–10 Best)

This vehicle emits 360 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel also create emissions; learn more at fueleconomy.gov.

Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 25 MPG and costs $9,000 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.00 per gallon. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.

fueleconomy.gov
Calculate personalized estimates and compare vehicles

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PARTS CONTENT INFORMATION:

FOR VEHICLES IN THIS CARLINE:
U.S./CANADIAN PARTS CONTENT: 0%
MAJOR SOURCES OF FOREIGN PARTS CONTENT: JAPAN 90%

NOTE: PARTS CONTENT DOES NOT INCLUDE FINAL ASSEMBLY, DISTRIBUTION, OR OTHER NON-PARTS COSTS.

FOR THIS VEHICLE:
FINAL ASSEMBLY POINT: HIROSHIMA, JAPAN
COUNTRY OF ORIGIN:
ENGINE: JAPAN
TRANSMISSION: JAPAN

This label is affixed pursuant to the Federal Automobile Disclosure Act. Gasoline, License and Title fees, State and Local taxes, and Dealer Installed options are not included.

GOVERNMENT 5-STAR SAFETY RATINGS

Overall Vehicle Score		Not Rated
Based on the combined ratings of frontal, side and rollover. Should ONLY be compared to other vehicles of similar size and weight.		
Frontal Crash	Driver	Not Rated
	Passenger	Not Rated
Based on the risk of injury in a frontal impact. Should ONLY be compared to other vehicles of similar size and weight.		
Side Crash	Front seat	Not Rated
	Rear seat	Not Rated
Based on the risk of injury in a side impact.		
Rollover		Not Rated
Based on the risk of rollover in a single vehicle crash.		

Star ratings range from 1 to 5 stars (★★★★★) with 5 being the highest.
Source: National Highway Traffic Safety Administration (NHTSA)
www.safercar.gov or 1-888-327-4236

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CX9--SP-2A---TK7UNAB-TA---TA---20160516

MAZDAUSA.COM

2016 CX-9

Model: 2016 CX-9 SPORT FRONT WHEEL DRIVE
Exterior Color: DEEP CRYSTAL BLUE MICA
Interior Color: BLACK

STANDARD EQUIPMENT

ENGINE/MECHANICAL FEATURES
- SKYACTIV-G 2.5T TURBO ENGINE
- SKYACTIV-DRIVE 6SPD SPORT MODE AT
- 310 LB FT TORQUE; 227 HP
- FRONT-WHEEL DRIVE
- 4-WHEEL DISC BRAKES
- ELECTRIC POWER ASSISTED STEERING
- INDEPENDENT FRONT/REAR SUSPENSION
- FRONT & REAR STABILIZER BARS

EXTERIOR FEATURES
- 18-INCH ALLOY WHEELS
- P255/60R18 ALL-SEASON TIRES
- VARIABLE INTERMITTENT WIPERS
- FIXED-INTERMITTENT REAR WIPER
- POWER MIRRORS W/TURN LAMPS
- REAR PRIVACY GLASS
- LED HEADLIGHTS W/ AUTO OFF
- LED DAYTIME RUNNING LIGHTS
- LED COMBINATION TAILLIGHTS
- REAR ROOF SPOILER
- ROOF MOUNTED SHARK FIN ANTENNA
- BRIGHT FINISH EXHAUST OUTLETS

INTERIOR FEATURES
- 7-PASSENGER SEATING
- TILT/TELESCOPIC LEATHER STEERING WHEEL W/ AUDIO & CRUISE CONTROLS
- POWER AUTOMATIC DOOR LOCKS
- POWER WINDOWS W/ONE-TOUCH (4)
- CLOTH-TRIMMED UPHOLSTERY
- CRUISE CONTROL & TRIP COMPUTER
- ELECTRONIC PARKING BRAKE
- REMOTE KEYLESS ENTRY
- PUSH BUTTON ENGINE START
- 3-ZONE AUTOMATIC CLIMATE CONTROL
- AM/FM/HD 6-SPEAKER AUDIO
- BLUETOOTH/AUX JACK/USB INPUTS (2)
- 7" COLOR DISPLAY W/REAR CAMERA
- MULTI-FUNCTION COMMANDER CONTROL
- DUAL VANITY MIRRORS
- CENTER ARMREST W/COVERED STORAGE
- CARPETED FLOOR MATS

SAFETY AND SECURITY FEATURES
- 60MO/60K MI POWERTRAIN & 36MO/36K MI BUMPER-TO-BUMPER WARRANTY
- 24-HOUR ROADSIDE ASSISTANCE
- 7-PASSENGER 3-POINT SAFETY BELTS
- LATCH CHILD SAFETY SEAT ANCHORS
- ANTI-THEFT ENGINE IMMOBILIZER
- TIRE PRESSURE MONITORING SYSTEM
- SKYACTIV BODY - RING STRUCTURE
- ABS WITH EBD AND BRAKE-ASSIST
- DYNAMIC STABILITY CONTROL
- TRACTION CONTROL SYSTEM
- ROLL STABILITY CONTROL
- TRAILER STABILITY ASSIST
- ADVANCED DUAL FRONT AIRBAGS
- FRONT SIDE-IMPACT AIR BAGS
- 3-ROW SIDE AIR CURTAINS

MSRP $31,520

OPTIONAL EQUIPMENT

AE1	ALL STATE EMISSION	NO CHARGE
1SP	POWER SEAT PACKAGE - 8-WAY PWR DRIVER'S SEAT W/LUMBAR - HEATED FRONT SEATS & SIDE MIRRORS	$950
	Total Vehicle and Options	$32,470
	Delivery, Processing and Handling Fee	$900
	Total MSRP	**$33,370**

Appendix E: Peer Review Feedback

"Laboratory Testing of a 2016 Mazda CX9 2.5 L I4 SkyActiv® with a 6 speed Transmission"

ANL APRF NHTSA Benchmark Report, March 2018

Peer Review by

Douglas J. Nelson, Ph.D., PE, Fellow SAE International
Professor of Mechanical Engineering
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Blacksburg, Virginia 24061

The subject report is a comprehensive document of the extensive chassis dynamometer testing performed by the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL, or Argonne). The purpose of the benchmark testing is to evaluate the efficiency and energy consumption of the advanced technologies in this vehicle, and provide quality data to support the Corporate Average Fuel Economy (CAFE) modeling and validation activities within NHTSA. The testing is not focused on fuel economy certification testing, however certification results are appropriately used to validate the benchmark testing.

The report reviews and documents laboratory facilities, methods and instrumentation used to generate the test results. ANL has world-class vehicle testing facilities and personnel in the APRF. The equipment, test methods and quality control are designed to produce accurate and reliable data for energy consumption.

The goals of the study are to produce a robust data set that can be used for model generation and validation of fuel consumption for the specific technologies present in this Mazda CX9 vehicle. The test plan is appropriately set up to first produce standard drive cycle certification data for validation of the test results, and then test specific sub-systems and off-cycle conditions. Specific attention is paid to thermal conditions, including ambient conditions, cabin temperature control, and transient powertrain warm-up. Powertrain thermal conditions and cabin heating/cooling are particularly important for accurately predicting fuel consumption from models, and also to develop new technologies to address this facet of energy consumption.

The Mazda CX-9 test vehicle used in this study is a popular example in one of the larger market segments (three-row crossover SUV) in the US. The specific vehicle configuration tested has a down-sized and turbocharged inline 4 cylinder engine using direct injection (DI), active grille shutters, and a 6 speed transmission. These advanced powertrain technologies are combined to provide improved fuel economy compared to the previous generation vehicle using a naturally aspirated 3.7 L V6 engine. Many of these new powertrain features are expected to supplant previous technologies, in part to meet future CAFE standards.

The test results presented in the report are documented to be of high quality and repeatability. The broad range of tests serve to characterize each of the features of the powertrain mentioned above, along with transmission shift strategy, effect of fuel anti-knock index (AKI or octane), and active grille shutter control strategy.

The individual tests and results are well documented using figures and tables in the body of the report, but the real value from testing is for component modeling using the detailed data logs that will be available. The parameters that are recorded from this non-invasive instrumentation are sufficient to characterize the component control, shift strategies and torque converter clutch lock-up behavior, decel fuel cutoff, and grille shutter position under many different conditions. Detailed, often invasive (and expensive) instrumentation of intermediate torque values (such as across a torque converter) are not required for model development of existing components like transmissions or torque converters. The details of each component operation as documented by the data is much more useful for model fidelity and control strategy emulation.

The bulk of the testing results are carefully reduced down to energy consumption as a function of each of the parameters investigated from the test plan. These parameters include; drive cycle, ambient temperature with cabin temperature control, powertrain initial conditions (cold start vs hot start), fuel AKI, and performance maneuvers. The report shows how component operation, such as engine load/speed and transmission gear, contribute to the fuel used for vehicle operation. This detailed analysis allows the test data to be properly applied to model development and validation.

The report also provides powertrain efficiency results based on SAE J2951 positive cycle energy output relative to fuel energy input. Fuel economy alone does not determine why a particular test used more or less fuel. For example, a US06 cycle generally has low fuel economy. The powertrain efficiency analysis reveals that the engine operates at relatively high thermal efficiency, and the fuel consumption is due to the high vehicle energy output at the wheels for the US06 cycle. Powertrain efficiency necessarily evaluates full vehicle level results, but the changes in powertrain efficiency as a function of each test condition is very useful in identifying component level technology behavior for model validation.

Overall, this report clearly documents the energy consumption behavior of the technologies employed on this Mazda CX-9 vehicle. The report is well organized, and accurately documents the results from the test program. Other than a short paragraph, the linkage between this benchmarking data and the CAFE fuel economy model (Autonomie) is not illustrated in this report. The detailed quality data generated as a result of this controlled laboratory testing should form the basis of robust models for technology evaluation in the CAFE program.

ANL APRF NHTSA Benchmark Testing of MY 2016 Mazda CX9

Summary Report

Prepared by Giorgio Rizzoni (see bio in Appendix)

1. Test Vehicle and Lab setup

1.a Please comment description of laboratory, instrumentation approach, and APRF certification testing. More specifically, your views of the laboratory facilities and equipment utilized, relative to other facilities. Is there any need to improve on the facilities or methods employed? If so, why?

Argonne National Lab (ANL) has operated an Advanced Powertrain Research Facility (APRF) for some 20 years. This reviewer is quite familiar with the operation and characteristics of the APRF, having served as an Associate Technical Team Member of the Vehicle Systems Analysis Technical Team of the U.S. DRIVE Partnership between 2013 and 2016. During this time, I had the opportunity to participate in numerous program reviews of the work done by ANL-APRF in characterizing and evaluating the fuel economy, energy efficiency and emissions of a number of vehicles, mostly with focus on alternative fuels and powertrains. During the course of these reviews, it became apparent that the test capabilities and instrumentation of the APRF are of the highest quality, and far exceed the minimum requirements for certification testing. The four-wheel-drive chassis dynamometer is operated in an environmental chamber capable of low- and high-temperature testing, and the available instrumentation permits both non-intrusive and intrusive testing to evaluate not only the fuel economy and emissions of the vehicle, but also to perform distinct and specific tests to evaluate the energy efficiency and power consumption of specific subsystems and components in the vehicle. In addition, the APRF team has developed considerable software analysis capabilities that allow the team to present results in comprehensive and carefully thought-out graphical and tabular forms. In my 30+ year career as an automotive researcher, I have not come across a public-domain test facility of this kind that matches the capabilities of the APRF. The work presented in this report is of the highest quality.

1.b Please comment on the test plan and its appropriateness to the goals of the study. Are there areas needing improvement, or not? If so, why?

The test plan is quite comprehensive and far exceeds the minimum requirements of certification testing. I have no suggestions for further improvement.

1.c Please comment on the specification of the test vehicle(s). How representative are they of current and future technology trends? Why?

The vehicle tested in this report represents a clear trend in today's SUV offerings, coupling a downsized, boosted, direct-injection engine coupled to a 6-speed automatic transmission. The results presented in the report clearly suggest that the technologies embodied in the current generation Mazda CX 9 are representative of future trends for conventional (i.e.: non-hybrid) powertrains.

2. Test Results and analysis

2.a Please comment on the quality of the tests conducted. Are they representative of how vehicle should be evaluated? What other tests within Level 1 instrumentation do you recommend?

The tests conducted in the study were comprehensive, and representative of a meaningful number of test conditions including certification tests, and of additional tests representing different fuels and environmental conditions.

2.b Please comment on the presentation of the individual test results and analysis. How else would you like to see the results? Do you recommend other parameters to be logged and presented from Level 1 instrumentation?

The graphical and tabular summary of the test results give a clear and concise representation of the results. I made some recommendations on minor improvements that I believe have been incorporated in the final report.

2.c Please comment on the energy analysis conducted?

The energy analysis, including both fuel economy and powertrain efficiency, is comprehensive and includes consideration of hot- and cold-start conditions, and of different vehicle modes of operation (accel/decel, cruise, stop), while also presenting the distribution of operating points in the engine speed-load plane, and an analysis of transmission operation and its effect in fuel economy.

2.d Please comment on the powertrain efficiency (J2951) analysis? Do you think this represents technology effectiveness appropriately in terms of full vehicle testing?

The J2951 analysis is clearly presented, and reflects the comments already made in *2.c* above.

3. General Comments

3.a Please comment on the organization, readability, accuracy, and clarity of the report

As part of the peer review process, I took the time to carefully review the report, and made a number of editorial suggestions that, in my opinion, further enhanced the already excellent quality of the report. I believe that the final product is a well-organized, readable, clear and accurate report.

3.b Please provide any other comments you may have on the Level 1 testing

The additional analysis presented in the report on: transmission and torque converter operating strategy; vehicle performance (acceleration and passing maneuvers); start-stop operation; vehicle fuel injection strategies; fuel cut-off strategies; cycle thermal test conditions; comparison of fuels with different AKI ratings; and active grill shutter operation further enhances the quality and completeness of the report.

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National Highway
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