

Analyzing the Energy Consumption Variation during Chassis Dynamometer Testing of Conventional, Hybrid Electric, and Battery Electric Vehicles

Jake Bucher and Thomas Bradley
Colorado State Univ

Henning Lohse-Busch and Eric Rask
Argonne National Laboratory

ABSTRACT

Production vehicles are commonly characterized and compared using fuel consumption (FC) and electric energy consumption (EC) metrics. Chassis dynamometer testing is a tool used to establish these metrics, and to benchmark the effectiveness of a vehicle's powertrain under numerous testing conditions and environments. Whether the vehicle is undergoing EPA Five-Cycle Fuel Economy (FE), component lifecycle, thermal, or benchmark testing, it is important to identify the vehicle and testing based variations of energy consumption results from these tests to establish the accuracy of the test's results. Traditionally, the uncertainty in vehicle test results is communicated using the variation. With the increasing complexity of vehicle powertrain technology and operation, a fixed energy consumption variation may no longer be a correct assumption. This paper will present the observed energy consumption variation as measured from the variation in the battery net energy change (NEC), and the variation observed during thermal dynamometer testing. Results will be provided for a variety of vehicle architectures tested on common drive cycles.

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INTRODUCTION

Chassis dynamometer testing allows for different types of vehicle architectures to be tested across a breadth of standardized drive cycles. In general terms, a chassis dynamometer replicates the various vehicle road loads (such as rolling resistance and aerodynamic drag) during the vehicle drive cycle test. In order to make sure that the majority of the vehicle losses are accounted for during dynamometer testing, road load coefficients are determined for each vehicle. These coefficients are normally derived from coast down tests conducted on a road course. These coefficients are then inserted into the road load force equation below.

$$F_{roadload} = A + BV + CV^2 \quad (1)$$

The road load coefficients are verified by performing coast down tests on the dynamometer itself. These new dynamometer coast down tests provide new coefficients that ensure the road load force observed during track testing is replicated by the dynamometer rollers [1].

For all five vehicles listed in [Table 2](#), a large set of data was collected using the chassis dynamometer facilities at Argonne National Laboratory's (ANL) Advanced Powertrain Research

Facility (APRF). The APRF incorporate both a two wheel drive (2WD) and a four wheel drive (4WD) chassis dynamometer for vehicle testing. The signals and calculations used during the energy analysis for the five vehicles in this paper are given in [Table 1](#). An inline fuel flow meter was used to measure the fuel flow into the engine, while a Hioki power analyzer was used to measure the electrical current in and out of the battery.

The purpose of this paper is to characterize the variation in vehicle energy consumption that is due to dynamometer setup, calibration, and testing procedures. Characterizing the variability in test results will help with the repeatability of these test. For this study, three of the EPA Five-Cycle FE drive schedules were used to measure the energy consumption variability of the vehicles listed in [Table 2](#) [2]. The Urban Dynamometer Driving Schedule (UDDS) is representative of city driving conditions, which incorporates frequent stops and lower speeds. The Highway Fuel Economy Driving Schedule (HWFET) represents driving at fairly constant highway speeds. Finally, the US06 driving schedule is representative of a more aggressive driving style, associated more with the way in which Americans actually drive [3]. All three drive cycles were used during the analysis of this paper as they are commonly used to report the performance of vehicles by numerous institutions.

Table 1. Signals measured during chassis dynamometer testing, and the values calculated for each of the vehicles in this paper during energy analysis.

Measured Values		Calculated Values	
Signal	Units	Signal	Units
Engine Speed	RPM	Engine On/Off Time	sec
Engine Fuel Flow Rate	cc/s	Integrated Fuel Consumption	gal
HV Battery Current	A	Eng/Fuel Power	kW
HV Battery Voltage	V	Integrated HV Battery Current	Ah
12V Battery Current	A	Integrated 12V Battery Current	Ah
12V Battery Voltage	V	Integrated HVAC Current	Ah
HVAC Current	A	HV Battery SOC	%
HVAC Voltage	V	Integrated Dyno Energy	MJ
Tractive Dynamometer Effort	N	Integrated Vehicle Power	kW
Vehicle Speed	MPH	Vehicle Acceleration	m/s ²

Table 2. Overview of the vehicles used to evaluate the effect of dynamometer variation on energy consumption.

Vehicle	2004 Ford Focus	2010 Ford Fusion Hybrid	2010 Toyota Prius	2012 Chevrolet Volt	2011 Nissan Leaf
Vehicle Architecture	Conventional Vehicle (CV)	Hybrid Electric Vehicle (HEV)	Hybrid Electric Vehicle (HEV)	Plug-In Hybrid Electric Vehicle (PHEV)	Battery Electric Vehicle (BEV)
Engine	82kW	116kW	73kW	63kW	-
Motor/Generator	-	79kW	60kW	111kW/54kW	80kW
Urban FE	23MPG	41MPG	51MPG	35MPG (CS)	-
HWY FE	30MPG	36MPG	48MPG	40MPG (CS)	-
Comb FE	25MPG	39MPG	50MPG	37MPG (CS)	-
EV Range	-	-	-	35mi	73mi

The Ford Fusion Hybrid, Toyota Prius, and Chevrolet Volt represent the wide range of hybrid electric vehicle (HEV) architectures available in today's automotive market. An HEV is able to utilize tractive energy from either an internal combustion engine (ICE) or a high voltage battery energy storage system (ESS), as depicted in Figure 1. Depending upon the size of the vehicle's battery, electric motor or engine, and its energy control strategy, a vehicle may utilize the energy from either source at different times during normal driving conditions [4]. The Ford Fusion Hybrid and Toyota Prius are built with a power split powertrain architecture where the engine, electric traction motor, electric generator, and final drive of the vehicle are attached through a planetary gear set. Both the Fusion and Prius represent full hybrids, which are generally controlled using a charge sustaining (CS) strategy. Each of these two vehicles are able to turn the engine off during vehicle idling and at low speeds, thus decreasing FC and emissions production.

On the other hand, the Volt is a plug-in hybrid electric vehicle (PHEV). It uses an all-electric drivetrain with a small conventional engine, which can provide energy to the high voltage battery in addition to providing energy directly to the wheels. The battery of the Volt can be charged from electricity off the grid, allowing the Volt to utilize only electricity for roughly 35mi. Once the energy capacity of the high voltage battery

reaches a set minimum limit, the generator engine turns on to provide enough power to the battery to keep a CS control strategy for the remainder of driving range. The Ford Focus and Nissan Leaf are each single power source vehicles. The Ford Focus is a conventional vehicle (CV) that uses a gasoline engine to propel the vehicle, while the Nissan Leaf is a battery electric vehicle (BEV) that uses the battery ESS to propel the vehicle. The relevant powertrain specifications and energy consumption data for each vehicle can be found in Table 2.

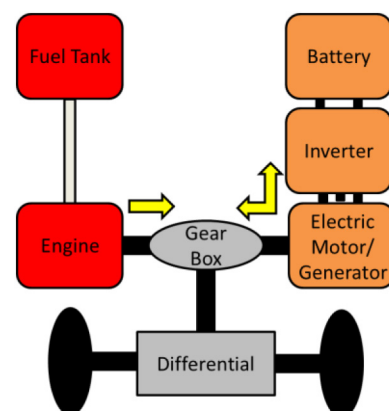


Figure 1. Block diagram of the energy flow from both gasoline and electric sources for an example hybrid electric vehicle architecture.

While chassis dynamometer testing provides an isolated environment in which many of the vehicle architectures described above can be repeatedly tested, there is an opportunity for variation between dynamometer test results. It is understood by members of government agencies and the automotive industry alike that variation will exist between energy consumption results for the same vehicle across multiple tests in the same environment and testing procedures [2][5][6]. In some cases a fixed measurement variation might be suggested [5], while in other cases it might be recommended to conduct a finite number of tests to validate the testing results [6]. In either case, the importance of conducting these vehicle dynamometer tests is to produce energy consumption results that the test takers are confident will represent the actual operation of the vehicle out on the road in a non-controlled environment. However, it has been shown that even with strictly controlled dynamometer vehicle testing, the testing results do not always match up with the real world condition results [2]. Therefore, in order to provide even more confidence in the dynamometer energy consumption results for the vehicle architectures listed in Table 2, further investigation might need to be made into the types of vehicle operation and environment that can alter the way in which a vehicle utilizes energy during normal driving.

The paper will first determine the amount of variation between similarly conducted tests for the vehicles listed in Table 2.

Then the effect a HEV's change in operation on the battery's NEC and vehicle's energy consumption results will be analyzed to determine the added effect of utilizing two energy sources. Finally, the effects of extreme thermal environments on the vehicle's use of accessory energy and total energy consumption will be analyzed.

It should be noted that this paper is only determining the effect of vehicle operation and testing environment on dynamometer energy consumption results. The uncertainties of the instruments used to measure the signals in Table 1 were not calculated.

TEST-TO-TEST ENERGY CONSUMPTION VARIATION

In order to analyze the sources of energy consumption variation during vehicle dynamometer testing, the amount of variation between similar dynamometer tests must be measured. These similar dynamometer tests utilize the same drive cycle, test weight, dynamometer vehicle road load conditions, vehicle powertrain control strategy (CS or CD), engine thermal state(hot or cold), and thermal environment for each vehicle. Each test was driven by the professional drivers at the APRF but no mechanism was available to assure the same test driver. By organizing the dynamometer tests using these criteria, it can be assured that comparisons and

conclusions are being made based on like test sets. As stated earlier, FC and EC are used to compare the energy consumption variation from test-to-test.

Figure 2 shows the variation of dynamometer tests for the Ford Fusion Hybrid on the UDDS and HWFET drive cycles. The particular test description is given under each bar plot of the x-axis. The number of individual dynamometer tests for each set is given above each bar plot. It was determined that a minimum of three tests would be required to make a variation calculation. The variation of the set of tests was calculated by dividing the sampled standard deviation over the sampled average. This calculation can show the range of energy consumption test results in comparison to the average energy consumption result of the test set. The figure shows that the majority of the tests driven by either the robot or normal test driver, including the different vehicle masses, had a variation lower than 2%. However, the test set that was driven by the different engineer drivers had a variation of ~3%.

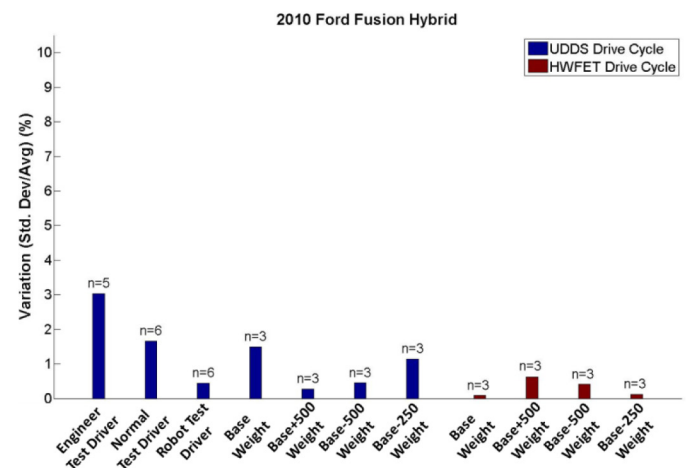


Figure 2. Fuel consumption variation for the Ford Fusion Hybrid.

The variation in test results for the Toyota Prius can be seen in Figure 3. The Toyota Prius was tested over a variety of test cell temperatures and using either a 4WD or 2WD dynamometer. The testing cell was never kept at exactly 72F or 95F, but it should be assumed that it was held very close to these temperatures throughout the entire dynamometer test. The figure shows that only the test results of the Prius on the 2WD dynamometer at a test cell temperature of 72F showed variation greater than 3%. However, as will be discussed in a later section these test results were used for battery net energy correction lines.

Figure 4 shows the variation in energy consumption results for the Chevrolet Volt. The Volt underwent extensive testing in CS and all-electric CD mode at the APRF. The Volt was tested at ambient temperatures of 20F, 95F, and 72F on the UDDS and HWFET drive cycles. The energy consumption of the Volt varies as a function of driving mode and ambient temperature. The widest variation occurred during CS operation on the UDDS at 20F (~8%) and on the HWFET at 95F (~5%).