

Real-World Thermal Effects on Wheel Assembly Efficiency of Conventional and Electric Vehicles

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ABSTRACT

It is widely understood that cold ambient temperatures negatively impact vehicle system efficiency. This is due to a combination of factors: increased friction (engine oil, transmission, and driveline viscous effects), cold start enrichment, heat transfer, and air density variations. Although the science of quantifying steady-state vehicle component efficiency is mature, transient component efficiencies over dynamic ambient real-world conditions is less understood and quantified.

This work characterizes wheel assembly efficiencies of a conventional and electric vehicle over a wide range of ambient conditions. For this work, the wheel assembly is defined as the tire side axle spline, spline housing, bearings, brakes, and tires. Dynamometer testing over hot and cold ambient temperatures was conducted with a conventional and electric vehicle instrumented to determine the output energy losses of the wheel assembly in proportion to the input energy of the half-shafts. Additionally, response surface methodology (RSM) techniques were applied to the conventional vehicle serving as predictive models of the wheel assembly efficiency as a function of its thermal state. For the conventional vehicle, data showed that under -17°C ambient conditions, nearly 40% of the wheel assembly efficiency is lost over an urban drive cycle. For the urban cycle driven at $+35^{\circ}\text{C}$, this loss reduces to less than 10%. For standard $+20^{\circ}\text{C}$ ambient conditions, the efficiency of a first urban cycle for a conventional vehicle is on the order of 78%, increasing to nearly 85% by the third cycle. For a battery electric vehicle, the first urban cycle at -7°C losses are on the order of 40%. At $+35^{\circ}\text{C}$, these losses are reduced to approximately 5%. Efforts to reduce such significant losses could positively impact vehicle system efficiency.

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INTRODUCTION

Understanding dynamic vehicle system efficiencies due to the range of conditions anticipated in real-world driving is required to optimize vehicle systems. In addition, understanding the benefits to addressing these losses is critical to receive proper fuel economy credit for technology adoption. In previous work that focused on real-world effects on powertrain efficiency [1], simplified thermal models of a conventional vehicle were developed and combined with ambient temperature data. These models then predicted the real-world thermal effects on vehicle efficiency. From this work it was shown that regional temperature variations are significant and dynamic throughout the year, with these variations playing a large role in full vehicle system efficiency. The temperature data were assembled from the National Renewable Energy Laboratory's Typical Meteorological Year Database (TMY3) [2]. Figure 1 shows a map of average yearly ambient temperatures across the continental United States, and Figure 2 shows hourly ambient temperature data from three sample U.S. climates.

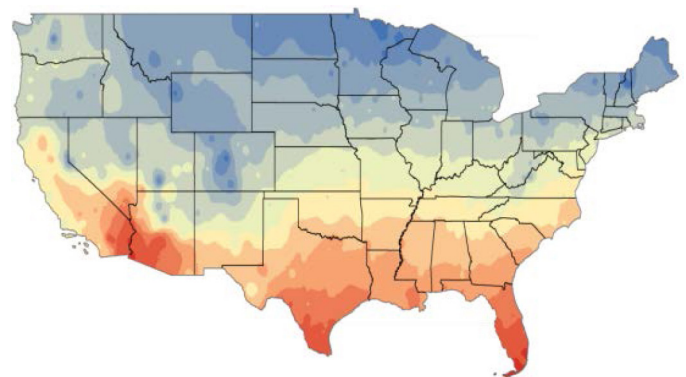


Figure 1. TMY map of average ambient temperatures for the contiguous United States (hot climates in red, cold in blue).

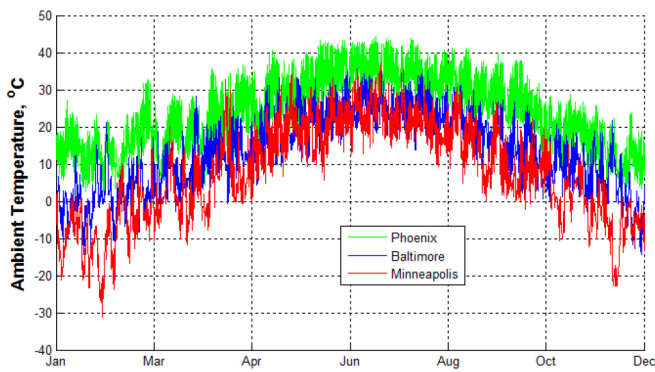


Figure 2. TMY hourly ambient temperature data for Phoenix, Baltimore, and Minneapolis.

In addition to this effort, a large number of studies and publications demonstrated the negative impact on fuel consumption and emissions due to cold ambient temperatures. Fuel enrichment and spark timing adjustments for catalyst light-off strategies, high rates of heat transfer, and non-linear viscosity of engine lubricants combine to negatively affect powertrain and drive cycle efficiency in cooler ambient conditions [3,4,5,6,7,8]. Although the focus of a number of these works centered on engine efficiencies for conventional vehicles [9, 11], the remaining vehicle system exhibits transient efficiencies as a function of thermal state and increase energy consumption. Together these factors define the total powertrain system efficiency and understanding the aggregate system is required to properly optimize powertrain system design. Large thermal transients, grades, road conditions, drive cycles, and other real-world factors need to be factored in system design. Properly accounting for the effect of these factors on real-world fuel economy becomes increasingly important, as there are a number of pathways that original equipment manufacturers (OEMs) may take in order to receive fuel economy credit.

In 2012, new light-duty fuel economy standards were set for the North American market. The U.S. Environmental Protection Agency (EPA), National Highway Traffic Safety Administration (NHTSA), California Air Resources Board, OEMs, non-government entities, and other stakeholders collaborated to define the 2012-2025 national fuel economy and greenhouse gas standards. The program called for a 4%-5% annual improvement in fuel economy with the final car and light-duty truck standard set to 54.5 miles per gallon [12]. Vehicle manufacturer fleet fuel economy certification for this Corporate Average Fuel Economy regulation is determined via a combination of on- and off-cycle methods. On-cycle certification is evaluated from weighted measured testing results of EPA's test cycles [13, 14]. On-cycle certification can be supplemented with off-cycle credits representing estimated real-world vehicle efficiency not captured by on-cycle testing. The EPA and NHTSA currently recognize three pathways by which technologies can qualify for off-cycle credit:

1. **On-Table** - An OEM gets a predefined credit value for technologies that are included in the credit table.
2. **5-Cycle** - An OEM uses a predefined 5-cycle test methodology to determine credit value.
3. **Alternative Method** - An OEM may develop and justify a test methodology and credit value using real-world data.

As powertrain system fuel economy optimization progresses, the pathway by which the technology is demonstrated will become increasingly important in order to receive appropriate credits.

The approach outlined in this paper involves experimental vehicle chassis dynamometer drive-cycle testing for both a conventional and electric vehicle conducted over a wide range of ambient temperatures and loads. The focus of this work centers on quantifying the energy lost in the wheel assembly and developing a simplified predictive model of such losses. Here, the wheel assembly is defined as everything from the half-shaft to the tire contact patch on the road (wheel bearings, brake system, and tires). The losses were measured and the data were used to develop simplified regression polynomials that predict the losses as a function of the wheel assembly thermal state. Engineering solutions to the losses presented in this paper may require an alternate method of calculating the real-world effects to properly account for real-world fuel consumption reduction.

APPROACH AND TEST SETUP

Tests were conducted at Argonne National Laboratory's (Argonne's) Advanced Powertrain Research Facility (APRF) two- and four-wheel-drive dynamometer test cells [15]. The four wheel-drive (4WD) dynamometer test facility is designed to handle light- to medium-duty sized (maximum 6,350 kg) vehicles capable of producing up to 373 kW of wheel power. The test cell is EPA 5-cycle-capable with an ambient temperature capability from -20°C to +36°C. A vehicle speed-matching simulation fan fulfills the test regulations for the SC03 air-conditioning test. The cell also contains solar lamps simulating real-world solar loading, with a typical target solar loading of 850 W/m² at the windshield base or rear window. The test cell contains emission benches measuring the criteria emissions of total hydrocarbons, oxides of nitrogen, carbon monoxide, and soot, as well as carbon dioxide for cycle fuel economy. A turbine wheel fuel cart is used to accurately measure fuel.

Additionally, wheel hub chassis dynamometer tests were conducted at the APRF two wheel-drive (2WD) facility to separate out tire from wheel assembly losses. This test cell is not EPA 5-cycle-capable, as ambient temperature is kept at only 22°C. However, the 2WD facility contains a nearly identical data acquisition capability as the 4WD facility. Dynamometers were connected directly to the wheel hubs (removing the tire/wheel assembly altogether), allowing for the separation of tire losses from the bearing/brake losses for the front axles on the conventional vehicle. The hub dynamometers are capable of absorbing 200 kW of power with a maximum torque of 1,902 Nm continuous. Torque uncertainty is cited as <1% of measured value, with speed uncertainty at 0.1 rpm. Measured repeatability is listed at 0.05%. Tests were conducted in which simulated Urban Dynamometer Driving Schedule (UDDS) cycles were driven in addition to stair-step velocity profile tests in which the hubs were driven directly by the dynamometers.

In this work, two vehicles were tested: a 2011 Ford Fusion conventional and a 2013 Ford Focus battery electric vehicle (BEV). The test vehicles and the APRF test facility are shown in Figure 3 and

Figure 4. The Ford Fusion connected to the wheel hub dynamometer system is shown in Figure 5. Table 1 summarizes information about the vehicle configurations.



Figure 3. 2011 Ford Fusion test vehicle on Argonne's APRF dynamometer for testing.



Figure 4. 2013 Ford Focus BEV test vehicle on Argonne's APRF dynamometer for testing.

For instrumentation, strain-based torque measurement systems were installed on the front wheel half-shafts. This enabled measurement of the transmission output torques and power levels. The half-shaft torque measurement transmits torque signals from rotating shafts to a stationary telemetry receiver. Strain gages are bonded to the half-shafts and measure a rotational strain. This signal is then transmitted to a receiver and matched to a calibration curve. Power to the pickup is supplied to the telemetry slip ring collar inductively through a stationary loop adapter. Full-scale torque measurements were set at 3,400 Nm with a maximum static measured error of 0.2%. The system installed on the 2013 Ford Focus BEV may be seen in Figure 6.

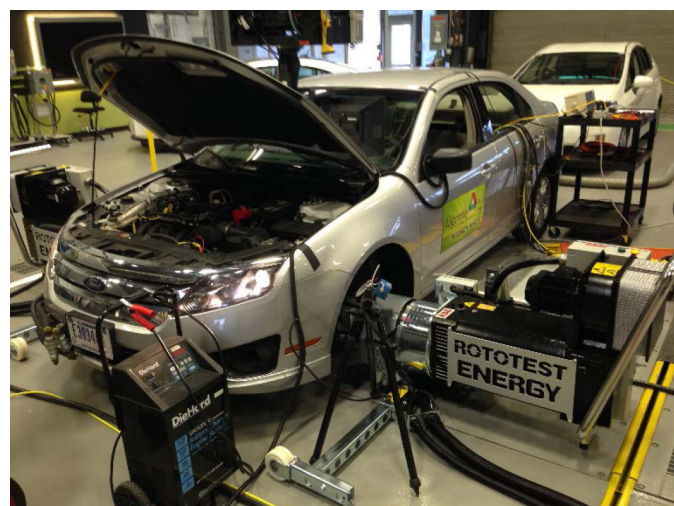


Figure 5. Ford Fusion wheel hub chassis dynamometer testing.

Table 1. Test vehicle specifications.

	2011 Ford Fusion conventional gasoline	2013 Ford Focus BEV
Drive	Front-wheel drive	Front-wheel drive
Engine/Motor	2.5L DOHC port-fuel injected aluminum engine	107 kW synchronous AC induction motor
Transmission	6-speed, hydraulic torque converter, automatic transmission	Single-speed direct drive
Battery	None	23k Wh, 320V, liquid heated/cooled lithium-ion battery system
Range (cited)	385/560 (city/hwy)	76 miles (EPA certified)
Wheelbase	272.8 cm	264.9 cm
Vehicle Test Weight	1,490 kg	1,674 kg

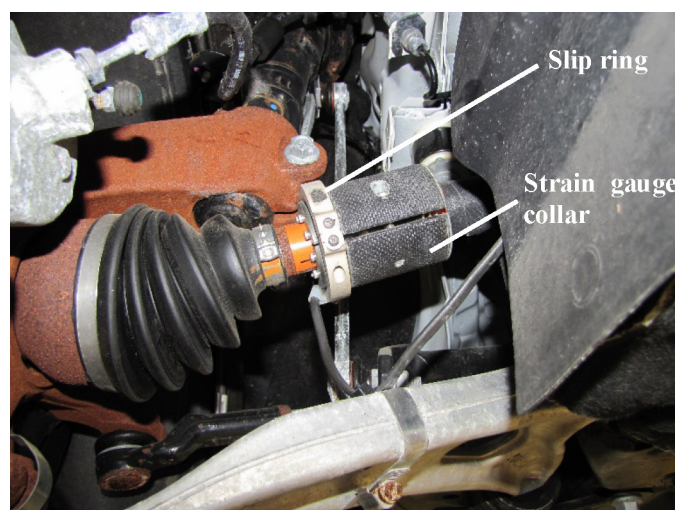


Figure 6. 2013 Ford Focus BEV half-shaft torque sensing system. An identical system was used for the 2011 Ford Fusion.

To calculate total half-shaft power, rotational speed measurements of the wheels were recorded directly. The power at the contact patch of the wheel and the dynamometer roll was recorded via the dynamometer load cell. The wheel hub dynamometer power was recorded by the wheel hub motor load cells. For this work, more complex instrumentation was not added to measure bearing surface or bearing grease temperature. As a proxy thermal signature, tire surface temperature was recorded by a stationary infrared sensor. The sensor was mounted to the dynamometer floor and pointed to the midpoint of the tire sidewall for both vehicles. [Figure 7](#) depicts the pertinent energy nodes collected for this work.

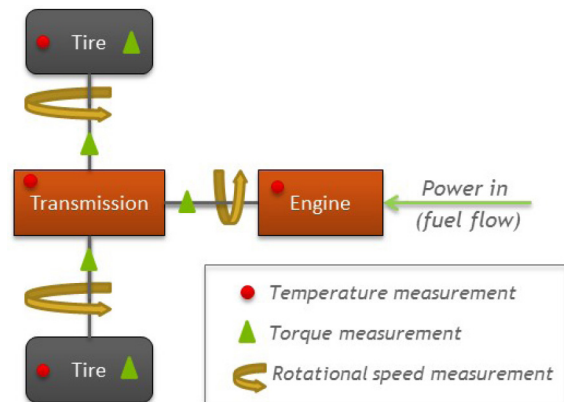


Figure 7. Test vehicle instrumentation layout.

EPA urban or US06 driving schedules were used for analysis at four ambient temperatures (-17°C, -7°C, +22°C, and +35°C) for the conventional vehicle and three temperatures for the BEV (7°C, +22°C, and +35°C). Vehicles were soaked at these ambient temperatures overnight prior to testing. For each testing sequence, vehicles ran multiple back-to-back urban cycles until relative thermal stability of the wheel assembly was achieved. This stability was achieved for a different number of cycles depending on the vehicle, ambient temperature, and drive cycle. [Table 2](#) summarizes the testing conditions for both vehicles.

Table 2. Testing conditions to measure half-shaft efficiency.

Drive Cycles	UDDS, US06, stair-step steady state
Starting Conditions	Cold start, hot start
Test Cell Temperature (-7°C min temp. for BEV)	-17°C (Fusion only), -7°C, +22°C, +35°C

[Figure 8](#) displays four back-to-back UDDS cycles completed at -7°C ambient cell temperature. At the start of the test, the entire tire and wheel assembly is at the ambient cell temperature. As the vehicle drives the cycle, the powertrain system warms and efficiency changes. Measuring wheel assembly torque, speed, tire torque, and tire temperature allows for the output energy to be contrasted. Results to the tests follow.

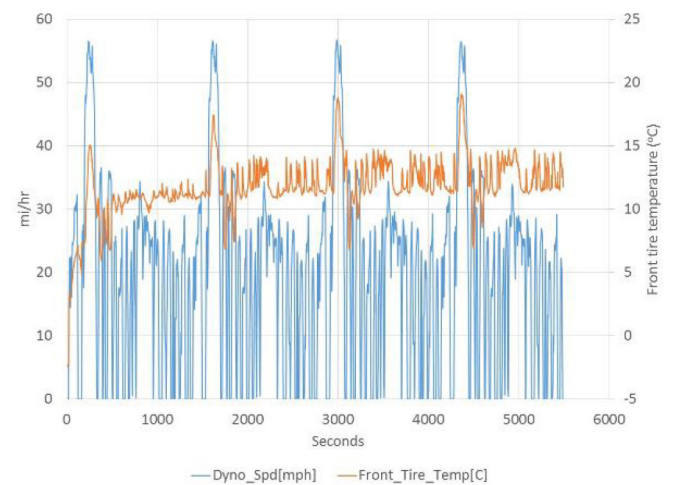


Figure 8. 2011 Velocity and tire temperature data over repeated UDDS cycles, with test cell at -7°C, Ford Fusion.

RESULTS

Conventional Powertrain Chassis Dynamometer Tests

The 2011 Ford Fusion was driven over a series of increasing and decreasing speed stair-steps. For 50-second increments, the vehicle remained at a constant speed followed by increasing velocity in increments of 10 mi/hr until 80 mi/hr was reached, then decelerated in mirrored increments. The test cell was kept at 20°C and the vehicle was fully warmed prior to testing. Half-shaft and dynamometer torques and speeds were recorded to calculate input and output power of the wheel assembly. Results from the full test are shown in [Figure 9](#), while details from that test are highlighted in [Figure 10](#).

Note that the half-shaft powers shown in this work are the sum of both driver and passenger sides.

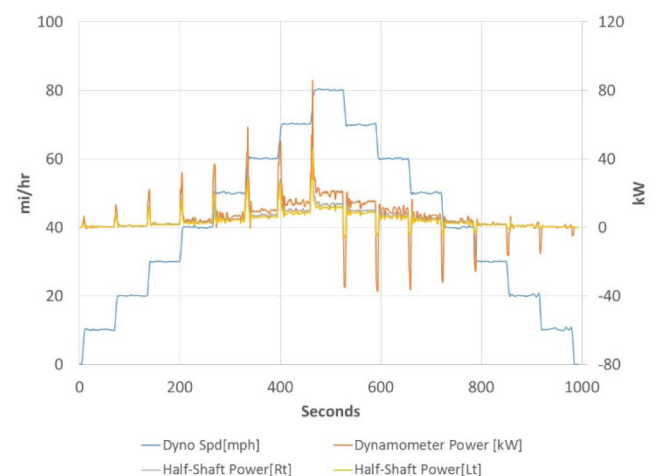


Figure 9. 2011 Half-shaft power, dynamometer power, and vehicle speed for stair/step tests, Ford Fusion.

In [Figure 9](#), there are a number of characteristics worth noting during steady-state and transient operation. The large positive power spikes present result from force impulses to accelerate the vehicle. Following a power spike are low-frequency damped oscillations that