

On-Road Validation of a Simplified Model for Estimating Real-World Fuel Economy

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ABSTRACT

On-road fuel economy is known to vary significantly between individual trips in real-world driving conditions. This work introduces a methodology for rapidly simulating a specific vehicle's fuel economy over the wide range of real-world conditions experienced across the country. On-road test data collected using a highly instrumented vehicle is used to refine and validate this modeling approach. Model accuracy relative to on-road data collection is relevant to the estimation of "off-cycle credits" that compensate for real-world fuel economy benefits that are not observed during certification testing on a chassis dynamometer.

CITATION: Wood, E., Gonder, J., and Jehlik, F., "On-Road Validation of a Simplified Model for Estimating Real-World Fuel Economy," *SAE Int. J. Fuels Lubr.* 10(2):2017, doi:10.4271/2017-01-0892.

INTRODUCTION

U.S. fuel economy standards are driving innovations in the automotive industry to meet the 2025 Corporate Average Fuel Economy target of 54.5 miles per gallon [1]. Some of these innovations, such as those influencing powertrain thermal response or driver behavior, can be difficult to assess using standardized chassis dynamometer testing over certification drive cycles. Discrepancies between certification and real-world fuel economy are problematic, both for regulatory bodies seeking to incentivize on-road efficiency and manufacturers pursuing credit for the actual efficiency benefits of their products.

One approach to overcoming discrepancies between tested and real-world fuel economy is to develop virtual models of vehicle efficiency that can be simulated under real-world conditions. Such an approach requires an understanding not only of how well fuel economy models can be calibrated to chassis dynamometer testing, but also of their predictive accuracy for real-world efficiency estimations.

This analysis quantifies the ability of a simplified powertrain model to predict real-world fuel economy. Vehicle data from chassis dynamometer testing of a conventional gasoline sedan are used to calibrate a simplified fuel economy model. The model's predictive performance is then quantified using on-road data collected from thousands of miles of real-world driving.

VEHICLE TESTING

The vehicle under inspection in this work is a 2011 Ford Fusion (2.5L, 6-speed automatic). Chassis dynamometer and on-road testing were conducted between 2014 and 2016 and are summarized in [Table 1](#).

Table 1. Testing summary on 2011 Ford Fusion.

Year	Test Conditions	Purpose
2014 (dyno)	Hot/cold starts on Urban Dynamometer Driving Schedule (UDDS)/US06 cycles at test cell temperatures from -17°C to +35°C	Measure cold start engine behavior
2015 (on-road)	2,843 miles of on-road driving under a variety of conditions	Measure on-road fuel economy
2016 (dyno)	Cold starts on UDDS/US06 cycles at -7°C and +22°C (with and without transmission oil preheating)	Measure cold start transmission behavior

Chassis Dynamometer Testing

Chassis dynamometer tests were conducted at Argonne National Laboratory's (ANL's) Advanced Powertrain Research Facility (APRF) [2] four-wheel-drive dynamometer test cell in 2014 and 2016. This 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 U.S. Environmental Protection Agency (EPA) 5-cycle capable with ambient temperature capability from -17°C to 35°C.

The test cell contains emission benches capable of bag measuring the criteria emissions (total hydrocarbons, oxides of nitrogen, carbon monoxide and soot) as well as carbon dioxide for cycle fuel economy. Additionally, a turbine wheel fuel cart is used to accurately measure fuel use in real time. An integrated data acquisition system allows for a multitude of controller area network, analog, and digital signals to be collected simultaneously. All data are collected and time aligned at 10 hertz frequency. The test vehicle and APRF test facility are shown in [Figure 1](#).



Figure 1. 2011 Ford Fusion test vehicle on APRF dynamometer for testing. Photo by Forrest Jehlik, Argonne National Laboratory

The vehicle was extensively instrumented to capture pertinent thermal and energy/power nodes. The engine was instrumented with K-type thermocouples to determine coolant, oil, air intake and exhaust temperature at various locations (including exhaust port to pre-, mid-bed, and post-catalyst). Additional K-type thermocouples were included in the transmission and vehicle interior. A strain-based torque measurement system was installed on the engine flex plate and half shafts, enabling measurement of engine out, transmission input, and transmission output torque and power. Flow measurements for fuel were calibrated within 1.8% of measured error. Engine speed and transmission gear were recorded via controller area network signals. [Figure 2](#) represents the pertinent instrumentation types and installation locations for the work.

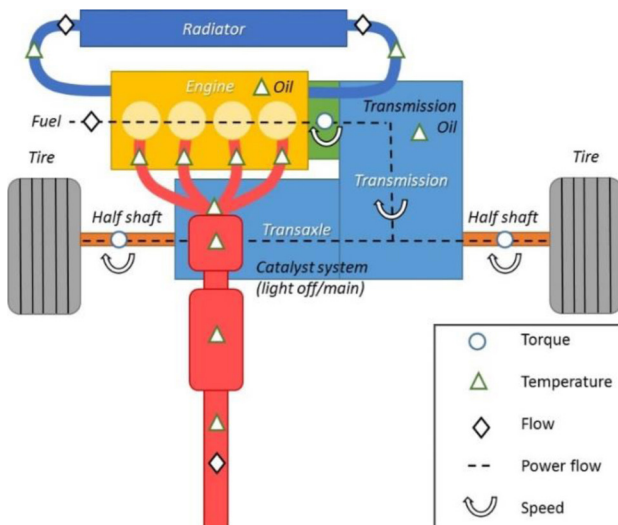


Figure 2. Test vehicle instrumentation layout.

The 2011 Fusion was tested for cold start engine performance in 2014 under the Urban Dynamometer Driving Schedule (UDDS) and US06 cycles at test cell temperatures ranging from -17°C to $+35^{\circ}\text{C}$. Each of these cycles was tested from cold and hot start conditions. The 2011 Fusion was tested again in 2016 as part of a sensitivity analysis on transmission oil temperature. APRF testing in 2016 included UDDS and US06 cycles at -7°C and $+22^{\circ}\text{C}$ with each test conducted twice: 1) with the entire vehicle thermally soaked to test cell temperature; and 2) with the entire vehicle soaked except for the transmission, which was preheated using external heating elements. Transmission preheating was done at a component-level thermal perturbation to exaggerate fuel economy impacts of transmission oil temperature (relevant to a separate effort).

On-Road Testing

The 2011 Ford Fusion was modified for on-road testing in 2015 by rerouting all analog and digital measurements to a mobile data acquisition system. Since fuel consumption is measured externally during APRF chassis dynamometer testing, an inline fuel flow meter was installed on the Fusion for on-road fuel economy measurement. The Fusion is shown during 2015 on-road testing in Colorado in [Figure 3](#).



Figure 3. 2011 Ford Fusion test vehicle during on-road testing in Colorado. Photo by Eric Wood, NREL

Sample time series data from on-road testing is shown in [Figures 4 to 7](#). For on-road testing, the fueling rate is derived from the inline flow meter; pedal position, and engine speed are obtained from the vehicle's controller area network signals; thermocouple and strain gauge torque measurements are retained from APRF instrumentation; and vehicle elevation and road grade are post-processed using global positioning system latitude/longitude coordinates per [3].

The vehicle was driven from ANL in Chicago, Illinois, to the National Renewable Energy Laboratory in Golden, Colorado. This trip enabled collection of a large volume of on-road data under a variety of highway speed, elevation, and road grade conditions. Once in Colorado, the vehicle was tested in a mix of city and highway conditions with various levels of traffic congestion. Colorado testing included three trips along the I-70 corridor into the Rocky Mountains,

notorious for extended stretches of steep grade. On-road testing footprints are shown in Figures 8 to 11 at various levels of magnification.

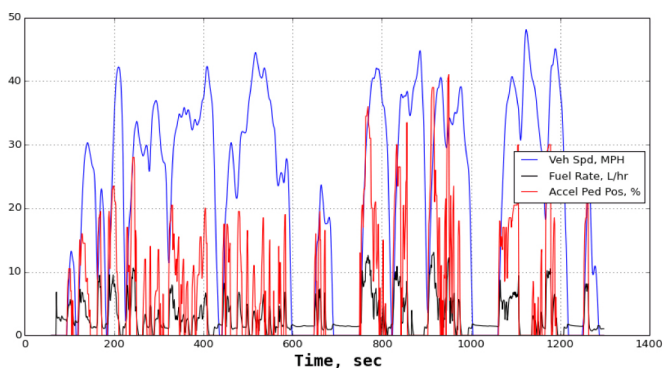


Figure 4. Vehicle speed, fuel rate, and pedal position.

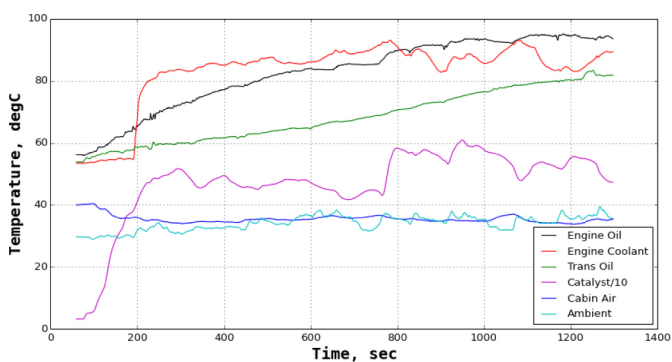


Figure 5. Temperatures (oil, coolant, transmission, catalyst, cabin, ambient).

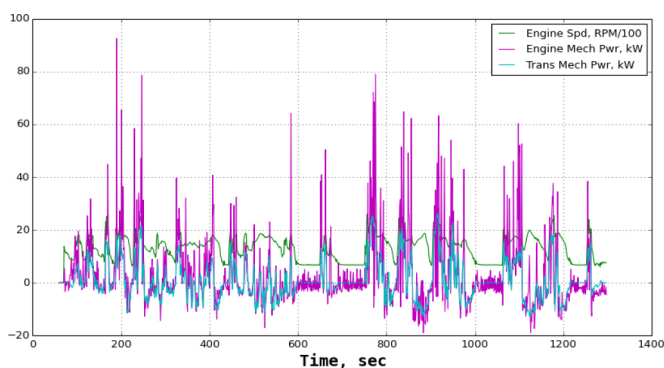


Figure 6. Engine speed and power, transmission power.

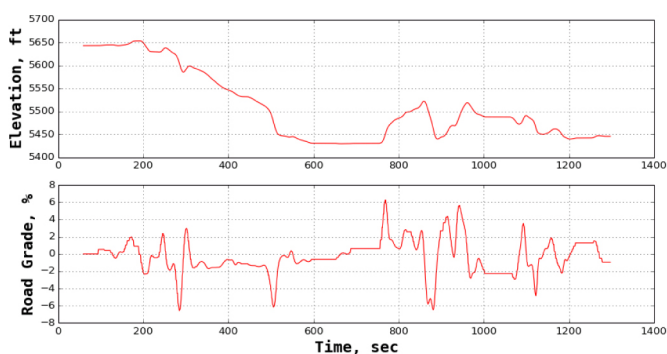


Figure 7. Elevation and road grade.



Figure 8. Rural interstates.

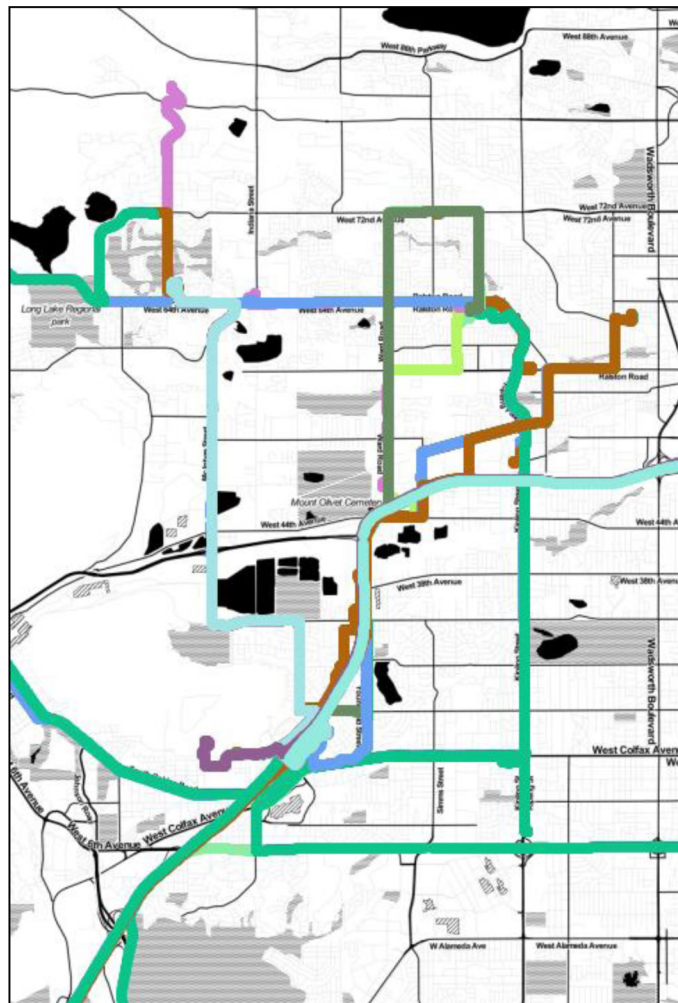


Figure 9. Arterial, collector, and local routes.

On-road data are summarized in Table 2 in terms of average driving speeds, initial engine oil temperature, ambient temperature, elevation, and road grade. The on-road dataset contains a mix of various driving conditions known to impact fuel economy.