

Response Surface Energy Modeling of an Electric Vehicle over a Reduced Composite Drive Cycle

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ABSTRACT

Response surface methodology (RSM) techniques were applied to develop a predictive model of electric vehicle (EV) energy consumption over the Environmental Protection Agency's (EPA) standardized drive cycles. The model is based on measurements from a synthetic composite drive cycle. The synthetic drive cycle is a minimized statistical composite of the standardized urban (UDDS), highway (HWFET), and US06 cycles. The composite synthetic drive cycle is 20 minutes in length thereby reducing testing time of the three standard EPA cycles by over 55%. Vehicle speed and acceleration were used as model inputs for a third order least squared regression model predicting vehicle battery power output as a function of the drive cycle.

The approach reduced three cycles and 46 minutes of drive time to a single test of 20 minutes. Application of response surface modeling to the synthetic drive cycle is shown to predict energy consumption of the three EPA cycles within 2.6% of the actual measured values. Additionally, the response model may be used to predict energy consumption of any cycle within the speed/acceleration envelope of the synthetic cycle. This technique results in reducing test time, which additionally provides a model that may be used to expand the analysis and understanding of the vehicle under consideration.

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INTRODUCTION

Chassis dynamometer testing of electric vehicles (EVs) using the standardized EPA drive cycles has been shown to be rather time intensive due to the high energy capacity of the battery systems. This greatly increases cost of testing and reduces testing facility output. Additionally, such testing is limited in predicting energy consumption for other drive cycles.

The operation of most EVs is less complex in comparison to vehicles powered by internal combustion engines. Transmissions are typically not present in EVs, therefore motor and vehicle speed is directly proportional. Such factors result in consistent power consumption characteristics for EV's. In this way, the electrical power required to propel an EV at any given operating condition is largely a state-dependent function, i.e. the power requirement is characterized primarily by the instantaneous operating state of the EV. This state dependence simplifies the EV energy efficiency evaluation.

In real world use, various electrical accessories on the EV consume additional power. This paper does not consider such auxiliary power loads. It may be expected that the energy consumed by the auxiliary loads can be treated independently from the drive motor energy consumption and the total energy used can then be determined by summing all of the separate energy sinks.

This paper demonstrates application of RSM techniques to estimate the electrical energy consumption of an EV following a given drive cycle. An abbreviated synthetic drive cycle was developed that includes speed and acceleration operating states contained in the UDDS, HWFET, and US06 drive cycles. This approach is intended to accurately estimate EV consumption for the standardized test cycles. Additionally, the model output allows accurate energy consumption predictions over drive cycles for which acceleration and velocity data are contained within the composite drive cycle's operational envelope. Although other methods may be used to model power use from experimental data, RSM techniques have been shown to be accurate and easy to implement.

SYNTHETIC DRIVE CYCLE DEVELOPMENT

The starting point for RSM model development is generation of a data set representing the battery power consumption from the EV over a range of operating conditions (input factors). The measured operating states cover a representative subset of the operating conditions that will be evaluated so that the power consumption can be accurately represented by the model. For this analysis, the vehicle speed and acceleration were used to define the operating state.

For a general characterization of any given vehicle, it would be appropriate to conduct measurements covering the expected speed range of normal operation and for deceleration/acceleration levels spanning those for which the maximum regenerative braking torque is generated (up to the maximum acceleration capabilities of the EV). For the present study, the three standardized drive cycles: UDDS, HWFET and US06 were of interest. The UDDS cycle is intended to represent typical city driving conditions, HWFET represents highway driving under 60 mph, and US06 is a supplemental drive cycle containing more aggressive (high acceleration) operating conditions.

The combined drive cycles are shown in [Figure 1](#). A drive cycle analysis tool, referred to as the duty cycle generation tool (DCGen Tool), was used for analysis of the data and the creation of a reduced length composite drive cycle. The software, developed by the Oak Ridge National Laboratory (ORNL), is used to facilitate the creation of drive cycles whose characteristics closely match those of an original set of drive cycles with a reduction in the length of the output cycle. A detailed description of the tool is provided in the reference section[1,2]. The DCGen Tool is flexible in the particular criteria used for creation of the final drive cycle, yet its main purpose is to create a representative drive cycle that provides a synthesis of all data contained in the original cycle(s). For the purpose of the present analysis, the composite drive cycle was developed to include an extensive set of operating points from all three drive cycles. Since this analysis assumes that energy consumption of the EV is a function only of the operating state condition, there is no need to include any repetition of the speed-acceleration operating conditions from the original drive cycles in the synthetic drive cycle. However, this may be desirable for other systems requiring additional model input variables.

To develop the synthetic drive cycle from the UDDS, HWFET and US06 cycles, analysis of the operating states was first conducted by considering the bivariate distribution of speed/acceleration. The speed and acceleration bin sizes were set in the DCGen Tool as desired to define the resolution of each operating condition. The combined cycle's total duration is 2734 seconds, and there are a total of 2052 distinct speed-acceleration operating conditions. Using a bin size of 0.1 m/s² for accelerations and 1 mph for speeds, 964 bins were included in the combined drive cycle. The bivariate histogram for this bin size is shown in [Figure 2](#).

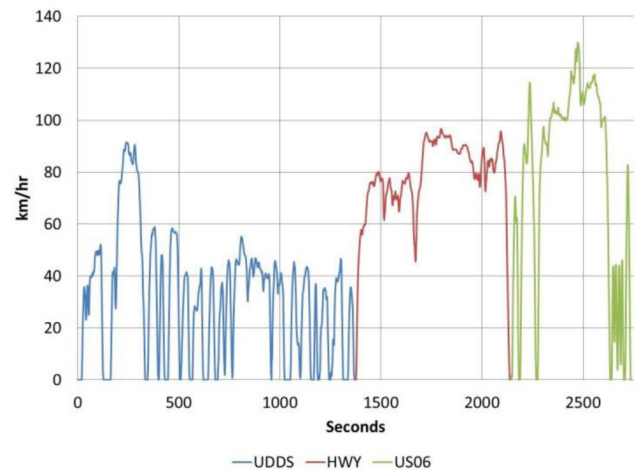


Figure 1. UDDS, HWFET and US06 drive cycles, combined.

For an EV, it is expected that the motor power varies little for speed and/or acceleration variations within a given bin of this size. It is probable that a synthetic cycle based on a coarser bin size would not deteriorate the ability of the RSM approach to approximate the power during each drive cycle using measurements based on the synthetic cycle. For the intended analysis, it was desired to have all of the operating states included in the synthetic cycle so that each condition could be evaluated directly from a measurement of the shortened cycle. (It is noted that prior analysis with the DCGen Tool was aimed at approximating the frequency of each operating state from relatively large quantities of measured test data using the synthetic cycle. However, no repetitions are needed in the cycle to be used for the current testing and analysis.)

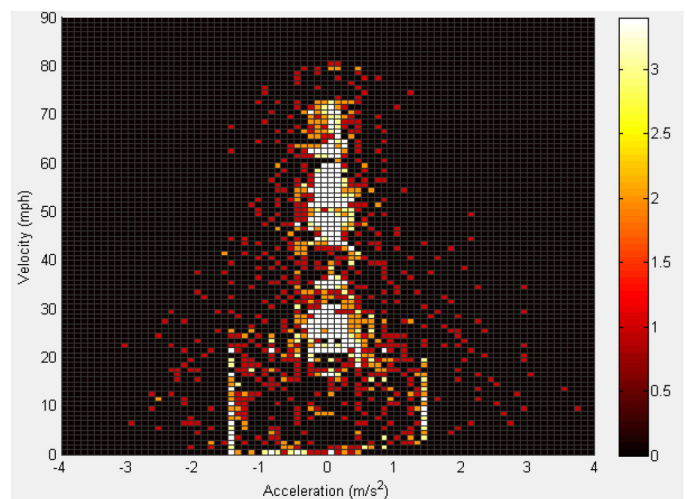


Figure 2. Bivariate speed-acceleration histogram of the combined cycle.

A synthetic cycle was sought that would be as close to 964 seconds—one second for each operating state contained in the original cycle's bivariate histogram—as possible. Since acceleration is the time derivative of the speed, the values defining each bin are not independent with respect to the speed trace, therefore it is improbable to generate a synthetic cycle that perfectly matches the original cycle's bivariate histogram.

drive cycle (which must continuously transition from one bin to another) that contains no repetitions or other extraneous states not included in the original histogram.

The synthetic cycle developed is shown in [Figure 3](#). The appearance of frequencies greater than one in the bivariate histogram for the synthetic cycle, (shown in [Figure 4](#)) indicates the repetition of several of the operating conditions in the synthetic drive cycle. Nonetheless, the original drive cycle was approximately 2.25 times longer in duration. Therefore the synthetic cycle provides a rather considerable reduction in the length of testing required for each vehicle relative to the complete drive cycles.

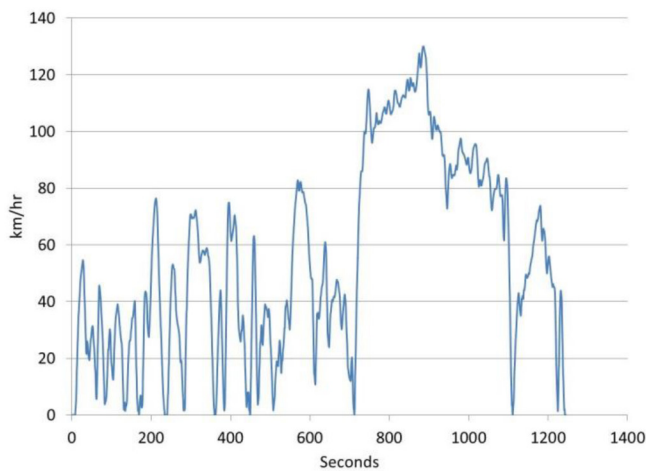


Figure 3. Speed trace for the composite synthetic drive cycle.

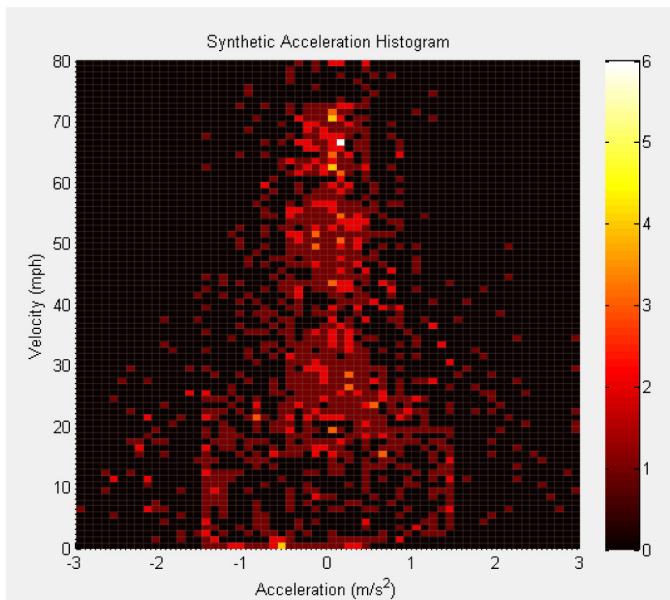


Figure 4. Bivariate acceleration-speed histogram for the synthetic drive cycle.

TEST SETUP

Tests were conducted at Argonne National Laboratory's (ANL) Advanced Powertrain Research Facility (APRF) four-wheel drive (4WD) dynamometer test cell. This 4WD drive dynamometer test facility is designed to handle light to medium duty sized (maximum 6350 kg) vehicles capable of producing 373 kW of wheel power. The test cell is EPA 5-cycle capable with ambient test ranges from -7°C to 36°C , including a fan system simulating wind proportional to vehicle speed. Data is collected and time aligned at 10 Hz frequency.

The test vehicle was a 2013 Ford Focus EV. For this work, test cell temperature was maintained at 22°C . Current clamps were located between the battery pack and the DC-DC converter. A voltage tap break out box that included its own fusing system was located at the DC-DC converter bus on the high voltage battery side allowing for power flow to and from the battery pack to be measured. No vehicle air conditioning or heaters were used. Vehicle specifications may be viewed in [Table 1](#).

Table 1. 2013 Ford Focus EV vehicle specifications.

Drive	Front wheel drive
Motor	107 kW synchronous AC induction motor
Transmission	Single-speed automatic
Battery	23kWh, 320V, liquid heated/cooled lithium-ion battery system
Range (cited)	76 miles (EPA certified)
wheelbase	264.9 cm
Vehicle Test Weight	1674 kg

For this testing, current and voltage measurements were collected using a Hioki power meter. The location of the current clamps and high voltage breakout box may be viewed in [Figure 5](#) and [Figure 6](#). The test vehicle itself may be viewed in [Figure 7](#). [Table 2](#) lists the pertinent test data signals collected.

Table 2. Instrumentation signal list.

Dyno_Spd [mph]
Dyno_TractiveForce [N]
Cell_Temp [C]
Cell_RH [%] (relative humidity)
Cell_Press [inHg]
Front_Tire_Temp [C]
Fan_Air_Spd [mph]
HVBatt_Volt_Hioki [V]
HVBatt_Curr_Hi_Hioki [A]
HVBatt_Curr_Low_Hioki [A]
DCDC_In_Curr_Hioki [A]
12VBatt_Volt_Hioki [V]
12VBatt_Curr_Hioki [A]