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A Simple Hybrid Electric Vehicle Fuel Consumption Model for Transportation Applications

Kyoungho Ahn and Hesham A. Rakha

Abstract

This study presents a simple power-based microscopic hybrid electric vehicle (HEV) fuel consumption model for use in microscopic traffic software and various connected and automated vehicle (CAV) applications, including eco-routing and eco-drive systems. While numerous HEV energy consumption models have been developed, these models are complex and require vehicle engine data deeming them difficult to implement and making them nontransferable. The proposed model was developed using empirical data for a 2010 Toyota Prius—the most popular HEV. The model was then extended to other HEVs thus extending the domain of application of the model. The proposed fuel consumption model estimates the instantaneous fuel consumption rates of an HEV using instantaneous vehicle operational input variables, including the vehicle's speed, acceleration, and roadway grade, which can be acquired from global positioning system (GPS) equipment or other sensors. The model estimates vehicle fuel consumption rates consistent with empirical data producing an average error of 2.1% for the Toyota Prius and up to 4% for other HEVs demonstrating the applicability and transferability of the model to various HEVs.

Keywords: HEV, energy model, fuel consumption model, Toyota Prius, microscopic model

1. Introduction

This study develops a microscopic hybrid electric vehicle (HEV) fuel consumption model that can be implemented in various transportation applications. In 2017, the transportation sector accounted for ∼71% of the world's total primary energy consumption [1]. Carbon dioxide (CO_2) emissions account for 98% of US emissions. Pollutions are mainly produced from the traditional combustion engines, including gasoline, diesel, and other heavy oils. Among fossil fuels, petroleum accounts for 92% of the total transportation energy consumption in the United States [2, 3].

Electric vehicles (EVs) utilize electricity for vehicle powertrain as either primary or to assist conventional vehicle designs. EVs are categorized as battery-only electric vehicles (BEVs), HEVs, and plug-in hybrid electric vehicles (PHEVs). HEVs use both a traditional engine and an electric motor. However, while PHEVs can plug into an electric source to charge a battery, HEVs are charged through regenerative braking and by the internal combustion engine and cannot be plugged in to charge the battery [4]. HEVs are more fuel efficient and produce lower tailpipe emissions

than the conventional internal combustion engine vehicles (ICEVs) and are typically easier and cheaper to build than PHEVs.

Connected vehicles (CVs) are an emerging technology that connects vehicles to other vehicles and to the road infrastructure using various vehicle communication technologies. CV technology is expected to generate transformative improvements in the roadway transportation system and will extend the benefits of intelligent transportation systems (ITSs) to entire networks by improving the efficiency, safety, energy consumption, and environmental footprint of the transportation system through the real-time exchange of information among vehicles and infrastructure. These technologies can assist drivers in avoiding congestion, reducing vehicle stops, and achieving optimal fuel efficiency. In order to evaluate the energy saving and the fuel efficiency of CV applications, simple and efficiency energy model is required. Many CV applications focus on improving the energy efficiency of various vehicle types, including electric vehicles (EVs). However, few fuel consumption models for HEVs have been developed for these CV applications.

A number of fuel/energy consumption models have been developed and employed to estimate the energy and environmental impacts of various transportation projects. Most models were developed with a special interest in measuring fuel consumption for transportation planning, transportation impact assessments, vehicle technology evaluations, traffic simulation models, and specific control conditions. Some models were developed to estimate the total fuel consumed and emissions of an entire network, city, or state, while other models were intended for a corridor or an intersection. While various models perform effectively their specific purposes, there are several requirements for an ideal fuel consumption and emission model that can accommodate real-time CV applications. A previous study [5] recommended four major criteria for eco-driving fuel consumption models: real-time computation, accuracy, model structure, and model calibration simplicity. Currently there are a number of HEV energy models; few HEV energy consumption models are eligible for real-time CV applications.

The objective of this study is to develop a microscopic HEV fuel consumption model that can be incorporated in CV applications. The proposed model estimates the instantaneous fuel consumption of HEVs using instantaneous vehicle operational input variables, including the vehicle's speed, acceleration, and roadway grade.

The paper is organized as follows: the next section reports the state-of-the art of HEV energy consumption efforts. Then, the paper describes the HEV fuel consumption data that were utilized for this study. The following section describes the proposed model development and validation. Finally, the conclusions of the study are presented.

2. Literature review

There are three types of HEV powertrain systems including series, parallel, and series/parallel systems [6]. A series powertrain system, which is typically efficient at stop and go operational conditions, uses electric power from either the battery or a generator produced by a vehicle engine. The series HEV system uses the gas engine to produce electricity for the electric motor. The series HEV controls the required power from the battery or the generator. Parallel HEVs utilize the battery electric motor and the engine in tandem. These vehicles typically use a small battery compared to series HEVs and operate the motor as a generator for recharging particularly when extra power is required [7]. Also these parallel HEVs are more efficient for highway driving conditions because the engine is directly connected to

the wheels. Series/parallel powertrain HEVs combine the benefits of other two HEV types [8–10]. Xiong et al. proposed a minimum-fuel energy control strategy by developing a fuel-optimum power management strategy of series/parallel hybrid [9]. Staunton et al. introduced the framework for a hybrid power control system and evaluated the Toyota Prius hybrid powertrain system [8]. The Toyota Prius is one of the most popular series/parallel drivetrain designs. The vehicle operates as a series HEV at low-speed and as a parallel HEV at high-speed conditions.

For all types of powertrains, the energy management strategies of most commercialized HEVs typically adopt rule-based methods to simplify switching operating modes [10, 11]. Mansour and Clodic demonstrated the model and design of the Toyota Prius hybrid powertrain system and developed a dynamic model of the electromechanical configuration [10]. Lin et al. designed a near-optimal power management strategy for a parallel hybrid vehicle and developed a fuel-optimum power management strategy [11].

A number of studies have developed control algorithms for HEVs. Barsali et al. developed a power control strategy to minimize fuel consumption for a series hybrid vehicle [6], and Delprat et al. developed an optimal control strategy for parallel hybrid vehicles by building a computationally efficient power control strategy to minimize fuel consumption [7]. Gao et al. proposed a fuel-optimized power control strategy for a series hybrid electric bus and developed a minimum-fuel power control strategy for a series hybrid electric vehicle [12].

Rule-based strategies are basically designed according to engineering intuition and simple analysis of component efficiency tables/charts [13]. For instance, Bowles developed a powertrain model and energy control strategy for a parallel hybrid vehicle and described new energy management strategies of HEVs.

A number of recent studies have investigated the impacts of the fuel/energy consumption of HEVs. For example, Fontaras investigated HEV fuel economy and pollutant emissions by measuring fuel consumption and emissions using various drive cycles. Fontaras et al. found that HEVs could save energy consumption and reduce vehicle emissions by up to 60% under urban driving conditions compared to ICEVs [14]. Al-Samari investigated the energy efficiency benefits of using HEVs in comparison to conventional vehicles using Autonomie and found that the fuel economy could be improved significantly (up to 68%) in a real-world driving cycle consisting of mostly city activity and up to 10% highway driving [15]. Oak Ridge National Laboratory researchers quantified the effects of aggressive driving with HEVs and the limitation of regenerative braking for HEVs. The study concluded that the limitation is a major reason to a bigger variation of HEV fuel efficiency data than the ICEV data [16].

The advanced vehicle simulator (ADVISOR) developed by the National Renewable Energy Laboratory (NREL) is one of the most popular models for estimating the fuel consumption of HEVs [17]. However, due to its complex modeling structure, it would be very difficult to implement ADVISOR into real-time eco-driving applications and CV applications. On the other hand, Boubaker et al. introduced an HEV energy model that employs a simplified module with two motors/generators (MGs) and planetary gear train (PGT) that estimates fuel consumption based on the engine speed (or RPM) and the output torque of the engine. However, the model also requires MATLAB/Simulink software to estimate model variables due to the complexity and was not validated against real-world data [18].

In recent years, a number of studies have investigated the modeling of HEV energy consumption. However, most of the developed HEV models are not general, cannot be calibrated to specific vehicles, or cannot be used in CV applications, due to the complicated vehicle-specific data requirements and/or the modeling structure. This study overcomes these problems by developing a new HEV energy model

that is general and transferable and can be easily used in various transportation applications. The proposed model does not require engine efficiency maps and calculates the fuel consumption of HEVs based on driving dynamics using vehicle speed, acceleration, and roadway grade data.

3. HEV energy consumption data

The study utilized a test dataset that was collected at the Advanced Powertrain Research Facility (APRF) at the Argonne National Laboratory. The test vehicle, a 2010 Toyota Prius, includes an Atkinson-cycle engine, two electric motors, and a power-split device used to control the allocation of energy between the electric and mechanical (fuel) power paths [19]. The data were downloaded from the Downloadable Dynamometer Database. The database is managed by the US Department of Energy (US DOE). APRF was built for vehicle benchmarking for the US DOE and utilizes two-wheel chassis dynamometers and four-wheel drive chassis
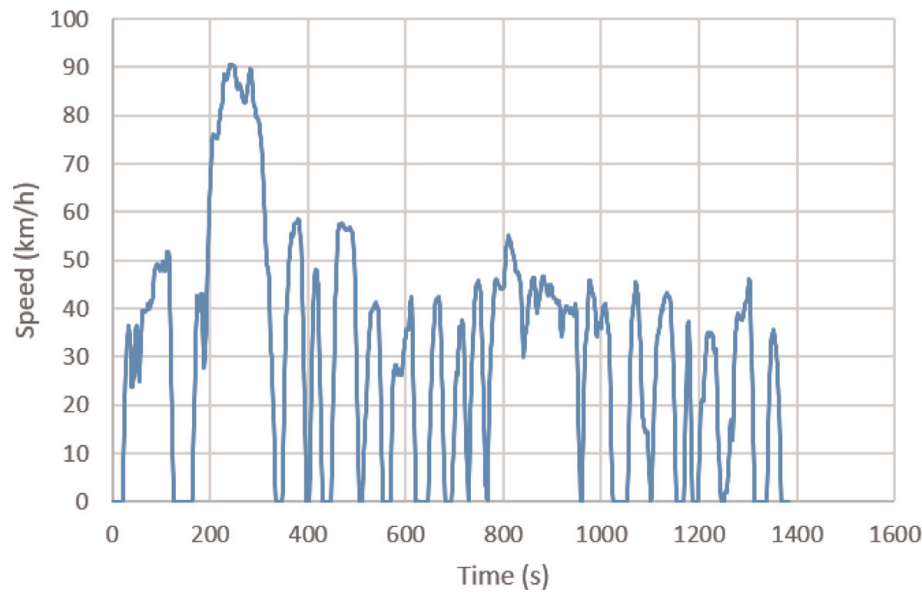
Figure 1.
UDDS (city) driving cycle.
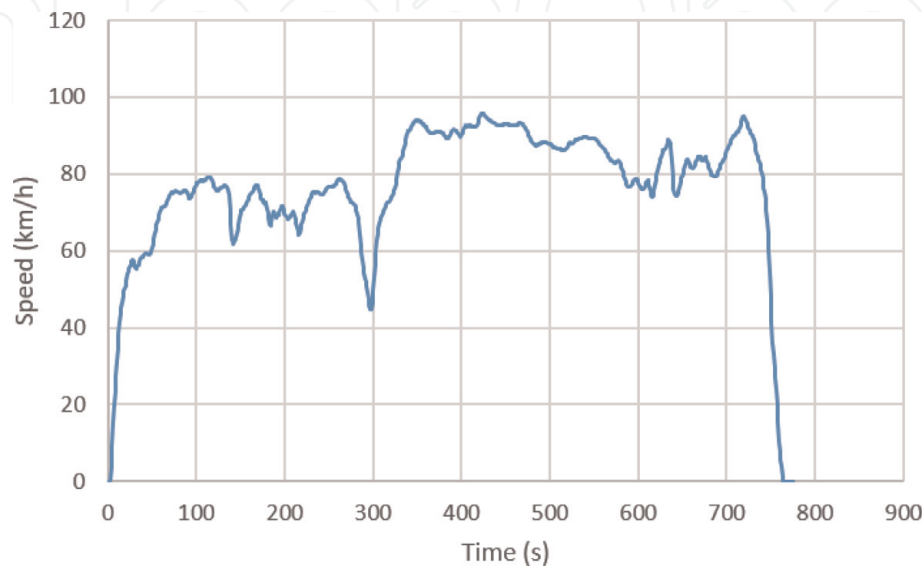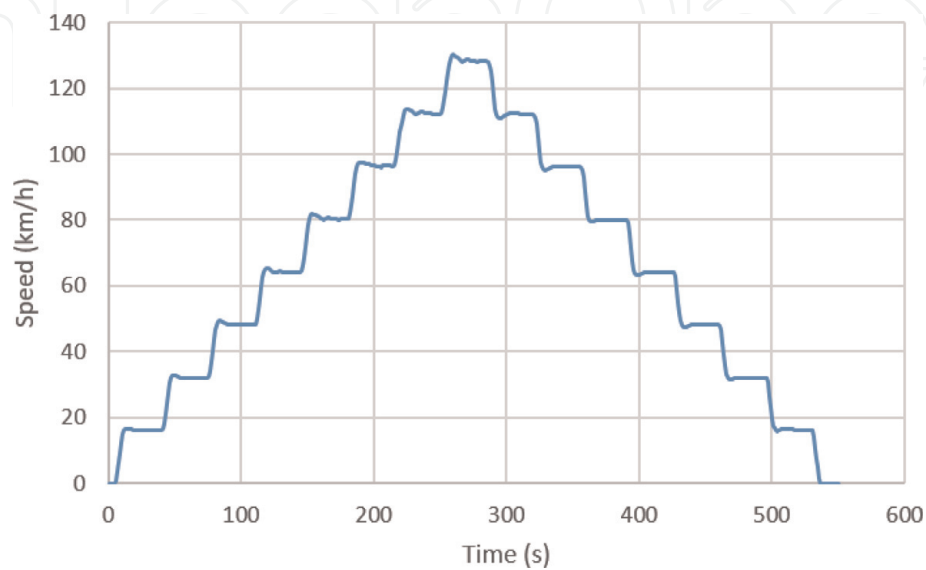

Figure 2.
Highway driving cycle.

dynamometers to collect vehicle energy consumption data, including both fuel and electricity, emissions, powertrain performance, and vehicle operational data. The test Toyota Prius data were collected using a two wheels chassis dynamometer.

APRF collected fuel consumption data for driving cycles: the Urban Dynamometer Driving Schedule (UDDS) (also referred to as the city test or LA4 cycle), Highway Fuel Economy Test (HWFET), the US06 cycle, and the steady-state speed cycle (or step speed cycle). This study utilized only hot-start trip data to only consider hot-stabilized conditions. **Figures 1–4** show the speed profiles of the four driving cycles. The UDDS represents city driving conditions and is typically used for light duty vehicle testing. The UDDS utilizes the same driving cycles of the Federal Test Procedure (FTP) without a cold start section, which is the first 505 seconds. The HWFET represents highway driving conditions at 96 km/h (60 mph). The US06 cycle is considered a "supplemental FTP" driving schedule and represents high-speed and aggressive-acceleration driving conditions. The steady-state speed cycle represents various steady-state speeds up to 128 km/h (80 mph).
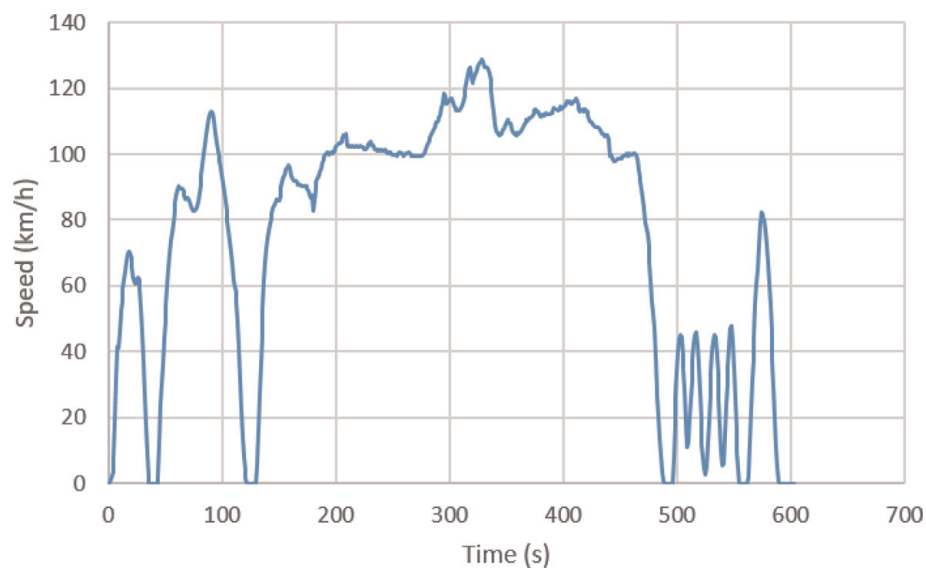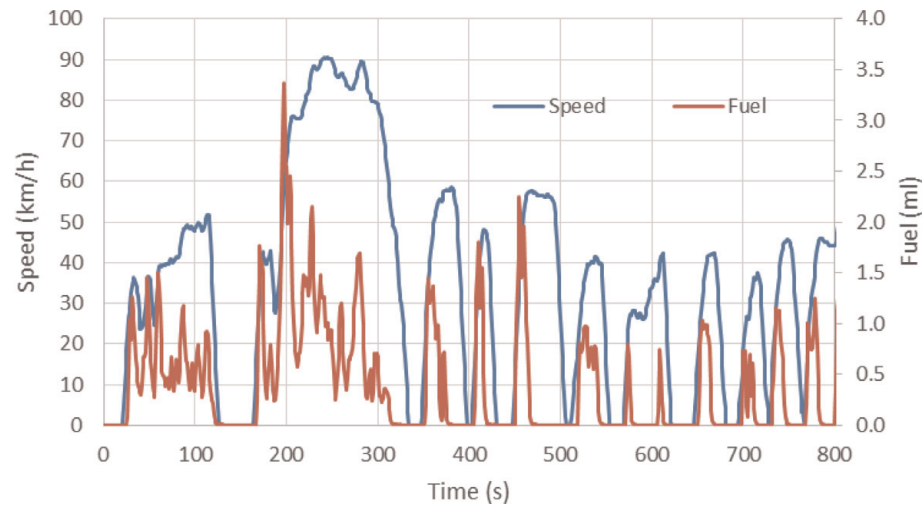

Figure 3.
US06 driving cycle.

Figure 4.
Steady-state speed driving cycle.

4. HEV energy consumption modeling

The study utilized a test dataset that was collected at the Advanced Powertrain Research Facility at the Argonne National Laboratory. The test vehicle, a 2010 Toyota Prius, includes an Atkinson-cycle engine, two electric motors, and a power-split device used to control the allocation of energy between the electric motor and the vehicle engine.

It is difficult to estimate HEV fuel consumption due to the complexity of the various ICE engine and electrical components. The powertrain of an HEV includes an internal combustion engine (ICE), two electric motors/generators (MG1 and MG2), a PGT, and a battery [18].

Figures 5 and **6** illustrate the variations in the vehicle fuel consumption for the UDDS cycle and the steady-state speed cycle. As illustrated in the figures, the fuel consumption rates are significantly affected by vehicle speed and acceleration levels. The figure demonstrates that the HEV uses only electric mode when significant vehicle power is not required, as shown in the case of the steady-state speed cycle.
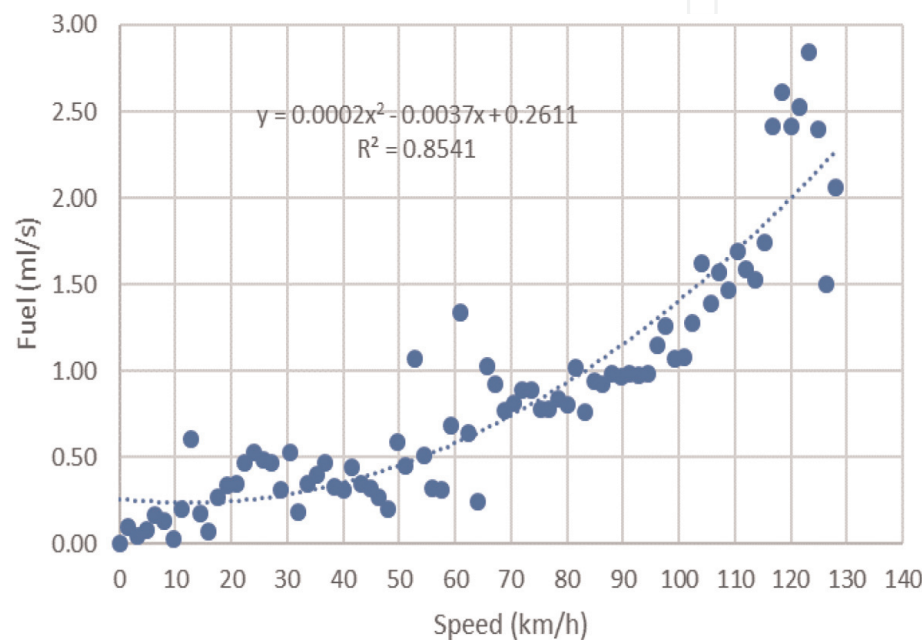

Figure 5.
*Fuel consumption of UDDS cycle.*
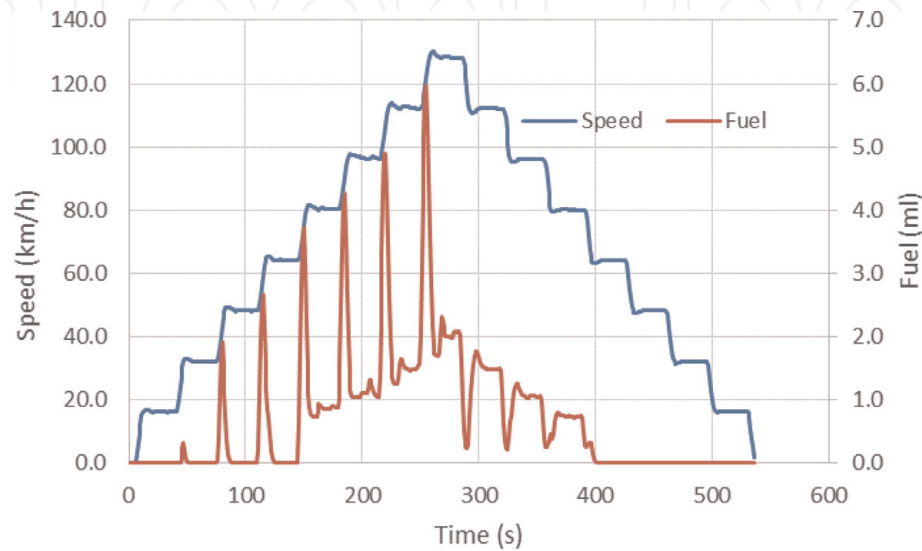
Figure 6.
Fuel consumption of steady-state speed cycle.

Figure 7 illustrates the relationship between vehicle speed and the fuel consumption rate from the Toyota Prius data. **Figure 8** shows the relationship between vehicle speed and power. The figures clearly show that fuel consumption is closely related to vehicle speed and power; as the test vehicle's speed increased, vehicle power increased proportionally.

We compared the speed observation and fuel data and found that there were time lags. In order to remove the temporal offsets, we utilized a procedure for offsetting the data and operational variables that was developed earlier [20] and applied it to the 2010 Toyota Prius data. We analyzed the test data and found the following HEV energy consumption behaviors. First, the amount of fuel consumed is proportionally related to both the vehicle power and speed; second, the HEV operates in EV mode when the power is negative; and third, the HEV utilizes only an electric mode when the speed is lower than an EV mode speed (v_a) and the

Figure 7.
Relationship between vehicle speed and fuel consumption.
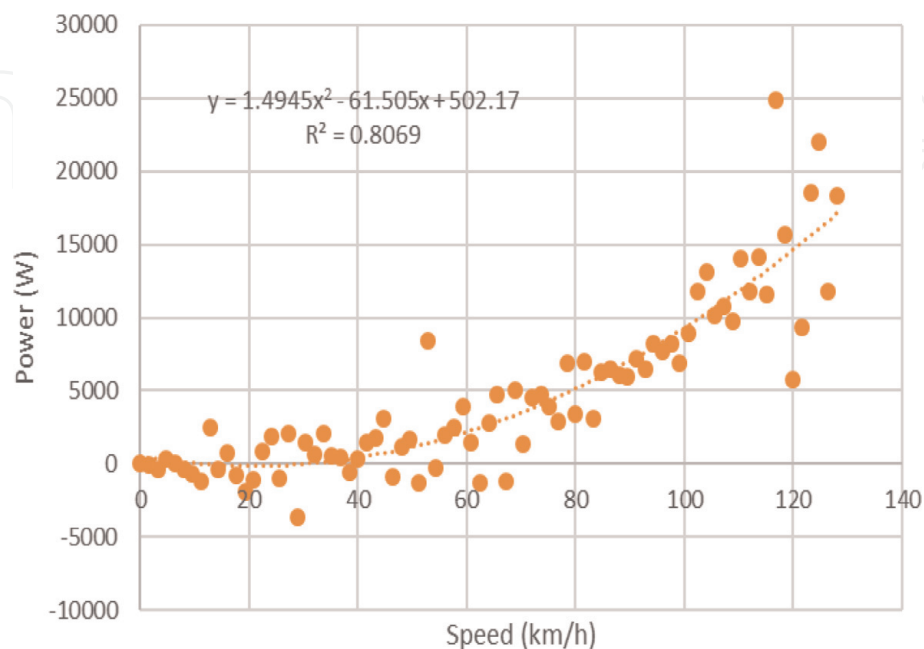
Figure 8.
Relationship between vehicle speed and power.

required power is lower than a specific power (P_a). Consequently, the proposed fuel consumption model is formulated in Eq. (1):

$$FC(t) = \begin{cases} FC_{EV\_mode} & \text{for} \begin{cases} P \leq 0 \\ v < v_a \text{ and } P < P_a \end{cases} \\ a + b*v(t) + c*P(t) + d*P(t)^2 & \text{for} \begin{cases} P > 0 \text{ and } v \geq v_a \\ v < v_a \text{ and } P \geq P_a \end{cases} \end{cases} \tag{1}$$

where $FC(t)$ is the fuel consumption rate (ml/s) and FC_{EV_mode} is the fuel consumption rate (ml/s) in EV mode and estimated as average fuel consumption in EV mode; $P(t)$ is the instantaneous total power in kilowatts (kW); and v is the instantaneous vehicle speed in kilometers per hour. Statistical analysis of the empirical data found that the optimum values for v_a and P_a are 32 km/h and 10 kW, respectively. The model coefficients a, b, c, and d for the 2010 Toyota Prius are 0.006, 0.003998, 0.077092, and $-9.155E-05$, respectively.

5. Model validation

Table 1 provides the fuel consumption results of the proposed model. The total fuel consumption for the UDDS, Highway, US06, and steady-state speed cycles, as measured in the laboratory, was 403.4, 576.8, 705.9, and 388.9 ml, respectively. The

Driving cycles	Raw data (ml)	Estimated fuel (ml)	Trip error (%)
UDDS	403.4	387.1	−4.1
Highway	576.8	611.2	+6.0
US06	705.9	668.2	−5.3
Steady-state speed	388.9	365.7	−6.0
Total	2075.0	2032.1	−2.1

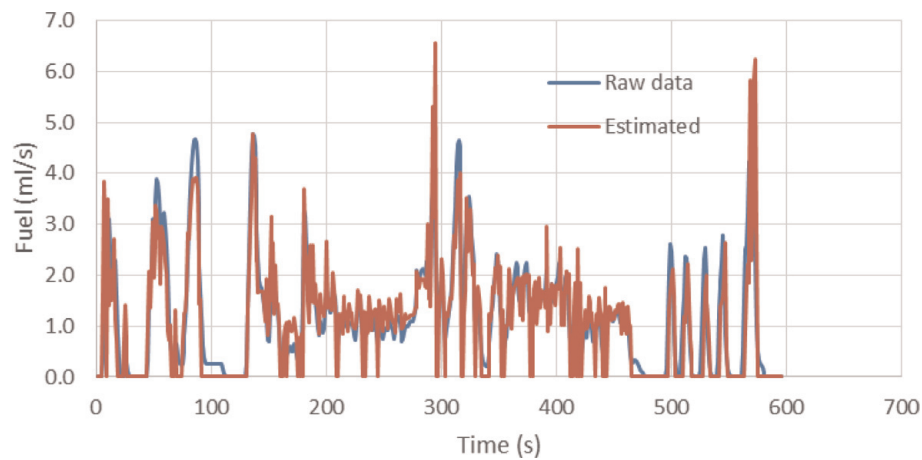**Table 1.**
Fuel consumption results.
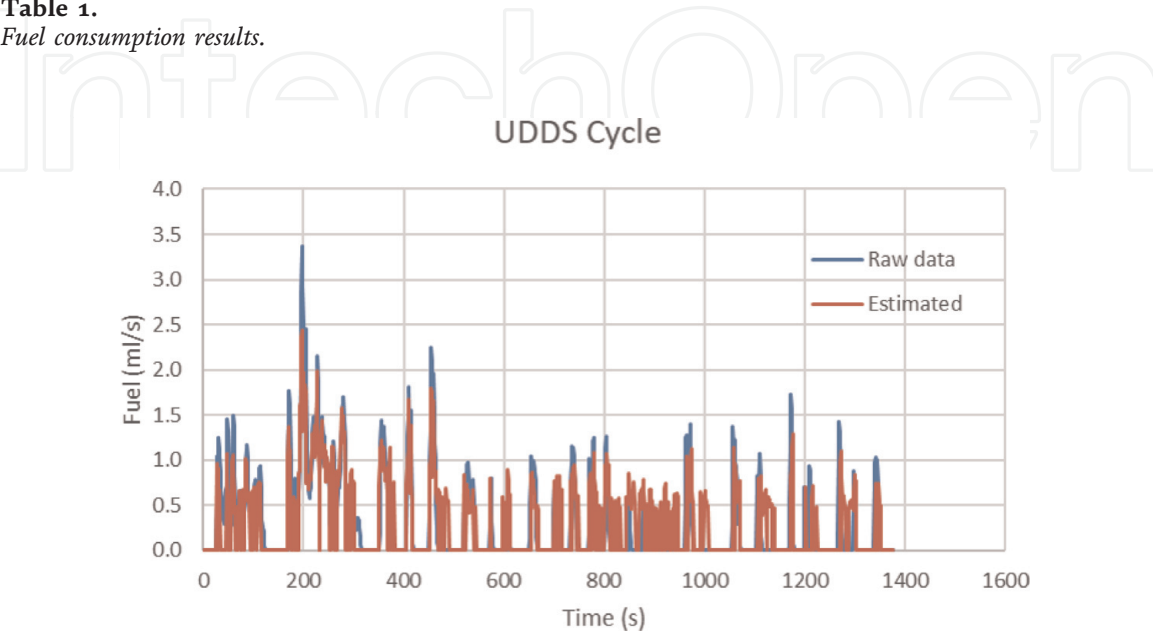
Figure 9.
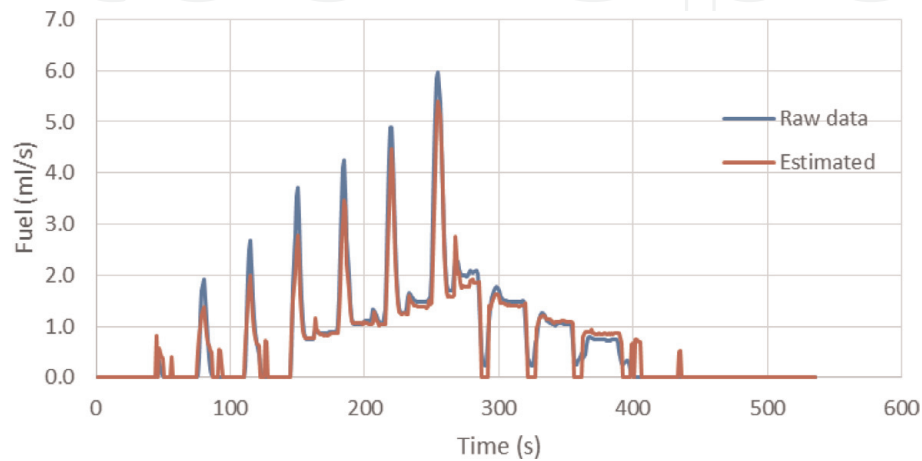*Instantaneous model validation (UDDS cycle).*

estimated fuel consumptions based on the proposed model were 387.1, 611.2, 668.2, and 365.7 ml, corresponding to a 4.1, 6.0, 5.3, and 6.0% difference in overall fuel consumption for each driving cycle.
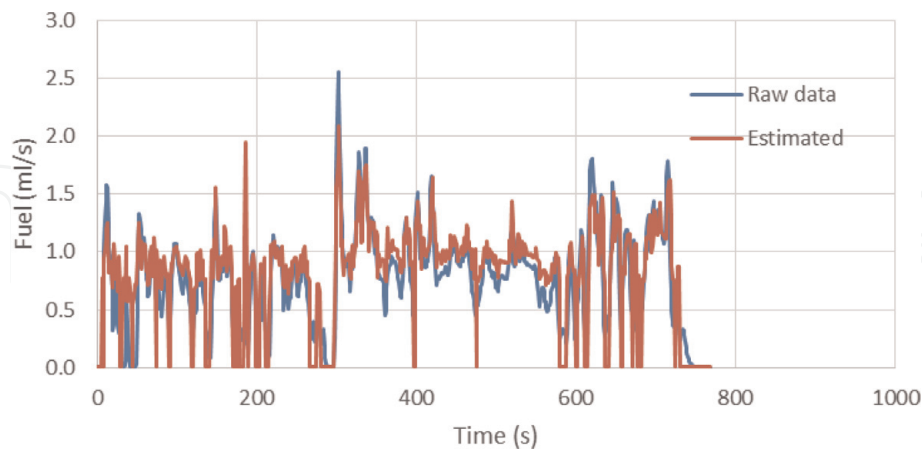
Figure 10.
Instantaneous model validation (highway cycle).

Figure 11.
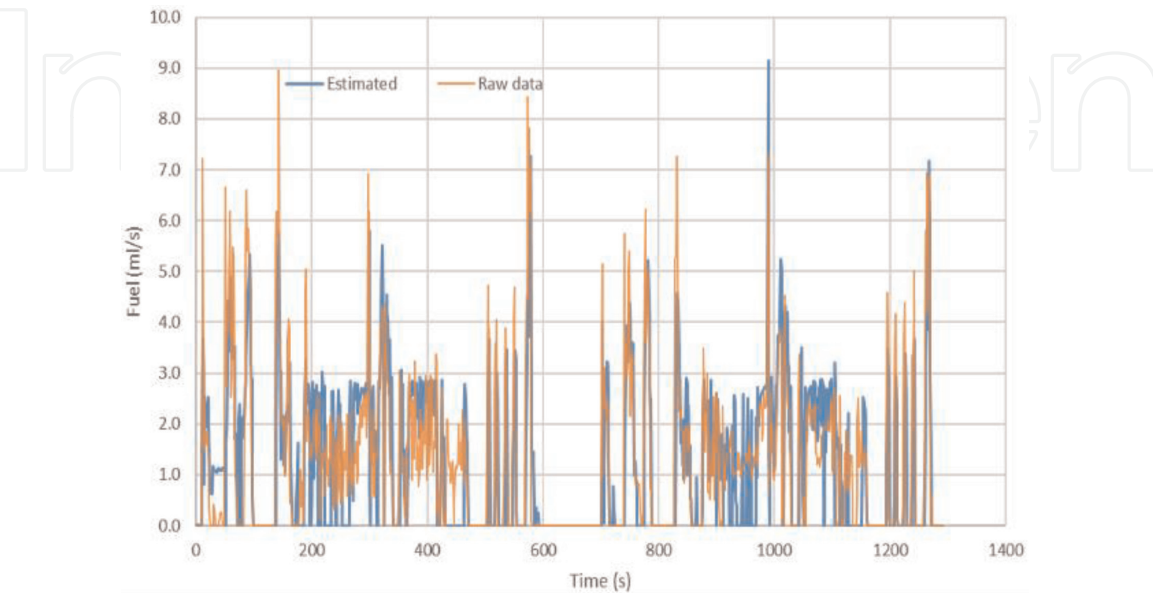*Instantaneous model validation (US06 cycle).*

Figure 12.
Instantaneous model validation (steady-state speed cycle).

9

Figures 9–12 illustrate the test vehicle's measured instantaneous fuel consumption rate for the four different driving cycles. The model estimates were calculated based on instantaneous power and vehicle speed levels. The figures show that the estimated fuel consumption generally follows the raw fuel consumption data. However, we found that the proposed model slightly overestimates or underestimates some fuel consumption rates for the four driving cycles. In particular, the proposed model slightly underestimates fuel consumption rates when the test vehicle accelerates from a steady-state speed. While the proposed model simplifies the conditional EV mode, the EV mode also depends on the state of charge (SOC) of the battery. The team will further investigate the impacts of SOC to improve the accuracy of the fuel consumption model. In general, however the model predictions follow the laboratory-collected fuel measurements of the steady-state speed cycle with a high correlation coefficient (0.951). The accuracy of the proposed model is good enough to assess the effects of transportation projects, including eco-driving and CV applications, to improve vehicle fuel economy.

6. HEV scale factor development

As demonstrated earlier, the 2010 Toyota Prius HEV energy model provides sufficient accuracy for use in various HEV applications. The study expanded the HEV fuel model to estimate the fuel consumption of various HEVs without specific calibration procedures. We tested various HEV fuel consumption models and found that the proposed scale factor method was the most accurate and efficient method. In particular, we utilize the EPA fuel economy data to estimate the second-by-second fuel consumption of HEVs. For example, the fuel economy of the 2010 Toyota Prius is 51 and 49 mpg for the city and highway cycles and 50 mpg for the EPA combined fuel economy. The fuel economy of the 2013 Honda Civic Hybrid is 43 and 44 mpg for the city and highway cycles, respectively, and 43.5 mpg for the EPA combined fuel economy. For the Honda Civic Hybrid, the relative difference of the combined fuel economy is 1.14 (50/43.5). We utilized this scale factor to

Figure 13.
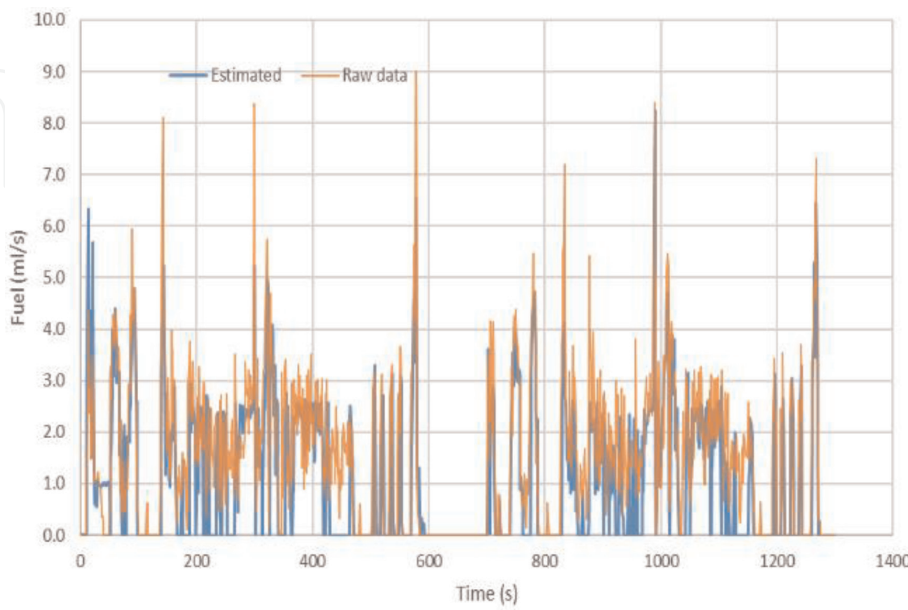*Instantaneous model validation (2013 VW Jetta hybrid).*
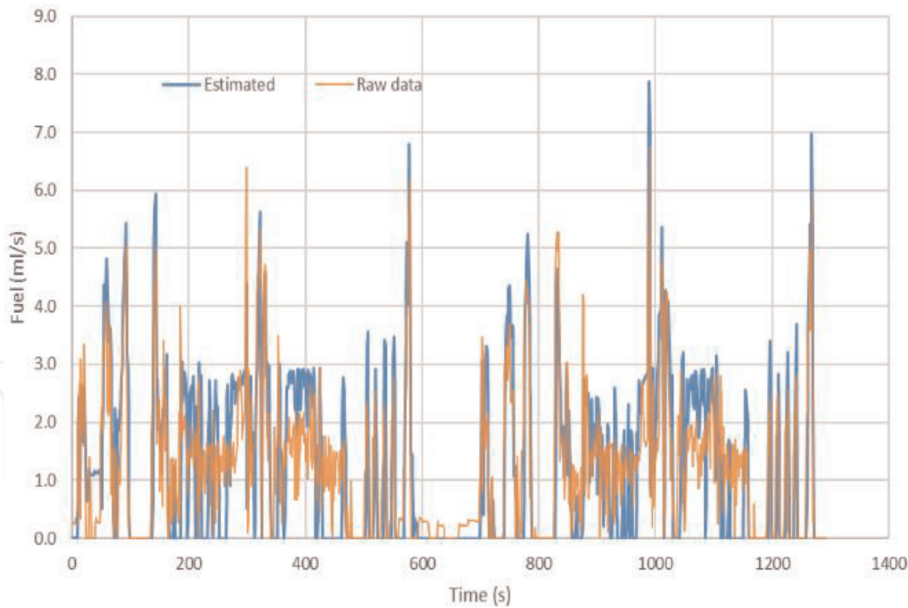
Figure 14.
Instantaneous model validation (2013 Honda civic hybrid).

estimate the energy consumption for the Honda Civic HEV. Consequently, the proposed fuel consumption model is formulated in Eq. (2):

$$FC(t) = \begin{cases} \left(FC_{EV_{mode}}\right) \times SC_i \text{ for } & \begin{cases} P \leq 0 \\ v < v_a \text{ and } P < P_a \end{cases} \\ \left(a + b * v(t) + c * P(t) + d * P(t)^2\right) \times SC_i \text{ for } & \begin{cases} P > 0 \text{ and } v \geq v_a \\ v < v_a \text{ and } P \geq P_a \end{cases} \end{cases} \quad (2)$$

where SC_i is the scale factor of vehicle i using the same v_a and P_a values of 32 km/h and 10 kW for the all test vehicles. **Figures 13–15** compare the measured and the estimated instantaneous fuel consumption rates for three different HEVs.
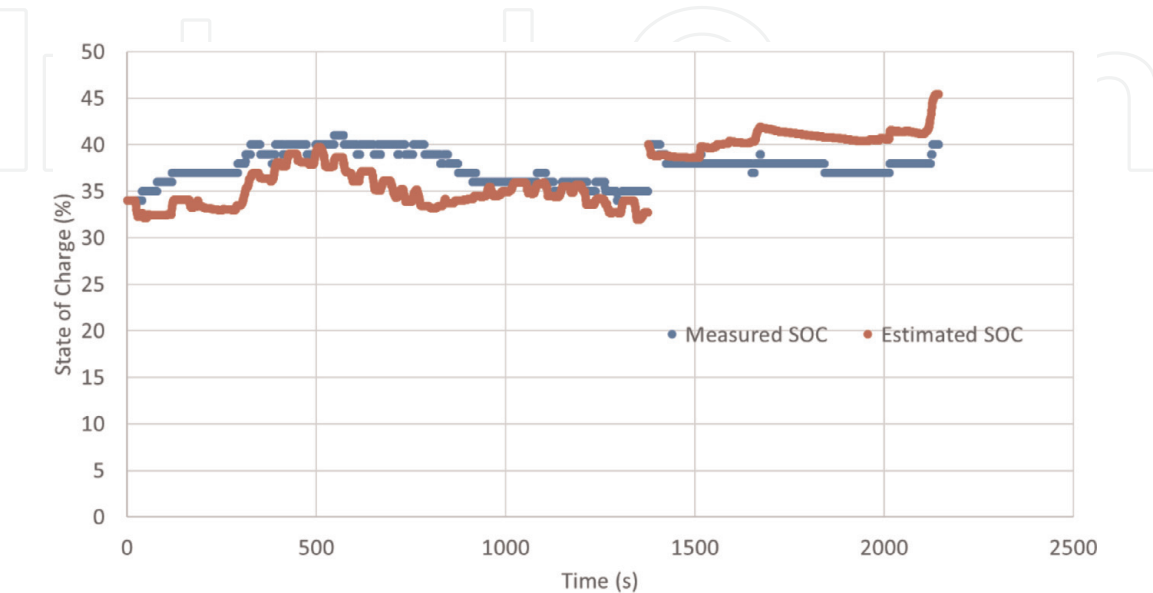

Figure 15.
Instantaneous model validation (2010 ford fusion hybrid).

We tested four HEVs that include a 2013 VW Jetta Hybrid, a 2013 Honda Civic Hybrid, and a 2010 Ford Fusion Hybrid. For the evaluation, we utilized the US06 driving cycle since it is a high speed and acceleration cycle and has aggressive driving behaviors with an average speed of 48.4 mph (77.9 km/h) and a maximum speed of 80.3 mph (129.2 km/h). As illustrated in the figures, the predicted fuel consumption generally follows the second-by-second measured fuel consumption. The measured fuel consumption for the 2013 VW Jetta Hybrid, 2013 Honda Civic Hybrid, and 2010 Ford Fusion Hybrid were 1.625, 1.583, and 1.924 L and the estimated fuel consumption was 1.564, 1.604, and 1.845 L, respectively. Consequently, the errors were 4, 1, and 4%, demonstrating that the proposed model could be utilized for various HEVs.

7. HEV state of charge evaluation

The state of charge (SOC) of the battery affects the energy consumption of EVs. Since HEVs can use an internal combustion engine, the relative impacts of SOC for HEV are smaller than the other EVs. However, when the SOC is low, HEVs must utilize an engine instead of using EV mode, and it reduces the fuel economy of HEVs. Thus, the EV mode of HEVs depends on the SOC of the battery. This study investigated how the SOC of HEVs changes during a trip.

Figure 16 illustrates the measured and the estimated SOC for the 2010 Toyota Prius. The study estimated the instantons SOC using an EV energy consumption model [21]. The model estimates instantaneous energy consumption of EVs using vehicle operational data. The figure shows the instantaneous SOCs of two trips, the UDDS (or the city cycle) and the highway cycles. The study found that the model occasionally underestimated and overestimated the HEV regenerative energy. As shown in the figure, the estimated SOC generally follows the measured SOC trend of the test HEV. However, we found that the estimated SOC of the highway trip generally underestimated the electric energy consumption and predicted a higher final SOC. The results demonstrate that the SOC remains fairly stable throughout the trip.

Figure 16.
The state of charge of HEV.

8. Conclusion

This study developed a simple fuel consumption model for a 2010 Toyota Prius HEV that can be utilized for CV applications. The model was then generalized for other HEVs using a scale factor that is computed as the ratio of the vehicle EPA combined rating relative to the Toyota Prius rating. The proposed model utilizes instantaneous vehicle speed, acceleration, and roadway grade as input variables. The model estimates the vehicle fuel consumption accurately with an average error of 2.1% for the Toyota Prius and up to 4% for different HEVs. Although this simple model serves the desired purpose, further refinement of the model could be achieved by refining the EV model to reflect the variations of fuel consumption at low speeds and low engine power levels.

Acknowledgements

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