Transportation Research Part D 63 (2018) 175–185

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Microscopic series plug-in hybrid electric vehicle energy consumption model: Model development and validation

Chiara Fiori[a], Kyoungho Ahn[b], Hesham A. Rakha[c,*]

[a] Università degli Studi di Napoli Federico II, Department of Civil, Architectural and Environmental Engineering (DICEA), Via Claudio, 21, 80125 Napoli, NA, Italy

[b] Center for Sustainable Mobility, Virginia Tech Transportation Institute, 3500, Transportation Research Plaza, Blacksburg, VA 24061, United States

[c] Charles E. Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Blacksburg, VA 24061, United States

A R T I C L E I N F O

Keywords:
Plug-in hybrid electric vehicles
Regenerative braking energy efficiency
Energy consumption
Emissions
VT-CPPM

A B S T R A C T

Plug-in hybrid electric vehicles (PHEVs) significantly improve vehicle fuel efficiency compared to conventional internal combustion engine vehicles (ICEVs) and also eliminate the “range anxiety” associated with battery-only electric vehicles (BEVs). This paper develops a simple PHEV energy consumption model that can be used in a real-time in-vehicle and smartphone eco-driving application, an eco-routing navigation system, and/or a microscopic traffic simulation software. The majority of PHEV studies have centered on the evaluation of energy consumption to analyze vehicle control strategies or the behavior of the battery system assuming an average constant value for the regenerative braking energy efficiency or regenerative braking factors that are principally dependent on the vehicle’s average speed. The proposed series PHEV energy consumption model estimates a PHEV’s instantaneous energy consumption using second-by-second vehicle speed, acceleration, and roadway grade data as input variables accounting for the regenerative braking efficiency using instantaneous vehicle parameters. The model developed in this study computes the vehicle’s energy consumption producing an average error of 4% relative to independently collected field data. Results show that PHEVs can recover a higher amount of energy in urban driving when compared to high speed highway driving. Finally, it is important to highlight the fact that this model is flexible and general and thus can model different PHEVs as there is no need for efficiency maps for the electric motor or the internal combustion engine.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) constitute a significant share of the total automobile market (Shao et al., 2009). For example, in 2015, 520,000 PHEVs were sold worldwide representing a 67% increase from 2014s sales of 315,000 PHEVs (Cobb, 2016). PHEVs have the characteristics both of conventional hybrids and battery-only electric vehicles (BEVs) (Goldman, 2014). Consequently, this study develops a microscopic PHEV energy model that can estimate second-by-second energy/fuel consumption levels of PHEVs using instantaneous vehicle speed and roadway grade inputs.

Reducing CO_2 emissions is a growing challenge for the transportation sector. The transportation sector accounted for approximately one third (27%) of the total world primary energy consumption in 2014 (U.S. Energy Information Administration (EIA), 2014). A recent study estimated that vehicle emissions from the transportation sector could increase at a faster rate when compared to emissions from other energy end-use sectors and could reach 12 Gt a year by 2050 (Edenhofer et al., 2014). PHEVs represent a

* Corresponding author.
E-mail addresses: chiara.fiori@unina.it (C. Fiori), kahn@vt.edu (K. Ahn), hrakha@vt.edu (H.A. Rakha).

https://doi.org/10.1016/j.trd.2018.04.022

Available online 26 May 2018
1361-9209/

Nomenclature

Nomenclature - Text

ADVISOR Advanced Vehicle SimulatOR
AVTA Advanced Vehicle Testing Activity
BEVs Battery Electric Vehicles
DOE Department of Energy
EC Energy Consumption
EG Electric Generator
EM Electric Machine
EREVs Extended Range Electric Vehicles
FC Fuel Consumption
GPS Global Positioning System
HWFET Highway Fuel Economy Driving Schedule
ICE Internal Combustion Engine
INL Idaho Nation Laboratory
PHEVs Plug-in Hybrid Electric Vehicles
SOC State Of Charge
TTI Texas A&M Transportation Institute
UDDS Urban Dynamometer Driving Schedule
US06 Supplemental Federal Test Procedure (SFTP) driving schedule
VT-CPEM Virginia Tech Comprehensive Power-based Energy consumption model
VT-CPFM Virginia Tech Comprehensive Power-based Fuel Consumption Model
VT-CPPM Virginia Tech Comprehensive Power-based PHEV Model

Nomenclature - Formulation

$a(t)$ acceleration of the vehicle
A_f frontal area of the vehicle
$\text{Capacity}_{\text{Battery}}$ capacity of the battery
C_D aerodynamic drag coefficient of the vehicle
C_r,c_1 and c_2 rolling resistance parameters
$FC(t)$ fuel consumption
g gravitational acceleration
m vehicle mass
$P_{Auxiliary}$ power due to the auxiliary systems
$P_{Electricmotor}(t)$ power at the electric motor
$P_{Electricmotormax}(t)$ power max of the electric motor
$P_{Electricmotor\,neg}(t)$ power while regenerative braking at the electric motor
$P_{Eletricmotor\,net}(t)$ electric power consumed considering the battery efficiency
$P_{ice}(t)$ power at the ICE
$P_{tot}(t)$ total power necessary for the traction of the vehicle
$P_{Wheels}(t)$ power at the wheels
$SOC_{Final}(t)$ final value of State Of Charge at the end of the Trip
SOC_{min} minimum level of the State Of Charge of the Battery System
SOC_0 initial value of State Of Charge at the begging of the Trip
$v(t)$ vehicle speed
α_0,α_1,α_2 vehicle-specific parameters using the VT-CPFM
ρ_{Air} air mass density
$\eta_{Battery}$ battery efficiency
$\eta_{Driveline}$ driveline efficiency
$\eta_{ElectricMotor}$ efficiency of the electric motor
η_{rb} regenerative braking energy efficiency
θ road grade

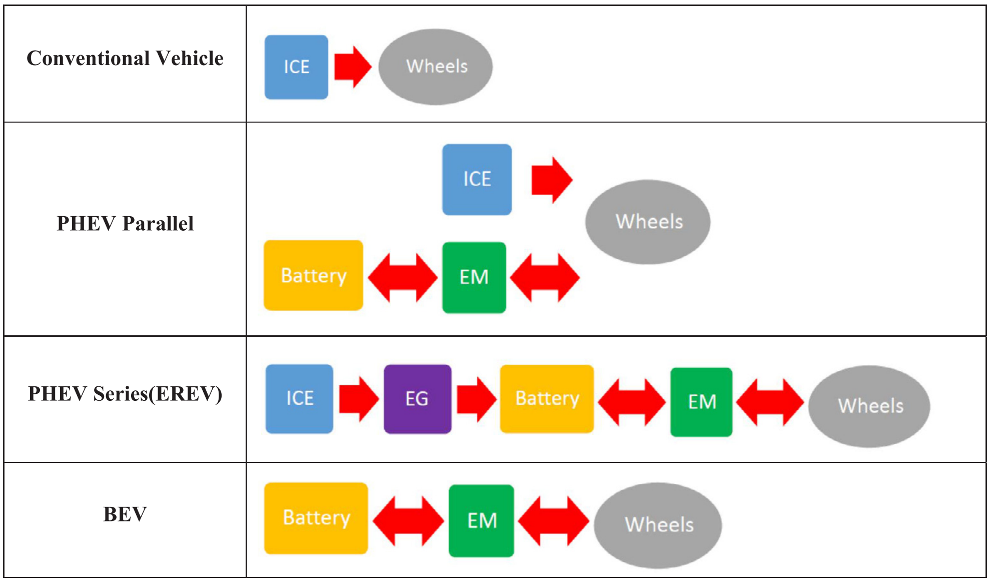

Fig. 1. Power flows for different vehicle types. In the figure: ICE is the Internal Combustion Engine, where EM is the Electric Machine that works as a motor to transfer energy to the wheels and as a generator to recover energy while braking and EG is the Electric Generator that works only to transfer energy from the ICE to the Battery system.

solution to reduce the CO_2 emissions, dependence on fossil fuels and improving the driving range of EVs.

According to the definition of Plug-in Electric Vehicles (PEVs) given by the U.S. DOE (Department of Energy of the United States) PEVs include BEVs (e.g. Nissan Leaf) and PHEVs. Furthermore, PHEVs include a PHEV blended/parallel (e.g. Toyota Prius Plug-in) type and an extended range electric vehicles (EREVs) (e.g. Chevy Volt) type, which is a series configuration. Fig. 1 illustrates the difference in the powertrains in the electrification process.

PHEVs can significantly improve vehicle fuel efficiency relative to conventional internal combustion engine vehicles (ICEVs) (Juul and Meibom, 2012). For example, the 2014 Chevy Volt can travel about 38 miles on the electric motor before the gasoline motor starts. This is very helpful in reducing vehicle fuel consumption and emissions because a recent study found that more than 50% of drivers travelm < 40 miles per day; meaning that a significant share of the Chevy Volt drivers would mostly use electricity, which is cheaper and cleaner than gasoline for most people (Goldman, 2014). Moreover, compared to BEVs, PHEVs have a lower price tag, a lighter battery system weight because of the lower amount of kWh installed on the battery pack, and a longer range. This leads to the elimination of the "range anxiety" issue (Sovacool and Hirsh, 2009).

The objective of this study is to develop a microscopic energy and fuel consumption model for PHEVs. In particular, the study focuses on the series configuration PHEV. The input variables to estimate the instantaneous energy/fuel consumption of PHEVs include the vehicle's instantaneous speed, acceleration, and roadway grade, which can be easily obtained from standalone GPS loggers or various smartphone applications.

A simple, accurate, and efficient energy/fuel consumption model is critical to quantify the PHEV's energy impacts and to develop a sustainable transportation system. Because of its simple modeling structure, the proposed model can be integrated within microscopic traffic simulation models and in-vehicle and Smartphone applications to quantify the energy impacts of a transportation system.

The remainder of the paper is organized as follows: Section 2 reports the *state-of-the art* of vehicle energy consumption efforts. Section 3 reports the proposed model development entitled VT-CPPM (Virginia Tech Comprehensive Power-based PHEV Model), while in Section 4 the results are shown. Specifically, the energy consumption of the Chevy Volt, a comparison of the Chevy Volt, the Nissan Leaf (using the VT-CPEM) and the Nissan Versa (using VT-CPFM) in terms of energy consumption and BEV range, are presented. Finally, the conclusions of the study are summarized in Section 5.

2. Literature review

Among the main advantages of PEVs is the possibility of energy recovery while braking. This is possible thanks to the ability of the electric machine to be a reversible machine that works also as a motor and a generator. When the electric machine works as an electric motor the electric energy is generated in the batteries and converted by the electric motor to mechanical energy to provide traction at the wheels. On the contrary, when the electric machine works as a generator the mechanical energy that derives from the wheels is converted to electric energy and stored in the batteries, in this way it is possible to recover energy during braking. Some studies demonstrated that the efficiency while driving is higher on urban routes than highway routes (Knowles et al., 2012). This is a very different situation compared with what happens with conventional vehicles. In fact, in this last case the energy consumption in urban driving was higher because of braking and thermal losses (Gao et al., 1999). Moreover, experimental studies have shown that the energy consumption in urban cycles are lower (De Gennaro et al., 2014) because in this situation it is possible to recover energy while braking.

Most recent PHEV studies estimate energy consumption using the manufacturer's fuel economy data, vehicle simulators (e.g. the Advanced Vehicle SimulatOR (ADVISOR) developed by the National Renewable Energy Laboratory (NREL) and Autonomie developed by the Argonne National Laboratory (ANL)) or "custom" energy consumption vehicle models (Doucette and McCulloch, 2011, Muratori et al., 2013). In their study Foley et al. (2013) tried to evaluate the effects of PHEVs charging for electricity market operations using an average energy consumption value that was derived from experimental analyses provided by Markel et al. (2009). Alternatively, Hilshey, (2015) adopted a constant value for the energy consumption [kWh/km] to estimate the impact of PHEV charging on the electric power infrastructure. However the energy estimation method using the fuel economy data of PHEVs or an average energy consumption [Wh/km] is an imprecise approximation that does not capture real consumption of EVs and cannot quantify the differences in energy consumption across different driving cycles that produce similar average speeds.

The most popular energy model in the United States is ADVISOR. Its primary role is to quantify the system-level interactions of hybrid and electric vehicle components and their impacts on the vehicle performance and fuel economy. Such impact assessment is carried out by means of a quasi-steady backward-forward simulation that handles the component performance limits in its backward-facing stream of calculations and the addition of a simple forward-facing stream of calculations (Markel et al., 2002). The model requires the vehicle features and drive cycles as input variables and the output are the vehicle fuel/energy consumption and emissions (Wipke et al., 1999). However, it is difficult to implement the simulator in traffic simulation models or smartphone applications due to their complexity and their long execution time. In particular, this simulator is very complex because it contains many libraries. An energy consumption model that can be easily integrated with traffic simulation models allows for fast computation times and reduces the complexity of the global integrated model.

Authors such as Lewis et al. (2014) and Lee et al. (2014) adopted Autonomie for the evaluation of the energy consumption needed for their studies. Autonomie "custom" PHEV energy consumption models have been realized to compute a PHEV's energy consumption values. Among these, Muratori et al. (2013) analyzed the total primary energy consumption related to personal transportation in the U.S. including different vehicle models to estimate how the charging system affects the electric power infrastructure at the distribution level. While for example, Doucette and McCulloch (2011) suggested a model to compute CO_2 emissions from BEVs and PHEVs, and compared the results to the published values for CO_2 emissions from conventional ICE vehicles. Khayyer et al. (2012) analyzed how the energy management strategies have a critical role on the fuel consumption of hybrids and PHEVs. Hu et al. (2013) focused on the tank-to-wheel (TTW) analysis of a series plug-in hybrid electric bus operated in Gothenburg, Sweden.

All of these *ad hoc* models are backward models, adopt dynamic equations, and evaluate the efficiency of the electric motor and internal combustion engine using efficiency maps that can only be generated by testing a vehicle on an engine or chassis dynamometer. Thus, there are critical limitations in the flexibility of adoption of these models. To overcome this critical limitation, any model should be general and should not require the use of efficiency maps.

Also, among the most recent simulators where efficiency maps are used are: Autonomie a forward-looking simulator, which was developed by Argonne National Laboratory for evaluating a vehicle's performance through simulation (Kim et al., 2012); the Future Automotive Systems Technology Simulator (FASTSim) is a high-level advanced vehicle powertrain systems analysis tool supported by the U.S. Department of Energy's Vehicle Technologies Office, this simulator provides a quick and simple approach to compare powertrains and estimate the impact of technology improvements on light- and heavy-duty vehicle efficiency, performance, cost, and battery life (Brooker et al., 2015); and ALPHA which is a physics-based, forward-looking, full vehicle computer simulation, developed by the EPA capable of analyzing various vehicle types combined with different powertrain technologies (Lee et al., 2013).

Mahmud and Town (2016) reviewed 125 simulation tools for modeling electric vehicles and associated infrastructure and summarized and tabulated the simulation tools by source, availability, and application. The study also evaluated the advantages and limitations of each application and the study concluded that no tool covers all areas of vehicle system analysis and control, renewable energy and vehicle to grid integration and impact analysis, energy market behavior and charge scheduling, vehicle energy management, and traffic system simulation.

There are a number of studies on PHEV energy consumption modeling; however, these models utilized average fuel economy data or complicated vehicle-specific data including engine map data that require testing the vehicle or the engine on a dynamometer. One of the most important contributions of this paper is the development of a simple energy model for PHEVs that can be calibrated in a very simple way using open-source PHEV data without the need for field data collection.

Specifically, this study compliments and extends existing PHEV energy consumption models in the following ways: (a) Novelty. The study adopts the instantaneous regenerative braking energy efficiency as a function of the vehicle deceleration level to estimate the instantaneous energy consumption for PHEVs. Many previous works adopted an average regenerative braking energy efficiency (Fleurbaey, 2012–2013) that is principally dependent on the vehicle speed (Panagiotidis et al., 2000, Yang et al., 2013). In particular, one of the aims of this study is to capture the instantaneous regenerative braking energy using vehicle speed and acceleration input parameters. The study uses vehicle decelerations to calculate the instantaneous regenerative braking energy efficiency, which is then used to compute the energy consumed by the vehicle; (b) Generalization/Flexibility. This model is general and does not use engine efficiency maps, for both the electric and internal combustion engines (ICEs) to estimate energy consumption. In particular, the electric energy consumption is evaluated using the same approach reported by the same authors in the VT-CPEM model (Fiori et al., 2016) while the fuel consumption is computed using the VT-CPFM model (Rakha et al., 2011); (c) Usability. The proposed model can be integrated in a very simple way in microscopic traffic simulation models as well as in in-vehicle and mobile eco-driving apps. Since the model utilizes vehicle speed profiles as input variables, the proposed method can accurately estimate the energy consumption based on driving dynamics compared to the models that utilize averages speed as an input variable. Previous studies also identified the average speed is not enough to reflect the traffic dynamics to estimate vehicle energy consumption (Ahn et al., 2002, Rakha and Ahn, 2004); and (d) Validation using real reliable data. The model is validated against reliable real data from two different research centers; the Idaho National Laboratory (INL) in the AVTA program of the United States Department of Energy (U.S. DOE) (2013) and by the Texas Transportation Institute (TTI) (2013), respectively.

3. Modeling: proposed VT-CPPM framework

The Virginia Tech Comprehensive Power-based PHEV Energy consumption Model (VT-CPPM) is a quasi-steady backward high resolution power-based model. In particular, the input required by the model are the following: the instantaneous speed profile and the characteristics of the vehicle analyzed. The output of the model are the following: the energy consumption (EC) [kWh/km], the instantaneous power consumed [kW], the battery state-of-charge (SOC) of the electric battery [%] and the Fuel Consumption (FC) [l/100 km] and [kWh/km]. It is noted that 1 kWh of EV energy consumption is equal to 3.6 MegaJoules, which would require approximately 0.1125 L of gasoline consumption to generate. In this study, the fuel consumption of an internal combustion engine is converted into energy consumption units. The proposed model is valid only for series configurations and can be utilized for any different model of series PHEVs. In particular, the 2013 Chevy Volt is utilized in this study.

The study utilizes the VT-CPEM model for the energy consumption in electric motor (Fiori et al., 2016). The power at the wheels of electric motor is computed using Eq. (1).

$$P_{Wheels}(t) = \left(ma(t) + mg\cdot\cos(\theta)\cdot\frac{C_r}{1000}(c_1v(t) + c_2) + \frac{1}{2}\rho_{Air}A_f C_D v^2(t) + mg\cdot\sin(\theta)\right)\cdot v(t) \tag{1}$$

where m is the vehicle mass ($m = 1860$[1] [kg]), $a(t) = dv(t)/dt$ is the acceleration of the vehicle in [m/s^2] ($a(t)$ takes negative values when the vehicle decelerates), $g = 9.8066$ [m/s^2] is the gravitational acceleration, θ is the road grade, $C_r = 1.75$,$c_1 = 0.0328$ and

[1] Chevy Volt total vehicle mass [kg] including the delivered curb weight, the weight of a man and the weight test tools.

$c_2 = 4.575$ are the rolling resistance parameters that vary as a function of the road surface type, road condition, and vehicle tire type. The typical values of vehicle coefficients are reported in (Rakha et al., 2011). $\rho_{Air} = 1.2256$ [kg/m^3] is the air mass density[2], $A_f = 2.1851$ [m^2] is the frontal area of the vehicle, and $C_D = 0.29$ is the aerodynamic drag coefficient of the vehicle and $v(t)$ is the vehicle speed in [m/s]. The driveline efficiency utilizes $\eta_{Driveline} = 92\%$ based on (Rakha et al., 2011) and, assuming that the efficiency of the electric motor is $\eta_{ElectricMotor} = 91\%$. This is a reasonable assumption as reported in (Fiori et al., 2016).

When the vehicle is in traction mode, the energy flows from the motor to the wheels. In this situation the power at the electric motor is higher than the power at the wheels and the power at the wheels is positive. On the contrary, in the regenerative braking mode, energy flows from the wheels to the motor. In this situation, the power at the electric motor is lower than the power at the wheels and the power is assumed to be negative.

The proposed model captures instantaneous braking energy regeneration as a function of the deceleration level. While decelerating, the electric power is negative and the regenerative braking energy efficiency (η_{rb}) is computed when $P_{Electricmotor}(t) < 0$ using Eq. (2). The details on how the $\eta_{rb}(t)$ is estimated is presented later in the paper.

$$P_{Electric\ motor}(t) < 0 \rightarrow P_{Electric\ motor\,neg}(t) = P_{Electric\ motor}(t)\cdot\eta_{rb} \tag{2}$$

The study adopts a PHEV control strategy to compute the energy consumption of the vehicle. Using the method, it is possible also to estimate the final battery state-of-charge (SOC) [%] using Eq. (3) and Eq. (4).

$$SOC_{Final}(t) = SOC_0 - \sum_{i=1}^{N} \Delta SOC_{(i)}(t) \tag{3}$$

$$\Delta SOC_{(i)}(t) = SOC_{(i-1)}(t) - \frac{P_{Electric\ motor\,net(i)}(t)}{3600\cdot \mathrm{Capacity_{Battery}}} \tag{4}$$

Here $P_{Electric\ motor\,net(i)}(t)$ is the electric power consumed considering a battery efficiency of $\eta_{Battery} = 90\%$ (2005). In addition, the power consumed by the auxiliary systems ($P_{Auxiliary} = 700$ [W] (2003)) is considered. $\mathrm{Capacity_{Battery}}$ is the capacity of the battery in [Wh]. The operation range of SOC is between 21% and 88% to guarantee the safety of the battery system (2010), in particular the initial SOC is assumed to be a $SOC_0 = 88\%$. The range of the SOC used are provided from experimental tests from TTI.Given the SOC it is possible to compute the energy consumption (EC) in [kWh/km] using Eq. (5).

$$EC\left[\frac{kWh}{km}\right] = \frac{1}{3600000}\cdot\int_o^t P_{Electric\ motor_{net}}(t)dt\cdot\frac{1}{d} \tag{5}$$

Here d is the distance in [km]. The parameters related to the specific electric vehicle used are reported in (Department of Energy (DOE). Advanced Vehicle Testing Activity (AVTA) of the Idaho Nation Laboratory (INL), 2013) where all the characteristics of the PHEV used are shown.

For a detailed description of the regenerative braking energy efficiency as a function of vehicle deceleration the reader is referred to some previous work (Fiori et al., 2016).In computing the fuel consumption of the conventional engine, the VT-CPFM is used (Rakha et al., 2011). The following formulation, reported in Eq. (6), is used:

$$FC(t) = \alpha_0 + \alpha_1\cdot P_{ice}(t) + \alpha_2\cdot P_{ice}(t)^2 \tag{6}$$

where α_0,α_1,α_2 are vehicle-specific parameters using the VT-CPFM. $P_{ice}(t)$ is the power at the ICE and is evaluated in the PHEV control strategy. The detailed description of the VT-CPFM is explained in (2011).The PHEV control strategy is characterized by two cases, as illustrated in Fig. 2. $P_{tot}(t)$ [kW] is the total power necessary for the traction of the vehicle.

<u>Case 1.</u> When the battery charge is greater than the minimum SOC ($SOC(t) > SOC_{min}$):

If $P_{tot}(t) \geqslant 0$, and

If $P_{tot}(t) < P_{Electric\ motor\ max}(t)$, then $P_{tot}(t) = P_{Electric\ motor\,net}(t)$;

where $P_{Electric\ motor\,max}(t)$ is the maximum power of the electric motor. In particular, if the total power required at the wheels is lower that the power that the electric motor can provide, this is the only motor that provides the power.

Otherwise if $P_{tot}(t) \geqslant P_{Electric\ motor\,max}(t)$, then $P_{tot}(t) = P_{Electric\ motor\ max}(t) + P_{ice}(t)$.

where $P_{ice}(t) = P_{tot}(t) - P_{Electric\ motor\ max}(t)$ is the power provided by the ICE. In particular, if the power required at the wheels is higher that the power that the electric motor can provide, additional power is provided by the ICE.

If $P_{tot}(t) < 0$ (or when the energy is recovered during braking), and

$P_{tot}(t) = P_{Electric\ motor\,negative}(t)$;

During the recovery period, the electric motor works as a generator and the battery can be effectively charged.

<u>Case 2.</u> When the battery charge is less than or equal to the minimum SOC ($SOC(t) \leqslant SOC_{min}$):

If $P_{tot}(t) \geqslant 0$,

$$P_{tot}(t) = P_{ice}(t).$$

[2] Density of air at sea level at 15 °C (59 °F).

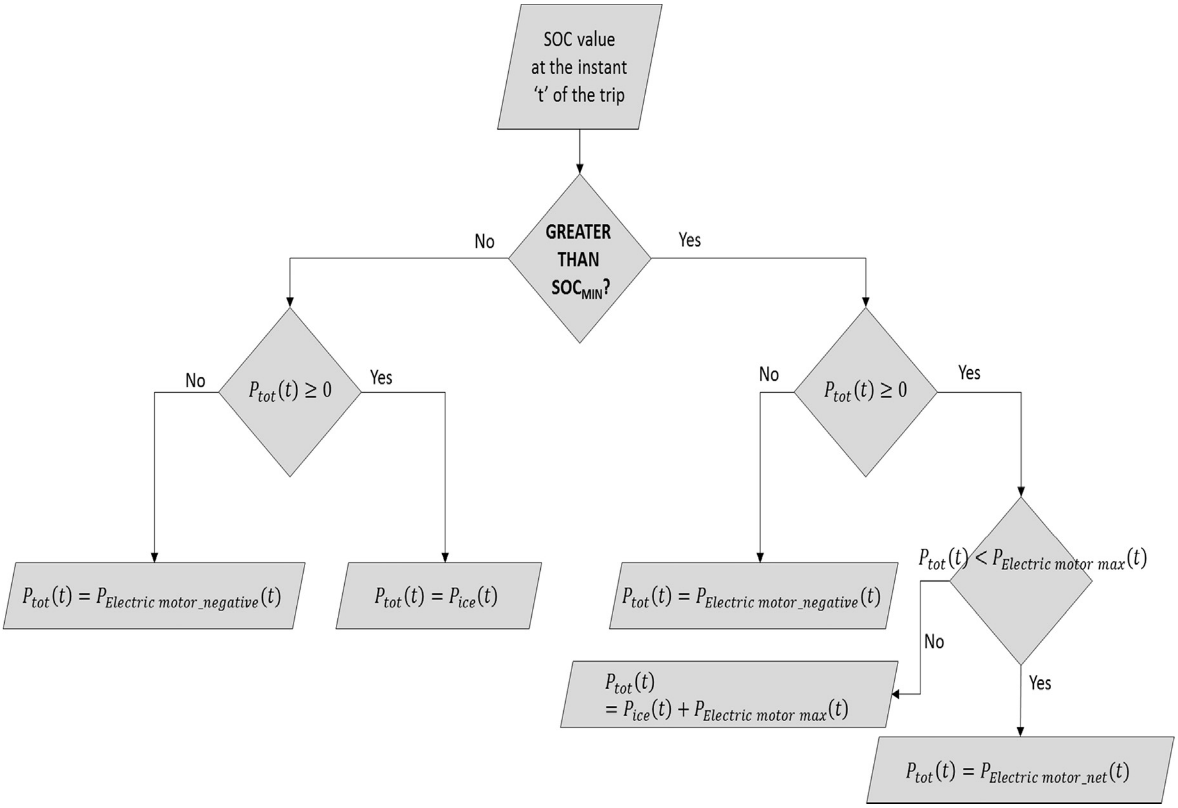

Fig. 2. Diagram for the PHEV control strategy.

If $P_{tot}(t) < 0$,

$$P_{tot}(t) = P_{Electric\ motor\ negative}(t).$$

During the recovery period, the electric motor works as a generator and the battery can be effectively charged.

The SOC_{min} value reported in Fig. 2 is the threshold that represents the minimum battery SOC value. If the SOC is higher than SOC_{min}, a PHEV is powered by the electric motor. Under this value the ICE starts and the traction is provided exclusively by the ICE. When the actual SOC is lower of the SOC_{min} but the $P_{tot}(t) < 0$ braking mode starts and the battery is charged. The SOC_{min} was set to 20.4% for this test.

4. Results

4.1. Model validation

The Chevy Volt PHEV series is the vehicle adopted for the validation of the VT-CPPM model for two reasons. First, it is simple to obtain data on this vehicle because it is one of the most popular PHEVs available on the market in the United States. Second, this vehicle has been tested by a few research centers and thus experimental data on the energy consumption are available. The vehicle features can be found in (Department of Energy (DOE). Advanced Vehicle Testing Activity (AVTA) of the Idaho Nation Laboratory (INL), 2013).

The validation effort used data collected by U.S. DOE's Advanced Vehicle Testing Activity (AVTA) of the Idaho National Laboratory (INL) (Department of Energy (DOE). Advanced Vehicle Testing Activity (AVTA) of the Idaho Nation Laboratory (INL), 2013). The AVTA data available are on the following driving cycles: the EPA Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Driving Schedule (HWFET), and the US06 (also referred as high acceleration aggressive driving scheduler "Supplemental FTP" driving schedule) (EPA). In addition, second-by-second data on the energy consumption and on the SOC behavior collected by TTI are used for validation purposes.

4.2. Energy consumption validation with DOE's AVTA data

In Table 1 the energy consumption in [Wh/km] and [Wh/mile] published by the DOE's AVTA, and the energy consumption computed using the VT-CPPM model are reported. In the last column of the table the error relative to the DOE's AVTA values is shown. The results demonstrate that the proposed model accurately estimates the energy consumption with an average error of 4% compared to experimental data.

4.3. Energy consumption and state of charge (SOC) validation with TTI data

The study utilized the Chevy Volt field data collected by TTI, which includes the energy consumption [Wh/km] and the SOC on two trips. The VT- CPPM model was tested on the same trips and the results are presented in Table 2. The study found that the proposed model estimates are almost identical to independent empirical data generating a −1.05% and −0.23% error for trips 1 and 2, respectively, with an average error of 0.64%. Moreover, a second-by-second analysis on the SOC was performed and the results of these analyses are reported in Fig. 3 for Test1 and in Fig. 4 for Test2, respectively. The Figure demonstrates the proposed model accurately estimates the SOC for both trips.

The estimated SOC has a higher deviation than the real value because there are some imperfections in the model that in some part of the driving cycle underestimate the energy consumption. Once the battery charge level is less than or equal to the minimum SOC, the PHEV operates similar to a hybrid vehicle, which uses both the ICE and the electric motor. Fig. 5 compares the estimated SOC and the field collected SOC data when the SOC level is close to the SOC_{min}, which is set to 20.4% for this test. The figure illustrates that in general the model prediction follows the field collected SOC measurements, demonstrating the uniqueness of the model in estimating the regenerative braking energy of the PHEV when the SOC level is low.

A comparison between the characteristics of the VT-CPPM and the two wider adopted simulators available in the open literature is reported in Table 3.

In particular, some recommendations for automotive industry can be the following: (i) to invest in a flexible and easy simulation model able to evaluate which energy recovery control strategy can allow higher electric range; (ii) to evaluate how the electric range available and energy consumption and recovery changes with the speed and grade profile characteristics. In fact, EVs and PHEVs have a completely different powertrain from the ICEVs and this enables different ways of driving in order to reduce the energy consumption and optimize the energy recovery while braking. On the basis of the optimal speed profile reachable in real-traffic condition (iii) specific training courses of eco-driving can be identified and this service can be a benefit that the automakers can provide with the selling of the car.

4.4. Comparison to conventional and EVs: Chevy Volt vs. Nissan Versa vs. Nissan Leaf

This section compares the energy consumption using the proposed PHEV models to a conventional vehicle and an electric vehicle. Sixteen driving cycles originally developed by the U.S. Environmental Protection Agency (EPA) were utilized for the comparison. Also the study utilized the VT-CPEM by Fiori et al. (2016) and VT-CPFM by Rakha et al. (2011). The Chevy Volt is compared to an electric vehicle, the Nissan Leaf that is modeled using the VT-CPEM and with a conventional vehicle, namely the Nissan Versa that is modeled using the VT-CPFM.

Fig. 6 illustrates the energy consumption of the PHEV and the BEV. These are significantly lower than the conventional vehicles. The reason for this phenomenon is related to a few factors such as: the higher energy efficiency associated with the use of the electric motor and to the capacity of electric vehicles to recover energy while braking. This evaluation, named in the literature as tank-to-wheels (TTW) analysis, counts only energy use associated with vehicle operation activities. In the general framework the TTW is a part of a global and larger framework named the well-to-wheels (WTW) analysis (2005). Specifically, Fig. 6 illustrates the average PHEV energy consumption that results in a 78.8% lower TTW energy consumption compared to ICE vehicles. The highest difference is reported for the LA92 driving cycle (average speed 39.6 [km/h]) with a gap of 89.6%, while the driving cycle with the lowest difference is the Fwy AC (average speed 95.7 [km/h]) with a gap of 67.8%. Results show that PHEVs in the urban driving environment produce lower energy consumption relative to the high speed driving cycles.

Furthermore, the study found that the conventional vehicle consumed very similar energy levels for the High Speed and the Fwy E cycles with 628.3 [Wh/km] and 607.5 [Wh/km], respectively. For the conventional vehicle, the Fwy E cycle is 3.4% more energy efficient than the High Speed cycle. However, for the PHEV, the Fwy E cycle is 54.8% more energy efficient than the High Speed cycle. The estimated energy consumptions for the PHEV are 181.9 [Wh/km] and 117.5 [Wh/km], respectively, for the High Speed

Table 1
Validation results using AVTA data (Chevy Volt).

		AVTA data		VT-CPPM		Error [%]
		[Wh/mile]	[Wh/km]	[Wh/mile]	[Wh/km]	
AVTA	UDDS	253.6	157.6	264.3	164.2	4.2
	HWFET	261.9	162.8	255	158.5	−2.6
	US06	364.8	226.7	383.8	238.5	5.2

Table 2
Validation results using TTI data.

Chevy volt					
	Avg. speed [km/h]	Trip length [km]	TTI (Field data)	VT-CPPM (Estimated)	Error [%]
Energy consumption: Trip1 [Wh/km]	70.99	34.35	193.3	191.3	−1.05
Energy consumption: Trip2 [Wh/km]	64.53	27.77	217.3	216.8	−0.23

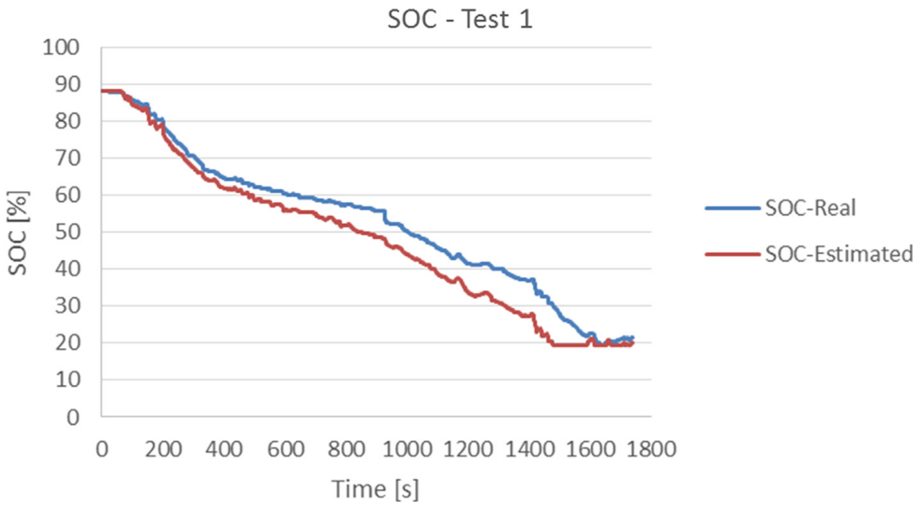

Fig. 3. SOC comparison for Test1.

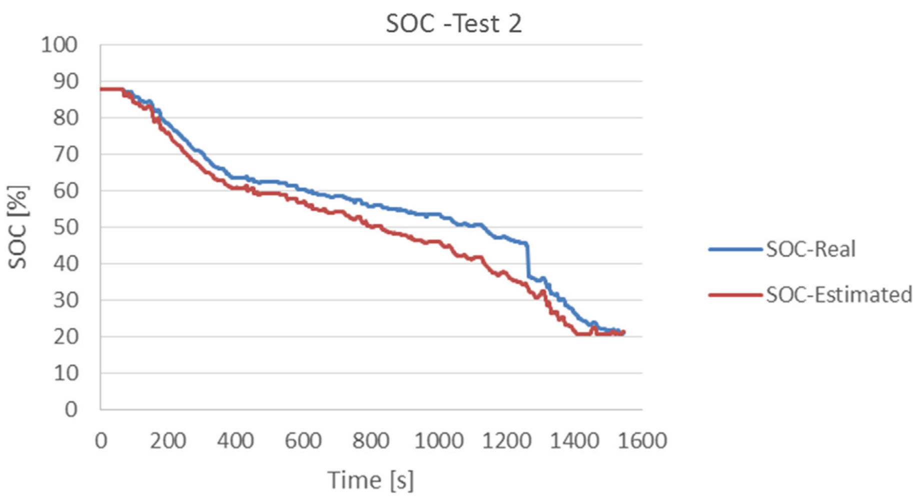

Fig. 4. SOC comparison for Test2.

and the Fwy E cycles. The reason for this result is related to the fact that in the Fwy E a higher amount of energy is recovered during braking, thus this cycle has a lower energy consumption in comparison to the High Speed cycle. Also the results shows that the PHEV consumes on average 19.9% more energy compared to BEVs. It is important to highlight that both the BEV and PHEV considered in this analysis only use the electric drive range for these tests since the trips are short and the distance travelled are lower than the available BEV ranges. Consequently, the differences shown in the results are due to the vehicle characteristics (mass, drag coefficient, etc.).

Fig. 7 shows a comparison of the electric driving ranges of the test vehicle (Chevy Volt) with and without accounting the energy recovered during braking. The figure highlights that the ST01 is the driving cycle characterized by the higher gap between the electric driving range with and without considering the energy recovered. The Fwy AC is the cycle where is registered the lowest percentage difference. This difference is due to the characteristics of the driving cycle. Specifically, driving cycles with lower average speed and several braking actions generates a higher amount of recovered energy during braking compared with driving cycles with higher

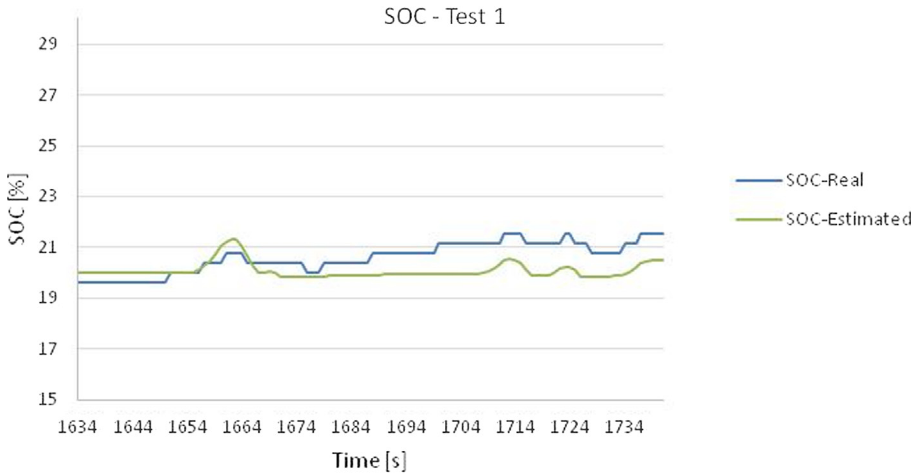

Fig. 5. Portion of SOC comparison for Test1.

Table 3
Comparison between VT-CPPM and other vehicle simulators.

Models	Characteristics	Efficiency maps use	Pros	Cons
VT-CPPM	Backward high resolution power-based model	No	1) Novelty 2) Generalization/Flexibility 3) Usability 4) Validation using real reliable data (see Section 2 for additional details)	1) Good compromise between simplicity and reliability
ADVISOR	Component-based (backward/forward) model	Yes	1) Reliable evaluation based on driving cycle and vehicle characteristics 2) GUI easy manipulation for input and output 3) Validated and widely adopted 4) Fairly fast execution time	1) Consider and simulate in block each component in general and not of the specific vehicle 2) Any phenomenon less than tenth of second timescale cannot be predicted 3) It deals in power, not in voltage or current 4) Difficult to be implemented in traffic simulation models
Autonomie	Command-based (forward) model	Yes	1) Realistic evaluation of the vehicle performances based on driver behavior 2) Slow execution time 3) Able to study transient effects and the interaction between components with accurate control commands	1) Slower than backward model 2) Toolbox has potential threat to quality and performance 3) Difficult to be implemented in traffic simulation models

average speed and not many braking actions. Figs. 6 and 7 also demonstrate that the EV ranges are significantly affected by driving cycles, vehicle routings, driving behaviors, and traffic patterns are very important factors that can significantly improve the efficiency of PHEVs.

5. Conclusions

This study develops a microscopic energy consumption model for PHEVs. This model computes instantaneous energy consumptions of PHEVs from the applied instantaneous power. In particular, the speed profile and roadway grade are used as input parameters. The model estimates instantaneous regenerative braking energy as a function of the vehicle deceleration level. This model can easily be incorporated in microscopic traffic simulation software and in-vehicle and mobile eco-driving apps given its straightforward formulation. In particular, this model is very flexible, compared with other PHEV energy consumption models. Most of other PHEV energy models require efficiency maps for the electric motor and the ICE. Results show that this model computes the energy consumption, generating an average error of 4% and 0.64%% relative to field experimental data. Furthermore, the study demonstrates that the tank-to-wheels energy consumption for the electric vehicle (Chevy Volt) is 78.8% lower than that for an equivalent conventional vehicle (Nissan Versa). The higher difference is reported for the LA92 drive cycle with a difference of 89.6% and the lower difference is reported for the Fwy AC cycle with a difference of 67.8%. These results show that in urban environments there is the chance to recover more energy due to the presence of several braking episodes in the drive cycle. The study found that

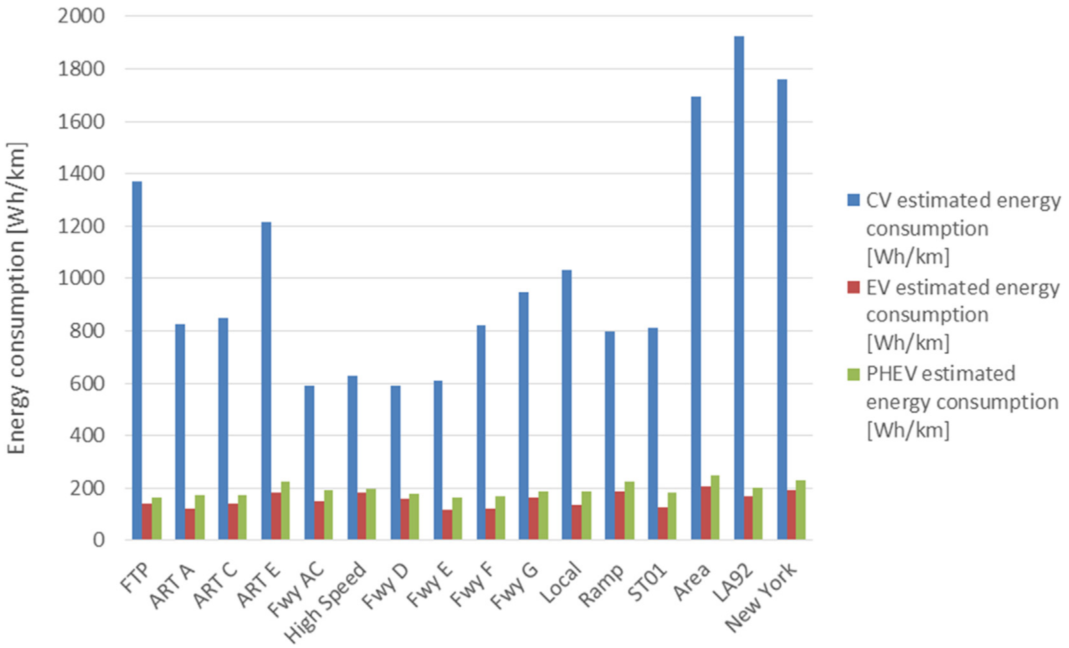

Fig. 6. Comparison between the energy consumption estimated values of Chevy Volt (PHEV), Nissan Leaf (BEV) and Nissan Versa (ICV).

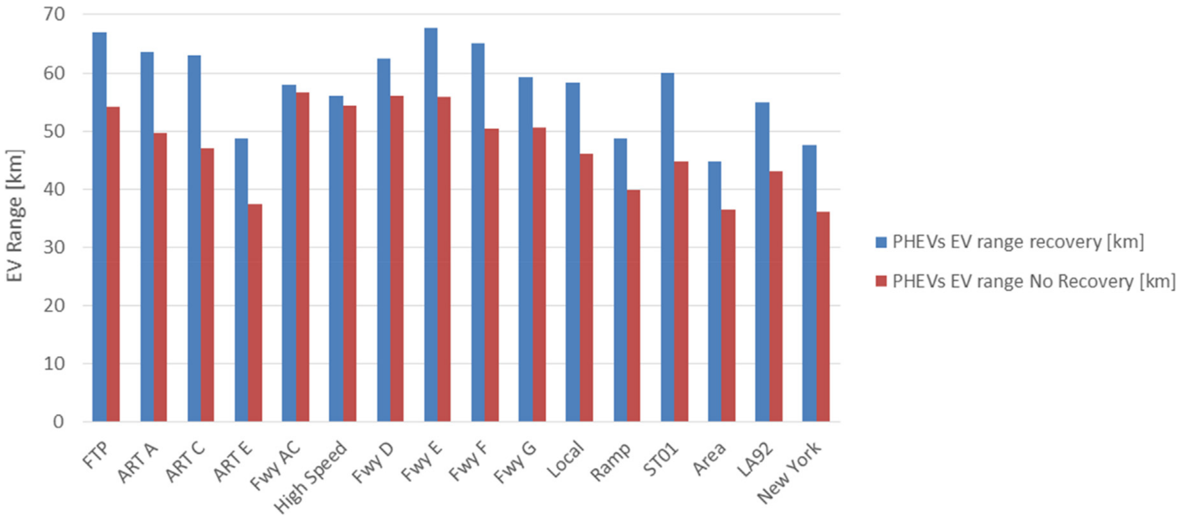

Fig. 7. Comparison of electric driving ranges of a PHEV (Chevy Volt) on the 16 driving cycles analyzed with and without the energy recovered during braking.

driving behavior and traffic patterns are very important factors that can significantly improve the efficiency of PHEVs. Finally, further research is recommended to identify the impacts of cold engine start/engine warm up mode on PHEV performance.

Acknowledgements

This research effort was funded by the Tran*LIVE* University Transportation Center. In addition, this research was partially carried out in the frame of Programme STAR, financially supported by UNINA and Compagnia di San Paolo. Moreover, the authors would like to thank the Texas A&M Transportation Institute and the Idaho Nation Laboratory for providing field data utilized in this study. Finally, the authors wish to thank Douglas Nelson at Virginia Tech for his valuable comments on the study.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2018.04.

022.

References

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. J. Transport. Eng. 128, 182–190.

Brooker, A., Gonder, J., Wang, L., Wood, E., Lopp, S., Ramroth, L., 2015. FASTSim: a model to estimate vehicle efficiency, cost and performance. SAE Technical Paper, No. 2015-01-0973.

Cobb, J. 2016. Top Six Plug-in Vehicle Adopting Countries – 2015. Available: http://www.hybridcars.com/top-six-plug-in-vehicle-adopting-countries-2015/(accessed April 18 2016).

De Gennaro, M., Paffumi, E., Scholz, H., Martini, G., 2014. GIS-driven analysis of e-mobility in urban areas: an evaluation of the impact on the electric energy grid. Appl. Energy 124, 94–116.

Department of Energy (DOE). Advanced Vehicle Testing Activity (AVTA) of the Idaho Nation Laboratory (INL). 2013. 2013 Chevloret Volt - Baseline Performance Testing. Available: http://avt.inl.gov/pdf/EREV/fact2013chevroletvolt.pdf (accessed 2016).

Doucette, R.T., McCulloch, M.D., 2011. Modeling the prospects of plug-in hybrid electric vehicles to reduce CO_2 emissions. Appl. Energy 88, 2315–2323.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., 2014. Climate change 2014: Mitigation of climate change. Working group III contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. UK and New York.

Fiori, C., Ahn, K., Rakha, H.A., 2016. Power-based electric vehicle energy consumption model: Model development and validation. Appl. Energy 168, 257–268.

Fleurbaey, K., 2012–2013. Analysis of the energy storage systems in series plug-in hybrid electric vehicles Master.

Foley, A., Tyther, B., Calnan, P., Gallachóir, B.Ó., 2013. Impacts of electric vehicle charging under electricity market operations. Appl. Energy 101, 93–102.

Gao, Y., Chen, L., Ehsani, M., 1999. Investigation of the Effectiveness of Regenerative Braking for EV and HEV. SAE Technical Paper.

Goldman, J. 2014. Comparing Electric Vehicles: Hybrid vs. BEV vs. PHEV vs. FCEV. Available: http://blog.ucsusa.org/josh-goldman/comparing-electric-vehicles-hybrid-vs-bev-vs-phev-vs-fcev-411 (accessed April 18 2016).

Hilshey, A.D., 2015. A trip-purpose based model of Plug-in Electric Vehicle charging demand. Power & Energy Society General Meeting. IEEE, 2015. IEEE, pp. 1–5.

Hu, X., Murgovski, N., Johannesson, L., Egardt, B., 2013. Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes. Appl. Energy 111, 1001–1009.

Juul, N., Meibom, P., 2012. Road transport and power system scenarios for Northern Europe in 2030. Appl. Energy 92, 573–582.

Khayyer, P., Wollaeger, J., Onori, S., Marano, V., Özgüner, Ü., Rizzoni, G., 2012. Analysis of impact factors for plug-in hybrid electric vehicles energy management. In: Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference On. IEEE, pp. 1061–1066.

Kim, N., Rousseau, A., Rask, E., 2012. Autonomie model validation with test data for 2010 Toyota Prius. SAE Technical Paper, No. 2012-01-1040.

Knowles, M., Scott, H., Baglee, D., 2012. The effect of driving style on electric vehicle performance, economy and perception. Int. J. Electr. Hybrid Veh. 4, 228–247.

Lee, B., Lee, S., Cherry, J., Neam, A., Sanchez, J., Nam, E., 2013. Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool. SAE Technical Paper, No. 2013-01-0808.

Lee, D., Rousseau, A., Rask, E., 2014. Development and Validation of the Ford Focus Battery Electric Vehicle Model. SAE Technical Paper.

Lewis, A.M., Kelly, J.C., Keoleian, G.A., 2014. Vehicle lightweighting vs. electrification: life cycle energy and GHG emissions results for diverse powertrain vehicles. Appl. Energy 126, 13–20.

Mahmud, K., Town, G.E., 2016. A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks. Appl. Energy 172, 337–359.

Markel, A.J., Bennion, K., Kramer, W., Bryan, J., Giedd, J., 2009. Field testing plug-in hybrid electric vehicles with charge control technology in the xcel energy territory. Citeseer.

Markel, T., Brooker, A., Hendricks, T., Johnson, V., Kelly, K., Kramer, B., O'Keefe, M., Sprik, S., Wipke, K., 2002. ADVISOR: a systems analysis tool for advanced vehicle modeling. J. Power Sources 110 (2002), 255–266.

Muratori, M., Moran, M.J., Serra, E., Rizzoni, G., 2013. Highly-resolved modeling of personal transportation energy consumption in the United States. Energy 58, 168–177.

Panagiotidis, M., Delagrammatikas, G., Assanis, D.N., 2000. Development and use of a regenerative braking model for a parallel hybrid electric vehicle. SAE Technical Paper.

Rakha, H., Ahn, K., 2004. Integration modeling framework for estimating mobile source emissions. J. Transport. Eng.-Asce 130, 183–193.

Rakha, H.A., Ahn, K., Moran, K., Saerens, B., Van den Bulck, E., 2011. Virginia tech comprehensive power-based fuel consumption model: model development and testing. Transport. Res. Part D: Transport Environ. 16, 492–503.

Shao, S., Pipattanasomporn, M., Rahman, S., 2009. Challenges of PHEV penetration to the residential distribution network. 2009 IEEE Power & Energy Society General Meeting 2009 Calgary, AB, Canada. IEEE, pp. 1–8.

Sovacool, B.K., Hirsh, R.F., 2009. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. Energy Policy 37, 1095–1103.

U.S. Energy Information Administration (EIA), 2014. Energy consumption by sector. Available: http://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2014_energy.pdf (accessed June 30th 2015).

Wipke, K.B., Cuddy, M.R., Burch, S.D., 1999. ADVISOR 2.1: A user-friendly advanced powertrain simulation using a combined backward/forward approach. Vehicular Technol., IEEE Trans. 48, 1751–1761.

Yang, S., Deng, C., Tang, T., Qian, Y., 2013. Electric vehicle's energy consumption of car-following models. Nonlinear Dyn. 71, 323–329.