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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 Research 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

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ABSTRACT

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

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

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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

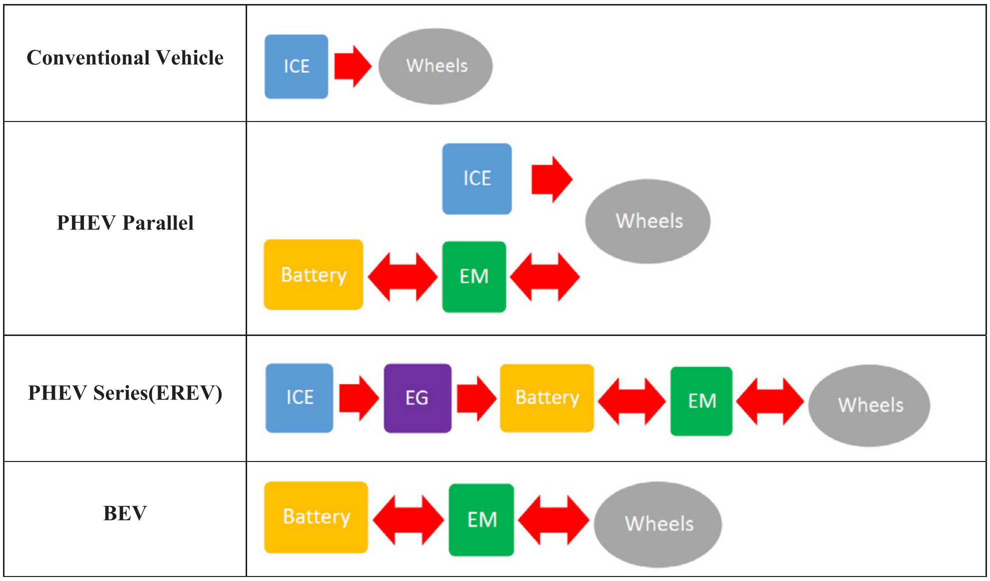

Fig. 1. Power flows for different vehicle types. In the figure: ICE is the Internal Combustion Engine, where EM is the Electric Machine that works as a motor to transfer energy to the wheels and as a generator to recover energy while braking and EG is the Electric Generator that works only to transfer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