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A Simulation Study on Energy Consumption and Cost Analysis of Hybrid Electric Motorcycle

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Abstract: Recent years have seen the development of the hybrid electric motorcycle in order to reduce pollutant emissions and the fossil-fuel consumption of transportation. This paper presents a research of energy consumption and essential cost of innovative technology that is applied on two wheels motorcycle based on the platform of Honda Lead 110cc. The front wheel is replaced by a DC electric hub motor powered by lithium-ion battery. The rear wheel is driven by drive train integrated with a continuously variable transmission as its origin. Both of them are able to provide propulsion torque separately or simultaneously. Through simulations of vehicle driving range using popular driving cycles, it is demonstrated that there is considerable benefit in fuel economy. The plug – in hybrid structure without generator is effective choice to renovate a traditional motorcycle in traffic condition of Vietnamese cities. The fuel consumption of plug – in hybrid motorcycle can be 0.567 l/100 km less than original in case of rider only. The results show that performance characteristics of the plug – in hybrid motorcycle are likely to achieve the desired acceptance that original one currently achieve. This study offers a favorable support for further development of hybrid electric motorcycle.

Keywords: Electric Vehicle, Hybrid Electric Vehicle, Hybrid Electric Motorcycle, Lithium-ion Battery

1. Introduction

Energy preservation, environment protection, and continuous economic development have given rise to demand on vehicles. The convenience of motorcycles in metropolitan areas is short daily trip distances, easy operation, low operating cost, and cater to a large group of people including students and commuters. Recently, the number of motorcycle has grown rapidly in many urban areas of Asia. According to Vietnam Association Motorcycle Manufactures (VAMM), total amount of two-wheelers continue to grow in the national market reached nearly 3.3 million vehicles in 2017, increasing by 4.8% [1]. In order to reduce emissions, different hybrid electric vehicles (HEV) and electric vehicles (EV) have been introduced recently. Several hybrid motorcycle designs have been developed to overcome limitations of conventional and electric two wheeler designs. These are possessed by parallel designs where electric motor and engine are connected to the wheels for independent driving or combination, see example in Figure 1. In comparison to HEVs, plug-in hybrid vehicles (PHEVs) have gained a great deal of momentum. This is because the PHEVs offer significant greenhouse gas benefit and greatly reduce the fuel consumption [2]. The most significant technical barrier in deploying commercially viable plug-in hybrid electric two-wheeler is the energy storage system and its requirements. The energy storage capacity of a battery pack is utmost importance.

Both high specific energy (Wh/kg) and energy density (Wh/l) are crucial to achieve high energy storage capacity without entailing significant additional mass/volume [3]. However, the additional battery capacity increases their manufacturing cost relative to a comparable conventional vehicle. For estimating the energy storage requirements and sizing of the battery pack, daily travel distance by a two-wheeler plays a vital factor. This paper discusses the methodology for simulating plug – in hybrid electric motorcycle (PHEM) using Matlab/Simulink to evaluate the energy consumption and cost analysis of PHEM.

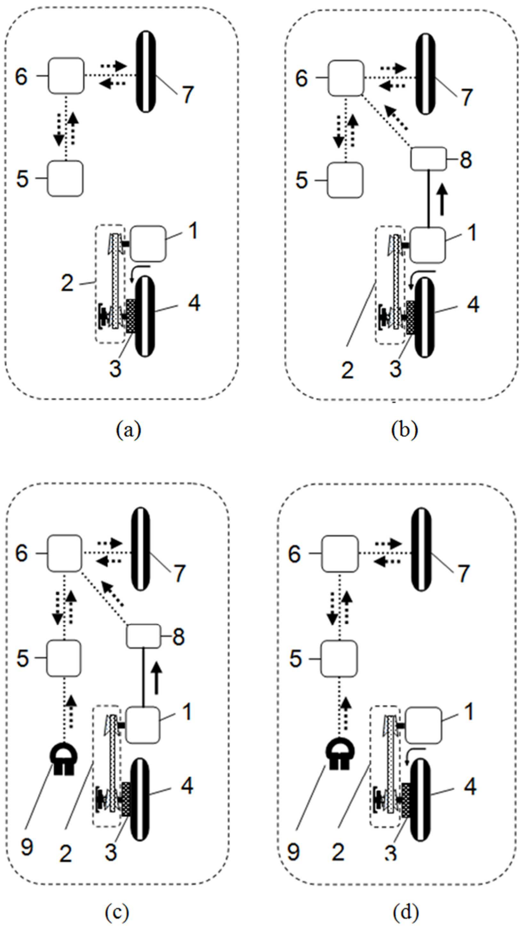

Figure 1. *Schematic diagram of the power configuration (a) parallel, (b) series-parallel, (c) plug-in with generator, and (d) plug-in without generator.*

1 – Engine;
2 - Continuously Variable Transmission (CVT);
3 - Final drive; 4 - Rear wheel; 5 – battery;
6 – Power splitter; 7 – Front wheel (BLDC motor);
8 – Generator; 9 – Plug-in

2. Plug – in Hybrid Powertrain Configurations

Figure 2 shows a block diagram of the proposed PHEM, which is the detail of the schematic diagram shown in Figure 1d. This plug – in hybrid powertrain uses a 1000W direct-driven front wheel motor [5], while rear wheel is driven by a gasoline engine through continuously variable transmission [4]. Energy storage systems using a 48V, 33Ah Lithium – ion battery is proposed. That battery could be charged from external electric source, such as civil electricity. A simple rule – based control strategy is then established, so both wheels can provide individual or simultaneous traction depending on the operating conditions of the motorcycle. There are four different modes in which to operate this system, based on the flow of power: (1) only the electric motor provides power directly to the front wheel; (2) only the gasoline engine provides torque to rear wheel through continuously variable transmission; or (3) both engine and motor operate simultaneously; (4) neither engine nor motor operate when braking or decelerating.

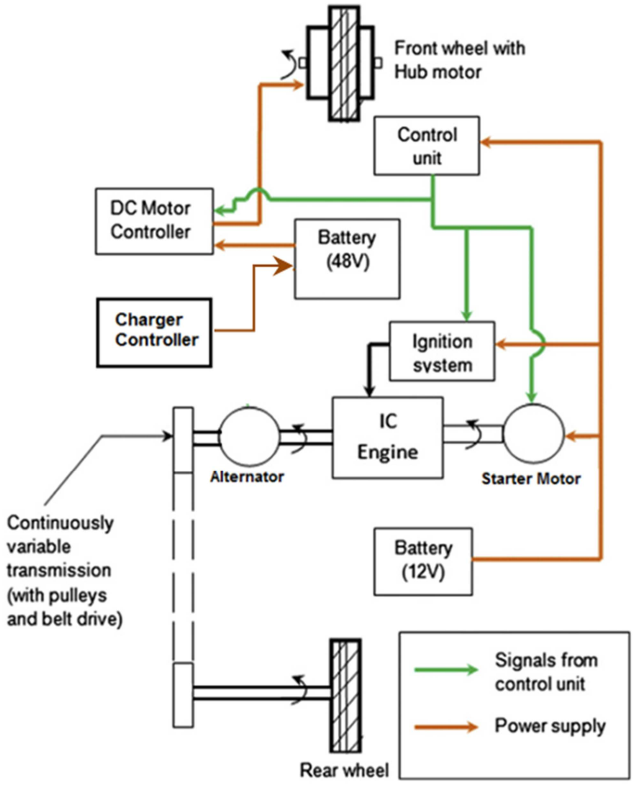

Figure 2. *Plug – in electric hybrid configuration.*

3. System Mathematical Model

The plug - in hybrid powertrain and storage system are modeled into six mathematical models that include: driver, engine and conventional powertrain, electric motor, battery system, vehicle body and Rule – based controller. Each module represents the data-processing elements or group thereof. Data flowing between them are the state of speed, torque, electrical signal and state of charge (SOC) level.

A. Driver model

The inputs of the driver model are motorcycle actual speed and driver desired speed (schedule vehicle speed), and the outputs are demanded power at wheels. The driver model here is implemented by a simple proportional – integral (PI) controller as follows [12]:

$$F_{demand}(t) = F_{load}(t) + F_{PI}(t) \tag{1}$$

$$F_{load}(t) = F_{rolling}(t) + F_{aero}(t) + F_{grade}(t) \tag{2}$$

$$F_{PI}(t) = K_p e(t) + K_i \int_0^t e(t) \tag{3}$$

$$e(t) = V_{demand}(t) - V_{act}(t) \tag{4}$$

$$P_{demand}(t) = F_{demand}(t).V_{demand}(t) \tag{5}$$

B. Gasoline engine and powertrain model

In order to build mathematical models for the engine and transmission, there are two methods: modeling each component (engine, clutch, transmission, final drive and wheel) or modeling the whole powertrain system clusters. An engine usually has four operating states: cranking, idle, engine on, and engine off. However, when the motorcycle is tested on a motorcycle dynamometer, it can be assumed that the engine will operate in only two states: (1) idle and (2) engine is on (and clutch is engaged). The motorcycle only starts once before running and does not shutdown during the test. Therefore, it is possible to model the entire cluster without paying attention to each component. By measuring the brake torque at the rear wheel and the amount of fuel consumed, gasoline engine and powertrain are represented as data map consists of brake torque map T_k (throttle angle, speed) and fuel consumption per second map g_{fuel} (brake torque, speed) (Figure 3 and 4).

Therefore, fuel economy are calculated based on 2 – D look-up tables extracted from engine mapping data as follows:

$$G_{fuel}(t) = \int_0^t g_{fuel}(\tau)d\tau \quad (6)$$

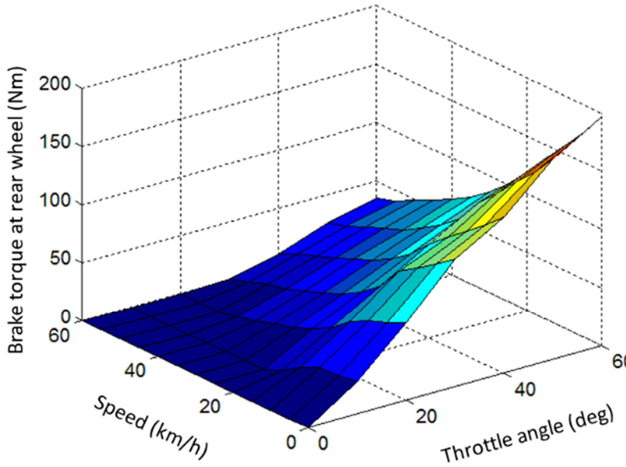

Figure 3. *Brake torque at rear wheel.*

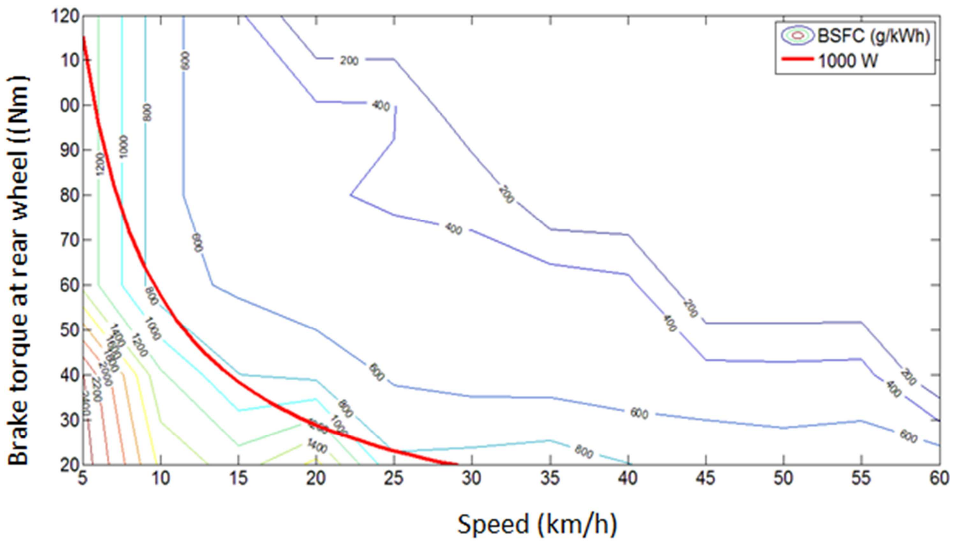

Figure 4. *Brake specific fuel consumption (BSFC) map.*

C. Electric motor model

When operating in propulsion mode, the motor provides propulsion torque to front wheel and torque value can be calculated [12]:

$$T_m = T_{m\_demand} + T_{loss} + J_{mot}\frac{d\omega_m}{dt}$$

$$where\ T_m < T_{m\_max} \quad (7)$$

Required electrical power and motor required current can be described by the equation [12]:

$$P_{elec} = \frac{P_m}{\eta_m}, i = \frac{P_{elec}}{U_{HV}} \quad (8)$$

Where motor max torque T_{m_max} and efficiency η_m are represented as lookup table of motor data maps. Because of durability battery and motor, the electric motor does not operate in regenerative mode.

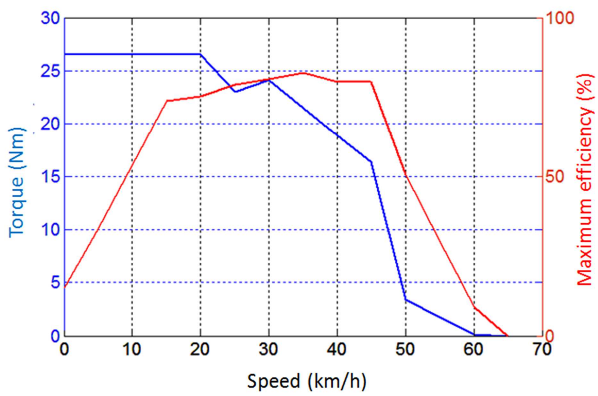

Figure 5. *Torque vs maximum efficiency of electric motor.*

D. Lithium – ion battery model

This paper presents a battery system consisting of 12 battery modules connected in series and each module includes 15 Lithium – ion battery cells connected parallel. The battery model is used to predict the state of charge and the current and voltage observed at battery terminals. The state of charge of the battery system can be calculated based on the battery ampere-hour capacity, current history, self-discharge, and charge/discharge efficiency, etc. The parameters of the battery model are generally identified offline based on tested data, such as the open – circuit voltage of each battery module U_{OC} is a function of SOC and temperature as shown in Figure 6.

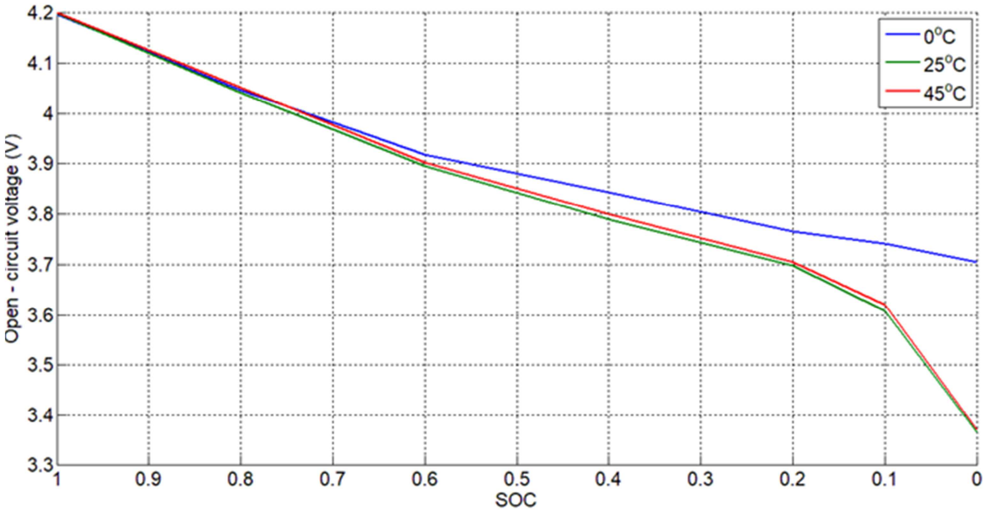

Figure 6. *Open – circuit voltage of one battery module.*

For hybrid vehicle system performance analysis and simulation as well as design, battery SOC calculation is usually implemented from the following current integration:

$$SOC(t) = SOC_0 - \frac{1}{3600}\int_{t_0}^{t}\frac{i(\tau)\eta_{batt}}{Q_i}d\tau \tag{9}$$

where $SOC(t_0) = SOC_0$

And the relationship between terminal voltage and current can be expressed with the following equations:

$$U_{HV} = U_{oc} - U_r \tag{10}$$

$where\ U_r = i.r$

Where η_{bat} is the Coulombic efficiency of the battery, Q_i (Ah) is the capacity in ampere-hours and r is the internal resistance of battery, which is function of SOC and temperature.

E. Motorcycle dynamic model

The longitudinal dynamic model of the vehicle provides resistance force to calculate the actual acceleration and velocity that the vehicle achieves. Then, the actual velocity (V_{act}) is calculated to compare with the test run used in the driver model. Resistance force values are calculated according to the equations:

$$\sum F_{wh} = F_{rolling} + F_{aero} + F_{grade} + F_{acce} \tag{11}$$

$$where\ F_{rolling} = m.g.f.\cos(\alpha) \tag{12}$$

$$F_{aero} = \frac{1}{2}.C_d.A_f.\rho.V^2 \tag{13}$$

$$F_{grade} = m.g.\sin(\alpha) \tag{14}$$

$$F_{acce} = m.\delta_j.\dot{V} \tag{15}$$

$$V_{act}(t) = \int_0^t \dot{V}(\tau)d\tau \tag{16}$$

F. Rule – based controller model

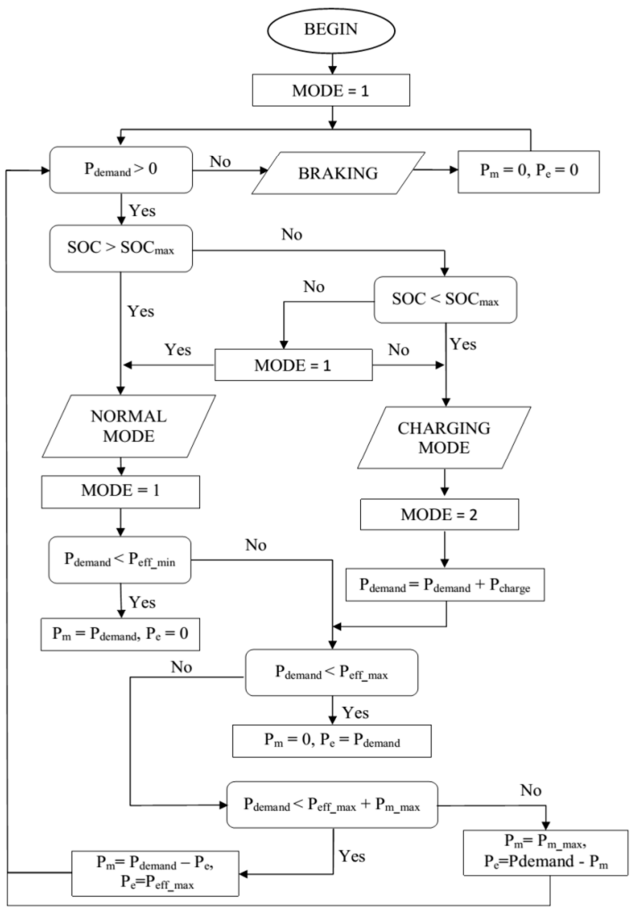

Figure 7. *The flowchart of rule – based controller.*

Rule-based algorithms are used to control the power managements of the proposed plug – in hybrid motorcycle [13-15]. There are two important rules in this controller: (1) internal combustion engines must operate in optimal performance areas and (2) the battery system must remain in the proper state of charge. Thus, there are three main inputs of the controller: the required power of the driver, the state of charge of lithium – ion battery and the actual speed of the motorcycle. Then, the required power to motor and engine are calculated properly. The flow diagram of this rule-based controller is shown in Figure 7:

4. Results and Discussion

To evaluate fuel economy and performance characteristics of the plug – in hybrid motorcycle, the model is simulated in Matlab/Simulink environment under four urban driving cycle, consist of Japan 10 - 15 Mode, ECE, INDIA URBAN and WVUCITY. In fact, these cycles are quite suited to traffic conditions in Vietnamese cities, in terms of speed limits, ramps, deceleration, and mileage. Speed response, power distribution, BSFC or fuel consumption rate, fuel consumption and SOC of proposed hybrid motorcycle are considered. Simulation results were compared between original Honda's motorcycle and the li – ion battery used one. Detailed simulation results when there are only one person in motorcycle running ECE R15 cycle are shown in Figure 8 – 11.

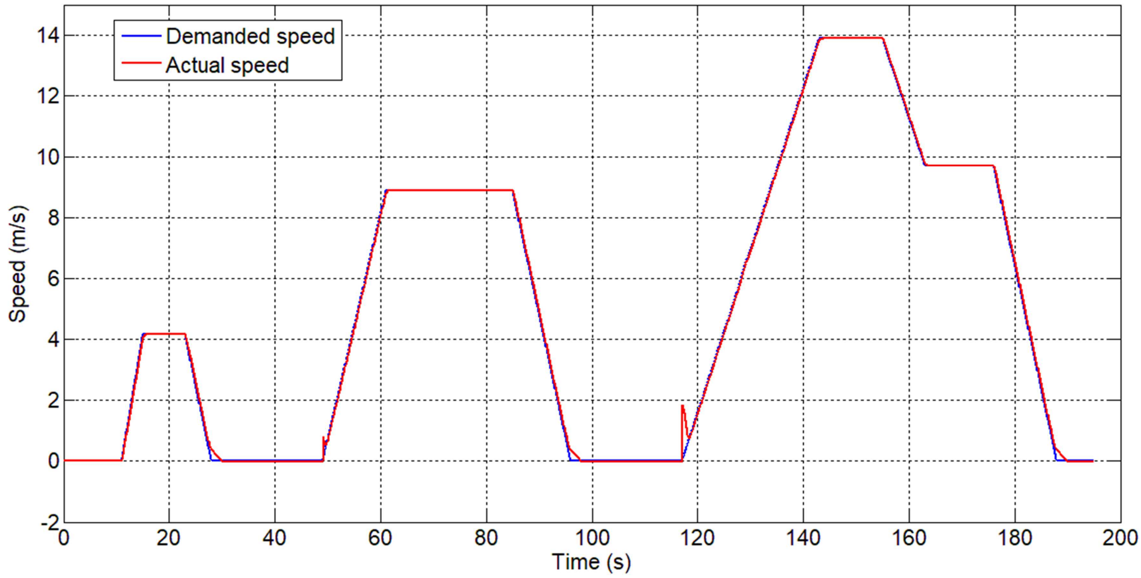

Figure 8. *Speed response.*

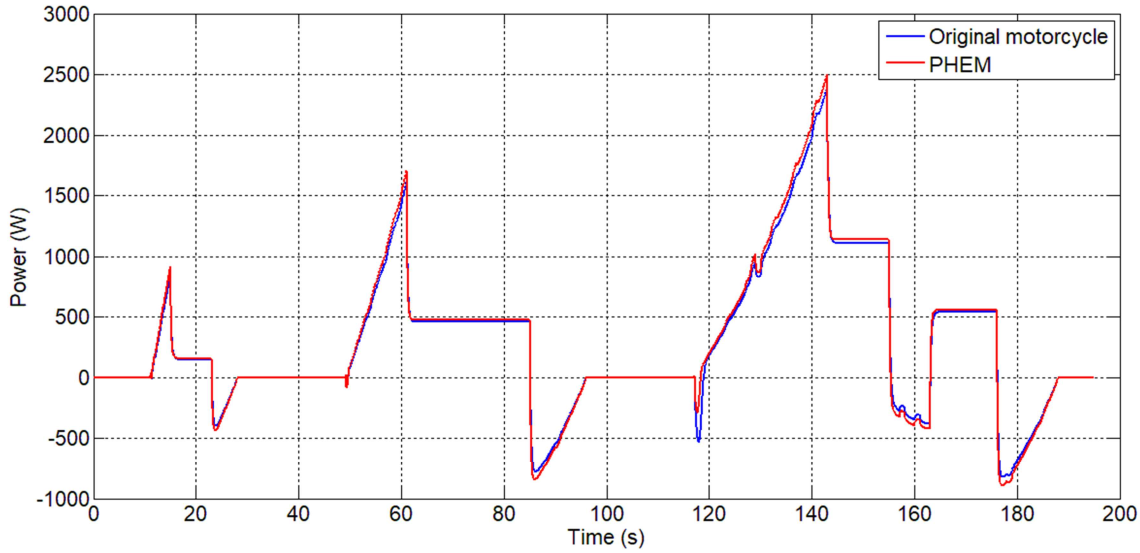

Figure 9. *Required power of the plug – in hybrid motorcycle.*

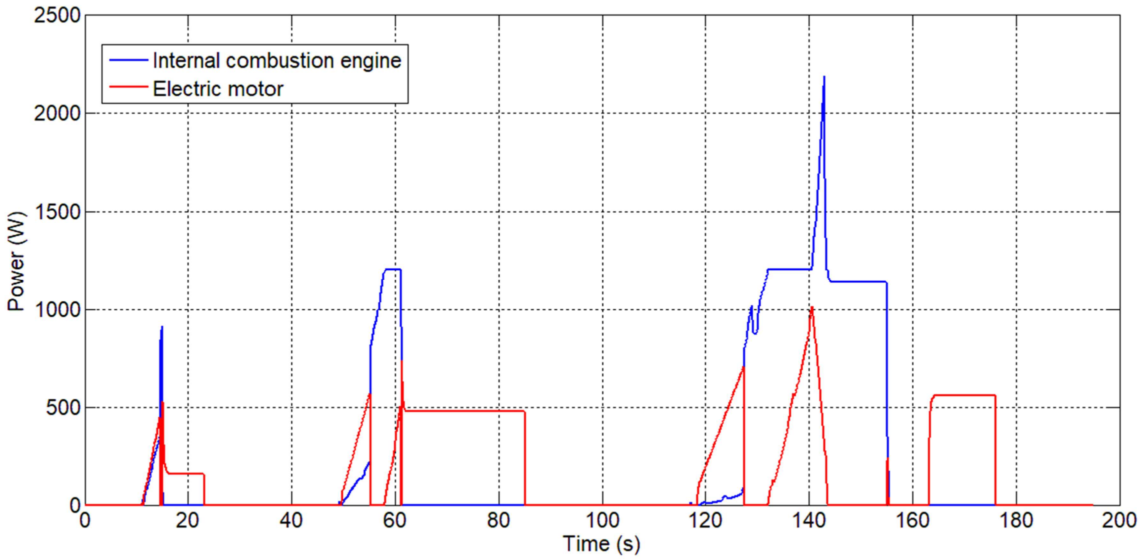

Figure 10. *Power distribution at rear wheel.*

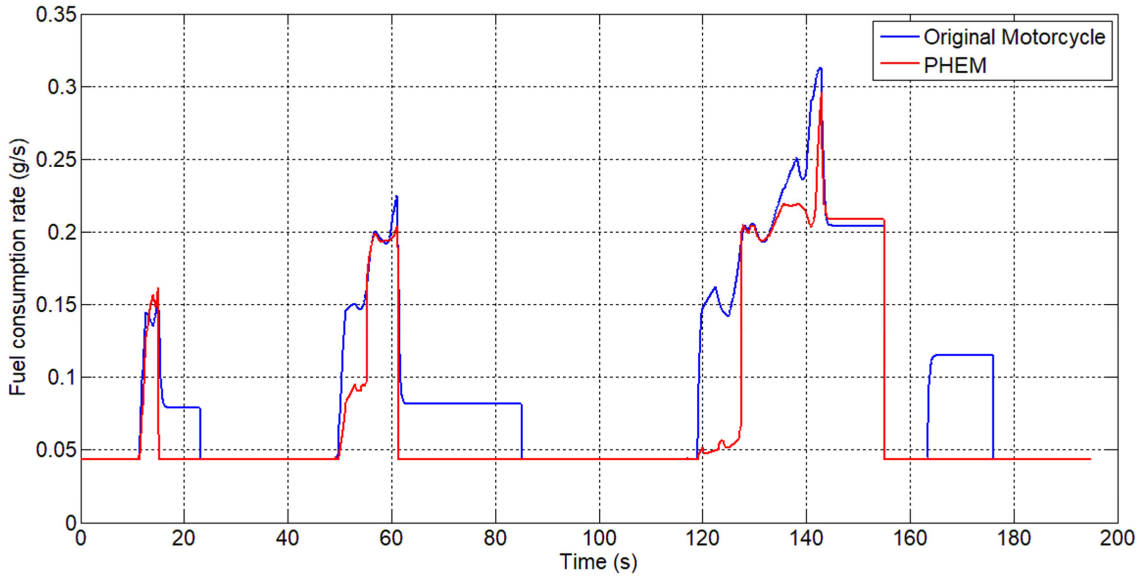

Figure 11. *Fuel consumption rate of original and plug – in hybrid motorcycle.*

Simulation results in different cycles show that proposed plug-in hybrid structure ensure dynamics. By operating of the motor in propulsion mode, the fuel consumption of the plug – in hybrid motorcycle decreased compared to the conventional one, although the plug – in is heavier. In detail, under ECE R15 cycle, fuel consumption of the configuration using Lithium – ion battery is up to 22%, less than original one. Traveling distance in hybrid mode until SOC of Lithium – ion battery under 0.5 is over 54 km, fully meet the daily travel require of almost people living in Vietnamese. In case of rider plus passenger, the fuel consumption is quite good as well, 2.061 litter/100 km only, and an acceptable travel distance at 43.071 km.

Table 1. *Simulation results of HEM.*

	An operator		**An operator and a passenger**
Configuration / **Driving cycle**	**Original motorcycle (litter/100km)**	**PHEM without generator (litter/ 100km)**	**PHEM without generator (litter/100km)**
ECE	2.447	1.909	2.061
JAPAN 10 – 15 MODE	2.907	2.444	2.929
WVUCITY	3.055	2.315	2.617
INDIAN URBAN	2.363	1.838	2.092

Table 2. *Cost analysis of HEM.*

	An operator		An operator and a passenger
Fuel Consumption	**Original motorcycle**	**PHEM without generator**	**PHEM without generator**
G_{fuel} (l/100km)	2.693	2.126	2.425
Expense* (VND/100km)	55,745	44,667	50,880

* 20,700 VND/litter gasoline and 1,600 VND/kWh

5. Conclusion

This paper describes the mathematical modelling analysis and simulation of a plug – in hybrid electric motorcycle renovated from Honda Lead 110cc. The simulation results using Matlab/Simulink environment show that fuel consumption of plug – in hybrid motorcycle are better than original one with similar performance characteristics. The average fuel consumption improvement can be increased up to 21.1%. The average travelling distance that the motorcycle can operate at hybrid mode is over 60 km, so urban people can use it for daily travelling and recharge the battery at night.

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Nomenclature

A_f	frontal area of vehicle, m^2
C_d	aerodynamic drag coefficient,
ρ	air density, kg/m^3
V	velocity, m/s
g	gravitational acceleration, m/s^2
α	slope angle, grad
t	time, s
η_m	motor efficiency
F_{demand}	demand tractive force, N
F_{aero}	aerodynamic drag force, N
F_{load}	total demand load, N
F_{PI}	demand force with PI algorithm, N
$F_{rolling}$	rolling force, N
F_{grade}	slope resistant force, N
V_{demand}	demand velocity at driving cylce, m/s
G_{fuel}	total fuel consumption, g
g_{fuel}	fuel consumption per unit time, g/s
i	current, A
P_{demand}	demand tractive power, W
P_{elec}	electric power of battery, W
r	internal resistant of battery, Ω
SOC_0	initial stage of charge
SOC	stage of charge
T_m	motor torque, Nm
$T_{m\ max}$	motor maximum torque, Nm
$T_{m\ demand}$	demand torque of frontal wheel, Nm
T_{loss}	loss moment of motor, Nm
U_{HV}	motor input voltage, V
U_r	voltage drop, V
U_{OC}	battery open-circuit voltage, V
V_{act}	acting velocity with simulation, m/s

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Biography

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