

Modelica-Based Modeling and Application Framework on Hybrid Electric Vehicles

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Abstract

In order to meet low-emissions criteria outlined in Chinese regulations, which require a progressively increasing percentage of automobiles to be ultralow or zero emissions, in this paper a sort of light hybrid electric drivetrain is studied and modeled in detail using Modelica. An application framework is also designed to improve the usability and the efficiency of the models. Performance of the whole vehicle and some key components are analyzed. Comparison between simulation results and experiment results is performed, which validates the effectiveness of the models. Based on the comparison, we conclude that, the methods presented in this paper can support a rapid design of hybrid electric vehicles and further optimization.

Keywords: hybrid electric vehicles, Modelica, MWorks, application framework, signal bus

1 Introduction

Hybrid electric vehicles (HEVs) have attracted a great deal of attentions due to its high efficiency and less fuel consumption, which combines the advantages of both conventional internal combustion engine (ICE) and pure electric vehicles (Liang et al, 2016; Jionas et al, 2002). HEVs can be classified into Micro hybrid system, light hybrid system, medium hybrid system and complete hybrid system depending on the degree of colloquial in the hybrid system (Liu, 2014). Light hybrid system has been widely used due to its relatively simple structure and braking energy recovery (Zhang et al, 2014).

Basically, modeling and simulation methods of HEVs can be classified into the following three types. The first type is the traditional calculation method using excel where static results are obtained and characteristics of key components are rendered. The second type is that simulation models have already been realized based on commercial software such as advisor, AVL Cruise or Matlab libraries Toolbox (Karen et al, 1999; Meradji et al, 2016), where these models are focused on general and complex predefined. The third type is Modelica, which is suitable for dynamic analysis

and developing components or function modules because of its support for multi-domain unified modelling, object-oriented physical modelling, non-causal modelling, and continuous discrete mixed modeling (Xiong et al, 2016).

In this paper, the structure of light hybrid drivetrain architecture of HEVs, is firstly studied and modeled in detail using Modelica, and an application framework is designed. Subsequently, the simulation results of the performance parameters of the whole vehicle and the key parts are obtained. Finally, the results are verified by experiment results.

2 System Descriptions

Before modeling the HEVs drive train represented in Fig.1 some characteristics of each element composing the system need to be mentioned:

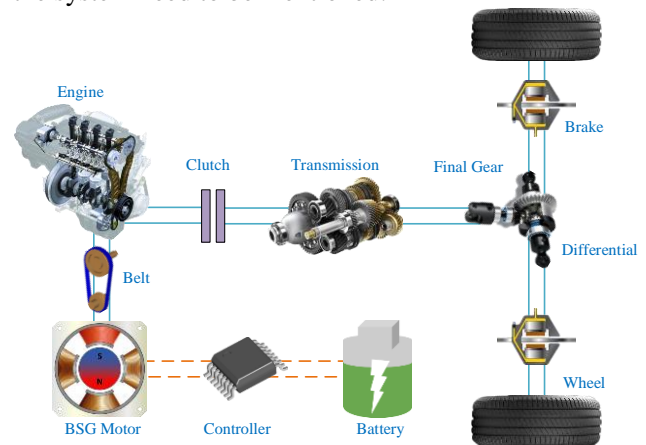


Figure 1. HEVs drive train structure.

Internal combustion engine characterized by torque-speed curve with optimal torque $T_{ICE, opt}=252 \text{ N} \cdot \text{m}$, The main indicator of the internal combustion engine is power output.

BSG(Belt Driven Starter Generator) motor is a belt drive integrated power generation integrated machine. Its function is to achieve fast start engine, electronic idle speed and boost when outputting positive torque, and to obtain high efficiency intelligent power generation and braking energy recovery when negative torque.

Battery of Nickel-Metal-Hydrate (NiMH) having a discharge power $P_{bat,dis}=33700$ W and a charge power $P_{bat,dis}=26040$ W, is responsible for outputting or storing electrical energy, connected to BSG and DC/DC converter. The main indicators of the battery module include SOC, the state of battery charge and discharge, battery output power, and the temperature impact on the battery module.

Transmission having five forward gears are used to transmit torque and speed, which should be gear ratio and efficiency, represented in Table 1.

Table 1. Speed ratio and efficiency of transmission.

Gears	1 st	2 st	3 st	4 st	5 st
Gear Ratios	3.769	1.862	1.298	1	0.765
Efficiency	0.87	0.89	0.91	0.93	0.95

Differential for distribute torque, is a mechanical transmission device capable of associating three shafts with the following rotation speed and torque relations:

$$\varphi_{in} = \frac{\varphi_{out,r}}{1+\lambda} + \frac{\lambda}{1+\lambda} \cdot \varphi_{out,l} \quad (1)$$

$$T_{out,l} = \frac{T_{in}}{1+\lambda} \quad (2)$$

$$T_{out,r} = \lambda \cdot T_{out,l} \quad (3)$$

With λ representing torque split factor, usually its value is 1.

Clutch used to transmit and cut off engine power, have a maximum transferable torque of 350 N·m.

3 Models

In this section, model interfaces are presentation firstly, and then introduce in detail the components and system model of HEVs developed by MWorks/Modelica.

3.1 Interfaces

The development is focused on standardizing the assemblies interface definitions without enforcing a standard vehicle model architecture, so that the same assembly models can be reused in different model architectures (C. Schweiger, 2005). The PowerTrain Library based on Dymola software uses expandable bus interface to facilitate the transfer of variable informations between different components, but this also leads to excessive connections and unclear connections. On the basis of PowerTrain, this paper introduces the inner/outer mechanism, which can make the variable information of each component pass through the inner component without an additional connection bus. The principle is each component contains a component signal bus pointing to the outside. The signal bus contains an expandable connector called as bus connector that sends or receives data to the bus connector within each component of the system. All components point to the same external component, allowing implicit connection of system components. The schematic diagram is shown in Fig.2.

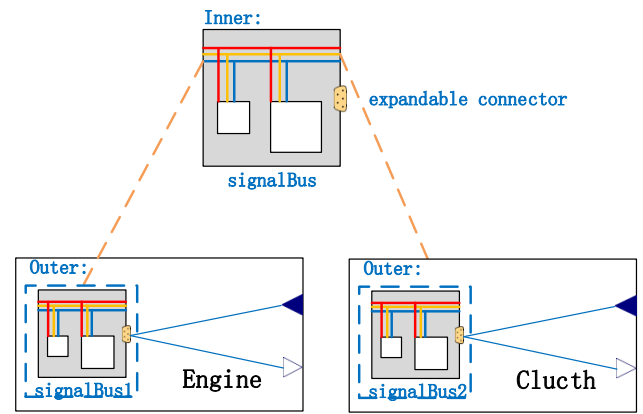


Figure 2. Bus connector design diagram.

3.2 Component Models

The BSG motor model consists of an internal heating model, inertia and BSG Core including both generator and motor modes. The internal heating model is used to calculate the BSG Motor temperature based on the law of conservation of energy. The BSG Core calculates the output torque and operating current of the motor, and the inertia model is used to calculate angular velocity and angular acceleration, represented in Fig.3.

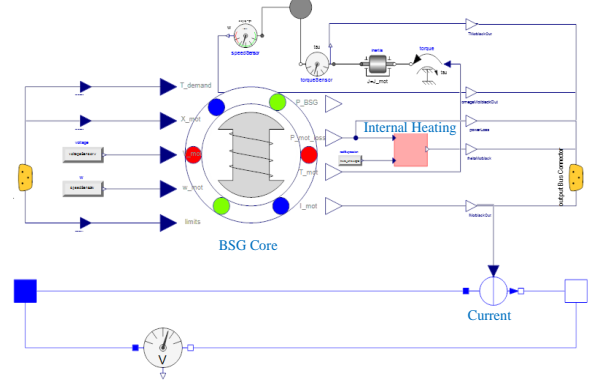


Figure 3. BSG Motor model.

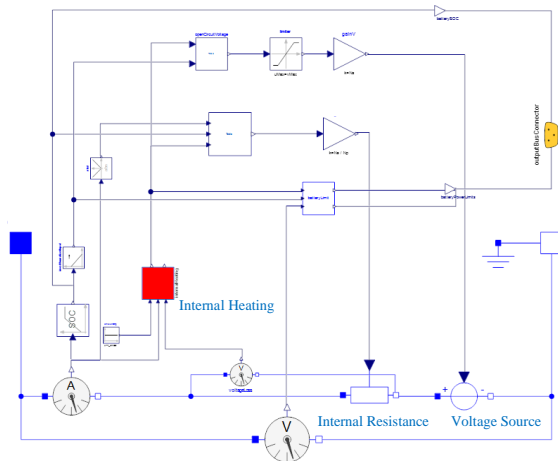


Figure 4. Battery model.

The battery model consists of a voltage source, battery internal resistance, SOC, and an internal heat module. The battery voltage is obtained by interpolation of SOC and temperature while the interpolation data

obtained by experiments. The SOC characterizes the remaining capacity of the battery and is obtained by integration of current. The internal resistance of the battery is obtained by interpolation of temperature, current and SOC. The internal heating module is used to calculate battery temperature. (Fig. 4)

The hyboost controller model includes several function modules such as electronic idle, the brake energy recovery, power train torque demand management and the intelligent charging and discharging module (Crolla et al, 2012; Zou et al, 2015; Sanz et al, 2012). The electronic idle determines whether the engine should be dragged by the BSG motor to maintain the idle speed. The brake energy recovery is used to recover the energy by BSG power generation during braking. Power train torque demand management is used to calculate the demand torque of the driving vehicle. The function of the intelligent charging and discharging module is whether the BSG should be charged or discharged to make the engine work in an efficient area as much as possible according to factors such as the optimal operating point of the engine and the current battery capacity. The results of each hybrid control module are combined to calculate the torque and finally provide for the engine and the BSG, respectively.

The engine model provides a power output based on driving needs. Engine torque is interpolated from engine speed and throttle opening, taking into account the effects of dragging. The fuel consumption of the engine is obtained by interpolating the engine speed and the engine output torque, considering the effects of idle fuel consumption and engine temperature on fuel consumption. In this model, the engine external characteristic curve and the universal characteristic curve should be provided, represented in Fig.5.

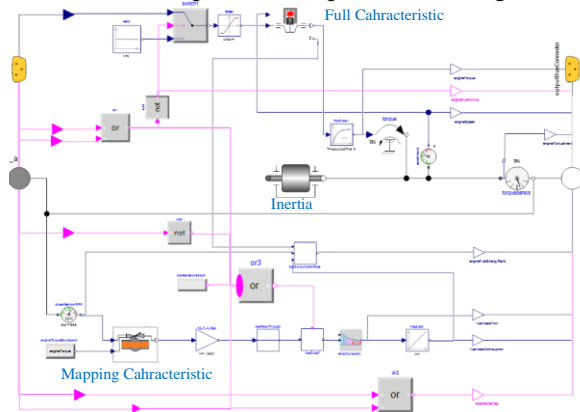


Figure 5. Engine model.

Driver model represented in Fig. 6, will determine the reference position of accelerator pedal, brake pedal and clutch pedal. Desired gear requested by comparing the vehicle speed to the desired one.

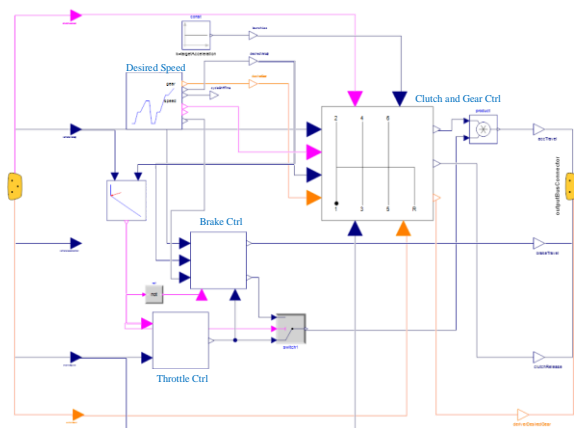


Figure 6. Driver model.

The vehicle body model is used to determine the resistant forces applied to the transmission. This is realized through a modular approach to determine different kinds of resistant forces applied to a vehicle, physical and aerodynamic drag force which provides four calculation methods. The force on the vehicle body is transmitted to the tires through the inner/outer mechanism of Modelica, represented in Fig.7.

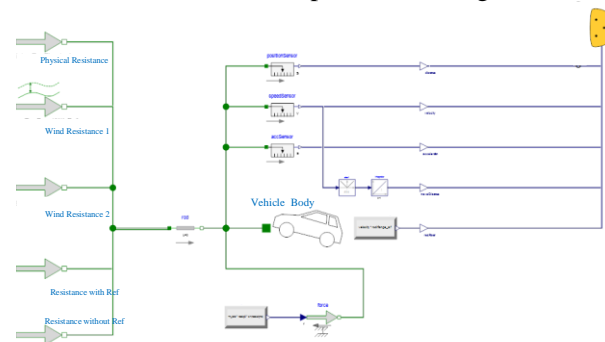


Figure 7. Vehicle body model.

The clutch, brake, final gear, transmission, and belt drive models are based on principles of the second chapter and derived from the Modelica Standard Library (version 3.2.1).

3.3 System Models

According to the model established in subsection 3.2 the system model of a light HEV constructed by building blocks and connecting lines, represented in Fig.8.

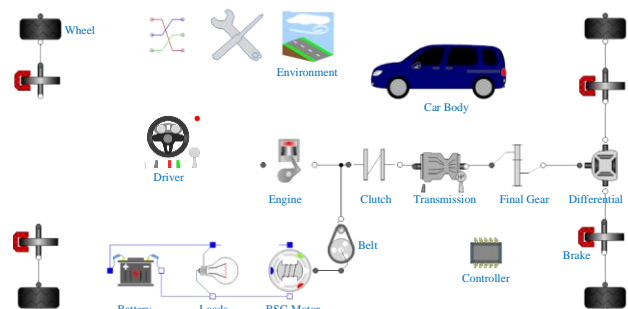


Figure 8. The light hybrid electric vehicles system model.

4 Framework Design

In order to improve the usability of the software, this paper designs a general software framework for vehicle dynamics and economic simulation based on MWorks software. The workflow is shown in Fig.9. The framework can also be easily used in other domain model libraries. The software's workflow is divided into 6 steps:

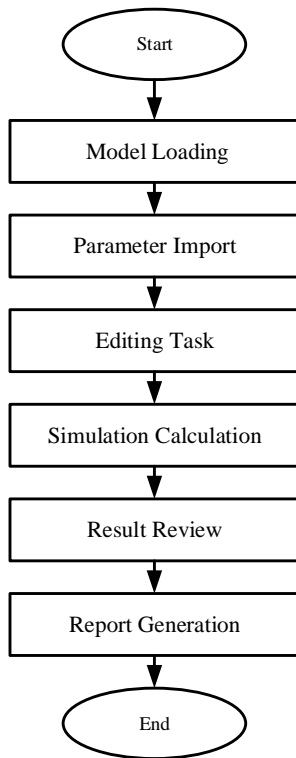


Figure 9. Flow chart of framework.

Step 1: Model loading. Select a model from the vehicle model library, for example, a manual transmission vehicle model or a Hyboost-equipped vehicle model, as shown in Fig.10;

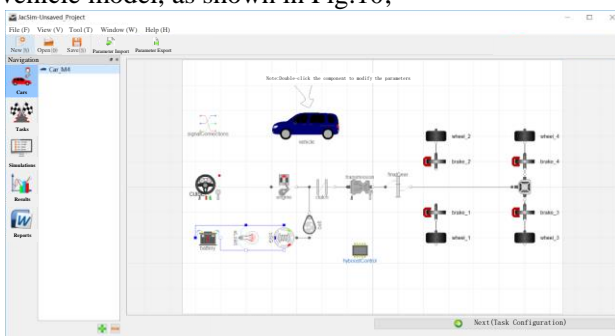


Figure 10. Model Loading.

Step 2: Parameter import. It can be set by using the parameter dialog box or importing the whole vehicle or component parameters from Excel;

Step 3: Editing task. Select tasks that need to be calculated, such as 0-100 km/h acceleration experiment,

or NEDC experiment, and then set experimental parameters, such as shift speed, as shown in Fig.11;

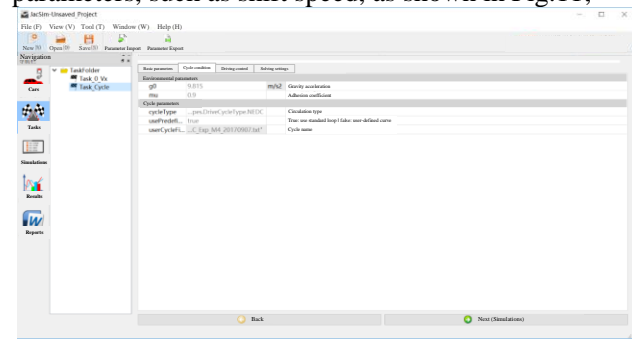


Figure 11. Editing Task.

Step 4: Simulation calculation. Three simulation methods are provided with single simulation, matrix simulation and composite simulation. Single simulation refers to the simulation of all active experimental tasks defined in the above steps. Matrix simulation means that some adjustment parameters in the model can be selected to be added to the matrix list, and then all parameters and their optional values are arranged, and then simulation is performed to all tasks for simulation. Composite simulation refers to adding components in the model to the composite simulation list, setting different batches of simulation parameters for the component, and then arranging and combining for simulation.

Step 5: Result review. The simulation results are displayed through the general and special curve windows, and the general curves are the MWorks simulation result curves, and the special curves are pre-configured curves using the xml method, such as the engine universal characteristic map.

Step 6: Report generation. The result report is automatically generated according to the configured Word template.

5 Results and Discussion

In this part, Modeling parameters is firstly explained based on the light hybrid vehicle (M4) of JAC, and then analyze the main performance indicators of the whole vehicle and parts on the acceleration condition from 0 to 100 km/h and the NEDC condition. Finally, the simulation results are compared with the experiment results. Modeling parameters are shown in Table 2.

Table 2. Parameter of HEVs system model.

Engine Specifications		Final Specifications	
Idle speed	700 rpm	Speed ratio	3.273
Maximum speed	6000 rpm	Wheel Specifications	
Idle fuel consumption	1.2 L/h	Rolling radius	0.333 m
Fuel density	0.75g/m ³	Moment of inertia	1.5 kg.m ²
Response	2 s	Adhesion	0.95

time		coefficient	
Heating Value	4400000 0 J/kg	Cluth Specifications	
Vehicle Specifications		Maximum Torque	350 N.m
Curb Weight	2082 kg	Input Inertia	0.0315 kg.m ²
Wheelbase	2.7 m	Output Inertia	0.0047 kg.m ²
Battery Specifications		BSG Secifications	
Rated capacity	8 Ah	Motor Inertia	0.005 kg.m ²
number of cells	15	Maximum Speed	6000 rpm

5.1 The acceleration condition from 0 to 100 km/h

The velocities of the simulation and the experiment are shown in Fig.12. It can be seen that simulation velocity tracks that of the experimental result well. The acceleration time from 0 to 100 km/h is 16.2 s.

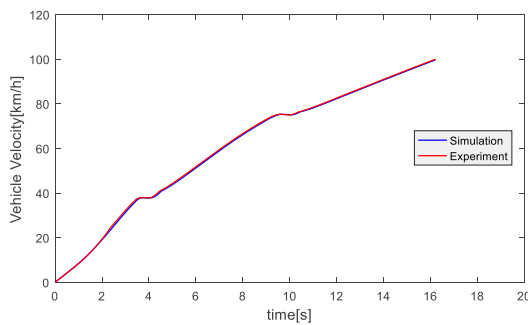


Figure 12. Results for velocities of the simulation and the experiment under condition of acceleration from 0-100 km/h.

Fig.13 and Fig.14 show variations of engine speed and engine torque respectively where simulation results are basically consistent with the experiment results. In Fig. 10, it is difficult to keep speed of model consistent with the actual engine speed in the starting phase because the throttle and the clutch need to be cooperated by controller , and in fact it is difficult to predict the driver's operation for the driver model.

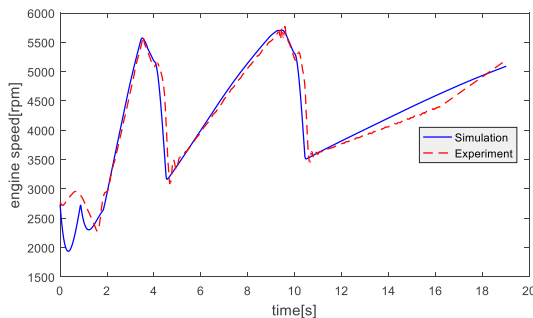


Figure 13. Results for engine speed of simulation and Experiment under condition of accelerated from 0-100 km/h.

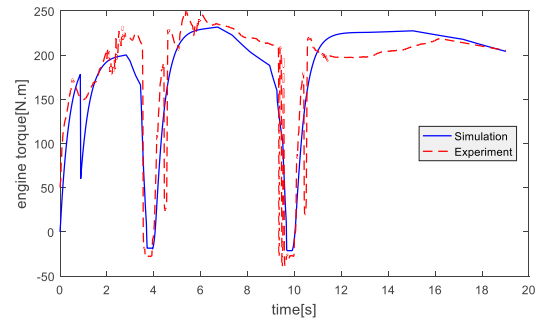


Figure 14. Results for engine torque of simulation and experiment under condition of accelerated from 0-100 km/h.

5.2 The NEDC condition

The vehicle velocities of the simulation and the experiment are shown in Fig.15. It can be seen that simulation velocities tracks that of the experiment well.

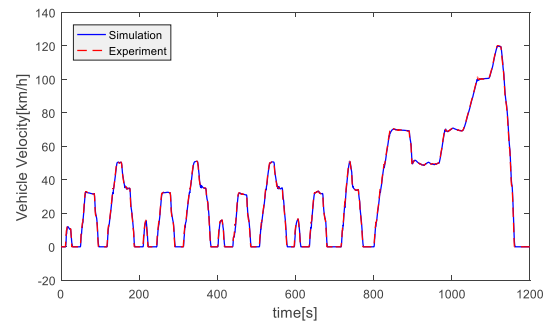


Figure 15. Results for vehicle velocity of simulation and Experiment under NEDC condition.

Fig.16 and Fig.17 show variations of engine speed and engine torque respectively where simulation results are basically consistent with the experiment results. The reason for having different results during the parking stages is that the simulation models consider the control strategy when the vehicle is idling, the fuel supply is cut off. For real vehicle experiment, while the engine is still running leading that energy is consumed due to friction during the experiment.

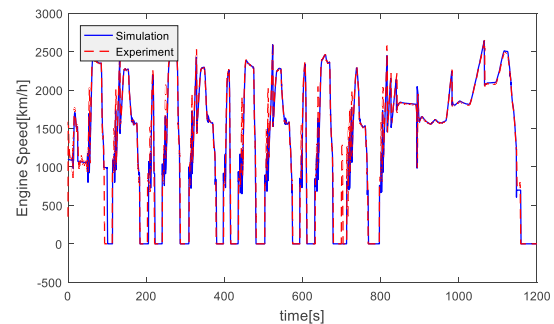


Figure 16. Results for engine speed of simulation and Experiment under NEDC condition.

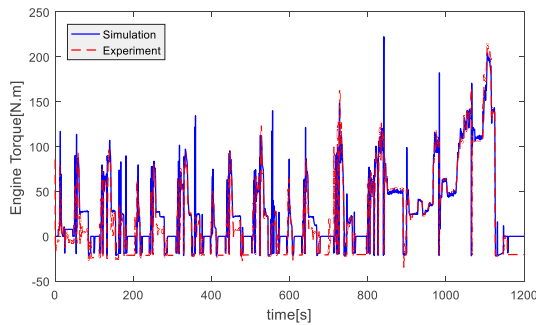


Figure 17. Results for engine torque of simulation and Experiment under NEDC condition.

Finally, Fig.18 and Fig.19 show variations of SOC and fuel consumption over the defined time period. The SOC is set as 56% initially, and the value becomes 56% at last. During the whole process of SOC is in a range from 45% to 75%, which is beneficial to battery health. The fuel consumption is 0.95 gasoline. Since the last battery's charge is equal to the initial charge, the fuel consumption per hundred kilometers is approximate 9.64 L/(100 km).

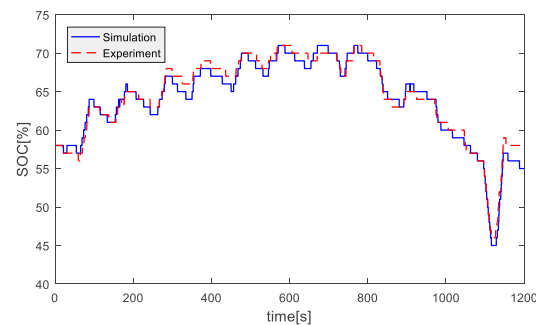


Figure 18. Results for battery SOC of simulation and Experiment under NEDC condition.

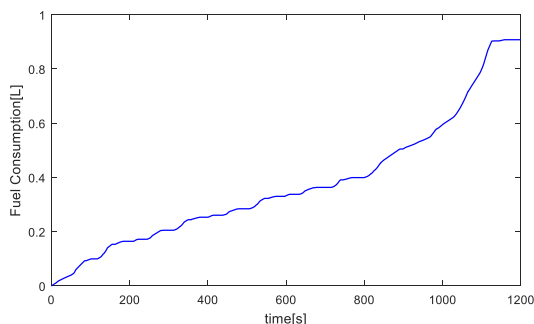


Figure 19. Results for fuel consumption of simulation and Experiment under NEDC condition.

6 Conclusions

In this paper a system model of a kind of light HEVs is developed, and an application framework is designed to simplify the simulation process. By using this application framework, the performance of the whole vehicle and components has been analyzed, and finally

compared with the experimental results. The conclusions are as follows:

- 1) The application framework proposed can improve the usability of the models and the simulation efficiency.
- 2) The simulation results are basically consistent with the experimental results, which shows the effectiveness of the Modelica based multiphysical modeling method.
- 3) Through the analysis of the performance of the whole vehicle and key components such as BSG, battery, engine and vehicle body, it helps the whole vehicle matching optimization and the rapid design and verification of the system.

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