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# Study on Forward-Facing Model and Real-Time Simulation for a Series Hybrid Electric Vehicle

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**Abstract:** To shorten design period and reduce development costs, computer modeling and simulation is important for HEV design and development. In this paper, real-time simulation for a Series Hybrid Electric Vehicle (SHEV) is made to verify its fuzzy logic control strategy based on dSPACE-DS1103 development kits. The whole real-time simulation schematic is designed and the vehicle forward-facing simulation model is set up. Modeling methods for the driver, controller and vehicle (includes engine, generator, motor, battery, etc.) under MATLAB/Simulink environment are discussed in detail. Driver behavior is simulated by two potentiometers and introduced into the real-time system to realize close-loop control. A real-time monitoring interface is also developed to observe the experiment results. Experiment results show that the real-time simulation platform works well and the SHEV fuzzy logic control strategy is effective.

**Key words:** Control strategy, forward-facing, modeling, real-time simulation, series hybrid electric vehicle

## INTRODUCTION

Effectively combining the advantages of traditional ICE vehicle and electric vehicle, Hybrid Electric Vehicle (HEV) can greatly improve fuel economy and reduce emissions at the same time, and it has become a research focus being paid much attention in recent years. In the design and development of HEV, computer modeling and simulation is one of its key technologies used to shorten design period and reduce development costs by testing configurations and energy control strategies before prototype construction begins (Guoqiang *et al.*, 2008).

According to the different information flow path, there are two kinds of HEV simulation. Backward-facing vehicle simulation takes the require/desired speed as an input, and determines what drivetrain torques, speeds, and powers would be required to meet that vehicle speed. This flow of information back through the drivetrain, from tire to axle to gearbox and so on. Generally it only reflects the static properties of the system, and mostly used in vehicle design stage for parameter matching, dynamic performance calculating and control strategy determining.

Forward-facing vehicle simulation includes a model of a driver, who senses the required speed and responds with an accelerator or brake position, to which the drive train responds with a torque. This type of simulation is well suited to the design of control systems, for example, down to the integrated circuit and PC card level-the implementation level. The simulation process in forward-facing is close to the real working process of the vehicle, and it can be used on the real-time simulation platform to achieve RCP (Rapid Control Prototyping) and HILS (Hardware-in-the-loop simulation), that is, the V-model development process (Zhang, 2004).

Real-time simulation platform, such as dSPACE, builds a bridge between HEV control strategy and the vehicle model, through which real-time feedback from the vehicle to the control strategy in controller can be achieved. This may verify the effect of HEV control strategy designed in functional design and off-line simulation stage under an actual vehicle working conditions.

In the previous study, the author has developed a Fuzzy Logic Control Strategy (FLCS) for a Series Hybrid Electric Vehicle (SHEV), and off-line simulation experiments based on backward-facing model are performed to verify its performances (Liu *et al.*, 2008). In order to further test the FLCS and achieve RCP and HILS, a real-time simulation for the SHEV based on forward-facing model is made in this paper using dSPACE real-time simulation platform.

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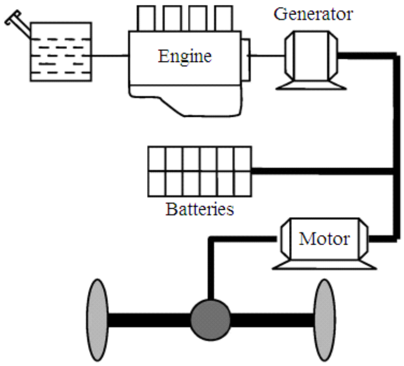


Fig. 1: Typical configuration of SHEV

## REAL-TIME SIMULATION SCHEMATIC DESIGN

**Shev model:** The vehicle studied in this paper uses typical SHEV configuration, as shown in Fig. 1. It includes an engine, a generator, batteries and a motor. The motor is the only component to drive the vehicle. An engine/generator set (APU) is added to the electric drivetrain to charge the batteries or provide power for driving. The batteries will change between the two states of charging and discharging based on the control strategy.

**Real-time simulation schematic:** The whole real-time simulation schematic is designed as Fig. 2 (Wu, 2008). It mainly includes hardware and software two parts. According to the function requirements, it can be divided into vehicle (controlled object), controller, driver and monitor 4 sub-modules.

**Forward-facing simulation model:** A forward-facing simulation model is set up for the SHEV studied under MATLAB/Simulink environment as Fig. 3. Driver module passes acceleration and brake pedal signals to the controller according to the request speed (cycle speed) and the vehicle speed. According to the pedal signals, controller uses the control strategy to split the power instantaneously. Vehicle speed information is given by the vehicle module and feedbacks to the driver module and controller module. Some component modeling methods are reference to ADVISOR2002.

**Driver model:** Driver model uses a PI controller to let the vehicle follow the request speed (Huang *et al.*, 2004). It changes the difference between request speed and vehicle speed into acceleration and brake pedal signals. The driver model can be expressed as:

$$\Delta T = K_p \cdot (u_r - u_a) + K_I \cdot \int (u_r - u_a) d_t \tag{1}$$

$\Delta T$ is the output pedal signal, which means accelerate when positive and brake when negative; $u_r$ and $u_a$ are request speed and real vehicle speed; $K_p$ and $K_r$ are the coefficients of PI controller, obtained by trial and error method.

**Engine model:** Engine model is accomplished mainly by testing approach, supplemented by theoretical modeling method. The steady torque of the engine is:

$$T_{e0} = f(T_{given}, \omega_{given}) \tag{2}$$

Dynamic equation of the engine is:

$$T_e = j\frac{d\omega}{dt} + T_{el} \tag{3}$$

Fuel consumption can be calculated as:

$$m_f = \int_0^t \dot{m}_f dt = \int_0^t f(T_e, \omega_e) dt \tag{4}$$

$T_{e0}$ is the steady torque of the engine; f(.) is a 2-D look-up table function; $T_e$ and $T_{el}$ are the torque and its correction value of the engine; j is the moment of inertia; $m_f$ is the fuel consumption per second (g/s).

It should be specially explained that the engine model excludes emissions because of the difficulty of emission experiments, also because emissions are not the main objective concerned by the control strategy designed for the vehicle. The engine simulation model is as Fig. 4.

**Generator model:** Generator connects engine with the same shaft. Dynamic equation of the generator is:

$$j\frac{d\omega}{dt} = T_e - T_L - c \cdot \omega \tag{5}$$

j is the moment of inertia; $T_e$ is the electro-magnetic torque; $T_e$ is the engine torque; ω is generator angular velocity and c is the damping coefficient.

Based on its universal characteristic MAP and formula (5), using interpolation, the generator output power can be calculated by 2-D look-up table. The generator simulation model is designed as Fig. 5.

**Motor model:** In an SHEV, the motor can be work at not only at motor mode, but also at generator mode. So the motor model must satisfy both the two working modes. In an SHEV, the motor and its controller are looked as one module.

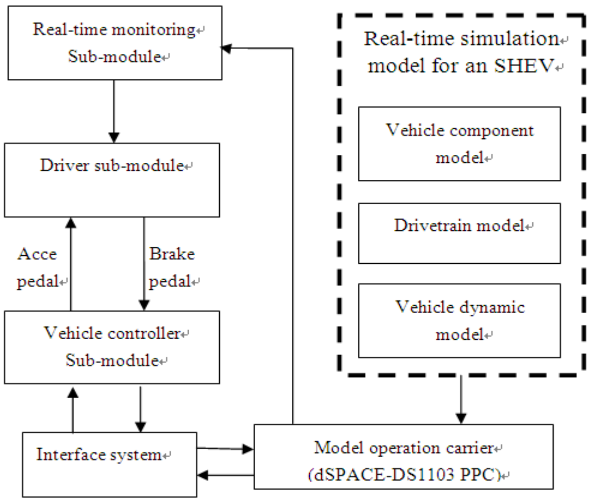


Fig. 2: Real-time simulation schematic

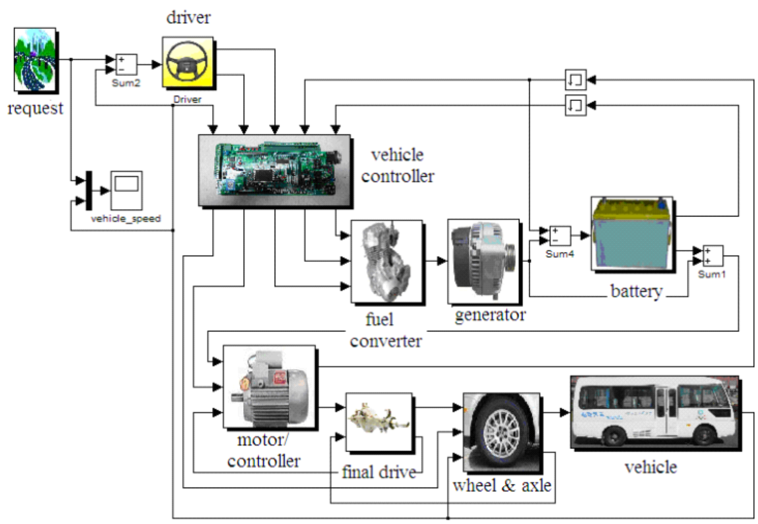


Fig. 3: Forward-facing SHEV model

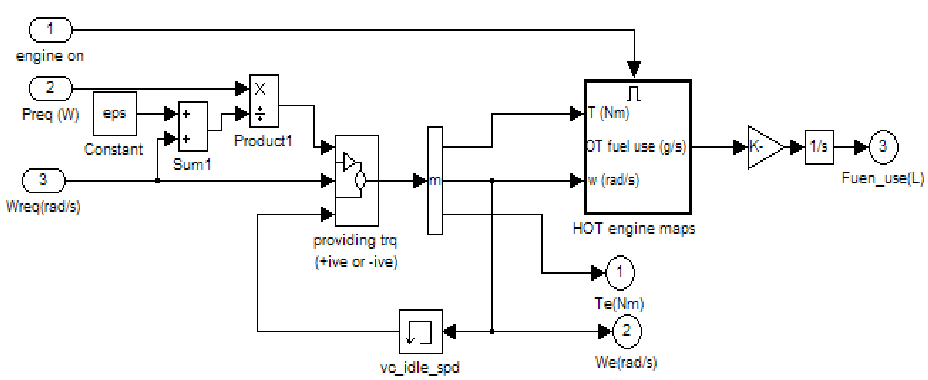


Fig. 4: Engine simulation model

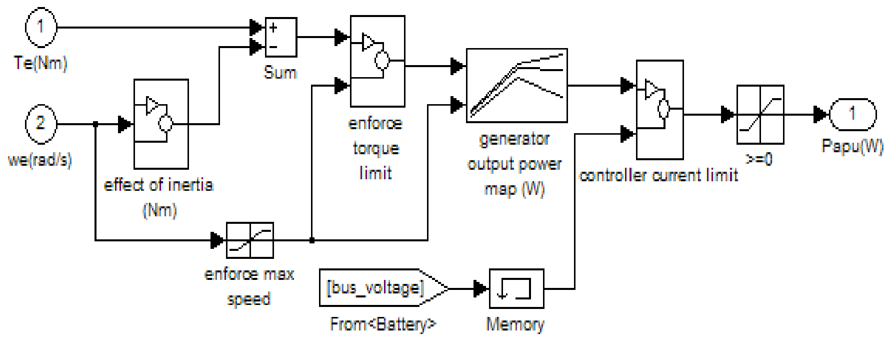


Fig. 5: Generator simulation model

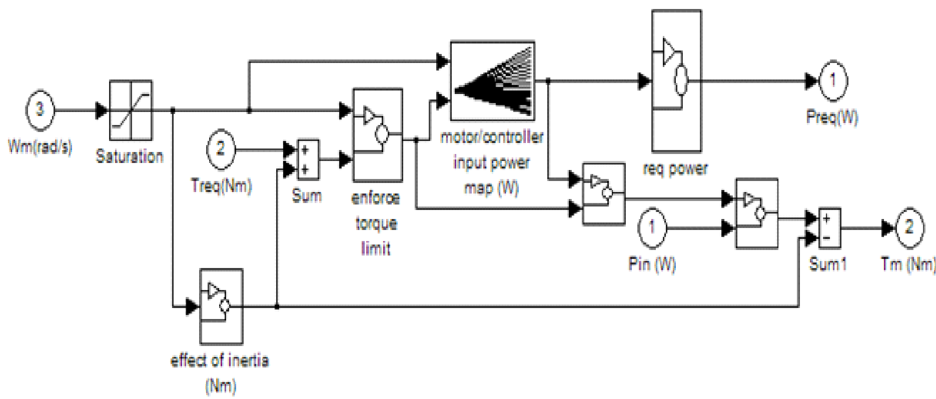


Fig. 6: Motor simulation model

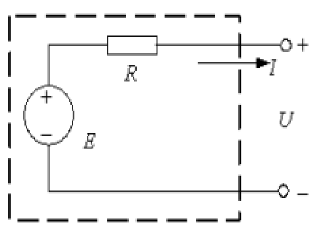


Fig. 7: Battery simplified model

According to the request torque and transmission speed, the motor request power are calculated by searching its universal characteristic MAP, also considering the additional torque caused by moment of inertia. Supposed the actual ratio of the rotor torque and the input power is the same as the ratio of the rotor torque and the request power, the motor output torque can be calculated from the actual input power. Also the maximum working current of the motor controller is limited. The motor model puts emphasis on its input and output characteristics, ignoring its inner complex physical process. It is achieved as Fig. 6.

**Battery model:** The battery charging and discharging process is a non-linear process affected by many factors. It is very complex. Referring to Advisor 2002, the battery model can be simplified as an ideal voltage in series with battery resistance (Johnson, 2002), (Fig. 7).

Using the battery experiment data of open circuit voltages and resistance under difference State-of-Charge (SOC) of the batteries, also considering the temperature influence, the battery simulation model is designed as Fig. 8. When charging and discharging, the relationship between open circuit voltage and battery resistance is different.

**Other model:** Vehicle model only studies the longitudinal dynamic model, that is, only drive and brake are concerned. The vehicle speed is calculated by its driving formula as follows:

$$F_t = fG\cos\theta + \frac{C_D A V^2}{21.15} + G\sin\theta + \delta m\frac{dV}{dt} \qquad (6)$$

$F_t$ is the total driving force of the vehicle; f is the rolling resistance coefficient; G is the vehicle weight; θ is

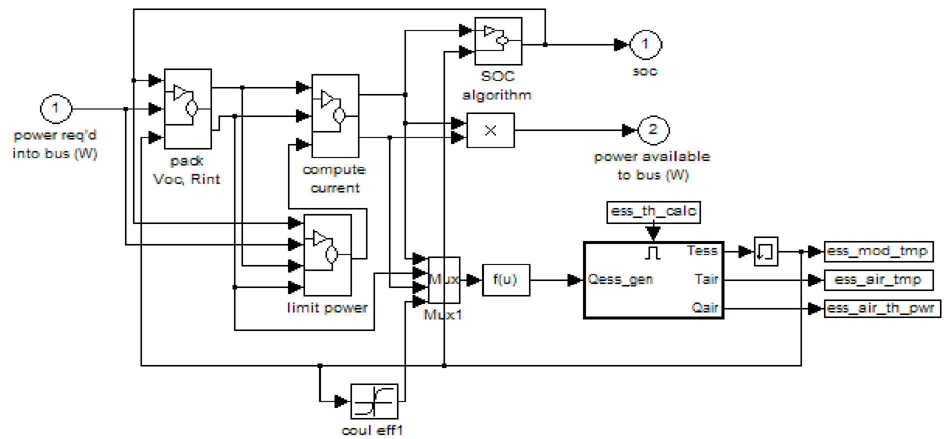


Fig. 8: Battery simulation model

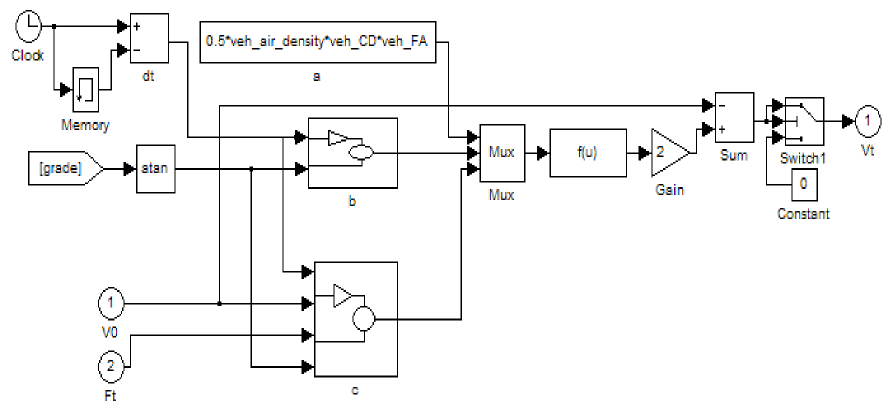


Fig. 9: vehicle calculating simulation model

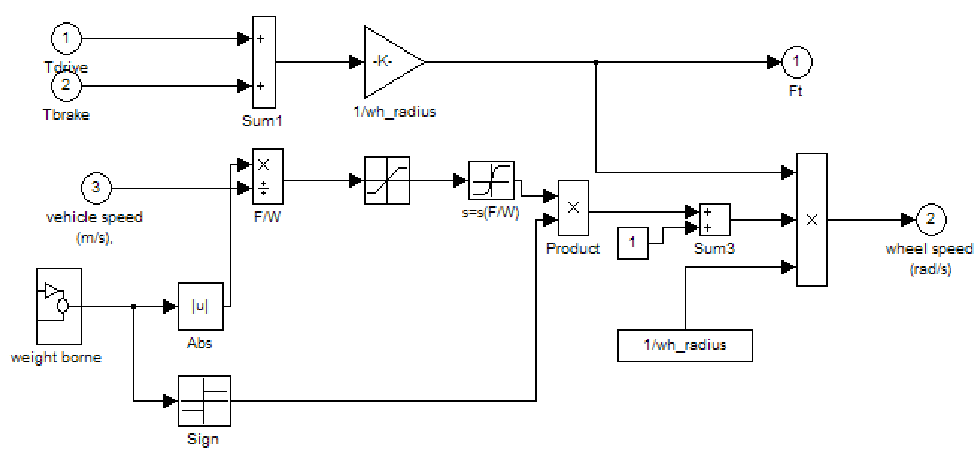


Fig. 10: Wheel simulation model

the road slope angle; $C_D$ is the air resistance coefficient; A is the frontal area of the vehicle; δ is the conversion factor of the moment of inertia; m is the vehicle mass and V is the average vehicle speed during an iteration step. The final speed $V_t$ of the step is calculated as (7), in which $V_t$ is the initial speed of the iteration step.

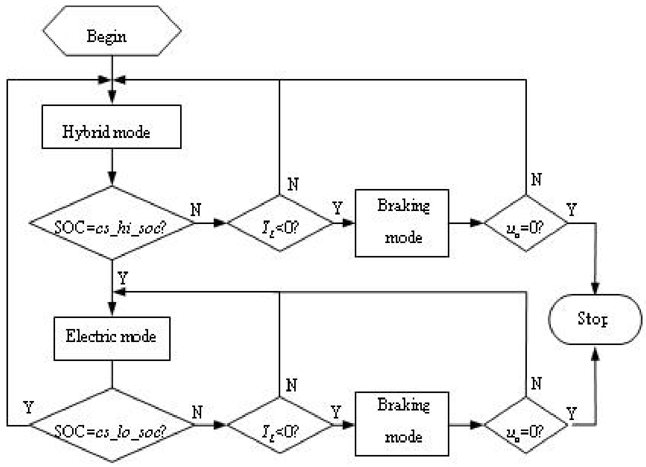


Fig. 11: Working mode switching diagram

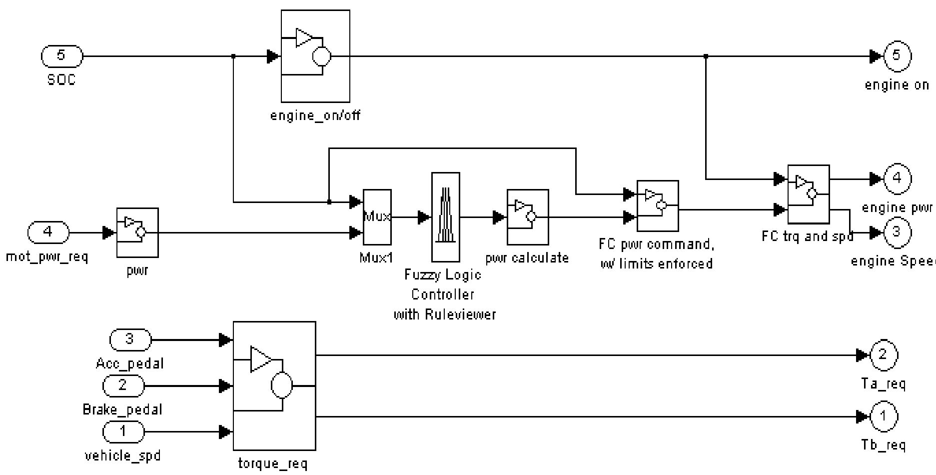


Fig. 12: Vehicle controller simulation model

$$V_t - 2V - V_0 \qquad (7)$$

The vehicle speed calculating simulation model is as Fig. 9. Wheel simulation model is as Fig. 10.

**Controller model:** The controller model receives instructions from the driver model and detects the vehicle driving mode real-timely. According to the control strategy, the controller outputs signals to manage the energy/power flow from the different power components, so as to achieve coordinated and optimal control of the SHEV. The controller can be divided into 3 parts: torque demanded module, vehicle working mode switching module and fuzzy logic control strategy module.

**Toque demanded module:** Acceleration/brake Pedal signal is changed into torque demanded signal according to the driver's intention, and then demand power is calculated out with the motor's speed.

For simplify, supposed the demanded driving torque $T_a$ has a linear relationship with the acceleration pedal signal $L_a$, that is:

$$T_a = L_a \cdot T_{max.mot} \qquad (8)$$

$T_{max\text{-}mat}$ is the maximum output torque of motor under the current speed.

When braking, also supposed the brake torque $T_b$ has a linear relationship with the brake pedal signal $L_b$, that is:

$$T_b = L_b. T_{b\,max} \qquad (9)$$

$T_{bmax}$ is the maximum brake torque, which has a certain value limited by the relevant national standard.

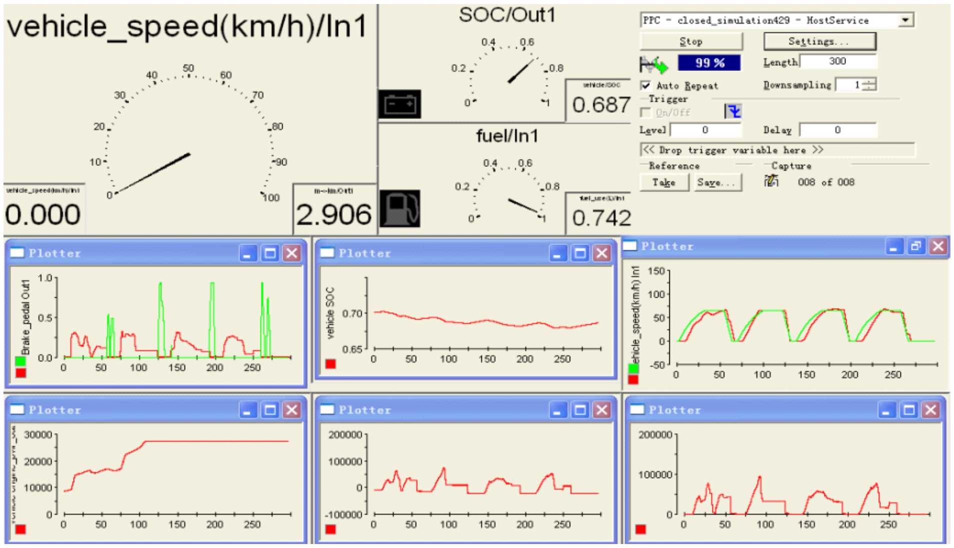


Fig. 13: Real-time monitoring interface

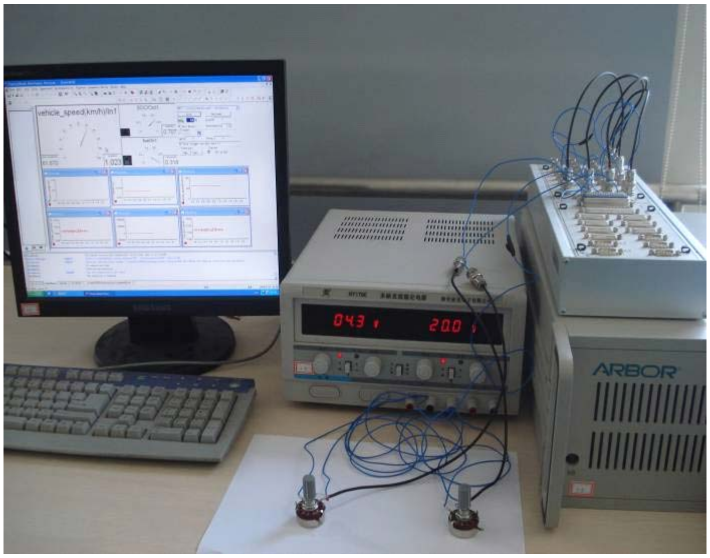

Fig. 14: Real-time simulation platform

Vehicle braking process is composed of friction braking and regenerative braking two parts. Define a regenerative braking torque coefficient α is:

$$\alpha = T_{gb} / T_b \tag{10}$$

$T_{gb}$ is the regenerative braking torque and $T_b$ is the total braking torque.

Relevant studies show that energy recovery effect of regenerative braking depends on the vehicle initial speed of the step, which is better on the high-speed step than on the low-speed step. Therefore, the regenerative braking torque coefficient a is adjusted with the vehicle speed.

**Working mode switching module:**

**SHEV has 3 working mode:** Electric mode, hybrid mode and braking mode. Working mode switching is mainly according to the SOC of the battery, vehicle speed and demanded torque, etc. The working mode switching diagram of the SHEV studied is as Fig. 11.

**Fuzzy logic control strategy module:** The SHEV studied in this paper uses a fuzzy logic control strategy, which is stated in reference (Liu *et al.*, 2008), and doesn't be introduced here.

In summary, the total vehicle controller simulation model is designed as Fig. 12.

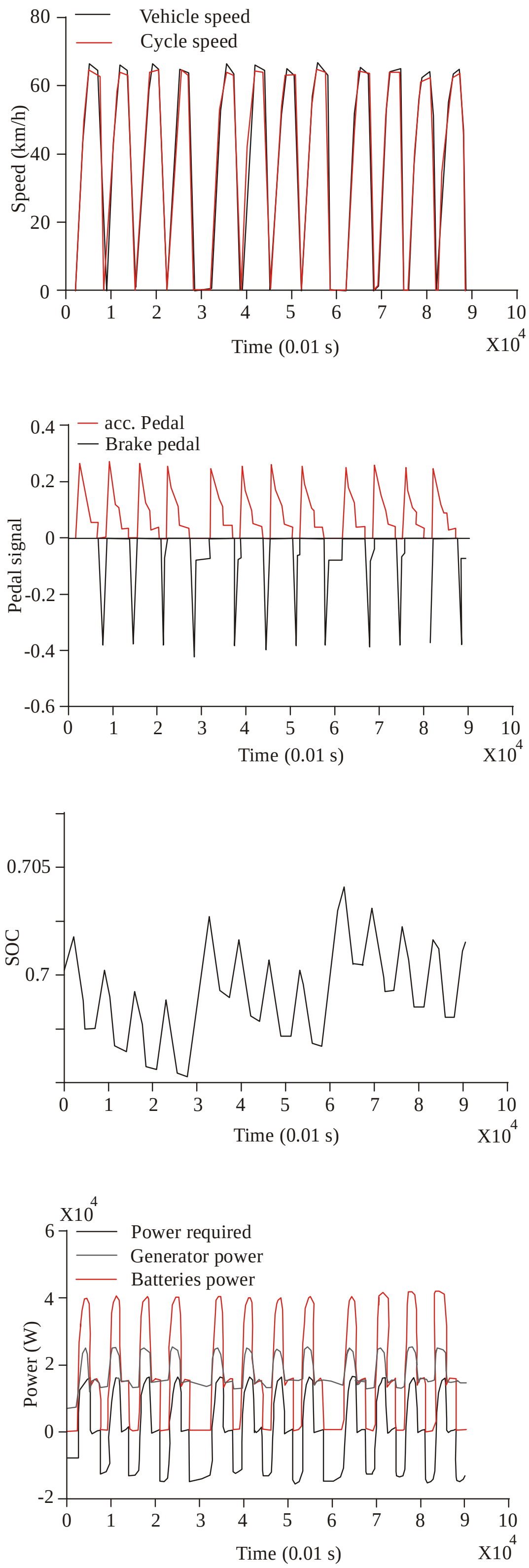


Fig. 15: Real-time simulation results

## REAL-TIME SIMULATION EXPERIMENT

**Real-time simulation platform:** In order to test the control performance of the HEV control strategy, it is very necessary to build a real-time simulation platform. In this paper, a dSPACE-DS1103 platform is chosen as the real-time operation carrier for the vehicle model and controller model.

The forward-facing model, as shown in Fig. 3, is divided into vehicle model and controller model, and both two models are packaged respectively. Real-Time Workshop (RTW) and Real-Time Interface (RTI) are used to convert the two simulation models into C code and downloaded into DS1103 PPC controller.

The vehicle model and controller model work separately in the DS1103. Communication between the two models is realized by using CP1103 panel to connect their I/O signals. DS1103 platform has abundant I/O resources, and different modules can communicate by set each module's I/O signals in respective channel, whose advantage is that the signal adjustment and interference may be don't care so as to enhance the system stability. By using the dSPACE/ControlDesk software, a virtual real-time monitoring system is also developed. Through the monitoring interface can easily see the changes of every signal, and also can adjust the parameters by need. The interface is as Fig. 13. Two potentiometers are used as the acceleration pedal and brake pedal to simulate the driver's behavior. Voltage range of the potentiometer is 0~5V, which corresponds to the pedal position signal, acceleration 0~1 and brake -1~0. Pedal signals are sent into the controller by connecting to CP1103 panel. By adjusting the two potentiometers manually, vehicle speed follows the given cycle speed. The whole real-time simulation platform founded in this paper is as Fig. 14.

**Experiment results:** ARTERIAL is used as the driving cycle, and the real-time simulation results are shown in Fig. 15. From Fig. 15 it can be seen that, with the manual adjustment of the two potentiometers, the vehicle speed may follow the driving cycle well. Power output by APU changes following the power required by the vehicle. When vehicle power required is high, both the batteries and APU provide power; when it is low, APU decreases its output power and the batteries are charged. And SOC can be steadily working nearby 0.7 and realize constant SOC control of the fuzzy logic control strategy.

## CONCLUSION

This study introduces the real-time simulation work based on the dSPACE development platform for an SHEV. First the whole real-time simulation schematic is designed. And then a forward-facing simulation model is introduced. Then modeling methods for the driver, controller and vehicle (includes the engine, generator, motor, battery, etc.) under MATLAB/Simulink environment are discussed in detail. By using MATLAB/RTW and dSPCAE/RTI, the vehicle model and controller model are downloaded into a dSPACE-DS1103 PPC controller board separately. A real-time monitoring system is also developed to observe the experiment results. Using two potentiometers as acceleration pedal and brake pedal to simulate the driver's behavior, so as to achieve close-loop control. Finally the real-time simulation experiments are performed under ARTERIAL cycle. By manual adjusting the two potentiometers, the vehicle speed may follow the driving cycle well, which shows the real-time simulation system works well. The SOC changing curves also shows the fuzzy logic control strategy developed in the previous work is effective.

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