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RESEARCH ARTICLE

Design and Analysis of a Novel Multimode Powertrain for a PHEV Using Two Electric Machines

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ABSTRACT A new dual-motor plug-in hybrid system has been developed in this paper. The system has a variety of operating modes such as ''pure electric drive'', ''series hybrid drive'', ''parallel hybrid drive'', and ''pure oil drive'', which can maximize fuel efficiency according to the driving conditions of the vehicle and the needs of the driver. By adding high-power on-board chargers and high-capacity lithium-ion battery packs to the system, more electric driving can be achieved. This paper introduces the parameters and performance indexes of the main components of the system, establishes the simulation model of the powertrain, formulates the control strategy, and analyzes the power performance and fuel economy of the system through simulation. The simulation results are as follows: the maximum speed of the vehicle can reach 180.82km/h; the acceleration time of 100 km/h is 7.72s; in the WLTC driving cycle, the fuel consumption of the hybrid power system is 7.648L/100km; the electric driving range is 156.63 km. The simulation results show that the powertrain can reduce fuel consumption while maintaining sufficient power performance, which proves the feasibility and fuel economy potential of the scheme.

INDEX TERMS Hybrid vehicle, novel multimode powertrain, two clutches, two electric machines, MATLAB/Simulink.

I. INTRODUCTION

Compliance with global strengthening of emission regulations is an urgent issue for the automobile industry. Well-established methods to reduce fuel consumptions and exhaust gas emissions consist of electrification, hybridization and substitution of alternative resources etc. [1]. Developing new-energy vehicles is considered to be one of the most practical and most promising solutions [2], [3]. Due to the high manufacturing cost, low power and energy density, and low consistency of batteries, pure electric vehicles (PEVs) cannot meet the demands of consumers. However, as a culmination of the technologies embracing the best of both internal combustion engine (ICE) vehicles and PEVs, the most notable advantages of hybrid electric vehicles (HEVs) are the long mileage, high reliability and low fuel consumptions, etc. [4]. In addition, in terms of alternative energy, hydrogen fuel cell electric vehicles (HFCEVs) account for the main part, and their cost and refueling system are the major concerns [5]. Therefore, HEVs are among the most promising solutions to overcome serious concerns over environmental deterioration and fuel shortage [6], [7]. Plug-in hybrid electric vehicles (PHEVs) use electric energy from the grid rather than fuel energy for most short trips, consumption, therefore drastically reducing fuel [8], [9].

Compared to conventional fuel vehicles, the energy efficiency and emissions of HEVs have been improved dramatically, which attracted extensive attention from the major

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automobile manufacturers and related research institutes researchers worldwide [10], [11], [12]. Many HEVs are designed to achieve the goals of reducing carbon emissions and dependence on fossil fuels, therefore, it is promising to study new energy vehicle projects [13]. Some researchers are enlightened to investigate the potential that a single electric machine (EM) helps the HEV to realize necessary operation modes and gain comparable performance to those HEVs with two EMs. The single-EM HEV uses a EM and has fewer associated power electronics systems, which imply advantages of compactness, low power loss, and low cost. On the other hand, the single EM cannot work as a motor and a generator at the same time, which makes the power flow management more challenging and might introduce limitation to the HEV performance [14]. Due to limited flexibility of engine operation, it is uneasy to improve the fuel economy of parallel hybrid electric vehicles with a single electric machine from control perspective only [15]. Zhang et al. proposed powertrain architectures and performance indexes for comparative analysis by combining market sales, and found that the fuel economy performance of the series hybrid transmission is not very good [16].

To satisfy the high-power requirements for accelerating, climbing or running at high speeds, the power of the single motor must be very high [17]. Therefore, HEVs with two electric machines have gradually become the mainstream choice. For most currently developed HEVs, two electric machines are used, e.g., Ford FHS [18], Toyota Hybrid System (THS) [19], GM-Allison AHS [20], Renault IVT [21], Honda i-MMD [22], Timken EVT [23], Saicmotor EDU [24] and BYD DM-I [25].

Dual-motor hybrid powertrain usually have two different configurations: power-split and parallel. Power-split configuration has an intrinsic structural drawback in that it does not allow direct mechanical torque transmission from the engine to the drive shaft. Because, there may be a penalty in mechanical energy loss due to the fact that a portion of the ICE output power may be routed through a mechanical to electrical to mechanical double energy mode conversion path in supplying driven-axle power from the engine [26]. Therefore, even if the engine is optimized to operate at the most efficient state, the vehicle fuel economy may not be the best [27]. Zhao et al. systematically made a comparative analysis of the generation, screening and optimization techniques of power-split powertrain configuration [28]. In contrast, the parallel configuration does not have these inherent energy loss penalties. Its disadvantage is that engine speed is coupled to the vehicle speed according to the set transmission ratios in some situations [26]. The mechanical power is transmitted directly from the engine to the drive shaft, which is also optimal under specific conditions. Because, the properly arranged clutches transmit power flow more flexibly, avoid spin loss for the engine and energy conversion loss for the electric components [14]. Graham, B discovered that the parallel was the best by using non-optimized models to compare four hybrid configurations [29].

However, from design perspective, it is likely to devise multiple operating modes on a powertrain system to achieve better fuel economy [10], [30]. On the same powertrain, it can have parallel modes, series modes, pure electric modes and fixed-gear modes at the same time. And having a number of operating modes makes it possible to fully realize the potential of the powertrain [31]. Using clutches can achieve multiple operating modes to improve powertrain operation flexibility and efficiency at the expense of higher complexity [32]. Especially for plug-in hybrid (charge depletion) operations, it was found that by adding clutches, fuel economy can be improved significantly [32]. Zhang et al. found that adding one clutch to the Prius transmission can significantly improve fuel economy in urban driving, whereas removing two clutches from the Volt transmission will not significantly affect fuel economy in both urban and highway driving [33]. The results of two classical power-split hybrid powertrains show that the existing configuration may have clutch redundancy or deficiency. Therefore, configurations with few or no clutches can be studied after adding clutches, and configurations with many clutches can be analyzed after reducing clutches.

In this paper, a dual-motor multi-mode PHEV powertrain with two clutches is proposed to match conventional gasoline vehicles. The powertrain is designed to help the engine operate in the most efficient zone to maximize fuel economy. The powertrain consists of two motors, two clutches, and fixed ratio gear transmission. It has the advantages of continuously variable transmission of most previous hybrid systems, and the structure is not complicated. The designed powertrain utilizes two clutches, including an engine-generating clutch and an engine-driving clutch, to create multiple operating modes and power flows. The engine-generating clutch can realize a series mode and starts/shuts the engine, thus reducing fuel consumption. The engine-driving clutch can realize both pure oil mode and parallel mode, taking full advantage of the high efficiency characteristics of the engine at high speed.

The rest of this article is shown below: Section II describes the configuration and operation mode of the powertrain. Section III introduces the modeling of powertrain. Simulation results, discussion, and analysis are in Section IV. Section V summarizes the key conclusions reached.

II. POWERTRAIN ARCHITECTURE

A. CONFIGURATION

The powertrain structure of the plug-in hybrid powertrain developed in this paper is shown in Figure 1. The system consists of an internal combustion engine (ICE), a generating motor (GM-MG1), a traction motor (TM-MG2), a battery pack (BAT), two wet multi-plate clutches and other components.

Compared with the traditional transmission, the transmission integrated with the hybrid system does not have the mechanical shifts. Each transmission component in the system is connected by a gear pair. Then through the power components (such as motor, engine) cooperate with each

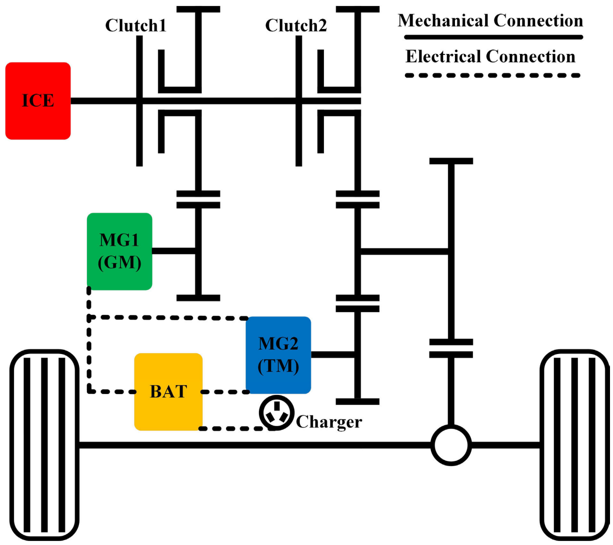


FIGURE 1. Configuration of the hybrid powertrain.

other, so as to achieve the transmission function. When traction motor drives wheels, due to the large deceleration ratio, it is equivalent to the low gear of ordinary transmission, which is suitable for starting, low speed, reversing and other working conditions. When the engine is used for driving, the power is transferred to the wheels through the clutch and the main reducer. It is a speed up gear ratio, so it is more suitable for high-speed scenarios. The whole power system not only hasn't complex mechanical structure, but also can realize the flexible switching of various driving modes through the separation and combination of the clutch.

B. OPERATION MODES

When the vehicle is parked, the engine, traction motor and generator are closed by default. If the battery power is close to the lower limit, in order to ensure that there is enough power to complete the following driving conditions with low engine efficiency (such as starting, climbing and reversing), start the engine and make it run within a high efficiency range to charge the battery pack efficiently. This mode is called parking power generation. As shown in Figure 2(a).

When the battery power is enough, pure electric drive is preferred. By using the characteristics of low speed, high torsion and high efficiency, the motor can not only fully achieve the purpose of reducing fuel consumption, but also improve the starting power performance. As shown in Figure 2(b), that is EV.

When the electric quantity is not abundant, the electric quantity is maintained by series drive mode. This mode involves two processes: mechanical energy to electric energy, and electric energy to mechanical energy, so the efficiency is relatively low, and the actual vehicle economy cannot be guaranteed. In series mode, the engine, generator and drive motor are started, clutch C1 is engaged, clutch C2 is disconnected. Because the traction motor and battery, generator and battery are two-way electrical connection, so the engine-generator set generated electricity can be used to charge the battery, or be used to power the traction motor directly. The battery supplies power to the traction motor according to the battery's ability and the driver's power needs. As shown in Figure 2(d), that is CHEV.

When the vehicle is running in series mode (CHEV) and the speed rises to a certain high speed, in order to improve the dynamic performance of the system, the parallel operation mode is entered. Because of the short power transmission route in the parallel working mode, less energy is lost in the process of mutual conversion and transmission. In the parallel drive mode, the motor adjusts its own output power according to the driver's total power demand, and the engine can still keep working in the high efficiency range. Because there are three power sources, the parallel dual drive mode can be divided into two combined parallel modes: engine-generator and engine-traction motor. Due to the transmission ratio, the speed of the TM motor is higher than that of the GM motor at the same engine speed. Therefore, according to the power requirements of the driver, one can reasonably choose from the TM motor and the GM motor to participate in the work in order to achieve the best efficiency.

When the power demand of the vehicle exceeds the total power provided by the parallel dual drive, another motor will also participate in driving and provide driving power if the vehicle condition permits (such as sufficient battery power). The frequency of this situation is not high, it belongs to the extreme condition, used to meet some extremely high-power requirements of the driving scene. As shown in Figure 2(e), that is BHEV. Since the motor has the function of driving and generating electricity, it can also generate electricity while vehicle is driving. As shown in Figure2(f), called the ENC.

When the vehicle speed is high and the driving power is close to the optimal output power of the engine, the pure engine operation mode is adopted. The pure oil drive mode is consistent with the operation mode of the traditional fuel vehicle, and the engine power is directly output to the wheel. As shown in Figure 2(c), that is ENG.

When the driver presses the brake pedal, the vehicle enters energy recovery mode, and the recovered energy is used to charge the battery. As shown in Figure 2(g), that is REG.

Since the powertrain has two motors, which can be mechanically connected to the engine through the clutch, there are two ways to start the engine: the generator starts the engine, and the traction motor starts the engine. As shown in Figure 2(h). The system preferentially selects the generator to start the engine.

C. VEHICLE PARAMETERS

Based on a compact SUV, this paper develops a hybrid powertrain with dual-motor structure and its control system. The system transforms the traditional fuel vehicle into a new energy vehicle, and realizes plug-in hybrid power, so that the performance of the vehicle can meet the requirements of the design objectives. The power components, vehicle

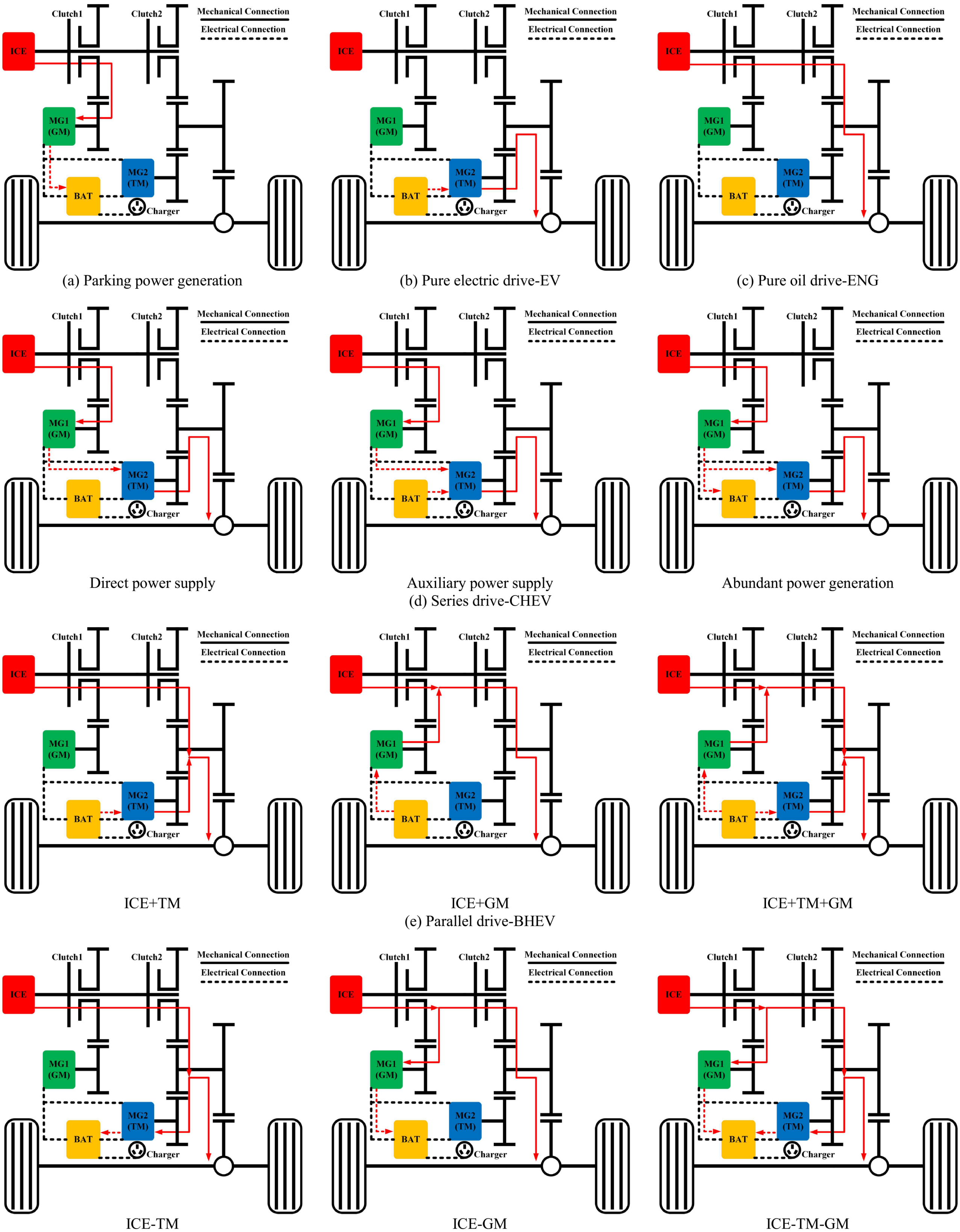


FIGURE 2. Power flow for operation modes.

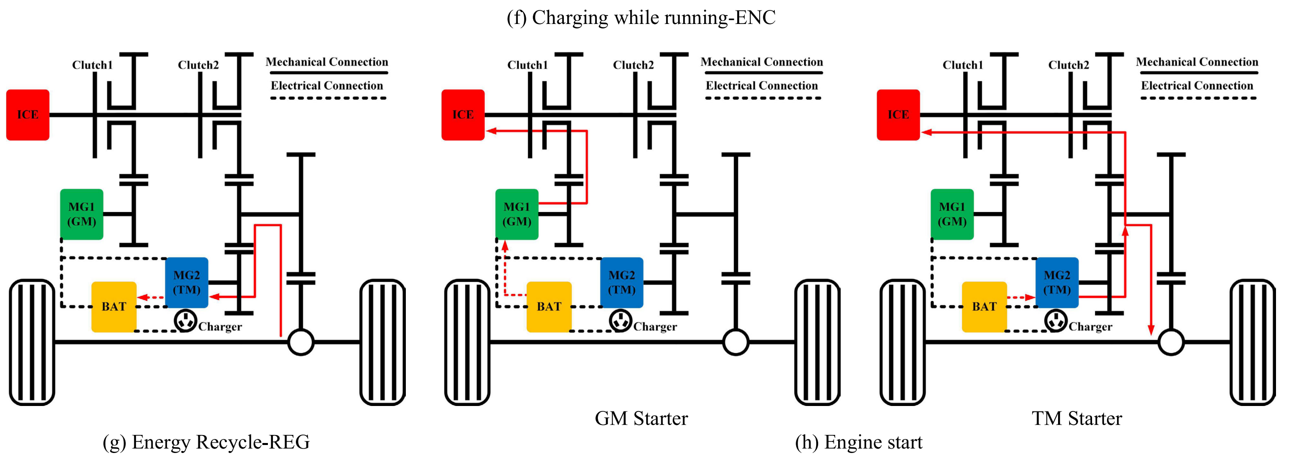


FIGURE 2. ***(Continued.)*** **Power flow for operation modes.**

parameters and mechanical parameters of the transmission are shown in Table 1.

TABLE 1. **Key parameters of powertrain.**

Component	Description	Value
Hybrid vehicle	Mass	1555kg
	Frontal area	2.638m2
	Air resistance coefficient	0.382
	Tire radius	0.335m
Drivetrain	Final drive ratio	3.421
	ICE increase ratio	0.9
	TM reduction ratio	2.45
	GM reduction ratio	1.949
ICE	Max.power	94kW@6000rpm
	Max.torque	168.6Nm@4000rpm
TM	Max.power(torque)	120kW(286Nm)
	Rated.power(torque)	60kW(143Nm)
	Rated speed(max)	4000rpm(12000)
GM	Max.power(torque)	60kW(140Nm)
	Rated.power(torque)	30kW(71Nm)
	Rated speed(max)	4000rpm(9000)
Battery	Voltage	343.1V
	Capacity	21.96kWh
Conventional vehicle	Mass	1452kg
	CVT ratio	0.422-2.432
	Middle axle ratio	1.452
	Final drive ratio	4.308

III. MODELING

A. INTERNAL COMBUSTION ENGINE

The fuel consumption rate of the engine at the optimal Brake Specific Fuel Consumption (BSFC) line, as shown in Figure 3, can be approximated by the quadratic function of the engine power P_e, as shown in (1):

$$\dot{m}_f = c_1 P_e^2 + c_2 P_e + c_3 \tag{1}$$

where, $\dot{m}_f$ represents fuel consumption rate, and c_1, c_2 and c_3 are three coefficients.

Engine power P_e is calculated from (2):

$$P_e = \pi n_e T_e / 30 \tag{2}$$

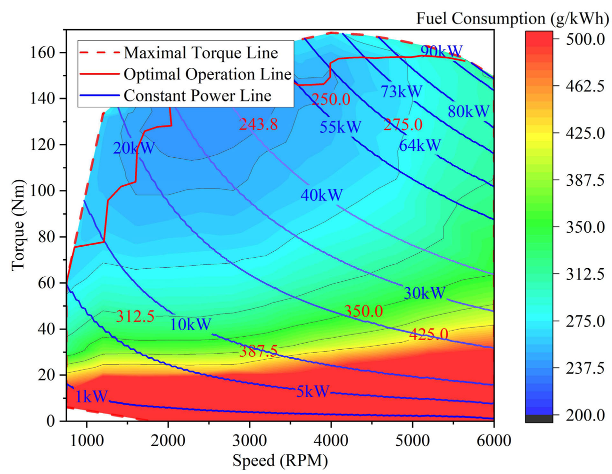


FIGURE 3. **Engine BFSC map.**

where, n_e and T_e represent engine speed and engine torque, respectively.

B. MOTOR

In the hybrid system, both GM and TM motors can play two roles: (1) As a generator motor, used to save excess energy of the engine, or maintain battery power, or energy recovery during braking; (2) As a traction motor, used to assist the engine drive, or start the engine, or the vehicle uses electric energy to drive.

When operating as a generator, the generator power P_g can be calculated as in

$$P_g = T_g \omega_g \eta_g \tag{3}$$

where T_g is the torque of the generator, ω_g is the angular velocity of the generator, and η_g is the efficiency of the generator.

When running as a motor, the motor power P_m can be calculated as in

$$P_m = T_m \omega_m / \eta_m \tag{4}$$

where T_m is the torque of the motor, ω_m is the angular velocity of the motor, and η_m is the efficiency of the motor.

Motor efficiency η_j, j∈ {m, g} is a function of ω_j and T_j:

$$\eta_j = f\left(\omega_j, T_j\right) \tag{5}$$

The efficiency of GM and TM is shown in the Figure 4.

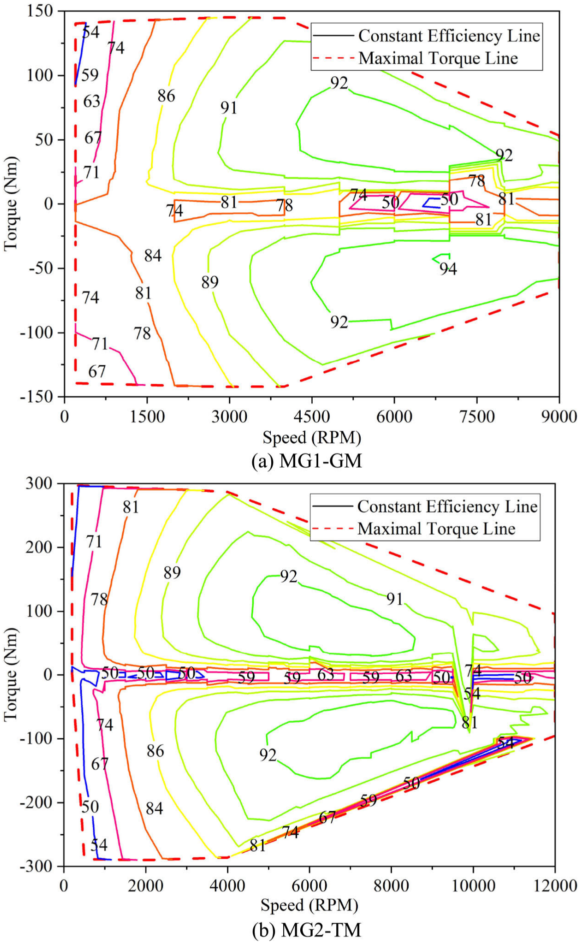


FIGURE 4. Motor efficiency map.

C. BATTERY

Battery P_{batt} power is related to motor power, as in

$$P_{batt} = T_{i,j}\omega_{i,j}\eta_{i,j}^{k}\eta_c^{k},\ i \in \{TM, GM\},\ j \in \{m, g\} \tag{6}$$

η_c is the average cycle efficiency of the power converter, i represents the running motor, j is used to describe the role of the motor, generating function or driving function, k depends on the direction of the current power, that is, $k = -1$, $P_{batt} \geq 0$; $k = 1$, $P_{batt} < 0$.

According to the battery model in Figure 5, P_{batt} is represented by the following formula:

$$P_{batt} = V_{oc} I_{batt} - I_{batt}^2 R_{batt} \tag{7}$$

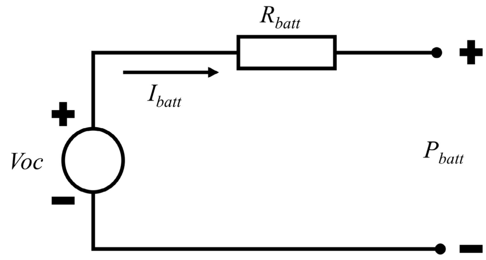


FIGURE 5. Battery model.

where I_{batt} is the battery current, V_{oc} is the open-circuit voltage, and R_{batt} is the internal resistance depending on the battery SOC and the direction of the current. By solving (7), I_{batt} can be obtained by the following formula:

$$I_{batt} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4R_{batt}P_{batt}}}{2R_{batt}} \tag{8}$$

Then, SOC can be obtained by the following formula:

$$SOC\left(k+1\right) = SOC\left(k\right) - \frac{V_{oc} - \sqrt{V_{oc}^2 - 4R_{batt}P_{batt}}}{2R_{batt}Q_c}\Delta t \tag{9}$$

where Q_c is battery capacity, Δt is sampling time. Battery parameters V_{oc} and R_{batt} are related to SOC, as shown in the Figure 6.

D. VEHICLE DYNAMICS

The longitudinal dynamics of the vehicle can be described as follows

$$F_t = F_f + F_w + F_i + F_j \tag{10}$$

That is:

$$\frac{T_e i_g i_0 \eta_T}{R_w} = mgC_r cos\alpha + \frac{C_d A}{21.15}v^2 + mgsin\alpha + \delta m\frac{dv}{dt} \tag{11}$$

where, F_t, F_f, F_w, F_i and F_j represent driving force, rolling resistance, air resistance, slope resistance and acceleration resistance, respectively. Transmission efficiency is η_T, g is gravity, and C_r is rolling friction coefficient. α is the road slope, C_d is the air resistance coefficient, A is the front area of the vehicle, v is the speed of vehicle, and the rotation mass conversion factor is expressed by δ.

E. RULE-BASED CONTROL ALGORITHM

As shown in the Figure 7, first of all, according to the driver's acceleration or brake pedal opening, combined with the proposed corresponding steady-state power, the driver's demand power is obtained. Secondly, considering the influence of power source batteries (such as SOC and charge/discharge power limits), power components (such as engine power and engine fuel consumption as well as motor power and motor efficiency limits), and transmission system (such as the efficiency of mechanical and electrical transmission lines)

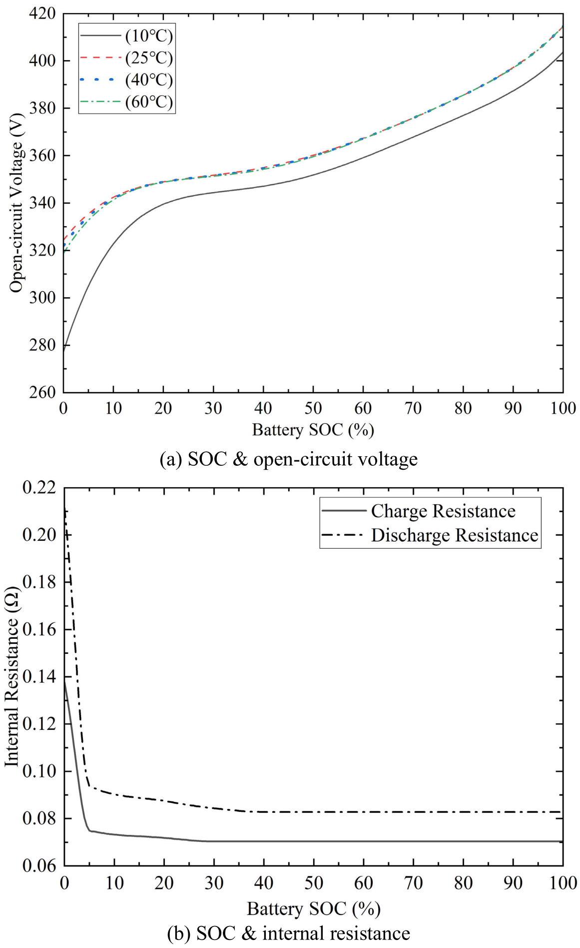


FIGURE 6. Battery parameters.

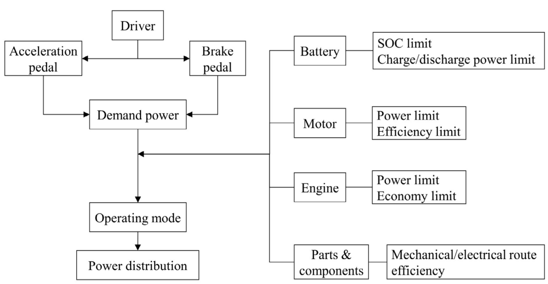


FIGURE 7. Control overview.

on vehicle state, the appropriate vehicle working mode is selected. Finally, the required power is allocated to each power element in the selected working mode.

Based on the logical threshold rules, threshold values represented by battery SOC, vehicle speed and power of each component are set to control mode switching, as shown in Figure 8. The process of switching the operation modes may involve the change of the operating state of the clutch. The clutch change process has three cases, namely clutch speed synchronization, clutch engagement and clutch

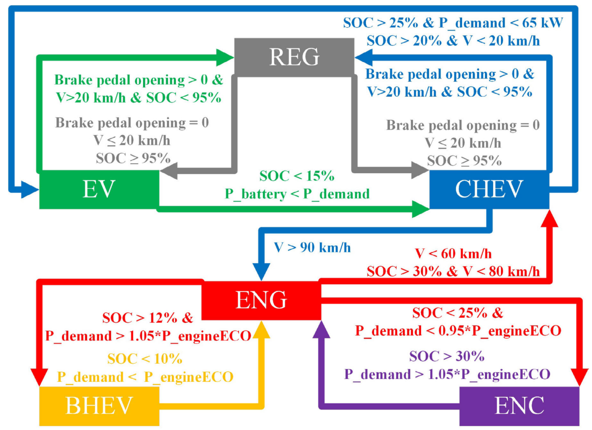


FIGURE 8. Key threshold for mode switchover.

disconnection. Since the state change of the clutch is a transitional process, it is not shown in Figure 8, which mainly describes the steady-state operation modes.

IV. SIMULATION RESULTS AND DISCUSSION

A. VEHICLE DYNAMICS

According to the balance diagram of driving force and driving resistance of the vehicle, as shown in Figure 9. The configuration has a maximum speed of 180.82km/h in both pure electric mode (EV) and series drive mode (CHEV), as the TM motor is the only power element providing driving force to the tire and is limited by the maximum speed of the TM motor. In pure oil mode (ENG), the maximum speed is 158.32km/h, which is determined by the intersection of driving force and driving resistance curve. The maximum speed in parallel mode (BHEV) is consistent with that in pure electric mode (EV) because it is also limited by the maximum speed of the TM motor. The conventional vehicle uses a continuously variable transmission (CVT), and its maximum speed is related to the CVT variable speed ratio. As shown in Figure 9(b), its value is 178.18km/h. The maximum speed of the modified hybrid vehicle is slightly higher than that of the conventional vehicle.

When the vehicle is in pure electric mode (EV), the TM motor outputs torque and driving the wheels to accelerate forward from a stationary state. When the vehicle is accelerated from rest in series drive mode (CHEV), the acceleration performance is the same as in EV mode because the torque to drive the wheels in this mode is still all from the TM motor. Because the powertrain uses a fixed speed ratio, the parallel drive mode (BHEV) cannot drive the wheels directly at low vehicle speeds. Therefore, in the process of accelerating from the stationary state to the maximum speed, the vehicle first adopts the CHEV mode, when the speed reaches the minimum speed of the engine can drive the wheels, and then switches to the BHEV mode. This allows the entire acceleration process to be completed and the acceleration time in BHEV mode to be obtained.

According to the acceleration performance curve of the vehicle, as shown in Figure 10, the acceleration time of

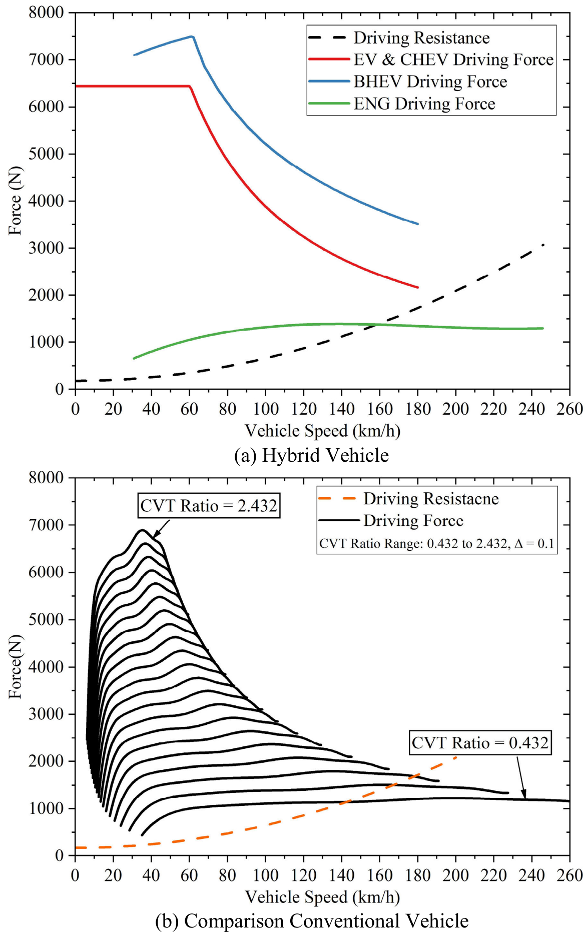


FIGURE 9. Maximum speed of vehicle.

TABLE 2. Acceleration of powertrain.

Time (s)	0-50 km/h	0-100 km/h
Pure electric mode (EV) & Series drive mode (CHEV)	3.83	8.99
Parallel drive mode (BHEV)	3.66	7.72
Conventional vehicle	5.87	11.56

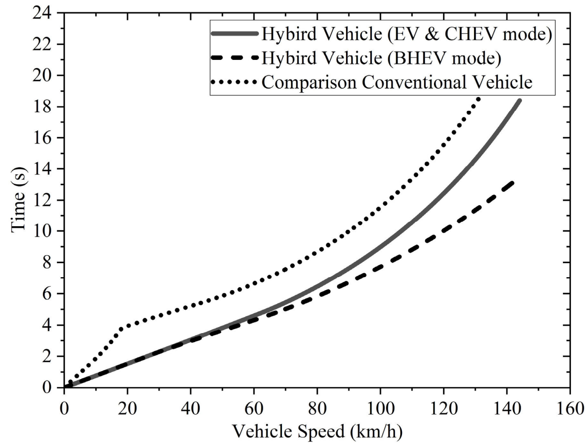


FIGURE 10. Acceleration time of vehicle up to 0.8 times the maximum speed.

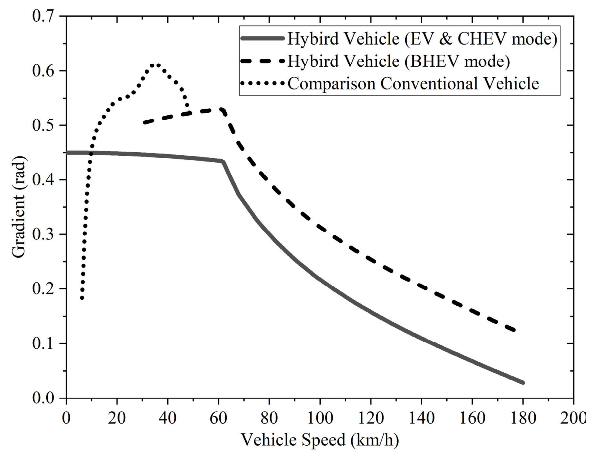


FIGURE 11. Maximum climb of the vehicle.

the parallel mode (BHEV) starting in place (accelerating to 0.8 times of the maximum speed) is 13.48s, while the results for pure electric mode (EV) and series mode (CHEV) are 18.41s.

The original conventional vehicle uses a CVT transmission with a torque converter, so the process of acceleration from the stationary state to the maximum speed is divided into three stages. The first stage is before the torque converter is locked. In the second stage, after the torque converter is locked, the CVT uses the maximum speed ratio to accelerate until the engine speed reaches the maximum. The third stage is to maintain the maximum engine speed and continuously reduce the CVT speed ratio until the entire acceleration process is completed. As can be seen from Figure 10, the acceleration performance of the modified hybrid vehicle is better than that of the original conventional vehicle in all working modes.

Acceleration performance of the powertrain is shown in Table 2. The hybrid vehicle in BHEV mode goes from zero to 100km/h in 7.72 seconds, which is reduced by 33.2% compared with that of the original conventional vehicle.

The climbing performance of the hybrid vehicle is also related to the working mode of the vehicle, the climbing performance in EV mode and CHEV mode are the same, and the BHEV mode can only be used for climbing at a specific speed range. The maximum theoretical climb of the vehicle in BHEV mode is 0.53 (27.93°). As is shown in Figure 11. When climbing this slope, the required road adhesion coefficient C_φ can be obtained from (12), which is 1.33.

$$C_\varphi = \frac{q}{\frac{b}{L} - \frac{h_g}{L} q} \tag{12}$$

where, L is the vehicle wheelbase, b is the distance from the center of mass to the rear axle, h_g is the height of the center of mass, and q is the slope.

Considering that this state exceeds the actual adhesion coefficient of the road surface by 0.7, the actual maximum slope that the vehicle can pass in BHEV mode is 0.32 and the maximum slope Angle is 17.53° after verification, which is calculated by (13). Where, φ is the actual road adhesion coefficient.

$$q = \frac{b/L}{\frac{1}{\varphi} + \frac{h_g}{L}} \tag{13}$$

The theoretical maximum gradient of the vehicle in pure electric mode (EV) and series mode (CHEV) are 0.45 (24.24°), and the required adhesion coefficient of the front drive vehicle in uniform speed uphill is 1.08, calculated by (12), which also exceeds the actual adhesion coefficient 0.7. The actual maximum gradient after checking is 0.32 (17.53°), the same as that in BHEV mode.

The theoretical maximum slope of the conventional vehicle is 0.61(31.48°), and the adhesion coefficient calculated by equation (12) for the front-driving vehicle to go uphill at a constant speed is 1.62, which also exceeds the actual adhesion coefficient 0.7. After checking, the actual maximum gradient is 0.32(17.53°). From the above, it can be seen that the modified hybrid vehicle and the conventional vehicle maintain the same climbing performance.

B. FUEL ECONOMY

When the vehicle is confined to pure electric mode, accelerate it to 100km/h and assume that it continues at that constant speed. According to vehicle motion equation (10) and energy conversion, the pure electric mileage of the powertrain is 83.17km, which can meet the commuting needs of short-distance commuters. If the vehicle is driven at a speed of 60km/h, the pure electric mileage of the powertrain can reach 156.63km.

When considering the hybrid performance of the powertrain, the test cycle condition of the international standard vehicle is taken as the simulation test standard of the powertrain Simulink model. The simulation results and discussion are as follows:

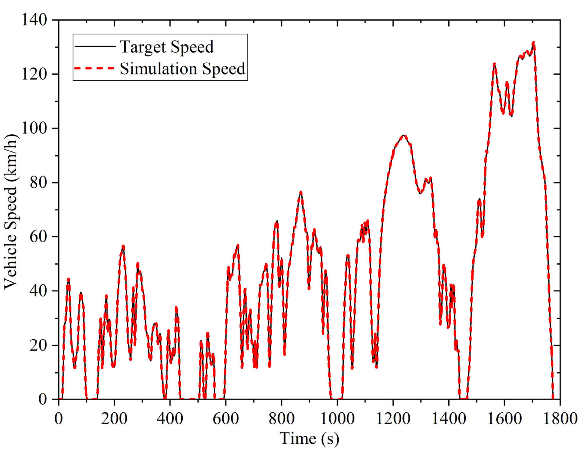


FIGURE 12. Speed tracking.

The simulated vehicle speed of the model in Figure 12 is very close to the target speed in WLTC standard condition, indicating that the design of the simulation model is good and can meet the driving speed requirements in cycle condition.

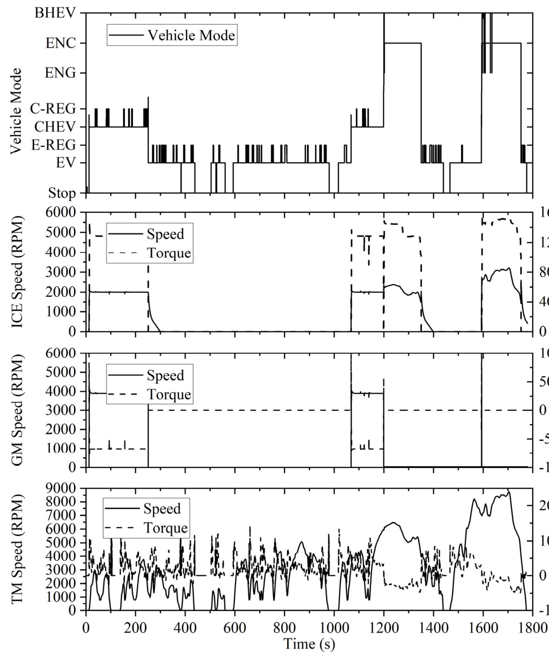


FIGURE 13. Power elements operating status.

Figure 13 shows the speed and torque of the power components (ICE, TM, GM) accompanied by the switching process of vehicle operation modes. In the hybrid powertrain, the switching between operating modes is divided into two categories according to the change in the operating state of the clutch. First, the switching of the operation modes requires the change of the clutch to complete. For example, between EV mode and CHEV mode, CHEV mode and ENG mode. Second, the switching of the operation modes only involves the functional changes of the power components. For example, EV mode or CHEV mode enters and exits energy feedback (E-REG or C-REG) mode, switching between BHEV mode, ENG mode and ENC mode. They mainly involve changes in the three functions of the driving motor TM (drive, generation, idling). In the whole driving cycle, the operation mode switching involving the change of the clutch state is less, and the phenomenon of frequent operation of the clutch does not appear. In addition, the energy feedback (E-REG and C-REG) is switched more frequently, which is consistent with the complex driving cycle.

The variation trend of the TM speed is consistent with the vehicle speed, which is due to the rigid connection. The speed change of the GM coincides with that of the ICE, as the two are connected via clutch C1 in series drive mode (CHEV). In pure oil mode (ENG), only the engine is working, and neither the GM nor the TM motors are running. The ICE speed changes the same as the TM, and they are jointly connected to the wheel after being engaged by the clutch C2. At this point, the power of the ICE is directly output to the wheels, and the TM motor simply idles with the vehicle speed. In ENC mode, the only difference from ENG mode is that the TM motor is in the generating state, whereas in BHEV mode, the TM motor is in the driving state. In conclusion, the output of the power components is consistent with the operation mode of the vehicle, indicating that the vehicle simulation model is logical.

In pure electric mode (EV), only TM is operated, commonly when the battery SOC is high in WLTC cycle. This mode avoids the inefficient area of ICE, which is beneficial to reducing the fuel consumption of the whole vehicle. When starting, the TM torque is large, and the torque falls back after the wheel rotation. After the vehicle enters the series mode (CHEV) from pure electric mode (EV), the torque of the TM is not jittered. At the same time, the GM starts the ICE and uses the ICE-GM generation group to provide part of the energy. The mode switching process is smooth. At high speed and with insufficient SOC, the vehicle mainly operates in ENC mode. As for pure oil mode (ENG), it requires the demand power to be close to the optimal output power of the engine, which is relatively rare. When accelerating, the vehicle will enter parallel mode (BHEV), and the TM is used to assist in providing power. On the premise of ensuring the acceleration performance, adjust the engine operating point to achieve efficient engine operation and improve fuel efficiency. No matter in series mode (CHEV), parallel mode (BHEV), pure engine mode (ENG) or charging while running (ENC), the output torque of the engine is relatively stable, and the output curve of the engine does not fluctuate sharply. In summary, the output torque of the power components conforms to the characteristics of the vehicle running mode, and the transition is stable, indicating that the vehicle simulation model can accurately simulate the running situation of the powertrain.

Figures 14(a) and 14(b) respectively show the operating point distribution of TM and GM in the whole WLTC cycle condition. GM operating points are mainly concentrated in the working area where the efficiency is greater than 90% from 3000rpm to 4000rpm. In series mode (CHEV), the corresponding engine speed falls within the range of 1500rpm to 2000rpm. Most of the other working points without aggregation are mainly caused by the process of starting the engine.

The working point of the TM motor is mainly divided into two parts, one part is the drive and the other part is the power generation.TM motor operation covers the entire WLTC operation: When the speed is above 4000rpm, it is often used for power generation in ENC mode and drive in BHEV mode, and the efficiency is greater than 0.8. When the speed is below 4000rpm, the efficiency of the TM motor is sometimes high and sometimes low, which is because the TM motor has little torque when the energy is fed back. Or the TM motor is also responsible for the start of the vehicle and the low speed of the vehicle, which is difficult to achieve high efficiency. Although the TM motor partially operates in the less than 0.5 efficiency zone, it is more efficient relative to the engine.

Figure 14(c) shows the working point distribution of ICE in the whole WLTC cycle condition. In the whole simulation time, the ICE is mainly in its efficient zone, and most of the fuel consumption is below 300g/kWh, among which the

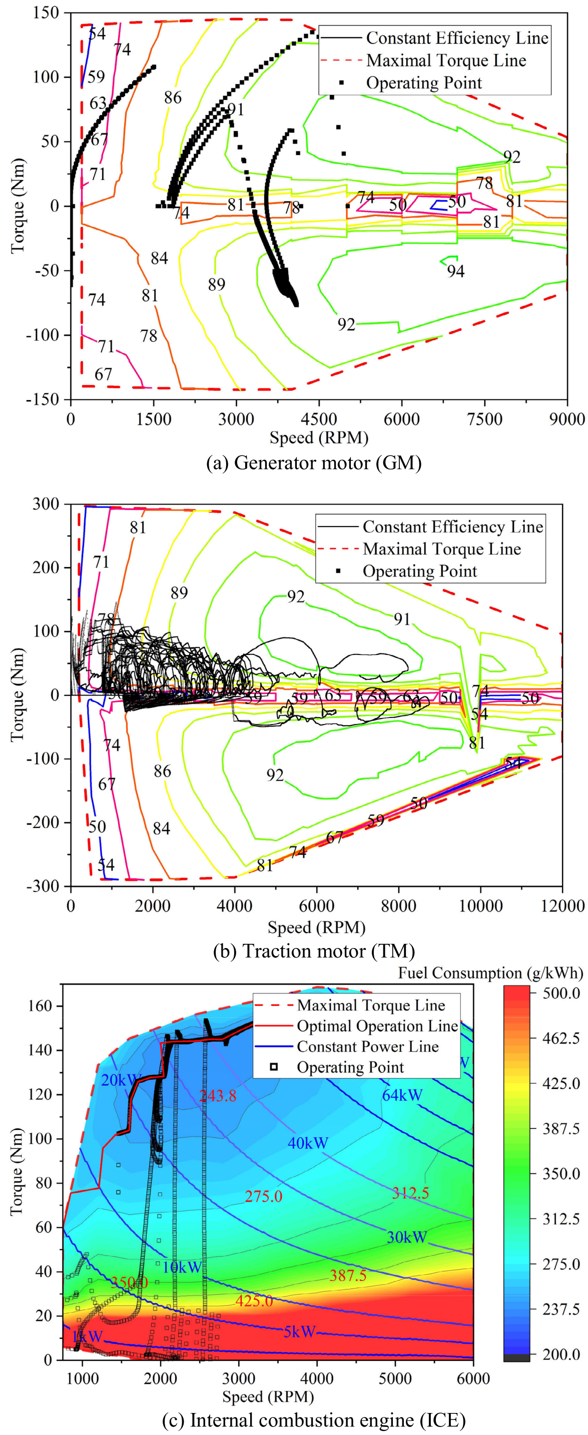


FIGURE 14. Operating point of the power element.

working point of some engines is distributed along the best economic curve as far as possible. After the engine is started, whether it is in ENG, ENC or BHEV mode, the power output of the engine is carried out along the optimal economic curve, which is also one of the common methods to reduce fuel consumption.

Figure 15 shows the Fuel Consumption of 100-kilometer. In the first half of the cycle, the fuel consumption value of the

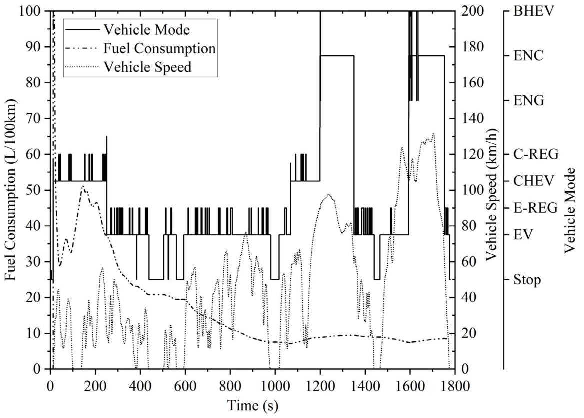


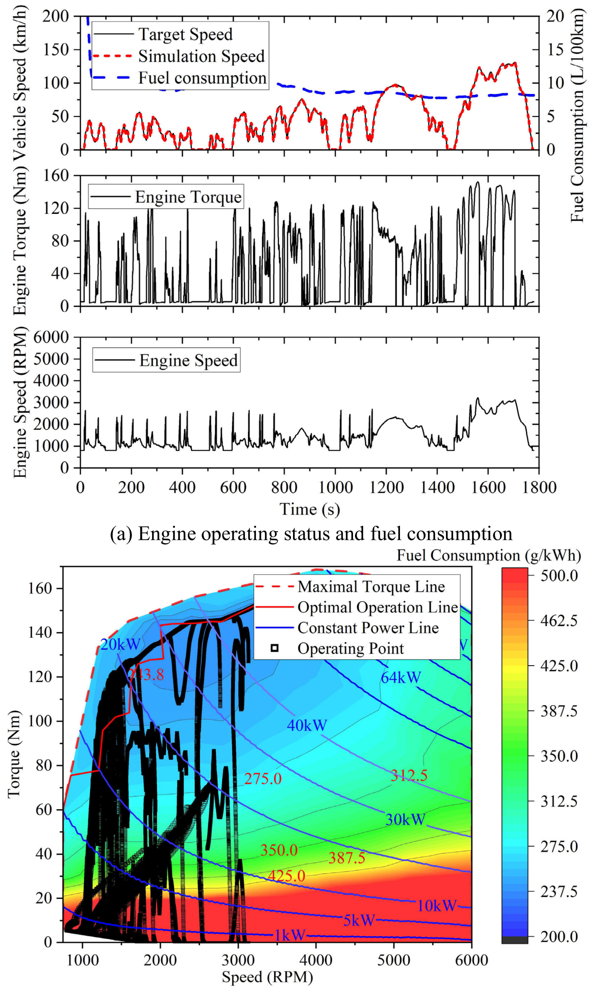
FIGURE 15. Fuel consumption of 100-kilometer with vehicle mode and speed.

vehicle changes greatly, which is because of the insufficient running time of the vehicle and the short distance of the vehicle. In the second half of the cycle, the fuel consumption of the vehicle tends to be stable. This is because the cumulative time of the simulation is longer, and the data information obtained by the simulation is more complete. This process does not take into account the fuel consumption converted from chemical energy to electric energy between the engine (ICE) and the generator (GM) or the traction motor (TM), and the fuel consumption of vehicle required by the simulation time is 8.471L/100km.

Figure 16 shows the simulation results of the original conventional vehicle running the same WLTC drive cycle. The fuel consumption of conventional vehicle is 8.191L/100km, which is better than the hybrid vehicle in the state of low electricity. This is because hybrid vehicle consumes some of the fuel to charge the battery when the battery is low, storing chemical energy as electricity and not driving the vehicle. In the following part, the comprehensive fuel consumption of hybrid vehicle will be analyzed and explained. As can be seen from the engine operating point in Figure 16(b), although there is a CVT speed ratio adjustment effect, the engine still works in a considerable number of cases in non-economic areas.

The engine operation ratio in the high efficiency zone is shown in Table 3. It is obvious that the engine efficiency is higher throughout the section, which also reflects the better fuel economy of the powertrain. Hybrid vehicles are very friendly to the operation of the engine, and more than 80% of the working points are located in the economic area, while the original conventional vehicle is difficult to exceed 30%.

Figure 17 shows the variation of battery SOC and current during the WLTC driving cycle. The variation trend of SOC is consistent with the variation of the output torque of the power element. When the motor is running, the current is positive and SOC decreases, and vice versa. According to the proposed control strategy, the battery SOC charge-sustaining mode is selected for simulation, which can more accurately reflect the economy of the vehicle. For the entire scheduled



(a) Engine operating status and fuel consumption

(b) Operating point of the engine

FIGURE 16. Comparison conventional vehicle simulation results.

TABLE 3. Engine operation ratio in high efficiency zone.

Efficiency zone（g/kwh）	0-240	0-260	0-280	0-300
Hybrid vehicle ratio	85.90	87.34	87.39	87.41
Conventional vehicle ratio	0	16.76	22.39	28.68

driving cycle, the power battery pack SOC is set from 15% to 17.23% as the end value. It shows that the formulation of control strategy is effective for electricity keep ability of the vehicle and meets the expectations.

When the battery is running in pure oil mode (ENG), SOC does not change and will decrease after entering parallel mode (BHEV) or pure electric drive mode (EV). The increase in battery SOC is through the vehicle's series drive mode (CHEV) or charging while running (ENC), which uses the ICE to generate electricity and convert fuel chemical energy into electricity. In order to simplify the complexity of calculation, a more efficient range of the engine at 3200 speed is selected for output power generation, and it is obtained that each liter of gasoline can generate 3.0095kWh of power. According to the mechanical and electrical efficiency loss

TABLE 4. Comprehensive fuel consumption per of 100-kilometer with different SOCs in WLTC cycle.

Init SOC (%)	10	15	20	25	30	35	40	45	50	60	70	80	90	100
Final SOC (%)	17.22	17.24	17.84	17.8	17.89	16.52	17.6	22.74	27.88	38.2	48.6	59.11	69.69	80.0
Fuel (L/100km)	11.71	8.47	6.88	5.01	3.35	1.32	0	0	0	0	0	0	0	0
Electricity (L/100km)	-2.66	-0.82	0.79	2.65	4.46	6.80	8.24	8.19	8.14	8.02	7.88	7.69	7.47	7.36
Comprehensive (L/100km)	9.05	7.65	7.67	7.66	7.81	8.12	8.24	8.19	8.14	8.02	7.88	7.69	7.47	7.36

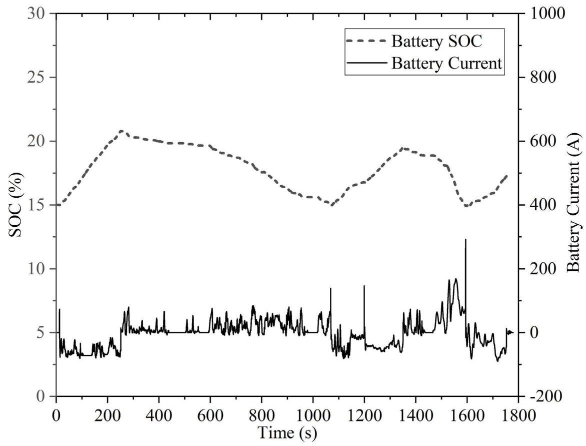


FIGURE 17. Battery SOC and current.

of generator GM and battery charging, the fuel consumption required for vehicle charging in this simulation time can be converted to 0.8231L/100km.

Different SOC values were taken as initial electric quantity for simulation, and the results as shown in Figure 18. When SOC is small, the fuel consumption of the vehicle increases, and the vehicle mainly uses fuel as the energy source. With the increase of SOC, driving fuel consumption decreases, and most of the vehicle is driven by electric energy. Through reasonable optimization control strategy, the maintenance of SOC is guaranteed when the battery is low.

In this hybrid powertrain, the fuel consumed by the engine is used partly to drive the vehicle and partly to charge the battery. The electric energy consumed by the motor is also divided into two parts, one part comes from the external grid to charge the battery, and the other part comes from the engine to charge the battery. Therefore, in order to comprehensively consider the fuel economy of this complex energy source, conversion and consumption, we give three physical variables: *fuel* (fuel consumption), *electricity* (electricity consumption), *comprehensive* (comprehensive consumption). *fuel* indicates the fuel consumption of the engine. *electricity* indicates the equivalent fuel consumption of the battery's electric energy consumption. *comprehensive* indicates the comprehensive fuel consumption after the offset of oil and electricity. By converting the SOC variation of the battery into the fuel consumption value, the comprehensive fuel consumption results as shown in Table 4.

While battery SOC is maintained, the average value of comprehensive fuel consumption under different SOCs is 7.6L/100km, which is lower than the fuel consumption of the original conventional vehicle, and its value is 8.191L/100km.

When the SOC is higher than 40%, only electric energy is consumed during the running of the vehicle, and no fuel is consumed. That is, when the vehicle battery has more power, it is in a state of power consumption and can work in pure electric mode (EV), like pure electric vehicles, which greatly improves the economy of the hybrid configuration. Because this part of the electricity can be obtained through the external grid. Furthermore, the higher the SOC, the smaller the internal resistance of the battery and the higher the open circuit voltage of the battery, so the stronger the discharge capacity of the battery and the less energy consumed by the internal resistance heating. Therefore, when the SOC is higher than 40% and the same cycle is running, the higher the SOC of the battery, the less the internal resistance consumption, and the corresponding comprehensive fuel consumption is also lower.

The actual use of most vehicles is often in a state of high battery SOC, so the economy of the hybrid power system has more advantages than the original fuel vehicle power system.

Figure 19 shows the operating point of TM motor when SOC is 80%. Since the vehicle is in a state of power consumption at this time, the entire WLTC driving cycle only runs in EV mode, while ICE and GM do not work. As can be seen from the figure, the TM motor is mainly in a driving state, and occasionally gives energy back. In addition to the vehicle running at low speed, TM motor efficiency will be less than 50%, when the vehicle running at high speed, TM motor efficiency reaches more than 90%.

C. MODEL ROBUSTNESS

In order to verify the robustness of the simulation effect of the model and understand the performance of the powertrain under different driving conditions, commonly used vehicle test cycles are selected to simulate the real vehicle operation, and the results are shown in Figure 20, Figure 21 and Table 5.

TABLE 5. Comprehensive fuel consumption per of 100-kilometer under different cycle conditions.

Fuel (L/100km) \ Cycle	NEDC	UDDS	HWFET	WLTC
Fuel	7.331	9.019	11.985	8.471
Electricity	-1.013	-2.531	-5.994	-0.823
Comprehensive	6.318	6.488	5.991	7.648
Conventional vehicle	8.195	8.036	6.355	8.191
Improved	22.90%	19.26%	5.73%	6.63%

The NEDC operating condition is composed of four UDCs (low speed condition) and one EUDC (high speed condition). First, when the battery is low, the vehicle enters the CHEV mode, and when the power generation reaches the threshold, it enters the EV mode. At low speed, the EV

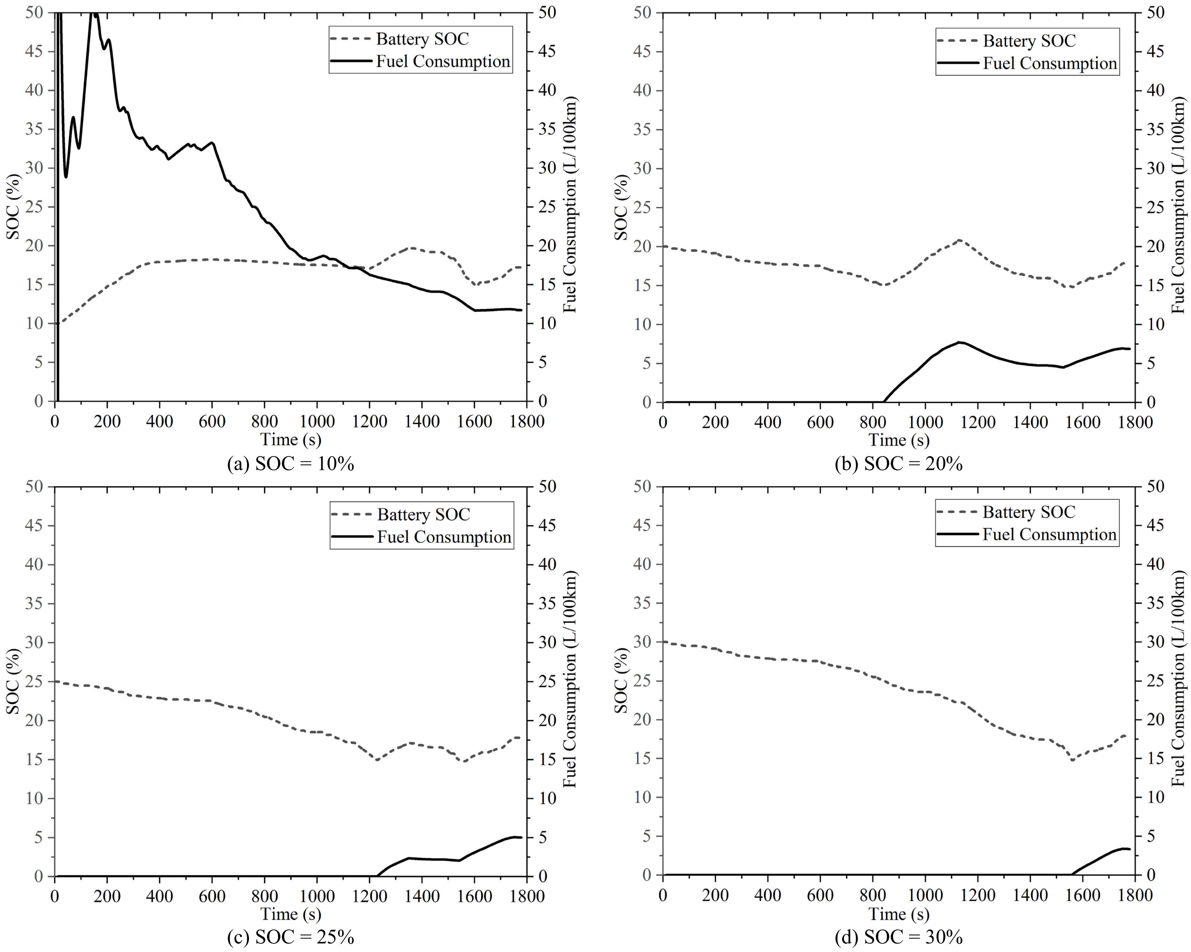


FIGURE 18. Fuel consumption of 100-kilometer corresponding to different SOCs in WLTC cycle.

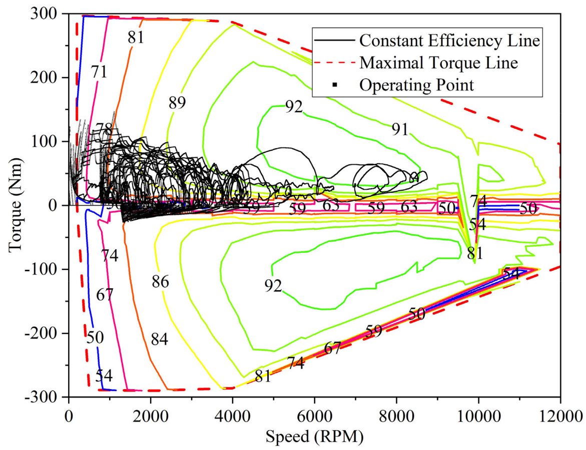
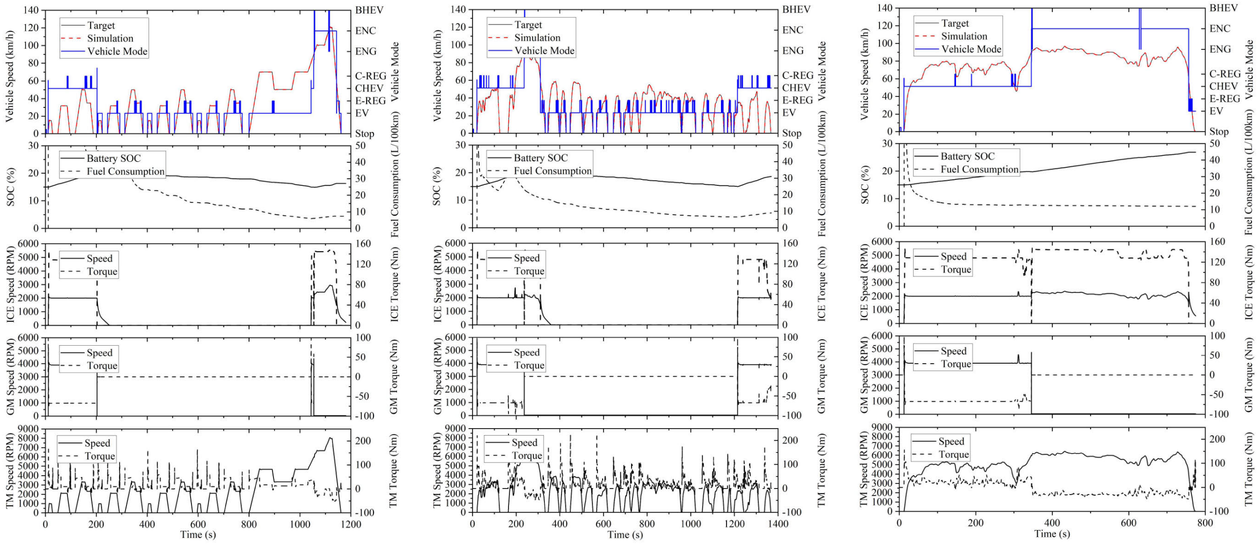


FIGURE 19. Operating point of the TM at 80% SOC.

mode is maintained, and at high speed, the engine power is directly output to the wheels, such as ENG, ENC and BHEV modes. Under NEDC conditions, the vehicle speed change is simple and linear. In addition, most of the conditions allow the vehicle to run at a low speed, so the fuel consumption of 100 km is 7.331L. Combined with the increase of SOC by 1.315%, the integrated fuel consumption under the SOC charge-sustaining mode is 6.318L/100km, which is better than that of the original conventional vehicle, which is 8.195L/100km, an increase of 22.90%.

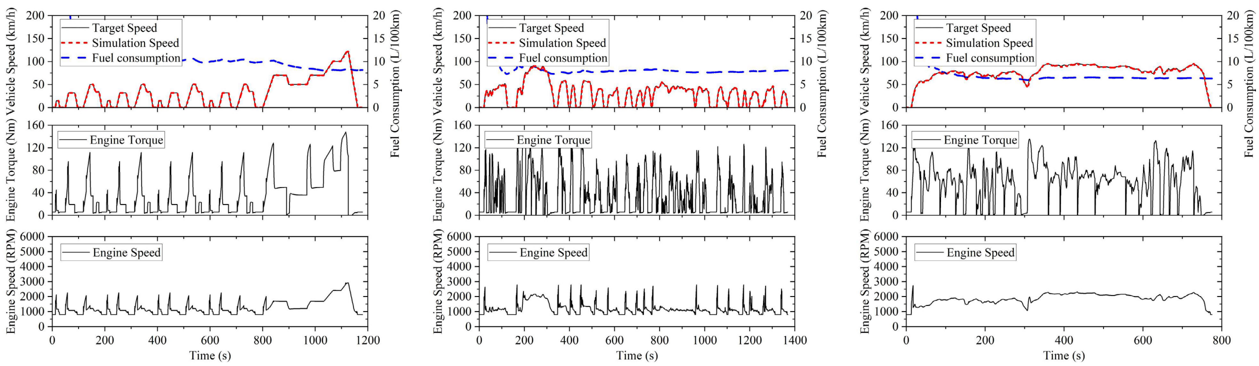
In UDDS condition, the driver's acceleration and deceleration are frequent and rapid. Compared with the NEDC driving cycle, the dynamic processes of the vehicle become more and the requirements for power components become higher. Therefore, the fuel consumption per 100 km is higher than that of NEDC, reaching 6.488L. The fuel consumption of the conventional vehicle under the same UDDS cycle condition is 8.036L/100km, which indicates that the modified hybrid vehicle is still more energy efficient.

HWFET operating condition belongs to the high-speed state, when the pure electricity cannot meet the speed demand, the engine will intervene, especially in the optimal economic range of the engine. Since the engine is always running, it will continue to charge the battery when the power is maintained, so the final battery SOC will increase greatly under this working condition. In the whole HWFET driving cycle, EV mode is not used, and the engine is at the best economic output power, so the fuel consumption can reach 5.991L/100km. In general, the fuel consumption of conventional vehicles driving on high-speed roads is also lower than



(a) NEDC (b) UDDS (c) HWFET

FIGURE 20. Simulation results of different cycle conditions under 15% SOC.



(a) NEDC (b) UDDS (c) HWFET

FIGURE 21. Simulation results of different cycle conditions of conventional vehicle.

that driving under urban congestion roads, and the value is 6.355L/100km, but the hybrid vehicle in this paper can further improve fuel economy. As can be seen from Figure 21(c), the output torque of the engine in the conventional vehicle is only adjusted according to the driver's needs. As can be seen in Figure 20(c), the output torque of the engine in the hybrid vehicle can be comprehensively optimized by combining various factors such as operation mode, driver demand and power component status.

WLTC operating condition is a more strict and real test standard, involving the simulation of urban roads, expressways and mountain roads, including low, medium, high and ultra-high speed. Vehicles are scheduled in each mode, so the fuel consumption is harsher than that of the other three driving cycles mentioned above, reaching 7.648L/100km. However, in terms of fuel consumption, the hybrid vehicle is still better than the conventional vehicle (8.191L/100km).

V. CONCLUSION

In order to improve fuel economy, a new plug-in hybrid electric vehicle with two clutches and dual-motor was developed by modifying the original fuel vehicle. The proposed hybrid powertrain model is established by using MATLAB/Simulink and rule-based control strategy. The dynamic performance and economic performance of the powertrain are obtained through simulation analysis, and the following conclusions are obtained:

(1) The powertrain has a maximum speed of 180.82km/h and a maximum climb grade of 0.32. Its 100 km acceleration time is 8.99s in both pure electric mode (EV) and Series mode (CHEV), and that is 7.72s in parallel mode.

(2) Optimizing the working point of the engine can significantly reduce fuel consumption. Under the NEDC cycle, the fuel consumption of hybrid vehicle is 6.318L/100km, which is up to 20.90% lower than the conventional vehicle. Moreover, the fuel consumption of hybrid vehicle under UDDS condition is 6.448L/100km, under HWFET condition is 5.991L/100km, and under WLTC condition is 7.648L/100km. While the conventional vehicle is 8.036 L/100km, 6.355 L/100km and 8.191L/100km. The fuel consumption of hybrid vehicle is reduced by 19.26%, 5.73% and 6.63% respectively compared with that of conventional

vehicle in the first three cycle conditions. In addition, the pure electric mileage can reach 156.63km, which can meet the commuting needs of ordinary people.

The configuration proposed in this paper uses other parts of the original car, such as vehicle body, vehicle chassis, etc., and the vehicle has strong stability. In addition, the powertrain is simple in structure and easy to refit. The research on the energy management and control strategy algorithm of the powertrain may be the focus of our future work. This paper provides ideas and reference for other projects or research on the conversion of fuel vehicles to electric vehicles.

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