

# Hua Zhou, Ming-Jun Zhang, Ren-Guang Wang\* and Bin Wang Further Analysis on Triple Mode Powertrain for HEV

**Abstract:** With addition of two clutches, a two driving mode powertrain is modified into a triple mode powertrain, which provides three different driving modes including pure electric driving mode, power split driving mode, parallel hybrid driving mode. It can be operated in proper mode according to real vehicle demand. The detail analysis on its operation and mode change are presented for understanding its working principle.

**Keywords:** Hybrid electric vehicle, Triple mode powertrain, Driving mode change

## 1 Introduction

In current days, the HEV technology is becoming more and more popular. The THS of Toyota is the most successful HEV system, its total production has been more than 10 million until end of 2016 [1], which uses one or two planetary gear sets and two e-motors to realize full hybrid function. THS system does not use any brake or clutches, which reduces its complicity and malfunction potential, and THS can get excellent fuel consumption by use of advanced ICE technology and optimized system integration approach. In reference [2], a three mode power train for HEV was briefly introduced. In this paper, the authors discuss its operation modes in detail and modify its mode change method from a synchronizer gear shift mechanism to two clutches.

## 2 Main Structure of Triple Mode Powertrain

As shown in figure one, the main structure are almost same as that in reference [2],

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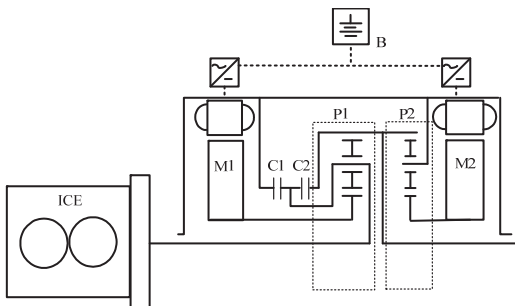
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they are ICE, first motor M1, second motor M2, first planetary gear set P1, second planetary gear set P2, power battery B and invertors between the B and two motors. The main difference are two clutches C1 and C2. The clutches are added to improve power train function, with these two clutches, the operation modes of the power train are pure electric driving mode (E mode), power split hybrid driving mode (H mode), and parallel hybrid driving mode (P mode).

The C1 is located between the power train case and carrier of P1, which is used as a brake to lock carrier of P1 and the ICE. The C2 is located between the ring gear and carrier of P1, which is used to lock these two parts together. In real design, the synchronizer can be selected to replace the function of clutches.



**Fig. 1:** The sketch of triple mode HEV power train

In the design without mode change mechanism such as clutch, brake, or other synchronizer, its pure electric driving mode is performed by only one motor M2. In the new design, it can combine two motor to drive vehicle simultaneously, which can improve driving torque to get better vehicle dynamical performance such as acceleration and slope climbing capability. Compared with one driving motor, the two motors can both operated as driving motor can reduce the motor size and reduce instalment space.

### 3 Analysis of Driving Mode Change Process

The triple mode HEV power train can provide three driving modes, two clutches are used to select proper operation mode. The E mode is mainly used in low speed and launching condition with SOC of power train at proper level. In the E mode, the engine is turned off and locked from rotation, and then both motors can be used to drive or brake the vehicle.

The H mode is suit for moderate speed range, which is a power split hybrid mode. In the conventional H mode, the motor M1 is used as a generator and adjust the engine speed. The engine power is distributed between the ring gear and sun gear, which are corresponded to driving through ring gear of P1 and generating electricity through the sun gear of P1 respectively.

The P mode is for higher speed condition, the engine can directly output its power to drive vehicle, and the two motors can boost and subtract the engine torque to drive vehicle as a parallel hybrid configuration.

With these two clutches, the E mode and H mode can be bidirectional changed, H mode and P mode can also be bidirectional changed. But the P mode and E mode can not be switched directly; the H mode should be the intermediate.

During the changing process from the E mode to H mode, the C1 is released and the M1 reduce its speed to 0 rpm and then change its rotation direction to be starter to start ICE. During the reverse process from the H mode to E mode, the engine is turned off and the M1 regulates the speed of carrier of P1 to 0 rpm and then C1 is engaged to lock the engine.

During the changing process from the H mode to P mode, the M1 is also performed as a speed regulator to make the speed difference of carrier and ring gear approaching to zero or nearly zero and then C2 can be engaged smoothly.

In addition to regulate the rotation speed of P1, the motor M1 can start the engine and turn it off very quickly, which can reduce vibration and improve drivability performance. The following parts describe the detail of three driving modes of the powertrain.

## 4 Detail Analysis of Three Driving Mode Operation

### 4.1 Analysis on Pure Electric Driving Mode(E mode)

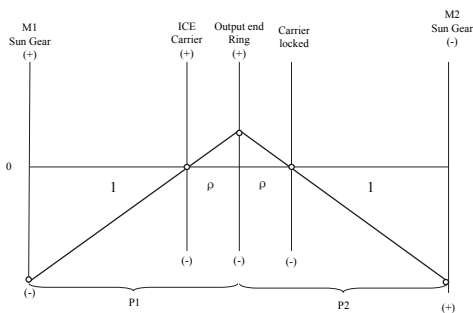
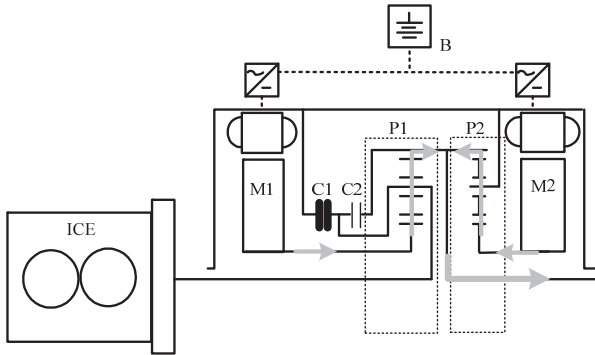


Fig. 2: Speed analogy lever of power train in E mode



**Fig. 3:** Sketch of power flow in E mode

In the E mode, the c1 is engaged and the make carrier of first planetary gear set P1 locked with case of power train, which means the engine shaft is mechanically connected to the power train housing and the engine is off. Judged from the figure 2, the E mode is suit for low velocity, because of the speed ratio is mostly between 2 and 3, and higher vehicle speed will make the motors rotate at extreme high speed.

During E mode, the power train supports the launch operation from standstill and at positive and negative driver torque demand. The E mode is generally used at high power battery SOC and lower speed such as under 30km/h. When the power battery is approaching its low SOC limit, or vehicle reaching higher speed or higher driving torque requirements will trigger the operation mode change, usually C1 disengaged and starting the ICE by motor M1, and enter Hybrid operation mode. In this mode, two motor can work together or just one motor to drive in smaller torque requirement. The power flow of E mode is shown in figure 3.

For recuperation in E mode, the M1and M2 can work as generators to charge power battery. But in most conditions, maybe only one motor is used to generate, the other one does not produce and braking torque, the power battery cannot absorb too much charging current because of charging current limitation.

## 4.2 Analysis on Power Split Hybrid Operation Mode (H mode)

In H mode with engine on, the vehicle is driving in low or medium velocity range, and both Clutch C1 and C2 are disengaged. In normal condition for H mode, the power train operates in power split mode, the mechanical power for driving vehicle is from the ICE and M2, and the M1 is generating electricity from part of the engine power and power the motor M2. Based on the vehicle operation conditions, the power battery is charged or discharged.

In H mode, the system can operated at three different conditions. With the motor M1 as a speed regulator for controlling ICE running at optimum operation line or area, there are three possible working sub-modes. The following section provides a detail discussion on these conditions. For common planetary gear set, the relation of the speed of sun gear  $\omega_1$ , carrier  $\omega_3$ , and ring gear  $\omega_2$  are describes as equation 1[3].

$$\omega_1 + k_p \omega_2 - (1 + k_p) \omega_3 = 0 \tag{1}$$

Where the  $k_p$  is the gear ratio defined by ring gear number divided by sun gear number. When speed of the sun gear is zero, a special transmission ratio  $k_0$  is gotten from equation 1, this is a special mechanical point.

$$k_0 = \frac{\omega_2}{\omega_3} = \frac{k_p}{1 + k_p} \tag{2}$$

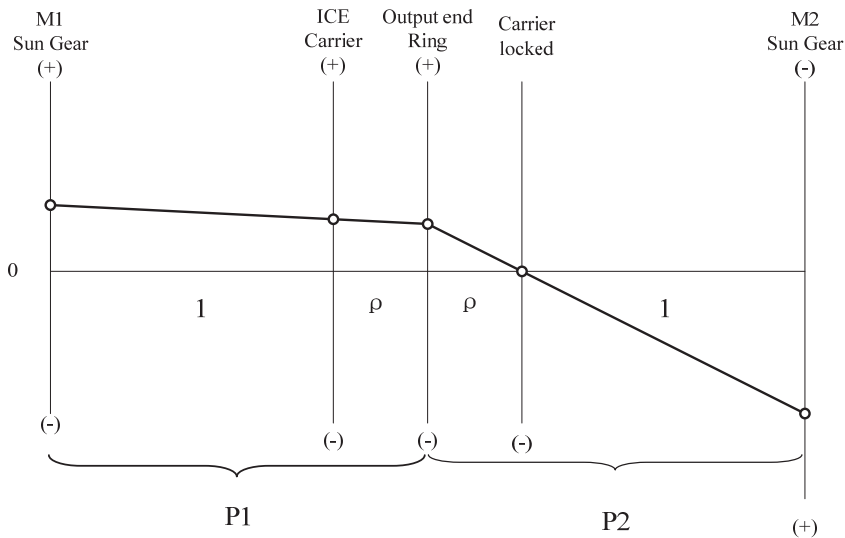


Fig. 4: Speed analogy lever of power train in H mode

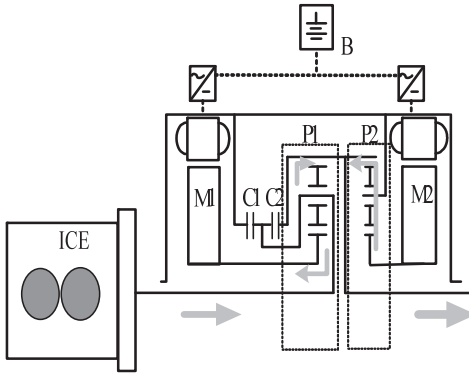


Fig. 5: Sketch of power flow in H mode

If the speed ratio  $k$  is defined as ICE speed divided by ring speed (same as the output shaft speed), then when the  $k$  is great than  $k_0$ , the power train is in true power split mode, the speed of different parts are showed in figure 4 (for simplicity, the planetary gear set P1 and P2 consumed the same gear ratio, and  $\rho$  is the reciprocal of  $k$ ). As shown in figure 5, the engine produce power, most of engine power is transmitted to ring gear through first planetary gear set, a small part is used to drive motor M1 to generate. And the motor M2 in this condition produces driving torque to boost vehicle driving, whose energy is from M1 or/and power battery. With the vehicle speed increasing, the motor M1 reduce its speed to maintain optimal ICE speed. When the M1 speed reduced to zero, a mechanical point is gotten, and at this point,  $k$  is equal to  $k_0$ .

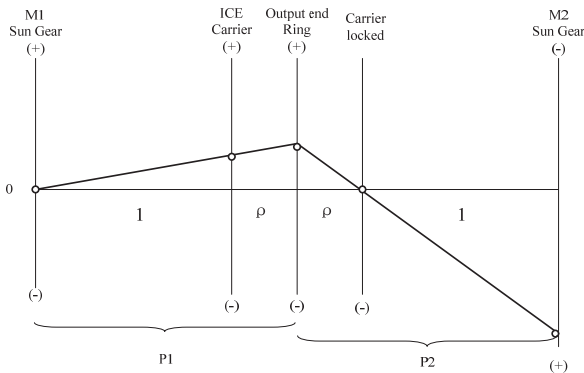


Fig. 6: The analogy lever in H mode with M1 stopping

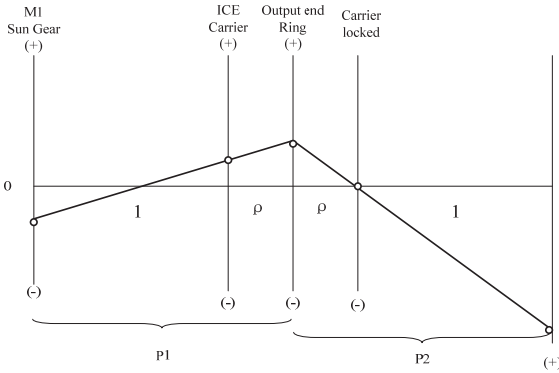


Fig. 7: The analogy lever in H mode with M1 driving

When the  $k$  is equal to  $k_0$ , the speed relation diagram is showed in figure 6, the motor M1 shaft is stopped. Whole torque from ICE is transmitted to drive vehicle without power split. Theoretically, there is no electric power goes between M1 and M2, and the M2 can boost or not. The mechanical point is characterized with top efficiency of the power train. But this point cannot maintain because of vehicle speed changing frequently if the engine speed keep constant, or at small speed range, this point can be kept by regulating engine speed with less efficiency loss. Even in this condition, the motor M2 can still provide additional torque to boost vehicle driving.

In the H mode, with increasing of vehicle speed and the engine speed is kept at constant value for optimal operation, motor M1 will pass the 0 rpm point and change its rotation direction to become a driving motor, as shown in figure 7. And at the same time the M2 operated as a generator to produce electricity to power M1 at very high speed. This sub mode is for only theoretically analysis, and it will not be used in real operation.

During the H mode, when the accelerator pedal is released and the brake pedal is released or pressed, the vehicle enter the reception condition, the engine can be cut off or still on, the M2 will driven by the vehicle kinetic energy to become a generator to charge the power battery. During the reception process in H mode, if the SOC reach its low limit, the engine can be started again to charge power battery.

### 4.3 Analysis on Parallel Hybrid Driving Mode(P mode)

When the vehicle is driving with speed increment in H mode, it will soon reach a specific speed threshold to mode change, and the power train is needed to be changed into operation of P mode. The motor M1 regulates speed to reduce speed

difference between carrier and ring gear of P1, the C2 is engaged at proper speed point, which make the ICE shaft is mechanically coupled to the ring gear. It means the P1 rotates as an integrated one without any speed difference between its three main parts such as sun gear, ring gear and carrier, the P mode can get higher transmission efficiency with energy conversion between electric energy and mechanical energy. As shown as figure 8.

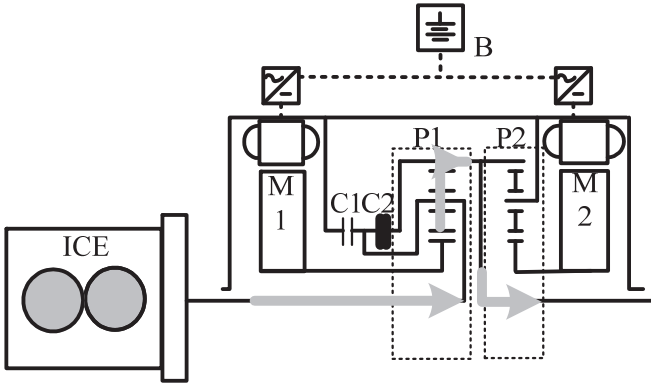


Fig. 8: Sketch of power flow in P mode

In normal P mode, the source of the driving power is from the ICE, and M1 and M2 can work as motor to provide additional torque to boost power train or operated as generator to charge power battery. The real working conditions of M1 or M2 are dependent on the vehicle operation control strategy. The other two conditions in P mode can be called driving with charging and driving with boost respectively.

In the driving with charge condition, the vehicle is driving only by engine propulsion with a constant speed. The source of the mechanical power is only the engine, M1 or M2 is operated in generator mode to supply the HV loads and to charge the power battery. This drive with charge in P mode is used mainly at cruising at medium and higher velocities with medium power demand conditions and low power battery SOC conditions.

In the drive with boost condition, the vehicle is driving mainly by engine propulsion with an increasing velocity. The accelerator pedal input is pressed for more torque. The source of the mechanical power is the engine, M1 or M2. The electrical energy is provided by the power battery. Which means this sub mode is used mainly at higher vehicle velocities with higher power demand conditions.

In the P mode, when the brake pedal is released or pressed and the accelerator pedal is released, and the engine is in fuel-cut-off mode, then the vehicle is moving



with a decreasing speed. The source of the power is vehicle kinetic energy, which drive the M1 or M2 to generate electricity to charge power battery, during this condition, sufficient energy can be regenerated by the M1 or M2. During the reception process in P mode, if the SOC reach its low limit, the engine can be started again to charge power battery.

#### 4.4 Analysis of Other Nun Driving Mode

There are also some nun driving modes, such as charging mode at standstill. In this mode, both C1 and C2 are disengaged; the vehicle is park mode which means that the ring gear of P1 cannot rotate any more. And the engine can be started by M1 and then it drives the M1 to generate and charge power battery. M2 is at zero torque and zero rpm condition.

For more function extension, the power train system can be a small power plant to provide electricity to power other utility out of vehicle. This system can also be easily extended to become plug-in HEV power train and receive external charging from grid.

## 5 Summary

The detail operation analysis of a triple mode power train for HEV was presented. With two clutches indifferent states, the pure electric driving mode, power split driving mode, and parallel hybrid driving mode can be selected to meet real vehicle driving condition. And three sub modes for H mode are discussed to benefit understanding its complicated operation. The triple mode power train can improve vehicle fuel and dynamics performance.

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