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Advancing Hybrid Vehicle Technology: A Systematic Review of Power Transmission Routes in Leading Hybrid Systems

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Abstract. This paper provides a comprehensive analysis of power transmission routes in contemporary hybrid vehicles, focusing on the characteristics and technological innovations of leading hybrid systems. The study examines five representative models: Toyota's Prius with THS (Toyota Hybrid System), Nissan's Sylphy with e-POWER, Honda's Accord featuring i-MMD (Intelligent Multi-Mode Drive), and BYD's models equipped with DM-i (Dual Mode Intelligent), as well as Great Wall's Harvard with Hi4 (Hybrid Intelligent 4WD) system. Through a systematic comparison of these hybrid powertrains, we identify key trends in hybrid vehicle technology development. Our analysis reveals a shift towards increased electrification, with motor-driven systems becoming more prevalent. We also observe a growing emphasis on optimizing engine efficiency and integrating advanced power-split mechanisms. The paper concludes by predicting future developments in hybrid power transmission, highlighting the potential for further improvements in fuel economy, performance, and emissions reduction. This research contributes valuable insights for automotive engineers, policymakers, and researchers involved in the advancement of hybrid vehicle technology.

Keywords: hybrid vehicles; power transfer routes; power-split hybridization; series-parallel hybridization.

1. Introduction

The global pursuit of carbon neutrality has become a pressing concern, with 151 countries proposing carbon-neutral targets. China, for instance, has committed to achieving carbon peaking by 2030 and carbon neutrality by 2060. The transportation sector accounts for approximately 20% of global carbon emissions, making the development of energy-efficient and new energy vehicles crucial for low-carbon transformation. In this context, hybrid vehicles have emerged as a significant technological solution, offering advantages such as extended range compared to pure electric vehicles and superior fuel economy compared to conventional fuel vehicles. Consequently, the market share of hybrid vehicles is experiencing rapid growth.

The history of hybrid vehicles dates back to 1900 when Ferdinand Porsche introduced the Semper Vivus, the first hybrid model [1]. This series hybrid vehicle utilized two engines to drive generators, charging lead-acid batteries and powering hub motors. Despite its innovative design, the Semper Vivus, with a top speed of only 35km/h, failed to gain widespread adoption due to cost disadvantages compared to contemporaries like the Ford Model T [2]. The oil crisis in the latter half of the 20th century renewed interest in hybrid technologies, particularly brake energy recovery and motor-assisted drive systems. Concurrently, advancements in engine technology, such as the Atkinson cycle (invented in 1882) and Miller cycle (invented in 1947) engines, offered improved thermal efficiency compared to Otto cycle engines. Initially hindered by complex mechanisms, these technologies found new relevance with the progress of engine electronic control and variable valve technology in the 1980s [3-4]. The modern era of hybrid vehicles began in 1997 with the introduction of the Toyota Prius, the first mass-produced hybrid vehicle [5]. Driven by the need to reduce oil dependence, Japanese automakers like Toyota, Honda, and Nissan developed highly competitive hybrid systems, establishing Japan's global leadership in this field [6]. In recent years, particularly since 2021, Chinese automakers have made significant strides in hybrid technology. Companies such as BYD, Great Wall, and Chery have introduced a new generation of self-developed hybrid powertrains, launching

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competitive products tailored to consumer needs. This diversification of technology routes has led to explosive growth in hybrid vehicle sales [7].

This paper aims to analyze the mainstream architectures and power transmission routes of hybrid technology powertrains, focusing on:

1) Comparing the hybrid technologies developed by pioneering Japanese companies with those of emerging Chinese automakers.

2) Examining the characteristics of various hybrid systems.

3) Exploring the future development direction of hybrid systems.

By providing an in-depth analysis of current market-leading hybrid vehicle power systems and rationally predicting future trends, this research offers valuable insights for the ongoing development of hybrid technology.

To understand the current state and future trends of hybrid vehicles, we first need to examine the fundamental technology routes that underpin these systems.

2. Hybrid Vehicle Technology Route

Hybrid vehicles realize the complementary advantages of the engine and electric motor through flexible system architecture and different mixing ratios to adapt to the power demand and consumption characteristics of different segments of the market, and thus develop diversified hybrid technology routes. In this section, we analyze the hybrid ratio and system architecture of hybrid vehicles to get a preliminary understanding of the development route of hybrid vehicles.

2.1. Hybrid Vehicle Mixing Degree Analysis

Degree of hybridization (DoH) is an important quantitative index that describes the hybridization ratio of oil and electricity in a hybrid powertrain [4]. Hybrid vehicles can be classified into four categories according to the degree of hybridization: micro-hybrid, light-hybrid, full-hybrid, and plug-in hybrid. Hybrid vehicles can realize such functions as gear shift assist, engine torque smoothing, idle stop, brake energy recovery, cruise energy recovery, etc. Pure fuel vehicles have only one power source, the engine, so they cannot realize the above functions. Hybrid powertrains with different degrees of mixing are shown in Figure 1 [8].

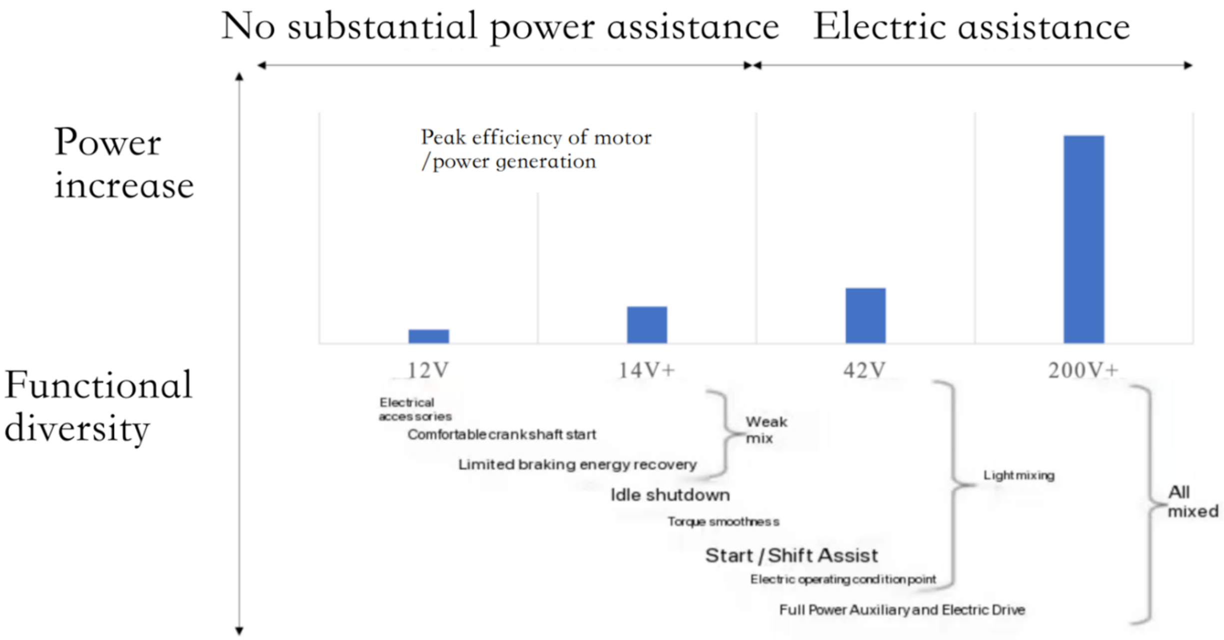


Figure 1. Hybrid systems with different degrees of mixing.

Cars with a weak mix are equipped with a BSG motor, also known as a P0 motor. Its main function is to provide additional torque during engine startup, making the engine startup process smoother. A vehicle with a light blend is equipped with a 42V motor, which cannot drive the vehicle alone, but only provides torque compensation when the vehicle is accelerating or braking. In addition, the 42V motor can be used as a generator to recover more braking energy and improve range. In a strong hybrid vehicle, the motor's operating voltage is usually above 200V compared to a light hybrid vehicle, and the motor can be used as the vehicle's sole power source, or it can be combined with the engine to form a more powerful power source. A full hybrid vehicle can be driven in purely electric mode with virtually zero emissions. Even when the battery is low, the vehicle's fuel economy can be improved by having the engine and electric motor work in tandem. Plug-in hybrid vehicles are based on full hybrid vehicles with increased battery capacity to provide a longer pure electric range. Plug-in hybrid vehicles can realize the working mode of "using fuel for short distances and electricity for long distances".

Through the above analysis, it can be seen that the development of hybrid vehicle power system is to gradually reduce the power output of the engine as a power source for automobile driving, and gradually increase the electric motor as a power source to drive the automobile driving. The electric drive system has become the main power source, the main role of the engine is to charge the battery, or in some working conditions, as an auxiliary power source to assist the motor to drive the car. With the continuous development of automobile electrification technology, the hybrid car with the power configuration of "motor as the main, engine as the auxiliary" will become the mainstream of development.

2.2. Hybrid Vehicle Drive Types and Characteristics

Depending on whether the internal combustion engine has a direct mechanical connection to the drive wheels or not, they are categorized as series hybrid vehicles, parallel hybrid vehicles and hybrid hybrid vehicles [9].

2.2.1. Series hybrid vehicles

There is no direct mechanical connection between the engine and the drive wheels, and the engine always works near the optimal operating point, driving the generator to generate electricity, as shown in Figure 2. When the power demand of the car is small, part of the electrical energy generated is used to drive the car and the other part charges the battery. When the power demand of the car is large, both the generator and the battery provide electrical energy to the motor to drive the car. During braking the motor acts as a generator and stores the recovered energy in the battery. Since the series-connected motor is independent of the vehicle's driving conditions, it is suitable for frequent starting, acceleration, and low-speed operation, which are common in urban areas.

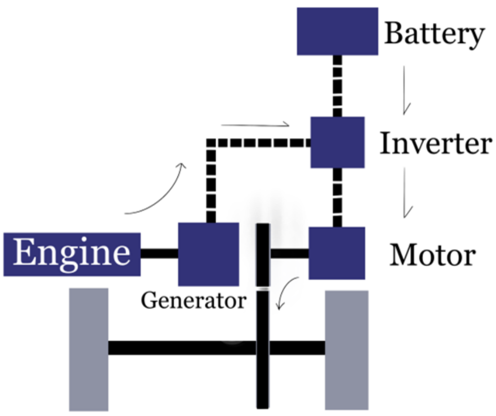


Figure 2. Tandem Hybrid Vehicle.

2.2.2. Parallel hybrid vehicles

The engine and electric motor can supply power to the drive wheels independently of each other, as shown in Figure 3. When the vehicle is traveling at low speeds, the electric motor can be made to drive the vehicle alone. When the vehicle is traveling at medium and high speeds, the engine can be made to drive the vehicle alone, and the surplus power of the engine can be charged to the battery. When the vehicle starts or accelerates, the power synthesis device realizes the joint drive of the engine and the electric motor. When the vehicle is braking, the electric motor can be made to work in the generator state to recover part of the braking energy and replenish the capacity of the battery.

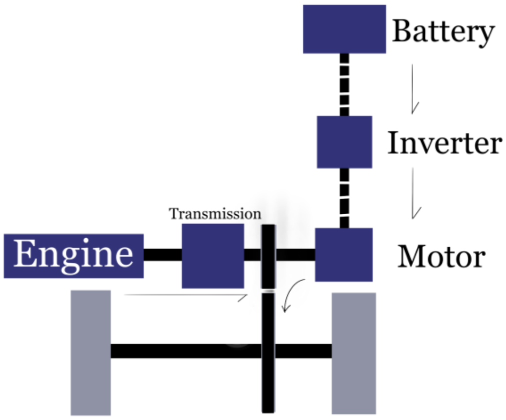


Figure 3. Parallel hybrid vehicle.

2.2.3. Hybrid (series-parallel) hybrid vehicles

Combines the advantages of series and parallel connection. The engine and motor can be driven either separately or together, as shown in Figure 4. At low speeds, the motor is driven alone; at medium and high speeds, the engine and motor are driven together; and at high cruising speeds, the engine is driven alone and the motor can charge the battery.

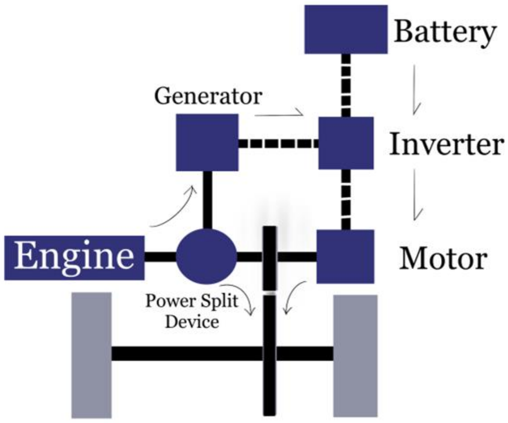
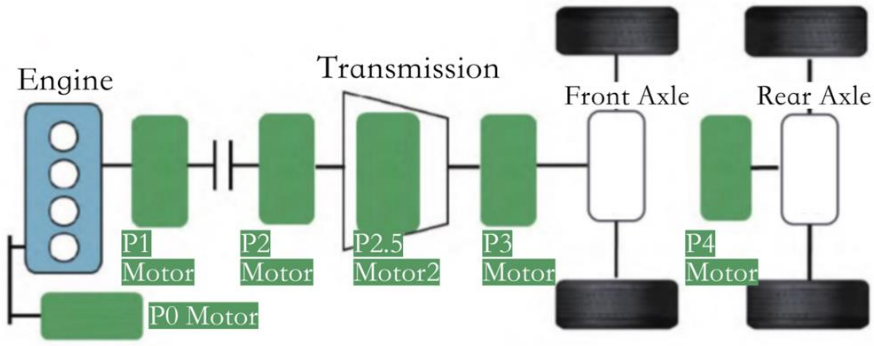


Figure 4. Hybrid (series-parallel) hybrid vehicle.

2.3. Hybrid Vehicle Motor Position

Hybrid vehicles can be equipped with one or more electric motors at the same time. The motors may be arranged at different positions in the power transmission chain. Motors at different positions play different roles, which in turn have different effects on power transmission and vehicle characteristics. As shown in Figure 5, according to different positions, the motors of hybrid vehicles can be categorized into six types: P0, P1, P2, P2.5, P3, P4, etc. The smaller the number after P, the closer the motor is to the engine [10].



Position	P0	P1	P2	P2.5	P3	P4
Engine ON/OFF	√	√	√	√	×	×
Braking energy recovery	√	√	√	√	√	√
Power generationextension	√	√	√	√	×	×
Pure electric drive	×	×	√	√	√	√

Figure 5. Location and functional characteristics of motors in the hybrid vehicle powertrain.

The P0 and P1 motors are directly connected to the engine to reduce energy consumption by controlling engine start/stop and recovering braking energy. In addition, P0, P1 motor can provide a small amount of auxiliary drive for the vehicle, or based on the state of charge of the power battery as a generator to generate electricity.P2 motor and engine output shaft with a set of clutches, clutch disconnect motor and engine decoupling, at this time the P2 motor can be driven alone to realize the vehicle pure electric driving. In order to reduce the axial size of the power system, some companies will be integrated into the motor inside the transmission to develop P2.5 motor technology. P3 motor is located in the output shaft of the transmission, and the axle is directly connected to the power output efficiency is higher. However, because the P3 motor is separated from the engine by the transmission, the P3 motor cannot control the engine start/stop or be used as a generator. Also, the power output of the P3 motor cannot be adjusted by the transmission in terms of speed and torque.The P4 motor is independent of the engine output shaft and is usually used in four-wheel drive models to improve the vehicle's power performance.

In a single-motor hybrid system, a single-motor series hybrid system typically uses a P0 or P1 motor. Single-motor parallel hybrid systems typically use a P2 motor. In a single-motor parallel hybrid system, the P2 motor can be used as a generator motor to generate electricity and as a drive motor to drive the vehicle alone or in combination with the engine. In order to further optimize the driving dynamics and fuel economy of the hybrid system, diversified multi-motor hybrid system technical solutions such as P1+P3, P1+P2, P2+P4, P1+P3+P4, etc., have been developed to realize the complementary advantages of different motors.

Having established the basic principles and classifications of hybrid vehicle technologies, we can now analyze how these concepts are applied in the current market-leading hybrid systems.

3. Analysis of Mainstream Hybrid Technology Routes in the Market

In the global market, in order to achieve higher fuel efficiency, performance optimization, and better driving experience for hybrid vehicles, automakers have launched their own hybrid powertrains. The following is a detailed analysis of the structure, transmission routes and features of the mainstream hybrid systems. We will now examine five representative hybrid systems that showcase different approaches to hybrid technology implementation.

3.1. Toyota THS System

The THS hybrid system equipped in the first mass-produced hybrid vehicle, Toyota Prius, is a typical power split hybrid technology.The THS hybrid system powertrain mainly consists of an engine, two electric motors, and a planetary gear row [11].The two electric motors and planetary gears form a PS-DHT (Power Split - Dedicated Hybrid Transmission).The THS hybrid system engine is connected to the planetary carrier, the generator is connected to the sun wheel, and the drive motor is connected to the output shaft reduction gear and outer gear ring as shown in Figure 6. Dedicated Hybrid Transmission).The engine of the THS hybrid system is connected to the planetary carrier, the generator is connected to the sun wheel, and the drive motors are connected to the output shaft reduction gears and the outer gear ring as shown in Figure 6.

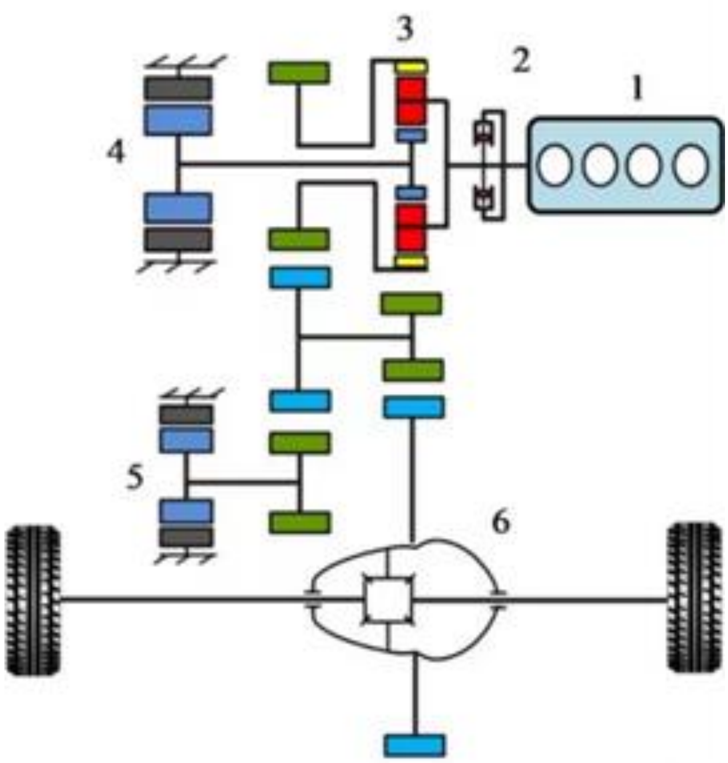


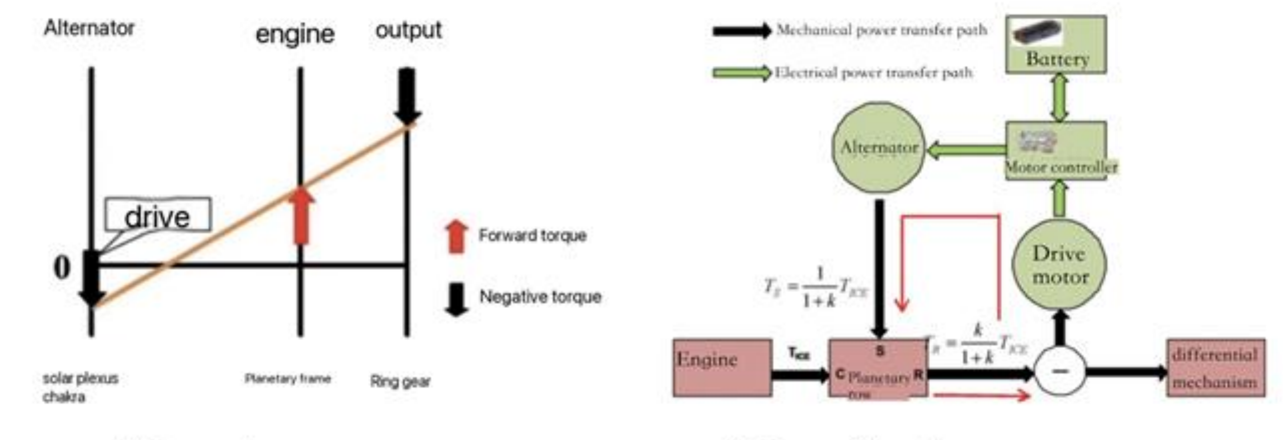
Figure 6. Schematic diagram of Toyota THS hybrid system. 1-engine; 2-torsion damper; 3-planetary gear; 4-generator; 5-drive motor; 6-differential.

The THS system does not use actuating elements such as clutches, which makes the structure simple and also achieves better fuel savings. Since there is no clutch, the system can realize fewer operating modes. The THS hybrid system has only three operating modes: pure electric mode, power-split (hybrid) mode and brake energy recovery. The operating states of each powertrain in the Toyota THS system's operating modes are shown in Table 1.

Table 1. THS operating modes.

operating mode	Engine operating status	Generator operating status	Drive motor operating status
Pure electric mode	(of a prepaid mobile phone) be out of credit	idle	drive (vehicle wheel)
power shunt	drive (vehicle wheel)	send a telegram	drive (vehicle wheel)
Brake Recovery	(of a prepaid mobile phone) be out of credit	idle	send a telegram

When the THS system vehicle is traveling in high-speed conditions, ideally, the engine power is transmitted in two paths: (1) part of the engine energy drives the generator to generate electricity, which is stored in the power battery; (2) part of the engine energy directly drives the vehicle. The drive motor drives the vehicle through the electrical energy provided by the power battery. In the high-speed working condition, the principle of THS system is shown in Figure 7, the lever diagram is shown in Figure 7(a), and the power flow is shown in Figure 7(b). When the power demand of the whole vehicle is small, the generator of the THS system needs to generate electricity by the drive motor in order to balance the power of the engine. Therefore, a portion of the power is generated through the drive motor to the generator to balance the engine power, thus creating a power return. The power backflow of the system reduces the efficiency of the system. To solve the power return problem, a multi-speed transmission can be added or the GM multi-mode shunt system can be used. GM's multi-mode shunt system uses a coupling of double-row planetary gears to control the clutch to realize five driving modes: single-motor-only, dual-motor-only, low-speed range-extension, fixed-ratio range-extension, and high-speed range-extension. The low-speed extended range and high-speed extended range modes are input and compound power shunts, respectively [12].



(a) Lever diagram at power return (b) Power flow diagram at power return

Figure 7. Principle of power return.

3.2. Nissan e-Power System

Nissan e-POWER belongs to series hybrid technology, and the powertrain mainly consists of engine, generator, gearbox, drive motor and power battery. The powertrain hardware structure of the Nissan e-POWER hybrid system is shown in Figure 8. The engine and generator are connected through a speed-increasing gear, which allows both the engine and generator to work in the high-efficiency zone, thus improving the oil-to-electricity conversion rate and the fuel economy of the whole vehicle. At the same time, the output speed of the engine is amplified by the gear set, which can increase the power generation and reduce the power requirement of the generator, thus reducing the space size and hardware cost of the generator. The power generated by the engine-driven generator is distributed through the inverter, with part of it used to charge the power battery and the other part fed directly to the drive motor, which is then adjusted to drive the wheels via a single-speed reducer. The Nissan e-POWER utilizes a small-capacity power type lithium-ion power battery of approximately 1.5kWh, which enables continuous high-power output while being small in size. The single-speed reducer and power-generating incremental gear are integrated into the gearbox, further optimizing the spatial compactness of the e-POWER hybrid system's powertrain.

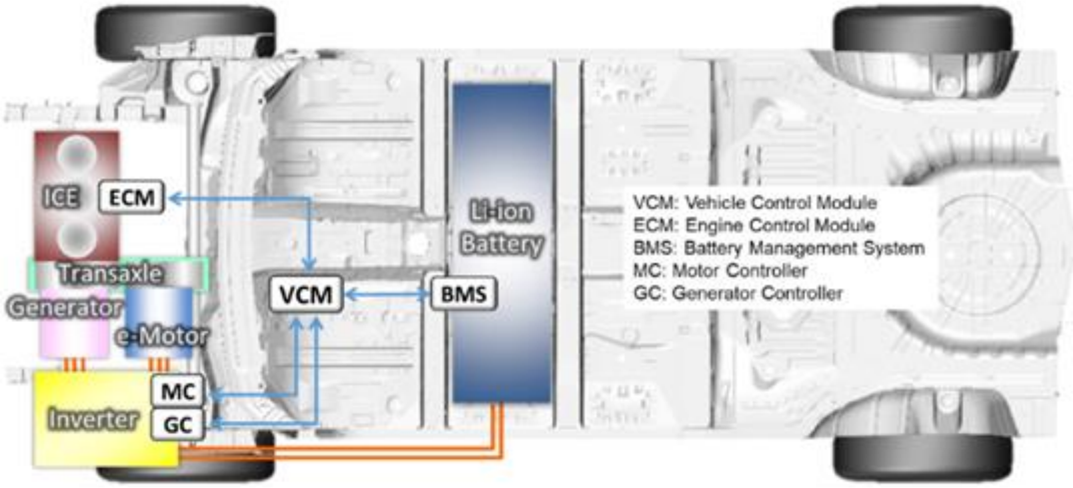


Figure 8. Schematic diagram of Nissan e-POWER hybrid system [13].

In the e-POWER hybrid system, the engine only drives the generator to produce electricity and does not drive the wheels directly. Therefore, the optimization technology around the engine is aimed at improving its thermal efficiency in extended-range operation. e-POWER Hybrid uses an engine that has been modified from one with a thermal efficiency of 38%. The engine used in the e-POWER hybrid system has been modified from an engine with a thermal efficiency of 38 percent to a maximum effective thermal efficiency of 43 percent by applying a strong roll-flow ratio and long-arc high-energy ignition technology and reducing pump gas losses. The WLTC (Worldwide Harmonized Light Vehicles Test Cycle) combined fuel consumption of the hybrid Hennessey model equipped with this e-POWER-specific engine is only 3.73L per 100km, which is a 37% reduction in fuel consumption compared to conventional fuel-only vehicles [30]. Moreover, through the application of thin combustion, waste heat recovery and other technologies, the maximum thermal efficiency of the e-POWER hybrid engine is expected to reach 50% in the future, which will further improve the fuel economy of the hybrid system [14].

3.3. Honda i-MMD System

Around the hybrid technology, Honda has launched four sets of hybrid configurations such as IMA, i-DCD, i-MMD and SH-AWD, of which the most distinctive and influential is the i-MMD hybrid system that debuted in the Accord model in 2014 [15]. Honda i-MMD belongs to the P1+P3 dual-motor series-parallel hybrid technology, as shown in Figure 9. The core components of the powertrain include the generation motor, drive motor, hybrid-specific engine and transmission. The dual motors are integrated into the transmission along with the clutch to form a multi-mode hybrid-specific transmission.

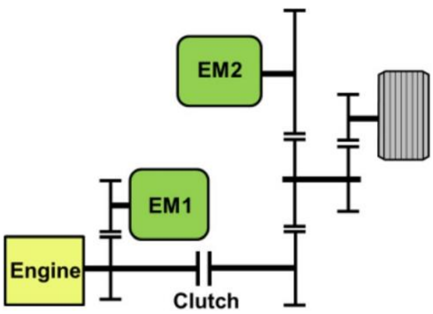


Figure 9. Schematic diagram of Honda Accord i-MMD hybrid system.

The realization mode of series-parallel DHT (Dedicated Hybrid Transmission) is shown in Figure 10, in which: at low speeds or when the battery SOC is high, the car operates in EV mode; at medium speeds or when the battery charge state is low, the car operates in series mode, where the engine charges the generator EM1, and the vehicle is driven by the generator EM2 by itself; and at high speeds, since the high efficiency of the engine driving the car directly, the engine can be used in single or parallel mode. The analysis of the working mode of the i-MMD hybrid system shows that there is always a transmission ratio or direct connection between the engine and the generator. Between the engine and the wheels, there is always one or two gear meshes.

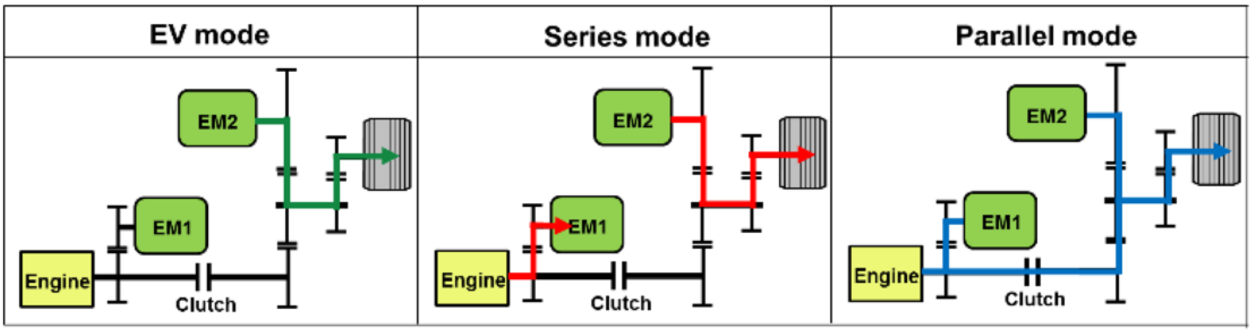


Figure 10. Honda i-MMD system operating modes and power transfer paths [16].

3.4. BYD DM-i System

The BYD DM-i Hybrid is a standard mixed-connection hybrid structure characterized by: The engine is a plug-in hybrid-specific Snapdragon engine, which BYD has optimized for every energy loss in a targeted manner. The Snapdragon Plug-in Hybrid engine's performance is positioned differently from that of a normal engine. There is no need to take low-speed torque into account, no need to pursue maximum power, and no need to maximize the efficient speed range. Only the peak thermal efficiency needs to be improved as much as possible, and all other issues can be solved by the hybrid system [17]. The P1 position motor is a 75kW flat-wire permanent magnet synchronous motor coupled to the engine output shaft through a gear, as shown in Figure 11.

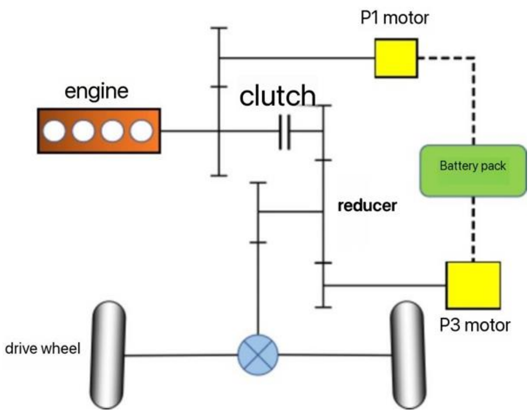


Figure 11. Schematic diagram of BYD DM-i hybrid system.

BYD's DM-i system has a longer pure electric operating time and the engine can work in the high-efficiency zone for a long time compared to Honda's i-MMD system [18].The main operating modes of the DM-i hybrid system include pure electric drive mode, series range-extended mode, parallel hybrid drive mode, and energy recovery mode, and the distribution of power between the engine and the motor in the various modes is shown in Figure 12.

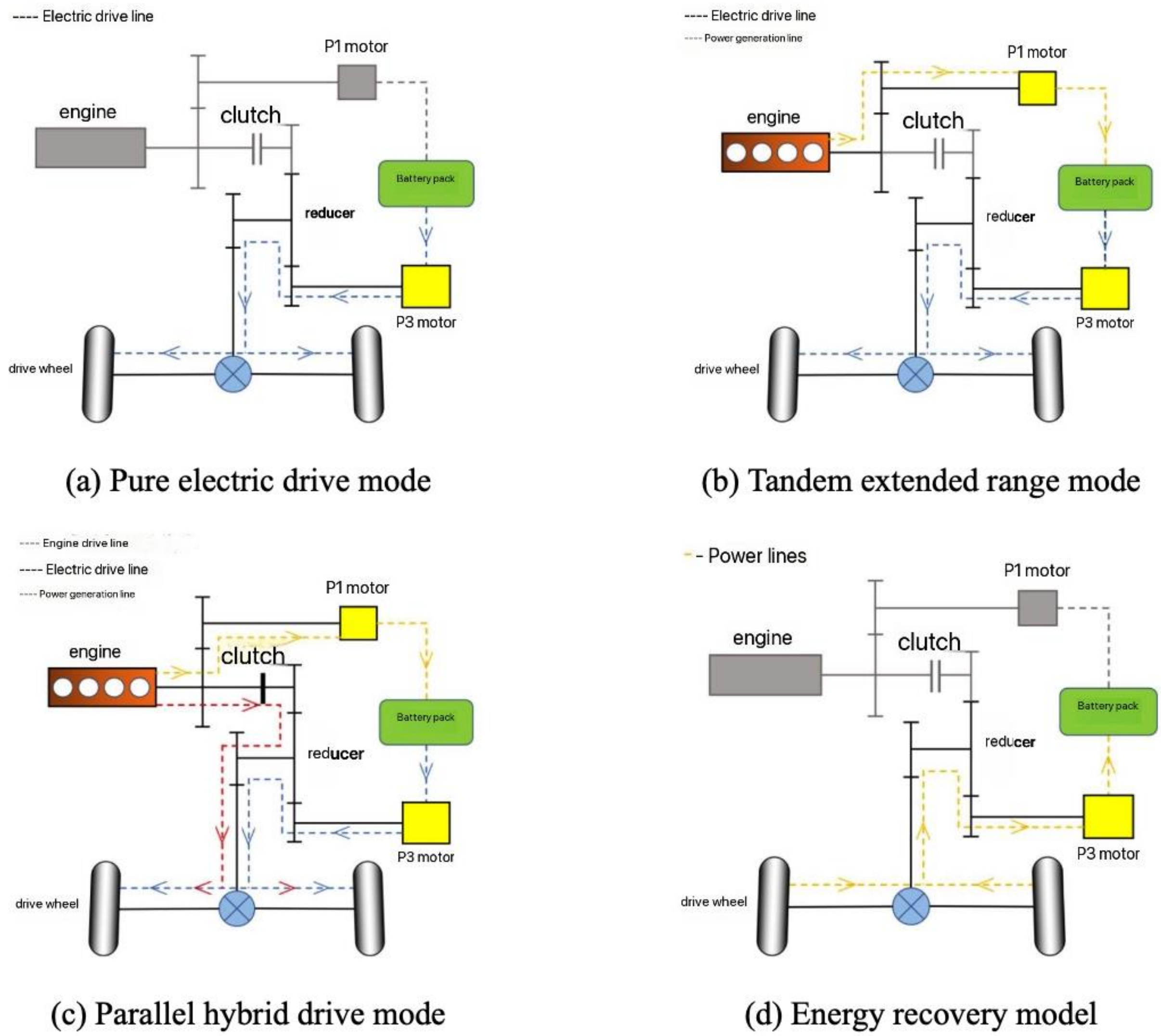


Figure 12. BYD DM-i system working mode and power transmission route.

3.5. Great Wall Hi4 System

The Hi4 system is a hybrid system developed by Great Wall to realize a low-cost 4WD hybrid vehicle. Honda's i-MMD system and BYD's DM-i system both use hybrid hybrid vehicles consisting of dual P1 and P3 motors. Among them, the P1 motor is mainly used to generate electricity and the P3 motor is mainly used to drive the vehicle. The Great Wall Hi4 system makes it possible to design the P1 and P3 motors as a single motor and integrate it with a two-speed gearbox, i.e. the P2.5 motor. Thus, the functions of both P1 and P3 motors can be realized with one P2.5 motor [19]. By arranging a P4 motor at the rear axle of the vehicle, the Hi4 system can realize the four-wheel drive function of the vehicle using two motors. The structure of the Hi4 system is shown in Figure 13.

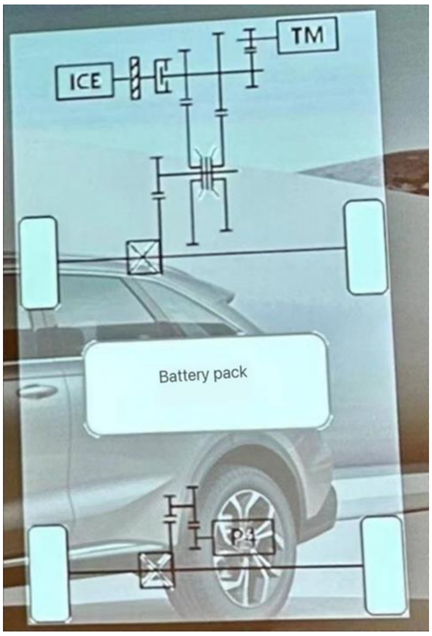


Figure 13. Schematic diagram of Great Wall Hi4 hybrid system.

Configuration	Engine	1st Gear	2nd Gear	Front Motor	Rear Motor	Dual-Motor Dual-Axle Series-Parallel Hybrid Architecture
Pure Electric Rear Drive					●	Yes
Series Rear Drive	●			●	●	Yes
Pure Electric AWD		●		●	●	Yes
1st Gear Direct Drive	●	●				
2nd Gear Direct Drive	●		●			
Parallel 2WD	●			●		
Parallel AWD	●			●	●	Yes
Single Axle Recovery					●	
Dual Axle Recovery				●	●	Yes

Figure 14. City Hi4 system operating mode and power transfer paths.

Based on the above new hybrid architecture, Great Wall Company uses the "3-engine 9-mode" working mode [20]. With the intelligent energy management system, the efficiency of the whole system can be optimized under all working conditions. The 3 engines and 9 modes in "3 engines and 9 modes" refer to one hybrid engine and two electric motors; the 9 modes are 9 working modes, i.e., electric-only 2WD/4WD mode, tandem mode, direct engine drive (1st gear/2nd gear) mode, parallel 2WD/4WD mode, and single/twin-axis energy recovery mode, as shown in Figure 14. The switching scenarios of these nine modes include: when driving at low speeds in urban areas, intelligent switching between pure electric 2WD, tandem, and 1-gear direct-drive modes according to the vehicle's throttle depth and speed; when accelerating sharply in urban areas or when climbing a hill, intelligent switching between pure electric 4WD and 1-gear direct-drive modes; at high speeds during cruising conditions, the engine operates in the most efficient zone in the 2-gear direct-drive mode; and during high speeds during accelerating conditions or when climbing a hill, the engine operates in the most efficient zone. When accelerating at high speed or climbing a hill, the engine works in the most efficient zone, and intelligently switches between parallel two-wheel drive and parallel four-wheel drive; when decelerating and braking, it intelligently switches between single-axle recovery and dual-axle recovery modes.

Having analyzed these diverse hybrid systems, we can now draw some conclusions about the current state of hybrid vehicle technology and its future direction.

4. Conclusion

This paper has provided a comprehensive analysis of the world's typical hybrid systems, focusing on the hybrid forms developed by pioneering Japanese companies and the emerging technologies from Chinese manufacturers. Our analysis reveals that the current mainstream hybrid vehicles predominantly utilize a two-motor series-parallel architecture, offering advantages such as fewer transmission gears, simple construction, and high reliability. There is a clear trend towards continuously improving the thermal efficiency of engines in hybrid systems, ensuring they operate in their high-efficiency range and leading to significant reductions in fuel consumption. The analysis of power transmission routes indicates that motor-driven automobile operation has become the primary direction for future hybrid vehicle development, aligning with the broader push towards vehicle electrification. Additionally, there is a move towards more integrated and compact hybrid powertrains, as exemplified by systems like Great Wall's Hi4.

Despite these advancements, several challenges persist in hybrid vehicle technology. These include the higher initial cost compared to conventional vehicles, limitations in battery technology affecting all-electric range, increased system complexity, weight management issues, and the need for more sophisticated control algorithms for optimal power distribution. The environmental impact of hybrid vehicle production, particularly battery manufacturing, remains a concern. Additionally, the expansion of charging infrastructure for plug-in hybrids and the need to continuously evolve to meet increasingly stringent emission standards present ongoing challenges. Addressing these issues will be crucial for the continued evolution and widespread adoption of hybrid technology in sustainable transportation.

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