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Structure Analysis and Cost Estimation of Hybrid Electric Passenger Vehicle and the Application in China Case

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Abstract

Hybrid electric vehicle (HEV) is regarded as an important technology in solving the energy and environment crisis. In this paper, the HEV technology applied in passenger cars by major automotive OEMs such as Toyota, Honda, GM, Ford, Volkswagen, BMW are investigated. The configuration diagrams for each OEM are presented. Based on the architecture analysis, a classification is done according to similar structures and performances. Furthermore, a cost estimation methodology for HEV is presented based on the preliminary tear-down research done by Environment Protection Agency (EPA). Meanwhile, the logarithmic relationship between fuel consumption (FC) reduction and degree of hybridization (DOH) is discovered by investigating 30 different hybrid cars. Combining the cost estimation and relation between FC&DOH, the hybridization cost for cars to meet the FC regulations can be calculated. Lastly, to check the cost and hybridization of HEV in the future, a car fleet of typical OEM is selected and the cost for its hybridization is calculated using the method mentioned above considering phase IV FC regulation in China.

Introduction

Hybrid electric vehicles (HEV) are currently regarded as promising emerging technology for propulsion of vehicle with potential to reduce greenhouse and other emissions from road transport [1, 2, 3]. HEVs provides increased efficiencies over the internal combustion engine (ICE) powertrain by an ability to operate the combustion engine at its higher efficiency levels for a greater percentage of time [4, 5, 6]. It also saves energy by shutting down the engine during low efficiency periods, and the motor would provide power supplement during engines shutting down. In addition, by regenerating the braking energy, and storing this portion of energy in battery system, HEVs provide a significant fuel consumption (FC) reduction [7, 8, 9, 10].

In recent years, the HEVs have thrived as a lucrative solution to the energy and environment problems with its intermediate approach to achieve long diving distance and low carbon emission. Taking the advantages of ICEs and electric vehicles (EV), HEVs are quite promising for vehicle technology development in short term to mid-term [11]. Lave and MacLean [12] compared a hybrid car to an ICE car, found that HEVs are not only effective in improving fuel economy or lowering emissions, with gasoline price rising in the future, the reduction of usage cost of HEVs would be significant. Morteza and Mehdi [13] developed a new energy management strategy for power split HEVs using multi-input fuzzy logic controller to further improve the fuel economy, air pollution and performance of hybrid vehicles in various driving cycles. Cummings and Bradley et al. [14] investigated the effect of sensitivity of sensing and prediction in vehicle fuel economy improvements. Finesso and Spessa et al. [15] applied an equivalent consumption minimization strategy tools to identify the optimal control strategy of a parallel hybrid vehicle. A downshifting strategy is introduced by Li and Wang et al. [16], the energy conservation of HEV regenerative braking with this strategy can be improved by 10-32% according to their hardware-in-loop validation.

HEV is driven by ICE in combination with one or more electric motors [17, 18]. A battery package is connected to the motors as a secondary storage system to provide power supply for motors. It is a complex combination of mechanical, electrical, electronic and power engineering technologies embracing the best of both ICE and EV. In general, HEVs can be classified into several categories based on their degree of hybridization (DOH) which is defined by the proportion of electric power in the total power: micro hybrid, mild hybrid, full hybrid [4]. Further, the full hybrid can be classified to three category: the serial hybrid, parallel hybrid, power split hybrid. However, the serial hybrid is mostly used in hybrid buses and plug-in HEVs, which are not discussed in this paper. Thus for full hybrid without plug-in function, they are classified into two type of power split and parallel hybrid, as presented in following content.

Despite the fuel economy and emission advantages of HEVs, the cost increment cannot be neglected. With more complicated transmission system and electrical systems introduced in, the manufacturing cost would surely take an increment. Prices of most HEVs in the market are higher than their benchmarking cars. There are several papers from since the last decade and even recently which previously have contributed to the compilation of reviews of HEV and EV cost from various authors [19, 20, 21, 22, 23, 24]. However, most of previous studies focus on the cost-effectiveness of energy system, or the usage of car life cycle. Studies aiming at manufacturing cost of OEMs are relatively inadequate. Still, some papers presented detail cost analysis methodologies for automotive industry [25, 26]. Major institutes such as the Environment Protection Agency (EPA), National Highway Traffic Safety Administration (NHTSA) and National Research Council (NRC) has processed thorough research by tear down research and full system simulations for cost-effectiveness of automotive energy saving technologies in almost all fields. The hybrid technology section of their study are cited in this paper as base data.

This paper is organized as follows. After the brief introduction in section 1, section 2 will showcase the HEV configuration analysis by investigating major HEV OEMs. Section 3 shows the cost estimation methodology for any full hybrid vehicle by further applying the base data. Section 4 shows the effectiveness study of HEV, where a logarithmic relationship between FC and DOH is given. Section 5 discusses the application of methodology mentioned in this paper by applying them to a particular car fleet of a China OEM. Section 6 concludes the paper and presents some further research directions.

HEV Configuration Analysis

HEVs can be categorized by the mechanical connections and DOH. DOH is the concept of the level of hybridization of a HEV. The classification of HEVs by DOH is categorized between DOH = 0 (ICE vehicle) and DOH = 1 (electric vehicle). The DOH can be expressed as

$$DOH = \frac{P_M}{P_E + P_M} \tag{1}$$

Where P_M is peak power of motor, P_E is peak power of engine.

With the configurations studies of major OEMs, a roughly classification of full hybrid configurations can be made into two major types: the power split (PS) type which implements planetary gear sets to realize the hybridization of motor and engine power; the parallel system, or so called P2 system, that combines different power sources with clutches. This is a classification that also be approved by EPA, NHTSA and NRC [27, 28, 29]. Brief descriptions including driving modes and configuration diagrams for each OEM are given as follow.

Power Split HEV Configuration

(1) Toyota Hybrid System (THS)

Toyota Motor Co. has introduced HEVs to world market since 1990s [30, 31]. Toyota could be considered as most important OEM in HEV domain with successfully developed and well sold vehicles such as Prius and Camry. They introduced planetary gears into the design of hybrid powertrain. This configuration is also called “Power Split” HEV architecture because of the driving modes. The basic power split or so called electronic CVT is depicted in Fig 1. The engine is connected to planetary carrier, the Motor/Generator (M/G) 1 is connected to sun gear, the ring gear connects to Motor/Generator 2 and final reduction drive (FD).

(2) Ford FHS system

The Ford Hybrid System (FHS) that developed by Ford Co. is an evolution of the THS with the addition of output gearing between the motor and final drive and between the input planetary ring gear and final drive. Fig 2 illustrates the FHS architecture [32, 33]. The presence of an output gear introduces a counter shaft into the FHS system that adds complexity to the structure, but overall the performance is similar to that of THS. The additional output gearing adds further mechanical advantage to motor and engine torque.

(3) GM AHS system

The General Motor Advanced Hybrid System (AHS) is illustrated in Fig 3. This architecture is commonly known as a compound split with 2-mode electrically variable transmission with both input and output planetary gear sets [34]. Note that three clutches are introduced in the electric powertrain lay out. When clutch 3 is actuated the AHS system is said to be in the input split mode, which is applied in low speed conditions. When clutch 3 is de-actuated, the AHS is in compound split mode, which is applied in high speed conditions. Neutral occurs when both clutch 2 and clutch 3 are disengaged. Other driving mode such as starting, idle, braking, AHS works similar with the basic THS system.

FIGURE 1 Toyota power split system

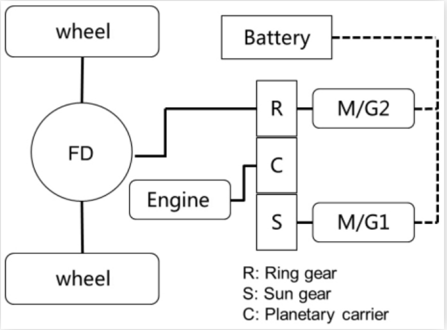

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FIGURE 2 Ford FHS system

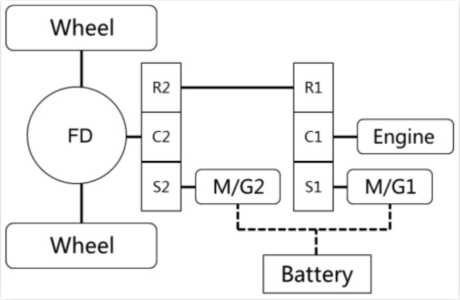

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FIGURE 3 GM AHS system

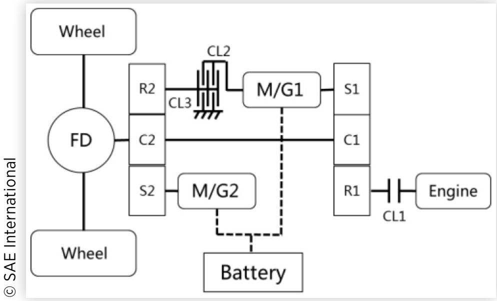
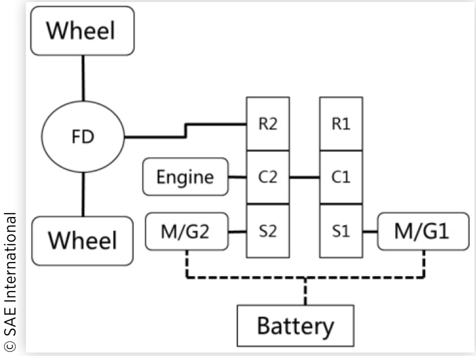


FIGURE 4 CHS system



(4) Geely CHS system

China Hybrid System (CHS) is a newly presented hybrid system developed by China OEM Geely Auto Co. In this system, two sets of planetary gears are applied, as the FHS and AHS. With the planetary gear sets working together, the motor and engine performance can be adjusted neatly. The counter shaft connects the planetary carriers of two gear sets, similar with the AHS. While the wheel is connected to ring gear of output gear sets, which is different with those mentioned above. With CHS system equipped, several hybrid drive mode can be realized to reduce fuel consumption.

Parallel (P2) HEV Configuration

(1) Typical parallel hybrid system

In a parallel hybrid system, the motor/generator takes place between the engine and transmission. Thus this configuration is also called position 2 (P2) configuration. Transmissions applied in this system is usually a multi-speed auto-transmission with high synergies with conventional transmissions. A separating clutch is located between the M/G and engine, allowing the combustion engine to be connected or disconnected from the drive considering the working condition demands [35]. This configuration is widely applied in OEMs such as Volkswagen, BMW, Mercedes.

(2) Honda IMA system

The Honda Integrated Motor Assist (IMA) system is a variation of P2 system as illustrated in Fig 6. In this configuration, the motor and engine is integrated together by connecting the motor output shaft and engine crank shaft directly [36]. With this design, enhanced motor and engine performance are more demanded. Because when the power is provided by motor alone, the engine friction and other resistance would have a direct effect on performance. Conversely, when the vehicle is driven purely by engine, the motor resistance must be dealt with. Honda applied their CVT transmission in the hybrid powertrain, which shows another difference with typical P2 system. The basic drive modes of IMA system is similar with a typical P2 except that in IMA case, the power is simply shut down instead of using a clutch.

FIGURE 5 Typical parallel system

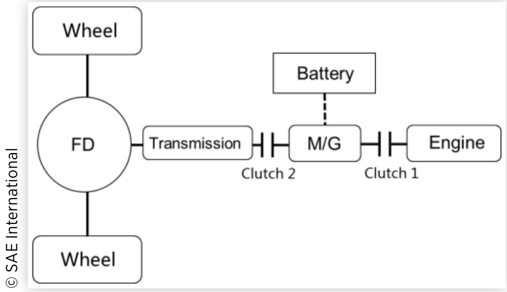


FIGURE 6 Honda IMA system

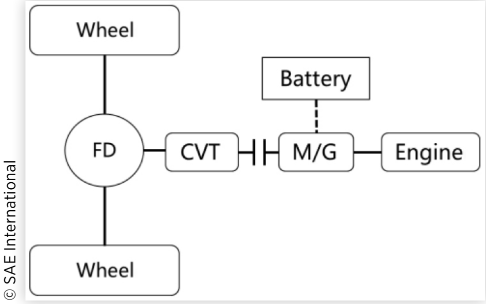
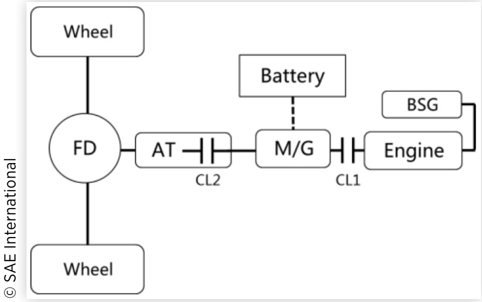


FIGURE 7 P2 system of Hyundai & Kia



(3) P2 system of Hyundai & Kia

Fig 7 illustrates a P2 configuration developed by Korea OEM Hyundai and Kia [37]. The main difference between this design and typical P2 system is that the clutch between motor and engine is integrated inside the transmission box. This made a more compact package design but may cause some extra cost.

Cost Estimation

Base Cost Data

Much work has been done for vehicle fuel consumption reduction by former researchers. Direct manufacturing cost (DMC) studies aiming at full hybrid vehicle technologies including P2 and PS are made based on tear down research of a typical hybrid car by EPA and FEV Inc., whose results are set as base data of studies in this paper [28, 29, 38, 39, 40]. The incremental direct manufacturing costs are calculated based on 2010/2011 economics, high production volumes (450 K units/year), and mature market conditions. Each technology selected is evaluated against a baseline vehicle technology configuration representative of the current state of vehicle design and similar overall driving performance.

Then, the cost results across the diverse light-duty vehicle fleet are obtained by considering the application of the hybrid technologies in six vehicle size classes. Though no costing was performed for cases in which a technology is not generally considered applicable to a vehicle class. The vehicle size classes are: subcompact; compact or small car; small to mid-size; mid-size car; mid to large size; large SUV.

To determine the increment DMC for applying hybrid technologies to other vehicle segments, a scaling methodology, utilizing the cost analysis done by tear down research as the foundation, was employed. Table 1 illustrates increment cost for applying the P2 technology to the six different vehicles size classes as an example [28]. Note that only system level costs are listed. Actually more subsystems and components are investigated, the system cost is a final roll up of all the data. In addition, it must be cleared out that the hybrid vehicle types of those vehicle segments listed in Table 1 are not really exist, this data is also an estimation done by FEV based on the data obtained in their tear down research.

Finally the data is used for the estimation of China market. Although the market conditions are different in China or US, the base data is still mostly in common. The data is firstly obtained by tear down research of FEV Inc. In their research, the cost of a new HEV technology is consist of material, labor, end item scrap, packaging, profit, manufacturing overhead and so on. For a technology using same structure and material, the core cost elements are similar in different regions. Some further studies [27, 29, 39] in US are done referring to the tear down research, although it is done by an European institute. Thus the estimation of HEV cost in China using the base data is also reliable to find its tendency.

Cost Estimation for Any Hybrid Cars

Work done by EPA/NHTSA and FEV Inc. is thorough and of high caliber. However, results given by them only focus on the six prototypes. Considering the hybrid cars are different in many characteristics such as DOH, curb weight, ICE power, it is not capable if one wants to refer the cost for some other vehicles. By further extending the basic methodologies they have used, a cost estimation for any hybrid vehicles can be obtained.

The scaling methodology used by FEV to obtain the cost of different vehicle size classes can be described briefly as follow: First, the primary base components must be established. Then, component costs within each system/subsystem is developed using cost-to-component-size ratios (CR). The CR is obtained both by considering key factors that influences the component cost. These key factors includes both the primary characteristics (e.g., traction motor power, battery capacity) and vehicle segment attributes (e.g. curb weight, passenger volume) [28].

Thus, basing on the data and calculation process provided by FEV, we can calculate each component cost of a particular hybrid car separately, then roll the costs up to obtain the system/subsystem and all the way to total cost of vehicle segment. In this way, we presented a cost estimation for any hybrid cars based on the studied of EPA and FEV. Note that for each hybrid vehicle using same technology (e.g. the BMW Active Hybrid 3 and Infiniti QX60 Hybrid both applied the PS architecture, while the components could not be all the same),

TABLE 1 Base data: increment cost for applying P2 to six vehicle classes [28]

Description	Subcompact	Compact or small	Small to mid-size	Mid-size	Mid to Large size	Large SUV
Curb Weight/kg	1082	1269	1494	1591	1698	2204
System Power/kw	74.7	90	117	132.6	174.8	271.8
ICE Power/kw	59.8	72	93.6	106.1	139.9	271.8
Traction motor Power/kw	14.9	18	23.4	26.5	35	54.3
High Volt Battery/V	140	162	188	199	211	269
High Volt Battery Capacity/kWh	0.743	0.857	0.994	1.053	1.118	1.427
ICE System/RMB	−1006.4	−451.4	−451.4	−451.4	−2841.6	0
Transmission System/RMB	4203.2	4440	4750.8	4958	5372.4	6497.2
Body System/RMB	44.4	44.4	44.4	37	44.4	44.4
Brake System/RMB	1206.2	1235.8	1265.4	1272.8	1287.6	1354.2
Climate Control System/RMB	1021.2	1065.6	1124.8	1184	1154.4	1361.6
Electric Power Supply System/RMB	6038.4	6719.2	7525.8	7866.2	8206.6	9953
Power Distribution and Control System/RMB	1095.2	1124.8	1147	1139.6	1176.6	1184
Net Incremental DMC/RMB	12609.6	14171	15392	16013.6	14407.8	20394.4

the systems and components still show some differences. So this cost estimation is a roughly result. Basing on the roughly results, some tendencies in full hybrid vehicle technologies could still be found, which is the main purpose of our research.

Components and Cost Influence Factors First, the cost influence factors for each component must be defined for obtaining CR used in component cost study. As mentioned above, the primary characteristics and vehicle segment attributes are considered as key factors for cost scaling. Table 2 partially lists the key factors and corresponding components. Some of the factors are derived from the FEV research if there is mentioned, others are obtained based on the characteristics and application of each component. The key factors were checked using the data derived from six given segments to ensure the validity.

Linear Fitting of Cost Data After key factors of each component is decide, the scale factor must be determined. This is done by linear fitting of base data. Component cost of all six vehicle segments can be obtained in base data. As for the key factors needed, investigations for the six vehicles listed in Table 1 are processed. Major parameters such as curb weight, passenger volume, engine power are obtained. Some of the key factors including motor power, battery capacity can be obtained in base data.

A linear fitting between the key factor and component cost is processed to obtain the scale factor of each component. Then cost of any parameter can be easily found. As the battery cost shown in Fig. 8 as an example. In this figure, the cost of battery capacity range within 0.6-1.5 kWh can be easily found (e.g. cost of battery with capacity 1.0 kWh is approximate €1050).

Linear fitting is used here because R^2 value is higher than 0.95, some are even higher than 0.99.

Determining Factors Values When applying the cost estimation to a conventional vehicle, most factors are the basic parameters or segment attribute of a certain vehicle which are easy to get. However, some parameters are not defined directly. These parameters are battery capacity and high voltage value.

TABLE 2 Key factor list

Key factor	Corresponding component (partial list)
Total power	Integrated Electric Motor/Generator and Clutch Assembly System
	Oil Pump and Filter Subsystem
Motor power	Traction Motor/Generator Subsystem
	Electric Motor/Generator & Clutch Cooling Subsystem
Battery capacity	High Voltage Traction Battery Subsystem
	Battery Cells & Cell Modules
High voltage	Battery Cooling Module Hardware
	Power Distribution and Control System
Curb mass	Brake System
	Service Battery Subsystem
Passenger volume	Climate Control System

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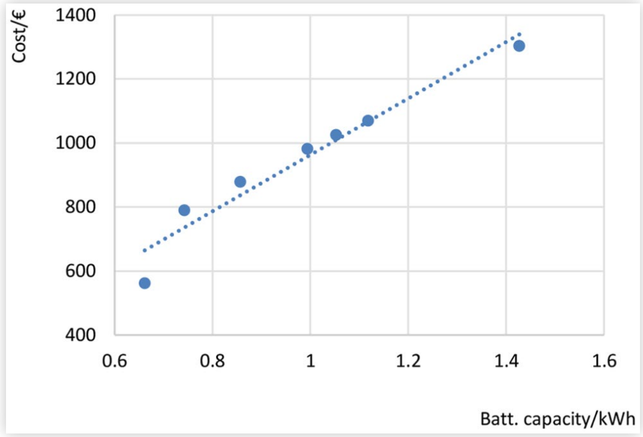
FIGURE 8 Battery cost fitting



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In calculation battery capacity, an empirical formula is applied. For hybrid vehicle design, the battery capacity could be estimated by 0.276 Wh/lb (that is 0.67 Wh/kg) [28].

As for high voltage value, it is calculated by battery capacity/5.5 Ah [28]. Because the current density in a vehicle power supply system is normally 5.5 Ah.

HEV Effectiveness Study

To investigate the FC reduction effect of hybrid vehicles, we collected data of 30 hybrid cars that are displayed in the announcement of Ministry of Industry and Information Technology (MIIT) of China. Actually there are more than 150 hybrid cars announced by MIIT since 2012. However, for the same vehicle type, OEMs would launch some new prototypes each period of time. In this case, old types are not as valuable as new ones. Sometimes many different versions of same car would be released, among which investigation of only one version is already enough. Filter the data of MIIT, we finally found the 30 different types of hybrid cars in China market. After obtaining the 30 car types, we further collected parameters of curb weight, engine power, traction motor power, fuel consumption value, and values of benchmarking cars. Actually when developing a hybrid car, OEMs usually add some other FC reduction technologies to the HEV version, thus the deviation of FC reduction data is inevitable. The selection of benchmarking car tried to reduce the influence of other technologies as possible.

The benchmarking models are also selected carefully. Some HEV models directly correspond with ICE models, namely, one model is divided into ICE version and HEV version, while some HEV models are developed without direct corresponding to ICE models. For the first case, ICE models can be directly selected as the benchmarking. For the second case, the models in the same car-series or designed in same platform can be selected for benchmarking. We select a benchmarking model considered similar major information such as curb weight, engine type and transmission type to ensure the accuracy of benchmarking.

A study on HEV effectiveness is done based on the data collected. Fig 9 shows the FC reduction distribution of HEV cars. There are two singular points which are marked in the

FIGURE 9 FC reduction distribution of HEVs

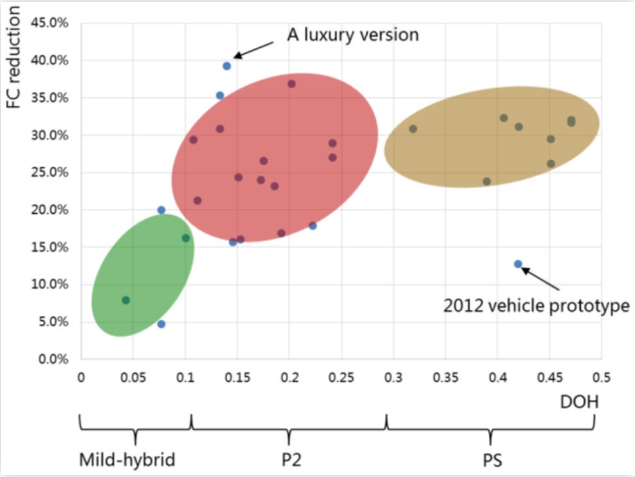

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figure. One of them is a luxury version that showed a significant effective FC reduction with its high FC benchmarking car. The other one is a 2012 former hybrid type, which shows rather low FC effectiveness with high DOH because hybrid technology of the very OEM was under developing in 2012.

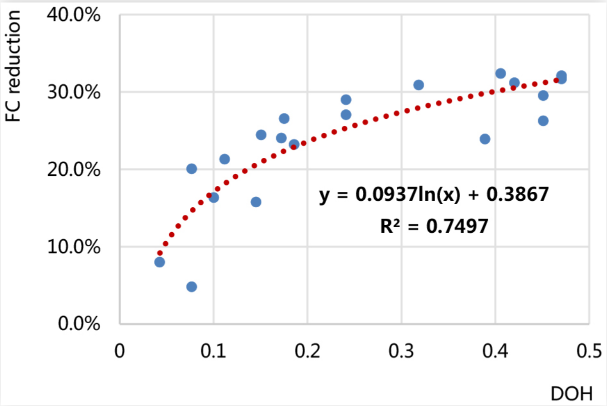
It can be figured out in Fig 9 that, the HEV architectures showed clear boundaries in the dimension of DOH, with ellipses as arbitrary demarcation lines. Yet the increment of FC reduction does not increase as fast as DOH does. In a mild hybrid car, the DOH is usually under 0.1, achieving an approximate 10% FC reduction. The P2 architecture takes place in DOH between 0.1 and 0.3, with a FC reduction of approximate 25% achieved. The PS is applied when DOH is more than 0.3, could bring a 30% FC reduction.

A logarithmic relation between FC reduction and degree of DOH is given as follow based on the study of 30 different hybrid cars.

$$Y = 0.0937\ln(x) + 0.3867 \tag{1}$$

Where Y is the FC reduction, x is DOH level of a certain hybrid car. The fitting is curved in Fig 10. Note that in Fig 10 there are less points than those in Fig 9. Actually 10 scatter points are filtered to obtain a better result. Among the 10 points: the 2 singular points are described above; the other 8 point are all scatter point of P2 architecture. 4 of the 8 points are all from the OEM Honda Co., and they all show better FC reduction effectiveness. This is cause by the additional technologies and advanced motor systems of Honda Co. While the other 4 points scattered in a low direction. That is because the FC of benchmarking cars of these HEVs are already low enough. Thus those 10 points are removed to obtain a more objective result.

FIGURE 10 Logarithmic relation between FC reduction and DOH



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Case Study: A Typical Car Fleet to Meet 2020 China FC Regulation

Phase IV FC Regulation in China

The world energy and environment statues pushes major countries to launch more strict FC regulations [41]. In this paper, the case of FC regulation in China is considered. China has applied a weight-class based per vehicle regulation structure. The final FC is calculated by corporate average value. The current phase III regulation was published to restrict car FC from 2015. Currently the phase III FC regulation specifies the average FC limit as 6.9 L/100 km at NEDC condition. This value would decrease to 5.0 L/100 km in 2020, phase IV, with 28% decrement. Besides, to promote the development of new energy vehicles like plug-in hybrid vehicle (PHEV) and electric vehicle (EV), China also introduced an NEV credit policy. With this policy, corporations could get benefit in corporate average FC value by selling new energy vehicles.

The phase IV regulation also applied a weight-class based per vehicle regulation structure. The 2020 new regulation will be substituted by new regulation in 2025, which is not fully constituted. Besides the average FC consumption, The FC reduction demand in phase IV regulation is not same with different vehicle segments. As shown in Fig.11, new FC regulation is stricter to heavier vehicles. Cars with 2600 kg curb

FIGURE 11 Current and future FC regulation of China [42, 43]

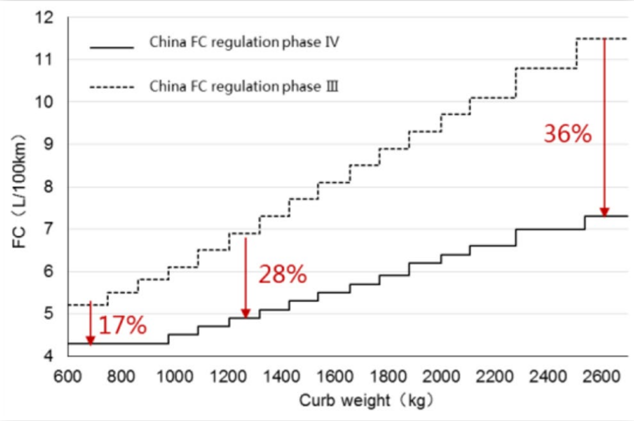

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TABLE 3 Car fleet of a typical Chinese OEM

Car type	Curb weight/kg	ICE power/kW	FC/L/ 100 km	Target FC/ L/100 km	Price/ RMB
A1	1091	85	5.6	4.7	50000
A2	1139	85	6.1	4.7	60000
A3	1270	78	5.9	4.9	50000
A4	1365	85	7.3	5.1	90000
A5	1410	110	7.3	4.1	90000
A6	1665	150	8.8	5.7	230000
A7	1800	150	8.9	5.9	140000
A8	1900	150	10.7	6.2	150000
A9	2020	184	10	6.6	160000
A10	2295	184	11.2	7.0	280000
A11	2350	120	9.6	7.0	300000
A12	2590	310	11.9	7.3	500000

mass will need a 36% FC reduction, comparing with the average 28% decrement and 17% decrement for small cars.

Car Fleet Selection

A car fleet covers vehicle segment from subcompacts to large SUVs is selected. These cars are all from a same Chinese OEM, and gasoline engine powered. Major parameters for the car fleet is shown in Table 3. These parameters are obtained by checking the local automotive selling websites. The price may vary in a wide interval, the average value in used in this paper. Most of the FC value listed could only just meet the current FC regulation, while for the phase IV scenario there is still a big margin. The hybrid technologies are potential options for meeting the future FC regulation demand especially for those heavier cars. The cost of hybridization of the selected car fleet should be analyzed as a reference for OEMs' technology rout decisions.

Non-electrification Technologies

To meet the strict FC regulation, non-electrification technologies are to be applied besides the hybrid technologies. Table 4 lists the most possible technologies that would be applied in recent years according to the research done by NHTSA/EPA and NRC. Technologies that apply in engine, transmission, mass reduction, aerodynamics, rolling resistance are considered. With application of these technologies, an approximate 19.1% FC reduction is expected [27], which is not enough for reaching phase IV FC Regulation in China. As to a particular OEM, this value may fluctuate depending on the technology applications. Here a conservation estimation of 15% FC reduction is made for the non-electrification technologies.

Cost Estimation and Results

TABLE 4 Non-electrification technologies [27]

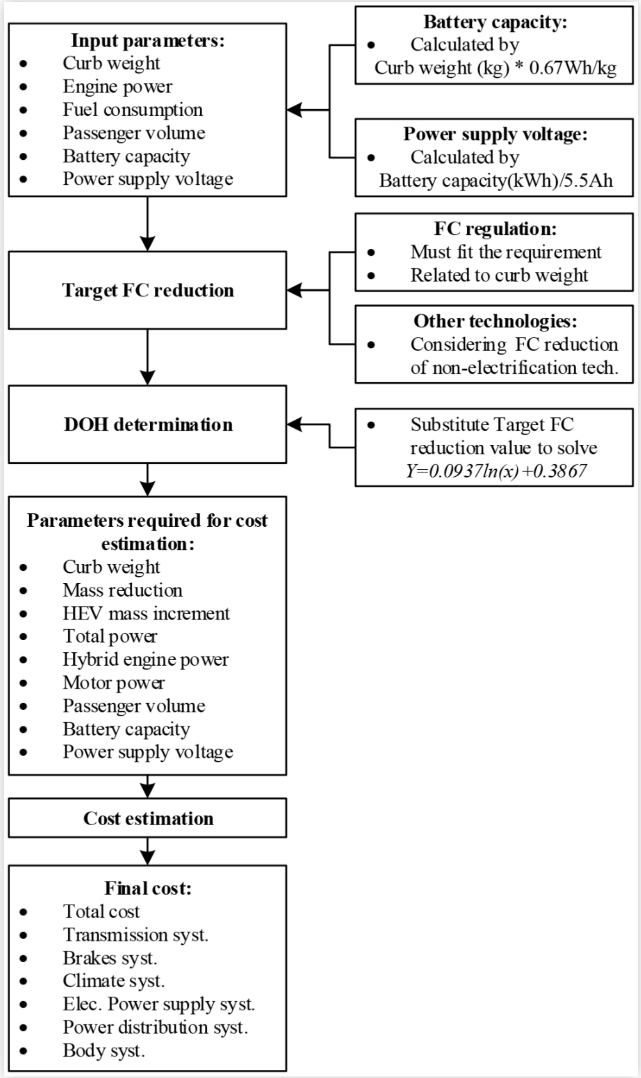
Tech. sector	Technology	FC reduction (%)	Domain total FC reduction (%)	Total FC reduction (%)
Engine	Variable valve timing: intake cam phasing	2.5-2.7	8.2	19.1
	Variable valve timing: dual cam phasing	2.4-2.7		
	Low friction lubricants	0.7-0.8		
	Engine friction reduction	2.4-2.6		
Transmission	Oil supply: low leakage valves	0.3	2.3	
	Oil supply: variable displacement pump	1		
	Drag losses	0.1		
Low resistance	Lower aerodynamic resistance 10%	2	3	
	Lower rolling resistance 10%	1-2		
Mass reduction	Mass reduction 10%	6-7	7	

With all parameters ready, cost estimation for a single car hybridization is processed as shown in Fig 12. Calculate all the cars in the fleet to obtain a set of cost values as shown in Table 5. In the calculation, the 10% mass reduction mentioned in Table 4 is considered. With hybridization technologies applied to vehicles, a 8% mass increment is assumpted [44].

It can be seen from Table 5 that in the case of smaller cars, the cost increment applying P2 or PS full hybrid system is relatively high. The car types coded as A1, A2, A3 even showed an increment more than 20%. While with the car goes heavier, the increment cost takes smaller proportion of the total cost. In A10, A11, A12, the cost increments are lower than 10%.

Actually the results in Table 5 did not consider the relationship between hybrid architectures and DOH. For example the P2 or PS systems are clearly not the optimum selections for car type A1, because the DOH of A1 is only set as 0.018454. According to the analysis of Fig 9, for those with a DOH lower than 0.1, it is suggested that a mild hybrid system such as Belt-driven Starter Generator system (BSG) is applied. For those with DOH between 0.1 and 0.3, a P2 system is suggested. Those with DOH higher than 0.3, PS system is suggested. A rearrangement for hybridization of the car fleet is shown in Table 6. The cost of BSG system is according to the tear down research done by FEV Inc.[38]. Cost for BSG is relatively low because there are less components needed and less reconfiguration of the original powertrain in a BSG system. Note that A11 applied P2 system with DOH of 0.073545. Because the engine power for original prototype is already 120 kW, the motor used in hybrid version would be easily beyond 10 kW if there is slightly more power demand. Thus a P2 system is selected in this car prototype.

FIGURE 12 Calculation flowchart for hybridization cost estimation



As for the car fleet selected, the P2 technology covers more car types. 7 out of 12 cars could apply P2 system to meet the phase IV FC regulation. While the PS system fits only 2 car types. As for BSG system, it is used in small cars. This may indicate a future hybrid technology distribution: BSG system applies in small cars; P2 system is spread in almost all car types; PS is for those with difficulty to meet future FC regulation.

Note that FC regulations are sale-based, and are fleet average standards. On one hand, OEMs do not need to make each car model to meet the target, and they can optimally select certain models to have better fuel economies than the target, while others could have worse fuel economies. Based on the modeling results from the study, it is important to understand which car model to be hybridized for minimizing the compliance costs for OEMs. On the other hand, the sale-based regulation means that consumer choices are important [45]. The hybridization cost as well as performance changes may affect consumer choices, and how that will affect the sale is an important research question.

Conclusion

In this paper, the configuration, cost, effectiveness of major full hybrid electric vehicle technologies are studied. Based on the configuration study of major HEV OEMs, a classification of PS and P2 for full hybrid is made. A cost estimation for PS and P2 system applying in any vehicle type is presented. 30 hybrid cars are selected from the MIIT of China announcement list for HEV technology FC reduction effectiveness study. The logarithmic relationship between FC and DOH is given, representing the less improvement of FC reduction with DOH increases. Finally, the hybridization cost for a typical car fleet from same OEM to meet the China 2020 FC regulation is given and analyzed by combining the cost study and FC&DOH relationship.

Finally, there are two directions for further study. 1) To obtain further cost of HEV technologies more precisely. The

TABLE 5 Cost estimation for typical car fleet

			P2		PS	
Car type	DOH	Cost/RMB	Cost Increment/ RMB	Increment Proportion (%)	Cost Increment/ RMB	Increment Proportion (%)
A1	0.018454	50000	12710.81	25.4	13591.73	27.2
A2	0.043774	60000	12930.62	21.6	13761.72	22.9
A3	0.020604	50000	13274.72	26.5	14119.24	28.2
A4	0.107911	90000	13944.33	15.5	14562.06	16.2
A5	0.107911	90000	14287.50	15.9	15101.39	16.8
A6	0.204472	230000	16511.55	7.2	16612.38	7.2
A7	0.16896	140000	16675.16	11.9	17090.46	12.2
A8	0.481949	150000	19947.57	13.3	21567.01	14.4
A9	0.225305	160000	18369.42	11.5	18386.31	11.5
A10	0.271997	280000	20382.78	7.3	21012.53	7.5
A11	0.073545	300000	17445.43	5.8	18582.22	6.2
A12	0.314463	500000	22582.18	4.5	22639.73	4.5

TABLE 6 Rearrangement of cost data

		Cost Increment/RMB		
Car type	DOH	P2	PS	BSG
A1	0.018454	-	-	3054.21
A2	0.043774	-	-	3054.21
A3	0.020604	-	-	3054.21
A4	0.107911	13944.33	-	-
A5	0.107911	14287.50	-	-
A6	0.204472	16511.55	-	-
A7	0.16896	16675.16	-	-
A8	0.481949	-	21567.01	-
A9	0.225305	18369.42	-	-
A10	0.271997	20382.78	-	-
A11	0.073545	17445.43	-	-
A12	0.314463	-	22639.73	-

cost would be different for same technology considering different production volume, application time, and application zone (e.g. cost of same technology are not the same in Europe or Asia). 2) Considering the consumer choices, investigating how the hybridization cost as well as performance changes may affect consumer choices and the sales volume.

References

1. Nordelöf, A., Messagie, M., Tillman, A.-M., and Söderman, M.L., "Environmental Impacts of Hybrid, Plug-in Hybrid, and Battery Electric Vehicles-What Can we Learn From Life Cycle Assessment?" *The International Journal of Life Cycle Assessment 19* 11:1866-1890, 2014.
2. Lo, Kevin. "A Critical Review of China's Rapidly Developing Renewable Energy and Energy Efficiency Policies." *Renewable and Sustainable Energy Reviews* 29 (2014): 508-16.
3. Gao, Guangkuo, Shuai Chen, and Jiameng Yang. "Carbon Emission Allocation Standards in China: A Case Study of Shanghai City." *Energy Strategy Reviews* 7 (2015): 55-62.
4. Hannan, M.A., Azidin, F.A., and Mohamed, A., "Hybrid Electric Vehicles and their Challenges: A Review," *Renewable and Sustainable Energy Reviews* 29:135-150, 2014.
5. Williamson, S.S., "*Energy Management Strategies for Electric and Plug-in Hybrid Electric Vehicles*," (New York, Springer, 2013).
6. Finesso, R., Spessa, E., and Venditti, M., "Robust Equivalent Consumption-Based Controllers for a Dual-Mode Diesel Parallel Hev," *Energy Conversion and Management* 127:124-139, 2016.
7. Shi, D., Pisu, P., Chen, L., and Wang, S., "Control Design and Fuel Economy Investigation of Power Split Hev with Energy Regeneration of Suspension," *Applied Energy* 182:576-589, 2016.
8. Du, J., Yang, F., Cai, Y., and Lei, D., "Testing and Analysis of the Control Strategy of Honda Accord Plug-in Hev," *IFAC-PapersOnLine* 49(11):153-159, 2016.
9. Montazeri-Gh, M. and Mahmoodi-k, M., "Development a New Power Management Strategy for Power Split Hybrid Electric Vehicles," *Transportation Research Part D: Transport and Environment* 37:79-96, 2015.
10. Dimitrova, Z. and Maréchal, F., "Techno-Economic Design of Hybrid Electric Vehicles and Possibilities of the Multi-Objective Optimization Structure," *Applied Energy* 161:746-759, 2016.
11. Shi, D., Pisu, P., Chen, L., and Wang, S., "Control Design and Fuel Economy Investigation of Power Split Hev with Energy Regeneration of Suspension," *Applied Energy* 182:576-589, 2016.
12. Lave, L.B. and MacLean, H.L., "An Environmental-Economic Evaluation of Hybrid Electric Vehicles: Toyota's Prius Vs. Its Conventional Internal Combustion Engine Corolla," *Transportation Research Part D: Transport and Environment* 7(2):155-162, 2002.
13. Montazeri-Gh, M. and Mahmoodi-k, M., "Development a New Power Management Strategy for Power Split Hybrid Electric Vehicles," *Transportation Research Part D: Transport and Environment* 37:79-96, 2015.
14. Cummings, T., Bradley, T.H., and Asher, Z.D., "The Effect of Trip Preview Prediction Signal Quality On Hybrid Vehicle Fuel Economy," *IFAC-PapersOnLine* 48(15):271-276, 2015.
15. Finesso, R., Spessa, E., and Venditti, M., "Robust Equivalent Consumption-Based Controllers for a Dual-Mode Diesel Parallel Hev," *Energy Conversion and Management* 127:124-139, 2016.
16. Li, L., Wang, X., Xiong, R., and He, K., "Amt Downshifting Strategy Design of Hev During Regenerative Braking Process for Energy Conservation," *Applied Energy* 183:914-925, 2016.
17. Morais, H., Sousa, T., Soares, J., and Faria, P., "Distributed Energy Resources Management Using Plug-in Hybrid Electric Vehicles as a Fuel-Shifting Demand Response Resource," *Energy Conversion and Management* 97:78-93, 2015.
18. Chen, F., Taylor, N., and Kringos, N., "Electrification of Roads: Opportunities and Challenges," *Applied Energy* 150:109-119, 2015.
19. Seixas, J., Simões, S., Dias, L., and Kanudia, A., "Assessing the Cost-Effectiveness of Electric Vehicles in European Countries Using Integrated Modeling," *Energy Policy* 80:165-176, 2015.
20. Muneer, T., Milligan, R., Smith, I., and Doyle, A., "Energetic, Environmental and Economic Performance of Electric Vehicles: Experimental Evaluation," *Transportation Research Part D: Transport and Environment* 35:40-61, 2015.
21. Polzin, Friedemann, Michael Migendt, Florian A. Täube, and Paschen von Flotow. "Public Policy Influence On Renewable Energy Investments-a Panel Data Study Across Oecd Countries." *Energy Policy* 80 (2015): 98-111.
22. Wu, G., Inderbitzin, A., and Bening, C., "Total Cost of Ownership of Electric Vehicles Compared to Conventional Vehicles: A Probabilistic Analysis and Projection Across Market Segments," *Energy Policy* 80:196-214, 2015.
23. Bishop, J.D.K., Martin, N.P.D., and Boies, A.M., "Cost-Effectiveness of Alternative Powertrains for Reduced Energy Use and Co2 Emissions in Passenger Vehicles," *Applied Energy* 124:44-61, 2014.
24. Haq, G., Martini, G., and Mellios, G., "Cost Effectiveness of Introducing a New European Evaporative Emissions Test Procedure for Petrol Vehicles," *Atmospheric Environment* 95:537-543, 2014.
25. Roy, R., Souchoroukov, P., and Shehab, E., "Detailed Cost Estimating in the Automotive Industry: Data and Information Requirements," *International Journal of Production Economics* 133(2):694-707, 2011.

26. Rogozhin, A., Gallaher, M., Helfand, G., and McManus, W., "Using Indirect Cost Multipliers to Estimate the Total Cost of Adding New Technology in the Automobile Industry," *International Journal of Production Economics* 124(2):360-368, 2010.
27. National Research Council. "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles." NRC report, 2015.
28. FEV Motorentechnik GmbH. "Light-Duty Vehicle Technology Cost Analysis - European Vehicle Market (Phase 1)." FEV report 10-449-001, 2012.
29. Environment Protection Agency. "Light Duty Technology Cost Analysis, Power-Split and P2 Hev Case Studies." EPA, 2011.
30. Arata, J., Leamy, M.J., Meisel, J., and Cunefare, K., "Backward-Looking Simulation of the Toyota Prius and General Motors Two-Mode Power-Split Hev Powertrains," *Sae International Journal of Engines*, 2011, doi:10.4271/2011-01-0948.
31. Yamada, T., Haga, H., Matsumoto, I., and Tomoda, T., "Study of Diesel Engine System for Hybrid Vehicles," *Sae International Journal of Alternative Power*, 2011, doi:10.4271/2011-01-2021.
32. Phillips, A.M., Mcgee, R.A., Lockwood, J.T., and Spiteri, R.A., "Control System Development for the Dual Drive Hybrid System," *Sae International Journal of Engines*, 2009, doi:https://doi.org/10.4271/2009-01-0231.
33. Zhao, Y., Srinivasaiah, S., Yan, Z., and Chen, Y., "Vehicle System Control Software Validation for the Dual Drive Hybrid Powertrain," *Sae International Journal of Engines*, 2009, doi:10.4271/2009-01-0736.
34. John, Miller, and Everett Michael. "An Assessment of Ultra-Capacitors as the Power Cache in Toyota Ths-11, Gm-Allision Ahs-2 and Ford Fhs Hybrid Propulsion Systems." In *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition*, 481-90, 2005.
35. Griebel, C. O., DIF Rabenstein, DI Manfred, and Klüting. "The Full-Hybrid Powertrain of the New Bmw Activehybrid 5." In Aachen Colloquium Automobile and Engine Technology 2011, 2011.
36. Hanada, K., "Development of a Hybrid System for the V6 Midsize Sedan," *Sae Transactions*, 2005, doi:10.4271/2005-01-0274.
37. Shin, S., Oh, J., Kim, J.C., and Hong, S.W., "A Method of Gear-Shift in Parallel Hybrid Electric Vehicle Using Motor Control," *Sae World Congress & Exhibition*, 2010, doi:https://doi.org/10.4271/2010-01-1305.
38. FEV Motorentechnik GmbH. "Light-Duty Vehicle Technology Cost Analysis - European Vehicle Market, Additional Case Studies (Phase 2).", FEV report 11-63-001, 2012.
39. EPA. "Joint Technical Support Document:Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards." (2012).
40. EPA. "Light-Duty Vehicle Technology Cost Analysis, Mild Hybrid and Valvetrain Technology.", 2011.
41. Atabani, A.E., Badruddin, I.A., Mekhilef, S., and Silitonga, A.S., "A Review On Global Fuel Economy Standards, Labels and Technologies in the Transportation Sector," *Renewable and Sustainable Energy Reviews* 15(9):4586-4610, 2011.
42. Standardization Administration of PRC. "Fuel Consumption Limits for Passenger Cars." China GB Standard GB 1578-2014. 2014.
43. Standardization Administration of PRC. "Fuel Consumption Evaluation Methods and Targets for Passenger Cars." China GB Standard GB 2799-2014. 2014.
44. Ernst C S, Olschewski I, Eckstein L. CO2 Reduction Potentials for Passenger Cars until 2020. IKA report 113510, 2013.
45. Fei, X. and Zhenhong, L., "Market-Driven Automotive Industry Compliance with Fuel Economy and Greenhouse Gas Standards: Analysis Based on Consumer Choice," *Energy Policy* 108:299-311, 2017.

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