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Analytical Study on the Fuel-Saving Potentials of a Series Hybrid Electric Vehicle

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Abstract

The fuel-saving potential of a series hybrid electric vehicle (SHEV) was investigated in this work based on the future goals and technical roadmaps proposed by China's automobile and internal combustion engine (ICE) industry. The genetic algorithm optimization method and dynamic programming energy management strategy are used to optimize the key component parameters of a typical SHEV SUV to improve the fuel economy of the vehicle. Results showed that the fuel consumption of the vehicle would be 3.24 L / 100km in 2035, which is 37.21% less than 5.16 L / 100km in 2020, following the industries' roadmaps. The results also indicated that the improvement of the ICE's thermal efficiency is the main reason for the decrease of the vehicle's fuel consumption. In addition, the improvement of working points and the reduction of energy losses of the key components also contribute to the improvement of the fuel economy.

1. Introduction

The dual carbon targets put forward by the government of China has accelerated the pace of carbon emission reduction in China's automobile industry. Major automobile companies are vigorously researching and developing new energy vehicles. However, due to the limitations of battery technology and charging infrastructure, it is difficult for new energy vehicles to be widely used in a short time. In view of this, hybrid electric vehicles (HEVs) have become the ideal technology for the transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) due to their advantages of both ICEVs and EVs. Among them, SHEVs has achieved good performance in the automobile market because of their simple structure and high efficiency, such as the Nissan Note e-POWER [1].

Research of automobile energy saving and emission reduction has always been the focus of the automobile industry, and hybrid vehicle is one of them [2]. A large number of studies show that the fuel consumption of HEVs depends not only on configurations [3], key component size [4], energy management strategies [5] and braking energy recovery [6], but also on driving cycles [7], driving styles [8] and even ambient temperature [9]. Therefore, it is necessary to investigate the fuel-saving potential or limit of HEVs. Considering the change of efficiency and weight of key components, this paper studies the fuel-saving potential of a typical SHEV SUV under the condition of the worldwide light-duty test cycle (WLTC). The impacts of energy management strategy are also considered. This research could provide a theoretical basis for the further development of SHEVs.

To fully tap the fuel-saving potential of SHEVs, it is necessary to optimize the key components sizing and energy management strategy at the same time [10]. It is also necessary to consider the performance improvement of key components. The performance milestone targets of the key components of SHEVs in 2020, 2025, 2030 and 2035 (2020-2035) are set based on the Energy Saving and New Energy Vehicle Technology Roadmap 2.0 (the Roadmap for short hereafter) [11] and the Plan for High Quality Development of the Internal Combustion Engine Industry (the Plan for short hereafter) [12] proposed in China. The genetic algorithm (GA) is utilized to optimize the key components sizing with the dynamic planning (DP) energy management strategy.

DP is adopted because it is the optimal method so that the effect of energy management strategies on fuel consumption can be eliminated, and hence the fuel saving potential can be fully reflected [13]. WLTC, which is a standard driving condition, not only eliminates the influence of driving behavior on fuel consumption, but the fuel consumption targets planned in China are also based on it. The multi-parameter optimization problem in the offline case can be solved well by the GA.

The rest of this paper is organized as follows: Section 2 describes the simulation models and economy multi-parameter optimization method. The results are then discussed in Section 3. The summary and conclusion are given in the last section.

2. Simulation Model

2.1. Vehicle Model

The research object is a typical SHEV SUV passenger car, and its key parameters are shown in Table 1. The SHEV's ICE is connected to the Integrated Starter and Generator (ISG) and supplies power for the battery or the traction motor (TM) through an electrical coupling. The decoupling between the ICE and the wheels can ensure that the ICE operates in a high-efficiency area, which is helpful to improve the fuel economy of the vehicle. The longitudinal dynamic model was used in this study.

The efficiency and other performances of the key components of the SHEV from 2020 to 2035 are assumed, based on the Roadmap and the Plan. The parameters are mainly shown in Table 2, and the reasons for setting these parameters will be introduced in the next section.

TABLE 2 Settings of the key components' parameters of the SHEV from 2020 to 2035.

Parameter\year	2020	2025	2030	2035
ICE efficiency (%)	40	45	50	55
ICE specific power (kW/kg)	0.8	0.9	0.95	1
ICE mass (kg)	100	90	85	80
Battery charge and discharge efficiency (%)	95/97.5	97.5	97.5	97.5
Battery specific energy (Wh/kg)	80	80	100	120
Battery mass (kg)	50	50	40	30
ISG efficiency (%)	97	99	99	99
ISG/TM specific power (kW/kg)	4	5	6	7
ISG mass (kg)	45	35	30	25
TM efficiency (%)	95	99	99	99
TM mass (kg)	60	50	40	35
Total mass of power components (kg)	255	225	195	170
Curb mass (kg)	1673	1643	1613	1588
Test mass (kg)	1829	1799	1769	1744
Full mass (kg)	2048	2018	1988	1963
Maximum climbing (%)	>35	>35	>35	>35
Maximum speed (km/h)	>160	>160	>160	>160
0-100 km/h acceleration time (s)	<10	<10	<10	<10

2.2. ICE Fuel Consumption Model

The ICE models mainly include the static graph model, static graph and lumped parameter dynamic model, mean value model, one-dimensional fluid dynamic model and three-dimensional fluid dynamic model. The former three methods are mainly used to study the complete system in vehicles or powertrains, while the latter two methods are mainly used to study the fundamental details of ICE subsystems. The fuel consumption of an ICE can be obtained by looking up the speed and torque tables in an ICE static map or map that is usually obtained from engine dyno experiments, which has the advantages of calculation speed and high precision. Because the present work focuses on the fuel economy of the vehicle, the physical part of the ICE model can be simplified by only considering its fuel consumption characteristics [14]. The static map model method was used in the ICE model.

TABLE 1 Specifications of the SHEV and its key components.

Vehicle & Component	Parameter	Value
Vehicle	Wheelbase (mm)	2700
	Frontal area (m^2)	2.66
	Drag coefficient	0.32
ICE	Displacement (L)	1.5
	Peak power (kW)	70
	Peak torque (Nm)	120
Battery	Battery capacity (kWh)	2
	Battery charge/discharge rate (C)	30/60
ISG	Peak power (kW)	88
	Peak torque (Nm)	220
TM	Peak power (kW)	124
	Peak torque (Nm)	330
Final drive	Ratio	8.28
	Efficiency (%)	99

The instantaneous fuel consumption of the ICE can be calculated by the following equation:

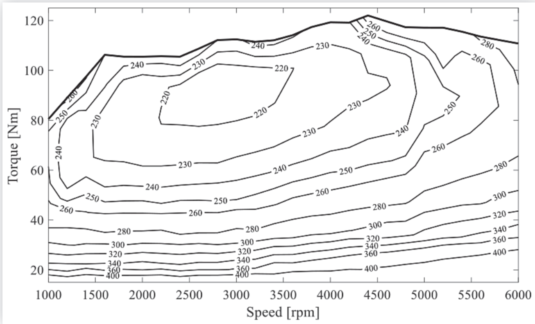
$$\dot{m}_f = f\left(T_e, n_e\right) \tag{1}$$

where, $\dot{m}_f$, T_e and n_e are the instantaneous fuel consumption, torque and speed of the ICE, respectively, and their corresponding relationship can be obtained from the Brake Specific Fuel Consumption (BSFC) map of the ICE.

The BSFC (g/kWh) map of the studied ICE in 2020 is shown in Figure 1 which has the max thermal efficiency of 40%. Since the BSFC maps of peak thermal efficiency higher than 40% are unavailable, this study used the weighted method to obtain the maps with the higher thermal efficiencies.

The peak thermal efficiency of an ICE is planned to reach more than 45% by 2025. Assuming one could obtain 45% efficiency with the current stoichiometric combustion technology, the BSFC map is thus similar to that of the base engine as shown in Figure 1. Beside the map in Figure 1, the other two BSFC maps of gasoline engines are also used in projecting the map for the 45%-peak efficiency engine. These two engines have the same displacement and similar wide-open throttle torque curves as those of the base engine. Three gasoline

FIGURE 1 BSFC map of the studied ICE with 40% thermal efficiency in 2020.



engines BSFC was used to project the BSFC for a 45% thermally efficient ICE in 2025. The process is as follows.

Step 1. The elliptical and quadratic curves in the three BSFC maps are extracted, and the corresponding algebraic and geometric parameters are obtained through curve fitting. Considering the length of the article, the extraction results of the other two BSFC maps are not repeated.

Step 2. The elliptical parameters and quadratic parameters of the engine with 45% efficiency were obtained by weighting the elliptical parameters and quadratic parameters of the three gasoline engines (in the sequence from the inside circle to the outside circle).

Step 3. The BSFC data of the 45% efficiency ICE were extracted and are plotted in Figure 3, based on the elliptical parameters and quadratic parameters obtained in Step 2.

Figure 2 shows the extracted elliptical and quadratic curves from the BSFC map as shown in Figure 1. Table 3 and Table 4 list the parameters of the elliptical and quadratic curves, respectively.

The weighting equation for the innermost elliptical xc parameter of the BSFC map with 45% efficiency is given as:

$$xc = \frac{\left(w_1 \cdot xc_1 + w_2 \cdot xc_2 + w_3 \cdot xc_3\right)}{\left(w_1 + w_2 + w_3\right)} \tag{2}$$

where the weighting factors of w_1, w_2 and w_3 are 6, 2 and 1, respectively.

FIGURE 2 Extraction of the elliptical and quadratic curves of the 40%-efficiency BSFC map.

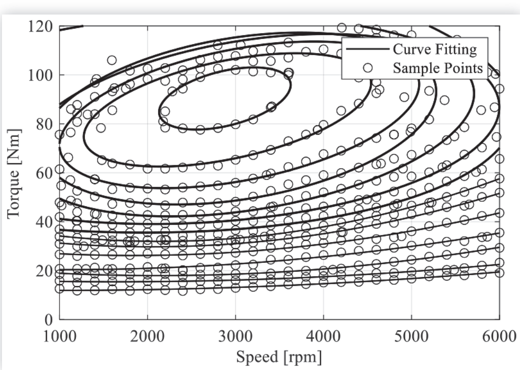


TABLE 3 Geometric parameters of the BSFC elliptical curves for the engine with 40% efficiency.

g/kWh	*xc*	*yc*	*a*	*b*	*Theta*
220	2878.97	90.36	747.5	11.42	0.43
230	2907.98	85.67	1632.44	20.39	0.38
240	3042.97	83.68	2043.62	27.23	0.35
250	3033.40	82.15	2246.76	33.35	0.28
260	3143.10	79.44	2567.40	34.97	0.29
270	2474.66	81.83	3522.82	42.46	0.08
280	1262.28	92.81	4905.76	56.67	-0.10

TABLE 4 Algebraic parameters of the BSFC quadratic curves for the engine with 40% efficiency.

g/kWh	x^2	*x*	*k*
290	1.72E-06	-7.34E-03	39.80
300	1.40E-06	-5.71E-03	35.57
310	1.15E-06	-4.45E-03	32.28
320	1.00E-06	-3.70E-03	29.59
330	8.44E-07	-2.75E-03	26.60
340	6.87E-07	-1.78E-03	23.54
350	6.14E-07	-1.31E-03	21.10
360	6.80E-07	-1.94E-03	21.07
370	7.49E-07	-2.66E-03	21.52
380	8.05E-07	-3.29E-03	21.86
390	7.68E-07	-3.26E-03	21.42
400	7.10E-07	-3.05E-03	20.72
…	…	…	…
500	2.98E-07	-5.81E-04	12.21

Similarly, *yc*, *a*, *c* and *theta* are weighted according to the above equation. Using the same approach, the elliptical parameters are weighted when the corresponding circles are all elliptical, and vice versa for the quadratic parameters.

The peak thermal efficiency of an ICE is planned to reach greater than 50% and 55% in 2030 and 2035, respectively, according to the Plan. Research works showed that lean burn technology is needed for a gasoline engine to achieve thermal efficiency of 50% and greater [15]. In this case, it is assumed that the engine's BSFC map has similar characteristics as those of the BSFC map of an automotive diesel engine which uses lean combustion. The 45%-efficiency BSFC map in Figure 3

FIGURE 3 BSFC map of the studied ICE with 45% thermal efficiency in 2025.

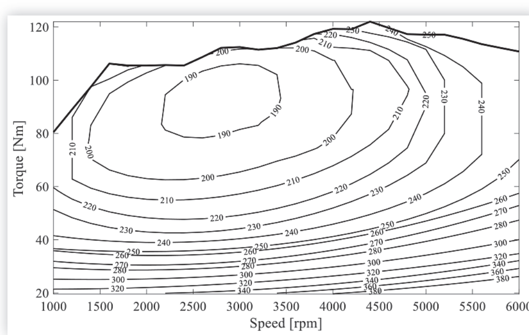
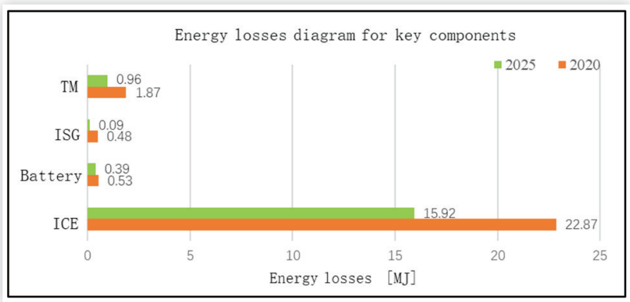


FIGURE 19 Energy losses of key components in 2020 and 2025.



are the main reason for the lower fuel consumption of the SHEV in 2025.

The ICE not only has a more concentrated distribution of working points in the highest efficiency area, but also the energy losses become less in 2025. The ISG is similar to the ICE. Although the TM's working points are not as concentrated as the ISG's, the increased efficiency of the TM contributes to the reduction in the energy losses. A reduction in battery energy losses is also seen which is related to the increased efficiency of the battery charging.

4. Summary and Conclusions

In this study, the fuel economy of a SHEV SUV was optimized in a multi-parameter manner under the WLTC conditions, based on the targets and technology development plans proposed by the automotive and ICE industries in China. considering the configurations and improvements of the key components' efficiencies are considered to explore the fuel-saving potential of the SHEV from 2020 to 2035. The main conclusions are as follows.

1. The fuel consumption of the SHEV under WLTC is calculated to be 5.16 L/100 km, 3.99 L/100 km, 3.66 L/100 km, and 3.24 L/100 km in 2020, 2025, 2030 and 2035, respectively, with a 37.21 % reduction in fuel consumption from 2020 to 2035.
2. If the performance of key components is improved as expected, the planned fuel-saving target of 2035 will be reached in 2025, and the fuel consumption value will exceed the planned fuel consumption target by 19% in 2035.
3. Thermal efficiency of the ICE is still the most important factor affecting the fuel economy of the SHEV. As the efficiency of the electric drive system approaches its theoretical limit, the fuel consumption of the SHEV is inversely proportional to the maximum thermal efficiency of the ICE.
4. After the optimization for the vehicle fuel economy, the SHEV tends to use a battery with smaller capacity (about 1.0 kWh).
5. The improvement of the performance of the key components not only results in the working points of key components more concentrated in the high-efficiency regions, but significant reductions of the energy losses of the key components. In addition, the multi-parameter optimization can reduce the energy losses. The largest reduction in quantity comes from the ICE, followed by the ISG, and the largest reduction in percentage is from the ISG, followed by the battery.

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Definitions/Abbreviations

HEV - Hybrid electric vehicle
ICE - Internal combustion engine
EV - electric vehicle
ICEV - Internal combustion engine vehicle
SHEV - Series hybrid electric vehicle
GA - genetic algorithm
DP - Dynamic planning
WLTC - Worldwide light-duty test cycle
ISG - Integrated Starter and Generator
TM - Traction motor
BSFC - Brake Specific Fuel Consumption

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