Research on PHEV comprehensive fuel consumption based on fuel-electricity conversion

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Abstract. In order to show the fuel-saving effect of Plug-in Hybrid Electric Vehicle (PHEV) [1]more intuitively, three conversion methods of fuel and electricity were introduced considering different aspects, namely conversion method of simple calorific value, comprehensive calorific value and carbon dioxide emission. Firstly, the energy consumption of two mainstream PHEVs according to the current domestic (China) energy consumption test regulation were tested [2], then the tested values were converted by the three conversion methods to get the equivalent fuel consumption. What's more, by the introduction of pure electricity Utilization Factor (UF) [3], the fuel consumption of PHEV at two stages (pure electric driving and pure fuel driving) were weighted to obtain the comprehensive fuel consumption. The effects of different conversion methods on fuel consumption were analyzed, and the results were compared horizontally with that of traditional fuel vehicles. The result shows that the comprehensive fuel consumption of PHEV converted by the method of carbon dioxide emission is the highest. Secondly, from the perspective of comprehensive calorific value, PHEV has obvious fuel-saving effect and a better development prospect comparing with traditional fuel vehicle. Last but not the least, PHEV has a significant fuel-saving advantage over traditional fuel vehicle in areas where the proportion of thermal power generation is relatively low, and with the continuous decrease of the overall proportion of thermal power generation, the fuel-saving effect of PHEV will become more and more obvious.

Abbreviations

PHEV	Plug-in Hybrid Electric Vehicle
UF	Utilization Factor

1 Introduction

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Fuel consumption has always been one of the most important indicators concerned by automobile consumers. For ordinary car users, the annual fuel expenditure accounts for about 40% of the total cost [4]. Meanwhile, more accurate comprehensive fuel consumption can more objectively reflect the energy consumption of vehicles. With the increasing support of the state for the development of new energy vehicles, Plug-in Hybrid Electric Vehicle (PHVE) has been witnessing a rapid development. Under the current energy consumption test regulations, the fuel consumption of PHEV is a value that weighted by the fuel consumption of pure electric driving stage and that of pure fuel driving stage, which is obviously lower than the fuel consumption of traditional fuel vehicles. Lower fuel consumption not only benefits individual consumers, but also reflects the national efforts and achievements in energy conservation and environmental protection.

The fuel consumption of PHEV is usually tested in the laboratory according to the current energy consumption testing regulations. The weighted fuel consumption is calculated according to equation 1 (no result correction included):

$$C = \frac{D_e \times c_1 + D_{av} \times c_2}{D_e + D_{av}} \tag{1}$$

C is fuel consumption/L•(100km) , c_1 is the fuel consumption under condition A(high charge state, which is at the pure electric driving stage) /L•$(100km)^{-1}$, c_2 is the fuel consumption under condition B(low charge state, which is at the pure fuel driving stage) /L •$(100km)^{-1}$, D_e is the distance of pure electric driving /km, D_{av} equals to 25km (the average mileage between two charges of an energy storage device assumed in the regulation).

Weighted fuel consumption is the weighted result of the fuel consumption under condition A and the fuel consumption under condition B. And with the increase of distance driven by pure electric, the proportion of condition A increases. For example, if the pure electric driving distance is 50km, the weight ratio of condition A to condition B is 2:1. The fuel consumption under condition A is 0, so the comprehensive fuel consumption is obviously reduced after weighted calculation.

The actual fuel consumption in use will be significantly different due to different driving habits, road conditions, distance, charging habits[5] and so on, which makes it difficult to measure the actual comprehensive fuel consumption of PHEV. In order to solve this problem better, the information about energy consumption of PHEV required in the current light vehicle energy consumption marking regulation[6] should include: weighted average of fuel consumption, fuel consumption at low charge state and equivalent fuel consumption of the weighted average of electricity consumption(1kW·h electricity equals approximately 0.113L gasoline). New cars sold in China must be labeled with the test fuel use level on the window [7].

Therefore, a variety of energy consumption results will appear on the energy consumption labels of PHEVs at the same time. In order to avoid confusion and understand the energy consumption of PHEV more clearly, two PHEV and two traditional fuel vehicles were selected for testing in this experiment. And three fuel-electricity conversion methods were used and then the energy consumption and fuel consumption were weighted by the appropriate pure electricity UF[8]. Finally, different reference results of PHEV's comprehensive fuel consumption were obtained. Different conversion methods represent different aspects of consideration. In order to judge the fuel-saving effect of PHEV comprehensively, this paper analyzed the influence of fuel-electricity conversion methods on the fuel consumption of PHEV, and horizontally compared fuel consumptions of PHEV and traditional fuel vehicle.

2 Energy consumption and fuel consumption test

2.1 Selection of sample cars

Two mainstream PHEVs and two traditional cars associated with them are selected for testing. There are obvious differences between traditional vehicle and PHEV in design, materials, driving form, equipment quality, energy utilization and power performance. At present, many PHEVs are new energy models based on whose traditional fuel models. And these new models have similarity on brand, appearance, space, comfort, handling and so on. In order to make a better horizontal comparison with traditional fuel vehicles. two mainstream PHEVs and their traditional fuel models (traditional fuel vehicles) were selected. The parameters of sample vehicles are shown in Table 1.

Table 1. Parameters of selected sample cars.

Vehicle serial number	Vehicle category	Curb weight /kg	displacement /L	Driving form
1-1	PHEV	2090	2	four-wheel drive
1-2	traditional fuel vehicle	1784	2	front drive
2-1	PHEV	1540	1.8	front drive
2-2	traditional fuel vehicle	1320	1.2	front drive

2.2 Test equipment and methods

The test was carried out in the Emission Laboratory of China Automotive Technology Research Center Co., Ltd. and in strict accordance with GB/T 19753-2013 "Light Hybrid Electric Vehicle Energy Consumption Test Method" and GB/T 19233-2008 "Light Vehicle Fuel Consumption Test Method". All the devices used are shown in Table 2. The test results are shown in tables 3 and 4.

Table 2. Test equipment parameters.

Chassis dynamometer	RODESIM 48”4*4 chassis dynamometer
Analyzer	MEXA-7200H/CVS-7400T vehicle emission test system
Electric energy testing equipment	HIOKI 3390

Table 3. Original test results of PHEV.

Vehicle serial number	1-1	2-1
Energy consumption under condition A E_A/Wh·km^{-1}	221.4	143.1
Fuel consumption under condition B FC_B/L·(100km)$^{-1}$	5.4	4.2
Weighted average of fuel consumption shown on car window FC_G/L·(100km)$^{-1}$	1.7	1.3
Carbon dioxide emission coefficient of gasoline φ_F/kg·L^{-1}	2.36	2.36
Pure electric driving distance D_E /km	55.9	55.2

Table 4. Original test results of traditional fuel vehicles.

Vehicle serial number	1-2	2-2
Fuel consumption FC /L·(100km) $^{-1}$	7.3	5.6

3 Conversion method of fuel and electricity

3.1 Introduction of pure electricity utilization factor UF

The Energy Consumption Test Method assumes that the average mileage between two charges of an energy storage device is 25km, but it is not clear how to obtain the value, so whether it can reflect the actual situation in China lacks basis.

In order to reasonably weight the fuel consumption of pure electric drive and pure fuel drive, it is necessary to determine the proportion of pure electric driving in daily travel, so as to determine the weighting coefficient. Therefore, the pure electricity utilization factor UF was introduced .

UF refers to the limited utilization of a specific initial mode of operation, and for PHEV, it indicates the degree of utilization of its CD mode (power consumption mode). [10] UF is fitted according to a large number of travel distance distribution data. At present, China, the United States and the European Union all have corresponding UF fitting curves, but how to obtain the value is not clear.

This paper referred the Gamma distribution [9] obtained by the research team of Tsinghua University on the daily travel distance of passenger cars in Beijing at the end of 2009. Its cumulative distribution function is shown as formula 2, and its cumulative distribution image is shown in figure 1:

$$UF(r) = \frac{27.87^{1.2}}{\Gamma(1.2)} \int_0^r t^{1.2} e^{-27.87t} dt \quad (2)$$

r is the daily travel distance /km.

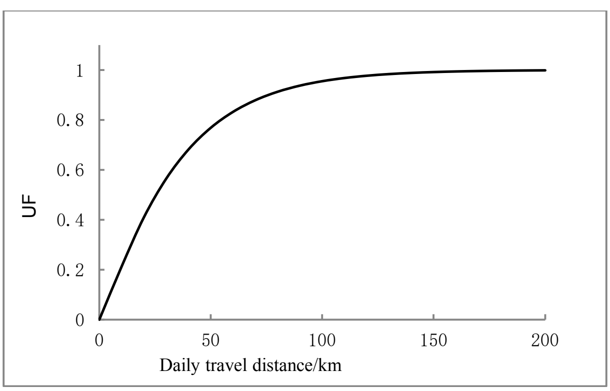

Fig. 1. Daily travel distance cumulative distribution.

PHEV should meet the following assumptions: the average charging frequency is once per day (each charge is fully charged), so that the distance between every two charges is the daily distance, and its distribution is consistent with the daily distance distribution.

The distance driven by pure electric of the two PHEVs selected was brought into formula 2 respectively to get their UF shown in Table 5.

Table 5. UF of sample cars.

Vehicle serial number	UF
1-1	0.81
2-1	0.8

3.2 Conversion method of simple calorific value

This method converts the electric energy consumption under condition A into the amount of fuel with the same calorific value.
The equivalent fuel consumption of electric energy was calculated according to formula 3:

$$FC_{A1} = \frac{E_A}{HV \times 10} \quad (3)$$

In the formula, FC_{A1} is the equivalent fuel consumption under condition A obtained by simple calorific value conversion /L•(100km) $^{-1}$; E_A is the power consumption under condition A /Wh•km^{-1}) ; HV is calorific value of gasoline, 8.92kWh•L^{-1}. [10]

The equivalent fuel consumption under condition A and the fuel consumption under condition B were weighted according to formula 4 to get comprehensive fuel consumption:

$$FC_1 = FC_{A1} \times UF + FC_B \times (1 - UF) \quad (4)$$

In the formula, FC_{A1} is the comprehensive fuel consumption calculated by simple calorific value/L•(100km) $^{-1}$; FC_B is the fuel consumption under condition B/ L•(100km) $^{-1}$; UF is utilization factor introduced above.

3.3 Conversion method of comprehensive calorific value

In this method, the electric energy consumption under condition A was converted into the energy consumed by the power plant, then the value was converted into fuel consumption with the same calorific value. And the equivalent fuel consumption of electric energy was calculated by considering the refinery efficiency and transportation efficiency.

The electric energy efficiency coefficient is the ratio of power generation energy consumption to vehicle energy consumption, which is calculated according to the formula 5 on the premise of considering power generation energy conversion efficiency and transmission energy loss.

$$\eta_E = \frac{1}{\eta_c \times (1-\eta_l)} \times \left[\frac{\varphi}{\eta_e} + (1-\varphi)\right] \quad (5)$$

η_E is the electric energy efficiency coefficient, and η_c is the charging efficiency (the ratio of the electric energy measured at the input of the charging device to that obtained on the power grid). η_l is the transmission loss rate: the percentage of the electricity loss in the process of power transmission and distribution; φ is the proportion of thermal power generation; η_e is the efficiency of energy processing and conversion (electric energy).

The reference values in the formula are shown in Table 6.

Table 6. The reference values in the formula 5.

Parameter	Value/%
η_l	6.4[11]
φ	72.23[12]
η_e	34.35[13]
η_c	1

Fuel efficiency coefficient is the product of direct energy conversion efficiency and transportation efficiency in gasoline production, and was calculated by formula 6:

$$\eta_o = \eta_g \times \eta_t \tag{6}$$

In the formula, η_o is the fuel efficiency coefficient, η_g is the direct energy conversion efficiency of gasoline production, and η_t is the gasoline transportation efficiency.

The reference values in the formula are shown in Table 7.

Table 7. The reference values in the formula 6.

Parameter	Value/%
η_g	83.36[14]
η_t	98.81[14]

The equivalent fuel consumption was calculated according to formula 7:

$$FC_{A2} = \frac{E_A \times \eta_E \times \eta_o}{HV \times 10} \tag{7}$$

In the formula, FC_{A2} is the equivalent fuel consumption under condition A, which is converted from comprehensive calorific value /L•(100km) -1.

Comprehensive fuel consumption was calculated according to formula 8:

$$FC_2 = FC_{A2} \times UF + FC_B \times (1 - UF) \tag{8}$$

where FC_2 is the comprehensive fuel consumption calculated by comprehensive calorific value /L•(100km) $^{-1}$.

3.4 Conversion method of carbon dioxide emission

This method uses the fuel coal carbon emission coefficient to convert the electric energy consumption under condition A into carbon emissions of thermal power generation, which then is converted to gasoline production. Taken into account the fuel transportation efficiency, the equivalent fuel consumption of electric energy is calculated.

The generating capacity of thermal power plant was calculated according to formula 9.:

$$E_g = \frac{E_A \times \varphi}{\eta_c \times (1 - \eta_l)} \tag{9}$$

In the formula, E_g is the generating capacity of a thermal power plant /W•h.

The standard coal consumption was calculated according to formula 10:

$$M_C = E_g \times M_E \tag{10}$$

In the formula, E_g is the standard coal quality of thermal power consumption / g, M_E is the standard coal consumption of thermal power supply /g•(W•h) $^{-1}$.

The reference values in the formula are shown in Table 8.

Table 8. The reference values in the formula 9.

Parameter	Value/g/W • h
M_E	0.309 [11]

Carbon dioxide emissions from coal power generation were calculated according to formula 11:

$$M_{CO2} = M_C \times \frac{\varphi_C}{\varphi_M} \quad (11)$$

In the formula, M_{CO2} is the carbon dioxide mass / g produced by the combustion of raw coal, φ_C is the carbon dioxide emission coefficient of raw coal, and φ_M is the conversion coefficient between raw coal and standard coal.

The equivalent fuel consumption was calculated according to formula 12:

$$FC_{A3} = \frac{M_{CO2}}{\varphi_F \times 10} \quad (12)$$

In the formula, FC_{A3} is the equivalent fuel consumption / L• $(100km)^{-1}$ obtained from carbon dioxide emissions, and φ_F is the carbon dioxide emission coefficient / kg $\cdot L^{-1}$ of fuel (gasoline).

The comprehensive fuel consumption was calculated according to formula 13:

$$FC_3 = FC_{A3} \times UF + FC_B \times (1 - UF) \quad (13)$$

where FC_3 is the comprehensive fuel consumption calculated according to carbon dioxide emissions /L•$(100km)^{-1}$.

The reference values in the formula are shown in Table 9.

Table 9. The reference values in the formula 11.

Parameter	Value
φ_C	1.9003[15]
φ_M	0.7143[15]
φ_F	2.36

4 Results and analysis

4.1 Results of different fuel-electricity conversion methods

According to the three fuel-electricity conversion methods proposed in this paper, the comprehensive fuel consumption of two PHEVs were obtained by conversion and weighting respectively, and were shown in Table 10.

Table 10. Results of three fuel-electricity conversion methods.

Vehicle serial number	1-1	2-1
Converted fuel consumption for method of simple calorific value FC_1/L•$(100km)^{-1}$	3.04	2.12
Converted fuel consumption for method of comprehensive calorific value FC_2/L•$(100km)^{-1}$	5.24	3.53
Converted fuel consumption for method of carbon dioxide emissions FC_3/L•$(100km)^{-1}$	5.84	3.92

It can be seen from the table that there are great differences among the three conversion results. These three methods were chosen to calculate comprehensive fuel consumption of PHEV from different angles. The three methods meet three prerequisites for the daily use of vehicles at the same time.

1. The daily driving condition is similar to that of NEDC.
2. Daily travel distance conforms to the Gamma distribution cited in this paper.
3. Charging frequency is consistent with charging habits assumed in this paper

4.2 The influence of fuel-electricity conversion method on the fuel consumption of PHEV

Before comparing the effects of the three fuel-electricity conversion methods on the fuel consumption, compare and analyze the differences of the three methods firstly, which was shown in Table 11.

Table 11. Comparison of three fuel-electricity conversion methods.

Method serial number	Method	Considering factors
Method 1	Simple calorific value conversion	Fuel electric calorific value conversion
Method 2	Comprehensive calorific value conversion	Charging efficiency, transmission loss, proportion of thermal power generation, electric energy processing conversion efficiency, direct energy conversion efficiency of gasoline production, gasoline transportation efficiency
Method 3	Carbon dioxide emission conversion	Charging efficiency, transmission loss, proportion of thermal power generation, standard coal consumption of thermal power generation, carbon dioxide emission coefficient of raw coal, conversion coefficient between raw coal and standard coal, carbon dioxide emission coefficient of fuel (gasoline)

The comprehensive fuel consumptions of PHEV converted by three methods were compared with the weighted fuel consumption shown on car window, which was shown in Table 12.

Table 12. Comparison between comprehensive fuel consumption and weighted fuel consumption shown on car window.

Calculating method \ Vehicle serial number	1-1	2-1
Weighted average of fuel consumption shown on car window / FC_G/L•(100km) $^{-1}$	1.70	1.30
Converted fuel consumption for method of simple calorific value FC_1/L•(100km) $^{-1}$	3.04	2.11
Converted fuel consumption for method of comprehensive calorific value FC_2/L•(100km) $^{-1}$	5.24	3.53
Converted fuel consumption for method of carbon dioxide emissions FC_3/L•(100km) $^{-1}$	5.84	3.92

It can be seen from Table 12 that the fuel consumption of the three fuel-electricity conversion methods are obviously higher than those of shown on car window, and are all obviously lower than the fuel consumption of traditional fuel models. And the comprehensive fuel consumption of carbon dioxide conversion (method 3) is slightly higher than that of method of comprehensive calorific value (method 2), and the comprehensive fuel consumption result of simple conversion algorithm (method 1) is obviously lower than that of method 2.

Because these three methods use the same UF, the comprehensive fuel consumption of each method is mainly affected by the equivalent fuel consumption under condition A.

Taking 1-1 and 1-2 as examples, the fuel consumption under condition A and condition B of the three methods were compared as shown in figure 2.

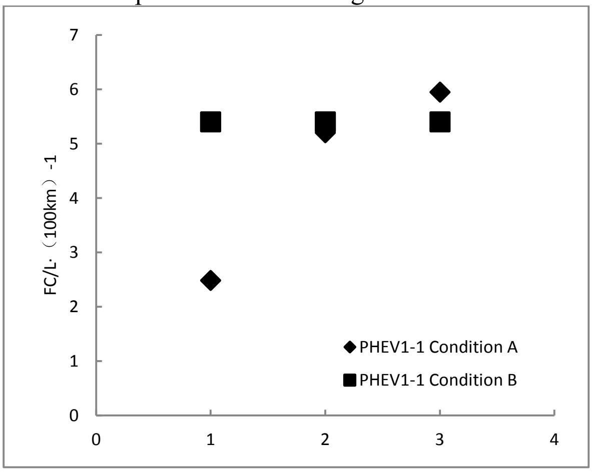

Fig. 2. Comparison of fuel consumption of 1-1 and 2-1 under condition A and B.

It can be seen from the figure that the equivalent fuel consumption under condition A of 1-1 exceeds that under condition B converted by method 3, which can be understood that according to method 3, 1-1 running at fully charged state is more fuel-consuming than running at a power deficit state.

Because the energy conversion of power generation is considered in the conversion process of fuel and electricity, thermal power generation[16] takes more energy consumption and brings higher carbon dioxide emissions than hydropower[17], wind energy, solar power and other power generation methods. Thermal power is still the main mode of power generation in our country, so the comprehensive fuel consumption of method 3 is significantly higher than that of method 1. However, the proportion of thermal power generation varies from region to region, and with the continuous increase of the utilization of renewable energy, the overall proportion of thermal power generation will decline in the future. As the proportion of thermal power generation changes, the comprehensive fuel consumption of PHEV varies, which is shown in figure 3.

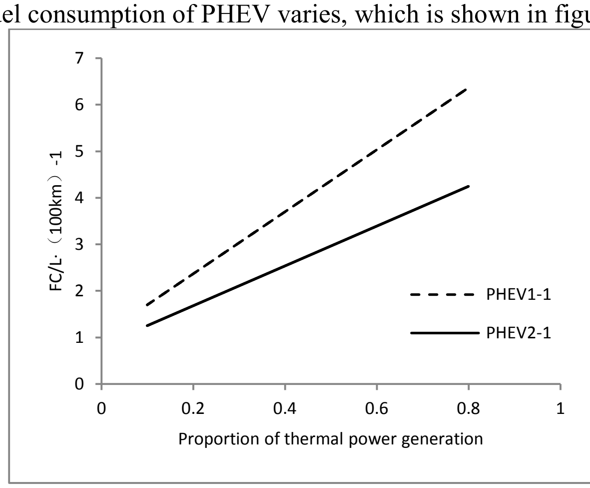

Fig. 3. Comprehensive fuel consumption varies with the proportion of thermal power generation with method 3.

It is obvious that with the decrease of the proportion of thermal power generation, the comprehensive fuel consumption of the two PHEV models converted by method 3 will decrease in degrees.

5 Conclusion

a) The comprehensive fuel consumption of PHEV converted as carbon dioxide emission is the highest, the second is that of comprehensive calorific value conversion, and the lowest is that of simple calorific value conversion.

b) From the perspective of comprehensive calorific value, compared with traditional fuel vehicles, PHEV is obvious fuel-saving for daily urban use.

c) PHEV has obvious fuel-saving advantages in areas where the proportion of thermal power generation is relatively low, and with the continuous decrease of the overall proportion of thermal power generation, the fuel-saving effect of PHEV will become more and more obvious.

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