Research on innovative plug-in hybrid electric vehicle comprehensive energy consumption evaluation method based on statistic energy consumption

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Abstract
The plug-in hybrid electric vehicle not only has the advantages of low emissions from electric vehicles, but also takes advantage of the high specific energy and high specific power of petroleum fuels, which can significantly improve the emissions and fuel economy of traditional vehicles. Studying its comprehensive energy consumption evaluation method is an important part of analyzing the economics of plug-in hybrid electric vehicles. This paper first puts forward the concept of statistical energy consumption and then proposes an innovative calculation method of plug-in hybrid electric vehicle energy consumption based on statistical energy consumption by referring to and analyzing the energy consumption test regulations of the United States, the European Union, and China. Given the two use case assumptions of charge depleting mode priority and charge sustaining mode only, considering the fuel consumption and the energy consumption that converts electrical energy consumption to fuel consumption, the probability density function of travel mileage distribution and energy consumption is derived. Finally, the interpretation and analysis of statistical energy consumption evaluation results are carried out.

Keywords
Hybrid electric vehicle, energy consumption, evaluation method, statistics

Introduction
The plug-in hybrid electric vehicle (PHEV) integrates the advantages of internal combustion engine vehicles and pure electric vehicles. It not only has the advantages of low...
emissions of electric vehicles, but also has the advantages of high specific energy and high specific power of petroleum fuels, which can significantly improve the traditional vehicle emissions and fuel economy. For PHEV, its energy consumption includes fuel consumption and electricity consumption. Studying its comprehensive energy consumption evaluation method is an important part of analyzing the economics of PHEV.1–4

Jeffrey Gonde used global positioning system (GPS) data to estimate the energy consumption of PHEV on the actual road, obtain all-weather driving conditions data from 227 GPS-equipped vehicles operating in the St Louis metropolitan area, and then use simulation software to build vehicle models to simulate the fuel consumption of each model under these actual driving conditions, the result shows that PHEVs with a BLENDED control strategy can save about 50% of fuel consumption compared to traditional fuel vehicles of the same level. Toshifumi Takaoka conducts a certification test on the energy consumption regulation evaluation method by choosing the plug-in Prius and referring to the European Union (EU), Japan, and the United States for PHEV. The test results show that PHEVs can significantly reduce fuel consumption compared to hybrid electric vehicles (HEV), and obtain the curve of the PHEV’s fuel consumption under JC08 operating conditions with the full-charged mileage. When the mileage is 30 km, the fuel-saving ratio (relative to the basic HEV) is 71%, and when the mileage increases to 70 km, the fuel-saving ratio drops to 28%. In addition, there was a greater increase in the actual fuel consumption on the road compared to the fuel consumption under JC08 operating conditions.5–9 Montazeri-Gh and Mahmoodi-k did much research on simultaneous multi-objective optimization of a PHEV power management system and component sizing in real-world traffic conditions, comparative study of different types of PHEV optimal control strategies in real-world conditions and optimized predictive energy management of PHEV based on traffic conditions, simulation results indicate that the proposed approach in real-world driving condition reduces emissions and fuel consumption significantly.10–12

Based on the reference and analysis of the PHEV energy consumption test regulations in the United States, the EU, and China, this paper proposes an innovative calculation method for PHEV energy consumption based on statistical energy consumption, which is verified and explained through examples.

Statistical energy consumption concept

Vehicle energy consumption, as an evaluation index of vehicle driving economy, refers to the energy consumed by a car driving a certain distance. The energy consumption of traditional gasoline and diesel vehicles usually refers to the quality of fuel consumed by the car for 100 km. Automobile energy consumption is affected by both its internal factors and external factors. To standardize and unify this automobile economy evaluation index, relevant laws and regulations of various countries have uniformly stipulated the test and measurement methods of automobile fuel consumption by given external factors. Chinese automobile fuel consumption data is measured in accordance with the national standard GB/T 19233-2008 “Light-Duty Vehicle Fuel Consumption Test Method,” measured by simulating typical driving conditions of vehicles in urban areas and suburbs (including highways) in the test room. The vehicle energy consumption
detection methods of national standards are carried out under the premise of determining the internal and external influencing factors of energy consumption, but for the same car, although the internal influencing factors remain unchanged, the external influencing factors will vary with the conditions of use. Therefore, the energy consumption test method that does not consider the change of external influence factors obviously cannot reflect the actual energy consumption during the use of the vehicle.\textsuperscript{13–15}

Since the external factors that affect the energy consumption of vehicles vary with the use conditions, and the use conditions of vehicles vary with individual users, they are random. Therefore, the parameters reflecting various external factors are random variables and often have statistical characteristics.

The research object of this paper is the energy consumption of PHEV. In actual use, energy consumption varies from vehicle to vehicle due to personal driving and travel habits.

The NREL laboratory in the United States conducted research on the distribution of fuel consumption per 100 km of internal combustion engine vehicles, HEVs, and PHEVs with different configurations, and the results are shown in Figure 1. For any vehicle type, even if the vehicle configuration is the same, due to various factors during use, its energy consumption is not a fixed value, actually a certain distribution form. For PHEV, the energy consumption distribution of different configuration models has different results. As a large proportion of people travel between 10 miles and 40 miles, PHEV10 runs more in charge sustaining (CS) mode, while PHEV40 mainly runs in charge depleting (CD) mode, so its fuel consumption is distributed at a peak at 0 L/100 km; while PHEV 20 electric mileage lies between the two, and its fuel consumption has a wide distribution range. The distribution of electric energy consumption per 100 km and the distribution of fuel consumption have opposite trends. The electric energy consumption of PHEV10 is distributed in the lower range, the electric energy consumption of PHEV40 is distributed in the higher range, and the distribution of electric energy consumption and fuel consumption of PHEV20 are similar with a larger interval range.

It can be seen from the above analysis that the energy consumption (including fuel consumption and electric energy consumption) of traditional internal combustion engine vehicles or new energy vehicles is not a fixed value. Under the condition of determining the parameters of the vehicle itself, due to the use of various vehicles related factors affect energy consumption with greater randomness. When studying the energy consumption of a certain car model in a group, it is necessary to analyze from a statistical perspective to obtain the statistical law of energy consumption, that is, the statistical energy consumption result.\textsuperscript{16,17}

There are many external factors that affect automobile energy consumption. Different external factors have their own distribution forms, which are independent or related to each other. The statistical energy consumption discussed in this article only considers the probability distribution and statistics feature of energy consumption under the influence of a single external factor.

Statistical energy consumption can not only help people obtain the actual energy consumption of vehicles, but also help to correctly understand the impact of vehicle use factors on energy consumption. At the same time, the statistical fuel consumption
based on the distribution of users’ actual usage habits can guide the design of an automobile power and transmission system, so that the vehicle can drive in the optimal economic characteristic zone with the greatest probability, thereby increasing the actual energy consumption of passenger cars.
Comparative analysis of PHEV comprehensive energy consumption test regulations

For PHEV, its typical working modes include power retention mode and power consumption mode. Electricity retention mode means that PHEV only consumes fuel while operating and maintaining the state of charge (SOC) of the energy storage device at a certain level; power consumption mode means that PHEV only consumes the energy of the energy storage device or is consuming electricity during operation. It will also assist in fuel consumption until it enters the power retention mode.

When the PHEV is fully charged and used, it generally runs in the power consumption mode (CD) first, and the SOC continues to decrease at this time; when the SOC drops to the lowest allowed value, the PHEV enters the power retention mode (CS) operation, and the SOC remains balanced.

The energy consumption test of PHEV should be able to reflect its basic working mode. For PHEV, there are two main test modes: one is to start the measurement from the battery retention mode, called the battery retention test (CST); the other is from the fully charged. The power consumption mode starts to measure, which is called the full charge test (FCT). FCT starts the test from the PHEV’s highest SOC and continues to repeat a certain number of test cycles until the SOC reaches the specified level.

CST and FCT are two typical test modes of PHEV. To better reflect the actual energy consumption, a utilization factor (UF) must be used to weigh the measurement results of the two modes. UF is the statistical probability that the user’s daily mileage does not exceed a certain value. The US PHEV energy consumption test standard (SAE J1711-2010) not only introduces UF, but also weights the energy consumption of each test cycle of FCT with UF, so that the results of the regulation test can be closer to the actual energy consumption.

At present, SAE J1711-2010 defaults that users charge once a day, and the main consideration is that the probability of “charging multiple times a day” is the same as the probability of “not charging every day”. In the future, the standard will also investigate the charging habits of users and obtain more data to study the possibility of weighted calculation.

In the EU’s energy consumption test regulations for PHEV (ECE R101), there are two test modes, the highest SOC (condition A) and the lowest SOC (condition B). Condition B only tests 1 cycle, similar to the US CST. There are two measurement methods for condition A. The first one only measures one cycle; the second one continuously repeats the measurement for a certain number of cycles until the energy storage device reaches the lowest SOC. Under the requirements of the manufacturer, the test cycle can be increased and will increase The cyclical test results are included in the energy consumption calculation. The second test method is similar to the FCT in the United States. The EU standard also weights the measurement results of the two states.

Chinese PHEV energy consumption test standards adopt the EU ECE R101 regulations. Therefore, a typical PHEV is selected for testing according to the requirements of ECE R101. The highest SOC test is carried out in accordance with ECE R101 regulations for three sets of tests: the first test method (only 1 NEDC (New European Driving Cycle) cycle is measured, \( N = 1 \)), the second test method (two and three test cycles are
performed, respectively, \( N = 2, 3 \). The minimum SOC test is conducted in a test cycle in accordance with the requirements of the ECE R101 regulations.

According to GB19753-2005-T, the light-duty HEV energy consumption test method, the weighted average of the vehicle fuel consumption obtained from the test is

\[
C = \frac{(D_e \cdot C_1 + D_{av} \cdot C_2)}{(D_e + D_{av})}
\]  

(1)

where \( C \) is the fuel consumption (L/100 km); \( C_1 \) is the fuel consumption under the power consumption mode (CD), the unit is liters per 100 km (L/100 km); \( C_2 \) is the fuel consumption in the power retention mode (CS), in liters per 100 km (L/100 km); \( D_e \) is according to the prescribed test procedures, the measured pure electric driving range, in kilometer (km); and \( D_{av} \) is 25 km (hypothetical average mileage between two charges of the energy storage device).

Weighted average power consumption

\[
E = \frac{(D_e \cdot E_1 + D_{av} \cdot E_2)}{(D_e + D_{av})}
\]  

(2)

where \( E \) is the power consumption, in watt-hours per kilometer (Wh/km); \( E_1 \) is the amount of electric energy consumed in the electric consumption mode, in watt-hours per kilometer (Wh/km); and \( E_2 \) is the amount of electric energy consumed in the electric energy holding mode, in watt-hours per kilometer (Wh/km).

According to the calculation method prescribed by the standard, for a PHEV60, its fuel consumption per 100 km in CS mode is 7.7 L, and its weighted average fuel consumption \( C \) will be 2.26 L/100 km.

The fuel consumption is significantly lower than that of traditional internal combustion engine vehicles, which shows the huge potential of PHEV in saving fuel consumption. However, this value does not fully reflect the fuel consumption of the PHEV in actual use. It only shows that after a PHEV60 drives 60 km in CD mode, the battery SOC reaches the minimum value, and then drives 25 km in CS mode. The fuel consumption of the vehicle: if the vehicle’s mileage is <60 km, its fuel consumption will be 0, which is equivalent to a pure electric vehicle; if the vehicle’s mileage is >60 km, and the vehicle’s energy storage device cannot be fully charged after continuing to travel for 25 km, then its fuel consumption will be >2.26 L/100 km, and in the case of insufficient charging facilities, this situation is very likely to happen. Therefore, the vehicle fuel consumption measured in accordance with regulations only reflects the fuel consumption under ideal conditions. It describes the possibility of PHEV fuel consumption in actual use, but it cannot fully reflect all possible situations.

**Improve comprehensive energy consumption evaluation based on utilization coefficient**

US PHEV energy consumption testing regulations adopt a variable such as \( UF \), which indicates the limited use rate of PHEV’s CD mode. As all-electric range (AER) increases, \( UF \) will approach 1.0. For a specific CD mileage, \( UF \) is obtained based on the daily travel mileage statistics of a large sample of people. Take the travel data of five PHEV40s as an example to illustrate the meaning of \( UF \), as shown in Figure 2. Based on this sample, the
The calculation method of UF is

\[
UF = \frac{30 + 40 + 40 + 40}{30 + 40 + 50 + 60 + 80} = 0.5769
\]  

(3)

**Figure 2.** Data statistics are based on five travel distances as samples.

**Figure 3.** Sorting of \( N \) vehicle mileage.
Assuming that the travel mileage is a set $S = \{d_1, d_2, \ldots, d_{N_s}\}$, $d_i$ represents the travel distance of the No. $i$ vehicle, and $d_i < d_{i+1}$, $N_s$ represents the total amount of data in the sample. Taking the number of trip mileage as the abscissa and the corresponding mileage as the ordinate, Figure 3 can be drawn. Assuming that the AER of the vehicle is $D$, the curve in the figure is divided by this value, and the result shown in Figure 4 is obtained. The calculation method of UF is $\text{UF}(D) = (A_1 + A_2) / (A_1 + A_2 + A_3)$, based on this method, the calculation formula of UF under any AER is given as follows:

$$\text{UF}(R_{CD}) = \frac{\sum_{d_i \in S \min (d_1, \text{AER})}}{\sum_{d_i \in S} d_i}$$

(4)

**PHEV economic evaluation method based on statistical energy consumption analysis**

**PHEV economic evaluation method**

Based on the concept of statistical energy consumption, referring to the use of UF in the US energy consumption regulations, the evaluation index of the fuel consumption of PHEV in actual use is established, and the distribution of PHEV fuel consumption is described. The energy consumption of PHEV includes fuel consumption and electric energy consumption. The fuel consumption and electric energy consumption are calculated separately in the regulations. This paper analyzes fuel consumption and energy consumption from two perspectives. The former is similar to the calculation method stipulated by laws and regulations and is called index 1 in this article. The latter is the conversion of electric energy consumption into fuel consumption and finally uses fuel consumption to express the total energy consumption. The conversion method is that
the energy per liter of gasoline is equivalent to 8.9 kWh, referred to as index 2 in this article. Consider the travel mileage distribution, and believe that the driver is rational, will choose a reasonable vehicle usage mode according to different travels, and make the following use assumptions:

Use hypothesis 1: CD mode priority principle.
Regardless of the mileage, PHEV preferentially uses the CD mode, and when the SOC reaches the lowest value, it enters the CS mode.

Index 1: calculation of fuel consumption

\[
C = \begin{cases} 
0, & D \leq \text{AER} \\
\frac{D - \text{AER}}{D} \cdot C_{cs}, & D > \text{AER} 
\end{cases} 
\tag{5}
\]

where \(C\) is the fuel consumption per 100 km (L/100 km); \(D\) is the vehicle mileage (km); \(\text{AER}\) is the all-electric range, PHEV pure electric driving range, the unit is km; \(C_{cs}\) is the fuel consumption per 100 km in the power holding mode, the unit is L/100 km.

Index 2: calculation of energy consumption

\[
E_{a11} = \begin{cases} 
\frac{E_{CD}}{8.9}, & D \leq \text{AER} \\
\text{AER} \cdot \left(\frac{E_{CD}}{8.9}\right) + (D - \text{AER}) \cdot C_{cs}, & D > \text{AER} 
\end{cases} 
\tag{6}
\]

where \(E_{a11}\) denotes all energy consumption in L/100 km and \(E_{CD}\) is the power consumption in power consumption mode, in kWh/100 km.

Use hypothesis 2: CS mode.
Assuming a specific mileage \(D_{NCD}\) the mileage corresponding to the non-use power consumption mode (none CD (NCD)), the assumption in this paper is 100, and the unit is km. The probability of a trip of 100 km is 97.5%.

When the travel distance is much greater than the driver always chooses the CS mode instead of the CD mode.

Index 1: calculation of fuel consumption

\[
C = \begin{cases} 
0, & D \leq \text{AER} \\
\frac{D - \text{AER}}{D} \cdot C_{cs}, & \text{AER} < D \leq D_{NCD} \\
C_{cs}, & D > D_{NCD} 
\end{cases} 
\tag{7}
\]

Index 2: calculation of energy consumption

\[
E_{a11} = \begin{cases} 
\frac{E_{CD}}{8.9}, & D \leq \text{AER} \\
\text{AER} \cdot \left(\frac{E}{8.9}\right) + (D - \text{AER}) \cdot C_{cs} \cdot C_{cs}, & \text{AER} < D \leq D_{NCD} \\
C_{cs}, & D > D_{NCD} 
\end{cases} 
\tag{8}
\]
Probability density function of travel mileage distribution

Whether it is the energy consumption calculation formula in the law or the formula proposed in this article, it involves the variable of travel mileage, which is a random variable, not a definite value. The distribution of travel mileage needs to be studied before analysis.

As mentioned above, the US travel mileage distribution is obtained according to the statistical results of the United States National Highway Traffic Safety Administration (NHTSA). According to the fitting result and the goodness of fit test, the gamma distribution can be used to describe, that is, Gamma (1.256, 26.7). The probability density function and cumulative probability density function of the distribution are shown in Figure 5. The average value of this distribution is 46 km, and the corresponding probability of this mileage is 61.7%, that is, 61.7% of the population’s travel mileage is not >46 km.

The daily travel mileage of the Chinese population is significantly different from that of the United States. If used the US mileage data for analysis, it will not be in line with the actual situation. Although there are no clear statistics on travel mileage in China, according to relevant statistics, the average daily travel mileage in Shanghai is 39 km. Therefore, the following reasonable assumptions are made: the daily travel mileage in the Shanghai area conforms to the gamma distribution, and the shape of the distribution is similar to the daily travel mileage in the United States, but the shorter travel mileage accounts for a larger proportion. Based on this assumption, the parameters of the gamma distribution are solved.

According to the aforementioned assumptions, the shape of the distribution is similar, so the shape parameter remains unchanged, and the scale parameter is 31.05 by solving the average travel distance. Thus the distribution of travel mileage in the Shanghai area,
Gamma (1.256, 31.05). The average value is 39, and the corresponding probability is 61.8%, that is, 61.8% of the population traveled <39 km, and 79.1% of the population traveled <60 km. Comparing the travel mileage distribution between the United States and Shanghai in Figure 6, the travel mileage in the Shanghai area accounts for a larger proportion in the small mileage range, and 99.5% of the population travels <180 km. In the subsequent discussion and analysis, the distribution of travel mileage in the Shanghai area obtained here will be used.

**Probability density function of energy consumption**

Knowing the probability density function of travel mileage distribution and the relationship between fuel consumption or energy consumption and travel mileage, the probability density function of fuel consumption or energy consumption distribution can be obtained. First, derive the relationship between travel mileage and fuel consumption or energy consumption based on the fuel consumption or energy consumption expression, and then substitute it into the probability density function of travel mileage to obtain the probability density function of fuel consumption and energy consumption, thereby obtaining actual use. The distribution of fuel consumption and energy consumption of medium PHEVs.

Use hypothesis 1

Index 1: distribution of fuel consumption

\[
D = \begin{cases} 
D, & C = 0 \\
\text{AER} \left\{1 - \frac{C}{C_{\text{cs}}} \right\}, & 0 < C < C_{\text{cs}} 
\end{cases}
\]  

(9)
Figure 7. Fuel consumption distribution of PHEV60, 40, and 20.
Substituting the probability density function of the gamma distribution to obtain the probability density function of fuel consumption

\[
f(c) = \frac{\{ \text{AER} / [1 - (C / C_{cs})] \}^{\alpha - 1} \cdot e^{-\beta \{ \text{AER} / [1 - (C / C_{cs})] \}}}{\Gamma(\alpha) \cdot \beta^\alpha}, \quad 0 \leq C < C_{cs} \quad (10)
\]

Study the distribution of fuel consumption of PHEV60, PHEV40, and PHEV20, as shown in Figure 7. Analyzing the PHEV60, the distribution of fuel consumption is more concentrated in the smaller range, and 79.1% of the population has a fuel consumption of 0, which shows that the purely electric driving range can meet the travel needs of this group of people. Combined with the PHEV60 test data, its fuel consumption is 2.26 L/100 km, and the corresponding probability is 90.0%. That is to say, according to the law of travel mileage in Shanghai, 90.0% of people driving a PHEV60 will consume <2.26 L/100 km. Therefore, the fuel consumption measured in accordance with the regulations reflects the fuel consumption under a certain probability and cannot describe the distribution of the fuel consumption of the entire population. The corresponding probability of 5 L/100 km is 99.7%, that is, the fuel consumption of 99.7% of the population is not more than 5 L/100 km. In Table 1, compare the fuel consumption of PHEV60, 40, and 20 calculated in accordance with regulations and their corresponding probabilities.

Comparing the fuel consumption of PHEVs with different AERs, in the entire fuel consumption range, as the AER increases, the distribution is concentrated in the small range, and the overall fuel consumption value decreases. AER60, 40, and 20, respectively, cover 79.1%, 62.9%, and 35.9% of the travel mileage of the population, that is, the probability of fuel consumption being 0 is 79.1%, 62.9%, and 35.9%. Accordingly, the probability of fuel consumption is, respectively, 20.9%, 37.1%, and 54.1%. The area enclosed by the curve and the horizontal axis and the vertical axis represent the probability. In the probability distribution diagram, with the increase of AER, the fuel consumption corresponding to 99% probability is 6.7 L/100 km, 6.0 L/100 km, and 5.0 L/100 km, respectively.

Index 2: distribution of energy consumption

\[
D = \begin{cases} 
D_r, & E_{CD} / 8.9 \leq E_{all} < C_{cs} \\
E_{CD} / 8.9 - C_{cs}, & E_{all} - C_{cs} \end{cases} \cdot \text{AER,} \\
\frac{8.9 \leq E_{all} < C_{cs}}
\]

**Table 1.** PHEV60, 40, and 20 fuel consumption and corresponding probability.

|                  | PHEV60 | PHEV40 | PHEV20 |
|------------------|--------|--------|--------|
| Fuel consumption measured according to regulations (L/100 km) | 2.26   | 2.93   | 4.19   |
| Corresponding to the probability of statistical fuel consumption (%) | 90.0   | 82.0   | 67.8   |

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Substitute the probability density function of the gamma distribution to get the probability density function of energy consumption.

\[
f(E_{\text{all}}) = \frac{\left(\frac{E_{\text{CD}}}{8.9} - C_{C_s}\right)/\left(E_{\text{all}} - C_{C_s}\right)}{\Gamma(\alpha) \cdot \beta^\alpha} \cdot A_{\text{ER}}^{\alpha-1} \cdot e^{-\beta \cdot \left(\frac{\left(\frac{E_{\text{CD}}}{8.9} - C_{C_s}\right)}{\left(E_{\text{all}} - C_{C_s}\right)} \cdot A_{\text{ER}}\right)}, \quad \frac{E_{\text{CD}}}{8.9} < E_{\text{all}} < C_{C_s}
\]

(12)

According to this function, the probability density function and cumulative probability density function of the energy consumption of PHEV60, 40, and 20 shown in Figure 8 can be obtained. Energy consumption takes into account the conversion of electrical energy consumption into fuel consumption, so the starting point of the horizontal axis is 2.1 L/100 km. Judging from the shape of the distribution curve, the energy consumption tends to concentrate on a smaller interval. For PHEV60, the corresponding probability of the starting point on the horizontal axis is about 79.1%, that is, the energy consumption of 79.1% of the population is no more than 2.1 L/100 km. This part of the population uses electric energy to drive the vehicle, while 99% of the population has no more energy consumption of 6 L/100 km. Comparing the energy consumption distribution of PHEVs with different AERs, the curve shape and distribution trend are similar to the fuel consumption distribution. The difference is that the starting point of the horizontal axis is different, and the interval range becomes smaller.

Use hypothesis 2

Index 1: distribution of fuel consumption

\[
D = \begin{cases} 
D, & \text{other} \\
\frac{A_{\text{ER}}}{1 - (C/C_{C_s})}, & A_{\text{ER}} < D < D_{NCD}
\end{cases}
\]

(13)

get the probability density function of the fuel consumption distribution

\[
f(C) = \frac{\left(A_{\text{ER}}/\left[1 - (C/C_{C_s})\right]\right)^{\alpha-1} \cdot e^{-\beta \cdot \left(A_{\text{ER}}/\left[1 - (C/C_{C_s})\right]\right)}}{\Gamma(\alpha) \cdot \beta^\alpha}, \quad 0 \leq C < \frac{D_{NCD} - A_{\text{ER}}}{D_{NCD}} \cdot C_{C_s}
\]

(14)

Compare the fuel consumption distribution of PHEV60, 40, and 20 in Figure 9. From the horizontal axis, as the AER increases, the range of fuel consumption values decreases significantly, with the maximum values of the ranges being 3.1 L/100 km, 4.6 L/100 km, and 6.0 L/100 km, respectively. From the vertical axis, as AER increases, the proportion of each fuel consumption value decreases significantly. For PHEV60, the horizontal axis range corresponding to the curve is 0–3.1 L/100 km. As the fuel consumption value increases, its share decreases significantly. When the fuel consumption value is 0, the corresponding probability is 79.1%. When the mileage is >100 km, the fuel consumption is 7.7 L/100 km, and the corresponding probability is only 6.35%.
Index 2: distribution of energy consumption

\[
D = \begin{cases} 
D, & \text{other} \\
\frac{\text{AER}}{1 - (C / C_{\text{CS}})}, & \text{AER} < D \leq \frac{D_{\text{NCD}} - \text{AER}}{D_{\text{NCD}}} \cdot C_{\text{CS}}
\end{cases}
\]  

(15)
The expression of the probability density function of energy consumption is

\[
f(E_{\text{all}}) = \frac{[(E_{CD}/8.9) - C_{cs}] / (E_{\text{all}} - C_{cs}) \cdot \text{AER}]^{\alpha - 1} \cdot e^{-\beta [(E_{CD}/8.9) - C_{cs}] / (E_{\text{all}} - C_{cs}) \cdot \text{AER}}}{\Gamma(\alpha) \cdot \beta^{\alpha}} \cdot \frac{E_{CD}}{8.9}, \quad E_{\text{CD}} \leq E_{\text{all}} < C_{cs}
\]

(16)

Figure 9. Probability of PHEV 60, 40, and 20 fuel consumption.
In Figure 10, compare the energy consumption distribution of PHEV60, 40, and 20. From the horizontal axis, as the AER increases, the energy consumption value interval becomes significantly smaller, with the maximum value of the interval being 3.1 L/100 km, 4.6 L/100 km, and 6.0 L/100 km, respectively. From the vertical axis, as AER increases, the proportion of each energy consumption value decreases significantly. For PHEV60, the horizontal axis range corresponding to the curve is 2.05–3.1 L/100 km. As energy...
consumption increases, its proportion decreases significantly. When the energy consumption value is 2.05 L/100 km, the corresponding probability is 79.1%. When the mileage is >100 km, the fuel consumption is 7.7 L/100 km, and the corresponding probability is only 6.35%.

**Interpretation of statistical energy consumption evaluation results**

The corresponding UF can be obtained by processing the travel mileage distribution Gamma (1.256, 31.1) in the Shanghai area. The curve is shown in Figure 11. The abscissa is AER and the ordinate is UF.

The calculation formula of fuel consumption in my country’s PHEV energy consumption test regulations is processed by imitating the UF calculation method:

\[
C = \left( C_1 \cdot \frac{D_e}{D_e + D_{av}} + C_2 \cdot \frac{D_{av}}{D_e + D_{av}} \right)
\]  

(17)

\(D_e / (D_e + D_{av})\) is UF. According to the regulations, \(D_{av}\) will be set to 25 km. According to this assumption and change the value, compare the difference between different curves of \(D_e / (D_e + D_{av})\) and UF with different \(D_{av}\), as shown in Figure 12. When \(D_{av} = 25\) km, under the condition that the CD range is not >10 km, the curves almost overlap; but when the CD range is >10 km, the two curves are very different, and UF is greater than \(D_e / (D_e + D_{av})\). When the value of \(D_{av}\) becomes smaller, although the overall trend of the two curves is closer, there is still a big difference. The UF method assumes that the battery is charged only once a day, and the mileage data is analyzed, and the calculation results are more in line with actual usage.

![Figure 11. Utilization coefficient of travel mileage in the Shanghai area.](image)
The utilization coefficient UF indicates the limited usage rate of the PHEV’s CD model. For a specific CD mileage, UF is obtained based on the daily travel mileage statistics of a large number of sample groups. It is a random variable in itself and is calculated by weighting the coefficient of fuel for 100 km. Consumption reflects an “average” of fuel consumption of a specific population, but it cannot fully describe the fuel consumption of the entire population.

If the UF calculation method is adopted, for PHEV60, its fuel consumption per 100 km is calculated as follows:

\[ C = C_{CD} \cdot UF + C_{cs} \cdot (1 - UF) \]  

where \( C \) is the fuel consumption per 100 km, in L/100 km; \( C_{CD} \) is the fuel consumption per 100 km in the power consumption mode, in L/100 km; and \( C_{cs} \) is the fuel consumption per 100 km in the power retention mode, in L/100 km.

For PHEV60, in this article, \( C_{CD} \) is 0 L/100 km, \( C_{cs} \) is 7.7 L/100 km, and for Shanghai area travel mileage distribution, UF is 0.8557, the calculation result of fuel consumption per 100 km \( C \) is 1.11 L/100 km.

Compare the fuel consumption value calculated by the UF method with the statistical energy consumption distribution, as shown in Figure 13. The fuel consumption of 1.1 L/100 km reflects an “average value” of PHEV60 usage in Shanghai. In the overall fuel consumption distribution, this calculated value corresponds to a probability of 84.4%, that is, 84.4% of the population of PHEV60 users per 100 km fuel consumption will not exceed 1.11 L/100 km.

According to its calculation method, it is assumed that the UF proportion of people use the CD mode when driving the vehicle, while the (1-UF) proportion of the people use the
CS mode and the fuel consumption of the vehicle in this mode is a certain value. The relationship between the fuel consumption per 100 km obtained by this calculation method and the fuel consumption obtained by the statistical energy consumption method needs further study. To calculate the average fuel consumption per 100 km for a certain group of people using a PHEV60, according to the statistical energy consumption method, it should be calculated according to the following formula:

\[
\bar{C} = \frac{C_{CS}}{\int C f(C) dC}
\]  

(19)

where \(\bar{C}\) is the average value of fuel consumption per 100 km, the unit is L/100 km.

The meanings of the remaining symbols are the same as those mentioned above. The calculated result is 1.13 L/100 km. From the results of the two calculations, the fuel consumption per 100 km obtained by the UF calculation method is the average fuel consumption per 100 km of a specific group of people, which is consistent with the results of statistical energy consumption.

Substituting the definition of UF into the formula of the UF method to calculate fuel consumption, the following formula is obtained:

\[
C = C_{CS} \cdot \left[ \frac{\sum_{i=1}^{N_{AER}} (d_i - d_i)}{\sum_{i=1}^{N_{AER}} d_i} + \frac{\sum_{i=N_{AER}}^{N} (d_i - AER)}{\sum_{i=N_{AER}}^{N} d_i} \right]
\]

\[
= C_{CS} \cdot \frac{\sum_{i=N_{AER}}^{N} (d_i - AER)}{\sum_{i=N_{AER}}^{N} d_i}
\]

(20)

Figure 13. Comparison of UF calculated fuel consumption and statistical fuel consumption.
where $C_{CD}$ is the fuel consumption per 100 km in the electric power consumption mode, in L/100 km, which is set as 0 L/100 km in this study, and $N_{N, AER}$ is the travel mileage is sorted from smallest to largest, and the corresponding sequence number when the travel mileage is equal to AER. The calculation formula of the average fuel consumption obtained by the calculation method of statistical energy consumption is as follows:

$$
\bar{C} = \frac{\sum_{i=N_{AER}}^{N} (C_{CS} \cdot \frac{d_i - AER}{d_i})}{\sum_{i=N_{AER}}^{N} d_i}
$$

From the above formula, the calculation formula used by the two methods is the same, so the results obtained are theoretically the same, that is, the fuel consumption per 100 km calculated by the UF method is the average fuel consumption per 100 km in the statistical energy consumption.

**Conclusion**

Refer to and analyze the PHEV energy consumption test regulations of the United States, the EU, and China, propose an innovative calculation method for PHEV energy consumption based on the statistical energy consumption, make the model scenarios assume of CD mode priority and only use CS combining the driver’s choice of PHEV driving mode, fuel consumption and energy consumption that convert electrical energy consumption into fuel consumption are considered, and the corresponding calculation methods are given. Based on the aforementioned energy consumption evaluation method and the distribution of travel mileage in Shanghai, PHEV60, 40, and 20 are used as the research objects to study the distribution of fuel consumption and energy consumption under two assumptions, and the probability density function of the distribution is solved, provide a set of credible statistical methods for the economic evaluation of PHEV and verify it with examples.

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