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From NEDC to WLTP: Effect on the Energy Consumption, NEV Credits, and Subsidies Policies of PHEV in the Chinese Market

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Abstract: The switching from new European driving cycle (NEDC) to worldwide harmonized light vehicles test procedure (WLTP) will affect the energy consumption of plug-in hybrid electric vehicle (PHEV), and then affect the new energy vehicle (NEV) credit regulation and subsidy policy for PHEVs. This paper reveals the impact on energy consumption, NEV credit regulation, and subsidy policy for PHEV in the Chinese market of the switching from NEDC to WLTP based on qualitative analysis and quantitative calculation. The results show that the WLTP procedure is stricter than NEDC in the determination of road load, test mass, driving resistance forces, and tire selection. Firstly, the electricity consumption (EC) of PHEV in charge-depleting mode (CD) under the WLTP procedure is 26% higher than NEDC on average, which makes the all-electric range (AER) significantly lower under WLTP. The weight EC tested in the WLTP procedure is higher than NEDC. Secondly, the fuel consumption (FC) of PHEV in CD mode is related to the adjustment of the engine management system (EMS) and the size of battery energy under the WLTP procedure. For the FC in the charge-sustaining (CS) mode of PHEV under the WLTP procedure is 20% higher than NEDC on average. However, the weight fuel consumption of PHEVs under WLTP with a long AER may be lower than that of NEDC due to the characteristics of utility factor in the WLTP procedure. Thirdly, most PHEVs fail to meet the requirements of 50 km AER due to the switching of the test procedures. However, the Chinese government reduced the technical specification of PHEV's AER under the WLTP procedure to 43 km to support the development of PHEV technology. It ensures that the switching of test procedures does not change the treatment that they could obtain, the NEV credits, and subsidy as a NEV in China. However, the increasing of the EC in CD mode and the FC in CS mode under the WLTP procedure makes the PHEV obtain lower credit and subsidy multiple compared with NEDC procedure.

Keywords: PHEV; NEDC; WLTP; energy consumption; NEV credit regulation; subsidy policy

1. Introduction

With the development of the automobile industry, China is facing the problems of energy security and environmental pollution [1–3]. The relevant national agencies have made a series of regulatory constraints on the energy consumption and emissions of vehicles to solve these problems [4,5].

According to the technical roadmap of energy-saving and new energy vehicles, the average fuel consumption (FC) of new passenger cars in 2020 and 2025 will reach 5 L/100 km and 4 L/100 km, respectively [6]. Because of the characteristics of the traditional internal combustion engine (ICE), it has gradually been unable to meet the stringent regulatory requirements [7]. Therefore, electrical upgrading based on the traditional internal combustion engine has become an effective way to solve the problem of energy consumption and emissions [8]. However, considering the battery costs and charging problems, there are still many obstacles in large-scale promotion of fully electrified battery electric vehicles (BEV). Therefore, the plug-in hybrid electric vehicle (PHEV), combining the ideal characteristics of BEVs with the range of traditional internal combustion engine vehicles (ICEV), has become the preferred technology choice for automobile manufacturers to meet increasingly stringent regulations [9–11].

Furthermore, it is an advantage of PHEVs that they can operate in two different modes due to its complicate powertrain configuration [12]. First, in charge-depleting mode (CD), the motor is responsible for propulsion and the ICE is switched off. Secondly, in charge-sustaining (CS) mode, the ICE provides power to drive the wheels and keep the SOC within a certain range [13]. However, due to the complexity of PHEV operation mode, it is difficult to accurately evaluate its energy consumption in tests [14]. In the past, the NEDC has been used to evaluate the fuel economy of Europe and China. However, the European Union has stipulated the gradual implementation of WLTP instead of NEDC to assess the fuel economy of light vehicles since September 2017. Furthermore, WLTP will be adopted as the FC test regulation of light vehicles in China from 2021 to 2025.

However, the switching of test procedures will change the energy consumption and emissions of the whole vehicle, which will have a certain impact on the development strategy of automobile manufacturers [15]. For example, several major European automakers have changed their development strategies for engine turbocharging and discontinued some PHEVs due to the switching from NEDC to WLTP. Thus, the switching of test procedure would affect the energy consumption of PHEV. Moreover, PHEV is one of the new energy vehicles vigorously promoted by the Chinese government. The change of test procedures will further affect the NEV credits and subsidy availability of PHEV on the basis of energy consumption. Therefore, it is necessary to study the effect of NEDC switching to WLTP in advance. On the one hand, it can help the government to accurately evaluate the energy-saving and emission reduction effect brought by the promotion of PHEV. On the other hand, it could help automotive manufacturers to develop new energy vehicle technology development routes.

However, there are few studies on the energy consumption of PHEV under different test procedures. Pavlovic et al. compared the differences from the energy consumption of PHEVs between NEDC and WLTP through experimental tests [16]. They found that the all-electric range (AER) determined by the WLTP procedure was significantly lower than NEDC. However, the FC tested from WLTP were often lower than the corresponding NEDC with the increase of battery energy. Tsiakmakis et al. studied the driving range and FC of PHEV under WLTP and NEDC based on the simulation method [17,18]. They found that the ratio of carbon dioxide emissions of PHEVs at WLTP to NEDC was largely dependent on battery energy. With the increase of battery energy, the proportion decreases rapidly. They also concluded that the ratio of energy consumption of PHEV between WLTP and NEDC is 1 when the battery energy is 25 kWh. Soulouk et al. investigated the main changes that the WLTP test procedure implies to a mid-size sedan electrified vehicle design (series, parallel P2, and power split) and quantifies their impact on the vehicles fuel economy [19]. They found that across different electrified vehicle architectures, the vehicles' fuel economy under the WLTP procedure in CS mode substantially decreases compared to the NEDC. Moreover, the battery needs to deliver more energy in the WLTP cycle compared to the NEDC to meet the AER requirement. The above-mentioned literatures analyze the change of energy consumption due to the switching of test procedures, but it does not systematically compare the differences between the NEDC and WLTP procedures for PHEVs. Moreover, there is a gap in the impact of the switching of test procedures on the policies for PHEVs, such as NEVs credit regulation and subsidy policy.

Therefore, this paper aims to reveal the impact of the switching from NEDC to WLTP on PHEV energy consumption and its external policies. This paper is organized as follows: In the first section, the significance of the research is introduced. Next, the differences between the NEDC and WLTP procedures are analyzed using qualitative analysis method. Then, the impact of test procedures switching on the energy consumption, NEVs credits regulation, and subsidy policy for PHEV is studied in the way of quantitative calculation method. Following that, the paper puts forward relevant policy suggestions for the problems caused by test procedure switching. Finally, the last section summarizes all findings from this paper.

2. Test Procedure Differences between the NEDC and WLTP Procedure for PHEV

2.1. Differences in Road Load Determination between NEDC and WLTP

The first difference is the determination of test mass between NEDC and WLTP. The mass of the test vehicle used to determine the road load is equal to the curb mass plus 100 kg in the NEDC procedure [20]. While for the WLTP procedure, the test mass is equal to the reference mass plus the mass of the fitted equipment of specific vehicles and the representative load mass [21]. It can be seen that test mass determination from WLTP will be significantly higher than NEDC. Therefore, the driving resistance of the whole vehicle will increase during the energy consumption tests, which will improve the energy consumption of PHEV under the WLTP procedure.

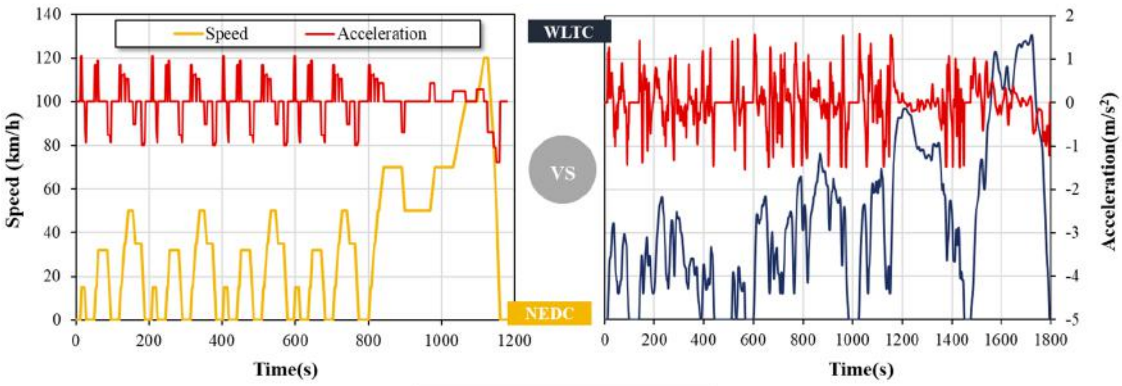
The second difference is the tire selection between NEDC and WLTP. The rolling resistance coefficient of a tire is the main contributor to the total rolling resistance. It is well-known that the influencing factors of the rolling resistance coefficient of the tire are mainly the width and circumference of the tire, the inflation pressure, and the tread depth [20]. In tire selection, NEDC requires that the widest tire must be selected for testing, while WLTP selects the tire according to the rolling resistance level of the tire according to the tested vehicles. Although NEDC is stricter than WLTP in terms of requirements, the rolling resistance coefficient of the widest tire specified in NEDC is not the largest. Therefore, the rolling resistance coefficient of the tire selected in WLTP is larger than that in NEDC to a certain extent. Generally speaking, the greater the inflation pressure, the lower the rolling resistance coefficient. There is no regulation on tire pressure in NEDC, so it is usually done to inflate the tire to the maximum allowable pressure. However, the road load is determined when the tire pressure is set to the minimum value as specified in WLTP. In terms of tire pressure, NEDC has more advantages than WLTP. Finally, it is known that the greater the tread depth, the greater the rolling resistance coefficient. The WLTP procedure for the minimum tire tread depth is more stringent (80%) than the NEDC requirement of 50% [21]. In a word, WLTP is stricter than NEDC in terms of tire selection, which leads to the higher energy consumption of PHEV when testing in WLTP.

The third difference is the determination of the coefficient of resistance force between NEDC and WLTP [22]. In the process of the coast down tests, paired runs in alternate directions must be performed due to the practical impossibility to have a perfectly flat test track. In the calculation method, NEDC averages the up and down test time. Unlike this, WLTP averages the resistance force not time in both directions. Due to the difference of test time in two different directions, the average time of the test track is relatively long compared to the real test time. Therefore, this method of average time leads to some errors and results in the final road load coefficient is lower than the coefficient calculated utilizing average force. Therefore, WLTP is stricter than NEDC in the way of calculating driving resistance. It will make PHEV require more energy in tests. Also, NEDC ignores the moment of the inertia effect of components in the process of determining the resistance force. The resistance force determined by the WLTP procedure is about 3% higher than NEDC due to the effect of the moment of inertia [20].

2.2. Differences in Test Protocol and Driving Cycles between NEDC and WLTP

The differences between the driving cycles of NEDC and WLTP are shown in Figure 1. The test cycle corresponding to the WLTP procedure is Worldwide harmonized light vehicles test cycle (WLTC).

It can be seen from the figure that the WLTC cycle has a longer test time and distance compared with the NEDC cycle. Furthermore, the WLTC cycle has a significantly higher average maximum speed and acceleration, which will significantly improve the testing energy consumption of PHEV [23]. Moreover, the large decrease in the idle ratio in the WLTC cycle will weaken the fuel-saving effect of the start/stop and hybrid power technology [24].



Parameters	Duration (s)	Distance (km)	Maximum speed (km/h)	Average speed (km/h)	Stop duration (%)	Constant driving (%)	Acceleration (%)	Deceleration (%)	Maximum acceleration (m/s²)	Minimum acceleration (m/s²)
NEDC	1180	11.03	33.6	120.0	23.7	40.3	20.9	43.8	1.04	-1.39
WLTC	1800	23.27	46.5	131.3	12.6	3.7	15.1	39.9	1.67	-1.50

Figure 1. Comparison of new European driving cycle (NEDC) and worldwide harmonized light vehicles test cycle (WLTC) driving cycles.

However, the higher engine loads experienced by vehicles under the WLTC cycle can make the engine work in the high-efficiency range, which might compensate for the FC caused by the higher dynamic effect to a certain extent [25]. Furthermore, the proportion of cold start for vehicles under the WLTC cycle is lower than the NEDC cycle, which will reduce the effect of cold start and further reduce FC. Moreover, the WLTP procedure introduced the specific gearshift strategy with a manual transmission by calculated the engine speed and vehicle characteristics, while in the NEDC procedure, the same fixed gear positions are used for all vehicles [21]. Thus, this new WLTP gearshift strategy results in engine speeds ranging in their lower end, which consequently provide better engine efficiency and lower FC.

In a word, the FC for the ICEVs will change limited (far less than expected) by simply analyzing the change from NEDC to the WLTC cycle assuming that other conditions remain unchanged. The amplitude of the FC change is related to the characteristics of the vehicle and the engine. This is also confirmed by other scholars [26–29]. They found that the CO_2 emission ratio of WLTC and NEDC cycle is between 0.89 and 1.16 when only considering the difference of the test cycle. However, the EC for BEVs will be significantly improved under the worse WLTC cycle not having the compensating effect from the engine.

Furthermore, the NEDC procedure only tests one cycle in CD mode for PHEVs, while WLTP extends to the whole CD mode until the battery reaches the SOC level in CS mode [16]. Therefore, the real EC of PHEV in CD mode cannot be accurately measured according to the measurement of NEDC if the EC of PHEV in CD mode is non-linear. Moreover, with the increase of the discharge depth, the energy consumption of the battery gradually increases, considering the discharge characteristics of the power battery [18]. It will result in that the EC in CD mode under WLTP will be significantly higher than NEDC. Meanwhile, there exist some differences when calculating the FC for PHEVs in CS mode between WLTP and NEDC. Under the WLTP procedure, PHEVs should be corrected the FC in CS mode for the difference of the SOC of the battery between the start and end of the CS test. If the change of SOC is greater than 0.5% and SOC is reduced (corresponding to battery discharge) in WLTP, FC correction will be enforced [16]. This is not considered under the NEDC procedure. From this point of view, WLTP will further increase FC in the tests.

2.3. Differences in Post-Processing of the Energy Consumption Data between NEDC and WLTP

For the calculation of energy consumption under the NEDC procedure, the final FC and EC are calculated by the following formulas [30]:

$$C_{weight}^{NEDC} = \frac{D_e * C_{CD}^{NEDC} + D_{av} * C_{CS}^{NEDC}}{D_e + D_{av}} = UF^{NEDC} * C_{CD}^{NEDC} + \left(1 - UF^{NEDC}\right) * C_{CS}^{NEDC} \quad (1)$$

$$E_{weight}^{NEDC} = \frac{D_e * E_{CD}^{NEDC}}{D_e + D_{av}} = UF^{NEDC} * E_{CD}^{NEDC} \quad (2)$$

where $C_{weight}^{NEDC}\left(E_{weight}^{NEDC}\right)$ represent the FC (EC) for PHEV; $C_{CD}^{NEDC}\left(E_{CD}^{NEDC}\right)$ indicate the FC (EC) in CD mode; C_{CS}^{NEDC} indicates the FC in CS mode. D_e is the electric range of the PHEV and D_{av} is the average distance has driven in CS mode, 25 km. To facilitate comparison with the method to calculate the weight energy consumption of the WLTP procedure, UF^{NEDC} is assumed the equivalent utilization factor. It assumes that the EC in CS mode is 0 under the NEDC procedure, which is the same as the WLTP procedure. It makes the comparison simplified between the EC under different test procedures in this paper.

As abovementioned, NEDC only tests one cycle for PHEV in CD mode, so the FC of PHEVs whose electric range is over 11.03 km (one NEDC cycle) in CD mode is 0. Considering that the current AER of PHEV is more than 50 km, the formula adopted to calculate the weight FC of PHEV under NEDC procedure can be simplified as follows:

$$C_{weight}^{NEDC} = \frac{D_{av} * C_{CS}^{NEDC}}{D_e + D_{av}} = \left(1 - UF^{NEDC}\right) * C_{CS}^{NEDC} \quad (3)$$

However, the favorable testing assumptions under the NEDC procedure in CD mode will be eliminated with the improvement of WLTP. Thus, the FC in the CD mode test cannot be ignored, which will make the FC of PHEV in CD mode higher than NEDC. In WLTP, the FC in CD mode and final weight FC is calculated according to the different weights of each phase in CD mode. The formula is as follows [21]:

$$\begin{cases} C_{weight}^{WLTP} = \left(\sum_{j=1}^{k} UF_j\right) * C_{CD}^{WLTP} + \left(1 - \sum_{j=1}^{k} UF_j^{WLTP}\right) * C_{CS}^{WLTP} \\ C_{CD}^{WLTP} = \frac{\sum_{j=1}^{k}\left(UF_j^{WLTP} * C_{CD,j}\right)}{\sum_{j=1}^{k} UF_j} \end{cases} \quad (4)$$

where C_{weight}^{WLTP} is the weight FC under the WLTP procedure for PHEVs, L/100 km, UF_j^{WLTP} is the utility factor of the CD phase j under the WLTP procedure; C_{CD}^{WLTP} is the FC under the WLTP procedure in CD mode and C_{CS}^{WLTP} is the FC under the WLTP procedure in CD mode, L/100 km; k represents the number of velocity segments tested from the CD test to the transition cycle; $C_{CD,j}$ is the FC of phase j in CD mode, L/100 km.

When calculating the weight EC under the WLTP procedure, the EC in CS mode is not considered, so the calculation formula is as follows:

$$\begin{cases} E_{weight}^{WLTP} = \left(\sum_{j=1}^{k} UF_j\right) * E_{CD}^{WLTP} \\ E_{CD}^{WLTP} = \frac{\sum_{j=1}^{k}\left(UF_j^{WLTP} * E_{CD,j}\right)}{\sum_{j=1}^{k} UF_j} \end{cases} \quad (5)$$

where E_{weight}^{WLTP} is the weight EC under the WLTP procedure for PHEVs, kWh/100 km, E_{CD}^{WLTP} is the EC under the WLTP procedure in CD mode, kWh/100 km; $E_{CD,j}$ is the EC of phase j in CD mode, kWh/100 km.

By comparing the calculation formula of weight energy consumption between NEDC and WLTP, the results of a PHEV are strongly affected by the utility factor related to the electric range [31,32]. Thus, it is not accurate for the NEDC procedure to set 25 km as the average distance of CS mode, which does not conform to the current travel characteristics [32]. It depends on the AER of the specific vehicle. If the vehicle has a high AER, it is likely to drive mainly in CD mode. If the AER of the vehicle is lower, the probability of driving in CS mode is higher. The WLTP procedure introduces the utility factor based on the driver's travel characteristics to more accurately describe the driving probability in CD and CS modes, as shown in Figure 2. It should be noted that since China's current test regulations refer to Europe, its utility factor curve also comes from Europe. However, considering the difference in travel characteristics between China and Europe, China should develop the utility factor that adapts to the travel characteristics of China [33].

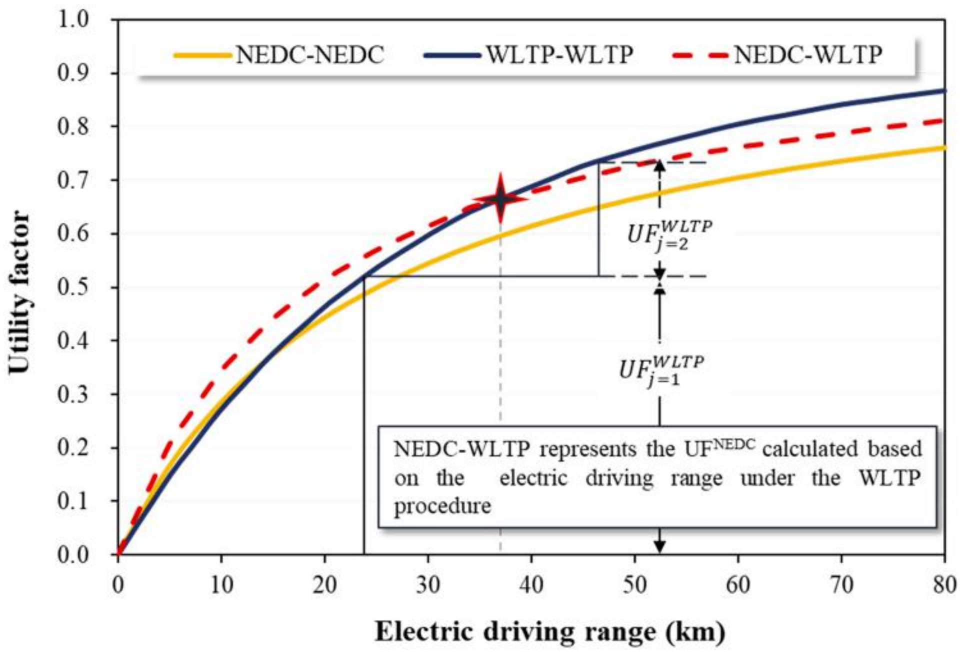


Figure 2. Comparison of utility factor between NEDC and worldwide harmonized light vehicles test procedure (WLTP).

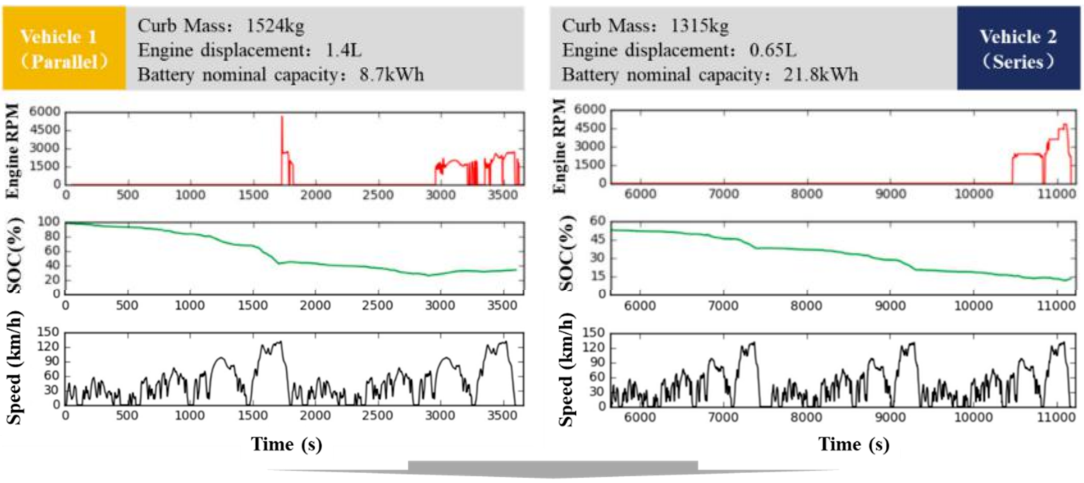
It can be seen from Figure 2 that the utility factor calculated based on NEDC-NEDC and WLTP-WLTP is approximately equal in the range of short driving range. However, the energy consumption of CD mode under the WLTP procedure is calculated by weighting the utility factor of each phase of cycles, so it is more consistent with the travel behaviors. Also, considering that the actual electric range under the two test procedures is not the same, to better evaluate the difference between the two utility factors, the equivalent utility factor of NEDC is calculated by using AER under the WLTP procedure (making the electric range in NEDC transferred to the electric range in WLTP), which is the NEDC-WLTP utility factor curve as shown in Figure 2. It can be found that the equivalent utility factor of the NEDC procedure is higher than that of WLTP when the AER is short. Therefore, this will reduce the proportion of FC of PHEV in CS mode when calculating FC. It results in the FC in CS mode measured by WLTP being relatively high compared to NEDC, derived from Formula (4). Meanwhile, the utility factor of WLTP is higher than the equivalent utility factor of NEDC when the AER of PHEV under WLTP is greater than 38 km (intersection point in Figure 2). Therefore, when calculating the weight FC, the FC of PHEV with a high driving range under the WLTP procedure will below. On the contrary, with the continuous increase of the AER, the utility factor of WLTP is significantly higher than the equivalent utility factor of NEDC. Hence, the weight value of NEDC may be lower than that of WLTP, when calculating the weight FC.

3. Effect on the Energy Consumption of PHEVs from NEDC to WLTP

In essence, the energy consumption test of PHEVs is to test the energy consumption in CD mode and CS mode, respectively. Then, calculate the weight energy consumption by different weighting methods according to the NEDC and WLTP procedures. To analyze the impact of switching from NEDC to WLTP on the energy consumption of PHEV accurately, this part makes quantitative analysis from three parts: Energy consumption in CD mode, energy consumption in CS mode, and final weight energy consumption. It should be noted that the energy consumption data are mainly collected from the literature [16,18,19], tested by the China Automotive Technology and Research Center (CATRC) [34], and provided by relevant automobile manufacturers in this paper.

3.1. Analysis of the Energy Consumption in CD Mode (C_{CD} and E_{CD})

As abovementioned, the NEDC procedure only tests one cycle for PHEV in CD mode, the FC will be 0 if the AER of the testing vehicle over 11.03 km. However, the WLTP procedure tests the complete CD phase. The engine of PHEV will start in the condition that the power demand is higher than the power provided by the battery or the SOC of the battery is relatively lower [16]. To understand the test procedure and the determination of energy consumption for PHEVs under WLTP, the testing results of two PHEVs tested in the Joint Research Centre (JRC) of the European Commission Laboratories are cited in this study [16], as shown in Figure 3. The results showed the driving cycles, SOC of battery, and engine revolutions per minute (RPM).



Testing Vehicles	Vehicle 1	Vehicle 2
FC in CD mode (L/100km)	1.366	0.067

Figure 3. WLTP charge depleting test sequence for two plug-in hybrid electric vehicles (PHEVs) from the study of Joint Research Centre (JRC).

For vehicle 1 in Figure 3, although the SOC was not already at its minimum value, the ICE started during the extra-high speed part of the first WLTC. It may be the consequence that the engine management system (EMS) for the specific vehicle was tuned by the OEMs to behave in a certain way on the NEDC cycle, thus bringing this unexpected behavior in the WLTP testing [16]. As abovementioned, the maximum speed of WLTC is much higher than that of NEDC, and that most likely was the cause of the behavior that ICE started early.

For parallel or hybrid PHEVs, if the EMS has not been tuned based on WLTC or the motor power is lower than the required power at the maximum speed, the engine will start even if the SOC is not at its minimum value. Meanwhile, the engine must start in the last WLTC due to the low SOC. Therefore, to reduce the FC of PHEV in CD mode, the vehicle manufacturer needs to adjust the EMS to avoid starting the engine of PHEV frequently in high SOC state. However, the engine decouples from the wheels or the series PHEV. The engine only started in the last WLTC in CD mode. Therefore, the FC mainly comes from the last cycle of CD mode if the EMS for the engine for PHEV is tuned based on WLTC, as shown in Figure 3.

At the same time, it can be found that the FC of Vehicle 1 in CD mode is significantly lower than that of Vehicle 2. This is mainly because the Vehicle 2 has a large power battery capacity so that the utility factor in the last cycle is significantly smaller than that of the Vehicle 2 (0.2% < 22.2%). According to Formula (4), the utility factor in the last cycle is lower, its FC in CD mode is lower. Therefore, the more WLTC cycles the PHEV experiences, the lower the FC in CD mode. In a word, the contribution of FC in CD mode to the real FC gets lower with the increase of battery capacity.

The EC in CD mode under the NEDC procedure is obtained by the meaning of dividing the electricity consumed in a test cycle by the range of an NEDC cycle (11.03 km). The EC in the CD mode under the WLTP procedure is to consider the weight value of each speed phase in the whole CD mode, as shown in Formula (5). Through collecting the EC of PHEVs from the CATRC in China and other research institutions in the world, it is the EC of 10 vehicles in the CD mode under the WLTP and NEDC, as shown in Figure 4.

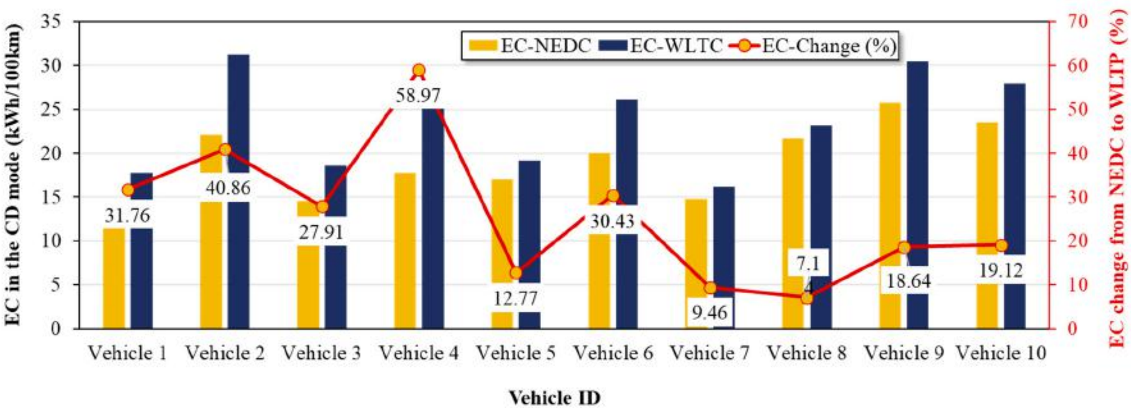


Figure 4. Electricity consumption (EC) of different PHEVs in charge-depleting (CD) mode under the NEDC and WLTP procedures.

It can be found that the EC in CD mode under the WLTP procedure is significantly higher than that under the NEDC procedure, with an average of about 26%. The results are consistent with those of JRC and ICCT reports [18,32]. It can be explained that the calculation of curb weight, tire selection, and driving resistance calculation of the WLTP procedure are stricter than those under the NEDC procedure. Meanwhile, The EC test of PHEV in CD mode is similar to that of battery electric vehicles, which is more sensitive to driving cycles as abovementioned. So, severe WLTP will cause higher EC. Furthermore, the JRC report points out that the EC ratio of the WLTP and NEDC procedure is related to the PHEV types [18]. It concluded that the heavier the vehicle type is, the larger the ratio is. This is mainly resulting from that the determination of road load is related to the curb weight. The calculation of curb weight under the WLTP procedure is stricter than that under the NEDC procedure. Because there are few vehicles selected in this study, there is no comparison on vehicle types. It could investigate the factor of vehicle type using the simulation method in the future work.

According to Formula (5), the EC of PHEV in CD mode could represent the AER of the corresponding vehicle. Therefore, it can be concluded that the AER of PHEV decreases by 26% on average with the switching of the testing procedure. Therefore, some PHEVs less than 63 km (NEDC) no longer meet the present regulatory requirements with the 50 km AER. So, the automotive manufacturers need to further increase the energy of the battery to meet the regulatory requirement for PHEV when designing after the switching of test procedures.

3.2. Analysis of the FC in CS Mode (C_{CS})

It can be seen from the calculation formula of weight energy consumption of PHEV that the EC in the CS mode is generally not considered. Therefore, this paper mainly analyzes the FC of PHEV in the CS mode. Considering that PHEV has the same FC characteristics as HEVs with a higher mixing degree when tested in the CS mode, the FC data of the HEVs are taken into account to analyze the FC in the CS mode for PHEV. The FC data are collected from the literature [16,18,19] and provided by an automotive manufacturer as shown in Figure 5.

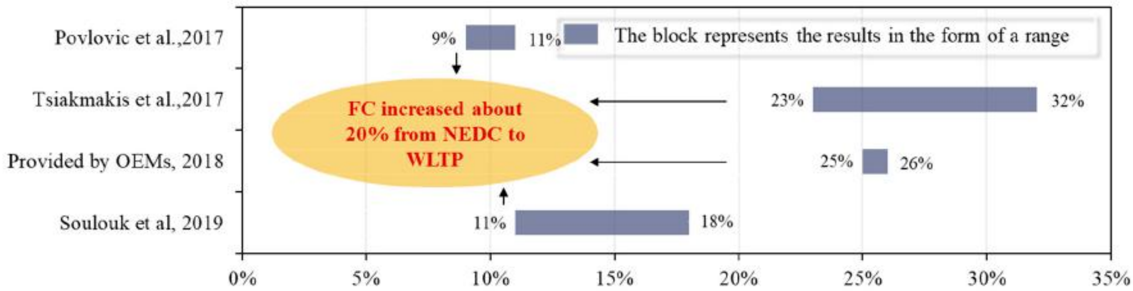


Figure 5. Fuel consumption (FC) change in the charge-sustaining (CS) mode of PHEVs from NEDC to WLTP.

As can be seen from Figure 5, FC in CS mode for PHEV under the WLTP procedure is significantly higher than that under the NEDC procedure, with an average of about 20%. This is explained in three aspects. First, the WLTP procedure is stricter than the NEDC procedure in the determination of test mass, tire selection, and driving resistance. Second, the correction of SOC under the WLTP procedure will also increase the FC of PHEV. Finally, the driving cycle of WLTC is stricter than the NEDC cycle for PHEV. On the one hand, the load can greatly improve FC due to the characteristics of the WLTC cycle. On the other hand, a small proportion of idle speed will reduce the fuel-saving capacity of the hybrid power system, which will also increase the FC of PHEV under the WLTP procedure.

3.3. Analysis of the Weight Energy Consumption for PHEV

The weight energy consumption of PHEV is calculated by weighting the energy consumption in the CD mode and CS mode. Table 1 shows the weight energy consumption of 10 different PHEVs, among which vehicle 1 and vehicle 2 are measured by JRC through experiments, while other data of eight PHEVs are from CATRC. It can be found that the weight EC of various PHEVs is lower than that in the CD mode, which is mainly due to the advantage of the weighted formula for EC. Furthermore, the weight EC of 10 PHEVs averagely increases by about 38% when switching from NEDC to WLTP, which is significantly higher than that in CD mode (26%). This shows that WLTP is stricter than NEDC in the calculation of weight EC of PHEV.

The weight FC of PHEV under the WLTP and NEDC procedure is shown in Figure 6. It can be seen that the weight energy consumption of PHEVs has increased significantly except for vehicle 1. The decrease of weight FC of vehicle 1 shows that the weight FC under the WLTP procedure might be lower than that under the NEDC procedure. It gives the credit to the difference of the calculation method of weight FC between NEDC and WLTP. In other words, the calculation method of WLTP is in favor of the PHEVs with a longer AER. Moreover, this phenomenon will be more significant with the increase in battery capacity. Thus, it can be said that the WLTP procedure is more friendly to the weight FC of PHEV with a larger battery.

Table 1. Weight energy consumption of 10 PHEVs.

Vehicle ID	Curb Mass (kg)	Engine Displacement (L)	Battery Capacity (kWh)	AER (km)		Weight FC (L/100 km)		Weight EC (kWh/100 km)	
				NEDC	WLTP	NEDC	WLTP	NEDC	WLTP
Vehicle 1	1315	0.65	21.8	161.8	122.8	0.68	0.40	11.67	16.71
Vehicle 2	1524	1.40	8.7	39.3	27.9	2.23	2.77	13.53	22.83
Vehicle 3	1505	1.80	8.0	55.0	43.0	1.30	2.70	10.00	13.58
Vehicle 4	1548	1.50	11.0	62.0	39.0	1.30	4.00	12.64	20.65
Vehicle 5	1665	1.50	9.0	53.0	47.0	1.40	3.30	11.54	14.02
Vehicle 6	1730	1.50	12.0	60.0	46.0	1.50	3.30	14.12	19.04
Vehicle 7	1955	1.50	12.0	81.0	74.0	1.30	2.30	11.32	13.56
Vehicle 8	2037	1.50	13.0	60.0	56.0	1.60	3.30	15.29	19.41
Vehicle 9	2281	2.00	18	70.0	59.0	1.60	3.80	18.95	25.51
Vehicle10	2390	2.00	19	81.0	68.0	1.80	2.90	17.92	23.36

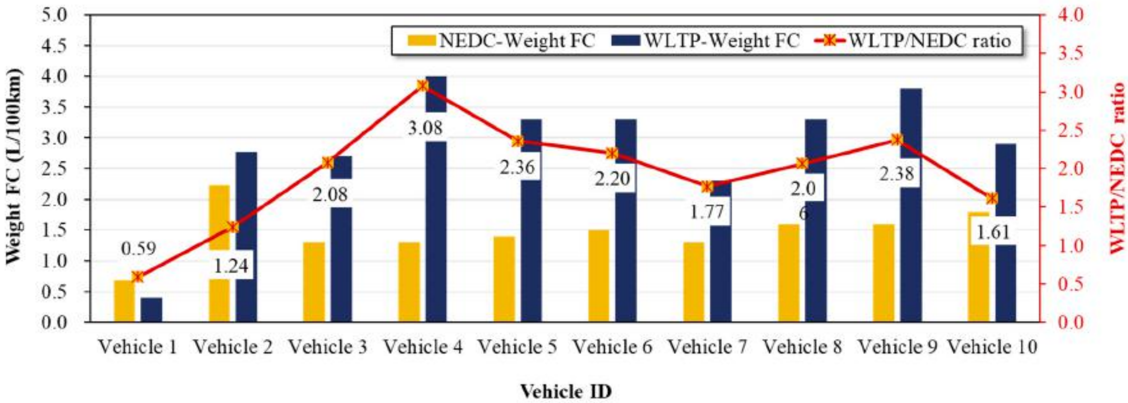


Figure 6. Weight FC of PHEVs under the WLTP and NEDC procedures.

It can be seen from the figure that the WLTP/NEDC ratio of weight FC is relatively large, with an average of about 1.94. This is quite different from the results (0.6 ~ 1.2) in the JRC report [18]. It needs to be explained that the weight FC data in this paper are all from the vehicle model currently on sale. The EMS of the engine of PHEV developed in China is tuned based on the NEDC cycle now, so the engine will start frequently under the WLTP procedure with the stricter driving cycle. Therefore, the engine will start frequently even if the SOC is high and to generate high FC in the CD mode. With the implementation of the WLTP procedure in China in 2021, automobile manufacturers will tune the EMS according to the WLTC driving cycle. This will make the engine not start frequently in the CD mode under the WLTP procedure. Then, the WLTP/NEDC ratio of weight FC will be further reduced in the future.

4. Effect on the Policies of PHEV from NEDC to WLTP

To promote the rapid development of the new energy automobile industry, the Chinese government proposed corresponding mandatory regulations and policy incentives, such as the NEV credit policy and subsidy policy [35–37]. In particular, the Chinese government delayed the decline of subsidies for two years in order to maintain the development of NEVs due to the COVID-19 outbreak in China. In order to ensure the development of NEVs driven by technology, the threshold value to meet the NEV credits regulations and subsidy policies is directly related to the energy-saving technology of vehicles.

The energy consumption of NEVs will change with switching from NEDC to WLTP, which will affect NEV credits and subsidy policies. The newly issued NEV credits regulation [38] and subsidy policy [39] in China, the following analysis is made on the impact of testing procedure switching on the policies for PHEVs. The NEV credit policy and subsidy policy for PHEVs are evaluated by the EC index in CD mode and the FC index in CS mode [38,39]. Table 2 presents the EC in CD mode and FC in the CS mode of the above 10 PHEVs under the NEDC and WLTP procedures. Among them, the FC in the CS mode of PHEV (Vehicle 3-Vehicle 8) in the China market is not given specific data. So, this paper assumes that the FC in CS mode under the WLTP procedure is 1.2 times of that in the NEDC procedure based on the above research.

Table 2. EC in CD mode and FC in CS mode of different PHEVs under the NEDC and WLTP procedures.

Energy Consumption	Vehicle ID									
	1	2	3	4	5	6	7	8	9	10
NEDC-CD EC (kWh/100 km)	13.47	22.14	14.55	17.74	16.98	20.00	14.81	21.67	25.71	23.46
NEDC-CS FC (L/100 km)	6.12	5.21	4.30	4.60	4.30	5.20	5.50	5.50	6.10	7.50
WLTP-CD EC (kWh/100 km)	17.75	31.18	18.60	28.21	19.15	26.09	16.22	23.21	30.51	27.91
WLTP-CS FC (L/100 km)	6.66	5.78	5.16	5.52	5.16	6.24	6.60	6.60	7.32	9.00

4.1. Effect on the NEV Credit Regulation of PHEV from NEDC to WLTP

The NEVs credits obtained by PHEV is equal to the basic credit multiplied by the credit multiple. According to the latest NEV credit regulation, the basic credit of PHEV is 1.6, while the credit multiple is determined by the values of the EC in CD mode and the FC in CS mode, which are 1 or 0.5. If the EC in CD mode for PHEV is greater than 135% of the EC targets of the same vehicle type BEV, or the FC in CS mode is greater than 70% of the FC limits for passenger car for the corresponding vehicle type, the credit multiple is 0.5, while the other is 1. The specific calculation is shown in Formula (6):

$$CR = \begin{cases} 0.8, \left(if\ E_{CD} \geq 135\%\ EC_{target}\ \ or\ C_{cs} \geq 70\%\ FC_{limit}\right) \\ 1.6,\ other \end{cases} \quad (6)$$

where CR is the credits that could be obtained by PHEV; EC_{target} indicates the EC targets for the same vehicle type BEV, which is the function of curb mass, kwh/100 km; FC_{limit} is the FC limits for the corresponding vehicle type, which is the function of curb mass, L/100 km.

The NEVs credits distribution for 10 PHEVs under the NEDC procedure is as shown in Figure 7. It should be noted that only when the EC in CD mode and the FC in CS mode are lower than the target and limit curves at the same time can one credit multiplier be obtained. It can be seen from the figure that 9 PHEVs can obtain NEVs credits except for vehicle 2 whose AER is less than 50 km. Among them, vehicle 3 and vehicle 9 can only get 0.5 times credit multiplier due to high EC, and the other seven PHEVs can get 1 credit multiplier.

The NEVs credits distribution for 10 PHEVs under the WLTP procedure is as shown in Figure 8. It can be seen from the figure that only two PHEVs can obtain one credit multiplier and three PHEVs can obtain a 0.5 credit multiplier after the test procedure is switched from NEDC to WLTP. The remaining five PHEVs could not obtain the NEVs credits. This shows that the switching of the test procedure has a great influence on the NEVs credit acquisition of PHEVs. The reason that five PHEVs cannot obtain NEVs credit is that their AER is less than 50 km under the WLTP procedure. It makes the PHEVs not meet the origin regulatory requirements and not enjoy policy privilege. Therefore, to obtain the NEVs credit of PHEV, the automobile manufacturers need to further increase the total energy of the battery and improve the AER of PHEV in the future. Furthermore, for the PHEV obtaining a 0.5 credit multiplier, the main reason is that the EC is too high, but the FC is still within the technological threshold of the NEV credit policy. It indicates that the influence of switching test procedures on the NEV credit policy for PHEV is higher in CD mode than in CS mode. Thus, the automobile manufacturers need to further consider the energy-saving technology of EC in the future vehicle design, such as the improvement of battery and motor efficiency, the optimization of the battery management system, and the further implementation of vehicle lightweight technology.

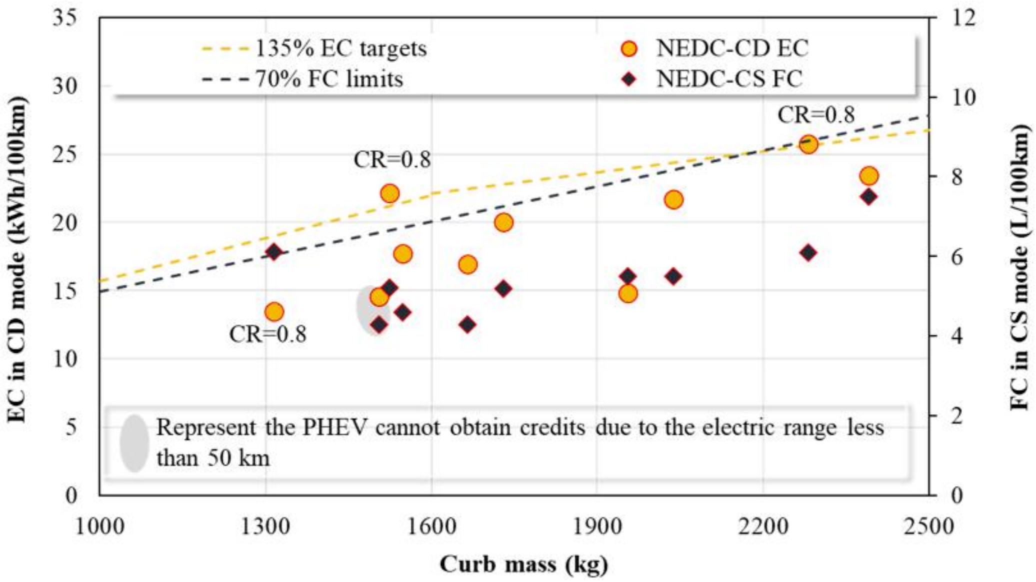


Figure 7. The new energy vehicles (NEVs) credits distribution for 10 PHEVs under the NEDC procedure.

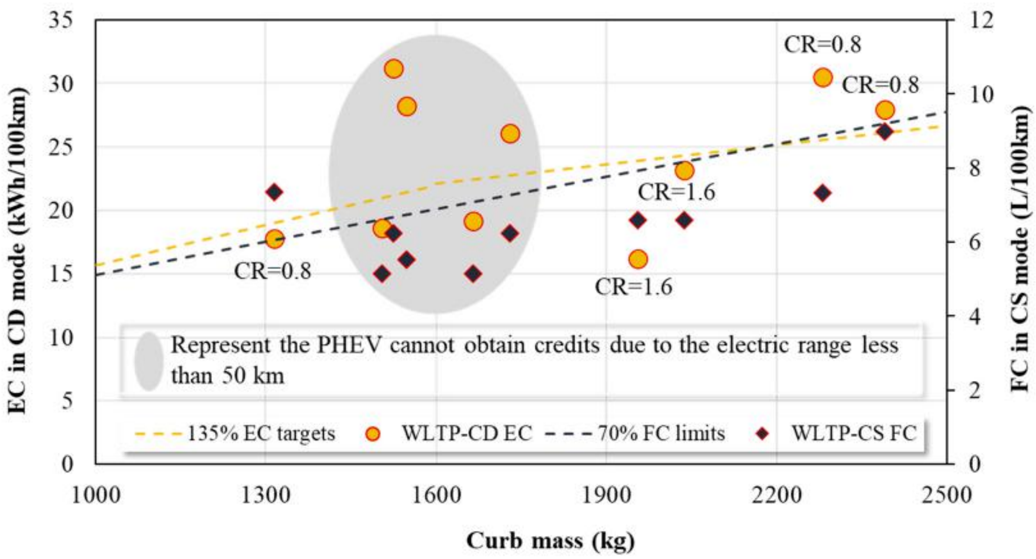


Figure 8. The NEVs credits distribution for 10 PHEVs under the WLTP procedure.

4.2. Effect on the Subsidy Policy of PHEV from NEDC to WLTP

According to the latest NEVs subsidy policy, the basic subsidy of PHEV is 8500 ¥ (RMB). The subsidy multiplier is related to the AER of PHEV and the FC in CS mode. According to the technological thresholds of subsidy policy, the FC in CS mode should be less than 60% compared with the FC limit of the same vehicle type for PHEVs with an AER of less than 80 km under the NEDC procedure. When the ratio is between 55% and 60%, the subsidy multiplier of the subsidy for PHEVs is 0.5. When the ration is less than 55%, the subsidy multiplier of the subsidy for PHEVs is 1. For PHEVs with AER under the NEDC procedure greater than or equal to 80 km, the EC in CD mode shall meet the requirements of the technological threshold for battery electric passenger vehicles in 2019. The specific calculation is shown in Formula (7):

$$SU = \begin{cases} 8500 * 0.5, \ (if \ \ 55\% FC_{limit} \ \le \ C_{CS} < 60\% \ FC_{limit} \ ) \\ 8500 * 1.0, (if \ C_{CS} < 55\% \ FC_{limit} \ \ or \ AER \ge 80 \text{ km}) \end{cases} \tag{7}$$

where SU is the subsidy that PHEV could obtain, ¥ (RMB); AER is the all-electric range of PHEV, km.

The subsidy distribution for 10 PHEVs under the NEDC and WLTP procedure is shown in Figure 9. It can be seen from the figure that all vehicles could obtain the one multiplier of subsidy except Vehicle 1 under the NEDC procedure. It should be noted that although the FC in CS mode of Vehicle 10 is within the range of 0.5 multiplier subsidy, it can also obtain 1 multiplier subsidy due to its AER over 80 km (81 km). However, only three PHEVs could obtain 0.5 multiplier subsidies, but no one could obtain one times subsidies when switching from NEDC to WLTP procedure. Five PHEVs could not obtain subsidies because their AER is less than 50 km, which does not meet range requirements for PHEVs in China. Two PHEVs cannot obtain subsidies due to their high FC in CS mode, which is over the FC limits. It can be concluded that the switching of the test procedure has a great impact on the subsidy policy of PHEV. Thus, the automobile manufacturers need to further increase the total energy of the battery and expand the AER to fit the switching from NEDC to WLTP, which is also the strategy commonly used by European automobile manufacturers. Therefore, to obtain more subsidies for PHEV, it is necessary to further develop energy-saving technology based on increasing battery capacity, to reduce the FC in CS mode to the scope of subsidies.

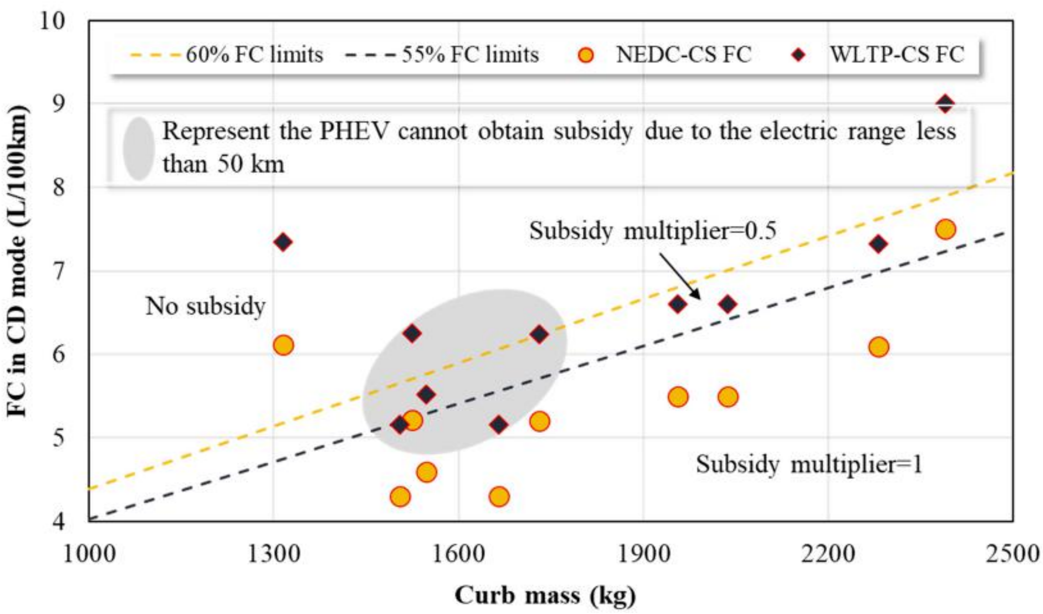


Figure 9. The subsidy distribution for 10 PHEVs under the NEDC and WLTP procedure.

In a word, the switch from NEDC to WLTP makes PHEV in a disadvantageous situation in the NEVs policy and subsidy policy. The main influence comes from two aspects: First, the switching of working conditions makes the AER of PHEV greatly reduced, which does not meet the requirements for the technical specifications of PHEV of the Chinese government, and cannot continue to enjoy the NEV credit and subsidy policies privilege; on the other hand, the switching of test procedures makes the energy consumption of PHEV in CD mode and CS mode increase, so that the PHEV can obtain the corresponding multipliers of the NEV credit and subsidy reduced.

However, the Chinese government has always adhered to the development route of PHEV. Although the test procedures are switched, it is not intended to make it difficult for automotive manufacturers to develop PHEV. In order to ensure that PHEV can still meet the requirements of technical specifications and obtain corresponding NEV credits and subsidies after the test procedure switching, the Chinese government has reduced the AER of PHEV to 43 km in the latest technical requirements.

Figure 10 shows the distribution of NEV credits and subsidies obtained under WLTP after reducing the AER technological specification of PHEVs. It can be seen from Figure 10a that three PHEVs can obtain one multiplier NEV credits after the AER of technological requirement is reduced. Moreover, five PHEVs can obtain 0.5 multiplier NEV credits while only two PHEVs cannot obtain NEV credits due to the AER is less than 43 km. Compared to the Figure 8, the decrease of AER technological requirement could improve the accessibility of NEV credits. Compared with Figure 7, the switching of test procedures could not alter the accessibility of NEV credits when the technological requirement of AER reducing to 43 km under the WLTP procedure. However, the increasing of EC and FC in the CD and CS mode under the WLTP procedure could decrease the multiplier of NEV credits compared to NEDC.

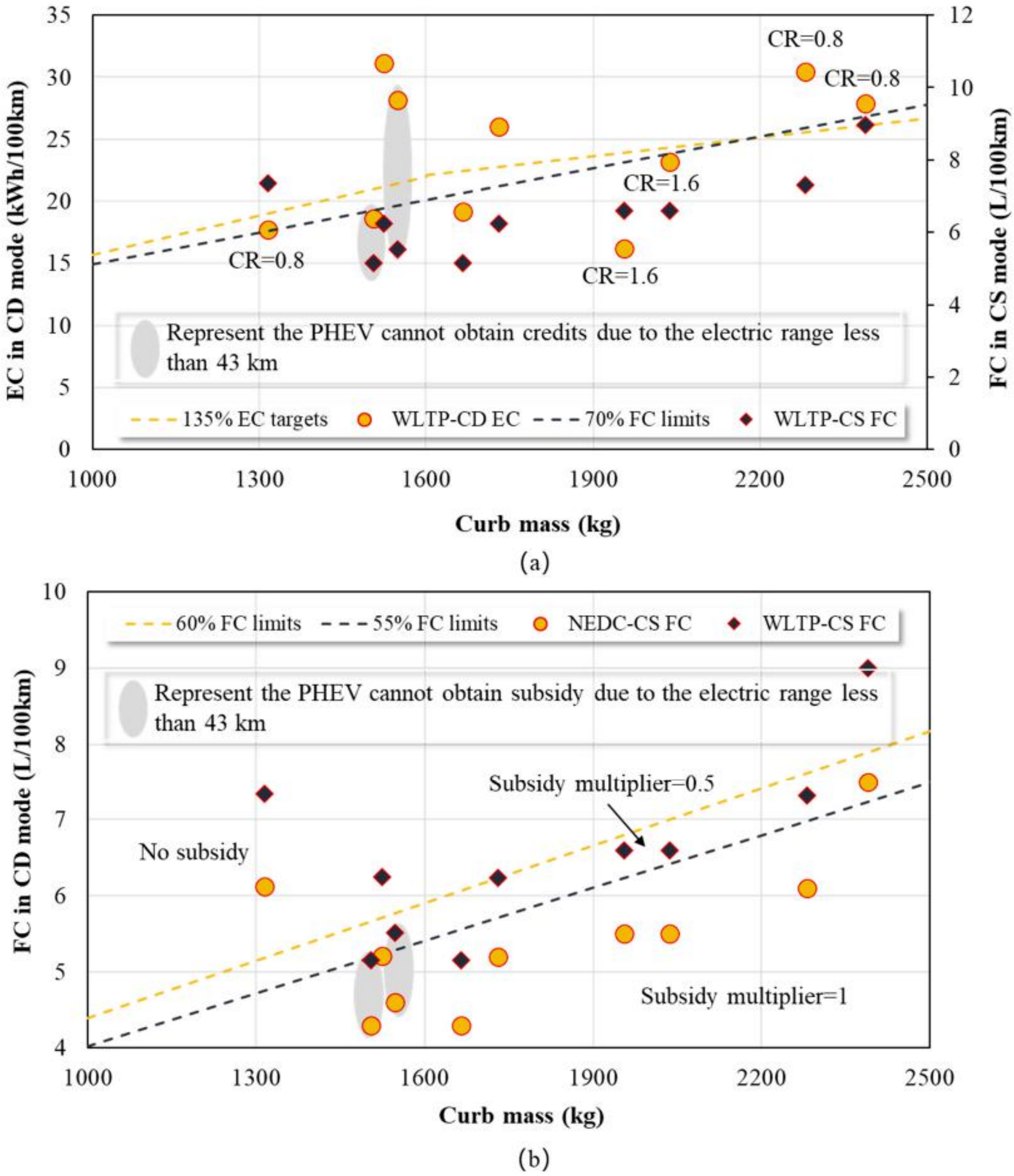


Figure 10. The NEV credits and subsidy distribution for 10 PHEVs under WLTP procedure after adjusting the all-electric range (AER) to 43 km in Chinese market: (**a**) NEV credits distribution; (**b**) subsidy distribution.

Meanwhile, it can be seen from Figure 10b that six PHEVs can get 0.5 multiplier subsidy under the WLTP procedure after the AER is reduced to 43 km, mainly because the FC in CS mode is too high to meet the technical thresholds of 1 multiplier subsidy. The remaining four PHEVs are not subsidized, of which two are due to the AER less than 43 km, and the other two are due to the FC in CS mode exceeding the threshold value of subsidy, so they are not subsidized. Compared to Figure 9, the decrease of AER technological requirement could improve the accessibility of subsidy while the higher FC in CS mode could lead to the lower multiplier subsidy.

This shows that the switching of test procedures has a limited impact on PHEV, which does not affect the availability of NEV credit and subsidies for PHEV with the support of the Chinese government. The switching of test procedure decreases the multipliers of NEV credit and subsidy due to the higher energy consumption. Thus, in order to further obtain the NEV credits and subsidies of PHEV, automobile manufacturers need to carry out the research and development of vehicle energy-saving technology, so as to reduce the EC in CD mode and the FC of CS mode. Therefore, it can be concluded that the switching of test procedure mainly puts forward higher requirements for the energy-saving technology of PHEV, but does not alter the availability of NEV credits and subsidies [40].

5. Policy Suggestion

The switching from NEDC to WLTP makes great changes in the energy consumption of PHEV in CD and CS modes to the extent that weight energy consumption, which affects the acquisition of NEV credit and subsidy of PHEVs to a extend. Therefore, to promote the reasonable development of PHEV in China after the test procedure change, the following suggestions are proposed:

First, the switching from NEDC to WLTP procedure increases the energy consumption of PHEV and makes most PHEVs unable to meet the requirements of 50 km AER. The Chinese government has changed the AER of PHEV to 43 km, indicating that the government has not tightened the requirements of PHEV, and the automotive manufacturer does not need to increase the battery to improve AER. However, the EC in CD mode and the FC of CS mode under the WLTP procedure are increased due to the condition switching. If the automotive manufacturers want to reach the corresponding fuel regulations, they need to further develop the energy-saving technology of the whole vehicle.

Secondly, the Chinese government's relaxation of PHEV's AER has little impact on the availability of PHEV's NEV credits and subsidies, so automotive manufacturers should not worry too much. However, with the increase of EC in CD mode and FC in CS mode, PHEV will obtain NEV credit and subsidy multiples. Thus, in order to obtain higher NEV credit and subsidy multiples, automotive manufactures need to research and develop energy-saving technologies of PHEV.

Thirdly, China automotive test cycle (CATC) will be used instead of WLTP to test the energy consumption of PHEVs after 2025. The Chinese government needs to evaluate the effect of the switching from WLTP to CATC in advance to make a smooth transition of PHEV's technical route. At the same time, automotive manufactures should prepare in advance, and develop and design PHEV according to the difference between CATC and WLTP.

Fourthly, China only considers the FC in the energy consumption test of PHEVs at present. In order to reasonably evaluate the energy consumption of PHEV, it is necessary to take the power consumption into account for comprehensive evaluation in the future. Then, the Chinese government should do a good job in policy planning, and automotive manufacturers should be prepared in advance.

6. Conclusions and Prospect

This paper studies the impact of switching from NEDC to WLTP on energy consumption, NEV credits, and subsidy policies of PHEVs through qualitative analysis and quantitative calculation methods. Firstly, the differences between the NEDC and WLTP procedures for testing energy consumption of PHEVs are qualitatively compared. Secondly, the effect of switching of test procedures on the energy consumption of PHEV is quantitative analysis. Finally, the NEV credit and subsidy changes of PHEVs are analyzed based on the energy consumption analysis after test procedure switching. According to the analysis results, the following conclusions are obtained:

(1) For the testing of PHEVs, the WLTP procedure is stricter in the determination of road load and test mass than those in the NEDC procedure. The weight calculation method for weight EC in the WLTP procedure is stricter than that in the NEDC procedure. The weight calculation method for weight FC in the WLTP procedure is stricter than that in the NEDC procedure for the PHEVs with a short AER. However, with the increase of the AER, the weight energy consumption under

the WLTP procedure may be lower than NEDC due to the weight calculation for weight FC in the WLTP procedure friendly to PHEVs with longer AER.

(2) The EC of PHEV in CD mode under the procedure is about 26% higher than that of NEDC, which greatly reduces the AER in WLTP. The FC in CD mode is related to the adjustment of the engine and the size of battery capacity. The higher the battery capacity, the lower the FC in CD mode. Furthermore, the FC in CS mode under the WLTP procedure is about 20% higher than that of NEDC. Because the EMS of PHEV on sale at present in China is tuned based on the NEDC cycle, not the WLTC cycle, the weight FC ratio of WLTP/NEDC is about 1.94.

(3) Most PHEVs do not meet the requirement of 50 km driving range due to the switching of test procedures. However, the relaxation of the requirement of 43 km AER under the WLTP procedure by the Chinese government has little impact on the availability of PHEV NEV credits and subsidies. However, the increase of the EC in the CD mode and the FC in CS mode have a great impact on the NEV credit multiple and subsidy multiple that PHEV can obtain. Therefore, automobile manufacturers need to further increase the research and development of vehicle energy-saving technology to obtain higher NEV credits and subsidies in the future.

(4) The Chinese government has reduced the technical specifications to 43 km of PHEV's AER under the WLTP procedure mainly for improving PHEV in term of the energy-saving technology after test procedure switching.

This paper only analyzes the differences between NEDC and WLTP procedures for testing energy consumption and to explore the effect of switching of test procedures on the NEV credits and subsidies for PHEV. However, it fails to give how to choose the power assembly of engine, battery, and motor to reduce the energy consumption of PHEV under the WLTP procedure to obtain more NEVs credit and subsidies. Moreover, the design value of the AER of PHEV under the WLTP procedure as well as the specific improvement measures of NEV credits and subsidy policies are not studied. Therefore, the battery and engine sizes of PHEV will be studied based on the WLTP procedure, and then evaluate the reasonability of NEV credit and subsidy policies based on the abovementioned study in the future work.

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Abbreviations

NEDC	New European Driving Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
CATC	China Automotive Test Cycle
PHEV	Plug-in Hybrid Electric Vehicles
AER	All-electric Range
EAER	Equivalent All-electric Range
CD mode	Charge-Depleting mode
CS mode	Charge-Sustaining mode

NEV	New Energy Vehicle
BEV	Battery Electric Vehicle
ICEV	Internal Combustion Engine Vehicles
SOC	State of Charge
EMS	Engine Management System
RPM	Revolutions Per Minute
EC	Electricity consumption
FC	Fuel Consumption
JRC	Joint Research Centre
CATRC	China Automotive Technology & Research Center

References

1. Chen, K.; Zhao, F.; Hao, H.; Liu, Z. Synergistic Impacts of China's Subsidy Policy and New Energy Vehicle Credit Regulation on the Technological Development of Battery Electric Vehicles. *Energies* **2018**, *11*, 3193. [CrossRef]
2. Hao, H.; Cheng, X.; Liu, Z.; Zhao, F. Electric vehicles for greenhouse gas reduction in China: A cost-effectiveness analysis. *Transp. Res. Part D Transp. Environ.* **2017**, *56*, 68–84. [CrossRef]
3. Hao, H.; Wang, S.; Liu, Z.; Zhao, F. Impact of China's CAFC standards on light-weighting strategy of automotive manufacturers. In Proceedings of the 2015 China Society of Automotive Engineers, Shanghai, China, 27 October 2015.
4. Ministry of Industry and Information Technology of People's Republic of China. Regulations and Policies of the Energy-Efficient and New Energy Vehicle. Available online: http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057585/n3057592/index.html (accessed on 25 December 2016).
5. Wang, S.; Chen, K.; Zhao, F.; Hao, H. Technology pathways for complying with Corporate Average Fuel Consumption regulations up to 2030: A case study of China. *Appl. Energy* **2019**, *241*, 257–277. [CrossRef]
6. SAE-China. *Technology Roadmap for Energy-Saving and New Energy Vehicles*; Chinese Society of Automotive Engineers: Beijing, China, 2016.
7. Liu, Z.; Hao, H.; Cheng, X.; Zhao, F. Critical issues of energy efficient and new energy vehicles development in China. *Energy Policy* **2018**, *115*, 92–97. [CrossRef]
8. Zhao, F.; Hao, H.; Liu, Z. Technology strategy to meet China's 5 L/100 km fuel consumption target for passenger vehicles in 2020. *Clean Technol. Environ. Policy* **2015**, *18*, 7–15. [CrossRef]
9. Weiss, M.; Zerfass, A.; Helmers, E. Fully electric and plug-in hybrid cars–An analysis of learning rates, user costs, and costs for mitigating CO2 and air pollutant emissions. *J. Clean Prod.* **2019**, *212*, 1478–1489. [CrossRef] [PubMed]
10. Badin, F. Energy efficiency evaluation of a Plug-in hybrid vehicle under European procedure, world harmonized procedure and actual use. *World Electr. Veh. J.* **2015**, *7*, 475–488. [CrossRef]
11. Ahmadian, A. A Review on Plug-in Electric Vehicles: Introduction, Current Status, and Load Modeling Techniques. *J. Mod. Power Syst. Clean Energy* **2020**, *8*, 412–425. [CrossRef]
12. Singh, K.V.; Bansal, H.O.; Singh, D. A comprehensive review on hybrid electric vehicles: Architectures and components. *J. Mod. Transp.* **2019**, *27*, 77–107. [CrossRef]
13. Shams-Zahraei, M. A Study on Plug-in Hybrid Electic Vehicles. In Proceedings of the 2009 IEEE Region 10 Conference, Singapore, 23–26 November 2009; pp. 1–5.
14. Li, M.; Peng, W.; Yan, F. An investigation into the comprehensive evaluation method of the energy consumption of PHEV. *Automot. Eng.* **2014**, *8*, 919–922.
15. Cubito, C.; Millo, F.; Boccardo, G.; Di Pierro, G.; Ciuffo, B.; Fontaras, G.; Serra, S.; Garcia, M.O.; Trentadue, G. Impact of Different Driving Cycles and Operating Conditions on CO_2 Emissions and Energy Management Strategies of a Euro-6 Hybrid Electric Vehicle. *Energies* **2017**, *10*, 1590. [CrossRef]
16. Pavlovic, J.; Tansini, A.; Fontaras, G.; Ciuffo, B.; Otura, M.G.; Trentadue, G.; Suarez-Bertoa, R.; Millo, F. *The Impact of WLTP on the Official Fuel Consumption and Electric Range of Plug-in Hybrid Electric Vehicles in Europe*; SAE: Warrendale, PA, USA, 2017.
17. Tsiakmakis, S.; Fontaras, G.; Ciuffo, B.; Samaras, Z. A simulation-based methodology for quantifying European passenger car fleet CO_2 emissions. *Appl. Energy* **2017**, *199*, 447–465. [CrossRef]

18. Tsiakmakis, S.; Fontaras, G.; Cubito, C.; Pavlovic, J.; Anagnostopoulos, K.; Ciuffo, B. *From NEDC to WLTP: Effect on the Type-Approval CO_2 Emissions of Light-Duty Vehicles*; Publications Office of the European Union: Brussels, Belgium, 2017; p. 50.
19. Solouk, A.; Kapadia, J.; Masterson, B.; Shakiba-herfeh, M. *Impacts of WLTP Test Procedure on Fuel Consumption Estimation of Common Electrified Powertrains*; SAE: Warrendale, PA, USA, 2019.
20. Pavlovic, J.; Ciuffo, B.; Fontaras, G.; Valverde, V.; Marotta, A. How much difference in type-approval CO2 emissions from passenger cars in Europe can be expected from changing to the new test procedure (NEDC vs. WLTP)? *Transp. Res. Part A Policy Pract.* **2018**, *111*, 136–147. [CrossRef]
21. GB/T 19753-2019. Test Methods for Energy Consumption of Light-Duty Hybrid Electric Vehicles. 2019. Available online: http://www.catarc.org.cn/StandardRevision/detail/1472.html (accessed on 23 September 2019).
22. Zhang, P.; Wang, X.; Tang, H. Analysis and comparison of Vehicle Sliding Resistance Based on CHINA 5 and CHINA 6. *Automible Applied Technol.* **2018**, *17*, 152–153.
23. Kim, N.; Moawad, A.; Shidore, N.; Rousseau, A. Fuel Consumption and Cost Potential of Different Plug-In Hybrid Vehicle Architectures. *SAE Int. J. Altern. Powertrains* **2015**, *4*, 88–99. [CrossRef]
24. Marotta, A.; Pavlovic, J.; Ciuffo, B.; Serra, S.; Fontaras, G. Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure. *Environ. Sci. Technol.* **2015**, *49*, 8315–8322. [CrossRef]
25. Guo, Q.; Zhao, D.; Chen, P. Comparison of WLTC & NEDC and Preliminary Study of Their Impact on Automobile Fuel Consumption. *Chin. J. Automot. Eng.* **2017**, *7*, 196–204.
26. Jon, A.; John, M.; Cecile, F.; Dirk, B.; Simon, D.V.; Matthew, H.; Matthew, K.; Jonathon, M. On-Road and Chassis Dynamometer Evaluations of Emissions from Two Euro 6 Diesel Vehicles. *SAE Int. J. Fuels Lubr.* **2014**, *7*, 919–934.
27. Bielaczyc, P.; Woodburn, J.; Szczotka, A. In Exhaust Emissions of Gaseous and Solid Pollutants Measured over the NEDC, FTP-75 and WLTC Chassis Dynamometer Driving Cycles. In Proceedings of the SAE 2016 World Congress and Exhibition, Detroit, MI, USA, 12–14 April 2016.
28. Bielaczyc, P.; Woodburn, J.; Szczotka, A. *A Comparison of Carbon Dioxide Exhaust Emissions and Fuel Consumption for Vehicles Tested over the NEDC, FTP-75 and WLTC Chassis Dynamometer Test Cycles*; SAE: Warrendale, PA, USA, 2015.
29. Pavlovic, J.; Marotta, A.; Ciuffo, B. CO_2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedures. *Appl. Energy* **2016**, *177*, 661–670. [CrossRef]
30. GB/T 19753-2013. Test Methods for Energy Consumption of Light-Duty Hybrid Electric Vehicles. 2013. Available online: http://std.samr.gov.cn/gb/search/gbDetailed?id=71F772D7EDD0D3A7E05397BE0A0AB82A (accessed on 23 December 2013).
31. Paffumi, E.; De Gennaro, M.; Martini, G. Alternative utility factor versus the SAE J2841 standard method for PHEV and BEV applications. *Transp. Policy* **2018**, *68*, 80–97. [CrossRef]
32. ICCT (The International Council On Clean Transportation). *How to Measure Fuel Consumption and CO2 Emission of Plug-in Hybrid Vehicles, Today and in the Future*; ICCT: San Francisco, CA, USA, 2017.
33. Goebel, D.; Plötz, P. Machine learning estimates of plug-in hybrid electric vehicle utility factors. *Transp. Res. Part D Transp. Environ.* **2019**, *72*, 36–46. [CrossRef]
34. National Technical Committee of Auto Standardization. Draft for Consultation on Technical Conditions of Plug-in Hybrid Electric Passenger Vehicles, 2019. Available online: http://www.catarc.org.cn/StandardRevision/detail/1471.html (accessed on 23 September 2019).
35. Wang, S.; Zhao, F.; Liu, Z.; Hao, H. Impacts of a super credit policy on electric vehicle penetration and compliance with China's Corporate Average Fuel Consumption regulation. *Energy* **2018**, *155*, 746–762. [CrossRef]
36. Zhao, F.; Chen, K.; Hao, H.; Wang, S.; Liu, Z. Technology development for electric vehicles under new energy vehicle credit regulation in China: Scenarios through 2030. *Clean Technol. Environ. Policy* **2018**, *21*, 275–289. [CrossRef]
37. Hao, H.; Ou, X.; Du, J.; Wang, H.; Ouyang, M. China's electric vehicle subsidy scheme: Rationale and impacts. *Energy Policy* **2014**, *73*, 722–732. [CrossRef]
38. Ministry of Industry and Information Technology of People's Republic of China. Amendments to the Measures for Parallel Management of Average Fuel Consumption of Passenger Vehicle Enterprises and Points of New Energy Vehicles (Draft for Comments), 2019. Available online: http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057585/n3057592/c7027601/content.html (accessed on 9 June 2019).

39. The State Council. Notice on Improving Fiscal Subsidy Policies for the Promotion and Application of New Energy Vehicles, 2020. Available online: http://www.gov.cn/zhengce/zhengceku/2020-04/23/content_5505502.htm (accessed on 23 April 2020).
40. Zhou, B.; Zhang, S.; Wu, Y.; Ke, W.; He, X.; Hao, J. Energy-saving benefits from plug-in hybrid electric vehicles: Perspectives based on real-world measurements. *Mitig. Adapt. Strateg. Global Chang.* **2017**, *23*, 735–756. [CrossRef]