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A Study of Testing and Evaluation Method of Energy Consumption for Plug-in Hybrid Electric Vehicle

Wang Peng[1] , Ou Yang[1] , Xu Lei[1] , Bai Qin[1] , Sun Hanwen[1] , Michael Duoba[2]
[1]*China Automotive Engineering Research Institute Co., Ltd.*
[2]*Argonne National Laboratory, U.S.A.*

Summary

Based on the advantages and disadvantages of the evaluation methods of energy consumption in European (including China) and USA, and the two aspects of test cycle selection and weighting, CD/CS stage division and weighting, a new energy consumption evaluation method was developed. Two different control strategy vehicles were verified by this method. The analysis shows the simulation of multiple power requirements of driving conditions and the possibility of test cycle weighting when UDDS and US06 are weighted according to the ratio of 55:45. UF（R_{CDA}）is used to achieve the exact division and weighting of the CD/CS stage. The method can fully reflect the characteristics of both AER and Blended-type PHEV control strategies, and restore the characteristics of CD/CS stage energy consumption simultaneously.

Key words: energy consumption evaluation, CD/CS stage, test cycle, division, weighting

1 Background and Motivation

PHEV (Plug-in hybrid electric vehicle, PHEV) is an effective solution to zero emission[1]. However, the energy consumption performance (both fuel consumption and electrical consumption, FC and EC) evaluation of PHEV is complex since power coupling technology and various energy management control strategy and obtaining energy from the grid.

In recent years, standard regulations, such as SAE J1711[2], ECE R101[3], GB/T 19753[4], have been revised to accommodate to energy consumption evaluation of PHEV. Some research have been studied on this area already. Based on Blended-type and AER (All Electric Range, AER) control strategies, paper [5] studied the FCT (Full Charge test, FCT) and the necessity of weighting CD (Charge Depleting, CD) and CS (Charge Sustaining, CS) according to the resident travel characteristics. Paper [6] made supplementary specification for SAE J1711-2010, introduced how to divide and weight CD/CS, and driving mileage related to energy consumption, and validated the Blended-type and AER control strategies of PHEV. Paper [7] divided the CD/CS by the CO_2 emission of TS (Transition cycle, TS) cycle. Paper [8] compared and analysed the influence of several typical control strategies on the energy consumption of PHEV under unknown trip length by simulation. These papers were embodied in the compatibility of the test method with the energy management strategy, the necessity of weighting the energy consumption data in the two stages of CD/CS. The influence of driving behavior, environmental, road conditions, control strategy and other driver-vehicle-road closed-loop system factors on the energy consumption evaluation results has been studied. The research above formed the PHEV energy consumption test and evaluation systems in European (including China) and USA, mainly focused on regulation certification, test method and evaluation index calculation, etc.

Based on the advantages and disadvantages of existing energy consumption evaluation methodology in test matrix design and data weighting, we referred to the factors affecting energy consumption and designed a new method with the selection and weighting of test cycle, the division and weighting of CD/CS stages. At last, we verified this method by using a Blended-type and an AER PHEV.

2 Comparisons of European (including China) and USA methods

2.1 Energy Consumption Testing Methods in Europe (including China) and USA

In Europe, tests have been developed according to ECE R101 regulation. The GB/T 19753 standard of China has followed this procedure. Based on the NEDC test cycle, the method tests condition A (maximum charged state) and condition B (minimum charged state), and weights the condition A and condition B with the average driving range of 25km between two charging behaviour. The European method is calculated with the equation (1).

$$C = \frac{D \times C_1 + 25 \times C_2}{D + 25} \qquad (1)$$

C is weighted fuel consumption or electrical consumption. C_1 and C_2 are fuel consumption and electrical consumption measured by condition A and condition B. D is AER (all electric range, AER) or D_{OVC} (off – vehicle charging range, D_{OVC}).

The USA method based on the typical five cycles in the United States is implemented by Federal regulations 40 CFR Part86[9], 40 CFR Part600[10], and recommended standard SAE J1711, SAE J2841[11]. The method carries out FCT at CD and CST[2] (Charge Sustaining Test, CST) at CS of PHEVs, and weights the test results of FCT and CST using the UF[11] (Utility Factor, UF). The USA method calculate the fuel consumption with the equation (2) and the electric consumption with the equation (3).

$$Y_{UF} = \sum_{i=1}^{lastCD} \left[UF(iD) - UF((i-1)D) \right] Y_i + \left[1 - UF(R_{CDC}) \right] Y_{CS} \qquad (2)$$

$$E_{UF} = \sum_{i=1}^{lastCD} \left[UF(iD) - UF((i-1)D) \right] E_i \qquad (3)$$

Y_{UF} is weighted fuel consumption. $UF(x)$ is UF coefficients corresponding to distance x. Y_i is fuel consumption of FCT in cycle i. D is cycle range. R_{CDC} is Charge-Depleting Cycle range. Y_{CS} is fuel consumption of CST. E_{UF} is weighted electrical consumption, and E_i is electrical consumption of FCT in cycle i.

2.2 Comparisons of the European (including China) and USA Methods

Considering the selection and weighting of the test cycle, the European (including China) method uses the NEDC test cycle, which is a steady-state test cycle and difficulty to take into account the transient state of the vehicle. The typical five cycle are used in the USA method, which covers different levels of transient conditions with drastic velocity changes and simulates different road condition and driving styles, fully considering the impact of control strategies on energy consumption.

Considering the CD/CS division, the European (including China) method obtains condition B by driving at a constant velocity until the engine starts. This setting does not guarantee the condition B has entered the CS stage, leading to an imprecise test boundary conditions. The US method strictly divides PHEV into CD/CS stages and achieves both AER and Blended-type control strategies. The FCT (full charge test, FCT) expresses the transition from CD to CS, and the CST (charge sustaining test, CST) embodies the convergence of SOC in CS stage.

Considering the CD/CS weighting, the European (including China) method, using a weighted coefficient of 25 km to represent the distance between two charging stations despite of the various charging facilities. This method does not take into account the difference in discharge rate of batteries in CD stage, and the results is more favorable for the AER control strategy. Based on the characteristics of resident trip and vehicle charging status in CD/CS stage, the USA method can adapt to the characteristics of both AER and Blended-type control strategies by taking the discharging rate in the weighted process of CD stage into account. However, the CS part of transitional cycle in the USA method during the weighting process of the CD stage will results to a higher fuel consumption of the CD stage. And the complex energy consumption weighting of five cycle makes it difficult to implement in the USA method.

3 Development of Energy Consumption Test and Evaluation Method

Based on the advantages and disadvantages of the European (including China) and the USA methods, an energy consumption test and evaluation method compatible with AER and Blended-type control strategies is developed. It consists of two parts: test method and data calculation.

3.1 Test Method

The test method designed CST and FCT based on UDDS and US06 cycle in room temperature environment, and simulated the frequent start/stop of the engine in the city condition and high velocity conditions with more aggressive highway driving style. So, this method reconstructed the transient characteristics of vehicles in low, medium and high velocity. The vehicle driving status, energy consumption and emission data, mileage and other parameters were collected during the test. NEC discriminant[2] is used to determine the validity of CST and FCT end-of-test criterion.

3.2 Data Calculation

3.2.1 CD/CS Division

The CD cycle, transition cycle and CS cycle are distinguished according to the NEC discriminant method. In order to solve the problem that the USA method can not quantitatively distinguish the two stages of CD/CS, we used CO_2 discriminant[7] is used to divide the CD/CS part of the transition cycle.

3.2.2 CD/CS Weighting

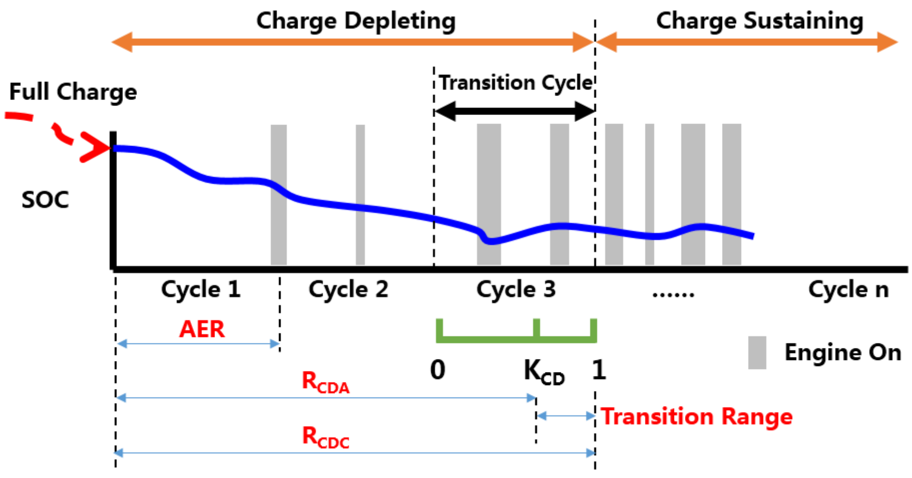


Figure1: Distance Definitions for PHEVs Energy Consumption Test

Distance definitions for PHEVs energy consumption test are defined in Figure1. We can figure out the relationship among AER, R_{CDC} (Charge-Depleting Cycle range, R_{CDC}), R_{CDA} (Actual Charge-Depleting Range, R_{CDA}) and TR (Transition Range, TR) clearly. Aiming at the disadvantage of using R_{CDC} weighted

CD/CS stage in the USA method, we weighted the fuel consumption and electrical consumption data of CD/CS by R_{CDA}, weighted every test cycle of the CD stage and overall the CS stage, assuming that the N cycle of the FCT is a transition cycle. As shown in Equation (4) and Equation (5).

$$Y = \sum_{i=2}^{N-1}\left[UF(d_{N-1}) - UF(d_{N-2})\right]Y_{N-1} + \left[UF(R_{CDA}) - UF(d_{N-1})\right]Y_R + \left[1 - UF(R_{CDA})\right]Y_{CS} \qquad (4)$$

$$E = \sum_{i=2}^{N-1}\left[UF(d_{N-1}) - UF(d_{N-2})\right]E_{N-1} + \left[UF(R_{CDA}) - UF(d_{N-1})\right]E_R \qquad (5)$$

Y and E are the fuel consumption and electrical consumption weighed by UF. d_{N-1} is the distance traveled during the first $N-1$ cycles. Y_{N-1}, E_{N-1} are the fuel consumption and AC power consumption during the first $N-1$ cycles. Y_R, E_R are the fuel consumption and AC power consumption in the CD stage of transition cycle. R_{CDA} is actual charge-depleting range. Y_{CS} is the fuel consumption of CST.

3.2.3 Test Cycle Weighting

Since the NEDC can not reflect the variety driving requirements, and the weighting between multiple cycles in five cycle method is too complex. In our method, the energy consumption obtained by UDDS and US06 cycles are taken into account in city and highway conditions respectively. The two conditions are weighted according to the ratio of 55:45.As shown in Equation (6).

$$X = \frac{1}{\frac{0.55}{City} + \frac{0.45}{Highway}} = \frac{1}{\frac{0.55}{UDDS} + \frac{0.45}{US06}} \qquad (6)$$

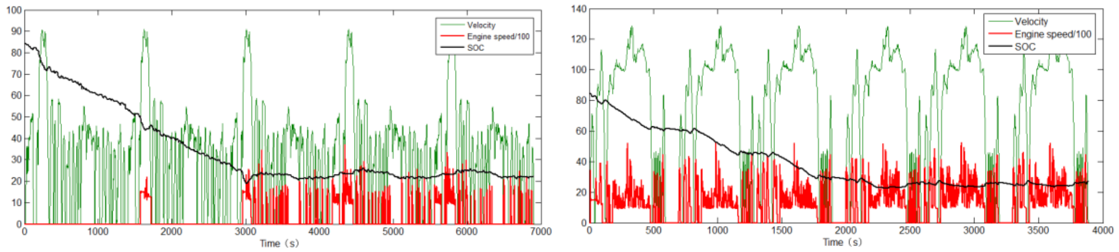
Each indicates the corresponding fuel consumption and electrical consumption. $City$, $Highway$, X stand for city condition, highway condition and weighed condition.

4 Method Verification

In order to verify the feasibility of this method, CAREI (China Automotive Engineering Research Institute Co., Ltd, CAERI) and ANL (Argonne National Laboratory, ANL) carried out a test jointly with Prius PHEV and Chevrolet Volt. The FCT of UDDS and US06 are shown in Figure 1 and 2 respectively. The examples of energy consumption calculations are shown in Tables 1 and 2.

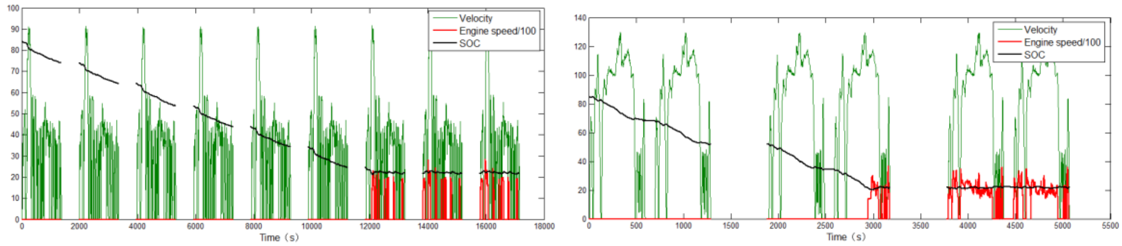
E_i is direct current electric consumption in cycle i. Y_i is fuel consumption in cycle i. GE is a recharging energy from grid. NEC is a net energy change tolerances[2]. $UF(x)$ is UF coefficients corresponding to distance x. E_{AC} is alternating current electric consumption in cycle i. FC_{CDCS} is weighted fuel consumption both CD and CS stage. EC_{CDCS} is weighted electric consumption both CD and CS stage. FC_{final} is weighted fuel consumption both UDDS and US06 test cycle. EC_{final} is weighted electric consumption both UDDS and US06 test cycle.

Limited by battery power and capacity, the Prius PHEV compensates for the lack of battery output by starting the engine in the CD stage. While the Volt can achieve almost all electric range in the CD stage. The energy consumption weighted UDDS and US06 test cycles of the Prius PHEV is 3.34L/100km and 3.49kWh/100km, and the Volt is 2.19L/100km and 11.24kWh/100km. It shows that AER PHEV is more dependent on electrical consumption than Blended-type PHEV, thus the replacement ratio of electrical energy to fuel is much higher. Therefore, this method can reflect the characteristics of AER and Blended-type control strategy, and reconstruct the energy consumption characteristics of CD/CS stages.



(a) UDDS FCT of MY2012 Prius PHEV (b) US06 FCT of MY2012 Prius PHEV

Figure1: UDDS FCT and US06 FCT of Prius PHEV



(a) UDDS FCT of MY2012 Chevrolet Volt (b) US06 FCT of MY2012 Chevrolet Volt

Figure2: UDDS FCT and US06 FCT of Chevrolet Volt

Table 1: Test Data Calculation of Prius PHEV

Test	cycle No.	E_i (Wh/km)	Y_i (L/100km)	GE (Wh)	NEC (%)	K_{CD}	R_{CDA} (km)	$UF(x)$	E_{AC} (Wh/km)
	1	97.887	0.000		/			0.166	123.369
	2	81.729	0.946		97.19			0.318	103.005
UDDS FCT	3	19.795	2.838	3036	7.85	0.155	25.73	0.335	184.208
	4	1.491	3.153		0.53			/	/
	5	-1.233	3.153		-0.44			/	/
UDDS CST			3.812						
FC_{CDCS} (L/100km)				2.696					
EC_{CDCS} (kWh/100km)				3.927					
	1	62.336	4.106		17.08			0.187	79.816
	2	36.632	4.400		9.37			0.335	46.903
	3	34.512	4.394		8.34			0.451	44.189
US06 FCT	4	31.787	4.394	2732	8.14	1	51.65	0.544	40.701
	5	-4.758	5.573		-0.96			/	/
	6	-1.612	5.280		-0.34			/	/
US06 CST			5.203						
FC_{CDCS} (L/100km)				4.710					
EC_{CDCS} (kWh/100km)				3.078					
FC_{final} (L/100km)				3.34					
EC_{final} (kWh/100km)				3.49					

Table 2: Test Data Calculation of Chevrolet Volt

Test	cycle No.	E_i (Wh/km)	Y_i (L/100km)	GE (Wh)	NEC (%)	K_{CD}	R_{CDA} (km)	$UF(x)$	E_{AC} (Wh/km)
UDDS FCT	1	138.107	0	11762	/	0.206	75.39	0.166	162.626
	2	132.301	0		/			0.318	155.789
	3	132.084	0		/			0.425	155.534
	4	131.206	0		/			0.523	154.500
	5	130.558	0		/			0.592	153.736
	6	129.848	0		/			0.655	152.900
	7	33.305	4.191		8.94			0.669	159.701
	8	-0.341	5.158		0.07			/	/
UDDS CST			5.110						
FC_{CDCS} (L/100km)				1.727					
EC_{CDCS} (kWh/100km)				10.494					
US06 FCT	1	203.382	0	11481	/	0.046	51.89	0.187	242.182
	2	196.491	0		/			0.335	233.978
	3	199.462	0		/			0.451	237.516
	4	141.497	2.053		77.53			0.544	168.491
	5	-6.905	7.333		-1.06			0.544	347.203
	6	-3.549	7.040		-0.57			/	/
US06 CST			6.730						
FC_{CDCS} (L/100km)				3.260					
EC_{CDCS} (kWh/100km)				12.314					
FC_{final} (L/100km)				2.19					
EC_{final} (kWh/100km)				11.24					

5 Conclusion

Based on the advantages and disadvantages of the evaluation methods of energy consumption in European (including China) and USA, and the two aspects of test cycle selection and weighting, CD/CS stage division and weighting, a new energy consumption evaluation method was developed. The analysis shows, this method realized the accurate division of CD/CS stages and the weighting of test cycles, embodied the characteristics of both AER and Blended-type control strategies, and reconstructed the characteristics of CD/CS energy consumption simultaneously.

Acknowledgments

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References

[1] Leitman S. Build Your Own Plug-In Hybrid Electric Vehicle[J]. McGraw-Hill Digital, 2009.

[2] Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid -Electric Vehicles, Including Plug –in Hybrid Vehicles[S]. SAE J1711-2010.

[3] Uniform Provisions Concerning the Approval of Passenger Cars Powered by an Internal Combustion Engine Only, or Powered by a Hybrid Electric Power Train with Regard to Measurement of the Emission of Carbon dioxide and Fuel Consumption and/or the Measurement of Electric Energy Consumption and Electric Range, and of Categories M1 and N1 Vehicles Powered by an Electric Power Train Only with Regard to the Measurement of Electric Energy Consumption and Electric Range[S]. ECE R-101 Rev.3, 2013.

[4] GB/T 19753-2013 轻型混合动力电动汽车能量消耗量试验方法[S]. 国家质量监督检验检疫总局、国家标准化管理委员会, 2013.

[5] Duoba M, Carlson R, Wu J. Test Procedure Development for “Blended Type” Plug-In Hybrid Vehicles[J]. Microprocessors & Microsystems, 2009, 1(1):359-371.

[6] Duoba M, Carlson R, Bocci D. Calculating Results and Performance Parameters for PHEVs[C]// SAE World Congress & Exhibition. 2009.

[7] Kawai T, Niikuni T. Fuel Consumption Test Protocol Concept for Plug-in Hybrid Electric Vehicle[J]. Fuel Consumption, 2009.

[8] Cong H, Liangfei X, Hewu W, et al. Energy Management of Plug-in Hybrid Electric Vehicles with unknown trip Length[J]. Journal of Franklin Institute, 2015, 352(2):500-518.

[9] U.S. Government, Code of Federal Regulations. Title 40, Part 86, Control of Emissions from New AND In-use Highway Vehicles and Engines [EB/OL]. [2012-11-27]. http://www.ecfr.gov/.

[10] U.S. Government, Code of Federal Regulations. Title 40, Part 600, Fuel Economy and Greenhouse Gas Exhaust Emissions of Motor Vehicles [EB/OL]. [2012-11-27]. http://www/ecfr.gov/.

[11] Utility Factor Definitionsfor Plug-in Hybrid Electric Vehicles Using Travel Survey Data[S]. SAE J2841-2010.

Authors

Peng Wang received the B.S. degree from Jilin University, Changchun, China, in 2008. He is currently a senior engineer in China Automotive Engineering Research Institute. His research interests include configuration and economic performance of hybrid systems, energy management control strategy, energy consumption saving technology of Plug-in Hybrid Electric Vehicles based on testing and evaluation.