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A Study on the Impact of Driving Quality on the Energy Consumption of Plug-in Hybrid Electric Vehicles (PHEV)

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Abstract: Plug-in hybrid electric vehicles (PHEVs) represent a critical technology for reducing emissions and enhancing energy efficiency, making their energy consumption assessment of paramount importance. This study investigates the impact of varying driving qualities on the energy consumption of PHEVs under the World Light Vehicle Test Cycle (WLTC). The assessment of driving quality adheres to the SAE J2951[1] standard. Through energy consumption tests conducted on a PHEV in pure electric mode under different driving qualities, six metrics were employed: Energy Rate (ER), Distance Rate (DR), Energy Efficiency Rate (EER), Absolute Speed Change Rate (ASCR), Root Mean Square Speed Error (RMSSE), and Inertial Work Rate (IWR). The results indicate that these metrics significantly reflect the impact of driving quality on energy consumption, with aggressive driving leading to higher energy usage. Although all driving qualities meet the requirements of the current Chinese energy consumption testing standard GBT 19753[2], the observed energy consumption differences due to varying driving qualities highlight the inadequacies of the current testing methods in evaluating and controlling driving quality. This underscores the necessity for improving energy consumption testing methods to more accurately assess the actual energy performance of PHEVs and to provide consumers with more reliable energy consumption information.

1. Introduction

In the background of the intensifying global energy crisis and the increasing awareness of environmental protection, energy conservation and emission reduction have become the core development direction of the automotive industry. Plug-in hybrid electric vehicles (PHEVs), as a transitional technology, are gradually becoming a key approach to reduce greenhouse gas emissions and enhance energy utilization efficiency.

Accurately assessing the energy consumption of PHEVs under different driving qualities is crucial for optimizing vehicle performance, formulating energy consumption labels, and guiding consumers to develop more environmentally friendly driving habits.

Currently, the standards for light-duty vehicle energy consumption testing in China mainly reference GB 18352.6-2016 "Limits and measurement methods for emissions from light-duty vehicles (China 6)"[3]. This standard makes clear requirements for the control of driving quality, mainly divided into two aspects: one is the quantitative specification of the allowable deviation between the actual vehicle speed and the prescribed speed of the test cycle; the second is the qualitative requirements for driving behavior, such as precise control of the accelerator pedal, to ensure that the vehicle strictly follows the predetermined speed curve.

However, the existing standards do not explicitly specify "avoiding unnecessary rapid acceleration or deceleration" and corresponding control indicators. This may lead to some frequent but small-amplitude acceleration and deceleration behaviors that, while meeting the standard requirements, adversely affect the energy consumption test results.

Jakub Lasocki's research [4] pointed out that the WLTC, as a new test cycle, better reflects the vehicle performance under actual driving conditions, helping to reduce the differences between laboratory tests and actual road tests. Matthew Blanks and Nathan Forster's research [5] emphasized the potential of automated control systems in improving the precision of fuel economy tests. The DEVCon system, by utilizing electronic control technology, significantly enhances the repeatability and accuracy of tests. Christian R. Tollefson's research [6] indicated that the ECMS strategy based on Willans Line not only reduces fuel consumption but is also significant for improving the energy efficiency of hybrid electric vehicles. Richard "Barney" Carlson et al.'s research [7] showed that the fuel and electric energy consumption of PHEVs is highly dependent on driving characteristics, especially driving intensity. PHEVs, by optimizing control strategies and power train configurations, can effectively reduce energy consumption even under variable driving behaviors. Edward Colin Chappell's research [8] improved the accuracy of chassis dynamometer emission testing by 6.5 times through the implementation of statistical process control tools. Yuhan Huang et al.'s research [9] indicated that novice drivers use the accelerator pedal more aggressively than experienced drivers, resulting in higher vehicle and engine speeds, with slightly higher average fuel consumption (2% higher). Iván Silva et al.'s research [10] proposeed a systematic methodology that can help researchers make more informed decisions in choosing machine learning models suitable for driving style classification, which is significant for the development of intelligent vehicle control and advanced driver assistance systems (ADAS).

This study aims to delve into the impact of different driving qualities on the pure electric energy consumption of light-duty plug-in hybrid electric vehicles under WLTC conditions and to conduct a comprehensive evaluation of driving quality based on the SAE J2951 standard, with the expectation of providing a scientific basis for the accuracy of energy consumption testing and the optimization of vehicle energy consumption performance.

2. Test method

2.1. Test sample vehicle

A PHEV passenger car was selected as the test vehicle in this study. Basic information is shown in Table 1.

Table 1: Prototype parameters.

Parameter	Parameter value
Curb weight(kg)	2330
Driving form	front-wheel drive
Displacement(L)	1.5
SEATS	5
Total capacity of power battery pack (Ah)	65

2.2. Test basis

The energy consumption tests involved in this study all referred to GB/T 19753-2021 "Test Methods for energy consumption of Light-Duty hybrid electric vehicles" and its referenced GB 18352.6-2016 "Limits and Measurement Methods for Emissions from Light-Duty Vehicles (China Phase VI)", using WLTC. At the same time, the test results and driving quality were evaluated, referring to the evaluation methods and indicators mentioned in SAE J2951 "Drive Quality Evaluation for Chassis Dynamometer Testing".

2.3. Test equipment

The equipment used in the experiment is shown in Table 2.

Table 2: Test equipment information.

Name	Type	Manufacturer
Chassis dynamometer	ROADSIM 48”	AVL
Power analyzer	PW3390	HIOKI

2.4. Test process

Before the test, prepare the vehicle according to GB/T 19753-2021, including road resistance fitting and charging the power battery to a full state.

Ensure that the prototype vehicle is soaked in an environment of (23℃±3)℃ for (6-36) hours before the test.

According to the energy consumption mode test method of GB/T 19753-2021, prepare the prototype vehicle for energy consumption testing (without analyzing exhaust emissions), ensuring that the prototype vehicle meets the test conditions for energy consumption mode, including engine oil, coolant temperature, tire pressure, etc.

Normal driving behavior: The driver should control the accelerator and brake pedals as smoothly as possible to make the actual driving speed curve as smooth as possible.

Aggressive driving behavior: The driver should control the accelerator and brake pedals as aggressively as possible, making the actual driving speed curve fluctuate with small amplitude and high frequency.

Ensure that both driving behaviors can meet the GB 18352.6-2016 requirements for the allowable deviation between the actual vehicle speed and the specified speed of the test cycle.

Alternately use the two driving behaviors to conduct WLTC cycle testing, recording the total energy change of the energy storage device during the test.

Stop the test immediately when the engine starts, and discard the results of that cycle test.

The above steps 1-8 constitute one set of tests.

Repeat to complete two sets of tests, ensuring that different driving behaviors are selected for the first driving cycle in each set of tests.

Test process is shown in Figure 1.

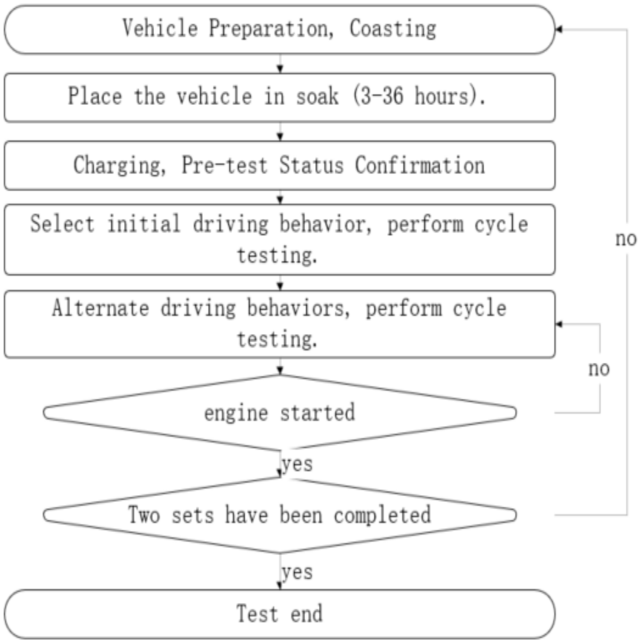

Figure 1: Test flow chart.

3. Results

3.1. Comprehensive assessment results

The test vehicle underwent two sets of tests under alternating driving behaviors, with each set consisting of three cycles of testing, resulting in three cycles of test results for each driving behavior. Each cycle of the test recorded the vehicle's speed data and changes in battery charge data. The testing method was carried out in accordance with the GB/T 19753-2021 power consumption mode test method, and all actual driving curves under the two driving behaviors met the standard's requirements for the validity of the test results. To analyze the impact of different driving behaviors on energy consumption, the first step is to quantify the driving behavior. According to the SAE J2951 standard, the Energy Rate (ER) reflects the energy consumption of the vehicle under different speed and acceleration conditions. A higher ER value may indicate that there are more accelerations and decelerations during the test cycle. The Distance Rate (DR) reflects the consistency of the vehicle's driving speed and distance during the test cycle. A larger DR value may indicate that there are significant speed changes during the test, making it difficult for the driver to maintain consistency with the target speed. The Energy Economy Rate (EER) reflects the vehicle's energy efficiency performance, with a higher EER value indicating lower vehicle efficiency and higher energy consumption during the test cycle. The Absolute Speed Change Rate (ASCR) reflects the driver's consistency in maintaining the target speed during the test. A lower ASCR value indicates that the driver can better follow the target speed curve. The Root Mean Square Speed Error (RMSSE) provides a comprehensive indicator, reflecting the overall level of speed errors throughout the test cycle. A lower RMSSE value indicates that the driver better followed the target speed curve throughout the test cycle. The Inertia Work Rate (IWR) reflects the work done by the vehicle during acceleration and deceleration processes. A higher IWR value indicates that there are more accelerations and decelerations during the test cycle. This paper evaluates the driving quality based on these six indicators, and lists the change in electrical energy for each driving cycle, △EREEC (wh), as shown in Table 3.

Table 3: Comprehensive assessment results.

Test group - serial number	Driving behavior	ER	DR	EER	ASCR	IWR	RMSSE	△EREEC(wh)
1-1	Normal-1	-1.38%	-0.20%	-1.20%	-2.39%	-2.54%	0.68	-4587
2-1	Aggressive-1	0.68%	-0.48%	1.15%	1.50%	5.06%	1.01	-4701
2-2	Normal-2	-1.00%	-0.44%	-0.57%	-1.24%	-0.55%	0.80	-4551
1-2	Aggressive-2	-0.23%	-0.29%	0.06%	0.52%	2.39%	0.82	-4558
1-3	Normal-3	-0.99%	-0.45%	-0.54%	-2.34%	-1.98%	0.87	-4496
2-3	Aggressive-3	0.39%	-0.62%	1.00%	2.65%	5.89%	1.04	-4565

3.2. Driving behavior evaluation

From the comprehensive assessment results, it is evident that the six indicators clearly quantify the differences between rough and normal driving behaviors. To more clearly demonstrate the differences between these two driving behaviors, this paper will combine the research findings of Liu Jun and others [11] for the evaluation of indicators. Their research conducted tests under various test conditions and concluded with the results of various indicators for smooth, normal, and rough driving styles. This paper will use the six indicators of normal and rough driving styles from their research as the evaluation criteria for the comprehensive assessment results of this paper. The evaluation criteria are shown in Table 4.

Table 4: Result evaluation indicators.

Driving behavior	ER	DR	EER	ASCR	IWR	RMSSE
Normal	0.0016	-0.0007	0.0023	0.0036	0.0061	0.49
Aggressive	0.0314	-0.0049	0.0350	0.0504	0.0622	1.51

The article uses evaluation indicators as the upper and lower limits for aggressive and normal driving behaviors. The comprehensive evaluation results of the six indicators for three test results of each driving behavior are shown in Figures 2 and 3.

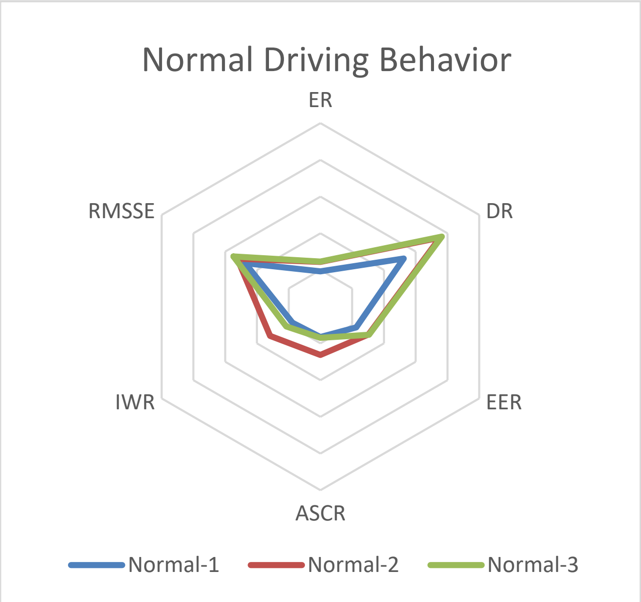

Figure 2: Normal driving behavior indicator evaluation.

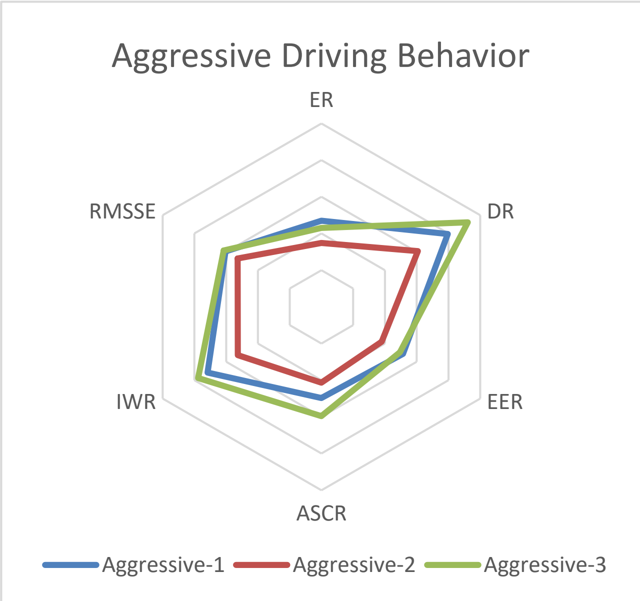

Figure 3: Aggressive driving behavior indicator evaluation.

From the comprehensive evaluation result schematic diagram, it is evident that the area of aggressive driving behavior on the radar chart is significantly larger than that of normal driving behavior. This demonstrates that these six indicators can highlight the differences between different driving behaviors. Since both driving behaviors are conducted around the standard test cycle curve, and all actual driving speed curves comply with the GB/T 19753-2021 standard requirements for the validity of the test results, the differences in the DR and RMSSE indicators between the two driving behaviors are not significant. This also proves that despite obvious differences in driving behavior, both have ensured good curve following throughout the entire test cycle.

Excluding the DR and RMSSE indicators, the performance of different driving styles in the other four indicators is shown in Figure 4.

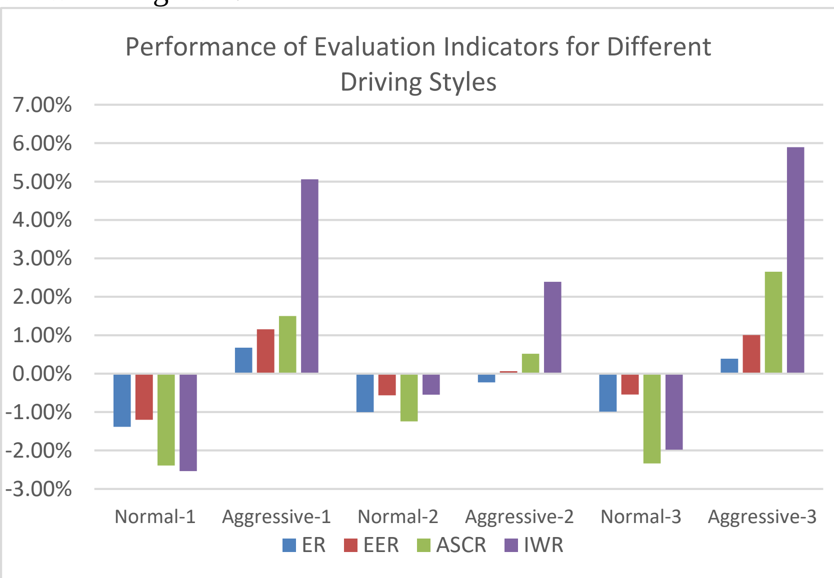

Figure 4: Performance of evaluation indicators for different driving styles.

From Figure 4, it can be observed that there are significant differences in the evaluation indicators between the smooth and aggressive driving styles. Additionally, it can be noted that the differences in the two driving styles adopted in the second cycle of each test set are relatively smaller.

3.3. Energy Consumption Impact Analysis

By recording the change in electrical energy for each pure electric driving cycle, the impact of different driving styles on energy consumption is shown in Table 5.

Table 5: Driving style's impact on energy consumption results.

Test group - serial number	Driving behavior	Electrical energy consumption (Wh)	Absolute deviation	Relative deviation (%)
1-1	Normal-1	4587	114	2.45
2-1	Aggressive-1	4701		
2-2	Normal-2	4551	7	0.15
1-2	Aggressive-2	4558		
1-3	Normal-3	4496	69	1.53
2-3	Aggressive-3	4565		

From Table 5, it can be seen that the impact of different driving styles on energy consumption reached up to 2.45%, which is significant. Comparing the results with Figure 4, it is evident that there is a clear correlation between the differences in evaluation indicators and energy consumption for the two driving styles in each test set. This proves that the evaluation indicators used in this paper can provide a relatively accurate quantitative assessment of driving style.

Although the test results show a significant impact of different driving styles on energy consumption, all tests involved in this paper meet the requirements for driving curves in the current energy consumption testing methods, so the differences in energy consumption caused by different driving styles are neglected. This highlights the necessity of quantifying the differences in driving styles to more accurately assess the actual energy consumption performance of PHEVs and to provide consumers with more reliable energy consumption information.

4. Conclusions

a) The research findings indicate that under the requirements of the current energy consumption testing standards, different driving qualities have a significant impact on energy consumption, and this difference is statistically significant.

b) The study shows that there is a clear correlation between the Energy Rate (ER), Distance Rate (DR), Energy Economy Rate (EER), and four other driving quality evaluation indicators with energy consumption, providing a basis for the quantitative evaluation of driving styles.

c) There is still room for optimization in the energy and power systems of PHEVs to reduce energy consumption.

d) The research indicates that although all driving behaviors comply with the requirements of China's current energy consumption testing standard GBT 19753, the differences in energy consumption caused by driving quality differences suggest that the current testing methods have shortcomings in evaluating and controlling driving quality.

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