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Article

Research on Hydrogen Consumption and Driving Range of Hydrogen Fuel Cell Vehicle under the CLTC-P Condition

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Abstract: Hydrogen consumption and mileage are important economic indicators of fuel cell vehicles. Hydrogen consumption is the fundamental reason that restricts mileage. Since there are few quantitative studies on hydrogen consumption during actual vehicle operation, the high cost of hydrogen consumption in outdoor testing makes it impossible to guarantee the accuracy of the test. Therefore, this study puts forward a test method based on the hydrogen consumption of fuel cell vehicles under CLTC-P operating conditions to test the hydrogen consumption of fuel cell vehicles per 100 km. Finally, the experiment shows that the mileage calculated by hydrogen consumption has a higher consistency with the actual mileage. Based on this hydrogen consumption test method, the hydrogen consumption can be accurately measured, and the test time and cost can be effectively reduced.

Keywords: fuel cell; hydrogen consumption; driving range; test methods; comparative analysis

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1. Introduction

As global energy and environmental issues continue to emerge, hydrogen energy's zero-emission and pollution-free characteristics make it an ideal clean secondary energy source. Hydrogen fuel cell vehicles are currently one of the most essential hydrogen energy application scenarios [1–3]. Environmental sustainability stimulates the development of electric vehicles with excellent energy-saving and emission reduction effects [4,5]. This has aroused great interest in new energy batteries. Major developed countries, such as the United States, Japan, South Korea, and Germany, as well as the European Union have vigorously developed hydrogen energy and fuel cell vehicle industries [6–9]. From the battery point of view, life evaluation and prediction help to extend the durability of fuel cells and accelerate their commercialization [10–12]. At the same time, from the perspective of the entire vehicle, the fuel economy of fuel cell vehicles cannot be ignored [13–15]. Therefore, the research on hydrogen consumption and the cruising range of fuel cell vehicles is also a hot issue. These two studies mainly focus on test method innovation, platform construction, and simulation modeling. The test methods of hydrogen consumption mainly include the temperature and pressure method, mass analysis method, and flow method [16]. Based on the calculation of fuel cell vehicles' actual hydrogen supply capacity, combined with the fundamental structure of the hydrogen supply system, Tian et al. [17] designed a test platform based on the weight method, temperature–pressure method, and flow method. Guo et al. [18] researched the fuel cell vehicle driving range test and evaluation method. The energy consumption and hydrogen consumption of electric-electric hybrid fuel cell vehicles are tested, forming a driving range evaluation method for different fuel cell vehicles. Considering the test and analysis results, suggestions and references for improving the driving range of fuel cell vehicles are put forward. J.S. et al. [19] proposed a method for measuring the fuel consumption of hydrogen fuel cell vehicles on a chassis dynamometer, which provides information for the development of hydrogen fuel economy test methods.

In terms of simulation modeling, the main research point is to improve the accuracy of the hydrogen consumption model. Hou [20] established a semi-empirical kinetic model of hydrogen consumption in a fuel cell engine and conducted experimental verification based on the steady-state hydrogen consumption model. The results show that the model has high accuracy, a simple structure, and few parameters and can better reflect the dynamic characteristics of hydrogen consumption of fuel cell engines. Javier et al. [21] calculated the hydrogen consumption of hybrid electric vehicles and simulated FC hybrid electric vehicles under standard operating conditions, developing an all-electric model and a thermal model of the entire vehicle. Fang et al. [13] designed a hydrogen consumption measurement research platform for a proton exchange membrane fuel cell vehicle (PEMFCV). They used the system to conduct multiple scheduled tests to verify that the platform meets the research needs. Hou et al. [22] introduced a dynamic model of hydrogen consumption in a fuel cell stack. Under the step load change, the hydrogen consumption changes with a specific time lag. The delay time of the load-up phase is shorter than that of the load-down stage. The overshoot duration and peak value are distributed in a normal range. Other studies to carry out hydrogen consumption prediction of the fuel cell system based on the hybrid intelligent method have achieved satisfactory results in the verification process of the model [23–25].

However, the above research is limited to studying the hydrogen consumption model and consumption alone, without linking hydrogen consumption with a driving range and lacking consistency between test and calculated data. This article takes Test vehicle A and Test vehicle B as the research objects to conduct hydrogen consumption and driving range tests of fuel cell vehicles to study the consistency of vehicle hydrogen consumption and moving range test data. This work can provide a data reference for supplementing or revising the hydrogen fuel cell vehicle standards. More importantly, referring to the above method to carry out the hydrogen consumption/driving range test for fuel cell vehicles, the testing time and cost will be significantly reduced on the premise of ensuring the testing accuracy.

2. Research Object

The research object of this article is based on two models, test vehicles A and B. The Type A fuel cell vehicle has a maximum fuel cell power of 114 kW and a battery power energy of 1.65 kWh/5.94 MJ. Type B fuel cell vehicles have a fuel cell system power of 95 kW and a power battery of 1.56 kWh/5.62 MJ. Two kinds of hydrogen storage-related parameters are listed in Table 1.

Table 1. Hydrogen storage parameters of car models.

Test Vehicle Model	Hydrogen Storage Pressure	Hydrogen Storage Volume	Hydrogen Storage	Driving Range (NEDC)	Fuel Cell Power (kW)
Test vehicle A	70 Mpa	122.4 L	5.0 kg/599.8 MJ	650 km	114
Test vehicle B	70 Mpa	156.6 L	6.33 kg/759.3 MJ	800 km	95

3. Test Method

The test environment meets the requirements of the GB/T39132-2020 fuel cell electric vehicle type test procedure of the driving range test method. The test room is equipped with air-conditioning, and the test environment temperature is 20~30 °C. The two test vehicles were running-in. The running-in mileage exceeded 1000 km, and 300 km within seven days before the test. The test vehicle A chassis dynamometer’s load setting follows the vehicle reference mass specified in GB18352.5–2013, and test vehicle B chassis dynamometer load is set under the provisions in GB18352.6–2016. The test parameters are listed in Table 2, and the test flowchart is shown in Figure 1.

Table 2. Specific parameters of test conditions.

Model		Loading Convention	Coefficient A	Coefficient B	Coefficient C
Test vehicle A	DYNO	1930 kg	8.50 N	0 N/(km/h)	0.05770 N/(km/h)^2
Test vehicle B	ROAD	2030.3 kg	156.85 N	1.3640 N/(km/h)	0.03630 N/(km/h)^2
	DYNO	2030.3 kg	−30.46 N	1.7424 N/(km/h)	0.03290 N/(km/h)^2

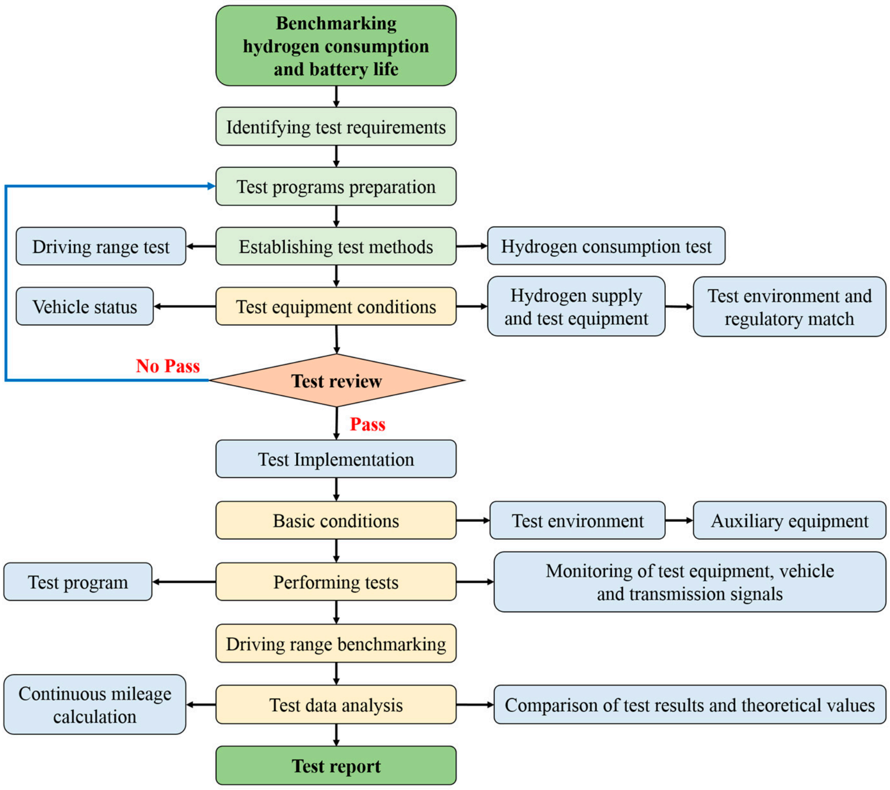

Figure 1. The test flowchart.

3.1. Introduction to the Test Methods for Hydrogen Consumption of Fuel Cell Vehicles

The New European Driving Cycle (NEDC) is a standard car cycle defined based on the road conditions in the European Union. Before 2020, most of the test cycle conditions of the country's automobiles adopt NEDC conditions. It is very different from the actual road conditions. The tested fuel consumption and emission data are also different from the existing conditions. Therefore, the application has significant limitations. The NEDC driving cycle curve is shown in Figure 2.

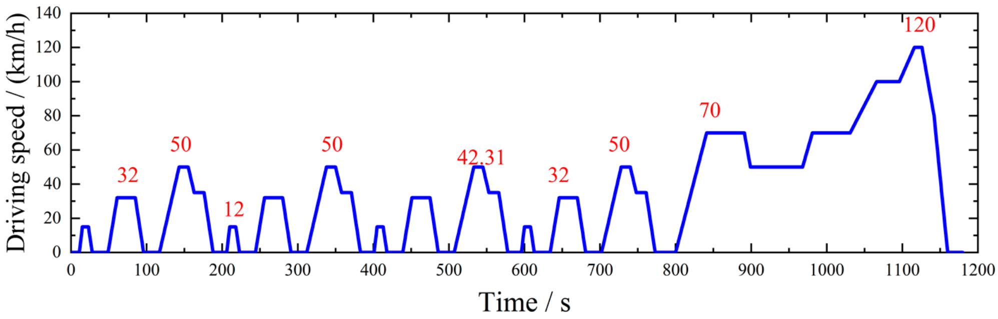

Figure 2. NEDC working condition curve.

Both Test vehicles A and B belong to category A vehicles. CLTC-P is a Chinese light-duty vehicle test cycle passenger car. First, the vehicle is preheated (1 CLTC-P cycle working condition, standing for 15 min), and then 6 CLTC-P cycle working conditions are established to complete the test. CLTC-P reflects the actual road conditions with Chinese characteristics more truly, including a more reasonable definition of average speed and maximum speed, more comprehensive driving conditions, a better proportion of parking modes, and richer dynamic acceleration and deceleration conditions. Figure 3 shows the driving curve of CLTC-P Chinese passenger cars.

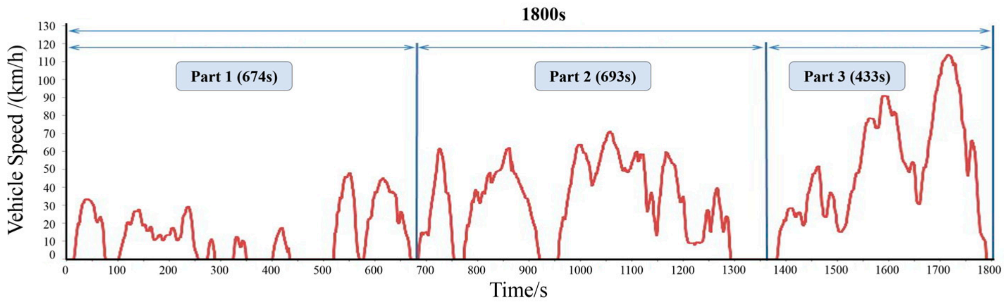

Figure 3. CLTC-P working condition curve.

3.2. Introduction of Fuel Cell Vehicle Driving Range Test Method

Fuel cell electric vehicle tests are carried out in accordance with the CLTC-P cycle conditions specified in GB/T38146.1. The car will stop the test if it meets one of the following two conditions:

(1) The vehicle meter will give a parking indication;
(2) The vehicle speed tolerance does not meet ±2 km/h or the time tolerance exceeds 10 s.

When the vehicle reaches the test end condition, keep the vehicle gear unchanged. Then, wait for the vehicle to coast to the lowest stable speed or 5 km/h, and depress the brake pedal to stop. After the test is over, the vehicle's mileage is rounded to an integer value to be the driving mileage of the test.

3.3. Test Method and Procedure

The test device and interface diagram are shown in Figure 4 [26]. The NEDC cycle conditions were not selected for the hydrogen consumption test for data comparison. The hydrogen consumption is consistent with the driving range test, and both use CLTC-P cycle conditions. To fully accumulate test samples and observe more comprehensive test results and comparisons, hydrogen consumption has been continuously carried out in 13 CLTC-P cycle conditions. Simultaneously, Test vehicle B cannot be connected to the test room to supply hydrogen, so the hydrogen consumption test uses vehicle-mounted hydrogen. The data were obtained according to the temperature and pressure method. The pressure and temperature data were collected by the sensor of the vehicle-mounted hydrogen storage bottle through the vehicle CAN communication.

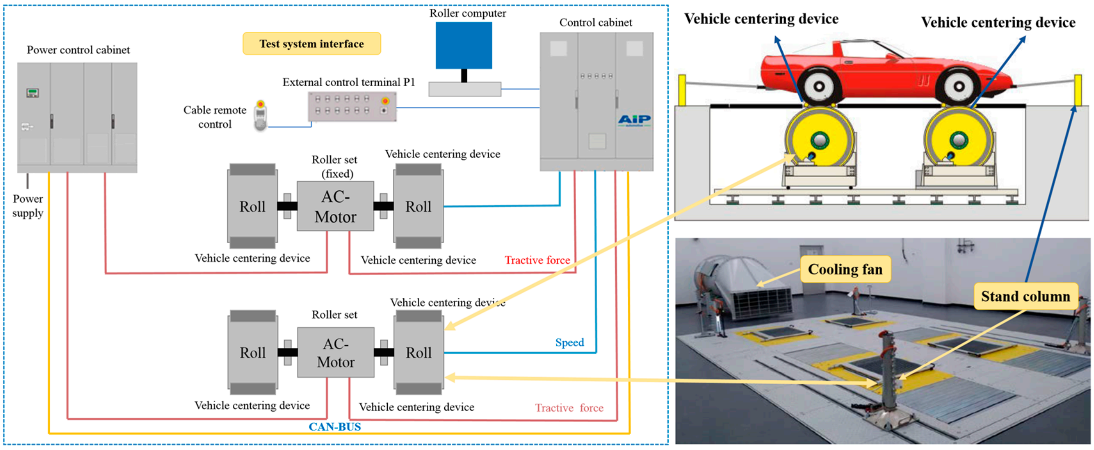

Figure 4. The diagram of the test device and interface.

3.3.1. Hydrogen Consumption Test for Fuel Cell Vehicles

Both models have undergone 13 CLTC-P cycle test conditions. The specific test steps are as follows:

(1) Test vehicle A vehicles close the on-board hydrogen supply system and use the hydrogen from the hydrogen supply pipeline outside the test room. In this study, Austrian AVL's hydrogen flow metering system was used to measure the value of vehicle hydrogen consumption. Test vehicle B vehicles use the pressure-temperature method of the vehicle's hydrogen storage tank to measure hydrogen consumption indirectly;

(2) After the vehicle is fixed to the chassis dynamometer, leave it at room temperature (20–30 °C) for 30 min;

(3) Vehicle road load and chassis dynamometer load are set following national standards;

(4) The vehicle is warmed up, the vehicle is driven on the chassis dynamometer, the vehicle is turned off after the CLTC-P cycle is completed, and the vehicle is set to the initial value for 15 min;

(5) Start the vehicle signal acquisition equipment. The acquired signals include but are not limited to each hydrogen cylinder temperature, hydrogen cylinder pressure, hydrogen fuel cell stack current, voltage, vehicle mileage, hydrogen consumption, and hydrogen flow, and the acquisition frequency of each signal is 10 Hz;

(6) Start the vehicle and perform 13 continuous working condition tests in accordance with the CLTC-P working condition table. The vehicle cannot be stopped during the test operation until the end of the test;

(7) Record the mileage at the end of each test cycle and keep the mileage to one decimal place. If the hydrogen flow rate is used to test the hydrogen consumption, the hydrogen consumption is recorded at the same time, and the hydrogen consumption is kept to one decimal place;

(8) After the vehicle completes 13 cycles of testing, record the total mileage and stop the vehicle;

(9) Stop data recording and analyze the data.

3.3.2. Hydrogen Consumption Test for Fuel Cell Vehicles

(a) Fill the vehicle-mounted hydrogen cylinder with hydrogen until the rated pressure is 70 MPa;

(b) Keep the car static at room temperature (20–30 °C) for 30 min, then fix the car to the chassis dynamometer;

(c) Start the vehicle, test according to CLTC-P working conditions, and stop when the test end conditions are reached;
(d) Record the mileage and accumulated mileage of each cycle working condition, keeping one decimal place for the mileage of each working condition. The accumulated mileage is rounded up.

4. Test Results and Discussion

4.1. Analysis and Discussion of Hydrogen Consumption Test Data

The vehicle test continuously carried out 13 CLTC-P cycle conditions and obtained hydrogen consumption per 100 km for 11 groups of three continuous CLTC-P cycle conditions and eight groups of hydrogen consumption per 100 km for six consecutive CLTC-P cycles. The actual hydrogen consumption per 100 km is calculated based on the actual hydrogen consumption of each cycle and the corresponding mileage. The relative deviation is calculated based on the actual value and the average value of hydrogen consumption ((Actual value − average value)/Average value × 100%).

4.1.1. Analysis of Test Vehicle A Test Results and Hydrogen Consumption Measurement Method

The actual hydrogen consumption of each CLTC-P cycle of Test vehicle A is measured using hydrogen from the hydrogen supply pipeline outside the test room and measured by the hydrogen flow metering system of AVL, Austria. The specific data are shown in Table 3.

According to the data in the above table, the hydrogen consumption per hundred kilometers of a single cycle is 0.977 kg/100 km, the hydrogen consumption of three cycles is 0.979 kg/100 km, and the hydrogen consumption of six cycles is 0.983 kg/100 km. The maximum deviation of hydrogen consumption in a single working condition from the average value is 3.59%. The maximum deviation of the hydrogen consumption from the average value for three consecutive cycles is 3.0%. The maximum deviation of hydrogen consumption from the average value for six consecutive cycles is 1.0%. The deviation distribution of each cycle is shown in Figure 5.

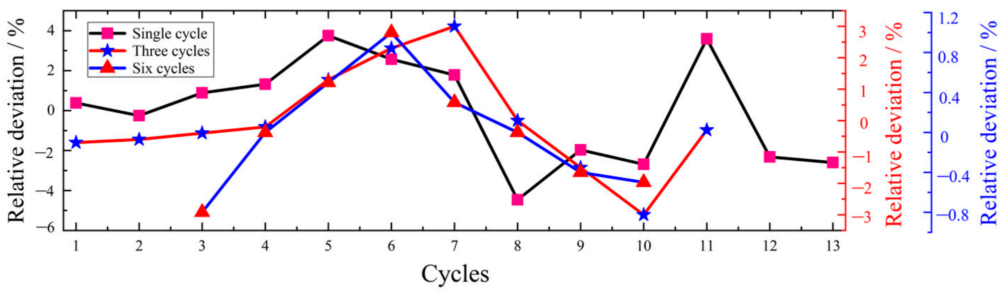

Figure 5. Cyclic deviation distribution.

4.1.2. Analysis of Test Vehicle B Test Results and Hydrogen Consumption Evaluation Method

The actual hydrogen consumption of each CLTC-P cycle of Test vehicle B uses vehicle-mounted hydrogen. It is calculated and measured following the pressure-temperature method with the vehicle hydrogen storage bottle. The vehicle hydrogen storage bottle's pressure and temperature sensor signals are collected and output by the vehicle CAN signal. Limited by the accuracy of the pressure and temperature sensors of the vehicle's hydrogen storage cylinder, the hydrogen consumption varies significantly among various cycle conditions. The specific data are shown in Table 4.

Table 3. Actual hydrogen consumption of Test vehicle A under the CLTC-P cycle.

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1	14.6	141.7	0.9702	0.38
2	14.4	140.8	0.9775	−0.25
3	14.5	142.4	0.9819	0.89
4	14.5	143.0	0.9860	1.32
5	14.4	146.4	1.0167	3.75
6	14.6	144.7	0.9911	2.57
7	14.3	143.6	1.0042	1.78
8	14.4	134.8	0.9361	−4.46
9	14.4	138.3	0.9604	−1.97
10	14.4	137.3	0.9535	−2.69
11	14.4	146.2	1.0146	3.59
12	14.4	137.8	0.9569	−2.32
13	14.4	137.5	0.9545	−2.60
Average value	14.4	141.1	0.9772	——

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1~3	43.5	423.1	0.973	−0.7
2~4	43.4	422.5	0.974	−0.6
3~5	43.4	423.1	0.975	−0.4
4~6	43.5	424.9	0.977	−0.2
5~7	43.3	429.6	0.992	1.3
6~8	43.3	433.5	1.001	2.3
7~9	43.1	434.7	1.009	3.0
8~10	43.2	423.1	0.979	0.0
9~11	43.2	416.7	0.965	−1.5
10~12	43.2	410.4	0.950	−3.0
11~13	43.2	421.7	0.976	−0.3
Average value	43.3	423.9	0.9791	——

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1~6	87.0	848.0	0.9747	−0.8
2~7	86.7	852.1	0.9828	0.0
3~8	86.7	856.6	0.9880	0.5
4~9	86.6	859.6	0.9926	1.0
5~10	86.5	852.7	0.9858	0.3
6~11	86.5	850.2	0.9829	0.0
7~12	86.3	845.1	0.9793	−0.4
8~13	86.4	844.8	0.9778	−0.5
Average value	86.6	851.1	0.9830	——

Table 4. Actual hydrogen consumption of Test vehicle B under CLTC-P cycle.

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1	14.5	118.8	0.8193	−1.0
2	14.4	135.7	0.9424	13.9
3	14.3	137.3	0.9601	16.0
4	14.3	91.6	0.6406	−22.6
5	14.4	122.9	0.8535	3.1
6	14.3	115.3	0.8063	−2.6
7	14.5	121.1	0.8352	0.9
8	14.4	118.0	0.8194	−1.0
9	14.4	95.8	0.6653	−19.6
10	14.2	124.8	0.8796	6.3
11	14.5	113.0	0.7793	−5.8
12	14.5	135.7	0.9359	13.1
13	14.2	116.8	0.8225	−0.6
Average value	14.2	119.0	0.8277	——

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1~3	43.2	391.8	0.907	10.4
2~4	43.0	364.6	0.848	3.2
3~5	43.0	351.8	0.818	−0.4
4~6	43.0	329.8	0.767	−6.7
5~7	43.2	359.3	0.832	1.2
6~8	43.2	354.4	0.820	−0.2
7~9	43.3	334.9	0.773	−5.9
8~10	43.0	338.7	0.788	−4.1
9~11	43.1	333.7	0.774	−5.8
10~12	43.2	373.6	0.865	5.2
11~13	43.2	365.5	0.846	3.0
Average value	43.1	354.4	0.8217	——

Cycles	Cycle Mileage (km)	Actual Hydrogen Consumption (g)	Actual Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Relative Difference Rate %
1~6	86.2	721.6	0.8371	2.9
2~7	86.2	723.9	0.8398	3.2
3~8	86.2	706.2	0.8193	0.7
4~9	86.3	664.7	0.7702	−5.3
5~10	86.2	698.0	0.8097	−0.5
6~11	86.3	688.1	0.7973	−2.0
7~12	86.5	708.5	0.8191	0.7
8~13	86.2	704.2	0.8169	0.4
Average value	86.3	701.9	0.8137	——

According to the data in the above table, the hydrogen consumption per hundred kilometers of a single cycle is 0.828 kg/100 km, the hydrogen consumption of three cycles is 0.822 kg/100 km, and the hydrogen consumption of six cycles is 0.815 kg/100 km. The maximum deviation of hydrogen consumption in a single working condition from the average value is −22.6%. The maximum deviation of hydrogen consumption from the average value for three consecutive cycles is 10.4%. The maximum deviation of hydrogen consumption from the average value for six consecutive cycles is 5.3%. The relative deviation decreases as the number of cycle conditions increases. The deviation distribution of each process is shown in Figure 6.

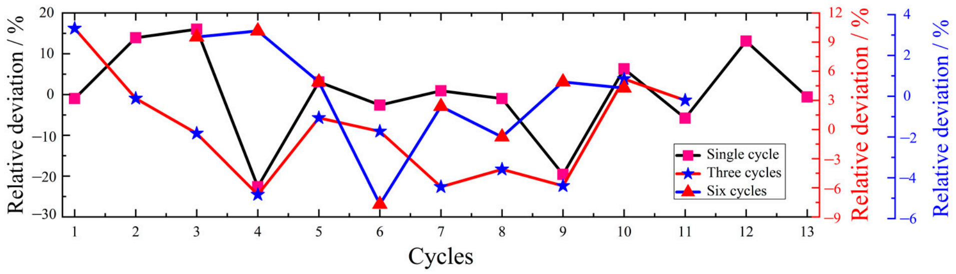

Figure 6. Cyclic deviation distribution.

4.2. *Analysis and Discussion of Test Data of Vehicle Driving Range*

The vehicle's driving range is based on the current national standard fuel cell electric vehicle test method. CLTC-P cycle conditions were used to obtain the actual test. At the same time, according to the test, the hydrogen consumption of the vehicle per 100 km (calculated by the trial and test of six consecutive CLTC-P cycle conditions) and the vehicle's available hydrogen amount is indirectly calculated to obtain the driving range (computed value). Hence, 13 successive CLTC-P cycle conditions are received in the actual test vehicle. Eight groups of six continuous CLTC-P cycle conditions are obtained for hydrogen consumption per 100 km. The driving range (calculated value) is obtained.

4.2.1. Analysis of Test Vehicle A Test Results and Driving Range Test Method

The actual hydrogen consumption of each CLTC-P cycle of Test vehicle A uses the hydrogen of the hydrogen supply pipeline outside the test room. It is measured by the hydrogen flow metering system of Austria AVL Company, Melbourne, Australia. The specific values are shown in Table 5.

Table 5. Driving range of Test vehicle A under CLTC-P cycle conditions.

Serial Number	Cycle Condition	Hydrogen Consumption (g)	Vehicle Mileage (km)	Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Driving Range (Calculated Value) (km)	Difference Rate %
1	1~6	848.0	87.0	0.975	513	0.6
2	2~7	852.1	86.7	0.983	509	−0.2
3	3~8	856.6	86.7	0.988	506	−0.8
4	4~9	859.6	86.6	0.993	504	−1.2
5	5~10	852.7	86.5	0.986	507	−0.5
6	6~11	850.2	86.5	0.983	509	−0.3
7	7~12	845.1	86.3	0.979	511	0.1
8	8~13	844.8	86.4	0.978	511	0.3

Test driving range (km): 510 km.

According to the data in the above table, the hydrogen consumption per hundred kilometers for six cycles is 0.978 kg/100 km. The maximum deviation between the continuous driving range and the average value of six stable cycle conditions is −1.2%, and the deviation distribution of each cycle is shown in Figure 7.

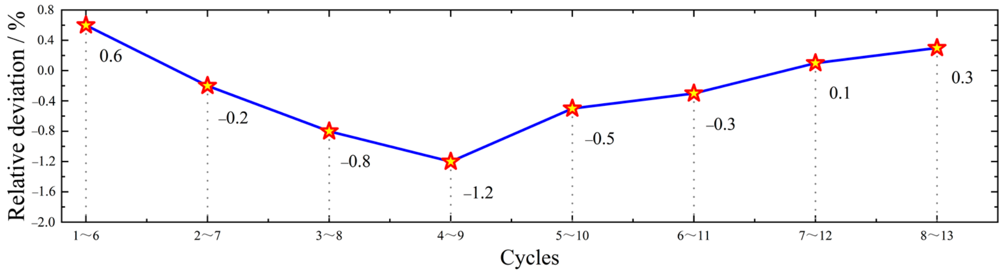

Figure 7. Deviation distribution of 6 continuous cycle conditions.

4.2.2. Analysis of Test Vehicle B Test Results and Driving Range Test Method

The actual hydrogen consumption of the Test vehicle B vehicle CLTC-P cycle working condition uses the vehicle-mounted hydrogen, which is calculated and measured by the pressure-temperature method of the vehicle hydrogen storage bottle. The vehicle hydrogen storage bottle's pressure and temperature sensor signals are collected and output by the vehicle CAN signal. The specific values are shown in Table 6.

Table 6. Driving range of Test vehicle B under CLTC-P cycle conditions.

Serial Number	Cycle Condition	Hydrogen Consumption (g)	Vehicle Mileage (km)	Hydrogen Consumption per Hundred Kilometers (kg/100 km)	Driving Range (Calculated Value) (km)	Difference Rate %
1	1~6	721.6	86.2	0.837	756	−5.7
2	2~7	723.9	86.2	0.840	754	−6.0
3	3~8	706.2	86.2	0.819	773	−3.7
4	4~9	664.7	86.3	0.770	822	2.5
5	5~10	698.0	86.2	0.810	782	−2.5
6	6~11	688.1	86.3	0.797	794	−1.0
7	7~12	708.5	86.5	0.819	773	−3.6
8	8~13	704.2	86.2	0.817	775	−3.4

Test driving range (km): 802 km.

According to the driving range (calculated value), hydrogen per hundred kilometers for six cycles is 0.817 kg/100 km. Given the test driving range and difference rate ((continuing driving range (calculated value) − test driving range)/test driving range × 100%), the maximum difference rate of each group of values is −6.0%. The specific distribution is shown in Figure 8.

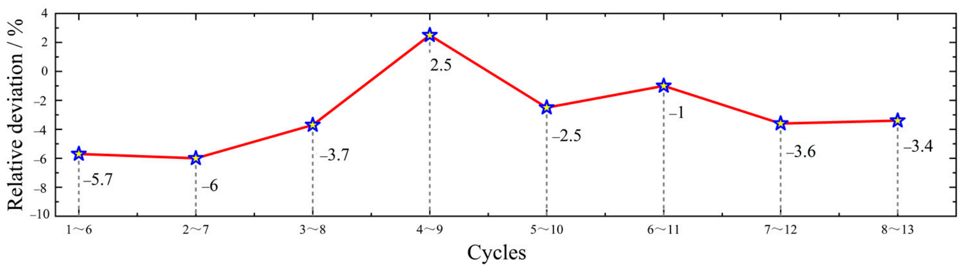

Figure 8. Deviation distribution of 6 continuous cycle conditions.

4.3. Energy-Saving Effect of the Braking Energy Recovery Strategy

This section compares the braking energy recovery strategy and the non-brake energy recovery strategy adopted by the Test vehicle B vehicle under the CLTC-P cycle. From Table 7 and Figure 9, it can be seen that the initial driving range increased by 135.8 km, and the driving range at termination was increased by 175.5 km after adopting the braking energy recovery strategy. The SOC values of the batteries with and without the braking energy recovery strategy are 57% and 51%, respectively, an increase of 6%.

Table 7. Parameter data of Test vehicle B's two strategies under CLTC-P conditions.

Main Parameters	With Braking Energy Recovery	Without Braking Energy Recovery
Initial driving range	612.4 km	476.6 km
Final driving range	463.3 km	287.8 km
Battery SOC	57%	51%

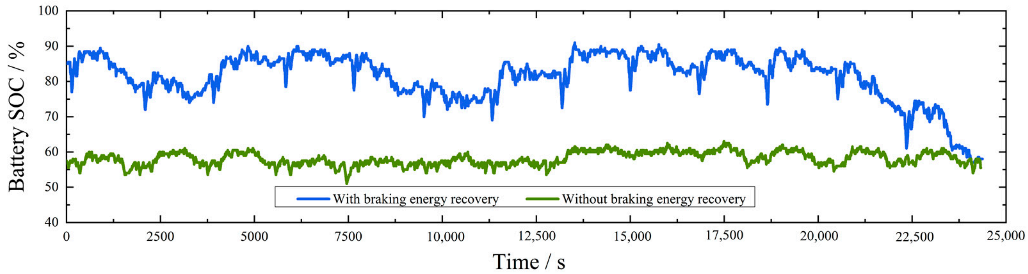

Figure 9. Comparison of battery SOC value changes.

5. Conclusions

Six consecutive standard cycles of external hydrogen supply were used to test the hydrogen consumption of fuel cell vehicles during CLTC-P operation. The difference between the calculated and tested driving ranges was less than 1.2%. The cycle conditions are divided into three groups, and the mileage is calculated by calculating the hydrogen consumption per hundred kilometers of each group. The difference between the actual mileage and the calculated average mileage decreases as the number of cycles increases.

After adopting the braking energy recovery strategy, the initial driving range was increased by 135.8 km, and the driving range at the end was increased by 175.5 km. The SOC values of the batteries with and without the braking energy recovery strategy are 57% and 51%, respectively, an increase of 6%.

Referring to the above method to carry out the hydrogen consumption/driving range test for fuel cell vehicles and calculate the driving range value of fuel cell vehicles, the fuel cell vehicle driving range test time and the test cost are significantly reduced. At the same time, the testing unit and the country of the testing organization can also guarantee the accuracy of the test values.

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References

1. Mathieu, T.; Kourosh, M.; Asmae, M. Techno-Economics of a New High Throughput Process for Proton Exchange Membranes Manufacturing. *World Electr. Veh. J.* **2016**, *8*, 431–442.
2. Speers, P. Hydrogen Mobility Europe (H2ME): Vehicle and Hydrogen Refuelling Station Deployment Results. *World Electr. Veh. J.* **2018**, *9*, 2. [CrossRef]
3. Zhou, S.; Jin, J.; Wei, Y. A Driving Cycle for a Fuel Cell Logistics Vehicle on a Fixed Route: Case of the Guangdong Province. *World Electr. Veh. J.* **2021**, *12*, 5. [CrossRef]
4. Hong, J.; Wang, Z.; Chen, W.; Wang, L.; Lin, P.; Qu, C. Online Accurate State of Health Estimation for Battery Systems on Real-World Electric Vehicles with Variable Driving Conditions Considered. *J. Clean. Prod.* **2021**, *294*, 125814. [CrossRef]
5. Hong, J.; Wang, Z.; Yao, Y. Fault prognosis of battery system based on accurate voltage abnormity prognosis using long short-term memory neural networks. *Appl. Energy* **2019**, *251*, 113381. [CrossRef]
6. Han, J.; Dongsuk, K.; Youngjin, P. Sensitivity analysis for assessing robustness of position- based predictive energy management strategy for fuel cell hybrid electric vehicle. *World Electr. Veh. J.* **2015**, *7*, 330–341. [CrossRef]
7. Andaloro, L.; Micari, S.; Napoli, G.; Polimeni, A.; Antonucci, V. A Hybrid Electric Fuel Cell Minibus: Drive Test. *World Electr. Veh. J.* **2016**, *8*, 131–138. [CrossRef]
8. Kim, N.; Moawad, A.; Vijayagopal, R.; Rousseau, A. Impact of Fuel Cell and Storage System Improvement on Fuel Consumption and Cost. *World Electr. Veh. J.* **2016**, *8*, 305–314. [CrossRef]
9. Cullen, D.A.; Neyerlin, K.C.; Ahluwalia, R.K.; Mukundan, R.; More, K.L.; Borup, R.L.; Weber, A.Z.; Myers, D.J.; Kusoglu, A. New roads and challenges for fuel cells in heavy-duty transportation. *Nat. Energy* **2021**, *6*, 462–474. [CrossRef]
10. Pei, P.; Chen, D.; Wu, Z.; Ren, P. Nonlinear methods for evaluating and online predicting the lifetime of fuel cells. *Appl. Energy* **2019**, *254*, 113730. [CrossRef]
11. Szałek, A.; Pielecha, I.; Cieslik, W. Fuel Cell Electric Vehicle (FCEV) Energy Flow Analysis in Real Driving Conditions (RDC). *Energies* **2021**, *14*, 5018. [CrossRef]
12. Pielecha, I.; Cieślik, W.; Szałek, A. The use of electric drive in urban driving conditions using a hydrogen powered vehicle-Toyota Mirai. *Combust. Engines* **2018**, *57*, 51–58. [CrossRef]
13. Maodong, F.; Mingjie, C.; Qingchun, L.; Zhenhua, J. Hydrogen Consumption Measurement Research Platform for Fuel Cell Vehicles. In Proceedings of the International Conference on Electrical and Control Engineering, Wuhan, China, 25–27 June 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 1142–1145.
14. Ahluwalia, R.K.; Wang, X.; Rousseau, A.; Kumar, R. Fuel economy of hydrogen fuel cell vehicles. *J. Power Sources* **2004**, *130*, 192–201. [CrossRef]
15. Offer, G.J.; Contestabile, M.; Howey, D.A.; Clague, R.; Brandon, N.P. Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK. *Energy Policy* **2011**, *39*, 1939–1950. [CrossRef]
16. Lai, X.; Ling, L.; Liang, W.; Wang, B. Test Platform Development for Fuel Cell Vehicle's Hydrogen Management System. *TELKOMNIKA Indones. J. Electr. Eng.* **2012**, *10*. [CrossRef]
17. Tian, Y.; Zhang, Y.F.; Jin, Z.H.; Wang, K.L.; Nie, S.F.; Lu, Q.C. Development of Hydrogen Consumption Test Platform for Fuel Cell Vehicles. *Adv. Mater. Res.* **2013**, *602–604*, 1031–1035. [CrossRef]
18. Guo, T. Research on the Measurement Method of Fuel Cell Vehicle Driving Range. *Power Technol.* **2021**, *45*, 848–850+931.
19. Lim, J.-S.; Lee, H.-W.; Hong, Y.-S.; Lee, K.-B.; Yong, G.-J.; Kwon, H.-B. Development on Fuel Economy Test Method for Hydrogen Fuel Cell Vehicles. *Trans. Korean Hydrog. New Energy Soc.* **2010**, *21*, 207–213.
20. Hou, Y.; Zhuang, M.; Wan, G. A study on a semi-empirical dynamic model for hydrogen consumption of a fuel cell engine. *Automot. Eng.* **2007**, *29*, 942–945.
21. Pino, F.J.; Marcos, D.; Bordons, C.; Rosa, F. Car air-conditioning considerations on hydrogen consumption in fuel cell and driving limitations. *Int. J. Hydrog.* **2015**, *40*, 11696–11703. [CrossRef]
22. Hou, Y.; Shen, C.; Hao, D.; Liu, Y.; Wang, H. A dynamic model for hydrogen consumption of fuel cell stacks considering the effects of hydrogen purge operation. *Renew. Energy* **2014**, *62*, 672–678. [CrossRef]
23. Montero-Sousa, J.A.; Aláiz-Moretón, H.; Quintián, H.; González-Ayuso, T.; Novais, P.; Calvo-Rolle, J.L. Hydrogen consumption prediction of a fuel cell based system with a hybrid intelligent approach. *Energy* **2020**, *205*, 117986. [CrossRef]

24. Li, Y.; Pei, P.; Wu, Z.; Ren, P.; Jia, X.; Chen, D.; Huang, S. Approaches to avoid flooding in association with pressure drop in proton exchange membrane fuel cells. *Appl. Energy* **2018**, *224*, 42–51. [CrossRef]
25. Chen, D.; Pan, L.; Pei, P.; Huang, S.; Ren, P.; Song, X. Carbon-coated oxygen vacancies-rich Co_3O_4 nanoarrays grow on nickel foam as efficient bifunctional electrocatalysts for rechargeable zinc-air batteries. *Energy* **2021**, *224*, 120142. [CrossRef]
26. Duan, Z.; Zhang, L.; Feng, L.; Yu, S.; Jiang, Z.; Xu, X.; Hong, J. Research on Economic and Operating Characteristics of Fuel Cell Cars Based on Real Vehicle Tests. *Energies* **2021**, *14*, 7856. [CrossRef]