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Article

Research on the Performance Comparison of Two Fuel Cell Electric Vehicles with Typical Energy Management Strategies

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Abstract: In the development of actual vehicles, manufacturers usually adopt a simplified control strategy to ensure the reliability of the control strategy based on the application scenarios. There are two main working modes for the fuel cell system in fuel cell electric vehicles in China. One is the stepped power type, and the other is the following power type. Therefore, the analysis and comparison of these two typical working modes in the power test of fuel cell electric vehicles helps determine how the fuel cell system works in the actual vehicle and how to choose energy management strategies in different application scenarios. We do the actual tests to explore how the two typical control strategies perform in actual vehicles. These two typical control strategies show different characteristics in the same test. It shows that the energy management strategies should be adopted according to the application scenarios and optimization goals. In the stepped power control strategy, the fluctuation of the fuel cell system and the frequency of starting and stopping are significantly reduced, which is beneficial to the durability of the fuel cell system. Compared with the stepped control strategy, the fluctuation of the output power of fuel cell electric vehicles with the following power control strategy increased significantly. At the same time, a simplified state of charge (SOC) test method is proposed. Due to the particularity of the stepped power control strategy, the change of capacity can be used to replace the change of SOC. For the following power control strategy, the change of electric energy can be used instead of SOC changes.

Keywords: fuel cell electric vehicle; power performance; energy management strategy

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1. Introduction

There are various technical routes for developing new energy vehicles, which are the critical solutions for an eco-friendly energy society [1]. Fuel cell electric vehicles are often compared with electric vehicles. The current disadvantages of fuel cell vehicles are the low conversion efficiency in the use phase and that the infrastructure construction is still at the preliminary stage. In terms of cost, fuel cell electric vehicles are still relatively expensive, but in long-distance transportation, fuel cell electric vehicles show better economy [2,3]. The advantages of fuel cell vehicles are high energy density, short refilling times, and better low-temperature performance [2]. The European Union, Japan, China, and South Korea have also released roadmaps to develop hydrogen energy [3–6]. The ultimate goal of developing hydrogen energy is a zero-emission hydrogen energy society. The energy management strategy has always been a research hotspot in fuel cell electric vehicles. The purpose of researching the control strategy is to cooperate with different power sources to meet the power demand of the whole vehicle to optimize economy, durability, and power. Different dynamic coupling methods will affect the choice of energy management strategy [7]. In 2006, Ouyang compared and analyzed the influence of different powertrain structures and energy management strategies on hybrid fuel cell buses [8,9]. In 2009, Xu further analyzed that braking energy contributes much more than the equivalent consumption minimization strategy (ECMS) to the fuel economy [10]. The fuel cell system does not leave much room for the optimal algorithm to improve efficiency. At the same time, Fadel's research also pointed out that, compared with combustion engines, the efficiency of fuel cell systems is higher, and the optimization space left for control strategies in terms of hydrogen consumption is limited [9,11]. In this case, the durability of the fuel cell system is more important than other factors. However, durability and economy are usually contradictory. Lv Qinyang et al. established an energy management strategy based on an improved dynamic programming algorithm that considers the vehicle's economy and durability. This strategy can improve the decline degree of vehicle performance by slightly increasing the vehicle's energy consumption [12]. The current research has revealed the advantages and disadvantages of different control strategies and tried to keep the balance between economy and durability. In terms of research methods, either simulation or simplified bench tests are used, or the influence of a single control strategy is studied, which is different from the actual situation. In the development of actual vehicles, the OEM usually adopts the simplified control strategy to ensure the reliability of the control strategy based on the application scenarios. There are two main working modes for the fuel cell system in fuel cell electric vehicles. One is the stepped power type, and the other is the following power type [13]. Therefore, the analysis and comparison of these two basic working modes in the power test of fuel cell electric vehicles helps understand how the fuel cell system works in the actual vehicle and how to choose energy management strategies in different application scenarios. In order to explore how the two typical control strategies perform in actual vehicles, this paper selects two representative vehicles for dynamic performance tests considering durability, economy, and application scenarios. One of the fuel cell systems adopts a stepped power control strategy. The other fuel cell system adopts the following control strategy.

Meanwhile, both of the control strategies are closely related to the SOC of the traction battery. Therefore, to ensure the conformity of the test results, it is necessary to adjust the SOC to a uniform value before the test during the verification test. However, the SOC value can only be read through the on-board diagnostic (OBD) port with the help of OEM. It significantly increases the complexity and difficulty of testing for both OEMs and third-party testing agencies and forming a standardized testing method. This paper proposes a simplified test method. It uses energy change, or capacity change indicates the change of SOC. This method can avoid reading the SOC and is useful for OEM and third-party test facilities. In this way, only the voltage and current output of the power battery are measured. This method also has reference value for the formation of standardized test methods.

2. Theoretical Analysis

In the early stage of the development of fuel cell electric vehicles, the dynamic response, durability, and power of the fuel cell stack are not good enough. Limited by the technical level, the performance of the fuel cell system in terms of dynamic response, durability, and fuel cell power is not outstanding. For example, it cannot quickly respond to the power demand of the vehicle, and the durability is only about 3000 h, while the power of a single stack is less than 30 kW. So, the fuel cell electric vehicles operating in the Chinese market were mainly the range-extended type about five years ago. The range-extended fuel cell electric vehicles are pure electric vehicles with a fuel cell range extender to extend the driving range. However, there is no mechanical connection between the fuel cell range extender itself and the drive system [14]. The energy management strategies that used in the range-extended fuel cell electric vehicles include thermostat control strategy, power following control strategy, and energy management strategy with minimum instantaneous power loss. The thermostat control strategy is generally adopted considering durability [11].

The downside of the above strategy is too many transmission processes, leading to efficiency loss. With the development of fuel cell technology, breakthroughs have been made in fuel cell system's power, durability, and dynamic response. Therefore, the energy management strategy is also changing. The significant difference is that the fuel cell system makes more contribution on driving. The diagram of the fuel cell electric vehicle powertrain system is shown in Figure 1.

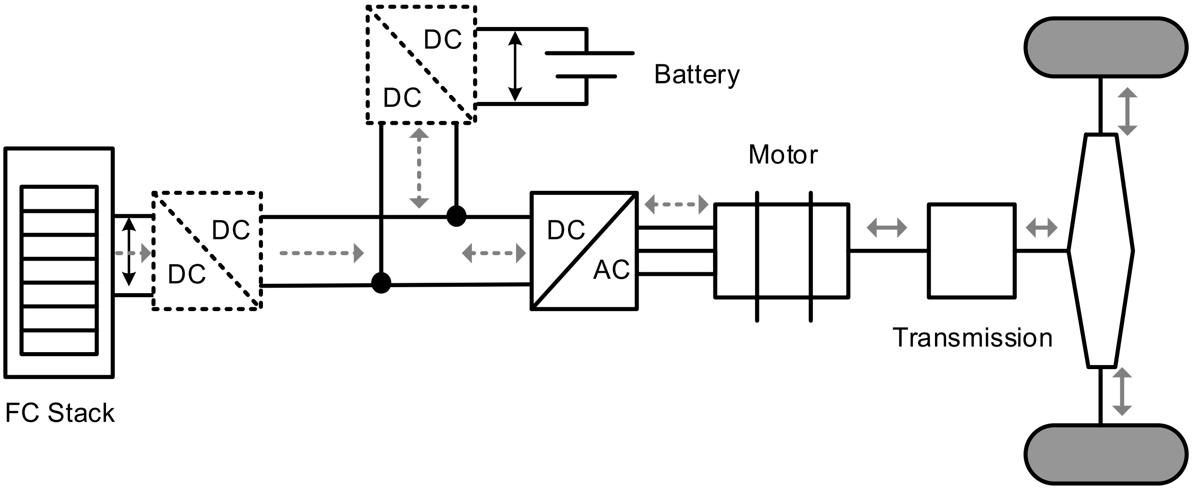


Figure 1. Structure diagram of the fuel cell electric vehicle powertrain system.

The fuel cell system's control strategies are more diverse in parallel fuel cell electric vehicles [15]. There are two main types of fuel cell system operating types: the stepped power type, which is mainly used in buses, and the following power type, which is mainly used for passenger cars. For more details about the stepped power type and the following power type, see Figure 3 of Fernández's article, which uses CI instead of the stepped power type and CS instead of the following power type [16]. Under the dynamic performance test, both the stepped power type and the following power type work mode need to meet the dynamic requirements of the whole vehicle, the vehicle driving equation [17].

$$\sum F = F_f + F_w + F_i + F_j \tag{1}$$

$\sum F$ is vehicle driving force, unit newton (N); F_f is the rolling resistance, unit newton (N); F_w is air resistance, unit newton (N); F_i is the slope resistance, unit newton (N); F_j is the acceleration resistance, unit newton (N).

In the above formula (1), each resistance calculation formula is expanded as follows:

$$F_f = \frac{Gfu_a}{3600} \tag{2}$$

$$F_w = \frac{Giu_a}{3600} \tag{3}$$

$$F_i = \frac{C_D A u_a^3}{76140} \tag{4}$$

$$F_j = \frac{\delta m u_a}{3600} \times \frac{du}{dt} \tag{5}$$

When the car runs, the power output by the engine is always equal to the sum of the power subtracted by mechanical transmission and the power consumed by all the motion resistance. Multiplying both sides of the car's driving equation by the driving speed and after unit conversion, we figure out the car's power balance equation as follows:

$$P_e = \frac{1}{\mu_T}\left(\frac{Gfu_a}{3600} + \frac{Giu_a}{3600} + \frac{C_D A u_a^3}{76140} + \frac{\delta m u_a}{3600} \times \frac{du}{dt}\right) \quad (6)$$

Among them: P_e is the sum of the output power of the fuel cell system and the traction battery, unit kilowatt (kW); μ_T is the DC/DC efficiency and the transmission efficiency, unit (%); u_a is the speed of the vehicle, unit kilometers per hour (km/h); G is vehicle gravity, unit newton (N); f is the coefficient of rolling resistance, i is the road slope, unit (%); C_D is the air resistance coefficient, A is the windward area, unit square meter (m^2); δu is the car's rotating mass conversion factor, m is the curb weight of the vehicle, unit kilogram (kg); du/dt is the driving acceleration, unit meter per second squared (m/s^2).

3. Experiment Preparation and Setup

This chapter describes the test vehicles' parameters, test methods, and experimental data collection in detail. Two different test vehicles adopted the same data collection and processing methods.

3.1. Test Vehicle

To ensure the representativeness of the test, we selected a city bus and sedan. The fuel cell system of the city bus adopted the stepped working mode and was equipped with a 50 kWh traction battery; the fuel cell system of the sedan adopted the following power working mode and was equipped with a 14 kWh traction battery. The rated power of fuel cell systems was both 50 kW. The specific parameters are as follows in Table 1.

Table 1. Test vehicle parameters.

	Vehicle Type	Commercial Vehicles (City Buses)	Passenger Car (Sedan)
Mode	Default mode	Mixed mode	Mixed mode
	Pure electric mode	Available	NA
Whole vehicle	Maximum thirty-min speed (km/h)	70	140
	BOP maximum power (kW)	NA	NA
Traction battery	Type (energy/power)	Energy	Energy
	Capacity Cap0 (Ah)	96	40
	Electrical energy Q0 (kWh)	50.45	14
	Voltage range (V)	432–604.8	240–403.2
	Current range (A)	<500	NA
	SOC balance range (%)	20–84	30–60
	Pure electric mileage (km)	65	30
Fuel cell system	Working mode (Stepped power type/Following power type/fixed-point power work type)	Stepped power type	Following power type
	Rated power (kW)	50	50

3.2. Test Method

We need to reach the lower limit of the SOC of the traction battery to ensure the fuel cell system is participating in the power output. So a maximum thirty-min speed test is performed first. Then the acceleration test and uphill tests are carried out after the transfer. Another reason for using a maximum thirty-min speed test for initialization and acceleration is explained further in Section 4.3.1. Before the test, we will adjust the SOC of the whole vehicle to the target value after finishing the maximum thirty-min speed test.

(1) Select the driving mode (default mode), start the on-board diagnostic (OBD) port recorder and the on-board power analyzer;

(2) Carry out maximum thirty-min speed test and record the SOC;
(3) Parking, data processing;
(4) Transfer to the straight track and adjust SOC to the target value when finishing the (2);
(5) Carry out the starting acceleration test (0–50 km/h) and the overtaking acceleration test (30 km/h–50 km/h). Before each test, confirm that the traction battery state is within the target value. Otherwise, repeat the procedure (4);
(6) Transfer to the following test site and complete the uphill test.

The workflow is illustrated in Figure 2.

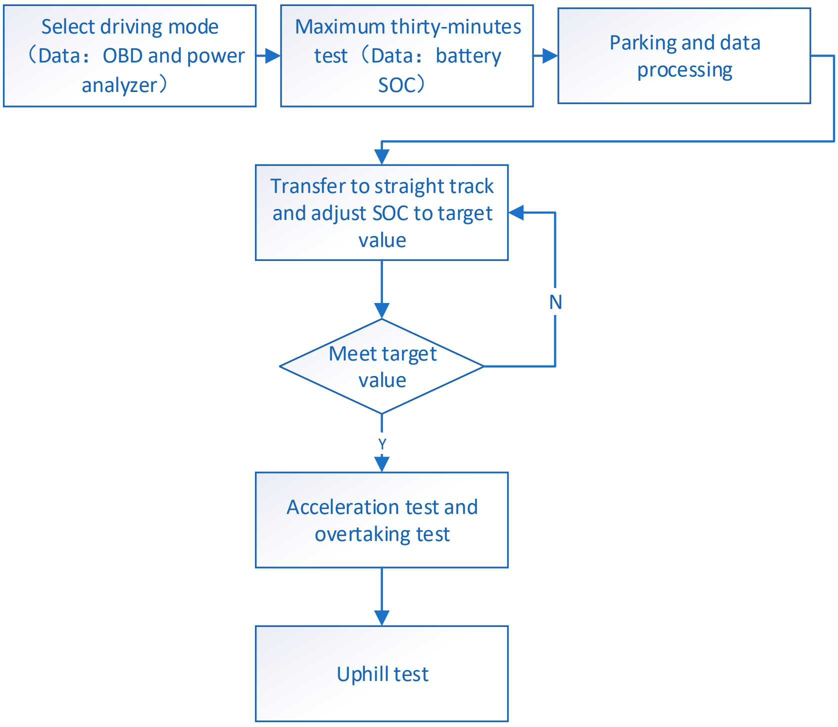


Figure 2. Maximum thirty-min speed test results.

3.3. Data Collection

The data to be collected during the test and the data processing methods are listed in Table 2 below.

Table 2. Data collection and processing.

Equipment	Recorded Data	Calculated Data	Calculation Formula
OBD Analyzer (The protocol is not public, the manufacturer offers the specialized equipment to analyze these data in this test)	Traction battery SOC_{OBD}	-	-
	Speed data	-	-
	Fuel cell system power	-	-
	Traction battery current I_1	Capacity change Cap_1	Capacity change $Cap_1 = \int I_1\, dt$
	Traction battery Voltage V_1	Electrical energy change Q_1	Electrical energy change $Q_1 = \int V_1 I_1\, dt$
HIOKI 3390 power analyzer HIOKI 9279 current clamp	Traction battery current I_2	Capacity change Cap_2	Capacity change $Cap_2 = \int I_2\, dt$
	Traction battery Voltage V_2	Electrical energy change Q_2	Electrical energy change $Q_2 = \int V_2 I_2\, dt$
	-	Calculate SOC_{cap}	Calculate $SOC_{cap} = Cap_2/Cap_0$
	-	Calculate SOC_Q	Calculate $SOC_Q = Q_2/Q_0$

4. Results and Discussion

This chapter summarizes the vehicle test results of the stepped control strategy and the following control strategy. The test results include maximum thirty-min speed, adjusting SOC, accelerated test, etc.

4.1. The Stepped Power Control Strategy Vehicle

Fuel cell systems usually have only a few fixed operating points with the stepped control strategy. However, it needs to be equipped with a large-capacity battery to balance power output. Subsequent test results will show this characteristic more clearly.

4.1.1. Maximum Thirty-Min Speed

The measurement results of the maximum thirty-min speed are shown in Figure 3. The vehicle's maximum thirty-min speed measurement result was 68.5 km/h. In maximum thirty-min speed test, the SOC was reduced from 44.99% to 37.34%, the maximum consumption capacity was 6.14 Ah, and the maximum electrical energy consumption was 2.97 kWh. The power of the fuel cell system remains constant during the maximum thirty-min speed test. Even if the vehicle speed dropped to zero at about 1000 s, the fuel cell system still outputs a high output power, thereby reducing the voltage fluctuation of the fuel cell stack and realizing fast charging of the traction battery. More discussion concerning this topic can be found in Section 4.3.2.

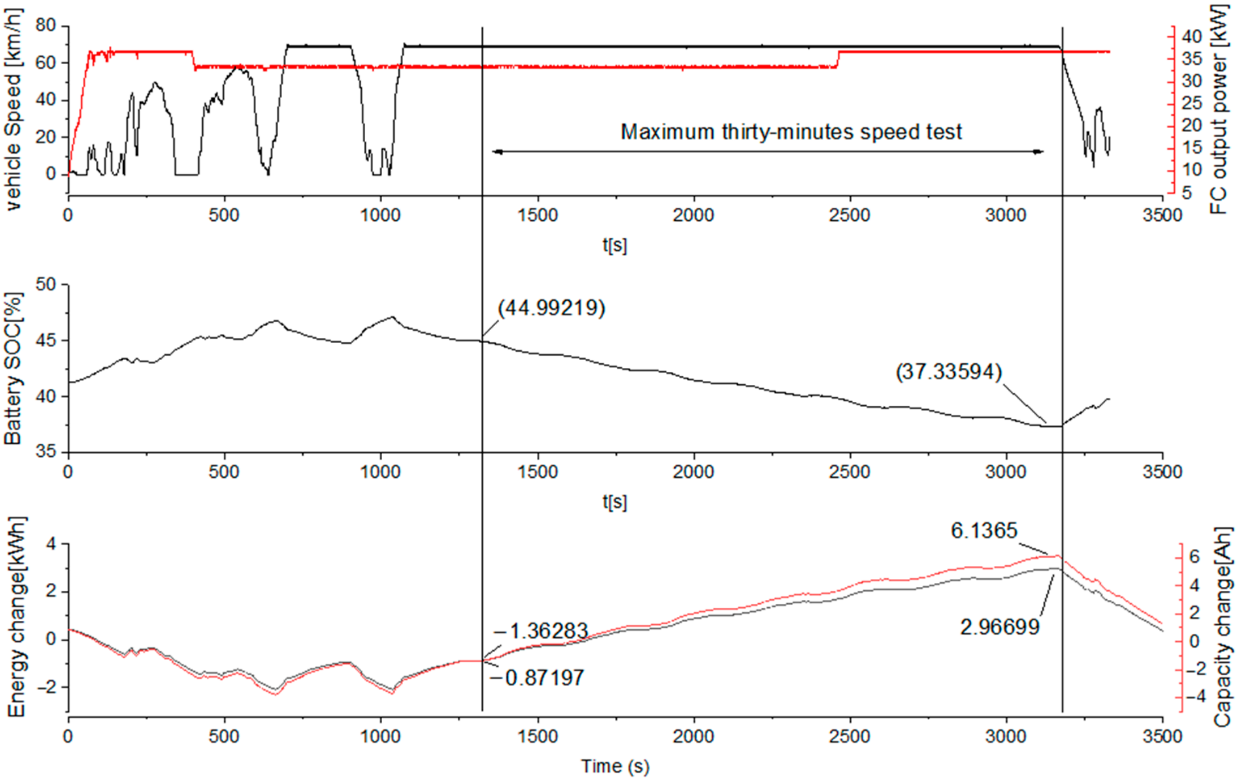


Figure 3. Maximum thirty-min speed test results.

4.1.2. Adjusting SOC

The charging data during the vehicle transition process is shown in Figure 4. After the maximum thirty-min speed test, it is necessary to transfer the vehicle to the acceleration track. During the transfer, the fuel cell system continues to charge the traction battery. The transfer time was about 500 s. Compared with the standard value of the maximum thirty-min speed of 2.97 kWh, the total charging value was 3.77 kWh, which showed that the vehicle with the stepped control strategy has a more aggressive battery priority strategy to meet the power output requirements. However, this strategy will decrease charging and discharging efficiency [5].

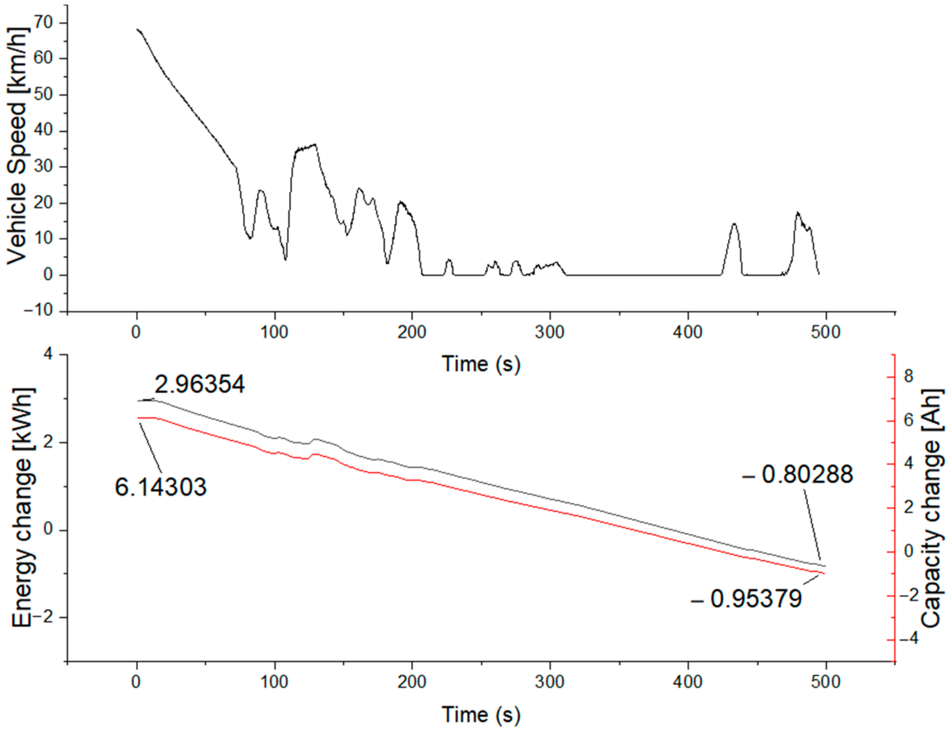


Figure 4. Charging data during transfer.

As mentioned above, the fuel cell system charged the traction battery during the transfer process. The power consumption test data are shown in Figure 5. Energy consumption needs to be performed before the accelerated test to ensure the results' consistency. The vehicle had a pure electric mode with the fuel cell stack closed. Air conditioning and auxiliary machines consumed the electrical energy coming from the battery until the capacity target value of 6.68 Ah. The electrical energy value is 3.15 kWh (target value 2.97 kWh), and the capacity value is 6.68 Ah (target value 6.14 Ah). At this time, the SOC drops from 45.02% to 37.48% (target value 37.34%). It means whether the energy change or capacity change can indicate the change of the battery SOC.

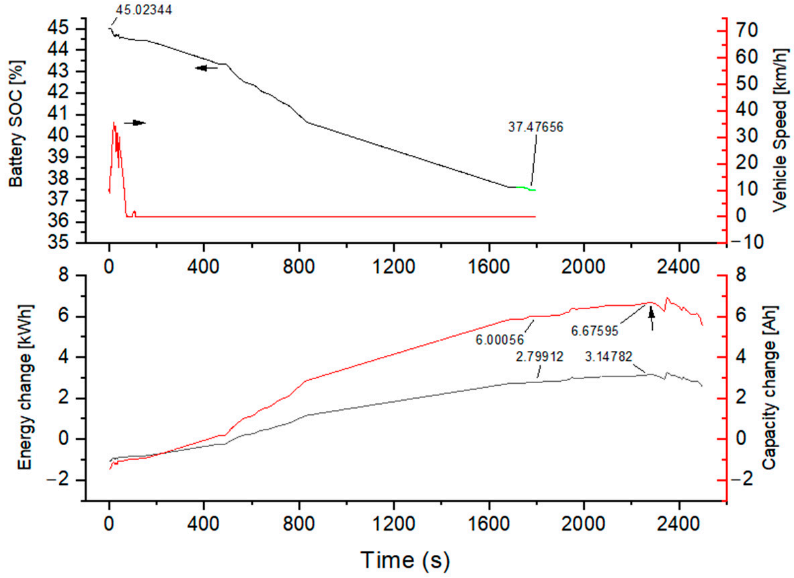


Figure 5. Battery SOC, energy change, and capacity change.

4.1.3. Acceleration Test

The 0~50 km/h acceleration test data are shown in Figure 6. The acceleration test started after reaching the target value. First, the 0~50 km/h acceleration test was carried out. During the 0~50 km/h acceleration test, the power of the fuel cell system was constant at 38 kW. In the first stage accelerated test, the SOC value changed from 37.94% to 37.41%, the electrical energy changed from 2.35 kWh to 2.32 kWh, and the capacity value changed from –1.12 Ah to –1.08 Ah. The changes were tiny. In the second stage accelerated test, the SOC value changed from 37.41% to 36.55%, the electrical energy changed from 2.32 kWh to 2.50 kWh, and the capacity value changed from −1.08 Ah to −0.59 Ah. The process of these two 0~50 km/h tests is different. Compared with the first time, the second acceleration test fluctuated more dramatically, and the output power of the fuel cell system could not meet the demand of the whole vehicle. At this time, the power battery fills the gap and causes the SOC of the battery to decline simultaneously.

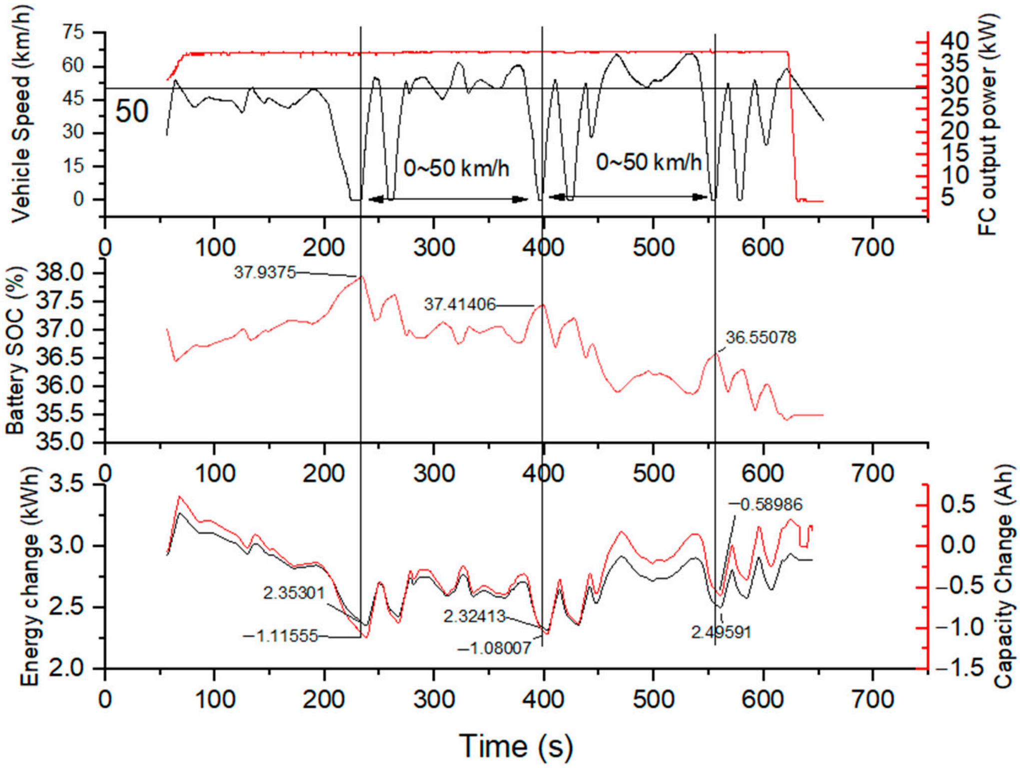


Figure 6. 0~50 km/h acceleration test.

In the 0~50 km/h acceleration test, the rated power of the fuel cell system was always constant at 38 kW. The traction battery balanced the power, and the overall SOC trend was downward. This trend indicates that the output power of the fuel cell system cannot meet the power demand of the vehicle at this time. At the same time, it shows that the changes in electrical energy, capacity, and SOC showed a high consistency.

The overtaking and uphill test data are shown in Figure 7. In the 30 km/h~50 km/h acceleration test, SOC changed from 35.95% to 38.48%, the capacity changed from 5.62 Ah to 3.02 Ah, and the electrical energy changed from 2.38 kWh to 0.87 kWh. The whole process is a charging trend. In the uphill test, SOC changed from 40.26% to 41.55%. Meanwhile, the capacity changed from 1.25 Ah to 0 Ah, and the electrical energy changed from −0.08 kWh to −0.76 kWh. The whole process is a charging trend too.

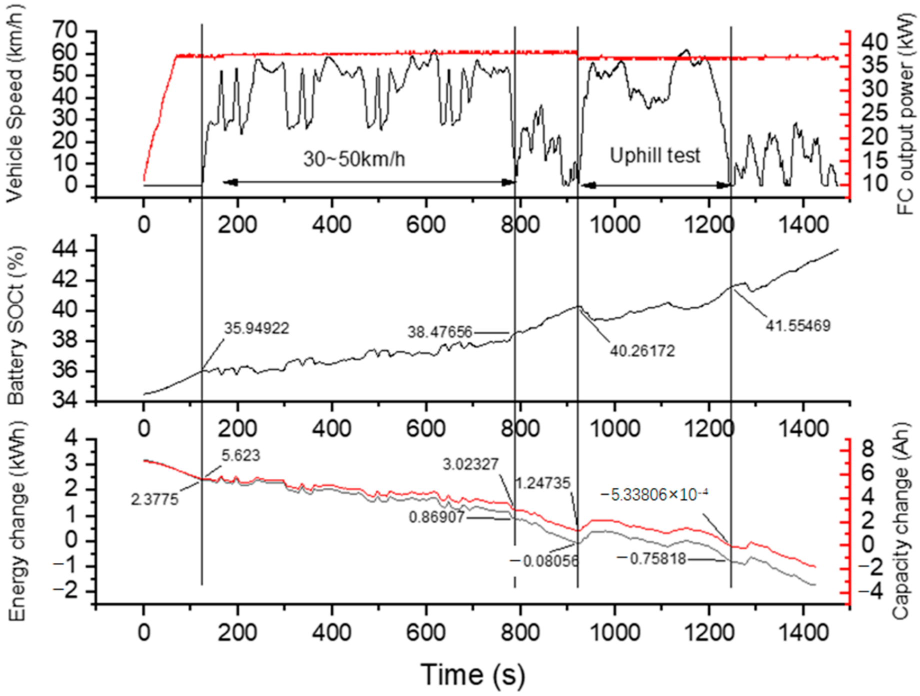


Figure 7. Overtaking test and uphill test.

During the 30 km/h~50 km/h acceleration and uphill tests, the vehicle maintained a constant output power, and the traction battery was used for power balance. Once again, such as the 0~50 km/h acceleration test, the electrical energy, capacity, and SOC changes showed a high consistency.

4.1.4. Summary of the Stepped Power Control Strategy

As for the fuel cell electric vehicles with the stepped control strategy, the fluctuation of the fuel cell system and the frequency of starting and stopping are significantly reduced, which is beneficial to the durability of the fuel cell system. However, adopting an aggressive battery priority strategy will increase the number of power conversion processes, and the loss of charge and discharge will increase and affect the vehicle's economy. This strategy is suitable for urban buses.

The output voltage of the fuel cell stack using the stepped control strategy is stable. The traction battery's SOC, capacity change, and electrical energy change showed high consistency in the test. Therefore, for vehicles that cannot measure SOC, the capacity change or electrical energy change could instead of SOC.

4.2. The Following Power Control Strategy Vehicle

Fuel cell systems can output the power continually based on the load. So only a small-capacity battery is equipped to balance power output. Subsequent test results will show this characteristic more clearly.

4.2.1. Maximum Thirty-Min Speed

The vehicle's maximum thirty-min speed test data are shown in Figure 8. The SOC changed from 57.8% to 44.9% at the maximum thirty-min speed. The capacity changed from 3.09 Ah to 8.20 Ah, and the electrical energy changed from 1.07 kWh to 2.79 kWh. The SOC of the battery continued to decrease during the whole test. At 1511 s, the SOC of the traction battery decreased to 44.8%. Then it was in a stable state, indicating that 44.8% is the lower limit of the SOC of the traction battery. At the same time, the power fluctuation of the fuel cell stack increases significantly. Since the electrical energy and electric power are constant, it clearly shows that the fuel cell system is currently following the load, which contrasts with the vehicle with the stepped control strategy. More discussion can be found in Section 4.3.1.

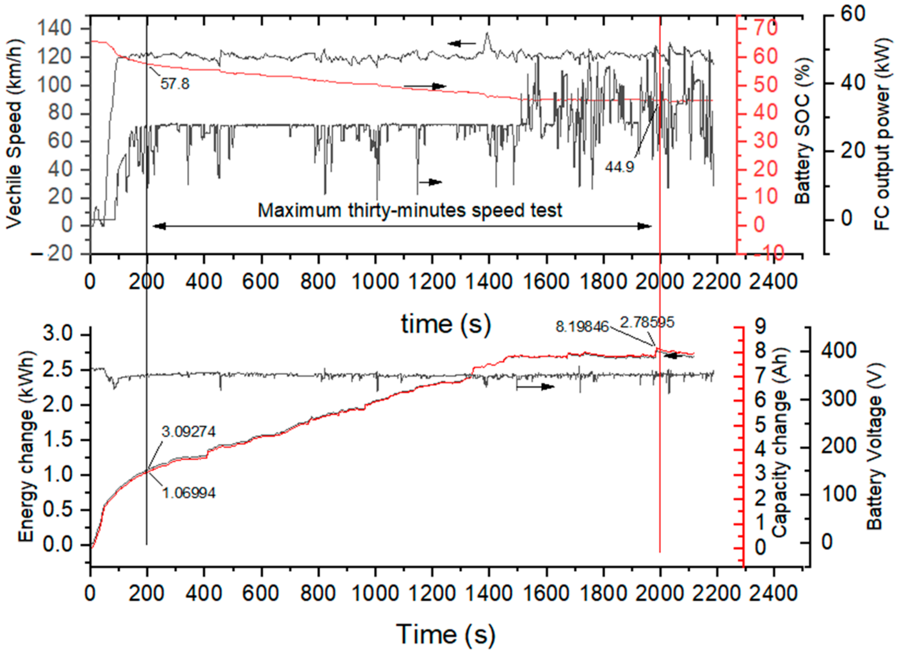


Figure 8. Maximum thirty-min speed test.

4.2.2. Adjusting SOC

After maximum thirty-min speed, the transfer is carried out. The vehicle transfer test data are shown in Figure 9. The fuel cell system charges the traction battery the same as the stepped control strategy during the transfer. However, the strategy is different. When the vehicle stopped at the 2400 s, the fuel cell system did not dramatically increase the power to charge the traction battery. After stopping, the fuel cell system charges the traction battery with a power of about 9.5 kW. To increase the efficiency of charging and discharging, the vehicle with the following power control strategy does not adopt the aggressive battery-priority control strategy as that of the stepped control strategy vehicle.

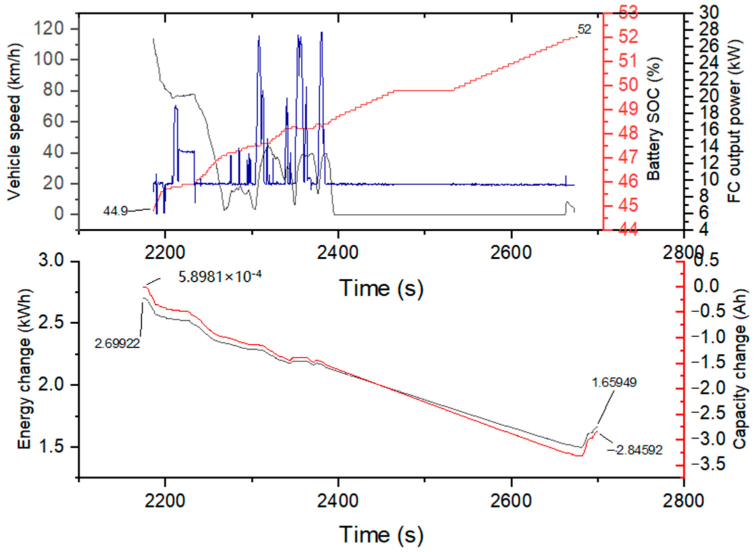


Figure 9. Charging data during transfer.

SOC changed from 44.9% to 52% during the transfer, the capacity changed from 2.67 kWh to 1.66 kWh, and the electrical energy changed from 0 Ah to −2.85 Ah. As in the stepped control strategy, the changing trend of the three parameters showed a high consistency.

The method of dynamic energy consumption was adopted to reach the target value of SOC. At this time, the stack was turned on. The test data of battery energy consumption is shown in Figure 10. The SOC has reached the lower limit of 44.9% in the process of energy consumption. However, the corresponding maximum electrical energy and capacity values were 2.38 kWh and 2.92 Ah. The target electrical energy value (2.79 Ah) and the capacity target value (8.20 kWh) were not reached, and then the static power consumption was carried out. At this time, since the stack has not been turned off, not only does the battery not consume power, but it is charged, and then the stack is turned off mutually, and the dynamic power consumption method is adopted. The capacity value reached 2.89 Ah, which was higher than the target value (2.79 Ah), but the corresponding electrical energy value was 6 kWh, which did not reach the target value (8.20 kWh).

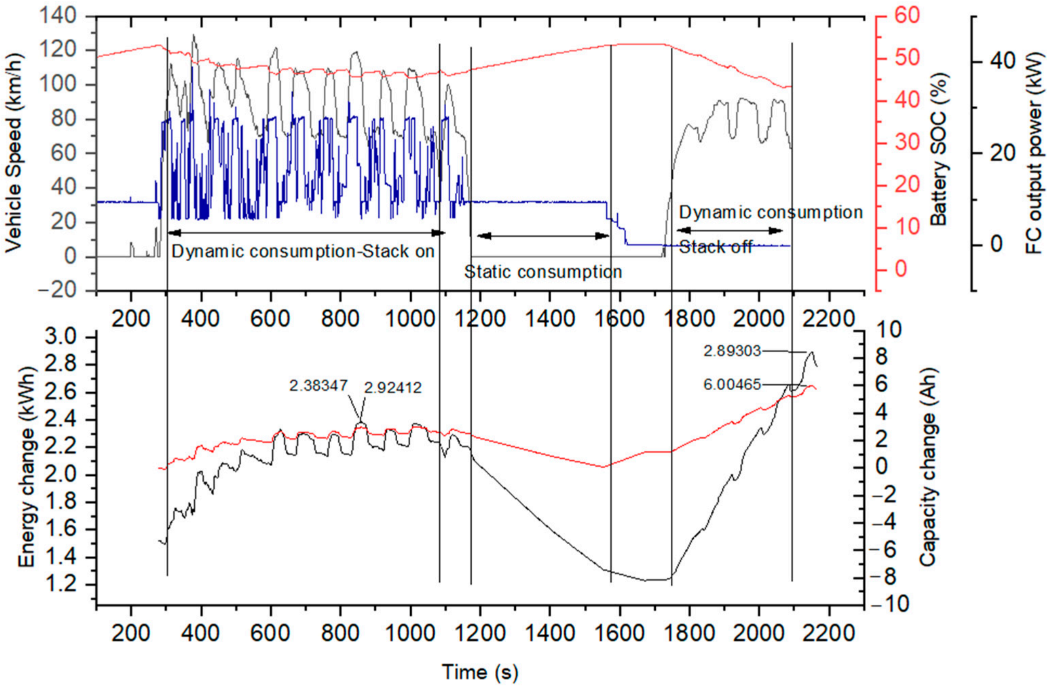


Figure 10. Battery SOC, Energy change, and Capacity change.

4.2.3. Acceleration Test

The vehicle acceleration test data are shown in Figure 11. The traction battery was charged from 41.6% to 43.3% in the 0~100 km/h acceleration test. The electrical energy changed from 2.84 kWh to 2.47 kWh, and the capacity changed from 0.17 Ah to −0.52 Ah. In the surpassing acceleration test, the traction battery was charged. The SOC changed from 43.3% to 44.3%. The electrical energy changed from 2.47 kWh to 2.23 kWh, and the capacity changed from −0.52 Ah to −1.11 Ah. Therefore, it proves that in the acceleration test of 0~100 km/h and 50~80 km/h, the output power of the fuel cell stack charged the traction battery while meeting the power demand of the whole vehicle. More Discussion is in Section 4.3.3. At the same time, the changes in electrical energy, capacity, and SOC showed a high consistency.

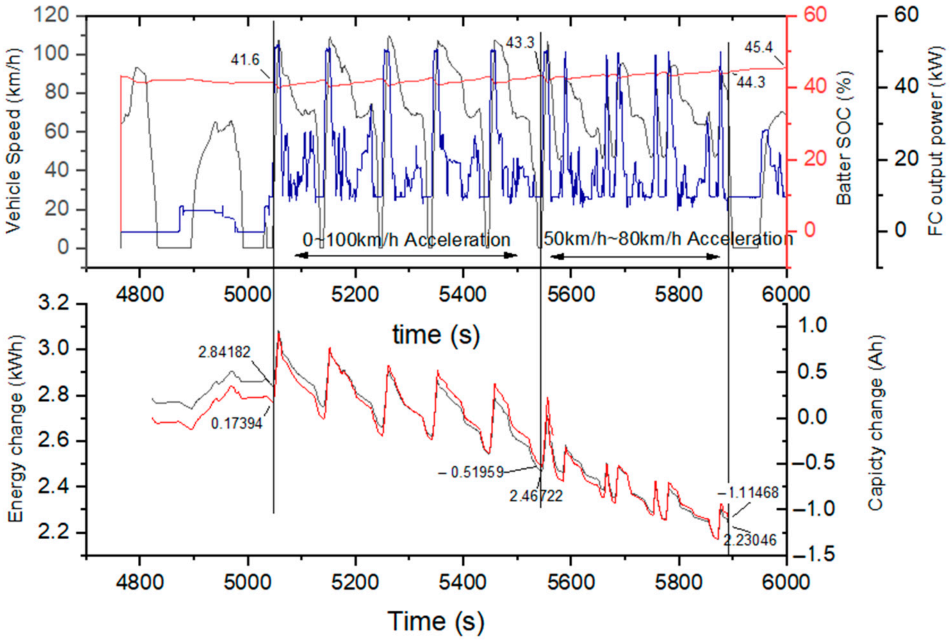


Figure 11. Acceleration test data.

4.2.4. Summary of the Following Power Control Strategy

Compared with the stepped control strategy, the fluctuation of the output power of fuel cell electric vehicles with the following power control strategy increased significantly. Furthermore, the charging strategy was also gentler. In this case, the energy consumption of the whole vehicle will be reduced however it is not beneficial to the durability of the fuel cell system. This control strategy is suitable for family cars.

The output voltage of the vehicle using the following power control strategy fluctuates more greatly. In the power test, the SOC, the capacity change, and the electrical energy change of the traction battery are consistent. However, it is found in the energy consumption test that the SOC and capacity reached the target value but not the electrical energy. For a vehicle with the following control strategy, when the SOC of the vehicle cannot be measured, the capacity can be used instead of the SOC change.

4.3. Discussion on the Performance Comparison

Further discussion on the maximum thirty-minute speed test and adjusting SOC are necessary to understand the characteristics of two typical control strategies.

4.3.1. Discussion on the Test Method

In Section 3.2, we mentioned that we first use the maximum thirty-min speed for the test to calibrate the initial SOC value of the subsequent test. The ideal case is similar to FCV B, which can achieve SOC limitations. Under these conditions, it is beneficial to improve the reproducibility of the test. Another reason has to do with the experimental setup. To reflect the actual situation, we chose commercial vehicles available on the market. The advantage is that it can reflect the actual situation. The disadvantage is that modifying the control strategy will be a highly complex matter, including technical issues and brand considerations. Therefore, two different control strategies are set on two different cars in our experimental setup. This creates a difficulty for analysis, and we need to take steps to address this difficulty.

After further analysis, we realized that since we used the acceleration condition, especially at the beginning of the test, we first used the maximum thirty-min speed test for initialization. Then we take the lowest value of SOC in this process as the starting test point to ensure the consistency of subsequent test results as much as possible. It means that if a bus adopts the following power control strategy, the result of external characteristics will be almost the same as that of the passenger car that uses the following power control strategy. To validate our idea, we conducted a verification experiment, and the results are as follows: Figure 12 shows the relationship between vehicle speed and SOC, and this periodic change can be seen clearly.

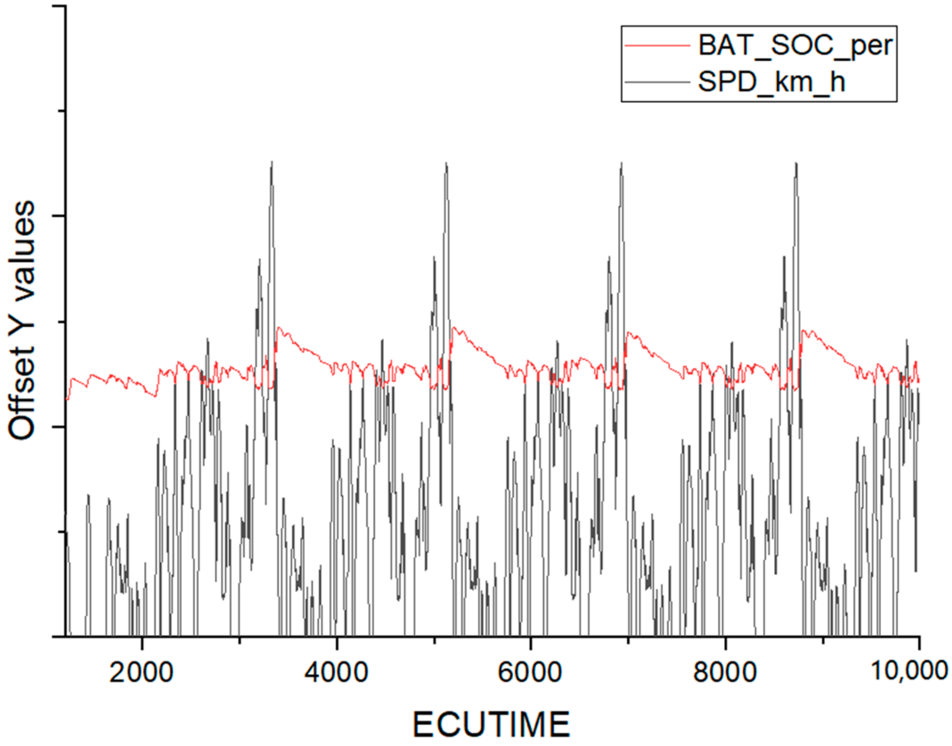


Figure 12. Comparison between speed and change of SOC.

4.3.2. Discussion on Maximum Thirty-Min Speed

This part will further compare and analyze the difference between the vehicle with the stepped control strategy (FCV A) and the vehicle with the following control strategy (FCV B), as shown in Figure 13. For further analysis, we take the maximum thirty-min speed as an example. During the maximum thirty-min speed test, no matter which control strategy was used, the SOC of the power battery showed a downward trend. The control strategy of SOC changed from 57.8% to 44.9%. At 1511 s, the SOC of the traction battery decreased to 44.8%. Then it was in a stable state, indicating that 44.8% is the lower limit of the SOC of the traction battery. Due to the lack of power battery balancing, the fuel cell system's output power shows a sharp fluctuation, which is entirely different from the situation where the power of the fuel cell system is almost a constant value in the stepped control strategy. The same regular changes were also present in the subsequent acceleration and climbing test. The test results clearly show that the focus of different control strategies is different. The stepped control strategy gives priority to the durability of the fuel cell. By equipping a large-capacity battery, the battery is given priority to balance the power demand so that the operating point of the fuel cell system is set. At the working point, reduce the voltage fluctuation, which is an essential factor affecting the durability of the fuel system. For the following control strategy, priority is given to vehicle space and product price. So it is equipped with a small-capacity power battery, thereby reducing product price and vehicle space occupied, but this does not mean sacrificing the durability of the fuel cell system, which depends on the application scenario.

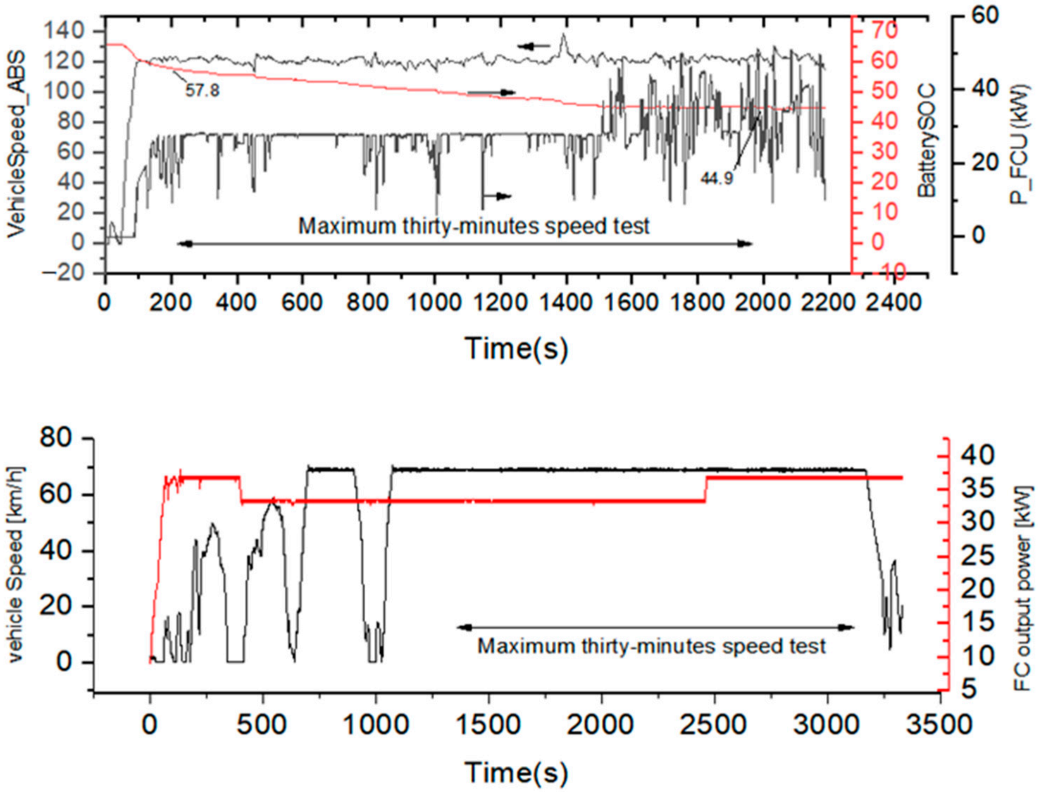
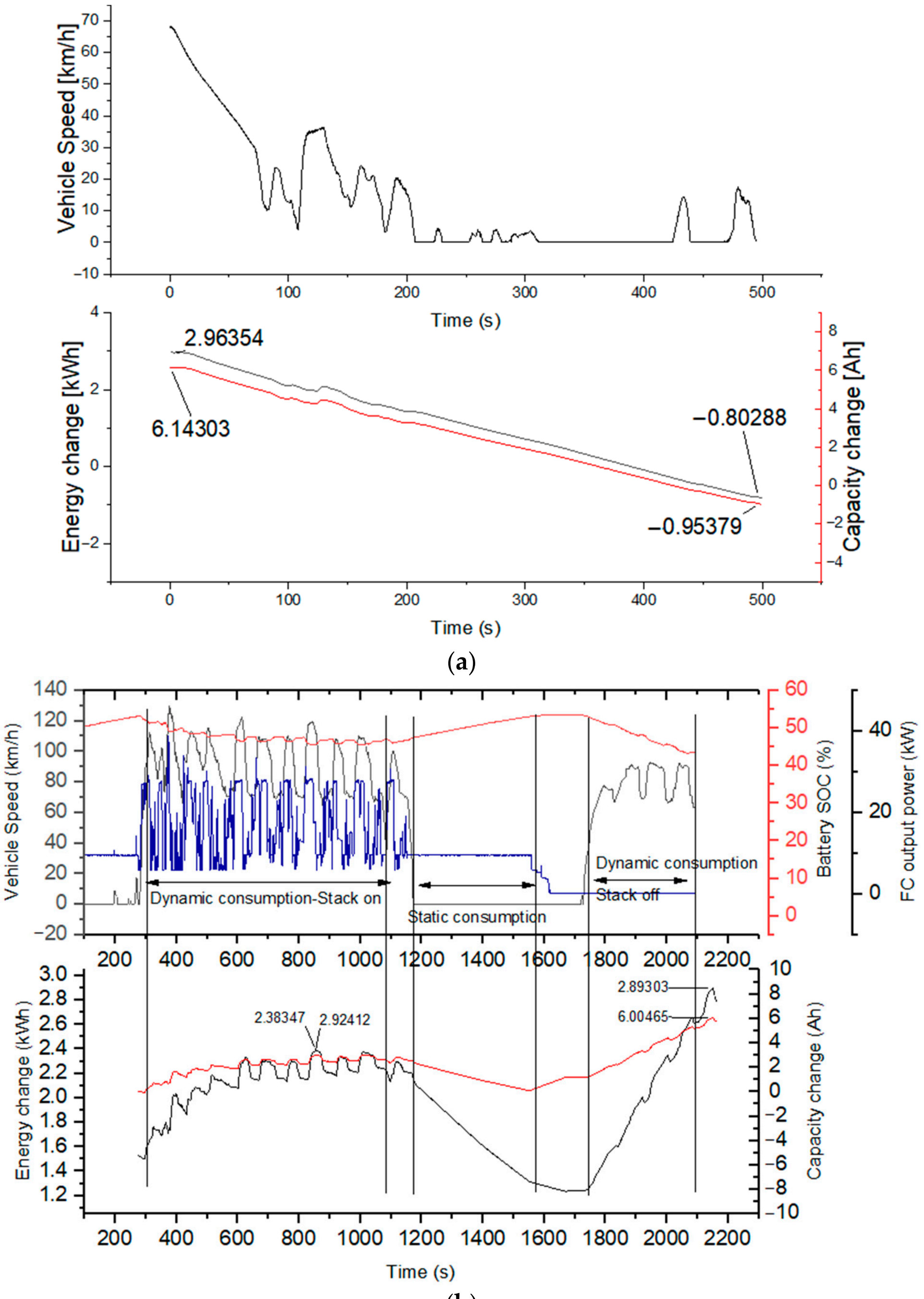


Figure 13. Comparison of maximum thirty-min speed test.

4.3.3. Discussion on Adjusting SOC

Conventional power consumption methods include static power consumption of accessory power consumption and dynamic power consumption of driving power consumption. The power consumption test is simple for FCV A, since FCV A vehicles have pure electric driving functions, but it is challenging for FCV B. In the power consumption test in Section 4.2.2, we found that for the vehicle that adopts the following control strategy, the conventional power consumption method cannot be used to reduce the SOC of the power battery to achieve the expected target. The target value of SOC is reached. There are two possibilities. One possibility is the influence of the control strategy. The control strategy does not allow the lower limit of SOC to be reached in this case. The corresponding SOC value is 45.6%. The other possibility is measuring error, since it was close to the lower SOC value (44.8%). However, the maximum electrical energy and capacity values were 2.38 kWh and 2.92 Ah, which is far from the target electrical energy value (2.79 Ah) and the capacity target value (8.20 kWh).

As mentioned in Section 4.2.2, we manually turned off the stack and successfully reached the SOC target value. However, unlike the stepped control strategy, the energy and capacity changes are not synchronized to achieve the target. The energy change value did, but not the capacity change. The reason is that the voltage is almost kept at a constant value in the stepped control strategy. However, the voltage changes more frequently in the following control strategy, resulting in a deviation between the energy and capacity changes, as shown in Figure 14.



(**a**)

(**b**)

Figure 14. Comparison of adjusting SOC: (**a**) FCV A and (**b**) FCV B.

5. Conclusions

In this paper, for analyzing and comparing the performance characteristics of the fuel cell system under different working modes in the power performance test, we use a bus with a stepped power control strategy and a passenger car with the following power control strategy to do the dynamic tests. Analyzing and comparing these two typical control strategies in the dynamic test of fuel cell electric vehicles will help developers understand how to choose energy management strategies in different application scenarios and how they work in the actual vehicle. The conclusion of our investigation are as follows:

These two typical control strategies show entirely different characteristics in the same test. It shows that the energy management strategies should be adopted according to the application scenarios and optimization goals. In the stepped power control strategy, the fluctuation of the fuel cell system and the frequency of starting and stopping are significantly reduced, which is beneficial to the durability of the fuel cell system, which is suitable for city buses. For the bus, the running time is relatively longer. The working conditions are severe. The durability of the fuel cell system is a priority factor. The follow-up control strategy does not equip with a large-capacity power battery, which is more economical and has a broader application scenario. Compared with the stepped control strategy, the fluctuation of the output power of fuel cell electric vehicles with the following power control strategy increased significantly, so the durability is relatively poor. The applicable scenario for this control strategy is a daily commute, such as a passenger vehicle.

In this paper, a simplified SOC test method is proposed. Due to the particularity of the stepped power control strategy, its operating voltage is constant, so the change of capacity can be used to replace the change of SOC. For the following power control strategy, the change of electric energy can be used instead of SOC changes. Although the accuracy is still challenging to be quantified, it dramatically simplifies the measurement of SOC with high accuracy and gives preliminary observation at least.

In the future, there are two things that should be carried out. One is establishing the quantitative relationship between typical application scenarios and fuel cell system durability and economic indicators. The other is verifying the application boundary through more extensive experiments, wherein the electric energy or capacity changes can substitute for SOC changes.

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