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Study on Performance Simulation Matching of One-Dimensional Hydrogen Storage and Supply System for Hydrogen Fuel Cell Vehicles

Qi Liu [1,2,*], Biao Xiong [1,3], Yuxuan Liu [1,3], Chuanyu Zhang [1,3], Shuo Yuan [1,2], and Wenshang Ma [1,3]

[1] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
[2] Research Institute of Hunan University in Chongqing, Chongqing 401120, China
[3] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
* Correspondence: author: hnuliuqi@hnu.edu.cn
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Abstract: With the improvement of environmental protection requirements, hydrogen fuel cell vehicles are considered one of the most potential and promising new energy vehicles because of their advantages, such as pollution-free emission, long cruising range, and short hydrogenation time. However, there are still unresolved problems between the storage and supply of hydrogen and the power demand during the operation of hydrogen fuel cell vehicles. In this study, a hydrogen fuel cell vehicle is taken as the research object, and a one-dimensional model is built according to the basic performance parameters so as to explore the operation law of the power performance demand of the hydrogen fuel cell vehicle, simulate the power demand in the actual operation process, summarize the influence of different parameters on the power economic performance of the vehicle, and put forward optimization strategies to improve the power, durability, and fuel economy of the vehicle.

Keywords: hydrogen fuel cell vehicle; power demand; simulation matching; hydrogen storage and supply system

1. Introduction

In recent years, with the rapid growth of global energy consumption, the reserves of traditional fossil energy such as oil and coal are gradually exhausted, and all countries are committed to researching and developing new alternative energy sources that are green, clean, low-carbon and recyclable [1]. As a clean, efficient and renewable energy, hydrogen energy has attracted extensive attention of governments and enterprises all over the world and has become a new trend of energy development [2]. According to the report on the future trend of hydrogen energy, by 2050, the demand for hydrogen energy will reach ten times that of today. In international competition, hydrogen energy has become an important strategy for countries to compete for advantages in energy and science and technology. Therefore, governments and enterprises all over the world are vigorously promoting the research and application of hydrogen energy technology, and realizing the further development and application of hydrogen energy in the energy field through continuous technological innovation and application promotion [3,4].

According to the Annual Report of Mobile Source Environmental Management, mobile source pollution has become an important source of air pollution in large and medium-sized cities in China, and the urgency of strengthening mobile source pollution control has become increasingly prominent. Nowadays, people pay more and more attention to environmental protection. With its advantages of environmental protection, low energy consumption, high intelligence and good driving experience, new energy vehicles have become an important direction of future automobile development [5]. Among them, hydrogen fuel cell vehicles have attracted much attention because of their advantages of no pollution emission, long cruising range and good low-temperature start-up [6]. Hydrogen fuel cell vehicles use hydrogen as the energy source, and hydrogen reacts with oxygen in the hydrogen fuel cell system to generate electric energy to drive the motor, and finally realize the operation of the vehicle. Hydrogen fuel cell vehicles have become one of the key research objects in the automobile industry at present, because hydrogen will only generate water and heat after reaction, and will not produce any harmful pollutants, which can effectively reduce the emission of harmful gases such as carbon monoxide and carbon dioxide during use [7–9].

It has been 180 years since the development of hydrogen fuel cell, and its application in automobile field has basically completed the performance research and development stage [10, 11]. As a new vehicle technology, fuel cell vehicle has unlimited development space. In this regard, all countries are actively promoting the development of fuel cell vehicles, and through the introduction of corresponding policies and financial support, accelerating the popularization and application of fuel cell vehicles [12]. Hydrogen fuel cell vehicle is one of the most promising types. On a global scale, the research on hydrogen fuel cell vehicle has been carried out for many years, and it has been designed by hundreds of enterprises and research institutions. As a new renewable energy vehicle, it is gradually moving towards commercialization and popularization [13].

Under the background that various countries actively promote the development of fuel cell vehicles and accelerate the popularization and application of fuel cell vehicles through the introduction of corresponding policies and funds [12], hydrogen fuel cell vehicles, as a new renewable energy vehicle, are gradually moving towards commercialization and popularization. With the United States, Japan, South Korea, the European Union and other developed countries, through the strong support of their governments for many years and the continuous promotion of subsidy policies [14 – 17], they have established and developed enterprises and institutions that can carry out independent research and development, basically realized their own research and production, and are now moving towards larger and more energy-saving target areas. As one of the largest development markets of hydrogen fuel cell vehicles, Japanese automakers such as Toyota and Honda have launched a number of hydrogen fuel cell vehicles including Mirai, Clarity and Miras, and built corresponding hydrogen refueling stations. In addition, the Japanese government has been actively supporting the promotion of hydrogen fuel cell vehicles, and has formulated policies and measures conducive to the development of hydrogen fuel cell vehicles, such as the subsidy plan for hydrogen fuel cell vehicles and encouraging fuel cell research [18]. At the same time, the U. S. government continues to invest in the research, development and construction of fuel cell vehicles, providing strong support for the popularization and application of fuel cell vehicles in accelerating the construction of hydrogen filling stations and promoting the commercial application of fuel cell technology. For example, California has dozens of hydrogen filling stations in operation, which support the daily operation of 8573 fuel cell vehicles and 48 fuel cell buses, and sets the goal of building 200 hydrogen filling stations in 2025. In recent years, Europe has also made great achievements in the development and application of hydrogen fuel cell vehicle technology. For example, German automobile manufacturers such as Daimler, Mercedes, BMW and Volkswagen, French Renault and British Nissan Renault have all launched their own hydrogen fuel cell vehicle products, which have been widely recognized by the market to some extent.

Although predecessors have done a lot of research on various aspects of hydrogen fuel cell vehicles, there are still some problems between hydrogen storage and supply and power demand during the operation of hydrogen fuel cell vehicles. In this study, a certain hydrogen fuel cell vehicle is taken as the research object, and a one-dimensional model is built according to the basic performance parameters, so as to explore the operation law of the power performance demand of the hydrogen fuel cell vehicle, simulate the power demand in the actual operation process, summarize the influence of different parameters on the power economic performance of the vehicle, and put forward optimization strategies to improve the power, durability and fuel economy of the whole vehicle.

2. Hydrogen Storage and Supply System

2.1. Hydrogen Storage System

The research and application of hydrogen storage technology are the keys to the development of hydrogen energy industry. Metal hydride hydrogen storage, high pressure hydrogen storage, low temperature liquid hydrogen storage and physical adsorption hydrogen storage are the main hydrogen storage technology schemes at present. Generally speaking, the hydrogen storage system is a highly integrated system, which requires the synergy among various components to effectively store and use hydrogen.

The hydrogen storage system mainly consists of the following components:

(1) Hydrogen storage tank: The hydrogen storage tank is the core component of the hydrogen storage system and the place for storing hydrogen. According to the working principle and design of hydrogen storage tank, it can be divided into two types: pressure hydrogen storage tank and liquid hydrogen storage tank. Pressure hydrogen storage tanks usually use renewable composite materials such as carbon fiber composites, metal alloys and glass fiber reinforced plastics. In order to effectively prevent the evaporation and leakage of hydrogen, liquid hydrogen storage tanks usually use special insulating materials.

(2) Hydrogen storage pipeline: The hydrogen storage tank is connected with other systems through pipelines to transport and store hydrogen. In order to ensure the safety of hydrogen during transportation and storage, the design of hydrogen storage pipeline needs to consider the pressure, flow rate and temperature of hydrogen, and the materials are usually light alloy materials such as aluminum alloy and titanium alloy.

(3) Hydrogen storage valves and pressure relief devices: The valves in the hydrogen storage system are used to effectively control the inflow and outflow of hydrogen and ensure the normal operation of the system. The pressure relief device is used to protect the safe operation of the hydrogen storage system under abnormal conditions, such as extreme temperature and pressure.

(4) Hydrogen storage sensor: Hydrogen storage sensor is used to detect the pressure, temperature and flow rate of hydrogen in the hydrogen storage system and send these data to the control system to ensure the safety and reliability of the hydrogen storage system.

2.2. Hydrogen Supply System

There are many components in the hydrogen supply system, and each component plays an important role. Only when all parts operate normally and cooperate well can the hydrogen supply system run smoothly and provide stable hydrogen supply for hydrogen fuel cells and other equipment. The hydrogen supply system is mainly composed of the following components:

(1) Ejector: Ejector is a device used to guide liquid or gas from one location to another. This equipment is usually used to spray, pump, mix or stir different fluids. Ejector usually consists of a group of nozzles, which convert energy into velocity and introduce flowing liquid or gas into a jet pipe, thus forming a powerful fluid flow. Ejector is used in many different applications, including combustion chamber, ejector, turbine, mixer, emission control equipment, water treatment engineering, etc. In the field of physics and chemical engineering, ejectors are also often used as laboratory equipment to study fluid dynamics, fluid heat transfer and chemical reactions.

(2) Pressure reducing valve: The pressure reducing valve can effectively reduce the pressure of hydrogen from the hydrogen storage system, so that the pressure of hydrogen participating in the reaction can reach the pressure range that the fuel cell can use.

(3) Check valve: The check valve is mainly used to control the flow direction of hydrogen in the pipeline, so as to prevent hydrogen from flowing backwards or reversely. When the fuel cell stops working, if the pressure of the hydrogen storage tank is lower than that of the fuel cell stack, the hydrogen will flow backwards, which will cause irreversible damage and even endanger the safety

of the system. Therefore, the function of check valve is extremely important, which can effectively prevent this from happening. When the system works, hydrogen can be smoothly delivered to the fuel cell through the check valve. When the system stops moving, the check valve will automatically close, thus preventing hydrogen from flowing backwards.

(4) Hydrogen circulating pump: The hydrogen circulating pump is one of the important equipments in the hydrogen energy hydrogenation station, and its function is to pump hydrogen from the hydrogen storage tank and send it to the hydrogenation machine for filling, so as to realize the rapid filling of hydrogen energy, realize the recycling of hydrogen in the fuel cell stack and promote the water balance in the fuel cell stack.

3. Vehicle Matching and Calculation

Because of the complexity of the hydrogen storage and supply system, this study plans to use a fixed hydrogen storage and supply system to calculate and match the battery and motor parameters according to the driving range, the maximum climbing performance, the acceleration time of 100 km, the maximum speed of the car, and then bring the calculation results into the model for verification. Finally, by optimizing some parameters of the battery motor, the purpose of improving the economic power is achieved.

3.1. Model Building

3.1.1. Complete Vehicle

The whole vehicle model is mainly composed of car body, half axle, tires, road conditions, environment and so on. After the parameters of each part are set, they are dragged into the software modeling area, and then connected through the corresponding components to form the vehicle model (Figure 1).

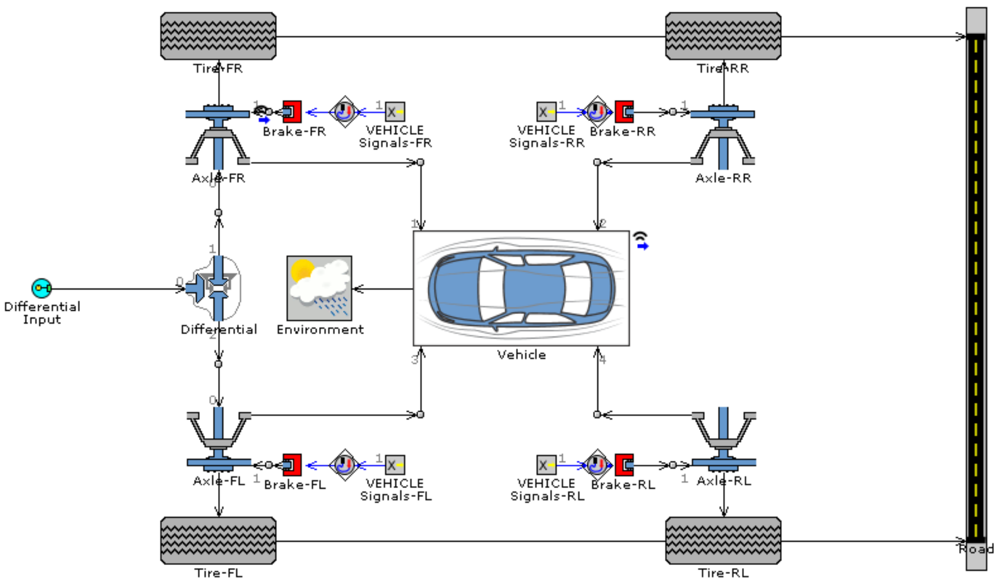

Figure 1. Vehicle model diagram.

The car body model is mainly used to set the properties of the car body parts, and calculate the longitudinal motion of the vehicle and the normal load on each axle. The parameters that can be input in this plate mainly include: (1) the mass of the vehicle, that is, the overall mass after unloading; (2) the quality of passengers and goods; (3) initial speed and initial position of the vehicle. In addition, the plate can also set aerodynamic parameters such as air resistance coefficient.

This plate is used to set some parameters in the vehicle axle, including axial moment of inertia, initial angular position and speed, etc.

The wheel model is used to represent the drag and rolling resistance characteristics of the tire in the transmission system model. The main parameters are: the wheel radius of the rolling tire, the tire width, the number of half shafts connected to the tire, and so on. In addition, the rolling tire resistance factor can be set, which is multiplied by the instantaneous normal (radial) load on the tire to calculate the rolling resistance force. In addition, there is no special setting for the road conditions and environment plates, just follow the default parameters given by the system. Finally, each model is connected to the appropriate position through small signals, that is, the model of the whole vehicle is constructed.

3.1.2. Motor

The motor model is mainly used to simulate the motor or generator in the automobile hybrid transmission system.

The first block in the motor model is mainly used to set the parameters in the motor operation: (1) the electromechanical conversion efficiency, that is, the conversion efficiency between electric power and indicated mechanical power, and the corresponding map diagram is obtained by calculation and then brought into the table; (2) friction torque, that is, the numerical value that specifies the friction torque of internal motor friction.

In the second block, three initial parameters are set: (1) the value of maximum and minimum braking torque is used to limit the output of maximum and minimum braking torque; (2) the basic speed and maximum rated power of the motor; (3) static speed threshold and static braking torque limit of the motor.

3.1.3. Battery

The battery model defines the properties of battery parts, which can be used to model the battery at the system level without connecting with the circuit model. The battery operates according to the setting of charge (SOC), which defines the remaining capacity level in the battery, and calculates the SOC according to the direction of current, the circuit or the power provided to the circuit.

The module needs to define the initial state of charge of the battery, which is a standardized part of the total battery capacity. The second is to determine the battery capacity. Then there is a map that defines the open-circuit voltage and the internal resistance of the battery during charging and discharging, which is usually a function of SOC and battery temperature (K).

3.1.4. Fuel Cells

PEM fuel cell is a device that converts the chemical energy related to the reaction between hydrogen (H_2) and oxygen (O_2) into electrical energy, and also generates heat and water during the electrochemical reaction. This process is similar to a battery. However, the fuel cell does not need to be charged, but uses a continuous fuel supply from an external fuel tank, which can directly provide hydrogen or obtain it from other fuels. When connected to an electric motor, the assembly can be used as an alternative source of vehicle propulsion.

3.1.5. Vehicle Controller

The controller model mainly simulates the driver's control of the whole vehicle during the normal driving of the vehicle, and is usually used in the dynamic driving cycle analysis of hybrid vehicles. The model consists of a feed-type component, which is used to calculate the necessary traction power or axle torque required for the target vehicle speed or acceleration.

The model mainly adopts four modes to control the vehicle: (1) setting the target speed; (2) setting the target acceleration; (3) simulation is carried out when the load demand is imposed; (4) mixed mode, that is, the controller is used to switch back and forth among the above three modes. Because this experiment studies the running state of the car in the dynamic process, it is more appropriate to adopt the mode of controlling the target speed.

3.2. Hydrogen Storage and Supply System

According to the software case, the following hydrogen storage and supply system is shown in Figure 2.

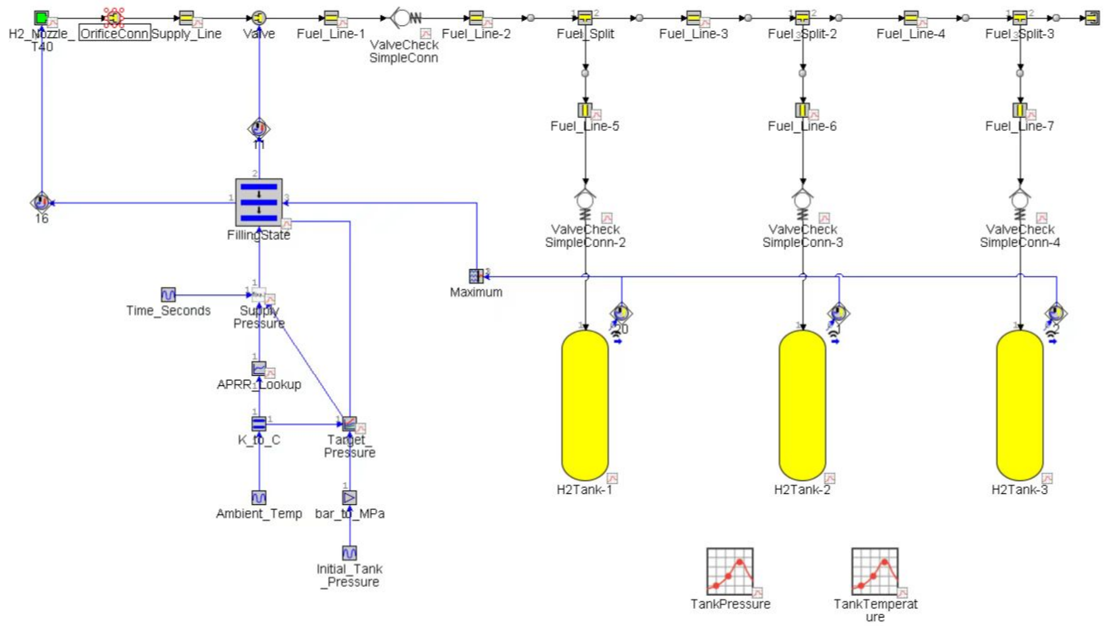

Figure 2. Hydrogen storage and supply system.

Because of the complexity of the hydrogen storage and supply system, this study will match the hydrogen storage and supply system with other parts of the car as a fixed block. In the whole operating condition, the mass flow of hydrogen is shown in Figure 3.

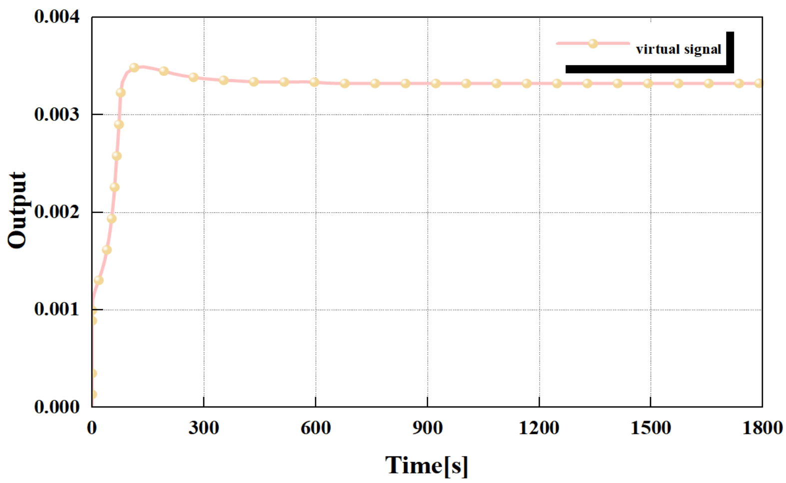

Figure 3. Hydrogen mass flow.

3.3. Vehicle Parameter Matching

When calculating, the basic structural parameters of the whole vehicle are determined first, and then the motor parameters such as torque, speed and power are calculated according to the above parameters through corresponding formulas.

The basic parameters of the small car used in this study are shown in Table 1.

Combined with the technical parameters of different brands of hydrogen fuel cell vehicles on the market

Table 1. Vehicle structural parameters.

Parameter	Numerical Value
Vehicle kerb mass/kg	1750
Fully loaded mass/kg	2000
Rolling resistance coefficient	0.01
Tire rolling radius/m	0.3
Drag coefficient	0.31
Upwind area /m^2	2
Vehicle size (length × width × height)/mm	4384 × 1718 × 1579
Conversion coefficient of automobile rotating mass	1.04
Wheelbase/m	2.67
Transmission ratio of main reducer	4.11
Mechanical efficiency of transmission system	0.94

at present, the performance design indexes of hydrogen fuel cell vehicles are determined as shown in Table 2.

Table 2. Performance design indicators.

Performance Index	Numerical Value
Driving range (km)	⩾60
Maximum climbing performance (%)	⩾30
100 km acceleration time/s	⩽20
Maximum vehicle speed Vmax/(km/h)	⩾130

3.3.1. Motor Parameter Matching

As one of the core components in a fuel cell vehicle, the motor's dynamic performance directly affects the performance and use experience of the vehicle, so it needs to be matched and configured according to the actual needs and use scenarios of the vehicle. Usually, motor matching needs to comprehensively consider the dynamic performance requirements of the vehicle and the actual performance level of the motor to ensure that it can meet the actual use requirements of the vehicle. For the acceleration time of 100 km, the demand for dynamic indicators such as the maximum speed also needs to be met as much as possible.

Calculate the motor parameters according to the performance and parameters of the whole vehicle. First, calculate the power of the motor, and calculate the power of the motor based on the highest speed during driving. The specific calculation formula is as follows:

$$P_1 = \frac{u_{max}}{3600\eta_t}\left(Mgf + \frac{D_c S u_{max}^2}{21.15}\right) \tag{1}$$

In the above formula, P_1 is the required power at the highest speed, and η_t is the total mechanical transmission efficiency of the automobile; M is the full-load mass coefficient of the small car; f is the resistance coefficient; u_{max} is the highest driving speed, taking 130 km/h; D_c is the air resistance coefficient; S is the windward area of the car.

Calculate the power of driving motor according to the index of climbing angle, and the formula is.

$$P_2 = \frac{u_\alpha}{3600\eta_{mc}}\left(Mgfcos\alpha + Mgsin\alpha + \frac{D_C S u_\alpha^2}{21.15}\right) \tag{2}$$

where the maximum gradeability index is 30%, α is the slope angle, and the size is set to 11; u_α is the speed when climbing, which is 39 km per hour. The power requirement of the power source is greater than the maximum value of the corresponding required power mentioned above. After calculation, it can be obtained that P_{max} is equal to 45.8 kW and the conversion efficiency η_{mc} equals 0.95. After the above data, the peak power of the drive motor should be greater than or equal to 48.2 kW. According to the parameter specifications of the existing motor, the value P_{max} is equal to 50 kW.

The speed of the motor is calculated according to the maximum driving speed, and its expression is shown in Equation (3).

$$n_e = \frac{iu_{max}}{0.377r} \tag{3}$$

where i is the product of the transmission ratio of the automobile main reducer and the highest gear transmission ratio of the automobile transmission. n_e is the rated speed of the motor. r is the tire rolling radius.

Take the motor extended power zone coefficient σ as 2, and the peak speed n_{max} of the driving motor is shown in Equation (4).

$$n_{max} = \sigma n_e \tag{4}$$

According to the theoretical knowledge of electrical machinery, rated power P_e, rated torque T_e and peak torque T_{max} can be obtained by the Equations (5)–(7).

$$P_e = \frac{P_{max}}{\lambda} \tag{5}$$

$$T_e = 9550 \times \frac{P_e}{n_e} \tag{6}$$

$$T_{max} = \lambda T_e \tag{7}$$

In the Equations (5) and (7), the overload coefficient λ of the motor is 2.5. The basic parameters of the driving motor matched in this paper are shown in Table 3.

Table 3. Basic parameters of driving motor.

Driving Motor Parameters	Numerical Value
Rated/peak speed/(r min^{-1})	3000/6000
Rated/peak power/kW	20/50
Rated/peak torque/(n m)	80/200

According to the matched driving motor parameters calculated at present, the motor efficiency map can be shown in Figure 4.

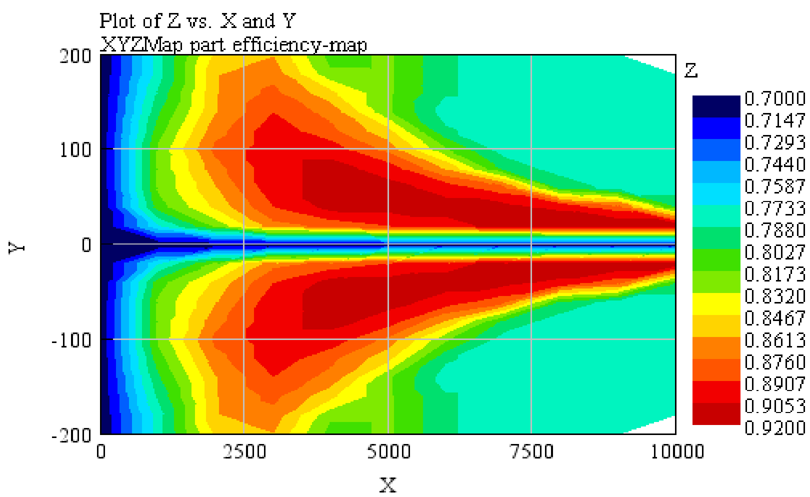

Figure 4. Motor efficiency diagram.

3.3.2. Fuel Cell Calculation

The output power of fuel cell is one of the most important parameters for hydrogen fuel cell vehicles, and the power demand of the vehicle under normal driving should be ensured first. The output power of the fuel cell can be obtained by the Equation (9).

$$P_{fc} = \frac{P_e}{\eta_{DC} \times \eta_t} \tag{9}$$

where η_{DC} is the working efficiency of DC/DC converter, with a value of 0.95.

4. Vehicle Performance Optimization Analysis

This part plans to optimize the activation area of fuel cell, the capacity of battery, the windward area, rolling resistance, automobile quality and so on. By running WLTC cycle road conditions to test the driving range of the car, the economy of the car is improved. By testing the acceleration time and maximum speed of the car in 100 km under the acceleration condition, the power performance of the car is improved.

4.1. Vehicle Power Performance

For the dynamic parameters, the acceleration time of 100 km and the maximum speed, this section mainly focuses on three parameters: the curb weight, the windward area and the deceleration ratio, and compares their influence on the dynamic performance, so as to optimize it.

Figure 5a shows that the curb weight of the car is increased in arithmetic progression from case1 to case 3 while keeping the windward area and deceleration ratio unchanged. The three cases obtained top speeds of 163 km/h, 161.5 km/h, and 160 km/h respectively, and 100 km/h acceleration times of 17.35 s, 20.15 s, and 23.09 s, respectively. According to the above data, it can be concluded that the maximum speed and acceleration time of 100 km are significantly improved when the kerb quality of the car is reduced. However, in reality, due to the existence of internal parts of the car, it is impossible to reduce the quality of the car indefinitely.

Figure 5b shows the result of reducing the windward area by 0.2 m^2 from case1 to case 3 while keeping the curb weight and deceleration ratio unchanged. The three cases yielded maximum speeds of 163 km/h, 168.4 km/h and 174.8 km/h, respectively. And the impact on the acceleration time of 100 km is very small, almost all of them are around 17.3 s. In order to verify whether the windward area has little influence on the acceleration of 100 km, it is decided to increase the reduction of windward area before judging. The results obtained are shown in Figure 5c.

By comparison, it can be found that after increasing the reduction of windward area, the acceleration time of 100 km under the three conditions is still not much different, so the windward area has a greater influence on the maximum speed, but a smaller influence on the acceleration time of 100 km.

Figure 5d is a comparison diagram in which the main reduction ratio decreases from case1 to case 3. The situation of main reduction ratio is more complicated than the above two parameters. Through the principle, we can know that if the same engine chooses a larger main reduction ratio, it can obtain greater maximum torque and stable and better acceleration performance, but the maximum speed will decrease accordingly, which can also be verified from the above image. For off-road vehicles, larger main reduction ratio can get more power, but the main reduction ratio is directly related to engine power and other parameters, so there are certain restrictions, which cannot exceed the tolerance range of engines, gearboxes and other components.

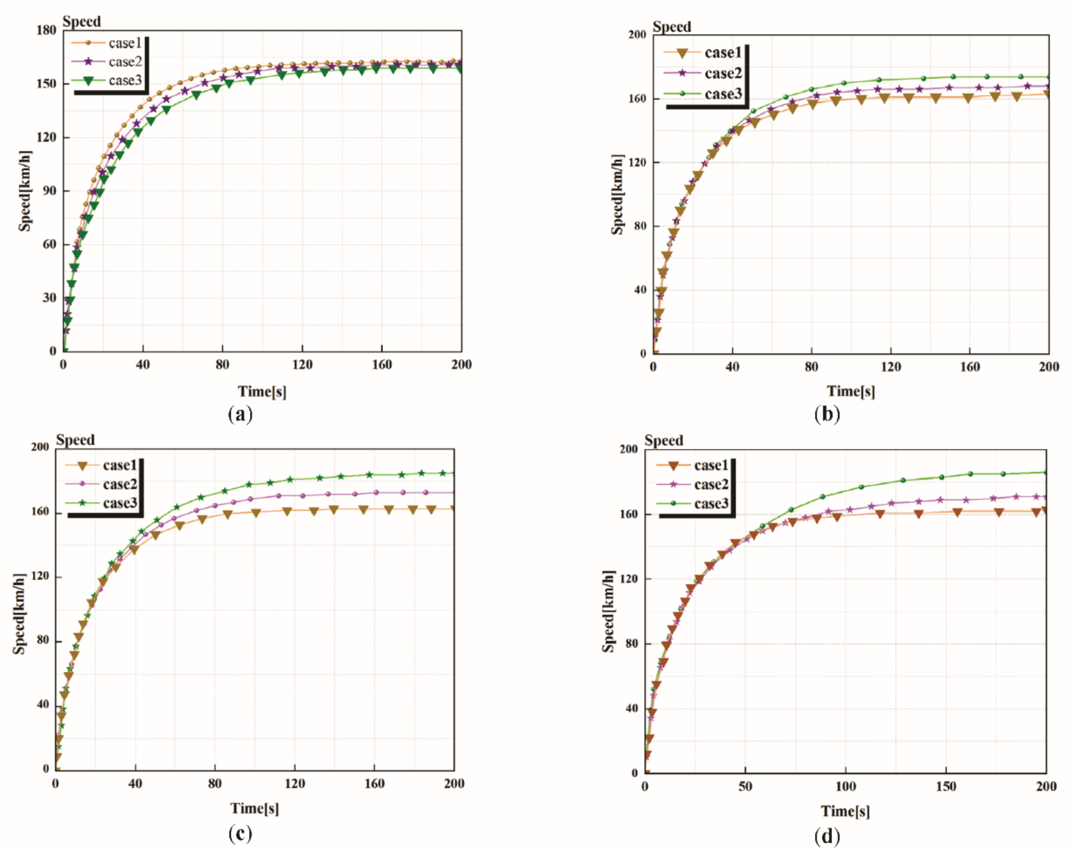

Figure 5. The vehicle dynamic performance data is displayed as shown in the figure above: (**a**) is comparison chart of servicing quality, (**b**) is comparison of windward area, (**c**) is comparison diagram of increased windward area and (**d**) is comparison diagram of main deceleration.

4.2. Vehicle Energy Consumption Economy

By running the same WLTC cycle, and comparing different battery capacities, open-circuit voltage and internal resistance of charge and discharge at the same time, the consumption rate of SOC under different parameters is compared, so as to study the driving range, that is, economy. Because the target speed is limited, the mileage of the car should be the same under different conditions at the same time, as shown in Figure 6a, so the economy can be judged according to the consumption rate of SOC.

In Figure 6b, the internal resistance in the process of charging and discharging is increased from case1 to case 3, and the economy can be judged by comparing the SOC consumption. Because the driving mileage is the same, the consumption of SOC in case1 is less, that is, it has a larger driving mileage.

In Figure 6c, from case1 to case3 in the above figure, the open circuit voltage of charge and discharge increases in turn, and the corresponding driving mileage increases in turn, which makes the economy of the whole vehicle better.

In Figure 6d, from case1 to case3, the battery capacity increases in turn. We can clearly see that in the case of case 3, that is, in the case of using a large-capacity battery, the consumption percentage of SOC is significantly smaller. Therefore, under the same speed condition, it will be more economical to use large-capacity batteries.

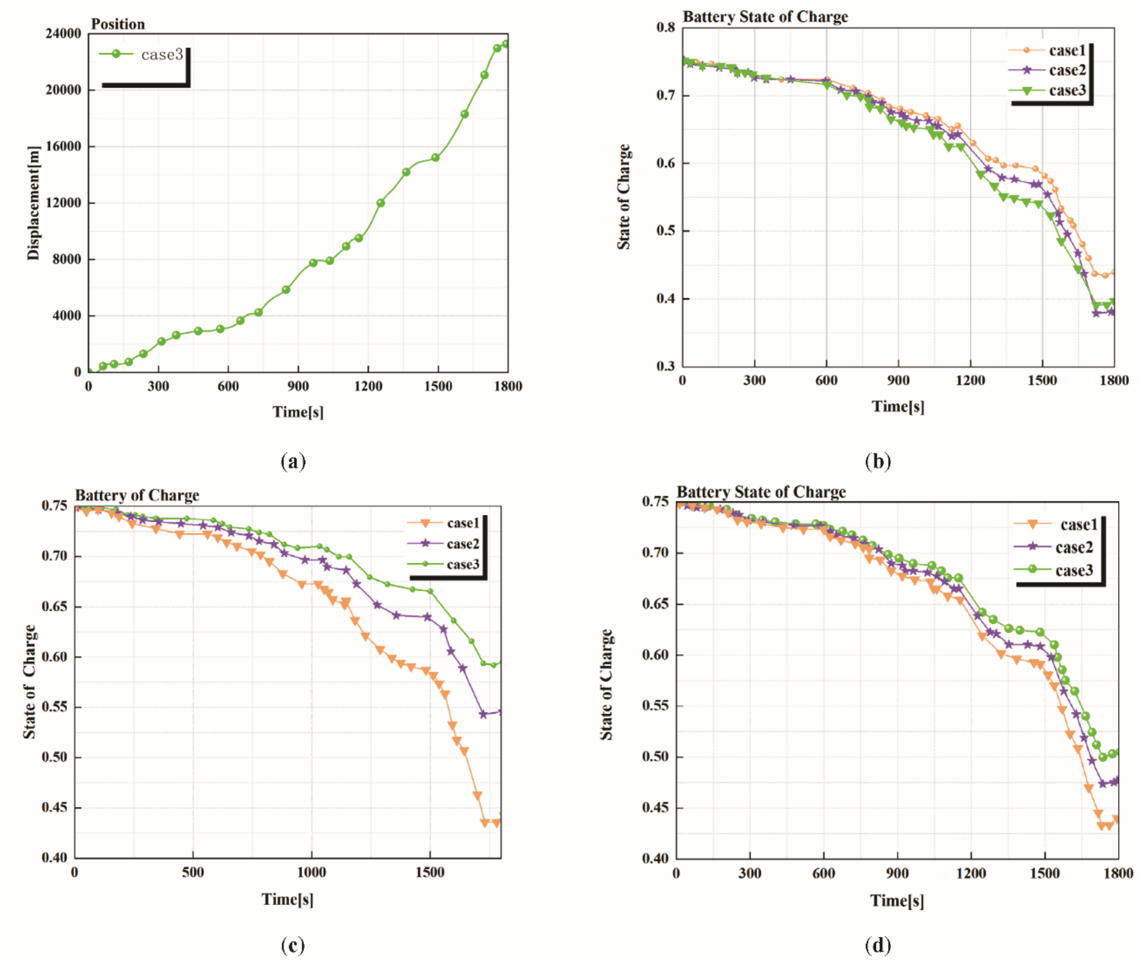

Figure 6. The data of *vehicle energy consumption economy* is shown in the figure above: (**a**) is cycle mileage, (**b**) is comparison of internal resistance, (**c**) is comparison diagram of open circuit voltage and (**d**) is comparison diagram of battery capacity.

5. Conclusion

In this paper, a small car is taken as the research object, and the key components are modeled by software, the battery and motor are studied to some extent, and it is simulated to run under different working conditions, the influence of some factors on the power economy of the car is discussed and summarized. The specific work is as follows:

Using one-dimensional modeling software, the models of key components such as car body, hydrogen storage and supply system, motor and fuel cell are established, and the components are connected into a whole through appropriate signals, and the basic parameters are set. Then the battery and motor parameters are calculated and matched according to the dynamic performance such as the acceleration time of 100 km and the maximum speed of the car. Finally, two different operating conditions are set, and the vehicle operation under different conditions is simulated by changing the parameters of parts, and the influence of different parameters on the vehicle power economy is discussed.

Author Contributions: Q. L.: conceptualization, methodology, software, investigation; B. X.: data curation, writing—original draft preparation, investment; Y.L.: visualization, investigation; C.Z.: supervision; S.Y.: software, validation; W. M.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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