Electric vehicle internal resistance test and optimization

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Abstract. In order to improve the energy-saving effect of a pure electric vehicle, this paper analyzes the causes and influencing factors of the internal resistance loss of the automobile, and expounds the necessity of internal resistance optimization. Select a model in research and development, determine the resistance through the sliding resistance test, and evaluate the energy saving potential of the vehicle through the benchmarking method. A method of resistance decomposition is proposed. The resistance values of key components are tested and analyzed, and the optimization scheme is given. In order to verify the effect of the optimization scheme, this paper proposes a theoretical calculation method. After verification, the proposed optimization scheme finally improves the energy-saving effect of the vehicle by 3%.

1 Introduction

With the development of pure electric vehicle technology, a lot of work has been carried out in the direction of energy consumption reduction in each vehicle enterprise. For example, power analyzer is used to measure the energy consumption of components in high and low voltage system and to optimize the work efficiency of each component. Although internal resistance optimization of electric vehicles has obvious potential for reducing energy consumption of the whole vehicle, due to the difficulty of testing and the long cycle, enterprises often neglect the optimization of internal resistance. In this paper, taking a vehicle in development as an example, a method of resistance decomposition test is proposed, which separately tests and analyses the resistance loss of key components on the transmission system, finds the direction of optimization, and verifies the optimization effect by means of theoretical calculation.

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2 Necessity of internal resistance optimization

In order to quantitatively analyze the necessity of optimizing the internal resistance of pure electric vehicles, the process and route of energy transmission inside pure electric vehicles are analyzed. The energy of the electric vehicle is output by the battery pack, distributed through the high-voltage power distribution unit (PDU), and flows to the low-voltage accessories and the electric drive system respectively. Since the optimization of low-voltage accessories is another topic, it is not reflected in the energy flow route of this article. After the energy is input by the motor controller (MCU), it is converted from direct current to three-phase alternating current, and the drive motor converts the three-phase alternating current into mechanical energy. After the reducer and differential, the torque is transmitted to the wheels to drive the vehicle forward. The driving energy is used to overcome air resistance and rolling resistance, and the remaining is transformed into vehicle kinetic energy. During braking, part of the vehicle's kinetic energy is dissipated to the outside in the form of heat energy through friction when the brake is applied, and the other part is recovered through capacity recovery. Back to the battery to be utilized. It can be seen that there are mechanical losses during the driving process and braking process of the vehicle.

In the energy transfer process, the vehicle exterior optimization measures mainly include the optimization of rolling resistance, windward resistance and acceleration resistance. Although acceleration resistance can be reduced by lightening, a reduction in mass also affects brake energy recovery and is therefore often not considered an optimization item. Rolling resistance and windward resistance have a high proportion of energy consumption, but the windward resistance of the vehicle freezes early in the development process and is not easy to rectify, so the potential of low-rolling resistance tires is limited. In the interior of the vehicle, the charge-discharge efficiency of the battery pack is generally about 98%, with little optimization potential. In the process of energy distribution, the energy loss of the PDU can be neglected. Through integration, the comprehensive efficiency of the motor and its controller can be properly increased to about 92%. In addition, the reducer, differential, half-shaft and calliper on power transmission route can be used as optimization objects. According to the research, the sum of motor loss and transmission loss of electric vehicle is about 22%, which accounts for 64% of all energy loss inside the vehicle and has a large proportion. It can be seen that reducing the mechanical loss of motor and drive system is of great significance to reduce the energy consumption of the whole vehicle[2][5].

3 Causes of internal resistance

According to the energy transmission route, the factor that affects the mechanical transmission efficiency of the power system can be obtained as the transmission efficiency of each component on the transmission route, that is, the resistance loss generated by each component during the power transmission process. According to the power transmission direction (from the drive motor to the wheel), the drive motor no-load loss, reducer loss, differential and axle shaft loss, and front and rear wheel brake jamming loss are in order. The reasons for the loss of each part are explained below[3].

(1) Loss of motor

At present, permanent magnet synchronous motor is used in mainstream pure electric vehicles, and its losses include stator winding loss, core loss, rotor eddy current loss and mechanical loss. The stator winding loss is the copper loss of the winding, which is caused by the resistance of the winding copper wire when current flows through the winding. Its size is determined by the resistance value of the motor winding and the current in the winding. Core loss refers to the eddy current loss caused by alternating magnetic field in the core. The stator core loss accounts for a large proportion of the total loss of the motor. The eddy current loss of rotor is caused by the existence of space and time harmonics of stator slotting, stator magnetic momentum. The loss is small. However, due to the difference of heat dissipation due to the high speed of rotor during the operation of motor, it will cause higher temperature rise and lower motor performance. Mechanical loss includes not only friction between shaft and bearing during motor operation, but also friction between rotor and air in air gap during motor operation. The operating state of the motor, the manufacturing accuracy of bearings and rotors will affect the mechanical loss of the motor. When the speed of the motor is high, the proportion of mechanical loss will increase, which makes the temperature rise of the motor larger[4].

(2) Reducer Loss

The reducer uses parallel-axle cylindrical gears. The main factors influencing the efficiency of the reducer are meshing loss, wear of shaft parts (including bearing and oil seal loss), loss of oil agitation and wind resistance, noise and vibration. When the gear is running at low speed, the loss of transmission power is mostly meshing loss, but at high speed, the loss of no load such as oil agitation and wind resistance accounts for a large proportion of transmission loss.

(3) Loss of differential and half-shaft

The power loss of differential like reducer mainly includes engagement loss of bevel gear, friction loss of bearing, oil seal loss and oil agitation loss. Causes and influencing factors are as above.

(4) Brake drag loss

Brake drag refers to the fact that after the brake is released, the friction pad still contacts the brake disc and generates friction, which results in a certain amount of wheel drag torque. Dragging is totally useless, which increases the energy consumption of the entire vehicle and shortens the range. The main influencing factors of brake drag are divided into three categories: working clearance, sliding resistance and installation. Working clearance refers to the clearance between friction plate and brake disc after braking is released. The size of working clearance can fully reflect the condition of braking. Excessive small working clearance is the basic reason for braking lag. Sliding resistance is mainly the sliding resistance of friction block and clamp body. Sliding resistance of piston affects braking drag through piston return. Sliding resistance of caliper body and friction block affects brake return process after brake is released, and then affects drag under the action of end runout. The installation factor is that the brake caliper is mounted on the steering knuckle, the outer ring of the hub bearing is mounted on the steering knuckle, and the brake disc is bolted to the base flange of the hub bearing.

4 Research program

4.1 Driving resistance test conclusion

According to the mathematical model formula specified in standard GB18351. 3-2005:

$$F = m\frac{\Delta v}{\Delta t} = a + bv + cv^2$$

An equation is established for the unknown dynamic parameters a, B and c, where a represents a constant term of resistance independent of speed (e. g. road friction), B represents resistance related to the primary term of speed (e. g. transmission resistance), and C represents resistance related to the secondary term of speed (e. g. wind resistance). It can be seen that the coasting resistance curve can be used as an intuitive evaluation method to determine the comprehensive resistance of the vehicle. F includes rolling resistance, windward resistance and internal resistance of the vehicle during driving[1].

In order to optimize the driving resistance of R&D vehicles, advanced competitive vehicles of the same level as the R&D vehicles are selected and their coasting resistance is tested respectively. The test results are shown in Figure 4. 1. It can be seen that there is a big gap between the driving resistance of R&D vehicles (blue) and competitive vehicles (orange). When the vehicle speed reaches 60km/h, the gap between the two vehicles becomes more and more obvious with the increase of speed, especially in the high-speed zone (100-120km/h), the coasting resistance is about 40-50N higher than that of competitive vehicles. Therefore, the medium and high speed zone is the next direction to be optimized.

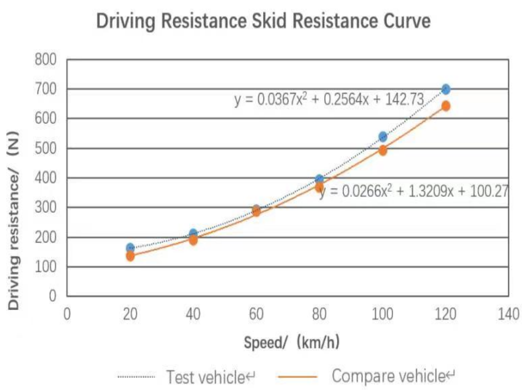

Fig. 4.1. Driving resistance skid resistance curve.

4.2 Calculation method of theoretical energy consumption

The test results in Figure 4. 1 show that there is a resistance gap between the two vehicles during coasting, but the energy consumption performance under cyclic conditions can not be visualized. In order to clarify the difference between R&D vehicles and competitive vehicles and find the optimum direction, a method for calculating theoretical energy consumption under cyclic conditions based on resistance coefficient obtained from coasting resistance test is proposed in this paper. The detailed process is as follows[6].

Drive demand can be calculated by the following formula during driving:

$$F_t = F_f + F_w + F_i + F_j$$

where: Ft is the demand driver, N;Ff is rolling resistance, N;Fw is windward resistance, N;Fi is the acceleration resistance, N;Fj is slope resistance, which is 0 N during drum cycling test.

In the cyclic test, the performance drum can accurately simulate the resistance of the vehicle on the road. For the convenience of subsequent analysis, the driving resistance equation can be written as:

$$\mathrm{P}_{propulsion} = (\delta \mathrm{m} \times \frac{\partial(V)}{\partial t} + F_{roadload}) \times \mathrm{V}$$

where: Ppropulsion is wheel-edge driving power, kW, while driving under cyclic conditions;M is the test quality, kg;V is the driving speed, m/s2;δIt is the mass conversion coefficient. T is the cycle operating time, s;Froadload is road resistance, including wind resistance, roll resistance and vehicle internal resistance while driving. It can be expressed as:

$$F_{roadload} = a + bV + cV^2$$

where: a, B and C are coefficient of sliding resistance, measured by road sliding test.
In order to verify the accuracy of the theoretical energy consumption calculation method, the wheel-side power obtained under the actual NEDC cycle condition of the test vehicle and the wheel-side power obtained by the calculation method are compared and analyzed. The comparison results are shown in Figure 4. 2. It can be seen that the difference between the calculated value and the actual value is small and the error is within 3%. The theoretical energy consumption calculation method can accurately assess the instantaneous power of the vehicle and save the test cost and cycle[7].

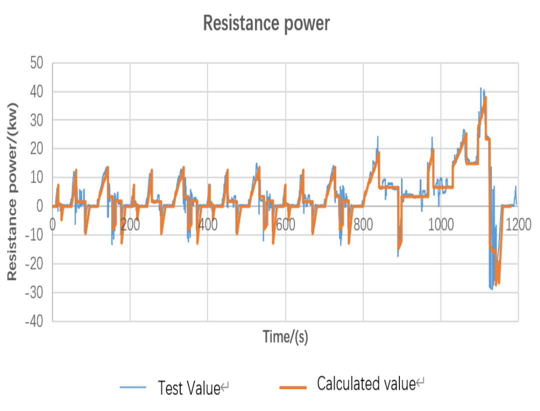

Fig. 4. 2. Calculation method feasibility verification.

Figure 4. 3 shows the instantaneous power (without acceleration resistance) of driving resistance and the accumulation of energy consumption for driving resistance. It can be seen that the resistance energy consumption of R&D vehicles is slightly higher than that of competitive vehicles when driving under the urban conditions of the first 0-780s. The instantaneous resistance power curves of the two vehicles basically coincide, i. e. there is no obvious difference between the resistance and competitive vehicles when driving at medium and low speeds, which is within acceptable range. However, when driving in suburban conditions with a higher speed after 780s, especially in high-speed areas, the energy consumption gap of driving resistance is significantly larger than that of competitive vehicles. Therefore, the main optimization direction of the R&D vehicle is the medium-high speed driving area. At the current development stage, the shape design and motor selection have been finalized. Therefore, the optimization of power transmission resistance becomes an important way to further reduce the energy consumption of the vehicle.

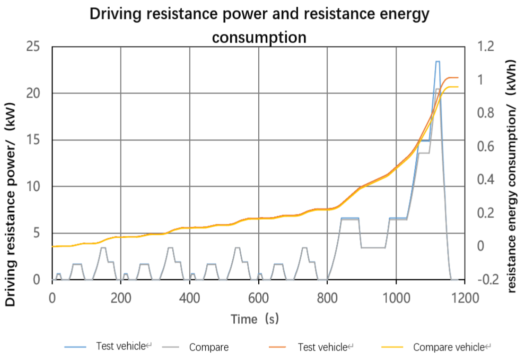

Fig. 4. 3. Comparison of instantaneous power and energy consumption of driving resistance.

4.3 Resistance decomposition test

In order to further explore the resistance loss on the internal transmission system of the car, the disassembly test of each loss component was carried out, and the loss size and proportion of each component of the energy flowing through the transmission system were analyzed. After disassembling each component in the powertrain system of the research and development vehicle in the power transmission direction, and configuring the corresponding load, the speed range of 10-100km/h is carried out on the rotating drum test bench, and every 10km/h is A constant velocity reverse drag test at a measuring point. The specific operation of the test is as follows:

(1) Disconnect the three-phase alternating wire of the drive motor and carry out the anti-drag test on the front wheel;

(2) Remove drive motor and carry out anti-drag test on front wheel;

(3) Remove the output gear of the reducer and carry out the anti-drag test on the front wheel;

(4) Remove output half-shaft and carry out anti-drag test on front wheel;

(5) Remove the two front brake calipers and carry out speed-up (10-120 km/h) back-tow test and speed-down (120-10 km/h) back-tow test on the front wheels;In order to determine the respective resistance of front and rear wheel calipers, reduce test error and ensure more accurate test data, speed-up and speed-down tests are carried out on the resistance parts of front and rear wheel calipers separately.

(6) Remove the two rear brake calipers and carry out the anti-drag test for the front wheels at increasing speed (10-120 km/h) and decreasing speed (120-10 km/h).

5 Analysis and optimization of test results

Through the above tests, three-phase alternating resistance, rotor resistance (collectively referred to as no-load loss resistance), speed reducer, differential, half-shaft resistance and brake caliper resistance of front and rear wheels can be obtained in turn. The resistance of each component can be calculated and analyzed.

(1) No-load loss of motor:

In terms of mechanical structure, when in neutral, pure electric vehicles only have zero power requirement to the motor, while the mechanical connection of the transmission system has not changed, which can not realize mechanical disconnection of the power transmission path of the whole vehicle as matched by traditional gasoline vehicles, such as

MT/CVT/DCT. Therefore, motor idling in neutral state has a great influence on vehicle coasting resistance.

It can be seen from Fig. 5. 1 and Fig. 5. 2 that when the motor is idle, the resistance torque generated by the motor is magnified by the reducer and converted to the wheel-side resistance of the vehicle. The overall level of drag torque fluctuates in the range of 0. 2-0. 8 (Nm). The overall trend is that the torque increases with the increase of vehicle speed and increases rapidly. The drag torque of higher vehicle speed (80-100 km/h) is about 2-3 times higher than that of lower speed (20-40 km/h). The main cause of preliminary analysis is the operation of motor three-phase alternating rectifier bridge circuit of motor controller. The three-phase alternating rectifier bridge of the motor can be switched off by optimizing the control strategy of the motor controller to reduce this part of resistance. On the other hand, the lubrication effect of the bearing on the rotor bearing of the drive motor decreases with the increase of speed, and the drag torque increases significantly with the increase of friction resistance. When the rotor runs at high speed, the mechanical loss accounts for a large proportion and has a great influence on the temperature rise of the motor. The mechanical loss can be reduced by replacing rotating bearings with higher precision, or the lubrication effect of lubricating oil at high speed and high temperature can be improved and the loss of oil agitation during operation can be reduced.

Fig. 5. 1. Motor drag torque.

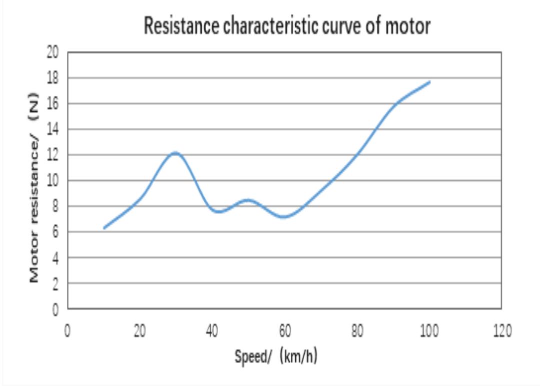

Fig. 5. 2. Motor resistance.

(2) Drag loss of main reducer:

As shown in Figure 5. 3, the overall resistance of the final drive increases with the increase in vehicle speed, reaching a maximum of about 12N. When running at low speed, the resistance is less than about 5N. The resistance of the reducer mainly includes gear meshing loss, shaft component resistance (including bearing and oil seal resistance) and oil stirring resistance. As the vehicle speed increases, the frictional resistance of the shaft components of the reducer increases, and the oil stirring resistance experienced by the gears when rotating in the lubricating oil is also increased, which makes the resistance of the reducer larger when running in the high-speed area. Reduce the resistance by adopting higher precision gears and bearing systems, and secondly replace the high-speed lubricating oil with better lubricating effect to reduce the resistance of the overall reducer and improve the power transmission efficiency.

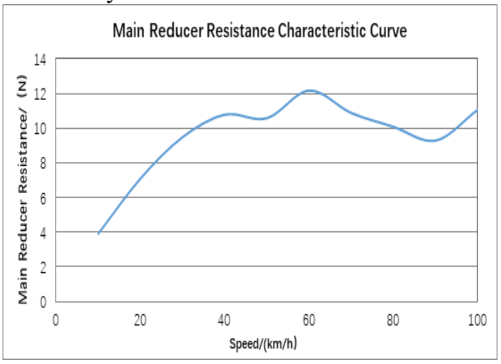

Fig. 5. 3. Main reducer resistance characteristics.

(3) Resistance of differential and half-shaft

As shown in Fig. 5. 4, similar to the resistance characteristics of the main drive, the resistance of the differential and the half-shaft increases as the vehicle speed increases, reaching a maximum of about 10N and about 4N at low speed. The reason for the high resistance in the high speed area is basically the same as that of the main drive, mainly due to increased mechanical losses when the gears and bearings are running at high speeds. The optimization aspects are still gears, bearings, lubricants, and the specific optimization methods are similar to those of the final drive.

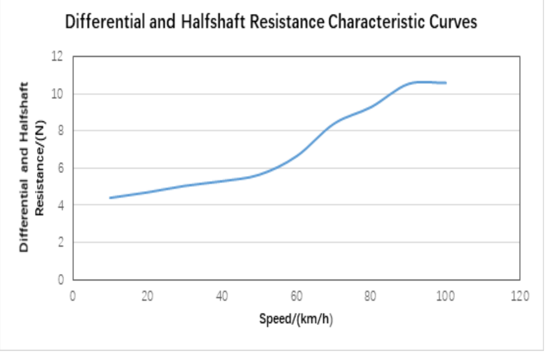

Fig. 5. 4. Differential and halfshaft resistance characteristics

(4) Loss of resistance of front and rear wheel calipers:

From Figure 5. 5, it can be seen that the resistance of the front and rear wheel calipers differs greatly at low speed (10-50km/h), while the resistance of the rear wheel calipers is larger. At 20km/h, the resistance of the rear wheel calipers is about 25N higher than that of the front wheel. As the vehicle speed increases, the resistance of the front wheel calipers increases gradually, and at the same time, the resistance of the rear wheel calipers decreases gradually. At 70-110 km/h, the resistance of the rear wheel calipers increases gradually. The resistance of both front and rear calipers gradually stabilizes in the range of 12-15N. When running at medium and low speed, the resistance of speed-up caliper is about 5N higher than that of speed-down caliper at the same speed. When the vehicle speed reaches 80km/h, the resistance of speed-up and speed-down are basically the same and there is no large fluctuation with the increase of speed. Caliper resistance losses on both wheels account for a higher percentage at medium and low speeds. The change trend of resistance of front and rear wheel calipers is quite different, which may be caused by the structure of calipers. The specific reasons need to be further studied. The friction between the caliper and the friction disc can be reduced by improving the rigidity of the caliper body in manufacturing, reducing the runout tolerance of the friction disc section, and reducing the position tolerance of the brake disc relative to the brake caliper in installation.

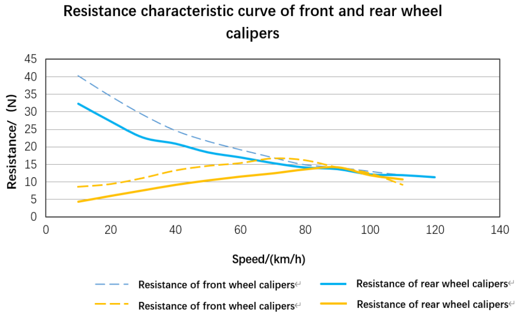

Fig. 5. 5. Resistance characteristics of front and rear wheel calipers.

6 Analysis of optimization effect

For each part of power transmission system, gear train, bearing system and lubrication system of each part are optimized in turn according to the suggestion of optimization method, and assembly accuracy of each part is improved as far as possible to reduce assembly error. Assemble the whole vehicle again, carry out sliding resistance test and NEDC cycle theoretical energy consumption calculation, and compare the analysis results with the optimization results before optimization.

Under the same conditions, the coasting resistance test is carried out again on the optimized test vehicle, and the resistance curve is fitted again and compared with the resistance curve before optimization of the test vehicle and that of the competitive vehicle, as shown in Figure 6. 1. After optimizing the transmission system, the driving resistance of the test vehicle decreases, especially in the high-speed area (80-100km/h), the optimizing effect is obvious, and the driving resistance of the vehicle decreases by about 15-20N, about 2-3%.

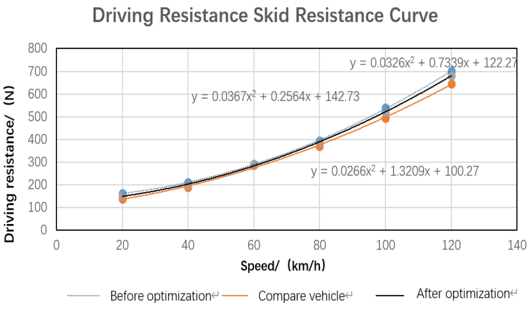

Fig. 6. 1. Optimized sliding resistance curve.

According to the theoretical energy consumption calculation method, the instantaneous power and energy consumption accumulation of driving resistance after optimization are obtained as shown in Figures 6. 2 and 6. 3. After driving in suburban conditions, especially in high-speed driving areas, the power consumption of driving resistance decreases by about 0. 7-0. 8kWh after optimization, and the comprehensive energy consumption of final cycle conditions decreases by 3%, which significantly reduces the gap with competitive vehicles.

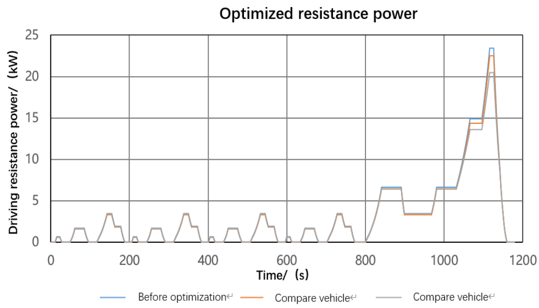

Fig. 6. 2. Resistance power after optimization.

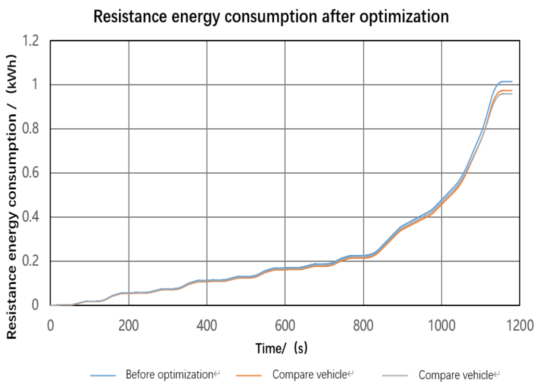

Fig. 6. 3. Resistance energy consumption after optimization

It can be seen that the method described in this paper can be used to test and optimize the internal resistance of pure electric vehicle, which can effectively reduce the energy consumption of pure electric vehicle.

7 Conclusion

Through the disassembly test on the internal loss components of pure electric vehicle, the energy loss of each component is analyzed, the optimization proposals for each component on the transmission system are put forward in turn, and the driving resistance instantaneous power and resistance energy consumption accumulation before and after optimization under NEDC conditions are compared through theoretical energy consumption calculation. The conclusions are as follows:

(1) By comparing the calculated theoretical energy consumption with the measured experimental value, it is verified that the theoretical energy consumption calculation method can accurately assess the energy consumption of driving resistance.

(2) Through the resistance disassembly test of each component, the resistance of each component can be obtained at different speeds, and the direction of resistance optimization of each component can be analyzed.

(3) The no-load resistance of motor, the resistance of main reducer, the resistance of differential and half-shaft, and the resistance of front and rear brake calipers are respectively rectified, which can produce 3% energy consumption reduction effect for the whole vehicle.

References

1. Yu Zhisheng, Automotive Theory [M]. 5th Edition. Beijing: Machine Industry Press, 2009:2-30.
2. Chen Yehan, Xiong Huiyuan, Zong Zhijian, etc. Energy Flow Simulation of ECUV Pure Electric Vehicle Based on Dymola [J]. Computer Engineering and Design, 2011.
3. Zhou Feiyu. Power System Parameter Matching and Vehicle Control Strategy Research of Pure Electric Vehicle [D]. Changchun: Jilin University, 2013.
4. Xu Rong. Loss analysis and temperature calculation of permanent magnet synchronous motor [D]. Shanghai: Shanghai Institute of Electrical Machinery, 2013.
5. Luo Wei, Lu Zhijian, Chen Xinbo. Efficiency Analysis of Electric Vehicle Drive System. Mechanical Design, 2018,4 (2)
6. Long Jinshi. A Test Method for Mechanical Resistance of Vehicle Driving: CN201510273949. 3 [P]. 2015-09-02, China.
7. Dong Jinsong, Xu Hongguo, anytime, etc. Study on Calculation Method of Rolling Resistance and Air Resistance Coefficient of Vehicles Based on Road Test. Traffic Information and Safety, January 2009 (27).