# Experiment of energy recovery efficiency and simulation research on EV's regenerative braking system

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**Abstract**

The proposed technique ECPS aims to design and implement a constant pressure hydraulic regenerative braking system with flywheel that can operate the problems of short driving range and improve efficiency of braking energy recovery about electrical vehicle. We established ECPS after comparing several hydraulic regenerative braking schemes .Then we explored the correlation between displacement of pump/motor and efficiency of energy recovery by undertook experiment on using variable displacement of pump/motor. After that, we investigated braking and ECE-15 driving condition simulation based on AMESim, evaluated correlation between displacement of pump/motor and efficiency of energy recovery. The results indicate that the driving range of electrical vehicle has been increased by 25% and the service life of battery was prolonged because depth of discharge was decreased.

*Keywords:* recovery efficiency, regenerative braking, experiment

## 1 Introduction

Regenerative braking system refers to the vehicle's braking energy recycling; there are a variety of forms, such as Electrical energy recovery and hydraulic energy recovery. Using motor regenerative braking energy recovery systems have a significant effect in pure electric vehicles, but there are still some drawbacks: it limited capacity of the braking energy recovery because of the electric energy storage's energy density is low, thus affecting the driving range of electric vehicles mileage; motor regenerative braking belongs to the electronic system, due to the brake factors, mechanical power system is more reliability than the electric power system [1]. Owing to hydraulic energy recovery power density is higher than the electric energy recovery [2], using hydraulic brake energy recovery in pure electric vehicle under the same conditions and at the same time can able to recover and release more energy, so it can better improve driving range of electric vehicles. In addition, automotive powertrain changes for the use of hydraulic energy recovery is little, relative to the electric energy recovery control link is simple and more reliability.

At present, there are many different forms of hydraulic fuel-efficient vehicles in foreign research and development, depending on its configuration and powertrain combinations in different ways, it can be divided into: series structure, a typical representative of the U.S. EPA's hydraulic hybrid system [3], Its structure is simple, the system is easy to control different parameters; parallel structure, such as Cumulo driving system from Swedish Volvo [4], it changes little on vehicle and has high energy efficiency; hybrid structure, such as the last century nineties developed Constant Pressure Source (referred to CPS) hydraulic drive system in Japan, it has become one of the main forms of vehicle energy recovery system due to its good energy saving and simple structure [5]. CPS system through the engine and flywheel hybrid drive for the power system, the use of Constant Pressure Source hydraulic system to transform energy.

The system in this article will use the rear-mounted parallel structure; CPS flywheel hydraulic regenerative braking system was put forward. Its high energy efficiency and control link is relatively simple, small changes to vehicle power system, also the cost is relatively low.

## 2 Electric vehicle hydraulic regenerative braking system

According to the CPS, we proposed electric vehicle regenerative braking hydraulic system (referred ECPS), in parallel with the power system, determine the drive system to be rear driveline parallel system. The ECPS system structure shown in Figure 1.

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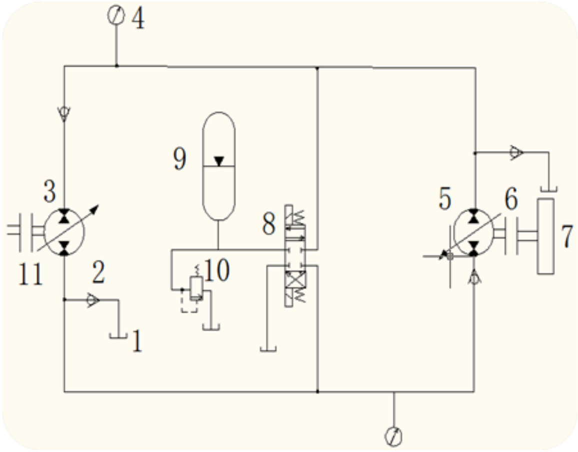


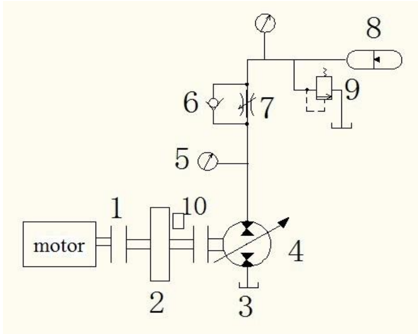

1. Tank 2. Check valve 3. Variable pump / motor connected with the drive axle 4. Manometer 5. Variable pump / motor connected with the flywheel 6., 11. Clutch 7. Flywheel 8. Three-way valve 9. Accumulator 10. Pressure relief valve

FIGURE 1 ECPS system structure

When the car braking deceleration, the drive wheel connected to the 3 pump/motor and the 3 pump/motor works as a pump, the resistance generated by this pump to brake wheel while the transform brake mechanical energy into hydraulic energy, the braking energy recovery. The braking force adjust by the displacement of 3 pump/motor to achieve. High pressure oil flow from 3 to 5, the 6 clutch connected flywheel 7 with 5, at this time 5 is as a motor driven flywheel, transform hydraulic energy into flywheel kinetic energy storage. If the car recovered energy is greater than the set maximum kinetic energy of the flywheel, then the clutch is disengaged. At this time 8 solenoid valve is energized, the excess energy is stored in the accumulator, if the system pressure exceeds the upper limit, the remaining energy release through the relief valve. When the vehicle accelerates, the 3 pump/motor as a motor, high pressure oil power the wheels, the system pressure is reduced. 5 Pump/motor as a pump, the system pressure is kept to a level, high pressure oil flow through the outlet 5 to the bottom of the entrance 3. When speed of the flywheel is in minimum speed allowed, the6 clutch and connecting the total driveline 11 clutch disconnect, ECPS system does not provide power. 9 Accumulator prevent the system pressure too volatile and maintain a substantially constant system pressure.

### 3 ECPS regenerative braking principle test system

Verify ECPS regenerative braking system energy recovery efficiency, the vehicle system can provide maximum braking torque is 1/16 to 1/8 for the calculation of the test standard. ECPS equivalence principle test device structure shown in Figure 2.




1. Electromagnetic clutch 2. Flywheel 3.Tank 4.Variable pump / motor 5. Manometer 6. Check valve 7. Throttle 8. Accumulator 9. Relief valve 10. Wheel speed sensor

FIGURE 2 Test apparatus schematic diagram of hydraulic regenerative braking system

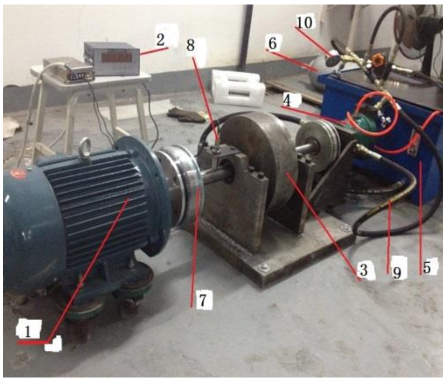
Its equivalence principle is: When the motor drives the flywheel, the clutch between flywheel and motor disconnected, this time representing the flywheel as energy components provide energy for the hydraulic system. Pump/motor as a pump regenerative braking energy, transforms mechanical energy into hydraulic energy can be stored in the accumulator until the flywheel stops; the accumulator release energy after its pressure stabilized, the pump/motor as a motor transforms hydraulic energy into mechanical energy stored in the flywheel. Flywheel as the energy storage element in the actual pure electric vehicles, along with the hydraulic system and electric power systems arranged in parallel chassis. The corresponding processes are when vehicle accelerating driving conditions and driving conditions when braking. Displacement of pump/motor as experimental variables, measured final pressure of accumulator and final speed of the flywheel, calculated the efficiency of energy storage about accumulator, flywheel energy storage efficiency and hydraulic energy efficiency of regenerative braking system, as the test results shown in Table 1.

TABLE 1 Braking energy recovery test results

| | Displacement of pump/moto r (L) | Initial kinetic energy of vehicle (J) | Final shaft speed of flywheel (r/min) | Energy store in flywheel (J) | Energy utilizati on of ECPS system |
|---|---|---|---|---|---|
| 1 | 85 | 167580 | 1200 | 39844 | 23.8% |
| 2 | 75 | 167580 | 1410 | 55134 | 32.9% |
| 3 | 95 | 167580 | 1550 | 66529 | 39.7% |
| 4 | 105 | 167580 | 1795 | 89320 | 53.3% |
| 5 | 115 | 167580 | 1910 | 101050 | 60.3% |
| 6 | 125 | 167580 | 2130 | 125685 | 75.0% |
| 7 | 135 | 167580 | 1790 | 88817 | 53.0% |
| 8 | 145 | 167580 | 1460 | 78763 | 47.0% |

### 3.1 EXPERIMENTAL INVESTIGATION

When displacement of hydraulic pump/motor 5L, according to Figure 3, connect 1clutch between the flywheel and motor, then disconnect clutch between 4 pump/motor and flywheel, close throttle, after the rotational speed of the motor driving the flywheel to 1500r/min, speed keep stability for 1 min. Then connect the pump/motor and flywheel clutch, disconnect 1 and 4 as a pump, high pressure system oil is stored in the accumulator. When flywheel stop, the accumulator's pressure is 3.61Mpa. Energy stored in accumulator is E1=3638J, the initial kinetic energy of system is E0=7395J, recovery efficiency of the accumulator is $\eta 1$ = 49.2%.




1. Motor 2. Tachometer 3. Flywheel 4.Variable pump/motor 5. Tanks 6. Accumulator 7. Electromagnetic clutch 8. Wheel speed sensor 9. Pipes 10. Manometer
FIGURE 3 ECPS test device

Changing the pump/motor displacement, do in the same test method, the measured results of the other seven sets of data shown in Table 1.

After the accumulator pressure is 3.61Mpa stable, open the throttle, connect the clutch between flywheel with 4 pump/motor, disconnect 1, using the stored energy in accumulator drives flywheel, 4 working as a motor at this time , wheel speed sensor records the flywheel in the process to achieve the maximum speed of 755r/min. The kinetic energy of the flywheel is *E2*=1784J. Flywheel energy recovery efficiency is of 51.5%.

In this same test method, the measured results of the other seven sets of data shown in Table 1.

The ratio of final kinetic energy of the flywheel to initial kinetic energy equals the hydraulic regenerative braking energy efficiency of the total system [6].

$$\eta = \frac{E_2}{E_0} = 25.3\%$$

In the same test method, the measured results of the other six groups of data shown in Table 1.

### 3.2 ANALYSIS OF TEST RESULTS

Experiments show that: with different displacement of hydraulic pump/motor, the final recovery of the energy and recovery efficiency of flywheel and accumulator is different, the greater displacement is the more energy is recovered. But when pump/motor displacement above a certain value, because the pump/motor resistance increases, energy recovery efficiency of hydraulic brake energy recovery system will decline; Further data indicate that accumulator energy recovery efficiency is lower than recovery efficiency of flywheel. Hydraulic system requires a good match between the components to achieve optimal energy recovery results.

## 4 System simulation analysis

Based on Figure 1 shown a hydraulic regenerative braking energy recovery system, created simulation model of the desired vehicle system on AMESim [7]. Vehicle simulation model shown in Figure 4, in which the hydraulic energy recovery system shown in Figure 5. Driver's control system parameters are divided into acceleration and braking control parameters, the control type is PID control [8].

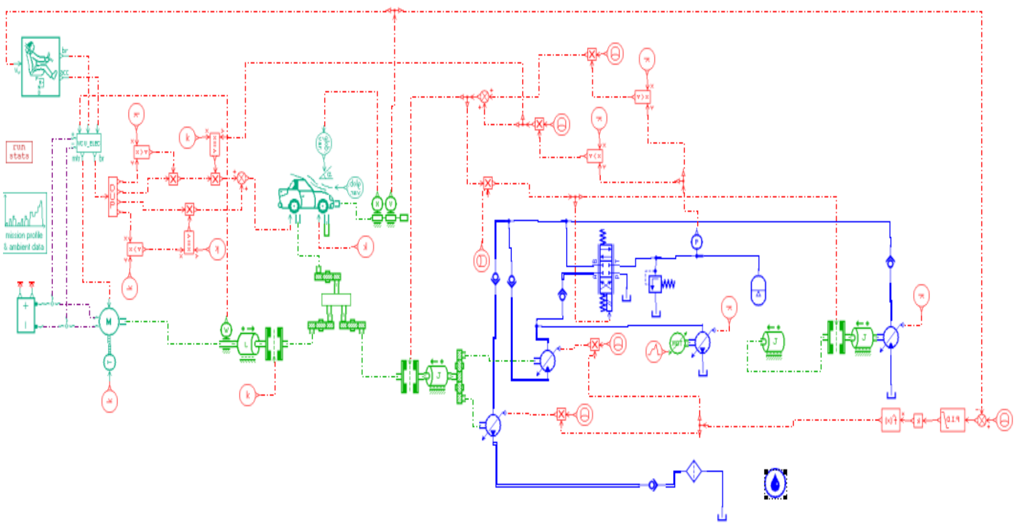


FIGURE 4 The simulation model of vehicle powertrain system with hydraulic regenerative braking system

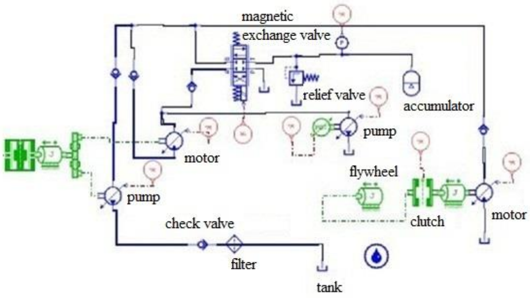


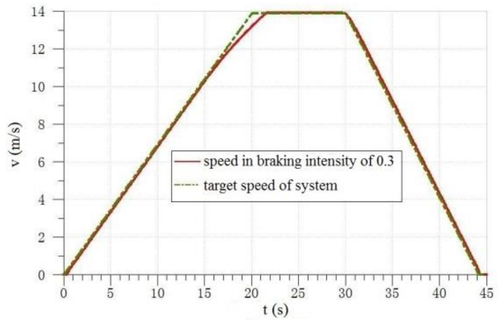

FIGURE 5 ECPS hydraulic system model

One model of electric vehicles as the research platform and determine the hydraulic regenerative device system parameters. Assuming that the vehicle goes straight, pump/motor drives alone, calculate displacement of pump/motor results. Make sure the flywheel size parameters: flywheel radius is 250 mm, flywheel thickness is 30 mm, maximum rotate speed is 2500 r/min. Since the hydraulic accumulator system pressure is substantially constant, the fluctuations between 20-25MPa. Select accumulator about the text minimal inflation pressure is 18MPa [9]. Calculate the total volume of the accumulator to be 10L.

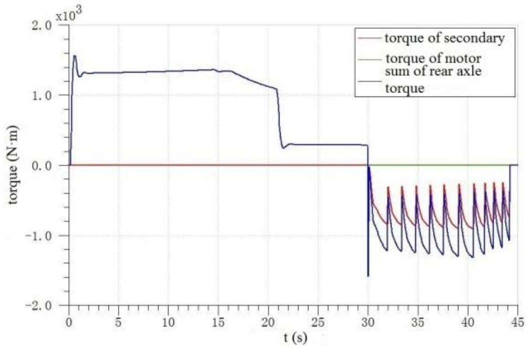
### 4.1 COMPOSITE REGENERATIVE BRAKING SYSTEM BRAKING CONDITION

According to Figure 4 shows a simulation model and vehicle simulation parameters be calculated, then do the simulation of vehicle braking condition. Fully loaded vehicle driving conditions: initial pressure accumulator be set 18Mpa, let hybrid electric vehicle accelerate to 50km/h in 20s, when the time is 30s begins to brake and park. Simulation purpose is to verify the ECPS system and its feasibility of the control system; changing pump/motor displacement to calculate braking energy recovery efficiency under different displacement of pump/motor, and comparison with the corresponding test results. When the brake intensity is $0 < z \leq 0.3$, simulation results shown in Figure 6.

When the brake intensity is $0 < z \leq 0.3$, Figure 6a shows vehicle can decelerate smoothly to stop when braking , driving state and control target is close, means good control effect. The solid red line in Figure 6b represents the secondary component during acceleration and constant speed don't work in the 0-30s, accelerating only by a motor torque which is represented in green solid line; in 30-45s secondary component recovered braking energy when braking, suppose rear tires without friction brake, braking force provided by the ESPS system only. Blue curve presents the sum of the rear axle torque, means motor torque in 0-30s and the toque after secondary component torque multiplied by the gear ratio in the 30-45s.




a) Vehicle speed comparison chart




b) The rear axle torque

FIGURE 6 The vehicle braking condition when $0 < z \leq 0.3$

Figure 7 is the change of flywheel rotate speed when change displacement of the pump/motor between 75L-145L.

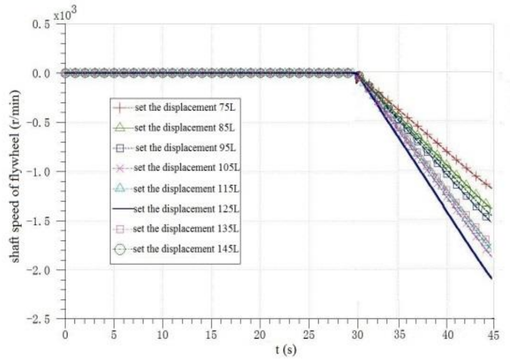



FIGURE 7 The flywheel shaft speed change

Figure 7 shows the rotate speed of flywheel can be affected by pump/motor displacement size. When the pump/motor displacement is small, flywheel rotate speed is increased with the increasing of displacement, and the more stored energy; but when the pump/motor displacement is above a certain value, flywheel rotate speed will reduce with increasing of pump/motor displacement, energy recovery is also reduced. From changing rotate speed of the flywheel can know how much energy storage in flywheel, according to the initial kinetic energy of vehicle can obtain energy recovery efficiency of the hydraulic regenerative braking system, the results shown in Table 2.

TABLE 2 Energy recovery efficiency of hydraulic regenerative braking system

| | Pump/motor displacement (L) | Initial Shaft speed of flywheel (r/min) | Final speed of flywheel (r/min) | Final pressure of accumulator (MPa) | The efficiency of energy storage of accumulator | The efficiency of energy storage of flywheel | Energy utilization of ECPS system |
|---|---|---|---|---|---|---|---|
| 1 | 5 | 1500 | 755 | 3.61 | 49.2% | 51.5% | 25.3% |
| 2 | 7 | 1500 | 775 | 3.69 | 50.2% | 53.4% | 26.8% |
| 3 | 9 | 1500 | 781 | 3.74 | 51.2% | 53.0% | 27.1% |
| 4 | 10 | 1500 | 812 | 3.80 | 52.3% | 56.0% | 29.3% |
| 5 | 11 | 1500 | 820 | 3.82 | 52.7% | 56.7% | 29.9% |
| 6 | 12 | 1500 | 809 | 3.79 | 52.1% | 54.7% | 28.5% |
| 7 | 14 | 1500 | 780 | 3.75 | 50.9% | 51.9% | 26.4% |
| 8 | 15 | 1500 | 774 | 3.70 | 50.7% | 50.7% | 25.4% |

Figure 6a shows, the simulation condition is consisted by acceleration and braking conditions, corresponding to the release energy and regenerative braking energy of ECPS system. Since the test parameters for the vehicle simulation parameters obtained according to certain scaling, so during the simulation and testing process will let pump/motor displacement as variables, respectively get the impact of pump/motor displacement for energy efficiency of regenerative braking system (shown in Table 2 and Table 1 ECPS system energy efficiency), the test results and simulation results can be verified with each other. In the test, the pump/motor variable range for 5-15L; in the simulation study, the pump/motor variable range for 75-145L.

By comparing Tables 1 and 2, when pump/motor displacement is small, the flywheel speed is increased with the increase of displacement and the more stored energy. But when the pump/motor displacement value higher than a certain time (in Table 1, this value is about 11L; simulation shown in Table 2, this value is about 125L), the flywheel speed will decreases with the increases of pump/motor displacement, also the recovered energy is reduced. Mainly due to resistance increases of the pump/motor, after displacement higher than a certain value, the energy recovery efficiency will decline, that indicate secondary component parameters need to good match to get the best effect of energy recovery.

Although tests can verify the system can recover some energy during braking (ECPS system as shown in Table 1, the highest energy efficiency is about 30%), but this is difference between energy recovery efficiency and simulation result (as Table 2 shows ECPS system energy use rate of 75%). Mainly reason in the test:

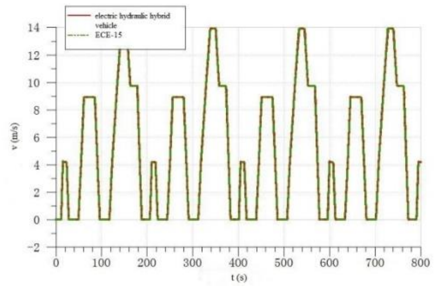
1) air resistance and bearing resistance caused energy loss during flywheel rotating in high speed, the bearing resistance is a larger proportion of energy loss account when flywheel in low speed;

2) there may be leaks in high pressure pipes, throttle adjustment is manual adjustment, there are some errors;

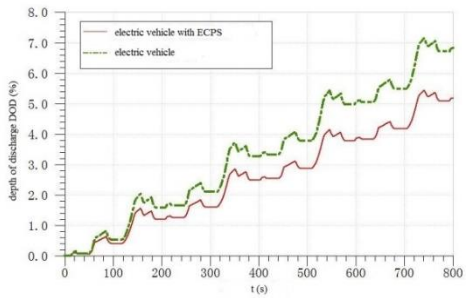
3) hydraulic components need to optimize matching.

### 4.2 COMPOUND REGENERATIVE BRAKING SYSTEM DRIVING CYCLE SIMULATION

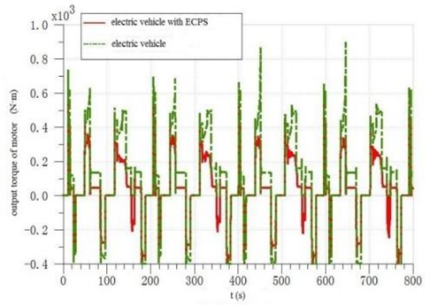
To test the effect of ECPS energy recovery system, this paper according to GB/T 18386-2005 specified urban driving cycle (condition ECE-15) to work conditions simulation [10], worked for 800s simulation in urban conditions. Simulation results are shown below.



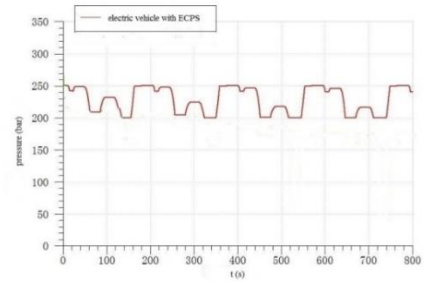

a) Driving- cycle speed comparison




b) Depth of discharge comparison




c) Output torque of motor comparison




d) System pressure comparison.

FIGURE 8 ECE-15 driving cycle simulation results

Figure 8a shows that vehicle speed curve of electro-hydraulic hybrid is basically close to speed curve of ECE-15 conditions, it's means that the braking efficiency of ECPS system is stability; Figure 8b shows, the depth of discharge of ECPS electro-hydraulic hybrid vehicle lower than pure electric vehicles (ECPS electro-hydraulic hybrid vehicles is 5.11%, pure electric vehicles 6.88%), the battery life can be increased accordingly. In terms of percentage calculations, ECPS electro-hydraulic hybrid vehicles compare to pure electric vehicles, driving range can increase about 25 %.

Figure 8c shows, motor load and load change of ECPS electro-hydraulic hybrid vehicle is small, basically the motor is working at rated torque , with little need to peak torque output; Figure 8d shows, ECPS system pressure is stable can avoid high pressure impact hydraulic components and good system dynamic performance.

## 5 Conclusions

Studies show that electro-hydraulic hybrid vehicle with ECPS's driving range increased by 25 % compared with electric vehicle without ECPS; Because of motor load decreases, reduce the depth of battery discharge, so battery life can be extended. The main factors impact recovery efficiency of ECPS braking energy is the pump/motor displacement, and how to control the pump/motor displacement change in a variety of braking intensity to achieve energy efficient recovery, there is reference value about the results of this study.

## Acknowledgments

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