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The Evaluation Model of Fuel Economy for Hydraulic Hybrid Vehicle

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***Abstract* – In order to evaluate the fuel economy of hydraulic hybrid vehicle, an energy management strategy and an energy conversion model which based on all kinds of work patterns were introduced through the analysis of the process of braking energy recovery and hydraulic energy regeneration for HHV. Then, an evaluation model of fuel economy for HHV which including rate of fuel saving, energy conversion efficiency, braking energy recovery rate, energy regeneration rate and energy consumption rate was established. In the last, the evaluation model was tested by road test data. The result indicated that the model of fuel economy evaluation can evaluate the HHV effectively.**

***Keywords* – Hydraulic Hybrid Vehicle, Energy Strategy, Economy Evaluation Model, Road Test.**

I. Introduction

The growing serious problem of energy and environment makes the technology of energy-saving and emission reduction be the development direction of the automotive industry, the hydraulic hybrid vehicle has become one of the hot researches because of its high power density and significant energy conservation[1-2]. The most commonly used index of fuel economy for hydraulic hybrid vehicle is fuel consumption per hundred kilometers, and also, some models are established to evaluate fuel economy. ADVISOR [3] is a kind of most widely used fuel consumption model [4] in automobile engineering field. Kyoungho Ahn has established a fuel consumption model [5] with instantaneous speed and accelerated speed as input parameters, and with specific fuel consumption as index to evaluate fuel economic. D.Y.C. LEUNG established the model of fuel consumption and emission [6] based on vehicle dynamics to predict the fuel economic in standard driving cycle. Andrew G. Simpson established a parameter analysis model[7] based on the energy consumption of the vehicle, to evaluate the fuel economic on certain road condition. Siqin Chang established the calculation model [8] of HHV fuel economic on different transport condition, and evaluated the fuel economic of HHV comparing with the traditional fuel economic. Jie Chen evaluated the fuel economic in the consideration of the HHV's starting mode[9]. Even though the fuel economic of HHV are evaluated from different angles by domestic and foreign scholars, there is no answer to improve the energy-saving effect of HHV in these evaluating models.

In order to figure out the fuel economic with the optimized control strategy under specific driving cycles, vehicle's concrete parameter must be obtained [10-11]. The construction principal and the control strategies of different operating modes of HHV were introduced firstly. Then, based on the analysis of energy conversion under HHV's different working patterns, the energy conversion mode covering different working patterns was proposed, and based on this model, the HHV fuel economic evaluating model, which synthesized fuel economy rate, energy conversion rate, braking energy recovery, energy regenerative using rate and energy consumption rate, was established. In the end, the power and economic performance was tested using the testing car refitted form Yutong bus ZK6126HG. Applied the tested data into the established fuel economic model, the ways how to improve HHV's fuel economic were analyzed from the parameters of the model. And this laid a solid technical foundation for the development of more efficient hydraulic hybrid vehicle.

II. The Structure Principal And Energy Management Strategy Of HHV

A. *The Vehicle Structure Principle of HHV*

HHV mainly consists of diesel-hydraulic hybrid system, hydraulic system and electronic control system, as figure 1.

When vehicle are downhill and braking, the hydraulic pump/motor works on pump operating condition, and the braking energy is recycled and stored by hydraulic accumulator; when vehicle are starting up and accelerating, the hydraulic pump/motor works on motor operating condition, and it provides auxiliary power for diesel, making the engine work on optimum operating condition area.

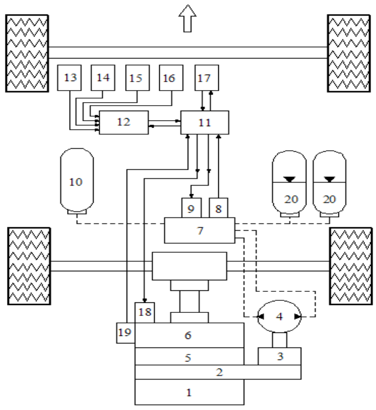

Fig. 1. Structure Principle of HHV

1.Diesel engine; 2.Transmission instrument; 3.Electromagnetic clutch; 4.Hydraulic pump/motor; 5.Clutch; 6.Gearbox; 7.Hydraulic valve control module; 8.Pressure sensor; 9.Electro-hydraulic directional control

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valve; 10.Low-pressure closed fuel tank; 11.Hybird power ECU; 12.Diesel engine ECU; 13.Clutch pedal switch; 14.Braking pedal sensor; 15.Acceleration pedal sensor; 16.Starting switch; 17.Working condition monitor; 18.Speed sensor; 19. N/R position sensor; 20.Hydraulic energy accumulator.

B. Energy Control Strategy

There are two power sources in HHV as engine and hydraulic pump/motor, in order to realize the optimal fuel economy, the minimum emission and the optimum vehicle performance, the energy management strategy must be designed to switch modes and distribute power according to starting mode, acceleration mode, braking mode, hydraulic drive mode and idle and stop mode of HHV [12-13].

Engine starting mode: before the vehicle starts, if the pressure of energy accumulator reaches starting value but not satisfies hydraulic driving value, the stored energy will be used to start engine through hydraulic motor; if the pressure of energy accumulator does not reach starting value, the starter will be used to start engine.

Start acceleration mode: when the vehicle starts, the energy supply manner will be decided according to the demanded power and the energy stored condition of energy accumulator. If the output energy satisfies the energy demands of air resistance overcoming, rolling resistance overcoming and acceleration, the stored hydraulic energy will be released to drive the vehicle's starting and acceleration with engine; otherwise, engine will drive the car alone.

Normal running mode: the energy supply mode is decided according to engine's operating regions, vehicle running speed and the stored condition of energy accumulator. If the running speed is low and the energy accumulator's pressure satisfies the driving demand, the energy accumulator's power will be released to parallel drive the vehicle with engine; if the running speed is high and engine works in economic area or the energy accumulator's pressure does not satisfy the driving demand, engine will drive alone.

Braking energy recovery mode: when vehicle brakes, the double-action variable displacement pump/motor will operate as hydraulic pump to recover the vehicle's kinetic energy as hydraulic energy and store it into energy accumulator. If energy accumulator's pressure reaches the highest security pressure value, the brakes will be used to brake.

Energy regeneration-hydraulic starting mode: when the stored condition of energy accumulator satisfies the power demand, hydraulic energy will be released to drive vehicle's starting and drive engine rotate until a certain value, then engine stars, it turns to engine driven mode.

Parking mode: when vehicle parks, engine will be flameout.

Backup maintain mode: when vehicle is backing, diesel drives, and braking energy recovery and regeneration system does not work.

III. The Establishment Of Fuel Economy Evaluation Model

A. Construction of Fuel Economy Evaluation Model

HHV's fuel economy evaluation model consists of three parts: energy conversion model, vehicle parameters, testing condition and energy-saving evaluation index [14]. It is shown as Fig.2.

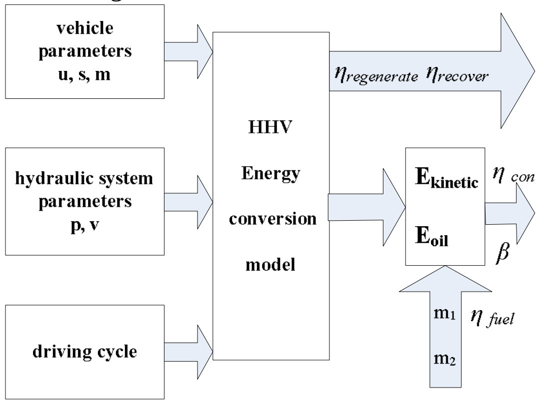

Fig. 2. Fuel economy evaluation construction of HHV

B. The Energy Conversion Model of HHV

The energy conversion process of HHV on special driving cycle can be analyzed through energy conversion model. The model includes the process of braking energy recovery and the process of hydraulic driving energy regeneration.

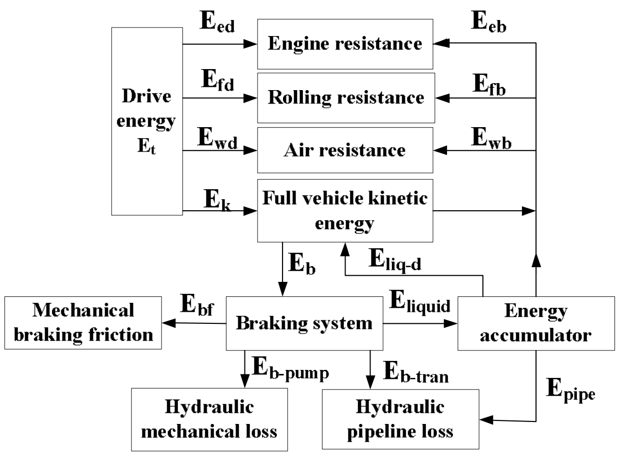

Fig. 3. Energy conversion model of braking energy recovery and regeneration process

When vehicle runs on special driving cycle, except for the overcoming of engine's and vehicle it selves frictional resistance, rolling resistance and air resistance, the other hauling energy from engine is translated into kinetic energy of vehicle. The energy conversion relation is:

$$E_t = E_{ed} + E_{fd} + E_{wd} + E_k \qquad (1)$$

Where, E_t —— total driving energy

E_{ed} —— the consumed energy of overcoming friction

E_{fd} —— the consumed energy of overcoming rolling resistance

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E_{wd} —— the consumed energy of overcoming air resistance

E_k —— the vehicle kinetic energy

When vehicle brakes, there is part of kinetic energy being expended by engine braking force, air resistance and rolling resistance, another part is consumed by mechanical friction as thermal energy, and the other is stored into energy accumulator as hydraulic energy. In the process of kinetic energy being translated into hydraulic energy, there is part of energy being consumed by hydraulic oil friction. So, in the process of braking, the energy conversion relation is:

$$E_k = E_b + E_{wb} + E_{fb} + E_{eb} \tag{2}$$

E_{fb} ——the consumed energy of overcoming rolling resistance (J)

E_{wb} ——the consumed energy of overcoming air resistance (J)

E_{eb} ——the consumed energy of overcoming engine braking (J)

E_b ——the consumed energy of braking system (J)

Among them, the consumed energy of braking system can also be expressed as:

$$E_b = E_{bf} + E_{b-pump} + E_{b-tran} + E_{liquid} \tag{3}$$

E_{bf} ——the consumed energy of brake (J)

E_{b-pump} ——the mechanical loss energy of hydraulic system (J)

E_{b-tran} ——the consumed energy of hydraulic pipeline (J)

E_{liquid} —— the hydraulic energy of accumulator (J)

Substitute (3) into (2):

$$E_k = E_e + E_w + E_f + E_{liquid} \tag{4}$$

When the hydraulic energy of accumulator satisfies the demand of vehicle running, the hydraulic driving mode will be used. The energy conversion relation is:

$$E_{liquid} = E_k + E_w + E_f + E_e \tag{5}$$

E_e ——the consumed energy of overcoming frictional resistance (J)

E_f ——the consumed energy of overcoming rolling resistance (J)

E_w ——the consumed energy of overcoming air resistance (J)

E_k ——the kinetic energy obtained by vehicle (J)

The kinetic energy when vehicle running is:

$$E_k = \left| \frac{\delta \cdot m \cdot (u_0^2 - u_a^2)}{2} \right| , \tag{6}$$

Where, δ is correction coefficient of rotating mass, $\delta = 1.05$

m ——the quantity of the whole car (kg）

u_0, u_a —— the initial and final speed of vehicle (m/s)

The consumed energy of overcoming rolling resistance is:

$$E_f = mgf \cdot s = mgf \cdot \int u(t)dt \tag{7}$$

Where, g is gravitational acceleration, and its value is $9.8\, m/s^2$;

f ——rolling resistance coefficient, according to empirical formula,

$f = 0.0076 + 0.000056 \cdot u_a(t)$

u ——vehicle running speed,

The consumed energy of overcoming air resistance is:

$$(E_w = \frac{C_D A u_a^2}{21.15} \cdot s = \frac{C_D A u_a^2}{21.15} \int u(t)dt \tag{8}$$

Where C_D ——vehicle air resistance coefficient

A ——vehicle windward area (m^2)

In the process of braking, the recycled energy of accumulator is the work outside do to the air inside energy accumulator:

$$E_{liquid} = -\int_{V_1}^{V_2} pdV = -\int_{V_1}^{V_2} p_1 \left(\frac{V_1}{V}\right)^n dV = \frac{p_1 V_1}{1-n}\left[1 - \left(\frac{p_1}{p_2}\right)^{\frac{1-n}{n}}\right] \tag{9}$$

Where, P_1 —— the initial pressure of energy accumulator (Pa)

V_1 —— the initial gas volume of energy accumulator (m^3)

P_2 —— the final pressure of energy accumulator (Pa)

n —— polytrophic exponent, in the process of isothermal change, $n = 1$; while in the process of adiabatic change, $n = 1.4$.

C. Fuel economy evaluation index of HHV

(1) Fuel saving ratio

On special vehicle cycle drive, the specific value of the difference value between consumed fuel quantities of running in traditional mode and hydraulic hybrid mode and the fuel value consumed on traditional mode is defined as fuel saving ratio. In order to eliminate the effects on testing accuracy caused by driver operation and testing environment, the testing data should be averaged after many experiments. Its expression is:

$$\eta_{fuel} = \frac{m_1 - m_2}{m_1} \times 100\% = \frac{\Delta m}{m_1} \times 100\% \tag{10}$$

Where, m_1 —— the consumed fuel quantity in traditional mode (kg)

m_2 —— the consumed fuel quantity in hydraulic hybrid mode (kg)

(2) Energy conversion ratio

The specific value of hydraulic energy (E_{liquid}) stored

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in energy accumulator and the consumed chemical energy (E_{oil}) which is used to store the hydraulic energy is defined as energy conversion ratio. Its expression is:

$$\eta_{con} = \frac{\sum_{1}^{n} E_{liquid}}{E_{oil}} \times 100\% \qquad (11)$$

Where, n ——the braking times in whole vehicle cycle drive

The relationship between the generated energy and the quantity of consumed fuel when engine is running is:

$$E_{oil} = Q \cdot q_e = \Delta m \cdot q \cdot q_e \qquad (12)$$

Where, q is diesel calorific value, and the value is $46.04 MJ/kg$; q_e is diesel engine energy efficiency, $q_e = 35\%$; Δm is fuel quantity(kg).

Substitute (9) and (12) into (11), the energy conversion ratio is:

$$\eta_{con} = \frac{E_{liquid}}{E_{oil}} \times 100\% = \frac{\frac{p_1 V_1}{1-n}\left[1-\left(\frac{p_1}{p_2}\right)^{\frac{1-n}{n}}\right]}{\Delta m \cdot q \cdot q_e} \times 100\% \qquad (13)$$

We can know from (13) that, the energy conversion ratio is affected by the hydraulic system parameters of HHV and fuel consumption in vehicle cycle driving, and the bigger the energy conversion ratio is, the higher the braking energy recovery and fuel efficiency are.

(3) Braking energy recovery

The specific value of the recycled hydraulic energy E_{liquid} in energy accumulator and the kinetic energy $E_{kinetic}$ of vehicle in baking process, which is in HHV's special vehicle cycle drive, is defined as braking energy recovery. And its expression is:

$$\eta_{rec} = \frac{E_{liquid}}{E_{kinetic}} \times 100\% \qquad (14)$$

Substitute (6) and (9) into (14), the braking energy recovery of HHV is:

$$\eta_{rec} = \frac{E_{liquid}}{E_{kinetic}} \times 100\% = \frac{\frac{P_1 \cdot V_1}{1-n}[1-(\frac{P_1}{P_2})^{\frac{1-n}{n}}]}{\frac{\delta \cdot m \cdot (u_0^2 - u_a^2)}{2}} \times 100\% \qquad (15)$$

The braking energy recovery represents the efficiency of hydraulic system, the bigger the parameter is, the better the braking energy recovery is, the better baking effect is, the better the economic efficiency of HHV is.

(4) Energy regeneration usage ratio

When vehicle is driven by hydraulic, the specific value of the sum of consumed energy overcoming air resistance and rolling resistance, the obtained kinetic energy and total released energy by energy accumulator is defined as energy regeneration usage ratio.

$$\eta_{reg} = \frac{E_{kinetic} + E_w + E_f}{E_{liquid}} \times 100\% \qquad (16)$$

Substitute (6), (7) and (8) into (16), the energy regeneration usage ratio of HHV is:

$$\eta_{reg} = \frac{E_{kinetic} + E_w + E_f}{E_{liquid}} \times 100\% = \frac{\left|\frac{\delta \cdot m \cdot (u_0^2 - u_a^2)}{2}\right| + \frac{C_D A u_a^2}{21.15}\int u(t)dt + mgf \cdot \int u(t)dt}{\frac{P_1 \cdot V_1}{1-n}\left[1-\left(\frac{p_1}{p_2}\right)^{\frac{1-n}{n}}\right]} \qquad (17)$$

(5) Energy consumption ratio

On specific vehicle cycle drive and engine with hydraulic motor parallel driving mode, the chemical energy consumed by engine is called E_{eng} , the hydraulic energy consumed by hydraulic motor is called E_{liquid} , and the corresponding released chemical energy by consuming E_{liquid} is called $\frac{E_{liquid}}{\eta_{con}}$, then the total energy this moment is $E_{eng} + \frac{E_{liquid}}{\eta_{con}}$.

On the same vehicle cycle drive, the consumed energy with engine driving alone is called E'_{eng} . The specific value of consumed energy with different driving mode on the same vehicle cycle drive is defined as energy consumption ratio. And its expression is:

$$\beta = \frac{E'_{eng}}{E_{eng} + \frac{E_{liquid}}{\eta_{con}}} \times 100\% = \frac{m_1 \cdot q \cdot q_e}{m_2 \cdot q \cdot q_e + \frac{\frac{P_1 \cdot V_1}{1-n}\left[1-\left(\frac{p_1}{p_2}\right)^{\frac{1-n}{n}}\right]}{\eta_{con}}} \qquad (18)$$

When $E_{eng} = 0$ is found, it is responding to hydraulic motor driving alone mode, and β is the energy consumption ratio with hydraulic motor driving alone. According to the definition of energy consumption ratio, when β is bigger than 1, parallel driving with engine and hydraulic motor or hydraulic motor driving alone is more fuel efficiency than engine driving alone. Otherwise, it will consume more fuel.

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IV. Road Test And Model Application

A. Parameters of Testing Vehicle

The testing vehicle is refitted from a traditional bus Yutong ZK6126HG, and its engine is WP7.270 produced by Weichai Power. Its specific parameters are shown as Table 1.

Table 1. The parameters of testing HHV

Projects	Projects
Car type	Yutong bus ZK6126HG
Full quantity/kg	16500
Diesel engine rated power /kW	185
Transmission ratios of different gears i_q	6.11/3.39/2.05/1.32/1.00
windward area A/m^2	6
Tire rolling resistance coefficient f	0.018
correction coefficient of rotating mass δ	1.05
Tire radius r/m	0.51
Transmission ratio of main reducer i_0	5.125
Transmission ratio between engine and hydraulic motor i_b	1
hydraulic pump/motor displacement mL/r$^-$	160
The working volume of hydraulic energy accumulator group /L	96
Working pressure of energy accumulator /MPa	16~31.5

B. Test Equipment and Conditions

The test car is equipped with the following equipment to obtain testing data: (1) DEWETRON VGPS-200, and its precision is ±0.5%; (2) DEWETRON-2600 data acquisition machine, and its precision is ±0.5%; (3) DF-2420 fuel consumption test instrument, and its precision is ±0.5%.

Chinese typical city bus drive cycle curve [16] is adopted to be vehicle cycle drive in this test, and the relationship between vehicle speed and time is shown as Fig.4.

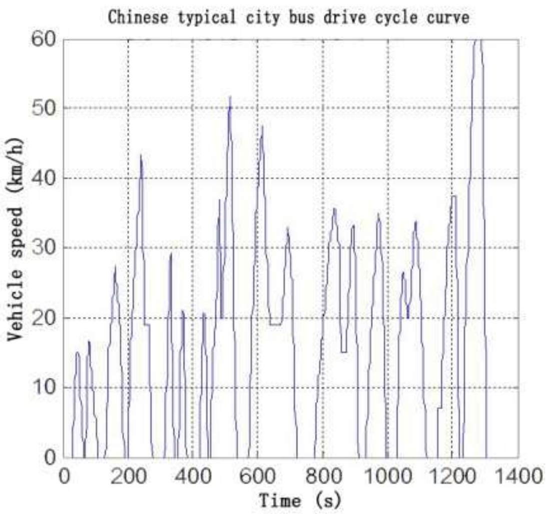

Fig. 4. Chinese typical city bus drive cycle curve

C. The Test Results

The engine hydraulic starting test, braking energy recovery test and hydraulic driving starting test were tested on HHV. The testing curves are shown as Fig.5-Fig.7. Engine hydraulic starting testing result data is shown as Table 2. Five gears braking energy recovery process testing result is shown as Table 3. And three gears hydraulic driving starting process testing results are shown as Table 4. Fuel consumption testing result of HHV is shown as Table 5.

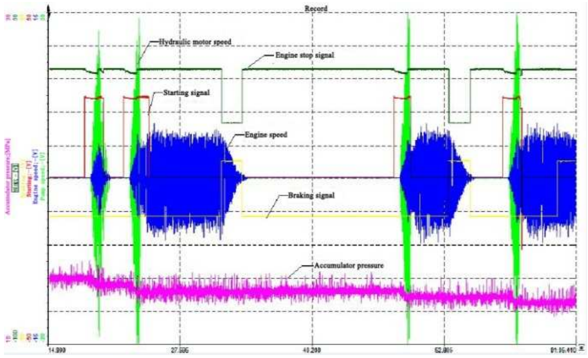

Fig. 5. Hydraulic start testing curve

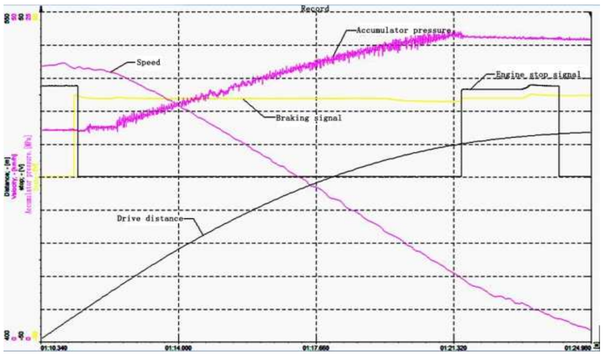

Fig. 6. Braking recovery testing curve

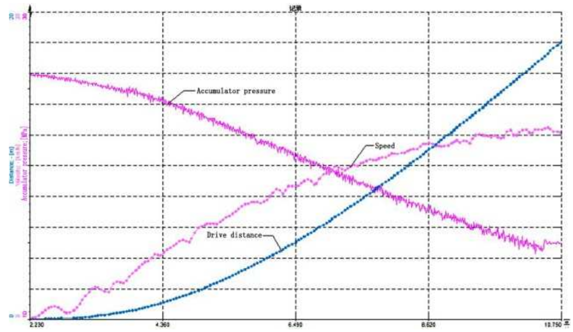

Fig.7. Hydraulic start testing curve

Table 2. Three times continue hydraulic start testing results

Test projects	Testing data
The initial pressure of hydraulic energy accumulator /MPa	19.6
The finial pressure of hydraulic energy accumulator /MPa	18.5
The consumed energy of energy accumulator each time /MPa	0.36
Engine speed/rpm	380~450
Starting time/s	1.7

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Table 3. Five gears braking energy recovery process testing results

Test projects	Testing data
The initial pressure of hydraulic energy accumulator /MPa	15.5~16.8
The finial pressure of hydraulic energy accumulator /MPa	26.1~28.9
Braking distance/m	93~115
Braking time/s	11.3~13.2
Vehicle initial speed/ $km \cdot h^{-1}$	41.2~42.8
Vehicle final speed / $km \cdot h^{-1}$	14.8~16.9

Table 4. Three gears hydraulic driving start testing results

Test Projects	Testing Data
The initial pressure of hydraulic energy accumulator /MPa	26.3~27.5
The finial pressure of hydraulic energy accumulator /MPa	15.6~16.2
Ending speed/ $km \cdot h^{-1}$	14.2~15.1
Driving distance/m	22.9~24.3
Driving time/s	10.1~11.2

Table 5. Fuel consumption test result of HHV

Traditional driving mode		Hydraulic driving mode	
Test projects	Testing data	Test projects	Testing data
Travel distance/km	7.001	Travel distance/km	7.000
Total running time /s	1383	Total running time /s	1503
Idle time/s	360	Idle time/s	360
Idle ratio /%	25.8	Stop ratio/%	24.0
Maximum speed km/h	40	Maximum speed km/h	40
Fuel consumption /kg	1.875	Fuel consumption /kg	1.595

D. Application of Fuel Economy Evaluation Model

Substitute testing data and vehicle parameters into the fuel economy evaluation model of HHV, the fuel economy evaluation index can be obtained as Tab.6.

Table 6. Fuel economy evaluation index calculation data

Evaluate projects	Evaluation data
η_{fuel}	14.93 %
η_{con}	36.58 %
η_{rec}	53.85 %
η_{reg}	29.72 %
β	1.1

E. The Methods to Improve Fuel Economy of HHV

From the fuel economy evaluation index calculation data, we can know that, the energy-saving effect of HHV is obvious, while the braking energy regeneration usage ratio and energy consumption ratio is still low. The following methods can be used to improve the two indexes:

(1) Optimize the parameters of hydraulic system, to make energy accumulator, hydraulic pump/motor and vehicle parameters reach optimal matching and to improve braking energy regeneration usage ratio.

(2) Optimize control strategies, to make engine work in optimal economy area. Beyond this area, vehicle power is provided by hydraulic motor.

V. Conclusion

Through the analysis of HHV's energy conversion process in different working modes, the energy conversion model including various working modes was proposed. And based on the energy conversion model of HHV, the HHV fuel economy evaluation model including synthesize fuel-saving ratio, energy conversion efficiency, braking energy recovery, energy regeneration usage ratio and energy consumption ratio was established.

Using the refitted testing car from Yutong bus ZK6126HG as research object, the power performance and economy performance experiments were carried on Chinese traditional city bus cycle drive. The testing data was analyzed based on the established HHV fuel economy model, the energy-saving efficiency of HHV is obtained from this, and the technology methods to improve the energy saving indexes were proposed.

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