Energy Efficiency and Fuel Economy Analysis of a Series Hybrid Electric Bus in Different Chinese City Driving Cycles

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Abstract

Based on analysis of the configuration and powertrain parameters of the series hybrid electric bus typically operating in certain Chinese city, this paper establishes simulation model of the series hybrid powertrain. The energy efficiency and fuel economy of the series hybrid electric bus are analyzed by energy flow method in the driving cycles of Chinese typical city, Zhuzhou city in Hunan province of China, and Hefei city in Anhui province of China. Simulation results show that, APU parts selection, braking system configuration and control of the series hybrid electric bus can be optimized. The fuel-saving ratios reach nearly 20% in all driving cycles.

Keywords: Series Hybrid Electric Powertrain; Driving Cycle; Energy Efficiency; Fuel Economy; Analysis

1. Introduction

The series hybrid powertrain configuration has a large proportion of the new hybrid electric bus. Although series hybrid powertrain parts (generator, battery and drive motor) increase the bus mass, this configuration influences little on the power performance for the bus mass is already large [1-2]. Series hybrid powertrain configuration can effectively recover braking energy for brake is frequent in city driving cycle.

Literature [3] put forward a control strategy of series hybrid electric vehicle based on the minimum fuel consumption. Literature [4] used energy management strategy of power follow and super-capacitor to optimize the dynamic performance of a four-wheel drive series hybrid electric vehicle. Literature [5] texted a mini-series hybrid electric vehicle with super-capacitor in changing driving cycles. Literature [6-7] put forward and verified an optimal algorithm for the torque and speed of engine-generator for the series hybrid electric vehicle. Literature [8] used a strategy combining the equal minimum fuel consumption and cost MAP to increase the system energy efficiency of the series hybrid electric vehicle. Literature [9] used stochastic Markov model in the optimization of the powertrain model selection of the series hybrid electric vehicle. Literature [10] selected the series hybrid electric vehicle as study object and fuel economy as control object, established an energy management strategy based on logic threshold and fuzzy algorithm.

As is shown above, now the studies of the series hybrid electric vehicle mostly focus on optimizing the algorithm of model selection and energy management strategy. This paper uses the typically operating series hybrid electric bus in certain Chinese city, establishes hybrid electric system model, and analyzes the energy efficiency and fuel economy by energy flow method in the city driving cycles of Chinese typical city, Zhuzhou city and Hefei city.

The energy efficiency optimization and fuel saving effect of the series hybrid electric bus is summarized in Chinese city driving cycle.

2. Configuration Analysis of Series Hybrid Powertrain

The configuration of the series hybrid electric vehicle is shown in Figure 1. Engine drives the generator to generate power and power is directly transferred to energy shortage unit or drive motor. Drive motor works in electric mode to drive the vehicle or in generating model to transfer mechanical energy to electric energy. The energy of the series hybrid electric vehicle is distributed by the vehicle controller. Vehicle controller distributes the energy between Auxiliary Power Unit (APU) and energy shortage unit according to the power demand of driver and parts condition. APU consists of diesel engine, electric excitation generator and three-phase uncontrollable rectifier, energy shortage unit uses super-capacitor, as is shown in Figure 2. APU output connects energy shortage unit and load.
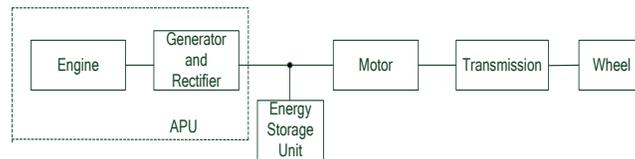

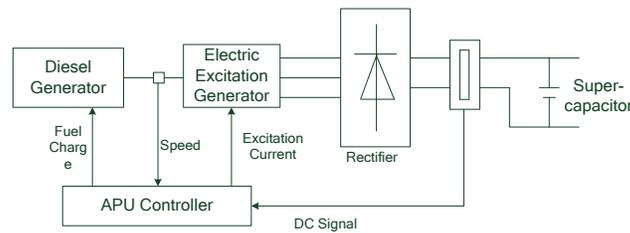**Figure 1. Series Hybrid Electric Vehicle Configuration**

Figure 2. APU Configuration

3. Modeling of Series Hybrid Powertrain

In literature [11], the modeling method of series hybrid electric bus has been introduced. Based on the method, this paper establishes the simulation model of series hybrid electric bus according to the actual data and part data from literature [12-13]. As is shown in Figure 3, the simulation model consists of APU model, energy shortage unit model, traction motor model, transmission model and vehicle dynamics model.
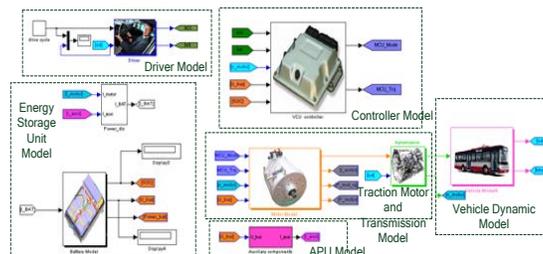

Figure 3. Simulation Model of Series Hybrid Electric Bus

In the series hybrid system, engine, generator, rectifier-bridge and traction motor are highly complex. So this paper takes bench test and obtains MAP according to the results. The simulation model is established according to the MAP. The benefit of this way is that: using the MAP instead of complex mathematical description can reduce the difficulty of modeling and increase the reliability of the model. In simulation model, the vehicle distributes the proportion of brake by traction motor and the method is the same with the series hybrid bus operating in typical Chinese city.

3.1. APU Simulation Model

APU of the series hybrid powertrain consists of diesel engine, generator and rectifier. Followings are main formulas:

$$n_{\text{eng}} = n_{\text{r}} \frac{1}{\tau_{\text{e}} s + 1} \tag{1}$$

$$T_{\text{eng}} = f_1(\alpha, n_{\text{eng}}) \tag{2}$$

$$C_{\text{eng}} = f_2(n_{\text{eng}}, T_{\text{eng}}) \tag{3}$$

$$\eta_{\text{g,r}} = f_3(n_{\text{eng}}, \lambda)\eta_{\text{r}} \tag{4}$$

Where, n_{eng} is diesel engine speed, unit is r/min. n_r is diesel engine objective speed, unit is r/min. τ_e is time constant, T_{eng} is diesel engine torque, unit is N·m. f_1 is MAP of diesel engine accelerator performance data, f_2 is MAP of diesel fuel consumption performance data, f_3 is MAP of the generator efficiency data, α is accelerator signal, unit is %. λ is generator load rate, unit is %. η_r is the efficiency of rectifier bridge, unit is %. C_{eng} is engine instantaneous fuel consumption, unit is g/kW·h. $\eta_{g,r}$ is the efficiency of generator and rectifier-bridge, unit is %.

3.2. Traction Motor Model

Traction motor model consists of the MAP of the steady efficiency performance of traction motor bench test and one order inertial link. Followings are the main formulas:

$$\eta_{\text{m}} = f_{\text{m1}}(n_{\text{m}}, T_{\text{m}}) \tag{5}$$

$$T_{\text{m}} = \min(T_{\text{r}}, T_{\text{max}}) \frac{1}{\tau_{\text{m}} s + 1} \tag{6}$$

$$T_{\text{max}} = f_{\text{m2}}(n_{\text{m}}) \tag{7}$$

Where, η_m is the efficiency of traction motor, unit is %. f_{m1} is the MAP of the efficiency of traction motor. T_m, T_r, T_{max} is traction motor output torque, objective torque and the maximal torque, unit is N·m, τ_m is time constant, f_{m2} is the MAP of the maximum output torque of traction motor, n_m is traction motor speed, unit is r/min.

3.3. Energy Shortage Unit Model

In the modeling of the super-capacitor, this paper references literature [14]. The following formulas can be obtained.

$$\begin{cases} V_C = \dfrac{-V_C}{C_U \times R_P} + \dfrac{i_L}{C_U} \\ V_L = V_C - ESR \times i_L \end{cases} \tag{8}$$

Where，i_L is input current, unit is A. V_L is output voltage, unit is V. ESR is equivalent resistance, unit is Ω. C_u is the volume of the super-capacitor, unit is F.

3.4. Transmission Model

The transmission system model mainly references literature [15] and the actual data of the driving series hybrid bus and the gearbox has only one shift. The speed ratio is 2.46 according to the matching calculation of the dynamic system and the actual driving data. The transmission system model can be described as the followings:

$$n_{\text{motor}} = 2.46 i_0 i_g u_a / r \tag{9}$$

$$T_{\text{motor}} = \frac{T_a}{i_0 i_g \eta_T} \tag{10}$$

Where, n_{motor} is the traction motor speed, unit is r/min. i_0 is the main speed ratio of the main reducer. i_g is the main gearbox reduction ratio. u_a is the speed, unit is km/h. r is the radius of the wheel, unit is m. T_{motor} is the traction motor output torque, unit is N·m. T_a is the full driving torque on wheel, unit is N·m. η_T is the system full efficiency, unit is %.

3.5. Vehicle Dynamics Model

In vehicle dynamics model, the absolute air speed is zero, the vehicle is driving on the well cement. The traction motor needs to overcome the driving resistances (F_t) of rolling resistance (F_f), air resistance (F_w), slope resistance (F_i) and acceleration resistance (F_j).

$$F_t = F_f + F_w + F_i + F_j \tag{11}$$

$$F_f = fmg \cos(\arctan i) \tag{12}$$

$$F_w = \frac{1}{2} C_d A \rho u_a^2 \tag{13}$$

$$F_i = mg \sin(\arctan i) \tag{14}$$

$$F_j = 0.28 \delta m \frac{du_a}{dt} \tag{15}$$

$$F_t = 3.6 \eta_T P_{\text{motor}} / u_a \tag{16}$$

Where, f is rolling resistance coefficient. m is the bus mass, unit is kg. g is gravitational acceleration, unit is m/s^2. i is road gradient, unit is %. C_d is air resistance coefficient. A is windward area, unit is m^2. ρ is air density, unit is kg/m^3. u_a is vehicle speed, unit is km/h. δ is correction coefficient of rotating mass. η_T is the system full efficiency, unit is %. P_{motor} is traction motor output power, unit is W.

4. Energy Management Strategy of Series Hybrid Electric Bus

Energy management strategy has the potential of increasing the fuel economy of the series hybrid electric bus. Although the common algorithms are fuzzy logic algorithm based on complex rule, global optimization algorithm based on set driving cycle and instantaneous optimization algorithm based on minimum fuel consumption, this paper mainly focuses on the influence of Chinese city driving cycle on the fuel consumption of the series hybrid electric bus, so in simulation, the algorithm is power follow algorithm based on rules.

Energy distribution strategy is based on SOC of energy shortage unit by estimating the stable output power. Power of energy shortage unit is defined as positive if energy shortage unit transfers power to bus. Power of energy shortage unit is defined as negative if energy shortage unit get power from bus.

Power of APU, energy shortage unit and drive motor fit formula 17 that is balance relationship of power energy. After the objective power of energy shortage unit is defined, the objective power of APU is defined.

$$P_{APU} = P_{mot} - P_{bat} + P_a \qquad (17)$$

In formula 17, P_{APU} is the APU output power, unit is kW. P_{mot} is the traction motor controller inlet power, unit is kW. P_{bat} is the energy storage unit power, unit is kW. P_a is the auxiliaries consumption power, auxiliaries include air condition, battery heat management system, interior heating system, lighting and control system, steering and braking consumption [16], unit is kW.

Energy distribution strategy is a kind of static distribution strategy, if APU can't fit the objective power, P_{APU}, in dynamic process; battery doesn't work in the distribution result of the steady distribution curve but in the energy balance relationship in formula 17 to fit the power demand of the drive motor. Energy management algorithm is realized by controlling the pedal and excitation of APU.

5. Simulation Results and Analysis

To analyze the fuel saving effect of the series hybrid electric bus in Chinese city driving cycle, this paper uses driving cycles of Chinese typical city, Zhuzhou city and Hefei city to analyze the energy efficiency and fuel saving effect in different driving cycles. The driving cycles in simulation are shown in Figure 4.
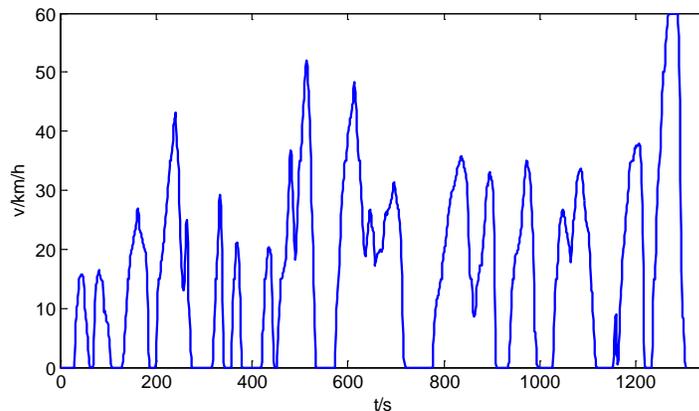
(a) Chinese typical city driving cycle
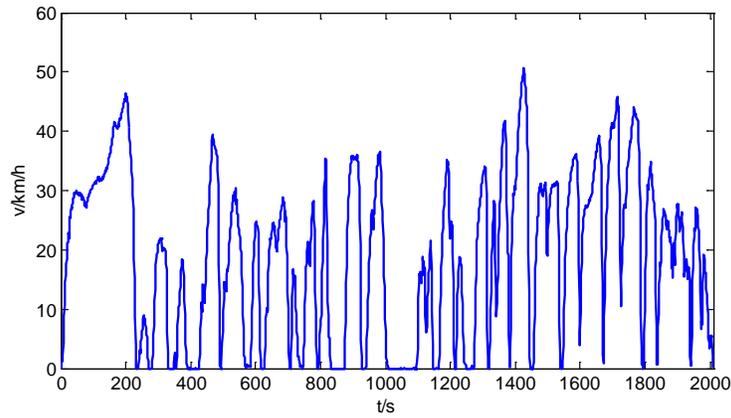
(b) Zhuzhou city driving cycle
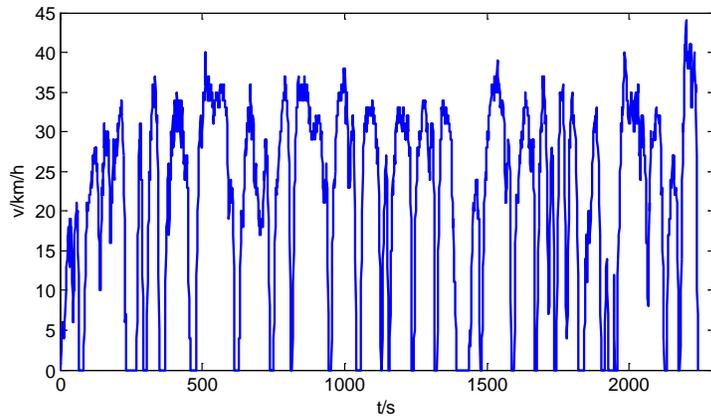
(c) Hefei city driving cycle

Figure 4. Driving Cycles in Simulation

Table 1. Characteristic Values of Driving Cycles in Simulation

Performance statistics	Chinese typical city	Zhuzhou city	Hefei city
Cycle time/s	1304	2010	2242
Trip mileage/km	5.83	10.56	13.37
Maximum speed/km/h	59.98	50.55	44
Average speed/km/h	16.1	18.91	21.48
Maximum acceleration/m/s^{-2}	1.25	1.26	1.944
Maximum deceleration/m/s^{-2}	-2.47	-2.75	-3.056
Average acceleration/m/s^{-2}	0.31	0.27	0.52
Average deceleration/m/s^{-2}	-0.43	-0.37	-0.59
Idle ratio/%	28.75	12.63	15.83

Parameters of the model in simulation are shown in Table 2.

To compare the influence of different driving cycles on economy of the series hybrid electric bus, the energy of air-condition and power steering is provided by engine, average power is 4kW. Initial and stop value is set same value in simulation.

Table 2. Parameters of the Model in Simulation

Length, width and height(mm)	11980×2550×3180
Mass(kg)	12900
Engine rated power(kW)	118
Engine rated power speed(r/min)	2500
Engine maximum torque (N·m)	600
Engine maximum torque speed(r/min)	1300
Generator maximum rotary speed(r/min)	1500
DC output voltage with full-wave rectification(V)	360 ~ 460
Energy storage unit	Super-capacitor11.7F
Traction motor type	JD147A
Traction motor maximum rotary speed(r/min)	4500
Traction motor highest/rated power(kW)	160 /80
Traction motor maximum torque	≥1300 N.m
Transmission main reduction ratio	6.333

5.1. Energy Efficiency Analysis of Chinese Typical City Driving Cycle

The model of series hybrid electric bus is simulated in Chinese typical city driving cycle, speed tracking curve, SOC of super-capacitor curve, bus voltage curve, in/out put current of super-capacitor curve, output current of APU curve, input current of drive motor curve are shown in Figure 5.

As is shown in Figure 5, in Chinese typical driving cycle, as the final acceleration of the vehicle reaches 59.98km/h, the output current of APU reaches the maximum value set by energy management strategy. To supplement the power needed in vehicle operation, output current of super-capacitor also reaches near 400A. Bus voltage is decreased rapidly, SOC of super-capacitor decreases near 40%.
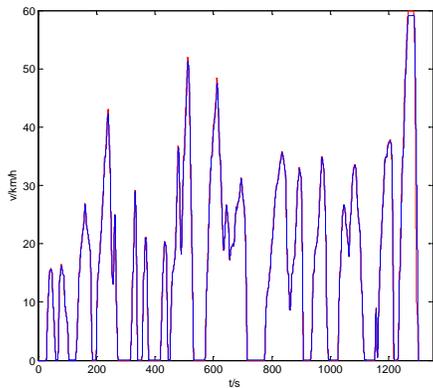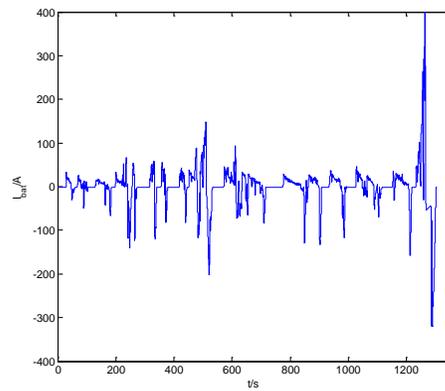
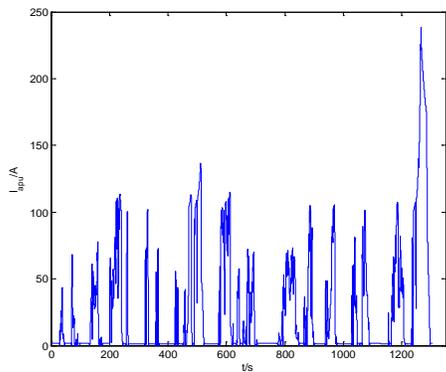

(a) Speed tracking cuvre
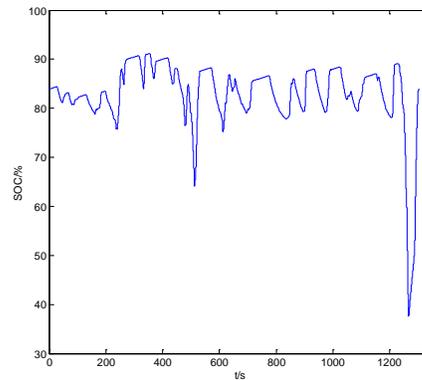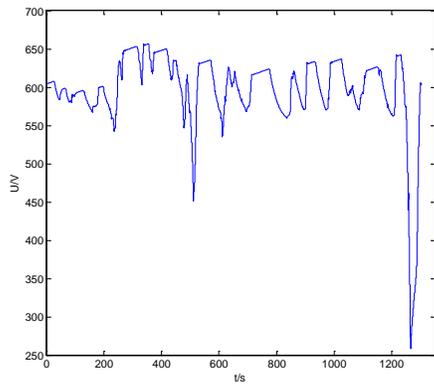
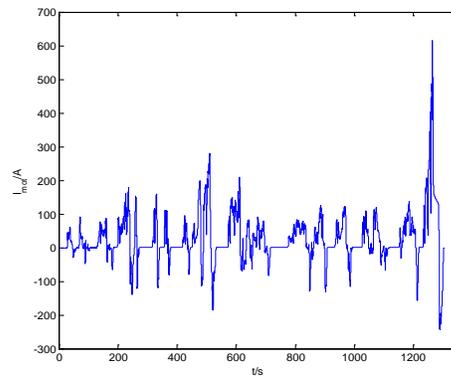(b) SOC of super-capacitor curve

(c) Bus voltage curve

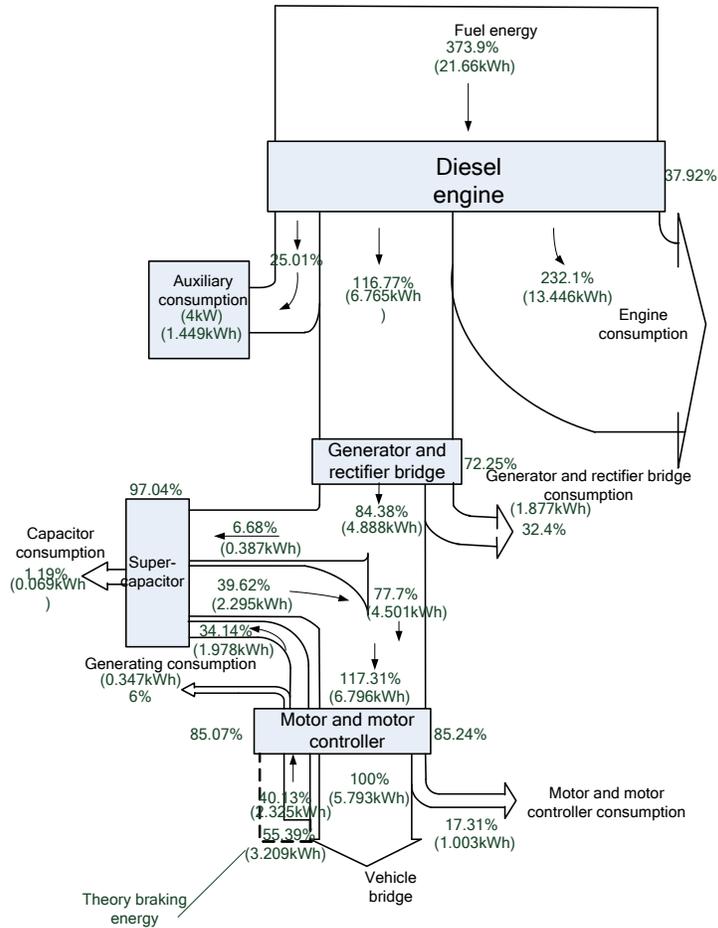(d) Input current of super-capacitor

(e) Output current of APU curve

(f) Input current of drive motor curve

Figure 5. Simulation Results in Chinese Typical City Driving Cycle
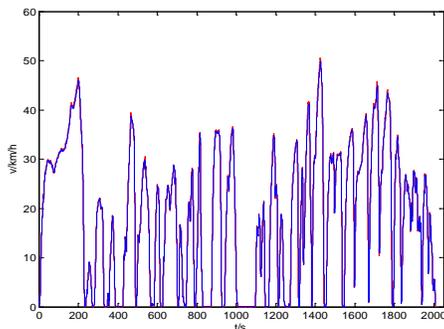
Figure 6 is the series hybrid powertrain energy flow chart in Chinese typical city driving cycle. As is shown in Figure 6, if using output energy that drives the vehicle as the reference value, in Chinese typical city driving cycle, braking energy in theory can reaches 55.39%. But actual recovery energy only reaches 34.147%, so the configuration and control of the series hybrid electric bus some the optimization space. As using super-capacitor, the charge and discharge ratio of the energy shortage unit can reaches 97.04%. The energy efficiency of generator and rectifier is low, only reaches 72.25%, so the optimization space of the configuration selection is large.

Figure 6. The Series Hybrid Powertrain Energy Flow Chart in Chinese Typical City Driving Cycle

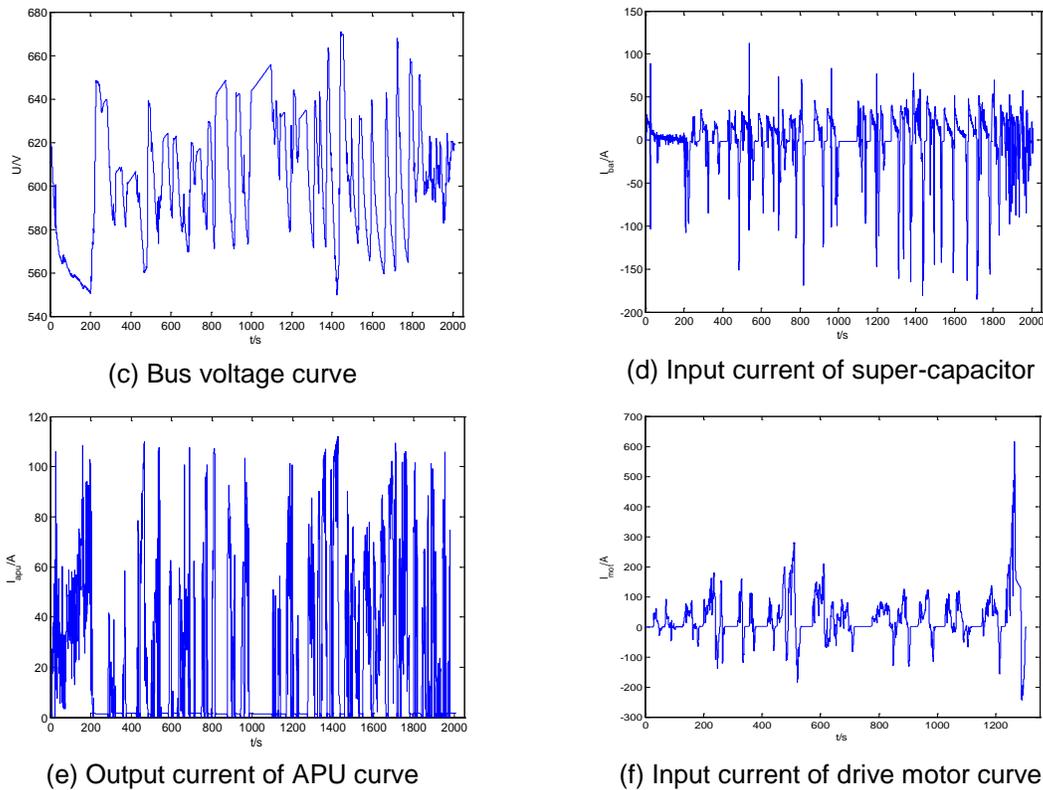### 5.2. Energy Efficiency Analysis of Zhuzhou City Driving Cycle

The model of series hybrid electric bus is simulated in Zhuzhou city driving cycle, speed tracking curve, SOC of super-capacitor curve, bus voltage curve, in/out put current of super-capacitor curve, output current of APU curve, input current of drive motor curve are shown in figure 7.
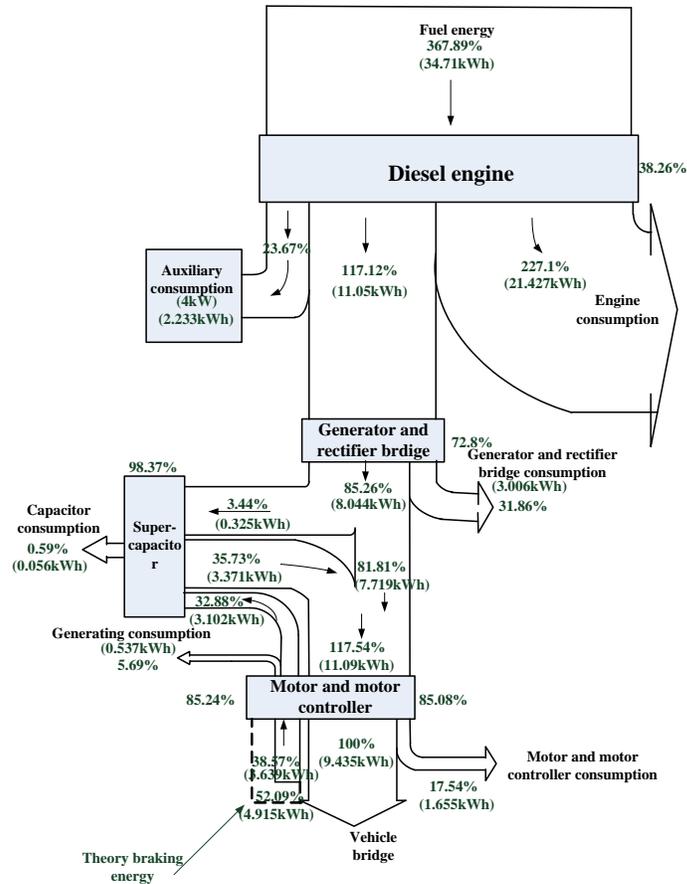

(a) Speed tracking cuvre

(b) SOC of super-capacitor curve

(c) Bus voltage curve

(d) Input current of super-capacitor

(e) Output current of APU curve
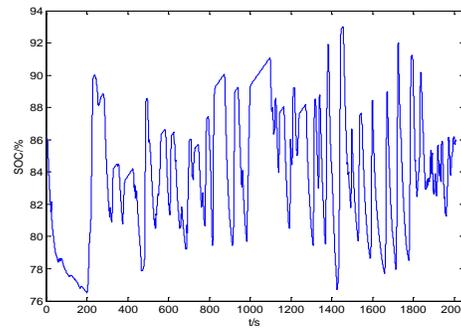
(f) Input current of drive motor curve

Figure 7. Simulation Results in Zhuzhou City Driving Cycle

As is shown in Figure 7, in Zhuzhou city driving cycle, as the maximum speed only reaches 50.55km/h, the maximum output current of APU only reaches 115A; output current of super-capacitor reaches nearly 110A. Range of bus voltage is narrow, SOC of super-capacitor ranges from 76% to 93%.

Figure 8 is the series hybrid powertrain energy flow chart in Zhuzhou city driving cycle. If using output energy that drives the vehicle as the reference value, in Zhuzhou city driving cycle, braking energy in theory can reaches 52.09%. But actual recovery barking energy only reaches 32.88%. As using super-capacitor, the charge and discharge ratio reaches 98.37%. The energy efficiency of generator and rectifier only reaches 72.25%.

Figure 8. The Series Hybrid Powertrain Energy Flow Chart in Zhuzhou City Driving Cycle

5.3. Energy Efficiency Analysis of Hefei City Driving Cycle

The model of series hybrid electric bus is simulated in Hefei city driving cycle, speed tracking curve, SOC of super-capacitor curve, bus voltage curve, in/out put current of super-capacitor curve, output current of APU curve, input current of drive motor curve are shown in Figure 9.
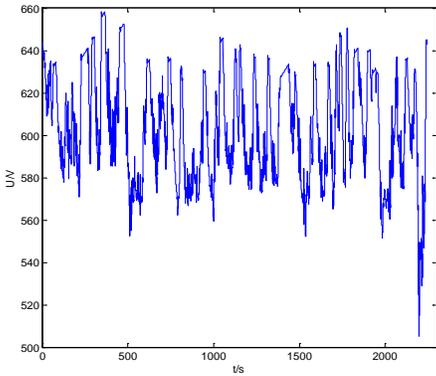
As is shown in Figure 9, in Hefei city driving cycle, as the maximum speed is only 44km/h, the maximum output current of APU only reaches 120A; output current of super-capacitor reaches nearly 150A. Range of bus voltage is narrow, SOC of super-capacitor ranges from 72% to 92%.
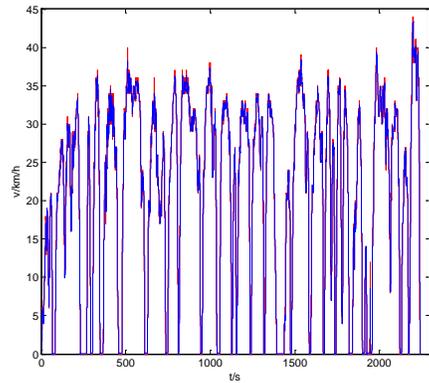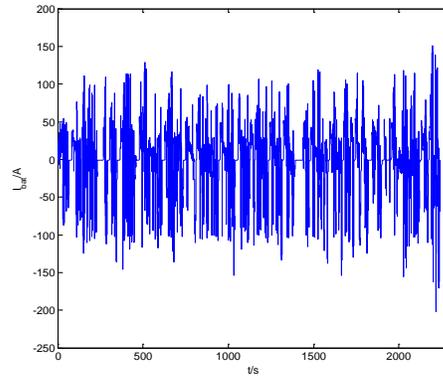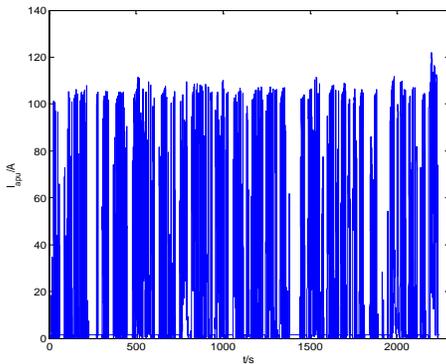
(a) Speed tracking curve
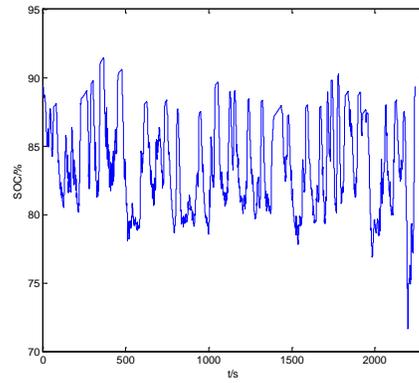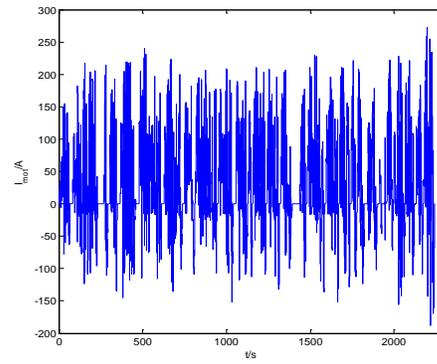
(b) SOC of super-capacitor curve

(c) Bus voltage curve

(d) Input current of super-capacitor

(e) Output current of APU curve

(f) Input current of drive motor curve

Figure 9. Simulation Results in Hefei City Driving Cycle

Figure 10 is the series hybrid powertrain energy flow chart in Hefei city driving cycle. If using output energy that drives the vehicle as the reference value, in Hefei city driving cycle, braking energy in theory can reaches 53.58%. But actual recovery barking energy only reaches 33.79%. As using super-capacitor, the charge and discharge ratio reaches 98.3%. The energy efficiency of generator and rectifier only reaches 74.5%.
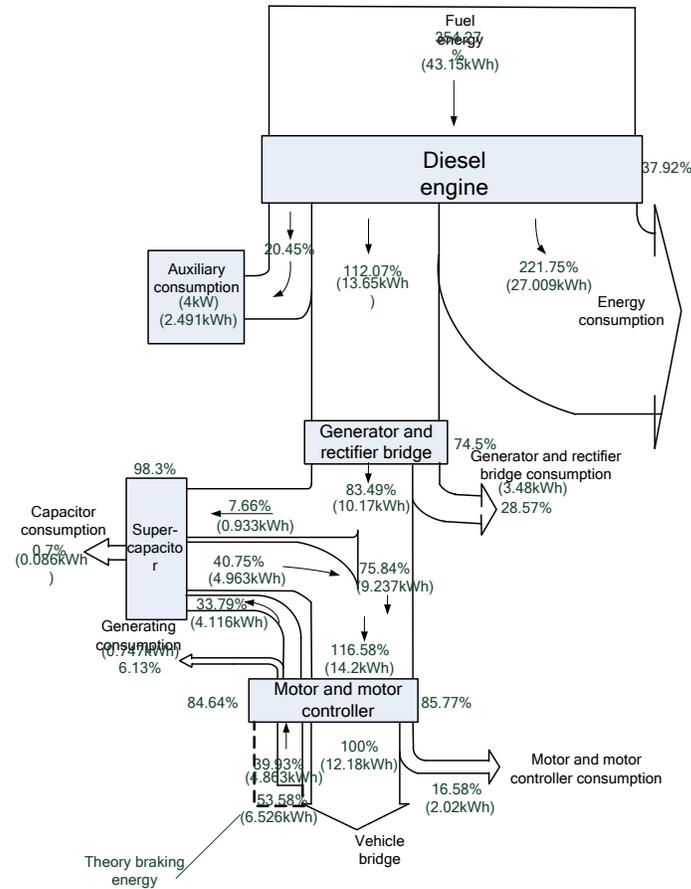
Figure 10. The Series Hybrid Powertrain Energy Flow Chart in Hefei City Driving Cycle

Table 3 is the economy comparison between series hybrid electric bus and conventional fuel bus in the three different city driving cycle.

Table 3. Economy Comparison between Series Hybrid Electric Bus and Conventional Fuel Bus

	Chinese typical city	Zhuzhou city	Hefei city
Fuel consumption of conventional fuel bus (L/100km)	38.64	34.74	33.83
Fuel consumption of series hybrid electric bus(L/100km)	31.21	27.73	27.21
Fuel saving ratio (%)	19.22	20.17	19.57

As is shown in Table 3, all the fuel saving ratios of the series hybrid electric bus can reach above 19% in different Chinese city driving cycles. In Zhuzhou city driving cycle, the fuel saving ratio can reach 20.17%. The result fits the experiment result of the typical city.

6. Conclusion

Based on establishing the simulation model of a series hybrid electric bus operating in certain Chinese city, this paper uses Chinese typical city, Zhuzhou city in Hunan province of China and Hefei city in Anhui province of China as driving cycles in simulation, analyzes the energy efficiency and fuel economy of the series hybrid powertrain.

(1) As the energy shortage unit uses super-capacitor, all the charge and discharge efficiencies in the three different city driving cycles are above 97%.

(2) All the braking energy in theory are above 50% of the vehicle drive energy in the three different driving cycles, but now the recovery braking energy of the series hybrid powertrain only reaches 32%-34%. So the brake system can be optimized.

(3) Now the energy efficiency of the electrical excitation generator and rectifier of the typically operating series hybrid powertrain only reaches 72%-74%, so optimization space of the parts selection is relatively large.

(4) All fuel saving ratios can reach above 19% in the three different Chinese city driving cycles. In Zhuzhou city driving cycle, the maximum fuel saving ratio can reach 20.17%.

Acknowledgements

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