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Fuel Economy Analysis of a Series Hybrid Electric Bus with Low-Speed Shutdown Control Strategy

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Abstract

The series hybrid electric bus that is demonstrated operating in China has the problem of non-ideal fuel economy for the conventional auxiliary equipment can't shut down the engine. Based on the series hybrid electric bus using electric auxiliary equipment, a control strategy is proposed based on the combination of engine low-speed shutdown and load following. The main control variables are battery SOC and vehicle speed, and the engine low-speed shutdown is realized. Three different driving cycles are employed: Chinese city driving cycle, Zhuzhou city of Hunan province driving cycle, and Hefei city of Anhui province driving cycle. By using the analysis method of the energy flow diagram, the fuel economy in different driving cycles is compared and analyzed. The simulation results show that the control strategy of the engine low-speed shutdown affects little on fuel economy in different driving cycles. All the fuel-saving ratios of the series hybrid system in different driving cycles can reach above 25%.

Keywords: *series hybrid, driving cycle, fuel economy, potential, comparison and analysis*

1. Introduction

In terms of the relatively heavy city bus, using the structure of series hybrid powertrain, although the engines, generators, batteries and the drive motors and other components are added, the dynamic performance of the bus will not be significantly influenced [1-2]. Meanwhile the series system configuration can effectively recover the braking energy in the case of frequently braking in city driving cycle [3-4].

In the present reports of the series hybrid city bus, literature [5] analyzed on the economy of series hybrid electric bus produced by Hyundai Heavy Industries and Daewoo Bus Company. In Busan city bus driving cycle, compared to the conventional diesel bus the fuel-saving ratio is improved by 22%. Literature [6] conducted a design on regenerative braking system based on the series hybrid city bus, and used dSPACE to realize the hardware in-the-loop experiment. Literature [7] analyzed and compared the series hybrid system using 75 Ah lead-acid batteries on some aspects such as the system efficiency of the bus driving cycle, braking energy feedback, idle shutdown and electrification of the auxiliary system. Literature [8] has constructed a simulation system of series hybrid electric bus, simulated with different control algorithms, and got a conclusion that load following control strategy is beneficial to the economy of the series hybrid electric bus. Literature [9] studied the influence of the auxiliary power system on the vehicle fuel economy with different configurations of the hybrid power system including the series hybrid city bus.

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Compared to the conventional diesel vehicle, the improvement of series hybrid electric bus fuel economy has a close relationship with the city bus driving cycle and the energy distribution strategy. In this paper, based on the data acquisition of the current Chinese city driving cycle, modeling method of literature [10] is used to establish the simulation model of the series hybrid electric bus, and a low-speed shutdown control strategy is put forward. The fuel economy of the series hybrid electric bus demonstrated operating in China is simulated and analyzed so as to get the fuel-saving potential of the series hybrid city bus with the low speed shutdown strategy.

2. Analysis of Different Chinese Driving Cycles

The driving cycles for the fuel economy analysis of the series hybrid electric bus use the actual data of the demonstrated operating bus in China, except Chinese city driving cycle. The time-velocity curve and velocity distribution are shown in Figure 1-Figure 3.

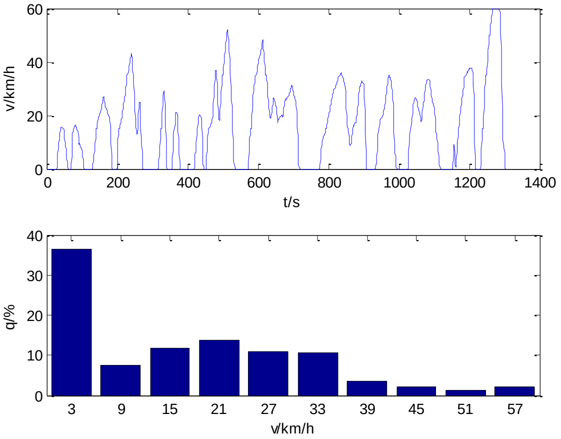


Figure 1. Chinese City Driving Cycle Curve and Velocity Distribution

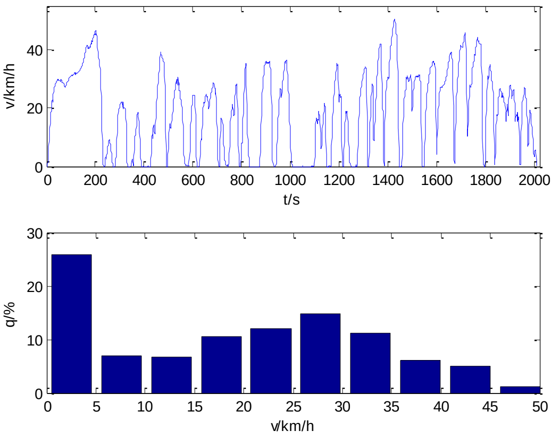


Figure 2. Zhuzhou City Driving Cycle Curve and Velocity Distribution

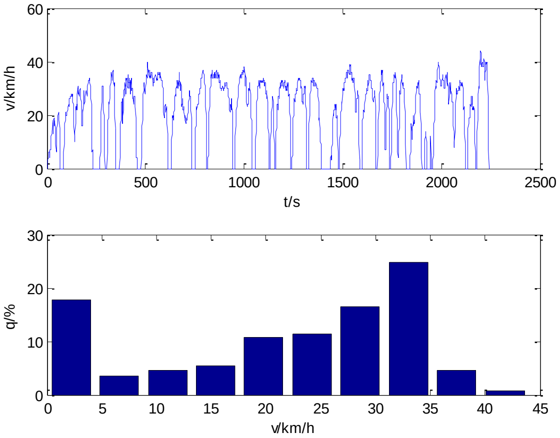
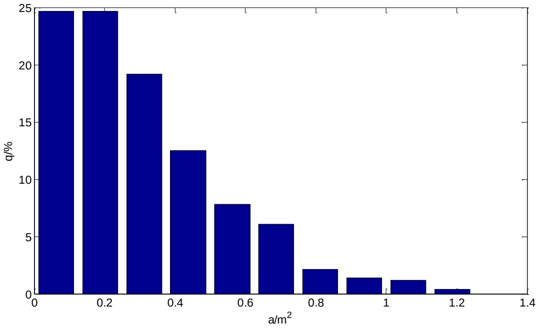


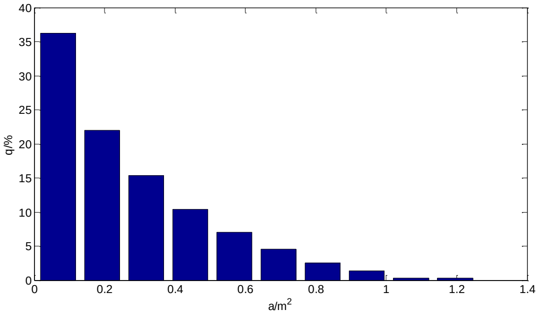
Figure 3. Hefei City Driving Cycle Curve and Velocity Distribution

As is shown in Figure 3, the velocity distribution is slightly different in different driving cycles. But in the driving cycles above, the low velocity region ranging from 0 km/h to 5 km/h has a large proportion. Only in Hefei city driving cycle, the velocity region ranging from 30km/h to 35km/h has a large proportion, indicating that, compared to others city cycles, Hefei city have a better traffic.

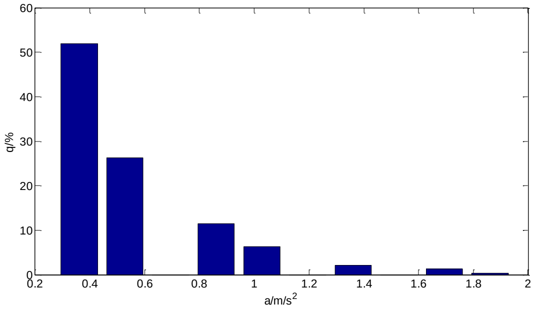
This paper makes a statistical analysis of the data above. The distributions of the acceleration and the deceleration are shown in Figure 4 and Figure 5.



(a). Acceleration distribution of Chinese city driving cycle.



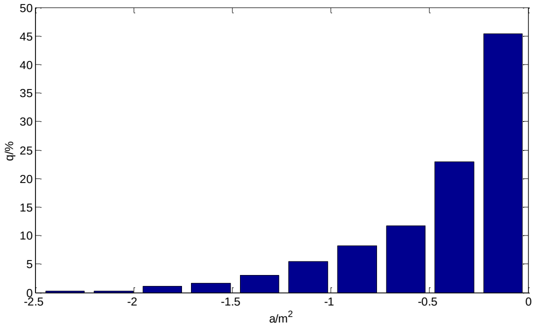
(b). Acceleration distribution of Zhuzhou city driving cycle.



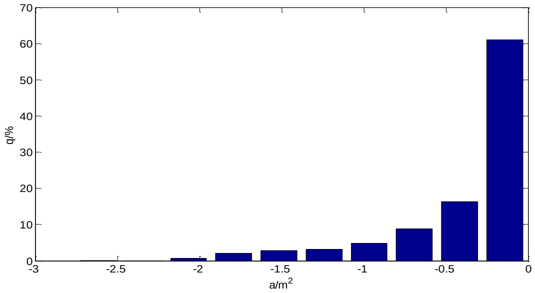
(c). Acceleration distribution of Hefei city driving cycle.

Figure 4. The Acceleration Distributions of Different Driving Cycles

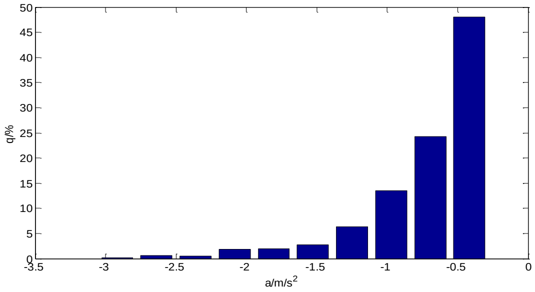
As is shown in Figure 4 the acceleration distribution is slightly different in different city driving cycles. But in the acceleration distribution of different city driving cycles, the proportion of the acceleration under 1m/s^2 is close to 90%.



(a). Deceleration distribution of Chinese city driving cycle.



(b). Deceleration distribution of Zhuzhou city driving cycle.



(c). Deceleration distribution of Hefei city driving cycle.

Figure 5. The Deceleration Distribution of Different Driving Cycles

As is shown in Figure 5, the deceleration distributions are mainly under $3 m/s^2$ in different driving cycles.

In summary, the statistical performance of different city driving cycles is shown in Table 1.

Table 1. The Statistical Performance of Different City Driving Cycles

Statistical performance	Chinese city	Zhuzhou	Hefei
Cycle time/s	1304	2010	2242
Travel distance/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
Idling proportion/%	28.76	12.64	15.83

3. Energy Management Strategy of the Series Hybrid Electric Bus

Optimization of energy management strategy has the possibility of improving fuel economy of the series hybrid system. There are fuzzy logic algorithm based on complex rules, global optimization algorithm based on the established driving cycle, and instantaneous optimization algorithm based on minimum fuel consumption, *etc.*, This paper presents a hybrid system energy strategy based on SOC of the energy storage component and speed status, and estimates the possible output power of the energy storage component in the steady state. The energy storage component power is positive in the definition of the energy storage component outputting power to the bus. The power is negative in the definition of the energy storage component getting power from the bus.

Auxiliary power unit (APU), energy storage component and traction motor power are required to satisfy the equation 1, which is a bus energy balance. After the energy storage component target power is determined, APU target power is also determined.

$$P_{APU} = P_{mot} - P_{bat} + P_a \tag{1}$$

Where, P_{APU} is APU output power, P_{mot} is the traction motor controller entrance power, P_{bat} is the energy storage component power, and P_a is the accessories power consumption. Accessories include: air condition, the battery thermal management system, vehicle heating (seat heating, windshield heating, *etc.*,), lighting and control system, braking steering consumption [11].

Energy distribution strategy is a kind of static distribution strategy. If in dynamic process the APU cannot meet the target power P_{APU}, the energy storage components will not be distributed in accordance with the results of the steady-state distribution curve. While the energy balances relationship is regulated according to equation 1, to meet the power requirement of the traction motor. Vehicle energy management algorithm is realized by controlling the pedal and the excitation of the auxiliary power unit.

In conventional transmission, the electrical auxiliary and other devices are driven by engine. In idle condition, general auxiliary equipment can't stop working, causing the engine to run at low speed and low load condition. In this situation, the engine efficiency is low, the fuel consumption increases substantially, emissions also increase. In the series hybrid system, the auxiliary equipment can be fully electric, driven entirely by electrical energy. On the one hand this energy comes from regenerative braking energy, on the other hand from the APU system. And this part of the electrical energy is generated with the engine controlled by the control system in high efficiency working region. Although there are energy storage component charging and discharging energy loss and other issues, the overall efficiency of the power system is still higher than the conventional system.

To solve the problems above, this paper studies the series hybrid bus with the engine idle shutdown and ensures the normal work of the electric auxiliary system, further reduces the fuel consumption. If all the engines achieve idle shutdown, fuel consumption can be significantly improved.

In summary, in this study, using idle shutdown control strategy based on logic rule, the control strategy can be described as shown in Figure 6.

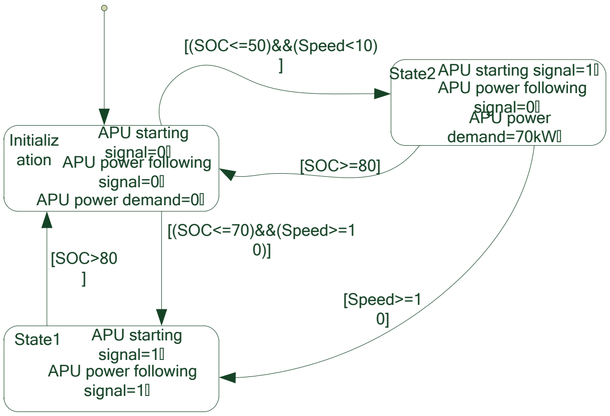


Figure 6. State-Follow Diagram of Idle Shutdown Control Strategy

4. Simulation Results and Analysis

In order to analyze the economic potential of the series hybrid bus, the parameters of series hybrid bus model mainly based on the domestic demonstrated operating vehicle parameters, as is shown in Table 2. In order to effectively evaluate the fuel economy of the hybrid electric bus in different driving cycles, set the same SOC initial state and final state in this simulation.

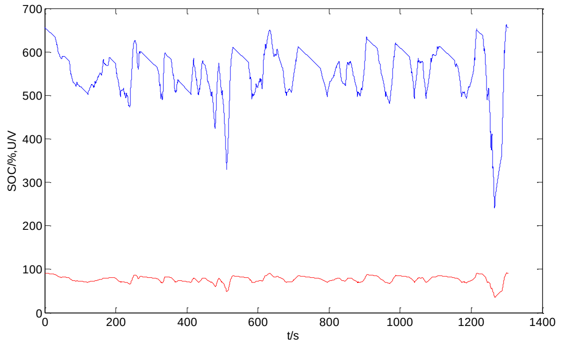
Table 2. The Main Parameters of the Series Hybrid Electric Bus Simulation Model

Length width height (mm)	11980×2550×3180
Whole mass (kg)	12900
Rated Energy power (kW)	118
Rated engine speed (r/min)	2500
Maximum engine torque (N·m)	600
Maximum engine torque speed (r/min)	1300
Generator maximum speed (r/min)	1500
The full wave rectified rated output DC voltage (V)	350 ~ 450
Energy storage component	Super-capacitor 11.7F
Traction motor maximum speed (rpm)	4500
Traction motor peak power/rated power (kW)	160 /80
Traction motor maximum torque	≥1300 N·m
Transmission main reduction ratio	6.333

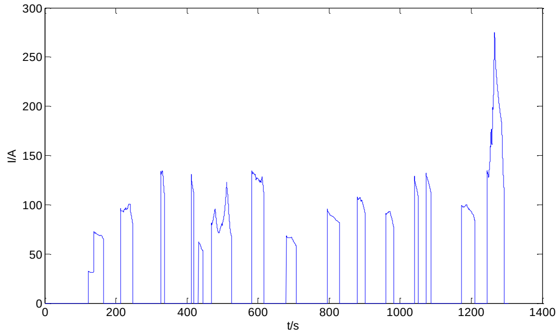
A. Fuel Economy Simulation of Chinese City Driving Cycle

Figure 7 is the working condition of each component of the series hybrid electric bus in Chinese city driving cycle.

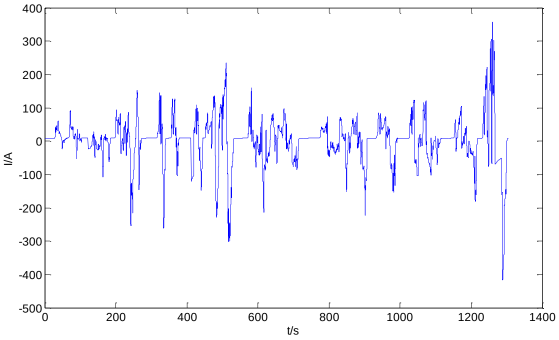
As is shown in Figure 7, the energy storage component using a super capacitor, so the bus voltage fluctuates acutely with the SOC, but the charge and discharge current of the super capacitor can reach above 400A, which can meet the demand of high frequency variation of SOC. APU realizes idle shutdown, APU and super capacitor are used to provide the power required for electrical auxiliaries and other auxiliary equipment.



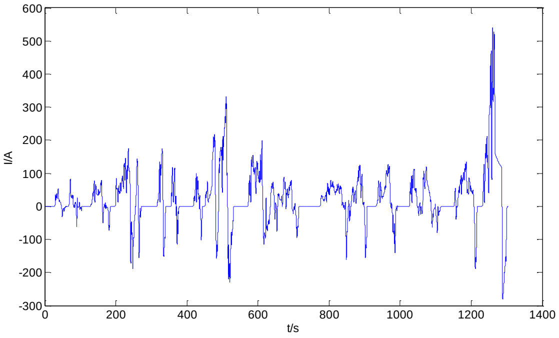
(a). The bus voltage and SOC curve.



(b). The discharge current curve of the super capacitor



(c). APU output current variation curve



(d). Traction motor working current curve

Figure 7. The Working Conditions of the Series Hybrid Power Train Components in Chinese City Driving Cycle

Figure 8 is the engine working point's distribution in Chinese city driving cycle, the engine working points fit the trajectory determined by the energy management strategy, so the engine works in the high efficiency region.

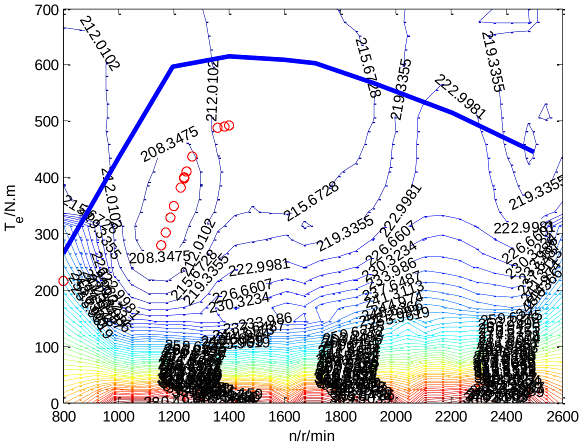


Figure 8. The Working Points Distribution in Chinese City Driving Cycle

Energy flow diagram in Chinese city driving cycle is shown in Figure 9.

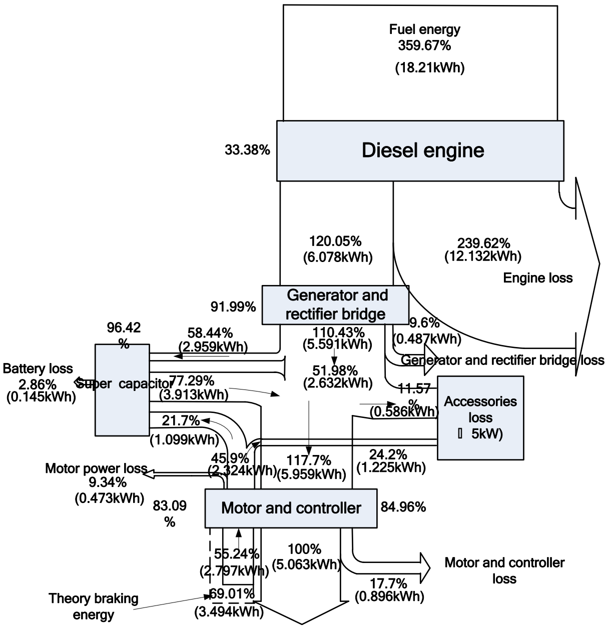
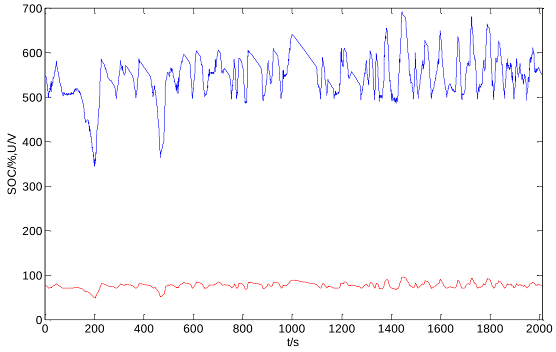


Figure 9. Energy Flow Diagram of Series Hybrid Electric Bus in Chinese City Driving Cycle

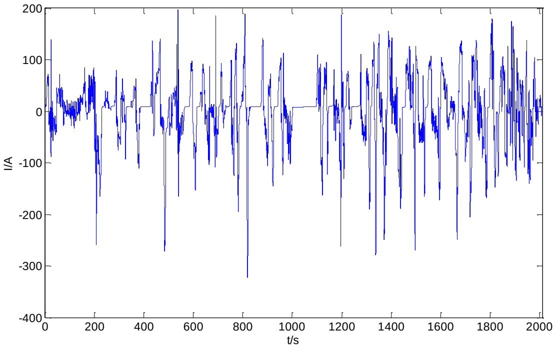
As is shown in Figure 9, with the energy management strategy used in this paper, the engine efficiency is improved to 33.3%. As using the super capacitor as the energy storage component, the charging and discharging efficiency of the energy storage component can reach 96.42%. While the generator using the permanent magnet synchronous generator, the working points efficiency is high, can reach 91.99%.

B. Fuel Economy Simulation of Zhuzhou City Driving Cycle

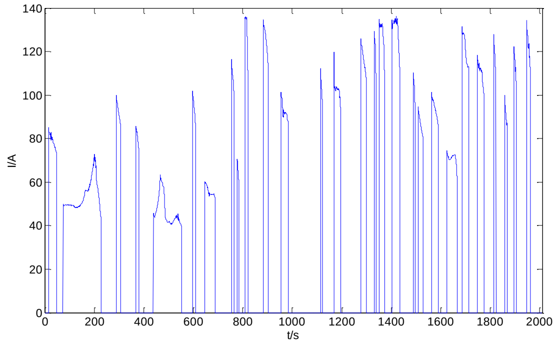
Figure 10 is the working conditions of each component of the series hybrid electric bus in Zhuzhou city driving cycle. As is shown in Figure 10, the maximum speed in Zhuzhou city bus is only 50.55km/h. Therefore, compared to Chinese city driving cycle, the highest power demand is low, the bus voltage changes in the range of 350V to 700V. APU realizes idle shutdown based on SOC of super capacitor and the speed.



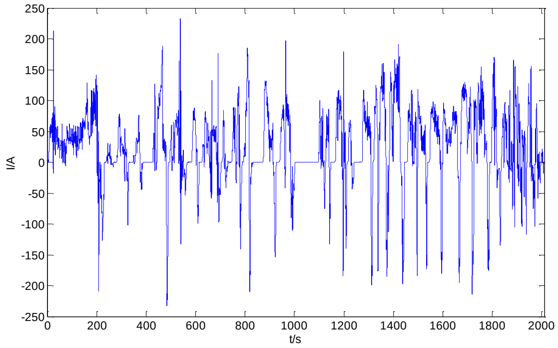
(a). The bus voltage and SOC curve



(b). The discharge current curve of the super capacitor.



(c). APU output current variation curve.



(d). Traction motor working current curve.

Figure 10. The Working Conditions of the Series Hybrid Electric System Components in Zhuzhou City Driving Cycle

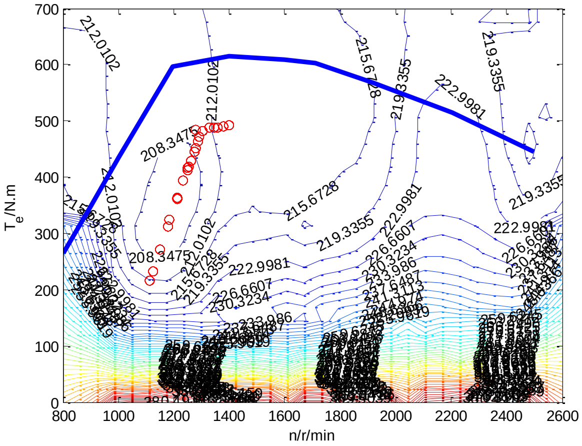


Figure 11. The Working Points Distribution in Zhuzhou City Driving Cycle

Figure 12 is the series hybrid powertrain energy flow diagram in Zhuzhou city driving cycle. With engine idle shutdown strategy, engine efficiency reaches 33.54%, and the engine and generator are both working in high efficiency region. The charging and discharging efficiency of super capacitor reaches 97.17%.

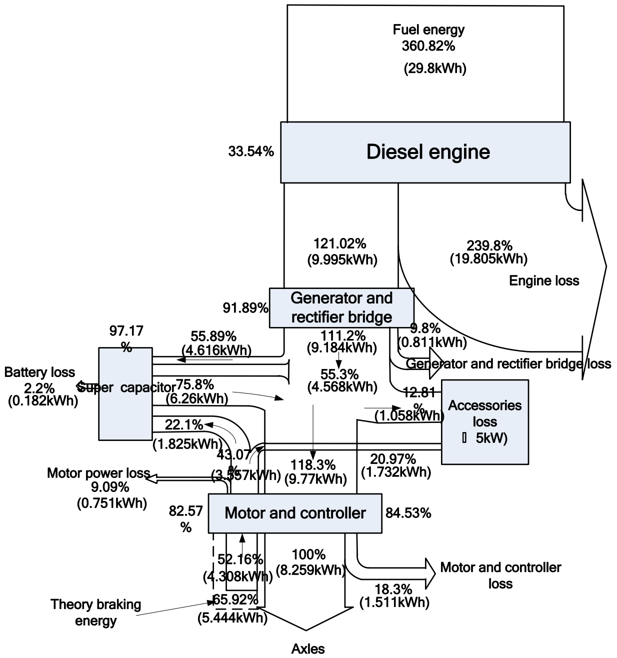
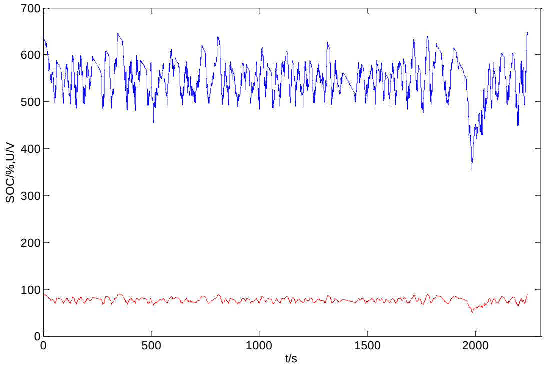


Figure 12. Energy Flow Diagram of Series Hybrid Electric Bus in Zhuzhou City Driving Cycle

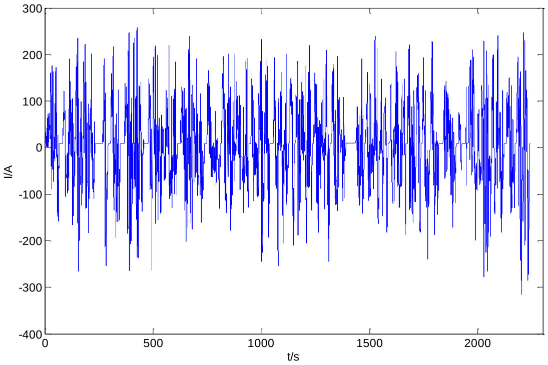
C. Fuel Economy Simulation of Hefei City Driving Cycle

Figure 13 is the working conduction of each component of the series hybrid electric bus in Hefei city driving cycle.

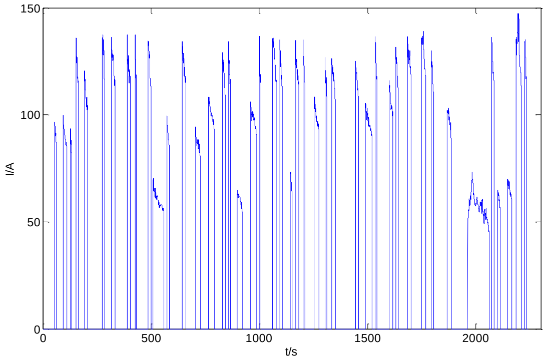
As is shown in Figure 13, in Hefei city driving cycle, the maximum speed is only 44km/h, so the highest power demand is low, SOC of the super capacitor and bus voltage changing range is little, and APU realizes idle shutdown based on SOC of the super capacitor and the working conditions.



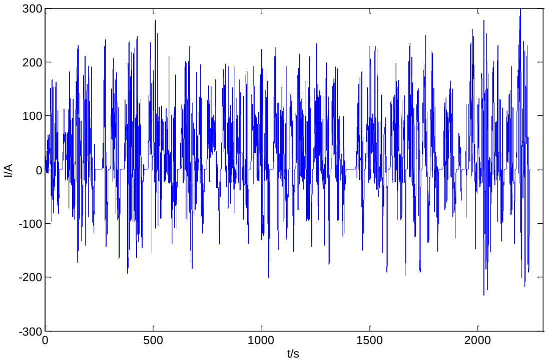
(a). The bus voltage and SOC curve



(b). The discharge current curve of the super capacitor.



(c). APU output current variation curve.



(d). Traction motor working current curve.

Figure 13. The Working Conditions of the Series Hybrid Electric System Components in Hefei City Bus Driving Cycle

Figure 14 is the engine working points distribution in Hefei city bus driving cycle.

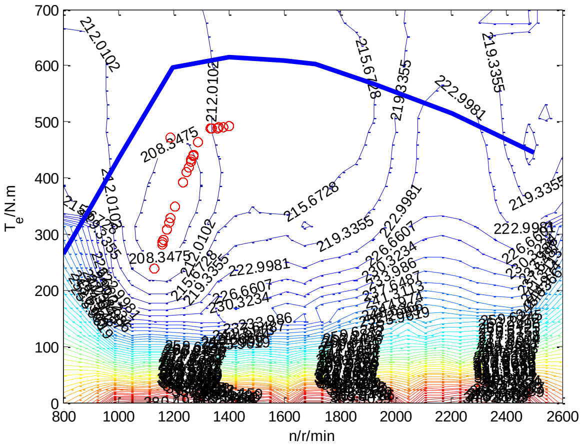


Figure 14. The Working Points Distribution in Anhui City Bus Driving Cycle

As is shown in Figure14, since APU realized idle shutdown, the engine achieves to work in a high efficiency region.

Figure 15 is the series hybrid power system energy flow diagram with Hefei city of Anhui province bus driving cycle.

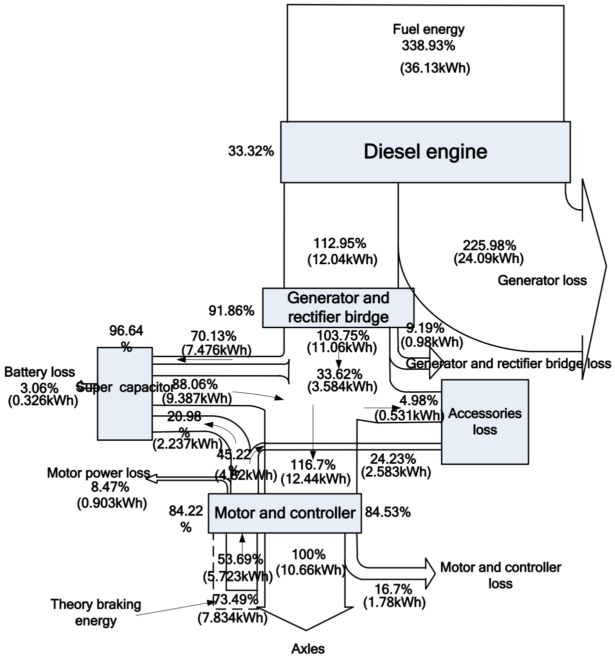


Figure 15. Energy Flow Diagram of Series Hybrid Electric Bus in Anhui City Bus Driving Cycle

As is shown in Figure 15, the engine and the generator are both working in a high efficiency region, the super capacitor charging and discharging efficiency reaches 96.64%.

Table 3 shows fuel consumption and fuel-saving ratio of the hybrid electric bus in different driving cycles. In Table 3, fuel consumption is different with different driving cycles, but fuel saving ratio are all above 25% compared to the conventional diesel bus.

Table 3. Fuel Consumption and Fuel-saving Ratio in Different Driving Cycles

Test cycle	Conventional diesel bus fuel consumption (L/100km)	Series hybrid bus fuel consumption (L/100km)	Fuel-saving ratio
Chinese city bus	35.42	26.25	25.89%
Zhuzhou Bus	31.88	23.82	25.28%
Hefei bus	30.98	22.97	25.85%

5. Conclusion

This paper establishes the energy management strategy based on the combination of the idle shutdown and load follow. The simulation driving cycles are Chinese city bus cycle, Hefei city of Anhui province bus cycle, and Zhuzhou city of Hunan province bus cycle. The fuel economy potential is analyzed in different driving cycles. The simulation results show that, the fuel saving ratio are all above 25% in the three driving cycles. The difference of the fuel economy is little in different driving cycles which indicate the energy management strategy influences the fuel economy little, under 1%, with different driving cycles. So with this energy management strategy in different driving cycles the fuel economy of the hybrid electric bus can be steady.

Acknowledgements

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