EVS30 Symposium

Stuttgart, Germany, October9-11, 2017

Design of control strategy for single-shaft parallel hybrid electric bus based on actual driving cycle

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Abstract

Based on the amount of data, the driving cycle is constructed by V-A analysis. The error between the developed driving cycle and sampling data shows that the developed cycle can truly reflect the actual operation status of Xi'an city bus. Based on the developed driving cycle and the parameters of single-shaft parallel hybrid electric bus, a simple logic threshold control strategy is given, and the critical rotational speed of engine is analyzed. Simulation results show that the critical speed of the engine has a certain influence on the vehicle's economic performance under the established control strategy based on developed driving cycle.

Key words: driving cycle; equivalent fuel consumption model; speed of engine operation point

1 Preface

There is a strong trend to use driving cycles extensively in vehicle design, particularly for the calibration and tuning of all powertrain systems for control and diagnosis of city bus [1]-[5]. The control strategy has a great influence on fuel consumption and emission based on the true driving cycle. The advantages of logic threshold control strategy are simple and easy to develop which has high stability. The logical threshold control strategy is to make the engine and motor work as efficiently as possible which is analyzed in detail in document [6]-[9]. This paper builds the driving cycle based on the variable step intercept and V-A analysis method. The error shows that the developed cycle can truly reflect the actual operation status of Xi'an city bus. This paper adopts the logical threshold control strategy and calibrates the critical rotational speed of the engine with the optimum fuel economy based on the developed driving cycle. Simulation results show that it is necessary to optimize the critical rotational speed of engine to improve the economy based on the logical threshold control strategy.

2 Driving cycle construction

This paper takes the typical route of Xi'an bus to carry on the condition. The GPS acquisition equipment is installed in the urban and suburban buses. The sampling frequency is 1Hz. The cumulative mileage of the experiment reached 2238km, totalling 544700 effective speed information. Variable step intercept and V-A analysis method is used to build the driving cycle. The flow chart of V-A analysis is shown in Figure1.

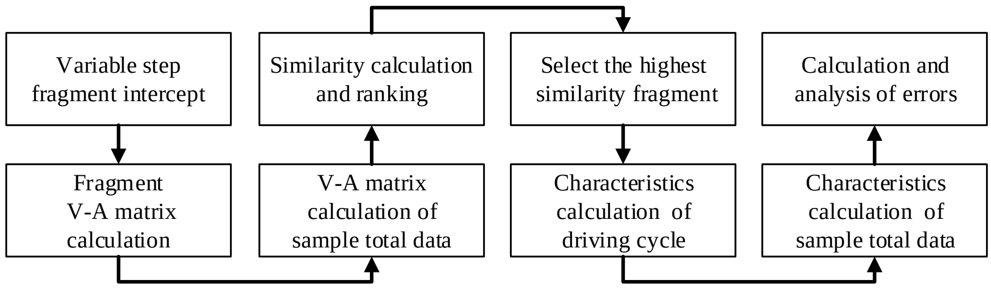

Figure1: Driving cycle construction flow chart of V-A analysis method

According to the process above, the highest similarity fragment is selected as the driving cycle (named XA-BUS). The length of XA-BUS is 1023s, as shown in Figure2.

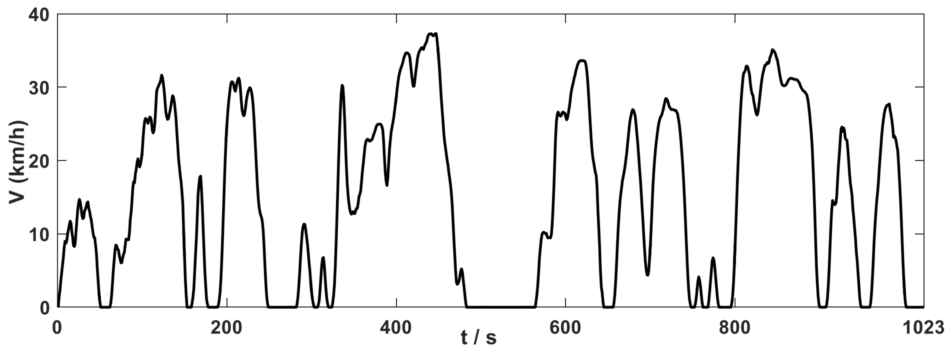

Figure2: Speed-time curve of the cycle

Ten major and statistical parameters are selected as the error evaluation index to evaluate the constructed condition, which are the average speed (V_{mean}), average running speed (V_{mr}), the standard deviation of velocity (V_{sd}), average acceleration (A_{mean}), average deceleration (D_{mean}), the standard deviation of acceleration (A_{sd}), the proportion of acceleration time(P_a), the proportion of deceleration time (P_d), the proportion of constant time (P_c) and the proportion of idle time(P_i). The eigenvalues of sampling data and driving cycle data are shown in the Table1. The formulas of average error of each index are shown in (1)-(2).

Table1: Eigenvalue of sampling data and driving cycle data

Eigenvalues	V_{mean}	V_{mr}	V_{sd}	A_{mean}	D_{mean}	A_{sd}	P_a	P_d	P_c	P_i
Sampling data	15.68	20.52	12.44	0.53	-0.57	0.48	0.27	0.25	0.20	0.28
Driving cycle	14.57	30.36	12.58	0.55	-0.60	0.53	0.30	0.27	0.18	0.24

$$\delta_{\mathrm{i}} = \frac{|A_i - A|}{A} \times 100\% \qquad (1)$$

$$\overline{\delta} = \frac{1}{n}\sum_{i=1}^{n}\delta_i \qquad (2)$$

The δ_i is the error of each eigenvalue index. A is the main eigenvalue of the sample data. A_i is the main eigenvalue of the constructed driving cycle. $\overline{\delta}$ is the average error of eigenvalues between sample data and constructed driving cycle. From the formula (1)-(2), the average error between the data of driving cycle and the total sample is 6.5%. The error shows that the developed cycle can truly reflect the actual operation status of Xi'an city bus. The developed cycle is adopted in the following calculation of this paper.

3 Logical threshold control strategy and speed threshold calibration

3.1 Structure of single-shaft parallel hybrid electric bus

The parallel hybrid power system can be divided into double-shaft parallel hybrid electric bus and single-shaft parallel hybrid electric bus. Single-shaft parallel has the advantages of simple structure, easy to implement. The typical characteristic is that the motor shaft as part of a drive shaft, which can be applied to electromagnetic torque of the motor itself, but also can transmit torque of the engine. The structure is easy to realize the integrated, and can greatly reduce the overall weight and the difficulty of assembling. In this paper, the data collected from the bus is a single-shaft parallel hybrid electric bus, and the structure of the pneumatic system is shown in Figure 3. Basic parameters of the bus are shown in Table2:

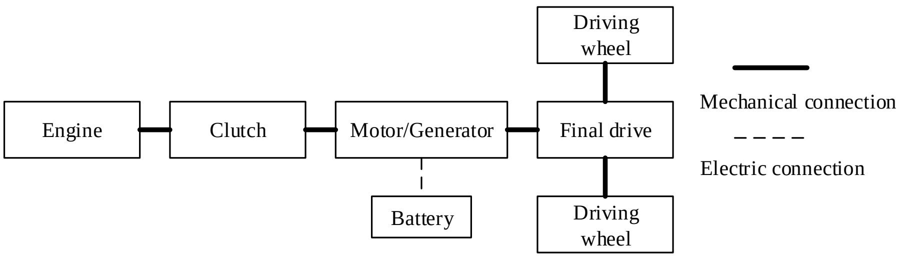

Figure3: Single-shaft parallel hybrid electric bus power system

Table2: The basic parameters of the bus

Curb weight	12400/kg	Windward area	7.6m2
Maximum mass	18000/kg	Air coefficient	0.67
Length /width/height	12000/2550/3150/mm	Tyre	295/80 R22.5
Final drive ratio	6.2	Additional power	20kW

The engine and motor parameters of this single-shaft parallel hybrid electric bus are shown in Table3:

Table3: Engine and motor parameters

Engine	Model	maximum power	Rated speed	Maximum torque/ torque speed	cylinders	displacement
	YC4E140-31	147kw	2500 r/min	730/1200-1700(N/m)	6	6.494L
Motor	Rated power	peak power	Rated speed	Peak speed	Voltage level	Cooling method
	50 kw	120 kw	1200 r/min	4000 r/min	538VDC	Liquid

3.2 Calculation of the equivalent fuel consumption model

The engine universal characteristic curve is considered as the two-element function of engine speed *n* and effective g_e. We can get the formula and Map diagram based on multiple linear regression method, shown in formula (3) and Figure4.

$$g_e(n_e, P_e) = 686.86 - 1.1526 n_e + 1.4734 P_e + 0.001154 n_e^2 - 0.009898 n_e \cdot P_e + 0.07935 P_e^2 - 4.3063\times10^{-7} n_e^3 + 3.4533\times10^{-6} n_e^2 \cdot P_e + 2.5025\times10^{-5} n_e P_e^2 - 0.0007083 P_e^3 + 5.6529\times10^{-11} n_e^4 - 3.7508\times10^{-10} n_e^3 P_e - 7.1322\times10^{-9} n_e^2 P_e^2 + 3.2172\times10^{-8} n_e P_e^3 + 1.5786\times10^{-6} P_e^4. \tag{3}$$

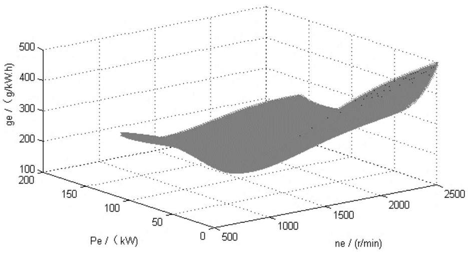

Figure4: Map diagram of engine

According to the fuel consumption model, the efficiency is defined as:

$$\eta_e(n_e, P_e) = \frac{P_e}{(P_e g_e E_D)/(D\times3.6\times10^9)} = \frac{D\times3.6\times10^9}{g_e E_D} \tag{4}$$

Where η_e is the engine efficiency, E_D is the diesel fuel energy density, D is the diesel density (0.808kg/L). The average thermal efficiency is 0.46 after calculation. Similarly, the motor efficiency and Map diagram are shown in formula (5) and Figure5:

$$\eta_M(n_m, P_m) = \frac{1}{100}(89.23 - 0.002031 n_m + 0.070243 P_m + 5.1365\times10^{-6} n_m^2 - 1.1865\times10^{-5} n_m \cdot P_m - 0.0003103 P_m^2 - 2.7487\times10^{-9} n_m^3 + 1.0744\times10^{-8} n_m^2 \cdot P_m + 4.8129\times10^{-8} n_m P_m^2 + 4.0198\times10^{-7} P_m^3 + 3.2631\times10^{-13} n_m^4 + 1.9119\times10^{-13} n_m^3 P_m - 3.1127\times10^{-11} n_m^2 P_m^2 + 1.1146\times10^{-11} n_m P_m^3 - 1.8892\times10^{-10} P_m^4). \tag{5}$$

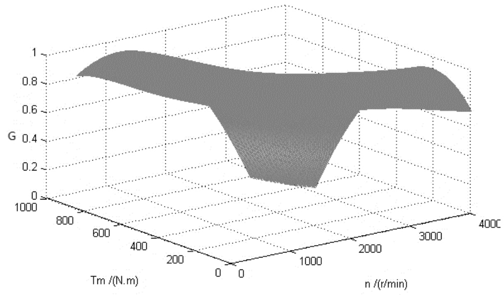

Figure5: Map diagram of motor

Normally, the charge, discharge, internal resistance and electromotive force of a battery are change with the change of SOC, $R_{SOC}=\psi(P_{SOC})$， $E_{SOC}=\phi(P_{SOC})$. The SOC value is usually in the 0.4-0.7 range.

Table4: Data of battery charge and discharge resistance and E_{SOC} change with SOC

P_{soc}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$R_{ch}(\Omega)$	0.72	0.66	0.61	0.59	0.56	0.56	0.56	0.57	0.58	0.59	0.63
$R_{dis}(\Omega)$	0.64	0.61	0.59	0.58	0.57	0.57	0.57	0.58	0.60	0.67	0.76
E_{soc}	510.2	524.7	532.5	534.4	535.6	536.3	537.4	538.6	539.1	544.7	565.6

Three polynomial fitting is used to get the formula with the charge of SOC, shown in formula (6)-(8) and Figure6:

$$R_{ch}(p_{soc}) = 0.7229 - 0.7757\,p_{soc} + 1.3601\,p_{soc}^2 - 1.1642\,p_{soc}^3 + 0.4839\,p_{soc}^4 \qquad (6)$$

$$R_{dis}(p_{soc}) = 0.6399 - 0.4053\,p_{soc} + 1.1404\,p_{soc}^2 - 1.8670\,p_{soc}^3 + 1.2516\,p_{soc}^4 \qquad (7)$$

$$E_{soc}(p_{soc}) = 511.05 + 142.70\,p_{soc} - 205.22\,p_{soc}^2 - 22.840\,p_{soc}^3 + 138.81\,p_{soc}^4 \qquad (8)$$

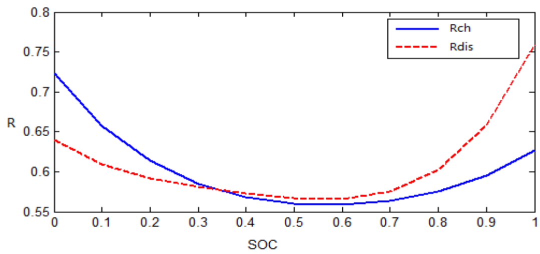

Figure6: Relationship between charge and discharge resistance of SOC

For the sake of simplification, the influence of the temperature and the number of battery cycles on the charge and discharge efficiency are neglected. The charge and discharge efficiency can be obtained, shown in formula (9) and (10).

$$\eta_{ch} = \frac{2E_{soc}}{E_{soc} + \sqrt{E_{soc}^2 - 4R_{soc}P_m}}, (P_M < 0) \qquad (9)$$

$$\eta_{dis} = \frac{E_{soc} + \sqrt{E_{soc}^2 - 4R_{soc}P_m}}{2E_{soc}}, (P_M > 0) \tag{10}$$

The current time integral method is simple and useful, and the algorithm is stable. This method is used to estimate the SOC. This model can be expressed as follows:

$$SOC = SOC_0 - \frac{1}{C}\int_0^t \eta i dt \tag{11}$$

SOC_0 is the initial state of SOC. C is the rated capacity of the battery. η is the efficiency of charge or discharge. The i is the instantaneous current (charge is negative, discharge is positive).

The current of charge $i = \frac{P_m}{U} = \frac{P_m}{E_{soc} - iR}$, Give up the invalid result $i = \frac{E_{soc} - \sqrt{E_{soc}^2 - 4R_{soc}P_m}}{2R_{soc}} = \zeta(p_{soc}, P_m)$

The SOC at t+1 can be calculated by motor efficiency at t+1 and SOC at t, shown in formula (12).

$$SOC(t+1) = SOC(t) - \frac{\Delta t}{C}\eta i = SOC(t) - \delta(SOC(t), P_m(t+1)) \tag{12}$$

For non-plug hybrid electric vehicles, the final energy can be derived from the chemical energy of fuel. The equivalent fuel consumption model is established as evaluation index to evaluate the comprehensive economic performance of the vehicle. Referring to the literatures at home and abroad, the engine fuel consumption rate is g_e (P_e, n_e). The energy absorbed or released of the battery can be equivalent as shown in formula (13):

$$g_m(P_m, n_m) = \begin{cases} SC \cdot P_m / (\eta_m \cdot \eta_{dis}) & P_m \ge 0 \\ SC \cdot P_m \cdot \eta_{ch} & P_m \le 0 \end{cases} \tag{13}$$

Where η_m is the efficiency of drive, η_{ch} is the efficiency of charge, η_{dis} is the motor efficiency of discharge. SC is the average conversion coefficient of oil to electricity, which can be expressed as:

$$SC = 1/(3.6 \times 10^6 / (\eta_e \cdot H \cdot \eta_t \cdot \eta_{ch})) \tag{14}$$

Where η_e is the engine efficiency, η_t is the mechanical drive efficiency of charge, H is the low fuel calorific value. In this way, the total fuel equivalent fuel consumption at t can be calculated shown in (15):

$$g = g_e(P_e, n_e) + g_m(P_m, n_m) \tag{15}$$

3.3 Optimization of logical threshold control strategy

The calculation formula of power requirement of the bus at a speed of u_a is shown in (16):

$$P_e = \frac{1}{\eta_t}\left(\frac{Gfu_a}{3600} + \frac{Giu_a}{3600} + \frac{C_D A u_a^3}{71640} + \frac{\delta m u_a}{3600}\frac{du}{dt}\right) \tag{16}$$

Where P_e is the power requirement of driving vehicle, η_t is the efficiency of transmission systems, m is the quality of vehicle, g is the gravitational acceleration, f is the coefficient of rolling resistance, C_D is the coefficient of air resistance, A is the windward area, u_a is speed, δ is the rotation level conversion coefficient which is defined as follow:

$$\delta = 1 + \frac{\sum I_w}{mr^2} + \frac{I_f i_g^2 i_0^2 \eta_T}{mr^2} \tag{17}$$

For easy calculation, we take the δ as 1.02. According to the XA-BUS data and the parameters mentioned above, the power demand of the bus is calculated based on the maximum mass of the vehicle. The result shows in the Figure 7.

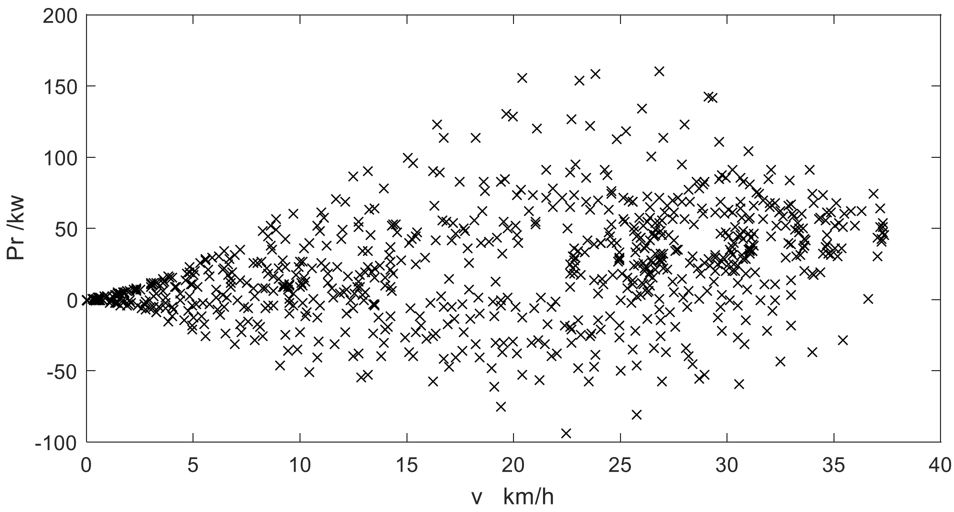

Figure7: The power point distribution based on XA-BUS

The efficiency and the resistance are change with SOC. In order to keep the battery in the best area, this paper sets the energy compensation strategy that four threshold values are made, $SOC_{\_L}$, $SOC_{\_B}$, $SOC_{\_W}$, $SOC_{\_H}$.

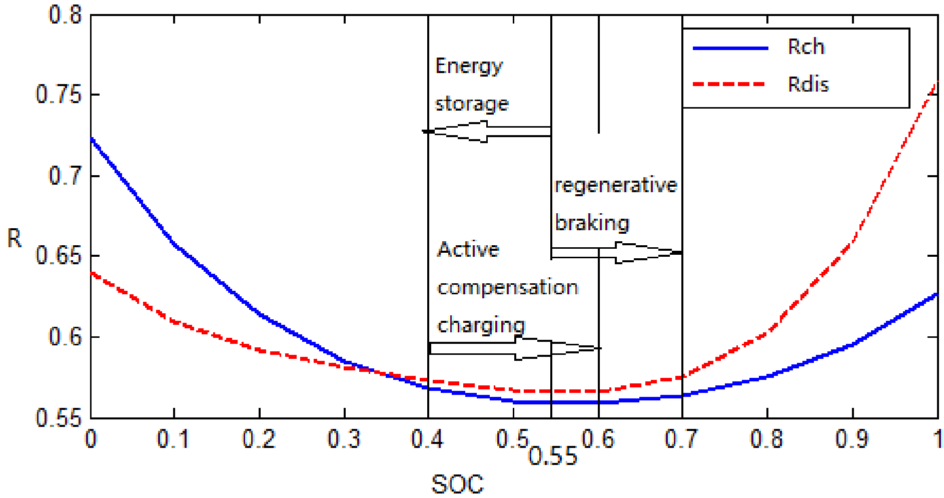

Figure8: Energy compensation strategy of SOC

Based on the demand power distribution of the developed driving cycle, the control strategy is formulated. The power mode distribution is shown in Figure9. The flow chart of logical threshold control strategy is shown in Figure10.

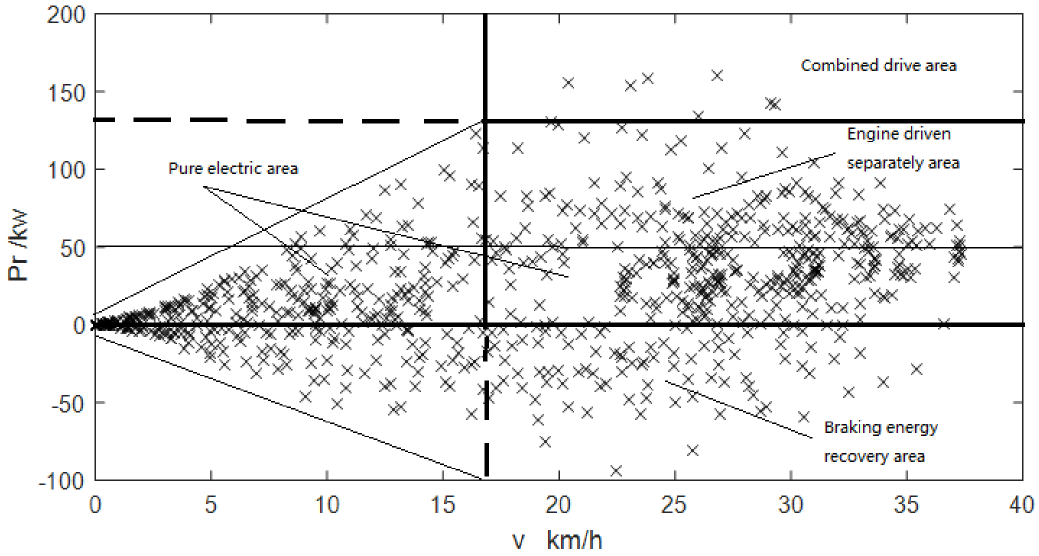

Figure9: Power distribution controlling strategy

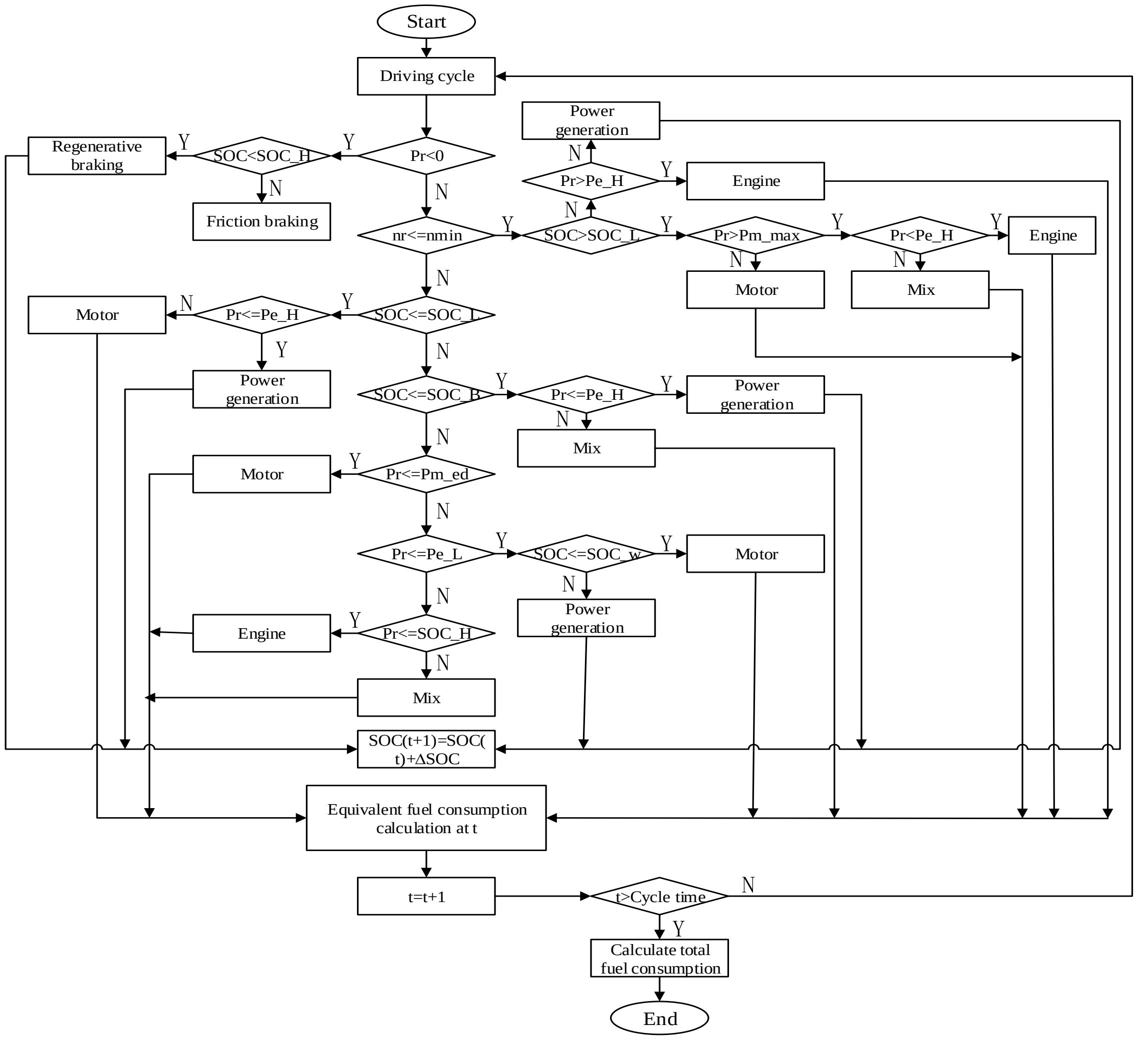

Figure10: Flow chart of equivalent fuel consumption calculation

The parameters of the flow chart are shown in the next.

$$m_a = 18000kg,\quad i_0 = 6.2,\quad P_{e\_max} = 147kw,\quad P_{e\_L} = 80kw,$$
$$P_{e\_H} = 130kw,\quad SOC_0 = 0.5,\quad P_{m\_max} = 100kw,\quad P_{m\_ed} = 50kw,$$
$$SOC_{\_L} = 0.4,\quad SOC_{\_B} = 0.55,\quad SOC_{\_W} = 0.6,\quad SOC_{\_H} = 0.7。$$

The engine idle is adjustable. The critical rotational speed of engine must be higher than the idle speed. This paper finds the optimal working point to achieve the best equivalent fuel economy by changing the critical rotational speed to. In order to make the result obviously, this paper selects the speed range for [600rpm, 900rpm]. The step is 50rpm. The calculated results are shown in Figure 11.

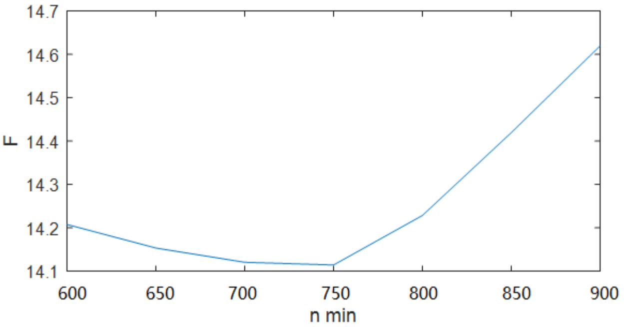

Figure11: Equivalent fuel consumption changes with speed

According to Fig. 11, the optimal engine operates at critical rotational speed is 750r/min. The corresponding engine operating critical speed is 17.1km/h. Thus, it is necessary to optimize the engine's critical rotational speed under the given control strategy based on the constructed driving cycle.

4 Conclusion

This paper constructs the driving cycle based on the variable step size and V-A matrix analysis method. The average error is 6.5% between the sample data and the developed driving cycle, which shows that the developed cycle can truly reflect the actual operation status of Xi'an city bus. And a simplified equivalent fuel consumption model according to the actual parameters of the vehicle is built. The logic threshold control strategy is optimized with the goal of fuel economy of the vehicle based on the constructed driving cycle. The key point is to compare and analyze the speed of the critical rotational speed of the engine with the best equivalent fuel economy. The results show that the critical rotational speed of the engine has a certain influence on the vehicle's economic performance under the established control strategy. It is necessary to optimize the critical rotational speed of the engine for the hybrid electric bus based on the actual driving cycle.

Acknowledgments

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 51207012, Shaan'xi Province Science and Technology Project under Grant 2016GY-069 and Key Laboratory of Small & Special Motor and Drive Technology of Shaan'xi Province under the Grant 2013SSJ2002

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