# Research on Route-Based Fuzzy Adaptive Control Strategy of PHEV

Jianhua Guo[1], Cui Liu[2,*] and Liang Chu[1]
[1]State Key Laboratory of Automotive Dynamic Simulation and Control, Jilin University, Chang Chun, China
[2]Mechanic and Electronic Engineering, Qingdao Binhai University, Qingdao, China
*Corresponding author

***Abstract*—In this paper, the route-based fuzzy adaptive control strategy(RFACS) of PHEV is designed based on the Intelligent Transportation System（ITS）. Through the ITS to get the speed characteristic of the future path and the fuzzy intelligent control, the RFACS strategy can improve the efficiency of PHEV system by the reasonable planning use of battery power. The system simulation model was established by Simulink and Cruise, and the results are contrastive analysis. The simulation results show that the RFACS strategy can adapt to driving cycle characteristics, and SOC of battery can be reasonably planned, then the economic performance of PHEV is improved.**

***Keywords-plug-in hybrid electric vehicle; intelligent transport system; fuzzy adaptive control strategy***

## I. INTRODUCTION

Currently, The energy management strategies of Plug-in Hybrid Vehicles (PHEV) are mostly based on the threshold control strategies by rules[1][8][9][10]. For example, Jeffrey and Tony designed a Rule-based PHEV Control Strategy (AER)[1] in which the PHEV driving modes are divided into Charge Depleting(CD) phase and Charge Sustaining(CS) phase. In CD phase, the vehicle is mainly driven by a motor and the engine is only an auxiliary power source. In CS phase, the vehicle is mainly driven by engine and charge the battery. The threshold control strategies have strong robustness and good real-time performance and easy to implement. However, this control strategy has poor adaptability to the changes of cycle. When the PHEV drives in the CS mode, the engine must start and to be forced working at inefficient area, resulting of high fuel consumption. To solve this problem, Eason and Noble[2] developed a hybrid bus (HEB) control strategy based on Dynamic Programming(DP) in which the neural network model was established to predict future driving speed. simulation results show that HEB economy can improve 7%. However, the algorithm is computationally intensive and the cycle must to know.

In this paper, an Route-based Fuzzy Adaptive Control Strategy of PHEV (RFACS) is designed based on the Intelligent Transportation System（ITS）. Through the ITS to get the speed distribution of routes, the adaptive control strategy can improve the efficiency of PHEV system by the use of reasonable planning battery power to improve PHEV economy.

## II. THE STRUCTURE OF THE PHEV

The structure of a coaxial parallel PHEV which mainly uses as private car is shown as Figure 1. The basic configuration of its power train is as follows: the 1.0L gasoline engine that peak torque is 170N.m/4000rpm is equipped in this car; The peak torque of the motor is 140N.m/4000rpm; The voltage rating of the battery is 300V with capacity of 35Ah.

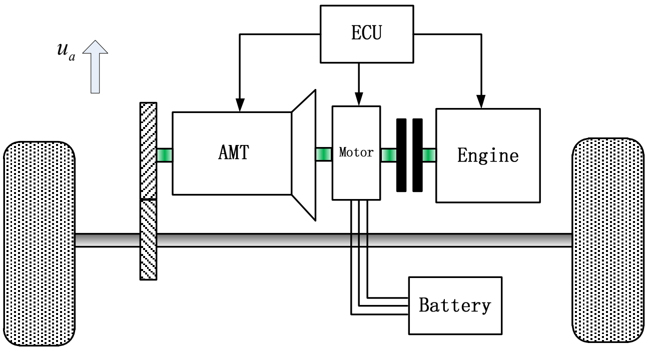


FIGURE I. STRUCTURE OF THE PHEV RESEARCH IN THE PAPER.

## III. ROUTE BASED FUZZY ADAPTIVE CONTROL STRATEGY

### A. Framework of the strategy

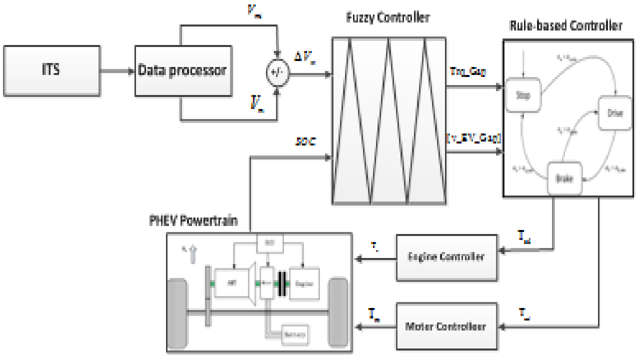
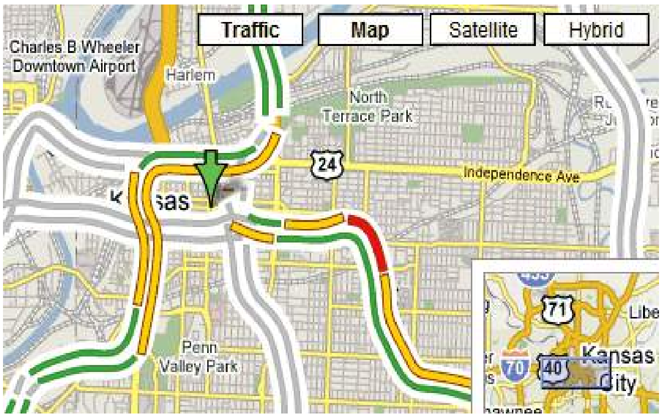


FIGURE II. FRAMEWORK OF PHEV CONTROL STRATEGY

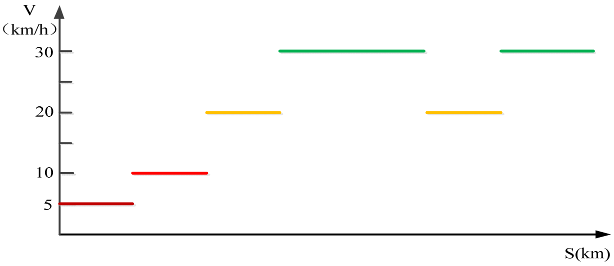
Figure 2 is the framework of the RFACS strategy the paper designed. The control principle is as follows:

(1) First, the driver enter the destination by the GPS, GPS calculates the drive path and transmits the data of the path to ITS(Figure 3(a)). The real-time traffic system of ITS monitors

the road traffic speed of each section of road(Figure 3(b)), and then the speed of information is sent to the data processor(Figure 2).



(a) realtime traffic system of ITS



(b) average speed of each road section

FIGURE III. REALTIME TRAFFIC SYSTEM AND AVERAGE SPEED DATA PROCESSOR CACULATED

(2)The data processor calculates the average speed of each section $V_{mi}$ and the average speed of the routes $V_m$ .The average speed difference $\Delta V_{mi}$ is calculated as follow:

$$\Delta V_{mi} = V_{mi} - V_m \tag{1}$$

(3)The $\Delta V_{mi}$ and the current SOC as the inputs, the fuzzy controller calculates the fixed motor torque threshold "[Trq_Gap]" and speed fixed electric drive threshold "[v_EV_Gap] "based on the fuzzy rules formulated in the paper.

(4)According to "[Trq_Gap]" and "[v_EV_Gap]", the rule-based controller (Fig.2) adjusts the drive mode of PHEV and calculates the engine torque $T_e$ and the motor torque $T_m$.

In a word, according to real-time traffic data of the ITS, the RFACS intelligently distributes engine and motor power to planing use the battery power reasonably.

### B. *Fuzzy adaptive controller*

Fuzzy control is a kind of intelligent control method by imitating the human way of thinking to realize the intelligent control[3][4]. Due to better real-time and robustness, the Fuzzy control is very suitable for the kind of nonlinear problem of PHEV/HEV energy management[5][6][7]. In this paper, the fuzzy logic toolbox of matlab is used to establish the fuzzy adaptive controller.

The fuzzy controller has two inputs ($\Delta V_{mi}$ and SOC) and two outputs($T_e$ and $T_m$), as shown in Figure 2. Each one of these variables is represented by mathematical membership functions describing states and variation domain of the variable that can be modeled under various forms (triangular, trapezoidal or Gaussian) as shown in Figure 4 and Figure 5.

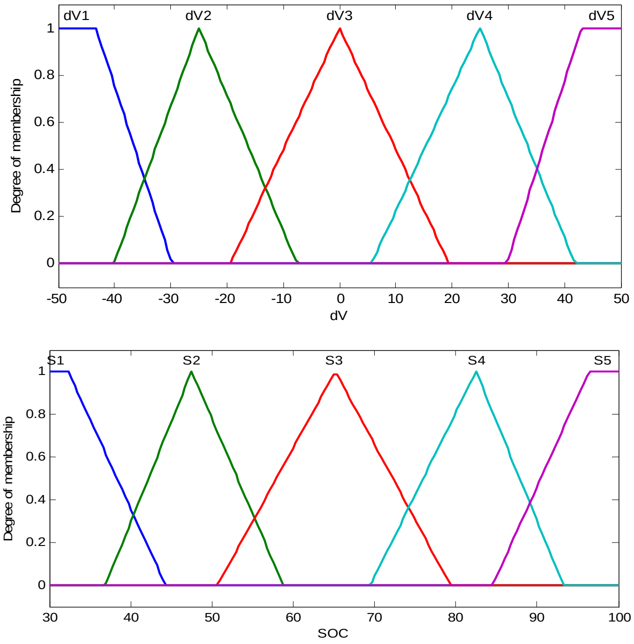


FIGURE IV. MEMBERSHIP OF THE INPUT VARIABLES

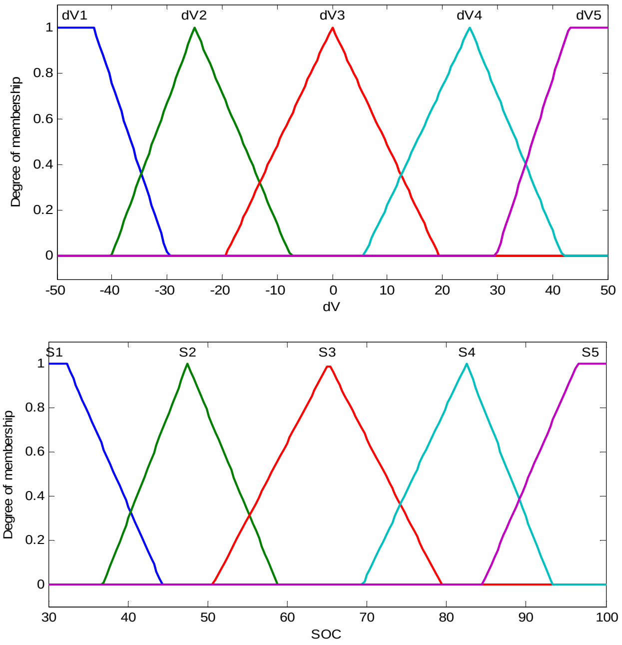


FIGURE V. MEMBERSHIP OF THE OUTPUT VARIABLES

In order to reduce the on-line complexity, the triangular and trapezoidal functions are adopt in this controller. For example, the different possible states to represent the average speed difference $\Delta V_{mi}$ are {dV1,dV2,dV3,dV4,dV5} which mean as follows:dV1 is High negative, dV2 is Low negative, dV3 is Medium, dV4 is Low, dV5 is High. The domain of discourse of input variable $\Delta V_{mi}$ is [-50,50] as Figure 4.

TABLE I. RULES BASE OF THE [TRQ_GAP]

| **SOC** | $\Delta V_{mi}$ | | | | |
|---|---|---|---|---|---|
| | **dV1** | **dV2** | **dV3** | **dV4** | **dV5** |
| S1 | T4 | T4 | T4 | T3 | T2 |
| S2 | T5 | T4 | T3 | T2 | T2 |
| S3 | T5 | T5 | T4 | T2 | T3 |
| S4 | T6 | T6 | T5 | T2 | T3 |
| S5 | T7 | T7 | T6 | T3 | T4 |

TABLE II. RULES BASE OF THE [V_EV_GAP]

| **SOC** | $\Delta V_{mi}$ | | | | |
|---|---|---|---|---|---|
| | **dV1** | **dV2** | **dV3** | **dV4** | **dV5** |
| S1 | V4 | V4 | V5 | V6 | V7 |
| S2 | V3 | V4 | V4 | V5 | V6 |
| S3 | V4 | V5 | V6 | V6 | V6 |
| S4 | V3 | V3 | V4 | V5 | V6 |
| S5 | V2 | V3 | V3 | V4 | V5 |

Using these membership functions (MFs), the rule base is defined by a set of 25 rules of each output, as listed in Tab.1 and Tab.2. The general logical behind these rules is running the engine at near optimal operating points as far as possible while the EM is used to assist or generate.

For instance, we consider a case: the Mfs of $\Delta V_{mi}$ is dV5 and the Mfs of SOC is S1 that means the current speed is high and the SOC is very low. The output of "[Trq_Gap]" is T2 that means the output torque of motor is small. The output of "[v_EV_GAP]" is V7 that means the probability of EV model (the motor drives the vehicle only) is lower . The both above cases reduce the proportion of the motor power in the drive demand power and increase the proportion of the engine's. Due to the high speed, the operating points of the engine are close to the high efficiency area.

In another case, whe the Mfs of $\Delta V_{mi}$ is dV1 and the Mfs of SOC is S5, the proportion of the motor power in the drive demand power is promoted and engine is almost not involved in driving the vehicle. In this case, the operating points of the engine is far away from the high efficiency area when the speed is lower.

### C. *Rules based control strategy*

In the thesis, the rules based control strategy model as the literature[8] mentioned is established by Matlab/Simulink as show in Figure 6. The module of the model includes: "Input Signals", "Drive Demand", "PT Mode Manager", "Torque Split" etc..

The PT Mode Manager (pattern recognition) module based on the state variables (the current speed ,SOC and the angle of accelerator/brake pedal etc.) of the vehicle to recognize the PHEV drive modes[9]. Figure 7 is the state flow mode of the drive subpattern that includes two drive mode: "motor drive" and "Engine on". The main control thresholds are Pure electric top speed basic threshold ([v_EV_Max]=60km/h), "[v_EV_Gap]" and SOC. When the "[v_EV_Gap]" threshold reduce, The "Engine on" mode (Figure 7) is easer to be selected that make the proportion of the engine power increase.

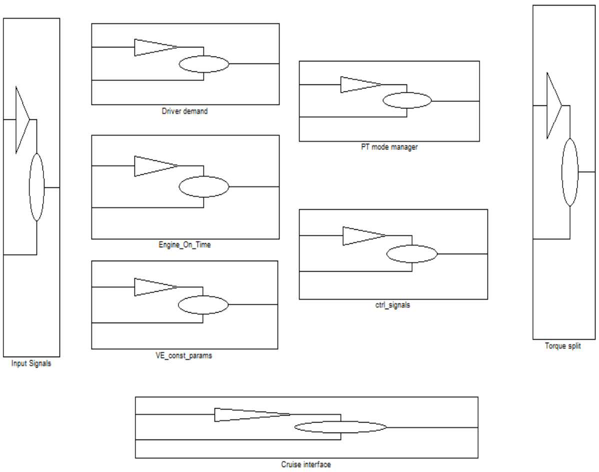


FIGURE VI. RULES BASED CONTROL STRATEGY MODEL BY MATLAB/SIMULINK

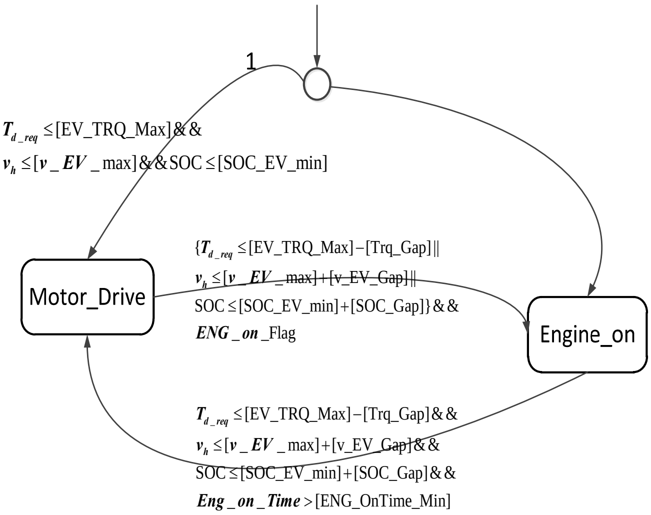


FIGURE VII. THE STATEFLOW MODE OF THE DRIVE SUBPATTERN

The "Torque Split" module calculates the torque of engine "$T_e$" and the torque of motor. Under the boost model, the formulas are as follows:

$$T_m = (T_{req} - T_{e\_\mathrm{opt}}) + [\mathrm{Trq\_Gap}] \qquad (2)$$

$$T_e = T_{req} - T_m \qquad (3)$$

where, $T_{req}$ is driver required torque, N.m; $T_{e\_opt}$ is the upper threshold of engine torque [10], N.m.

From formulas (2-3), It can be seen that the increase of the threshold [Trq_Gap] can make the motor torque increase and engine torque reduce.

## IV. SIMULATION VERIFICATION

In order to verify the effectiveness of the proposed control strategy, the combined simulation model is established using Matlab/Simulink and AVL Cruise. Figure 7 is the Cruise vehicle model which is combined with the Matlab/Simulink control mode through the “Cruise interface ”module as shown in Figure 2.

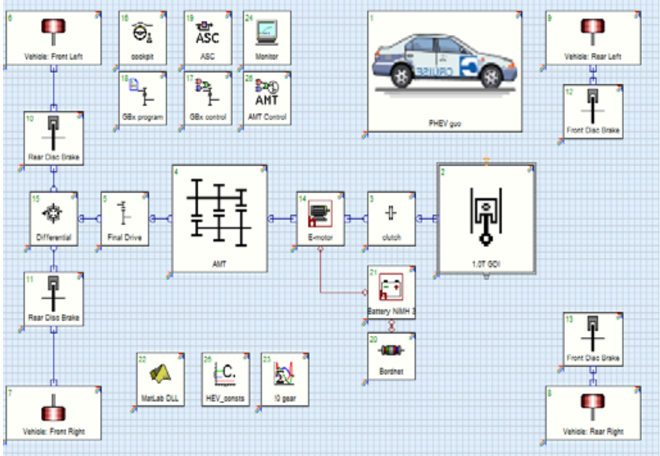


FIGURE VIII. THE CRUISE VEHICLE MODEL

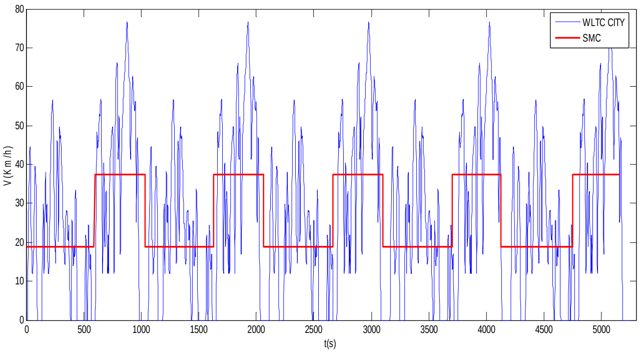


FIGURE IX. WLTC CYCLE AND AVERAGE SPEED

In order to verify the validity of the strategy, The WLTC cycle is selected as shown in Fig.9. The distance of the cycle is 39.1km; Average speed of the routes $V_m$ is 26.8km/h; The runtime is 5245s; The average speed of each section $V_{mi}$ is shown in Figure 8(read line, SMC).

All electric-range (AER) strategy which only uses the motor driven vehicle in CD phase and Blended control strategy which have a fixed control threshold are established for comparison validation.

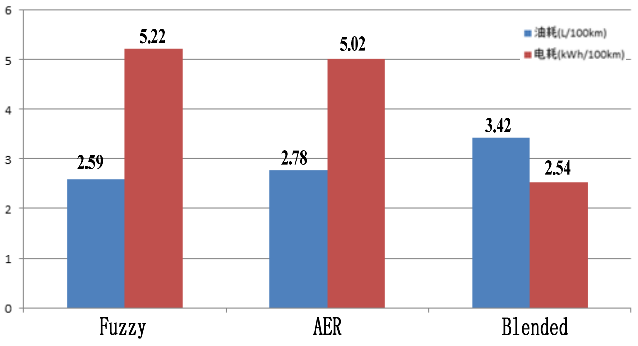


FIGURE X. SIMULATION RESULTS OF FUEL ECONOMY

The simulation results of fuel economy are shown as Fig.10. It is shown that the fuel consumption of RFACS (Fuzzy) the paper established is lowest. Compared to AER and Blended strategy are respectively decreased 6.8% and 24.2%.

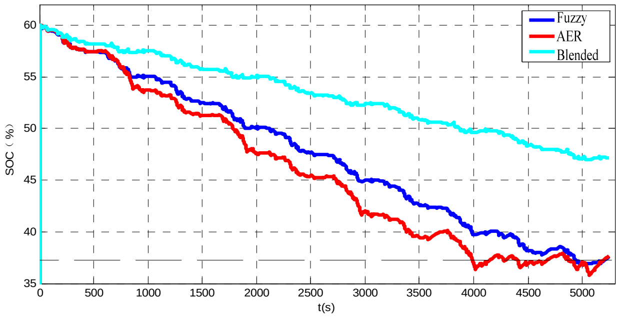


FIGURE XI. TIME COURSE OF SOC

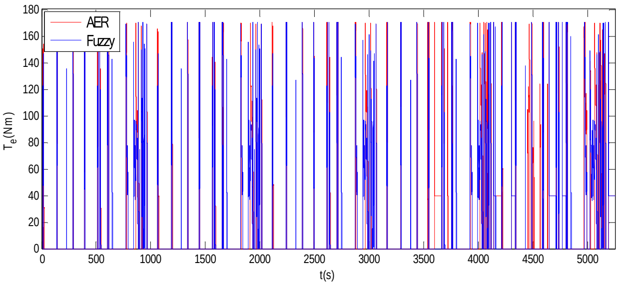


FIGURE XII. TIME COURSE OF ENGINE TORQUE

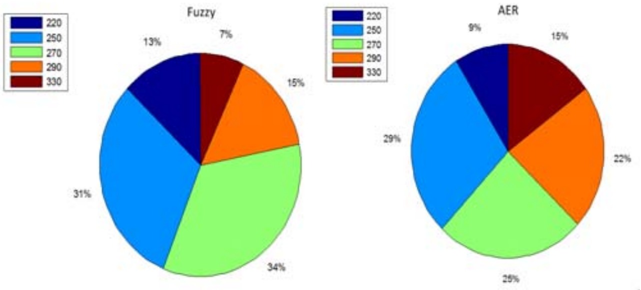


FIGURE XIII. COMPARISON OF ENGINE EFFICIENCY

Figure 11 is the time course of SOC. There are three kinds of simulation results:

- The SOC of the RFACS (Fuzzy) just dropped to the CD lowest value(35%) at the end of the trip.
- The SOC of AER dropped to the CD lowest value(35%) at 4000s. After this time, the PHEV work in CS mode which need engine to drive vehicle and recharge the battery (Figure 12). Figure 13 is the engine efficiency comparison. It is shown that the overall efficiency of RFACS (Fuzzy ) is higher than the AER. This suggest that the RFACS strategy can improve the efficiency of engine.
- The SOC of the Blended dropped to the 47% at the end of the trip. It means that there are still 12% SOC unconsumed to make the fuel consumption soared.

The above analysis shows that the RFACS strategy this paper established can improve the economic benefit of PHEV.

## V. CONCLUSION

In this paper, the route-based fuzzy adaptive control strategy of PHEV (RFACS) is designed based on the Intelligent Transportation System（ITS）. The framework of the RFACS strategy is designed and the key technical problems are researched. Through the ITS to get the speed of the future path of the distribution, the RFACS strategy can improve the efficiency of PHEV system by the reasonable planning use of battery power. The system simulation model was established by Simulink and Cruise, and the results are contrastive analysis. The simulation results show that the PHEV (RFACS) can adapt to driving cycle characteristics, and make SOC reasonably planning, then the economic performance of PHEV is improved.

## REFERENCES

[1] Jeffrey Gonder, Tony Markel, “Energy Management Strategies for Plug-in Hybrid Electric Vehicle,” Advanced Hybrid Vehicle Powertrains. Michigan, SAE. 2007-01-0290, April 2007.

[2] Scott J. Moura, Hosam K. Fathy, Duncan S. Callaway, et al, “A stochastic optimal control approach for power management in plug-in hybrid electric vehicles,” 2008 ASME Dynamic Systems and Control Conference. Michigan, USA, DSCC2008-2252, October 2008.

[3] MA Xianghua, YE Yinzhong, “Study on genrtic-fuzzy control strategy for PHEV Drive system,”Proceeding of the 32nd chinese congtrol conference. Xi’an , China, pp. 7575-7579, July 2013.

[4] Wu Jian, “Fuzzy Control Strategy of Parallel HEV Based on Driving Cycle Recognition,” 2012 IEEE 7th International Power Electronics and Motion Control Conference. Harbin, China, pp. 2636-2639, June 2012.

[5] A.Neffati,S.caux,M.fadel, “Double Fuzzy Logic Decision in HEV Engergy Management,” EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium. Barcelona, Spain, pp. 1-5, November 2013.

[6] Yacine Gaoua, Stéphane Caux, Pierre Lopez, “Energy Management Using Fuzzy Logic, on HEV,” EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium. Barcelona, Spain, pp. 1-5, November 2013.

[7] Amir Poursamad, Morteza Montazeri, “Design of genetic-fuzzy control strategy for parallel hybrid electric vehicles,” Control Engineering Practice. pp. 861–873, November 2007.

[8] Phillip B. Sharer, Aymeric Rousseau, Dominik Karbowski, Sylvain Pagerit, “Plug-in Hybrid Electric Vehicle Control Strategy: Comparison between EV and Charge-Depleting Options,” Argonne National Laboratory, SAE. 08PFL-554, April 2008.

[9] Namwook Kim, Aymeric Rousseau, “Comparison between Rule-Based and Instantaneous Optimization for a Single–Mode, Power-Split HEV,” Argonne National Laboratory, SAE. 2011-01-0873, January 2011.

[10] Guo Jianhua, Chu Liang, “Optimal torque distribution strategy of hybrid electric bus based on instantaneous optimization,” 2013 IEEE 3rd International Conference on Information Science and Technology. Jiangsu, China, pp. 226-229, March 2013.