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Connected HEVs Energy Management Strategy Research Under the Traffic Information Preview

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Abstract—The traditional energy management system of hybrid electric vehicle did not take into account the future driving information. To realize the further energy optimization, the Bi-level energy management strategy in connected environment is studied in this paper. The upper controller is to predict the optimal velocity. Firstly, the target velocity range is first calculated based on the signal phase and timing (SPAT) information. Then the optimization function is designed to obtain the optimal acceleration. The lower controller is designed to follow the optimal acceleration and to save energy by optimizing the power split between the engine and motor under the condition of meeting the physical constraints. The rule-based and fuzzy logic controller based on genetic algorithm are adopted in this paper. Simulation results indicate that optimizing vehicle velocity trajectory in connected environment can effectively reduce fuel consumption and pollutant emission. Meanwhile, compared with Rule-based strategy, the fuzzy logic controller based on genetic algorithm contributes to realize the superior fuel economy performance and lower emissions.

Keywords—Hybrid electrical vehicle, Energy management strategy, Intelligent traffic system, Connected environment

I. INTRODUCTION

With the improvement of people's living standards, cars have become a common means of private transportation. However, the increasing number of fuel vehicles leads to the increase of fuel consumption and pollutant emissions[1,2]. In order to reduce the fuel consumption and pollutant emissions of vehicles, pure electric vehicles become an effective solution. However, due to its long charging time, less charging pile layout and battery safety, pure electric vehicles cannot be widely promoted in the near future. To solve the problems mentioned above, hybrid electric vehicle which combines the advantages of pure electric vehicle and fuel vehicle becomes an effective solution.

Hybrid electric vehicle has two power sources: motor and engine. According to the different combination of motor and engine, hybrid electric vehicle includes series hybrid electric vehicle, parallel hybrid electric vehicle and hybrid electric vehicle. Furthermore, according to the different clutch positions, parallel hybrid electric vehicles include different forms. Although there are many kinds of hybrid electric vehicles, their working principles are similar. In a word, the hybrid electric vehicle optimizes the power distribution between the engine to make the engine working in the high efficiency range.

Therefore, the energy management strategy of hybrid electric vehicle is the key to achieve energy saving and emission reduction[3]. A good energy management strategy can effectively allocate the required power, so as to achieve lower fuel consumption and lower pollutant emissions. The traditional energy management strategy only optimizes the demanded power under the current driving cycle. However, the performance of HEVs' energy management strategy is closely related to many factors, such as vehicle velocity, driver behavior, traffic information, etc. That means the future working conditions significantly influence the energy saving effect of hybrid electric vehicle under actual operating conditions. However, the traditional hybrid electric vehicle cannot achieve the prediction of the future working conditions and optimize the future driving speed[4].

With the development of intelligent transportation system, the performance of vehicles can be further improved. Using V2V communication, vehicles can exchange information such as speed, acceleration and expected trajectory with surrounding vehicles. The intelligent transportation system can make the vehicle interact with the traffic facilities. Taking the traffic light as an example, the vehicle can obtain the future state of traffic light in advance, so as to plan the velocity trajectory and reduce the low-speed driving condition.

Reference [5] shows that economic driving using traffic information in urban traffic environment is an important research field of Internet of things. In reference [6], a detailed practical test of economical driving is carried out, which proves the advantages of V2I communication in improving energy efficiency. Butakov et al. used V2I communication to obtain the time and position information of traffic lights, and proposed a driving speed optimization method[7]. The potential improvement in fuel efficiency is about 60% compared to driving at an un optimized driving speed. In a word, economic driving in connected environment is a relatively low-cost effective way to reduce fuel consumption and emissions [8].

In this paper, the Bi-level energy management strategy in connected environment is studied. The velocity trajectory of vehicle is optimized in upper controller, and the energy distribution strategies based on Rule and Genetic fuzzy algorithm are designed in the lower controller.

The structure of this paper is as follows. The second section introduces the speed trajectory planning of hybrid electric vehicle in the connected environment, and the speed trajectory in the non- connected environment is used for comparison. In the third section, the optimal power distribution between motor and engine of hybrid electric vehicle is studied. And the fuzzy logic control algorithm based on genetic algorithm is applied in the energy management strategy. The conclusion of this study is summarized in the fourth section.

II. Velocity Optimization

A. Velocity Range Caculation

In order to reduce fuel consumption in the process of driving, vehicles should be avoided to frequently start and stop as much as possible. To keep vehicles going under the green light in the intelligent traffic system, first of all, the speed range of the vehicle can be obtained based on the signal phase and timing. The upper speed limit and lower speed limit are shown in (1) and (2) respectively.

$$v_{up}(t)=\begin{cases} v_{\max} & case1 \\ \dfrac{d_a(t)}{kt_c-t} & case2 \\ \min\left(\dfrac{d_a(t)}{kt_c-t}, v_{\max}\right) & case3 \end{cases} \quad (1)$$

$$v_{low}(t)=\begin{cases} \dfrac{d_a(t)}{kt_c-t-t_y-t_r} & case1 \\ \dfrac{d_a(t)}{kt_c-t+t_g} & case2 \\ \min\left(\dfrac{d_a(t)}{kt_c-t+t_g}, v_{\max}\right) & case3 \end{cases} \quad (2)$$

$$\text{Signal Status}=\begin{cases} green & 0\le \text{mod}\left(\dfrac{t}{t_c}\right)<t_g \\ yellow & t_g\le \text{mod}\left(\dfrac{t}{t_c}\right)<t_g+t_y \\ red & t_g+t_y\le \text{mod}\left(\dfrac{t}{t_c}\right)<t_c \end{cases} \quad (3)$$

where, $v_{\max}$ is the maximum vehicle speed allowed, d_a is the distance between the vehicle and the traffic lights ahead, t_c is the cycle time of traffic light, k is the times of traffic light cycle, t is the current time. mod() is the remainder function. The vehicle path trajectory and some parameters are shown in Fig.1.

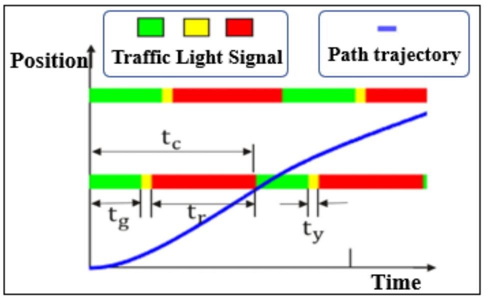

Fig 1. Vehicle path trajectory

Specially, case1 means that the traffic light status is green and $d_a(t)/(kt_c-t)<v_{\max}$, case2 stands that the traffic light status is green and the vehicle cannot pass at its maximum speed, case3 stand that the traffic light status is yellow or red.

B. Velocity Optimization Function

Under connected environment, the optimization function of vehicle acceleration planning takes fuel consumption, road patency and acceleration amplitude into account. The optimization function is shown as (4). The first objective is to optimize fuel economy, the driving force required in the driving process of the vehicle is replaced by the driving resistance，and the output power shown as (5) is obtained based on the longitudinal dynamic balance equation of the vehicle. The second one is to optimize the difference between the target speed and the maximum driving speed to improve the traffic fluency. The third one is to optimize the longitudinal acceleration range of the vehicle to improve ride comfort and fuel economy. $\omega_1,\omega_2,\omega_3$ are the optimization objective coefficients.

$$\text{Func}=\underset{a(t)}{\arg\min}\left\{\omega_1\frac{P(t)\Delta t}{\eta_{eff}}+\omega_2\left[v(t-1)+a(t)\Delta t-v_{up}(t)^2\right]^2+\omega_3 a(t)^2\right\} \quad (4)$$

$$P(t)=\frac{1}{2}\rho_a C_D A_f v(t)^3+Mgv(t)(f+\theta)+\beta v(t)Ma(t)-(1-\beta)\eta_{rec}v(t)Ma(t) \quad (5)$$

$$\begin{cases} \omega_1=100+50e^{0.04(v_{up}(t)-v_{low}(t))} \\ \omega_2=20+800e^{-0.07(v_{up}(t)-v_{low}(t))} \\ \omega_3=200+100e^{-0.1(v_{up}(t)-v_{low}(t))} \end{cases} \quad (6)$$

$$\beta=\begin{cases} 1 & driving \\ 0 & breaking \end{cases} \quad (7)$$

For comparison, the mathematical description of the change of vehicle driving acceleration in the non-connected environment is as follows. In non-connected environment. Within the field of vision, which d_{view} stands for, the driver can obtain the traffic signal information such as the current signal status and the remaining time of signal status switch, and make decisions on vehicle acceleration and deceleration based on the information. When the traffic lights are out of sight, the vehicles aim at the maximum permissible speed on the current road. If the speed reaches the maximum speed, the vehicles keep the uniform speed.

$$a(t)=\begin{cases} a_{\max}\left(v(t)<v_{\max}\right) & case1 \\ 0\left(v(t)=v_{\max}\right) & case2 \\ \min\left(0,-\dfrac{v(t)^2}{2d_a}\right) & case3 \end{cases} \tag{8}$$

where, case1 means the status that the traffic light ahead is out of the driver's vision field and the current vehicle velocity is below the maximum speed. Case2 occurs while the vehicle is running at maximum speed. Case3 stands for the case that the current distance between traffic light ahead and vehicle position is within the driver's vision field, meanwhile, traffic light status is green and vehicle cannot pass through traffic lights ahead while maintaining maximum speed or traffic light status is yellow or red.

C. Simulation Results

In this part, the initial vehicle velocity is set as 0m/s, and the maximum speed and the minimum speed allowed on roads are set to 20m/s and 0m/s, respectively. The simulation vehicle driving distance is 6 kilometers. In a traffic cycle time, the green light time is 20 seconds, the yellow light time is set as 2 seconds, and the red light time is 18s. The distances between adjacent traffic lights are set as 450m, 500m, 300m, 500m, 700m, 500m, 600m and 1000m, respectively. The simulation step time was 0.05s.

Based on the part B, vehicle acceleration planning under connected and non-connected environment are simulated in MATLAB with code form. The velocity trajectories shown as Fig.3 are obtained by integrating the acceleration. And the vehicle path trajectories are gained by integrating the velocity shown as Fig.2.

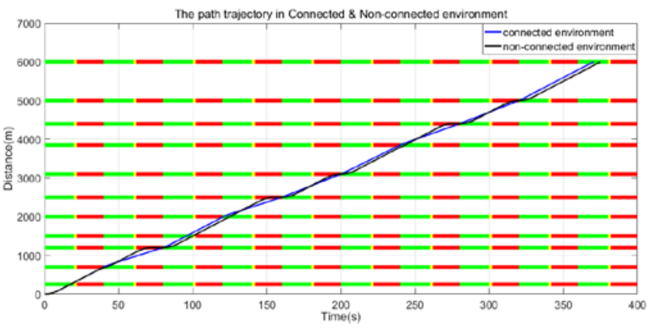

Fig 2. Vehicle simulation path trajectories

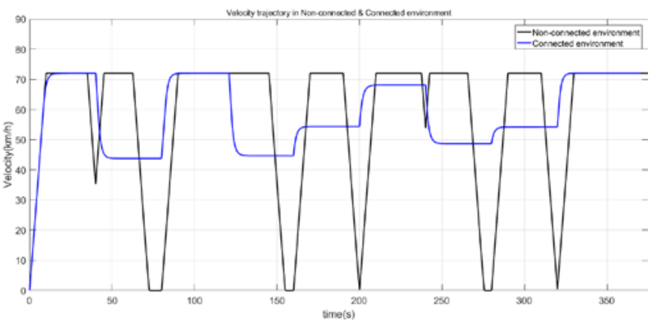

Fig 3. Vehicle velocity change under connected and non-connected environment

Fig.2 indicates that, under the connected environment, the vehicle passed through all the traffic lights without stopping，and did not run the red light. As seen from Fig.3, the velocity trajectory under the connected environment is more stable than that under the non-connected environment. The acceleration amplitude of the former is also smaller than that of the latter. The stable velocity contributes to improve the fuel economy and the ride comfort.

III. HEV ENERGY MANAGEMENT STRATEGY

A. Hybrid Electrical Vehicle Model

The parallel hybrid electric vehicle shown as Fig.4 is our study object. Specially, the vehicle model in Advanced Vehicle Simulator (ADVISOR) is adopted in this paper.

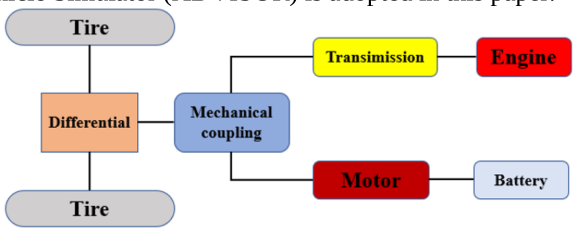

Fig 4. Hybrid electric vehicle structure

B. Fuzzy Logic Controller Based on Genetic Algorithm

When designing the fuzzy controller, it is necessary to make the engine working in the economic range as far as possible. Only when the motor output torque cannot meet the demand torque, or the battery SOC is too low, the engine will deviate from the economic range. In the process of vehicle driving, the engine should be kept in the efficient working range or in the stop state as far as possible, and the battery SOC value should be kept in a reasonable range. According to the above objectives, the fuzzy logic controller takes the vehicle demand torque T_req and battery SOC value as the inputs, and the engine demand torque T_eng as the output. The strategy based on fuzzy control is shown in Fig 5. The inputs and output membership function of fuzzy algorithm are shown in the Fig 6.

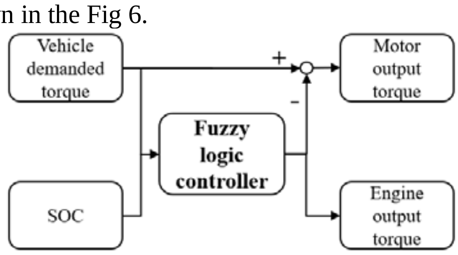

Fig 5. Strategy diagram based on fuzzy control

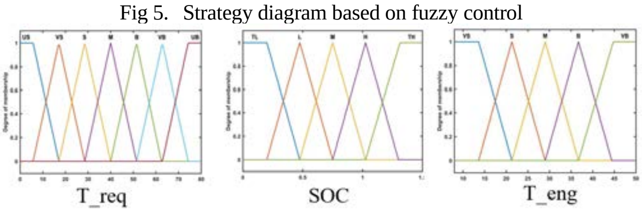

Fig 6. membership functions of fuzzy algorithm

Due to the characteristics of fuzzy control, the membership function of fuzzy controller based on expert experience cannot achieve its optimal control. Therefore, the genetic algorithm is used to optimize the membership function of fuzzy controller. The fuzzy controller optimized by genetic algorithm is applied to the energy management strategy of hybrid electric vehicle. The genetic algorithm is introduced in following part.

1. *Optimization method design*

Fig 7 shows the flow chart of fuzzy controller optimized by genetic algorithm. In the simulation process, the parameters of fuzzy controller are adjusted by the search function of genetic algorithm to obtain the optimal result.

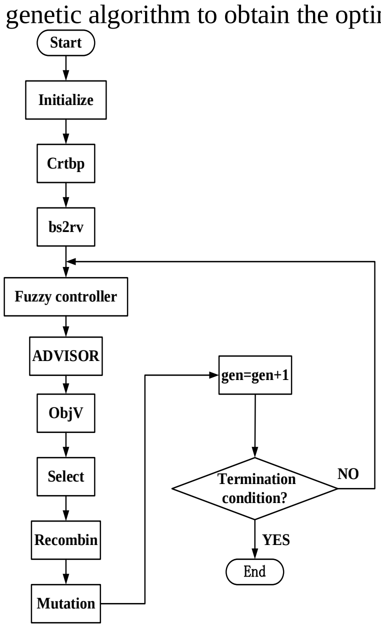

Fig 7 the flow chart genetic algorithm.

The parameter optimization of parallel HEV is a typical nonlinear constrained optimization problem, the specific formula is as follows:

$$\begin{cases} \min f(x) \\ \text{s.t. } g_i(x) \geq 0,\ i = 1,2,3\cdots\cdots m \\ x_j^{\min} \leq x_j \leq x_j^{\max},\ \ j = 1,2,3\cdots\cdots n \end{cases} \tag{9}$$

where, the objective function $f(x)$ is the fuel economy and emissions of hybrid electric vehicles. $g_i(x)$ represents the constraint conditions of vehicle dynamic performance index. x_j is the membership value of fuzzy controller, and its upper and lower limits are $[x_j^{\min},\ x_j^{\max}]$.

2. *Coding Membership Function Parameters*

The T_req input of fuzzy control is divided into seven levels(x1~x7), shown as Fig 8. Battery SOC is divided into five levels(x8~x12), and T_eng output of fuzzy control is divided into five levels(x13~x17). Thus, a one-dimensional matrix with a length of 17 is formed. At the same time, each partition point is represented by a 5-bit binary number, thus forming a 0-1 digit string with a length of 85. In genetic algorithm, the initial population is generated by random method.

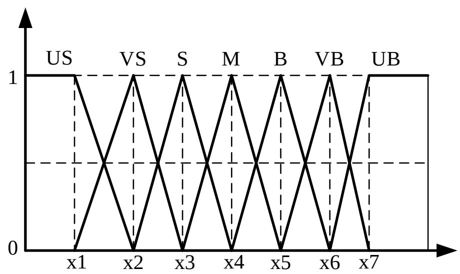

Fig 8 division of T_req membership function

3. *Fitness function selection*

In this paper, the fuel economy and emission (including HC, CO, NOx) of the vehicle are selected as the control objectives, and the multi-objective optimization function is established as follows:

$$ObjV\ \ (x) = \frac{\left(\begin{array}{l} w_1 \int_0^{T_{DC}} \frac{FC}{\overline{FC}} dt + w_2 \int_0^{T_{DC}} \frac{HC}{\overline{HC}} dt + \\ w_3 \int_0^{T_{DC}} \frac{NO_x}{\overline{NO_x}} dt + w_4 \int_0^{T_{DC}} \frac{CO}{\overline{CO}} dt \end{array} \right)}{w_1 + w_2 + w_3 + w_4} \tag{10}$$

where, FC、HC、NO_x、CO are the fuel consumption and emissions, respectively. $\overline{FC}$、$\overline{HC}$、$\overline{NO_x}$ 、$\overline{CO}$ are the ideal values of the object function. w_1、w_2、w_3、w_4 are the object weights of the objective function. T_{DC} is the whole simulation time.

4. *Operating parameter setting*

The parameters need to be set in genetic algorithm mainly include population size M, length of individual coding string L, crossover probability P_C, mutation probability P_M, termination evolution algebra n, etc., as shown in the following table:

TABLE I. TABLE OPERATING PARAMETER

Parameter	Value
Population size	60
Length	85
Crossover rate(*Pc*)	0.7
Mutation rate(*Pm*)	0.01
Number of generations	100

5. *Parameter Constraints*

In order to prevent the large fluctuation range of SOC value, the change rate of SOC is limited as follows:

$$\Delta SOC = SOC_{end} - SOC_{init} \leq 0.05$$

In the decoding of genetic algorithm, every variable cannot exceed the upper and lower limits of the corresponding membership function segment.

The membership function of fuzzy controller optimized by genetic algorithm is shown in Fig 9.

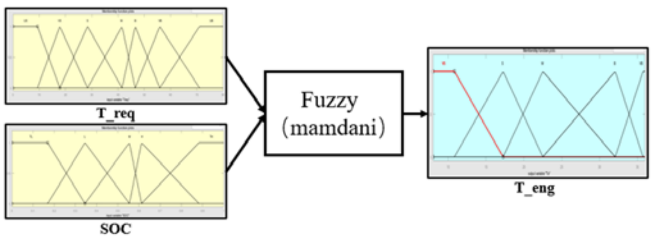

Fig 9. Fuzzy logic controller

C. Simulation Results

The vehicle speed trajectories in the connected environment and in the non-connected environment are obtained by simulation in the second part. This vehicle speed trajectories are regarded as the driving cycle of the vehicle model in advisor. In part III, the energy management strategy of fuzzy control algorithm optimized by genetic algorithm.

And the rule-based energy management strategy is compared with the algorithms used in this paper.

The initial SOC value is set as 0.7, and the Fig.10 indicates the change of SOC value during driving. The emissions including the HC，CO and NOx are represented in Fig.11. Table.2 shows the comparison of simulation results.

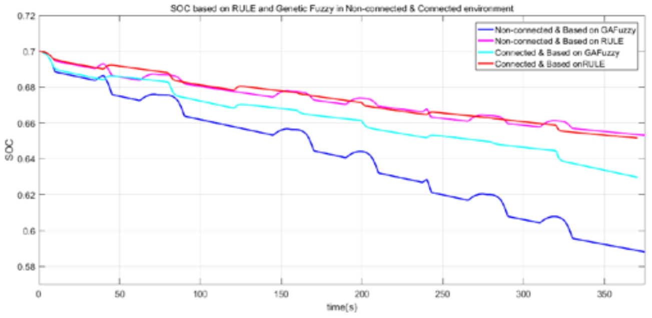

Fig 10. SOC change based on Rule and Genetic fuzzy

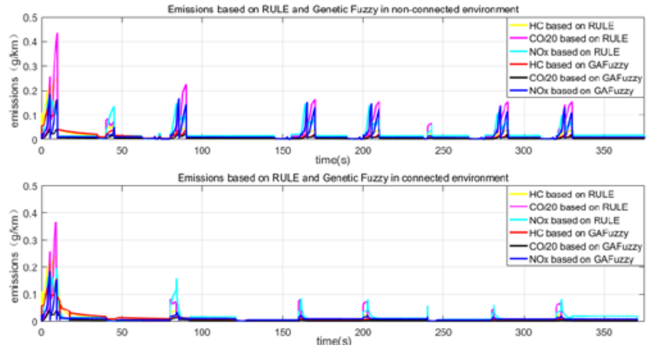

Fig 11. Emissions change based on Rule and Genetic fuzzy

TABLE II. COMPARISONS OF SIMULATION RESULTS

		FC (L/100km)	**HC (g/km)**	**CO (g/km)**	**NOx (g/km)**	**end SOC**
Non-connected environment	*Rule*	6.5	0.592	7.876	0.463	0.6532
	Fuzzy controller based on GA	4.3	0.518	2.554	0.384	0.5881
Connected environment	*Rule*	4.4	0.571	5.868	0.376	0.6516
	Fuzzy controller based on GA	3.8	0.51	2.491	0.279	0.6298

Shown as TABLE II, in non-connected environment, the fuel consumption and emissions of vehicle are 6.5L/100km, 0.592g/km, 7.876g/km, 0.463g/km under rule_based energy management strategy. The fuel consumption and emissions of vehicle are 4.3L/100km, 0.518g/km, 2.554g/km, 0.384g/km under the fuzzy logic controller of energy management strategy.

In connected environment, the fuel consumption and emissions of vehicle are 4.4L/100km, 0.571g/km, 5.868g/km, 0.376g/km under rule_based energy management strategy. The fuel consumption and emissions of vehicle are 3.8L/100km, 0.51g/km, 2.491g/km, 0.279g/km under the fuzzy logic controller of energy management strategy.

By comparing the data of fuel consumption and pollutant emission, it can be clearly seen that through optimizing vehicle velocity trajectory in connected environment, fuel consumption and pollutant emissions can be effectively reduced. Meanwhile, the case with same environment and different strategy demonstrate that, compared with Rule-based strategy, the Fuzzy controller optimized by Genetic algorithm contributes to realize the superior fuel economy performance and lower emissions.

IV. CONCLUSION

The energy management strategy of hybrid electric vehicles in connected environment is researched in this paper, and the Bi-level structure is adopted.

The upper controller aims to plan the vehicle acceleration and speed trajectory after obtaining the information of intelligent traffic system. The simulation results indicate that the velocity trajectory in connected environment can be more smooth compared with it in non-connected environment. Vehicles in the connected environment can avoid stopping at traffic lights as much as possible.

The lower controller is designed to follow the optimal acceleration and to save energy by optimizing the power split between the engine and motor. And the energy management strategy based on fuzzy logic controller optimized by genetic algorithm is adopted in this paper. The simulation result indicates that the energy management strategy in this paper shows a superior performance than the energy management strategy based on rule algorithm.

In general, in addition to studying more effective energy management strategies for hybrid electric vehicles, making full use of the development of intelligent transportation system can make vehicles achieve lower fuel consumption and less pollutant emissions.

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