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A real-time ICE on/off control strategy for hybrid electric bus based on route information prediction

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Abstract: Hybrid electric vehicle (HEV) has several driving modes including hybrid mode and motor-only mode. The motor-only mode would suffer from limited power and continuous electric energy consumption. The advantage of hybrid mode can compensate for the weakness of motor-only mode. However, the additional fuel consumption caused by frequent startup and shutdown of internal combustion engine (ICE) is extraordinary. ICE on/off control strategy optimization is still a critical problem. Hybrid electric bus's future drive trajectory was prior predicted by using the estimating algorithm on the available trip information. Minimum principle was used to research for a global optimum by evaluating the advantages between hybrid mode and motor-only mode. Experiments prove that the route-based control strategy for hybrid electric bus proposed in this paper has 18.0% fuel cut compared with control strategy without ICE off, which is similar to the dynamic programming (DP)-based control strategy and far exceeds the "Stop and go" control strategy.

Keywords: Hybrid electric bus; ICE on/off control; route-based control; DP-based control

1. Introduction

HEV has begun to be used in transportation due to its great fuel-saving potential. Different with conventional vehicle, the motor of HEV is connected to powertrain in order to assist ICE propelling vehicle. In an HEV, an idling ICE consumes significantly more energy than estimated by consumers. ICE on/off control strategy is determined based on the information such as state velocity and acceleration of HEV, SOC (state of charge) of battery, ICE on/off state, driver demands and so on [1]. Many methods are designed to minimum time intervals of switching ICE on and off state, in order to avoid frequently starting up ICE.

The thermostat control strategy [2-4] is proved to be robust, which can control the battery SOC in a preset SOC window, but cannot optimize the total efficiency of HEV. The Baseline control strategy or electric assist control strategy [5,6] is designed to avoid ICE operating with an inefficient low torque demand or low target speed. The threshold values of the low torque and low speed can be tuned by the genetic algorithm [7], and dynamic programming [8] at a given driving cycle. However, the driving condition that consists of frequent acceleration and deceleration especially in urban traffic will lead the ICE on and off state switching too frequently and unreasonably.

Some novel ICE on/off control strategies are presented to solve this problem mentioned above. Real-time control strategy is used to optimize ICE on/off state [9]. Real-time control strategy using the markov chain is defined by the preceding speed trajectory and estimation of the optimal variables is obtained by approximate dynamic programming [10]. Real-time control strategy is subjected to

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complex calculation and requires a large memory controller [11]. Therefore, It`s necessary to propose a real-time control strategy to overcome those drawbacks.

The remainder of this paper is organized as follows. DP-based control strategy is proposed as a real-time control strategy for comparison in Section 2. Section 3 presents a real-time ICE on/off control strategy based on route information prediction. Then, the results have been obtained from experiment in Section 4. Finally, some final remarks about this paper are given in Section 5. Before ending this introductory section, it is worth mentioning the main contributions of this paper as follows:

(1) The proposed route-based control strategy significantly improves the fuel economy, which is better than the conventional control strategy such as "Stop and go" control strategy, and close to the typical real-time control strategy such as DP- Based control.

(2) The route-based control strategy can be implemented in real time. There are no complex calculations in real-time control state and does not require a large information processing and computational chip for route-based control strategy, which is better than DP-based control.

2. DP-based control strategy

The $\Delta E_{on/off}(t)$ indicates fuel energy consumption for turning on the ICE and it is far greater than instantaneous energy consumption. This parameter which is added to Hamiltonian reflects a significant effect on ICE on/off control.

$$H(t) = P_f(t) + \lambda_1 * P_{bp}(t) + \Delta E_{on/off}(t) \tag{1}$$

From Eq. (1), a shutdown ICE would not tends to restart unless λ_1 at an unreasonable value. Therefore, Real-time optimization of ICE on/off state is very difficult. DP is utilized from global perspective to resolve the problem. DP is based on the Bellman–Dreyfus principle [12] of optimality [13, 14]. N is a multi-stage optimal policy for the discrete-time deterministic dynamic optimization problem which minimizes the cost H function. The optimization problem is to find the control input *u(k)* to minimize the following cost function:

$$J = \sum_{k=0}^{N-1} L[x(k),u(k)] = \sum_{k=0}^{N-1} [P_{fuel}(k) + \lambda P_{bp}(k) + \Delta E_{on/off}(k)] \tag{2}$$

A linear regression is then used to calculate the final fuel economy corresponding to the zero SOC change over the cycle. The optimal control trajectory can be gotten.

$$\left\{u_1^*(S,P_{ice}), u_2^*(S,P_{ice}), \cdots, u_N^*(S,P_{ice})\right\} = \arg\min\left(\sum_{k=1}^{N} [P_{fuel}(k) + \lambda P_{bp}(k) + \Delta E_{on/off}(k)]\right) \tag{3}$$

Where $u_1^*(S,P_{ice}), u_2^*(S,P_{ice}), \cdots, u_N^*(S,P_{ice})$ are the optimal decisions or control variables at discrete times.

Take one driving cycle as an example, the optimal results are shown in Fig.1 and Fig.2. When ICE is on, the power-split is optimal to minimize Hamiltonian value. As shown in Fig.1, the blue line is the velocity and the red line is the optimal ICE state, if the value of the red line equals to zero, it indicates ICE off, otherwise indicates ICE on. The ICE is on when the bus starts to move and ICE is off under the deceleration condition in most situations. However, in some locations, such as A and B in Fig.1, the ICE is also off while driving. So other factors' affection of ICE on/off should be considered.

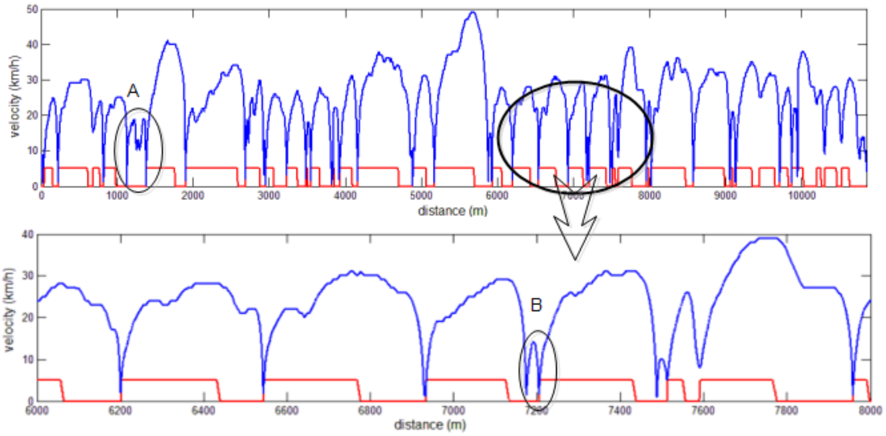

Fig.1. Optimal ICE on/off control at driving cycle

The Fig.2 shows the relation between Hamiltonian value and ICE optimal on/off status along the bus trip. Large Hamiltonian values appear when ICE is on. This phenomenon is in accordance with the Fig.5. It indicates that the Hamiltonian mean value is bigger than appropriate threshold value in a period of time

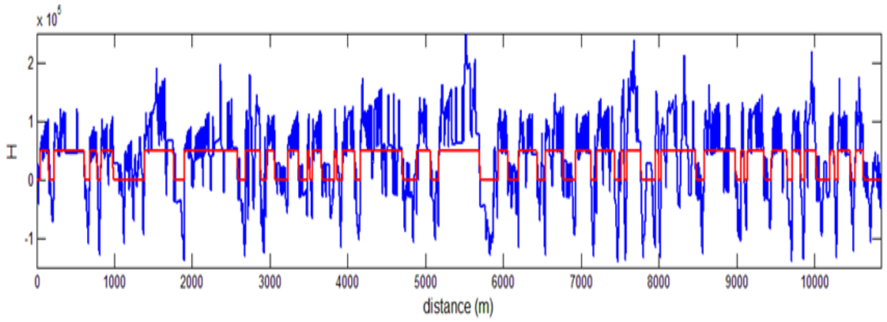

Fig.2. Relationship between Hamiltonian value and ICE optimal on/off

3. Route-based control strategy

3.1 Speed trajectory estimation

The driving trajectory detection algorithm which is derived from collected real vehicle speed data. The data information is obtained from a global position system (GPS), which is installed in vehicle to determine the geographical positions of the observed road information. Fig.3 shows a section of driving trajectory of the line 1 in Suzhou, China. Four measurements were taken randomly on a hybrid electric bus driving along a certain bus line. There are several road segments with similar speed trajectory, especially at vehicle shop and start situation. The deviation of speed between two stops is mainly caused by congestion level and traffic light. As the stored route information gradually increases, the traffic flow pattern differences at different times in a day and different days in a week can be detected. In order to get more precise driving trajectories, the driving data can be classified into different periods as well. Therefore, vehicle speed trajectory prediction is available.

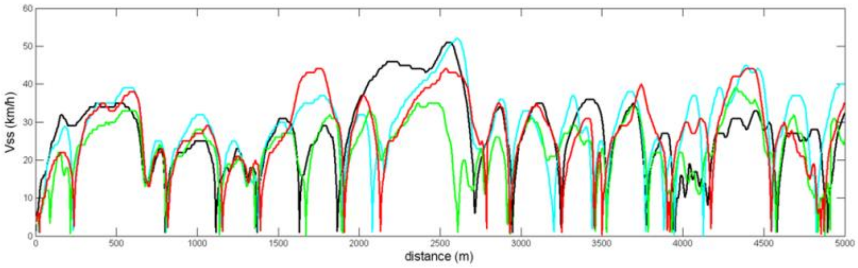

Fig.3. Bus route speed trajectory

A bus trip is defined as a driving path from an origin to a destination. The driving trajectory along a bus trip is associated with road information such as segment length, slope, speed limit, traffic flow and bus stops distribution. The uncertainty of instantaneous traffic flow can be modeled as a particular statistical distribution and can be considered to be stochastic disturbances in the trip model [15,16]. For a segment between two stops, constant acceleration rate a_a and deceleration rate a_b are assumed as mean values during past-period driving process, the max speed level can be seemed as the maximum speed V_{max}.

$$L = \int_0^{t_1} v dt + \int_{t_1}^{t_2} v dt + \int_{t_2}^{t_3} v dt \tag{4}$$

Where, $t_1, t_2 - t_1$ and $t_3 - t_2$ refer to the acceleration region, the constant speed region, and the deceleration region.

Fig. 4(a) shows the case of a long segment where the speed is limited while Fig. 4(b) shows the case of a short segment where the vehicle cannot reach the speed limit. The overall speed profile for a single segment can be obtained by solving Eq. (5):

$$L = \frac{1}{2} \cdot \left(\frac{V_{\max} - V_0}{a_a} \right)^2 * a_a + V_{\max} \cdot t + \frac{1}{2} \cdot \left(\frac{V_{\max} - 0}{a_b} \right)^2 * a_b \tag{5}$$

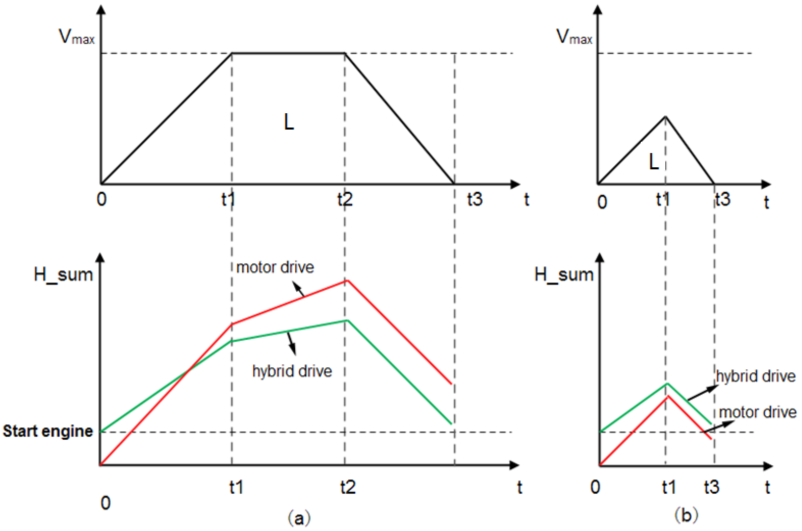

Fig.4. Comparison of Hamiltonian under the hybrid mode and motor-only mode at different distance

3.2 ICE on/off state optimization

ICE has two states in vehicle driving, which is shown in Eq. (6). S is the Boolean variable to determine the fuel consumption. When clutch is in the coupling position, it means ICE output power $P_{f,out}$ is delivered to power-train.

$$P_f(S(t), P_{ice}(t)) = \begin{cases} 0 & S(t) = 0 \\ P_{f,out}(w_{ICE}(t), T_{ICE}(t)) & S(t) = 1 \end{cases} \tag{6}$$

Where w, T indicate speed and torque respectively.

When S=0, ICE is not working. There is no need for optimization, since there are no degrees of freedom. When S=1, ICE outputs torque to powertrain. There are several free degrees that need to be selected. This situation makes the optimization of ICE state control more complex. Battery power flows as shown in Eq. (7).

$$\dot{E}_{bp}(t) = P_{bp}(T_{dm}(t), w_{dm}(t), SOC(t)) \tag{7}$$

Where, E_{bp} indicates the energy stored in the battery pack, P_{bp} is the battery power.

The SOC can be expressed as:

$$SOC(t+1) = SOC(t) - \frac{I(P_{bp}(t))}{Q_{bp}} \tag{8}$$

Where, I indicates current, Q_{bp} indicates nominal capacity.

Considering battery aging and charge/discharge energy loss, SOC remains in a reasonable range.

$$SOC(N) - SOC(t) < \xi \tag{9}$$

The optimization process is based on PMP, and more details can be seen in ref [17]. λ is the weighting factor. Hamiltonian function is given by:

$$H(\lambda(t+1), SOC(t), P_{ice}(t), P_{dem}(t), w(t)) = P_f(S(t), P_{ice}(t)) + \lambda(t+1)P_{bp}(P_{dm}(t), SOC(t)) \tag{10}$$

$$\frac{\partial H(\cdot)}{\partial \lambda(t+1)} = SOC(t+1) \tag{11}$$

$$\frac{\partial H(\cdot)}{\partial SOC(t)} = \lambda(t) \Leftrightarrow \lambda(t+1) = \lambda(t) \tag{12}$$

It is clearly that $\lambda(t)$ is a constant that can ensure minimize Hamiltonian at the whole driving cycle. If λ_0 is given, the decision variables are numerically calculated to minimize Hamiltonian at the sample time.

$$P^*_{dm}(t) = \arg\min(P_f(t) + \lambda_0 * P_{bp}(t)) \tag{13}$$

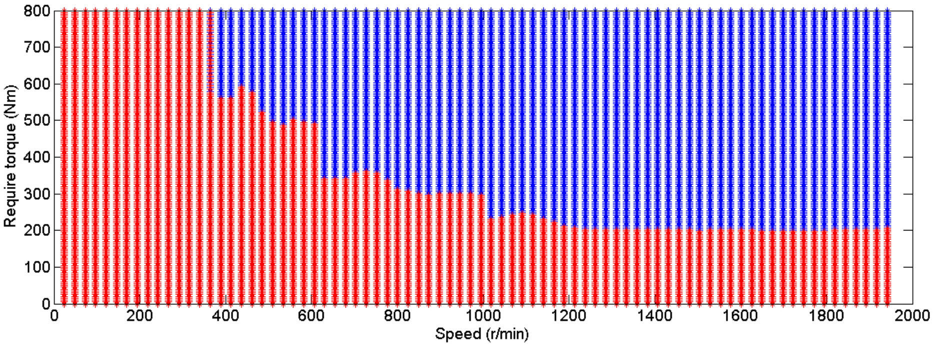

Fig.5. Decision on ICE on/off at given speed and require torque on wheel

Considering ICE has two states, combining Eq. (6) and (13), different control variable S leads to two results respectively. The comparison of H value under different rotate speeds and torques is shown in Fig.5, blue indicates ICE on, red indicates ICE off. It is an example of taking λ_0 equal to 1.9. ICE needs injecting fuel to produce torque to overcome friction. Under the low torque request condition, motor-only mode has better efficiency. The hybrid mode is more suitable for higher torque request condition.

The ICE state control strategy is designed by optimizing approximated future drive scenarios. The expected minimum sum of H value and switching ICE state is approximated by a route section optimization process. The equivalence factor is kept constant over the prediction section.

The vehicle output power can be expressed as

$$P_{drive} = P_{acc} + P_{friction} \tag{14}$$

Where, P_{acc} is the power for vehicle acceleration, P_{drive} is the powertrain output power, and $P_{friction}$ is vehicle resistance which is increased along with vehicle speed.

The drive power is determined by vehicle acceleration condition and vehicle velocity. The vehicle on free travel time means the fast acceleration and more drive power is required to support vehicle in high speed for a long time. As shown in the Fig. 5, hybrid mode has low cost function at high output power. In despite of, H value of ICE starting is overwhelmingly higher than the difference between hybrid mode and motor-only mode. The continued benefit of hybrid mode outweighs that of motor-only mode in long term. In other word, if integration of H value is higher than the H value of ICE start, ICE off switch to on state have more advantages for fuel saving.

We can also conclude from the Fig.4(a) that hybrid mode of ICE switches from off to on is more suitable for the higher power demand. In contrast, when traffic jams occur, vehicle hybrid mode would lead to increase fuel consumption, as show on the Fig.4(b). Thus for every road segment, cost function minimum can be expressed as:

$$J_{ICE\_state}^{opt} = \min\left\{ \sum_{k=t_0}^{t_2} [P_{fuel}(k) + \lambda P_{bp}(k) + \Delta E_{on/off}(k)], \sum_{k=t_0}^{t_2} [\lambda P_{bp}(k)] \right\} \tag{15}$$

Therefore, the rules of ICE state is determining from off state to on state is affected by the drive distance and max vehicle speed, it can be expressed as

$$S_{off\_on} = g(v_{\max}, L) \tag{16}$$

Where, v_{max} is determined by road type and also affected by traffic congestion level, and the L is determined by bus stop which determines the duration of accelerate time.

ICE state from on to off does not consume fuel and battery energy. However, inappropriate control strategy would make ICE on/off switching frequently. The running vehicle has more complex traffic condition, especially at crossroad and traffic lights. The dynamic control schedule is designed to optimize ICE on/off state. Because of minimum cost function is incline to motor-only mode at low torque demand, future low output torque scenarios is identified. Assuming the acceleration and deceleration is constant, the energy required to propel vehicle to another bus stop is expressed as:

$$E = \frac{1}{2} m * (V^2_{target} - V^2_{current}) = (T_r / r - f) * T' \tag{17}$$

The mean T_r level can be expressed as:

$$\overline{T}_d = \frac{1}{2}(m*(V^2{}_{target} - V^2{}_{current}) / S' + f)*r \tag{18}$$

Where, $V_{current}$ indicates the bus driving velocity collected by sensors. V_{target} indicates the scheduled end location of three region of acceleration, speed constant, deceleration. f is the friction on vehicle wheel, can be estimated by empirical formula. T_r is the require torque on the wheel, r is the radius of wheel. T' indicates the distance between bus current position and next bus stop.

The $\overline{T}_d$ is related to the output torque and the gear selection. At a given $V_{current}$ and T_r, if the ICE keeps running at high rotate speed, the vehicle is apt to use motor individually, or vice versa. Usually. The gear selection is based on driver's habits. And if the gear selection is established, the ICE on/off decision also can be established. If $\overline{T}_d$ is lower than the limit threshold, the ICE is shutdown, otherwise $\overline{T}_d$ is higher than the threshold, the ICE starts up. Besides, the duration and $\overline{T}_d$ also make a trade-off to avoid frequent ICE on/off.

From states found by trip-modeling estimation, a set of decision rules can be established. Based on discussed above, the ideal region of ICE on/off is estimated. The position of bus got by GPS is a feedback signal when the vehicle is driving. The public bus driving process can be summarized as below: the bus leaves a bus stop and drives towards another, during the acceleration process ICE needs to start up to provide power to propel bus. When the bus arrives at the next bus stop, ICE can be off due to required power is low for a long time.

4. Experiment

4.1 Experiment setup

Experiments are carried out on experiment bench with electric dynamometer in FAW Jiefang Automotive CO. Wuxi diesel ICE works. The purpose is to compare results of the ICE on/off control between route-based and conventional control scheme. An overview of the setup is shown in Fig 6, the dynamometer realizes the vehicle operating environment, coordinating the speed of hybrid power-train at each moment. Operating environment and cool water temperature of hybrid electric system are set in the fixed range.

Based on a given driving cycle, assuming the stops are already known and calculated in advance. The position of vehicle driving is a feedback variable which is used to predict the $\overline{T}_r$ level. The $V^2_{cureent}$ is zero at stops. The Eq. (4) can be expressed as:

$$\overline{T}_r = (-\frac{1}{2}m*V^2{}_{current} / S' + f)*r \tag{19}$$

The f is the resistant, and can be expressed as:

$$f = c_0 mg\cos\alpha + mg\sin\alpha + c_1 * V_{current} + c_2 V^2{}_{current} \tag{20}$$

Where, c_0 is the coefficient for rolling resistance, α is the road slope, m is the vehicle mass, c_1 is the resistance proportional to the vehicle $V_{current}$ and c_2 is the aerodynamic coefficient.

Considering that $m \gg c_1$, $m \gg c_2$, in order to connect current velocity $V_{current}$ and drive distance S', c_1 and c_2 are neglected, and α is set to zero, Eq. (14) can be simplified to $f = c_0 mg$.

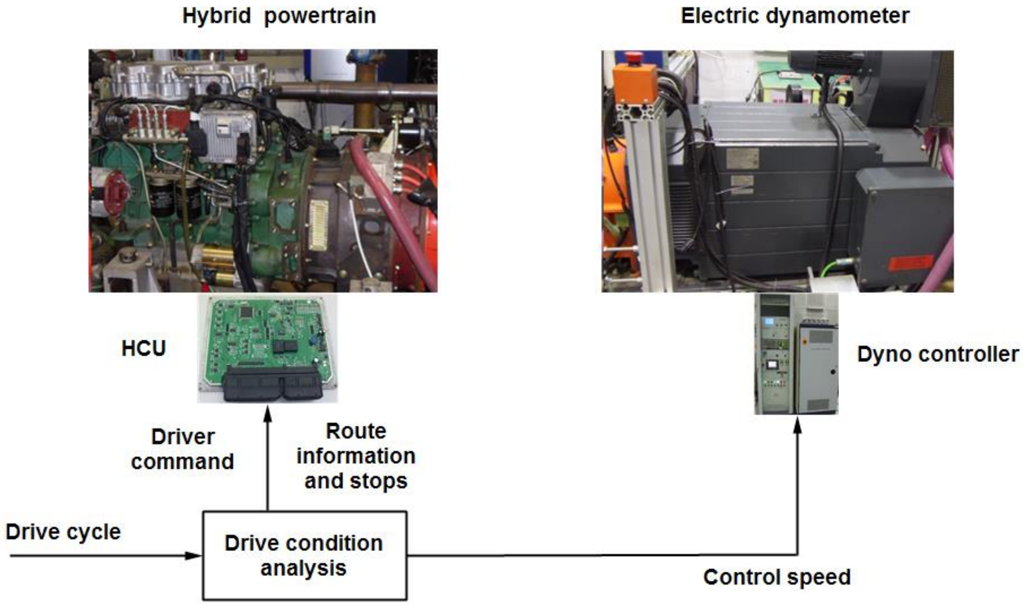

Fig.6. Overview of experiment set up

4.2 Experiment results

The fuel consumption results are compared with different control strategies. The power-split is based on minimum principle, in order to make contrasted the fuel consumption with other different control strategies, the deviation of SOC between starting and ending is set to zero through tuning the equivalence factor λ. Four different ICE on/off control strategies are evaluated:

(1) Control strategy without ICE off, keeping the ICE on all the time.

(2) “Stop and go” control strategy, ICE off at the bus station, where the vehicle will be standby

(3) Route-based control strategy ICE on/off control based on route information prediction

(4) DP-based control strategy, ICE on/off states are optimized in advance.

The ICE on/off control results of different control strategies are shown in Fig.7.to Fig.9. DP-based control and route-based control have similar ICE off trajectory, ICE is on at acceleration process and constant speed driving. The ICE is off at short micro-trip and deceleration process, which is more often than that in “Stop and go” control strategy.

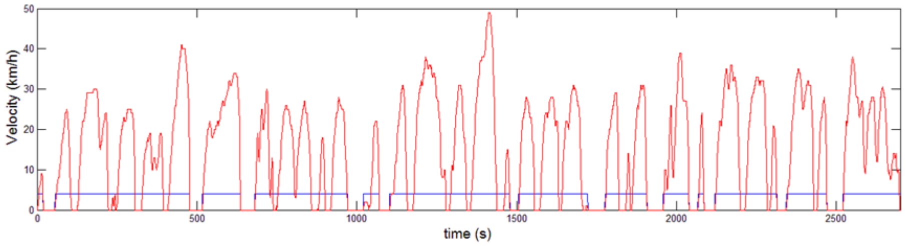

Fig.7. ICE on/off control results based on “stop and go” control strategy

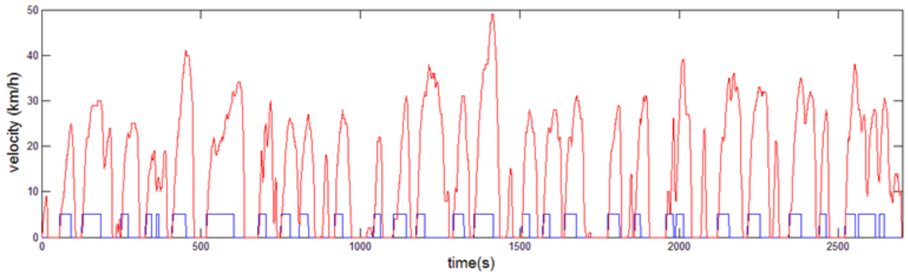

Fig.8. ICE on/off control results based on route-based control strategy

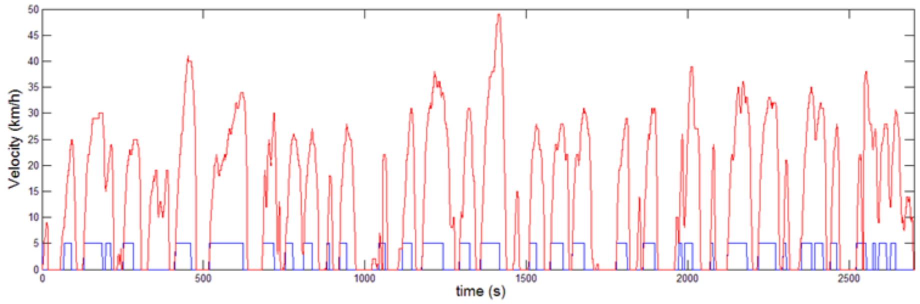

Fig.9. ICE on/off control results based on DP-based control strategy

The fuel consumption is presented for powertrain on the studied route in Table.1. The results are average value of 10 randomly picked trajectories along each bus route. It is seen that the route-based control strategy and DP-based control strategy are better than the control strategy without ICE off, with significant fuel savings. Compared with control strategy without ICE off, the "stop and go" strategy has 4.2% fuel cut, route-based control strategy has 18.0% fuel cut and DP-based control strategy has 18.8% fuel cut. Route-based control strategy has the biggest equivalent factor which determines power-split between ICE and motor. It means that route-based control strategy use more ICE power to propel vehicle when ICE is on.

Table.1. Compare results of control strategies

	Control without ICE off	Control with ICE off	Route-based control	DP-based control
Duration of ICE off (s)	0	447	1723	1616
ICE off times	0	12	30	34
Fuel consumption(L/100km)	22.22	21.29	18.23	18.04
equivalent factor λ	1.685	1.685	1.905	1.745

5. Conclusion

This paper proposes a novel real-time ICE on/off control strategy based on route information prediction. The route-based control strategy is established from analyze driving characteristic on bus trip, and gets the optimal region of hybrid mode and motor-only mode by comparing the Hamiltonian value based on minimum principle. The important conclusions we have obtained are as follows:

It is seen that the route-based control strategy and DP-based control strategy are better than the control strategy without ICE off and "Stop and go" control strategy, with significant fuel savings. Compared with control strategy without ICE off, the "Stop and go" control strategy has 4.2% fuel cut. However, the "Stop and go" control strategy is not ideal for reducing energy consumption. This is related to the “Stop and go” control strategy based on fixed rules and cannot adapt to changes in different working conditions.

Compared with control strategy without ICE off, the route-based control strategy has 18.0% fuel cut and DP-based control strategy has 18.8% fuel cut. Route-based control strategy has the biggest equivalent factor which determines power-split between ICE and motor. It means that route-based control strategy use more ICE power to propel vehicle when ICE is on. However, the long duration of ICE off time results in less of fuel consumption, which leads to a slightly better fuel economy of the DP-based control strategy than the route-based control strategy.

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