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A RULE-BASED ENERGY MANAGEMENT STRATEGY FOR NEW ACHITECTURE PHEB

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ABSTRACT

Plug-in hybrid electric bus (PHEB) have more potential fuel efficiency than traditional hybrid electric vehicle (HEV) [1]. For rule-based energy management, the fuel consumption can be significantly influenced by vehicle architectures and driving condition. Firstly, a specific PHEB transmission configuration utilizing two planetary gear sets was determined for urban road conditions, and different driving modes have been divided by controlling the clutch state. A PHEB model is built by MATLAB/Simulink in accordance with rule-based strategy characterized as a flow chart. Simulation results on china city bus cycle (CCBC) show that fuel economy (13.90 L/100km) still have room for improvement compared with dynamic programming (DP) based energy management strategy (EMS).

Keywords: plug-in hybrid electric bus, energy management strategy, power-split system, State flow, fuel economy

NONMENCLATURE

Abbreviations	
SOC	State of charge
PHEB	Plug-in hybrid electric bus
EMS	Energy management strategy
CCBC	China city bus cycle
DP	Dynamic programming
E1	Electric machine 1
E2	Electric machine 2
ICE	internal combustion engine
PGS	Planetary gear set
R1	Ring gear of the PGS I
C1	Carrier of the PGS I
S1	Sun gear of PGS I
R2	Ring gear of the PGS II
C2	Carrier of the PGS II
S2	Sun gear of PGS II
PI	Proportional-Integral
HEV	Hybrid electric vehicle
EV	Electric vehicle
THS	The Toyota Hybrid System
Symbols	
ω	The rotation speed
M	The torque
k_1	The Characteristic parameter of PGS I
k_2	The Characteristic parameter of PGS II
J	The inertia

1. INTRODUCTION

HEVs are proven to improve vehicle fuel economy and reduce emissions significantly while meeting vehicle power demand and making the driving experience comfortable [1]. The stringent global emission regulations and the year-on-year decline in oil reserves has made it urgent to improve vehicle fuel economy. PHEBs have many advantages over traditional buses. One advantage is that PHEB minimize the size of the internal combustion engine (ICE) while satisfying the vehicle power demand owing to the ability of the power coupling mechanism to couple the power of the engine and the motor. Also, the introduction of the electric system makes it possible for the braking kinetic energy recovery, which is completely lost in the mechanical braking [2,5].

PHEBs' fuel economy is largely influenced by its architecture. A new architecture with two planetary gear sets was developed, in which the first planetary gear set plays a vital role in power split and the other one provides a dual-mode for PHEB.

As an another key technology for HEVs, EMS decided the performance of the vehicle after the architecture was determined.

Compared with traditional HEVs, PHEBs have longer pure electric driving range, reducing engine utilization and dependence on fossil fuels to cut down harmful and greenhouse gas emissions. Compared with electric vehicles (EVs), PHEVs have lower battery cost and eliminate the "low battery anxiety" through self-charging with engine or power grid.

On the one hand, plug-in hybrid buses can meet the driving cycle of the city's buses, and specify rule-based EMS for specific bus routes to improve overall fuel economy. On the other hand, the presence of engines makes long -trips between cities possible. PHEBs are well combined with the low fuel consumption of conventional HEVs and the low pollution of EVs.

2. DUAL-MODE PHEB TRANSMISSION MODEL

The simplified diagram of the power-split PHEB is shown in Fig 1. The dual-mode transmission contains: ICE (with buffer lock), Electric machine 1 (E1), Electric machine 2 (E2), two PGSs, brake B1, brake B2 and clutch C1. ICE can transmit torque to the carrier of the power-split PGS (C1) through buffer lock. E1 works as brake B2 is engaged which is connected with the sun gear of the power-split PGS (S1). E2 transmits power to S2 when the clutch C1 is disengaged, otherwise the power applied to the output shaft of the PGS II directly with brake B1 disengaged. Also the ring gear R1 is connected with the carrier C2, which is the output of the transmission.

When buffer lock and brake B1 is engaged, and disengaging brake B2 and clutch C1, dual-mode transmission is in EVT I mode (urban mode). And the power flow is shown in Fig 1(a), where the direction of the arrow represents the direction of the power flow.

When disengaging clutch C1 and engaging brake B2, dual-mode transmission is in EVT II mode (direct gear). E1 and E2 work as a generator and a motor in both EVT modes.

2.1 Static model

It can be obtained from the schematic diagram of the coupling mechanism system that there are two planetary gear sets (PGSs). The engine and motor E1 can be locked to the ground. There are two modes in the planetary gear set II by switching brake B1 and clutch C1. In both PGS, the equations for the rotation speed and torque relationships can be obtained as follows:

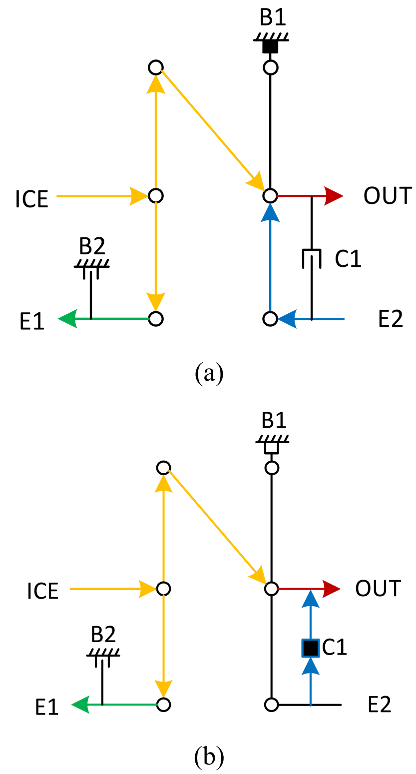

Fig 1 dual-mode transmission power flow

$$\begin{pmatrix}\omega_{e1}\\ \omega_{e2}\end{pmatrix}=\begin{bmatrix}1+k_1 & -k_1\\ 0 & 1+k_2\end{bmatrix}\begin{pmatrix}\omega_e\\ \omega_o\end{pmatrix} \quad (1)$$

where brake B1 is disengaged and clutch C1 is engaged, the vehicle is in urban mode.

$$\begin{pmatrix}\omega_{e1}\\ \omega_{e2}\end{pmatrix}=\begin{bmatrix}1+k_1 & -k_1\\ 0 & 1\end{bmatrix}\begin{pmatrix}\omega_e\\ \omega_o\end{pmatrix} \quad (2)$$

where brake B1 is engaged and clutch C1 is disengaged, the motor E2 works in direct gear.

the equations for the torque relationships can be obtained as follows:

$$\begin{pmatrix}M_{e1}\\ M_{e2}\end{pmatrix}=\begin{bmatrix}-\frac{1}{1+k_1} & 0\\ -\frac{k_1}{(1+k_1)(1+k_2)} & \frac{1}{1+k_2}\end{bmatrix}\begin{pmatrix}M_e\\ M_o\end{pmatrix} \quad (3)$$

$$\begin{pmatrix}M_{e1}\\ M_{e2}\end{pmatrix}=\begin{bmatrix}-\frac{1}{1+k_1} & 0\\ -\frac{k_1}{1+k_1} & 1\end{bmatrix}\begin{pmatrix}M_e\\ M_o\end{pmatrix} \quad (4)$$

where M_e, M_{e1} and M_{e2} are the torques of the engine, E1 and E2. Where M_o is the required torque at the output side of the coupling mechanism.

From the speed matrix equations below, we can control the speed of E1 to push the engine to the target speed. And then, using the speed PI and throttle to control the engine to work in the high efficiency zone. After knowing the engine torque, we can control the torque of E2 to satisfy the required torque at the output side.

2.2 *Dynamic model*

The inertias of the engine, E1, E2 and vehicle are converted to the equivalent inertias, when the power components connect with two planetary gear sets [4].

$$\begin{cases} J_{S1}\dfrac{d\omega_{s1}}{dt} = M_{e1} - M_{s1} \\ J_{out}\dfrac{d\omega_{r1}}{dt} = M_{r1} - M_{c2} - M_f \\ J_{C1}\dfrac{d\omega_{c1}}{dt} = M_e - M_{c1} \\ J_{S2}\dfrac{d\omega_{s2}}{dt} = M_{e2} - M_{s2} \end{cases} \quad (5)$$

where J_{S1} is the equivalent inertia of the engine and S1, J_{C1} is the equivalent inertia of E1 and C1, J_{S2} is the equivalent inertia of E1 and S2, J_{out} is the equivalent inertia of vehicle, R1 and C2.

$$\begin{cases} J_{S1}\dfrac{d\omega_{s1}}{dt} = M_{e1} - M_{s1} \\ J_{out}\dfrac{d\omega_{r1}}{dt} = M_{r1} + M_{e2} - M_f \\ J_{C1}\dfrac{d\omega_{c1}}{dt} = M_e - M_{c1} \end{cases} \quad (6)$$

where J_{S1} is the equivalent inertia of the engine and S1, J_{C1} is the equivalent inertia of E1 and C1, J_{out} is the equivalent inertia of vehicle, R1 and the second planetary gear set.

3. RULE-BASED ENERGY MANAGEMENT

3.1 *Speed division*

For this PHEB, there are two different driving conditions, medium-low speed urban condition and medium-high speed intercity condition.

When the battery is in the normal state, PHEB always starts in pure electric mode and continues to drive in pure electric mode in urban and CD mode condition. When the battery enters CS mode, the vehicle is under EVT mode to maintain battery power. When the vehicle speed is high, the motor E2 is in intercity mode, and assisting the engine to drive the vehicle.

3.2 *SOC division*

Divided by the power battery state of charge (SOC), three SOC thresholds are set [3]: $\mathrm{SOC_{high}}$ is the upper limit of the power battery, set to 0.95; $\mathrm{SOC_{mid}}$ is the target value of the power battery, set to 0.40; $\mathrm{SOC_{low}}$ is the lower limit of the power battery, set to 0.30. When the SOC is between $\mathrm{SOC_{high}}$ and $\mathrm{SOC_{mid}}$, the battery is in charge depleting mode (CD); when the SOC is between $\mathrm{SOC_{mid}}$ and $\mathrm{SOC_{low}}$, the battery is in the battery maintenance mode (Charge sustaining, CS).

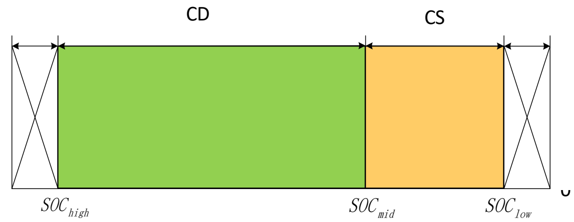

Fig 2 CD-CS

3.3 *Mode switching*

The vehicle mode switching is divided into three parts: drive mode, brake mode and parking mode. The state in each mode is decided by the vehicle speed, the engine working area, and the power battery SOC. The state switching conditions are characterized by these parameters, which is shown in Fig 3.

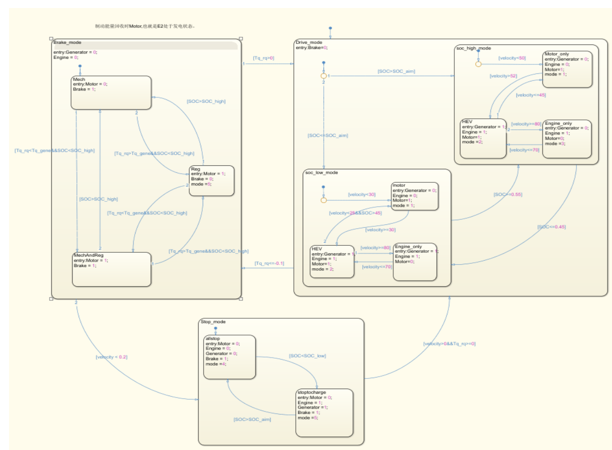

Fig 3 Mode switching state flow

4. EXPERIMENTS

4.1 *Model build-up*

The PHEB model is built in MATLAB/Simulink, and the plug-in hybrid bus model is divided into six subsystems, including: driver model, power battery model, motor model, internal combustion engine (ICE) model, mechanical transmission system model and vehicle dynamics model.

Table 1 Model parameters

Vehicle parameters	Value
Gross vehicle weight	16500 kg
Cross section	7 m^2
Rolling resistance coefficient	0.0063
Air resistance coefficient	0.65
ICE power	147 kW/2100 rpm
E1 power	86 kW/2500 rpm
E2 power	136 kW/2000 rpm
Battery capacity	60 Ah

Verifying the rule-based EMS and vehicle performance under the China City Bus Cycle (CCBC) which is shown in Fig 2, preparing for the subsequent hardware-in-the-loop (HIL) experiment.

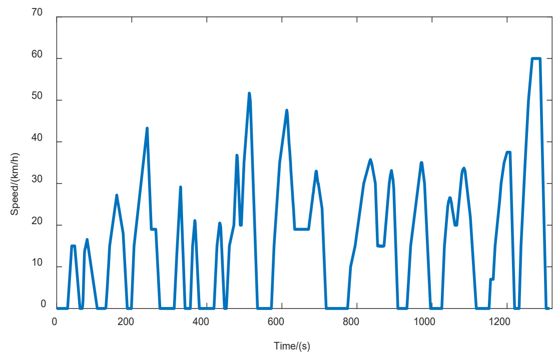

Fig 4 CCBC

4.2 Results

The SOC curves of rule-based EMS have been displayed in Fig 5. In CD mode, we can get that the battery charge is reduced gradually under pure electric mode. In CS mode, battery capacity can sustain around the target SOC under EVT mode. The fuel consumption under rule-based and DP EMS are shown in Table 1. And the weighting fuel consumption is calculated.

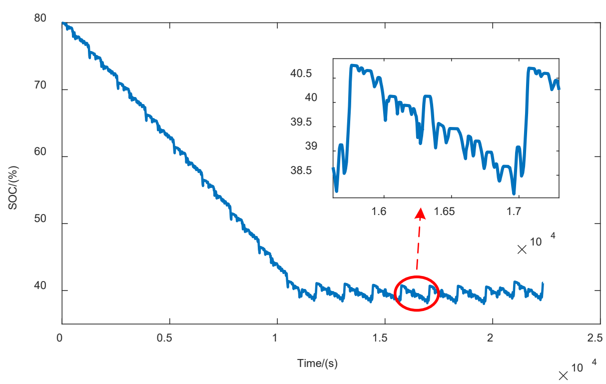

Fig 5 SOC curve under rule-based EMS

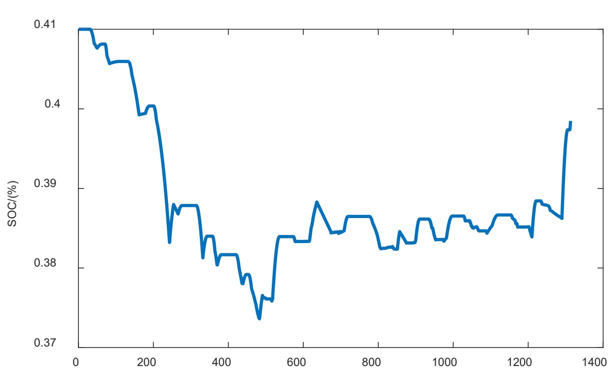

Fig 6 SOC curves in under DP based EMS

In the whole range, the fuel consumption under DP EMS is higher because of the pure electric mode in CD condition. And then, the consumption under DP EMS is lower in charge sustaining condition.

Table 2 Fuel consumption

EMS	Fuel consumption(L/100km)
Rule-based in 17 cycles	13.90
Rule-based in CD mode	25.80
DP in CD mode	18.14

5. CONCLUSION

In this paper, a new dual-mode PHEB transmission is developed to satisfy the driving demand under urban and intercity condition, and the power distribution is determined according to the rule-based EMS to minimize fuel consumption. The results show that rule-based EMS keep the PHEB's weighting fuel consumption is 13.90 L/100km.

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