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INTEGRATED MODEL PREDICTIVE CONTROL IN HYBRID VEHICLE POWERTRAIN FOR IMPROVING FUEL CONSUMPTION

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ABSTRACT

This article aims to develop a model predictive power source or mode control governing power management for Toyota Prius 2013 model, a Plugin power-split hybrid electric vehicle (HEV). The integrated powertrain control has been developed considering the engine torque, motor torque, generator torque and power source mode of the vehicle as control variables and wheel torque as system output. The driving pattern used in this work is by combining five popular driving cycles on which the developed model is applied it results into a 7.93 % improvement in fossil fuel economy. In certain situations, this improvement can be very high considering real time driving data, not strictly based on a driving cycle, and a studied case shows an improvement of 38.24%.

Keywords: Power-split hybrid electric vehicle, Fuel economy, Mode selection, Model predictive control, Power management

NOMENCLATURE

Abbreviations	
FTP	*Federal Test Procedure*
HEV	*Hybrid electric vehicle*
HWFET	*Highway Fuel Economy Test*
ICE	*Internal combustion engine*
MG	*Motor generator*
MPC	*Model predictive control*
NEDC	*New European Driving Cycle*
PHEV	*Plugin hybrid electric vehicle*
PMS	*Power management system*
RB	*Rule-based*
UDDS	*Urban Dynamometer Driving Schedule*
US06	*Federal Test Procedure 06*
WLTC	*Worldwide harmonized light vehicles test procedure*

Symbols			
A,B,C,D,K	*System matrix*	*w*	*weight*
x	*state*	*u*	*Control signal*
y	*System output*	*N*	*Number of input*
t	*time*	*k*	*Horizon time*
e	*error*	*J*	*Cost function*

1. INTRODUCTION

The gradual decline in global oil reserves, in addition to strict emission regulations around the world, has made the need for an improved vehicle fuel economy even more critical [1]. As a secondary energy source, electric propulsion systems have been added to conventional internal combustion engine (ICE) systems to form hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) to address global issues such as energy crisis, air pollution and conventional vehicle health challenges [2,3]. A typical hybrid vehicle uses an internal combustion engine (ICE), a source of energy storage, electrical motor and inverter. Types of HEVs available in the market includes (a) series HEV, where the engine drives a generator whose electrical power is added to the battery power and then transmitted to the vehicle's electrical motors via inverters (b) parallel HEV, where the mechanical power, sourced both from the engine and the electric motor is merged where the engine and electric machines are connected a gear set, a chain or a belt, so that their torque is combined for transmission to the wheel through the driveshaft. (c) The series-parallel or power-split HEV configuration uses both series and parallel powertrain operation with a planetary gear mechanism [4].

In the literature, it can be found that the recent trends in HEV research focuses on (i) Integrated powertrain control (ii) system stability (iii) Robustness (iv) Battery ageing and hybrid storage (v) vehicle to grid (V2G) interaction and (vi) new technology integration. In this article, the research aim is to develop integrated HEV powertrain control and mode control for better power management. Power management strategy is very important for improving the fuel economy, which has bearing on HEV energy efficiency. Based on previous research, HEV / PHEV power management strategies can be divided into two main categories, rule-based strategies and optimization based strategies [5]. The rule-based strategies are categorized into two types: fuzzy logic based and heuristic rule-based. Again, optimization based strategies are also two types, online and offline. A special type of rule based control considers Charge-Depleting and Charge-Sustaining control strategies in PHEVs [6].

It has been found in the literature that for propulsion selection several approaches mainly categorized as route preview based and predictive energy management system. For example, the former type is presented in reference [7] and [8]. Whereas the latter the type is considered in reference [9] and [10].In reference [7] the authors presented a fuzzy propulsion selection considering the road grade, vehicle speed vehicle torque and battery state of charge. In reference [8] a self-organizing fuzzy controller was developed for four modes split hybrid control to minimize fuel consumption. Reference [9] presents a nonlinear model predictive EMS, based on velocity prediction in dual mode split HEV. An online control approach for integrated mode selection in a series-parallel hybrid vehicle can be found in reference [10] where the offline analysis result is used for online application. A velocity prediction-based model predictive control for power management can be found in reference [11] where the fuel economy improved by 21.88 % in MANHATTAN driving cycle. The work in the article [12] proposed a Pontryagin's minimum principle based energy management, which uses the Markov chain for speed forecasting. All the above MPC based methods improve the vehicle performance by improving the utilization of hybrid energy sources for better fuel economy and also this leads to optimal energy supply to the wheels, improving the overall powertrain energy efficiency. The main advantages of Model predictive control (MPC) is the robustness and the optimal control strategy, which helps the vehicle to achieve better reference tracking. This article attempts to design an integrated two-level MPC based mode control , which considers the detailed mode of operation in PHEV powertrain. This detailed consideration of mode for MPC design is the novility of this article. The objective of the control design is to increase the utilization of electric source and regenerative breaking and reduce charging from engine for increasing the electric range and reduction in utilization of engine energy. This further reduces the fossil fuel consumption and increase the mileage of the vehicle.

2. VEHICLE MODEL

The vehicle model has been considered in this study is the Toyota Prius 2013 model, which is a plug-in HEV. The details of the vehicle parameters are listed below in table 1. In this study, the mode of the HEV is redefined for improving the power management. In a typical HEV, the mode of operation is three types (1) EV mode (2) ICE mode (3) Hybrid mode. These three modes are divided into seven modes, which are defined below in table 2.

Table 1: Vehicle parameters

Parameters	Values
Max. Engine power	73 kW at 5200 rpm
Max. power/torque of MG1	60kW/207 Nm
Max. Speed of MG1	13,500 rpm
Max. power of MG2	42 kW/ 146 Nm
Max. speed of MG2	10,000 rpm
Total weight with max payload	1840 kg
Battery module information	56(series), 4.4kWh rated pack energy, 21 Ah rated pack capacity, 76 kg pack weight. Nominal System Voltage 207.2 V
Ground clearance	0.13 m
Tire (P195/65R15) radius	0.32 m
Front area	2 m^2

Table 2 Modes of hybrid vehicle

Mode	ICE	MG1	MG2	Mode Description
1	0	1	-1	Pure EV
2	1	0	1	Pure engine
3	1	-1	1	Engine + charging
4	1	1	1	Pure hybrid
5	1	1	-1	Hybrid + regenerative braking
6	1	-1	-1	Engine + charging+ regenerative braking
7	0	-1	-1	Pure regenerative braking

1: ICE, MG are supplying positive torque, 0: ICE, MG is disengaged,-1: regenerative braking or torque is negative.

A two-stage discrete state space model of the torque control and fossil fuel consumption model is provided in model1 (A,B,K,C,D) and model2 (Af,Bf,Kf,Cf,Df). The controller is designed for model 1, where the mode, engine torque, MG1 torque and MG2 torque are considered as control variables and wheel torque as model output. The second system model is the fuel consumption model where the mode, Battery charge depletion rate, vehicle speed and engine torque are considered as input variables and the fossil fuel consumption is considered as output. The discrete state space equation is provided in equation 1.

$$x(t+Ts) = Ax(t) + Bu(t) + Ke(t) \qquad (1)$$
$$y(t) = Cx(t) + Du(t) + e(t)$$

Powertrain torque supply model

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0.0198 & 0.138 & 0.661 & 0.169 \end{bmatrix}$$

$$B = \begin{bmatrix} 3.04 & 7.54 & -2.02 & -37.06 \\ 1.80 & 2.27 & 10.63 & 39.34 \\ -0.67 & -2.17 & -3.57 & -30.99 \\ 0.38 & 1.26 & 1.99 & 20.87 \end{bmatrix}$$

$$C = [1 \quad 0 \quad 0 \quad 0] \ , \ D = [0 \quad 0 \quad 0 \quad 0]$$

$$K = \begin{bmatrix} -0.0021 \\ 0.0034 \\ 0.0060 \\ 0.0008 \end{bmatrix}$$

Fuel consumption model

$$Af = \begin{bmatrix} 0.78 & 0.60 & -0.10 & 0.02 \\ 0.11 & -0.26 & -0.81 & 0.39 \\ -0.06 & -0.01 & -0.37 & -0.91 \\ 0.03 & 0.02 & -0.38 & 0.026 \end{bmatrix}$$

$$Bf = \begin{bmatrix} 810 & 10 & -0.0704 & -3.48 \\ -3540 & -20 & 0.361 & 40 \\ -2200 & -5.3 & -0.661 & -20 \\ -440 & -5.2 & -0.344 & -100 \end{bmatrix} \times 1e-05$$

$$Cf = [26.80 \quad -6.84 \quad 2.41 \quad -3.47], \qquad Df = [0 \quad 0 \quad 0 \quad 0]$$

$$Kf = \begin{bmatrix} 0.016 \\ 0.0004 \\ 0.0028 \\ -0.0019 \end{bmatrix}$$

Model is validated with testing data available with Argon lab testing results [13]. The validation result is provided in table 3.

Table 3 Validation data

Response	Real Time (kmpl)	Model(kmpl)
45 mph	21.34	21.13
60 mph	20.45	19.81
HWFET at 20°F	18.92	18.62
HWFET at 72°F	20.40	19.85

3. MODEL PREDICTIVE CONTROL DESIGN

The controller design objective is to design an integrated powertrain controller for supplying the demanded torque to the wheel. The state space model for the system is described in the previous subsection. Based on the system model, the model predictive controller is designed. The controller is designed with the help of MATLAB Simulink. The optimal control problem is formulated with the deviation of torque demand and supply and minimum control input. The optimal control problem with control constraints has is presented as equation 2. The main contribution of this article is the methodology of designing the control. The conventional three mode has been decided in to seven different mode of operations. This mode of operations is defined with the direction of the supplied torque. This type of approach of designing the predictive power control approach is a novel concept and can improve the existing HEV power management which will further lead to improved hybrid energy source management and improvement in powertrain energy efficiency.

$$\underset{u_0,u_1 \ldots u_{N-1},}{min} J \qquad (2)$$
$$min_{u_0,u_1..u_{N-1},} \sum_{i=1}^{N-1} w_{t+1}^{y} \left\| y(k+i+1|k) - y_{ref}(k+i+1|k) \right\|^2 + w_i^u \left\| u(k+i|k) \right\|^2$$

s.t.

$$y_{min} \leq y(k) \leq y_{max}, k = 0,1, \ldots., N-1$$
$$u_{min} \leq u(k) \leq u_{max}, k = 0,1, \ldots\ldots, N-1$$

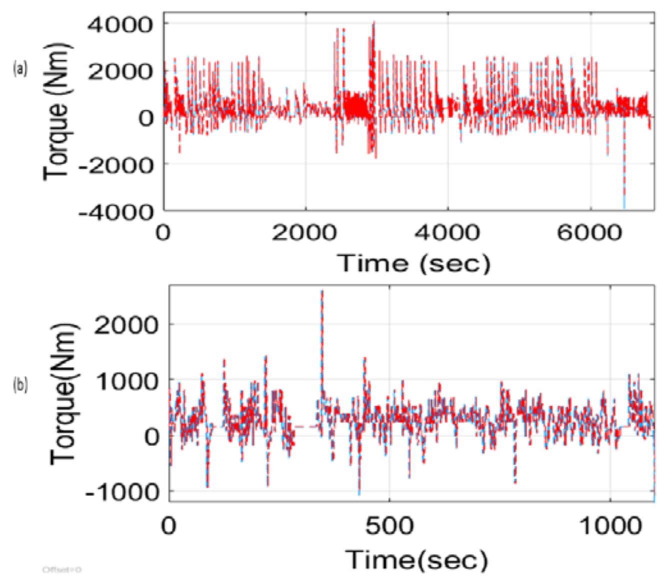

Fig. 2 Torque at Wheel (a)UDDS+WLTC1+US06+NEDC+FTP+HWFET combined (b) Real time driving cycle (Blue line indicates torque demand, Red indicates supplied torque)

The quadratic programming base optimization is used for the optimal control problem. The state estimation model has a prediction horizon as 5 sec and the control horizon as 2 sec. The input variables are bounded in the maximum and minimum range of operation as mentioned in the powertrain specification. The engine torque is bounded zero to maximum torque similarly the motor generator units also constrained to the minimum and maximum torque value. The mode values are constrained 1 to 7 as mentioned in table 2.

4. SIMULATION AND RESULT DISCUSSION

The simulation is performed in two driving patterns and control model is validated in DSpace/VEOS software. The first driving pattern is the combination of five popular driving cycles (UDDS, WLTC1, US06, NEDC, FTP, HWFET) and another is the real-time driving data which is provided in Fig 1 a and b. The MPC is applied for the mode selection to increase the utilization of electric power source in HEV and results in a significant improvement in the utilization of electric sources. The fossil fuel economy improves by 7.93% in the first combined driving cycles. A study is conducted, not following any specific driving cycle but based on real-time observations and capturing GPS data which in a situational context exhibits improvement of a very high order that is 38.24% is compared to rule based mode selection.

Table 4: Mode selection time percentage(%) and mileage (kmpl)

Model	1(%)	2(%)	3(%)	4(%)	5(%)	6(%)	7(%)	Mileage kmpl
UDDS+WLTC1+US06+NEDC+FTP+HWFET								
RB	6.4	5.8	11.7	52.7	5.6	2.4	5.2	7.57
MPC	12.2	7.9	5.8	5.9	10.1	12.1	23.9	8.17
Real-time driving data								
RB	9.17	2.2	8.2	4.3	57.2	11.0	0.8	7.74
MPC	9.45	13.6	6.7	9.1	15.5	9.2	16.8	10.47

This has been achieved by proper mode control while driving. The summary of the percentage mode selection has been provided in table 4. The proposed control approach reduces the pure hybrid driving (mode 4) and increases the regeneration (mode 7) and EV mode operation (mode 1). As a result, the charging from the engine is reduced in both driving patterns. Although the control strategy increases the percentage utilization of engine mode (mode 2), because of the increment in regenerative braking, the electric energy recovery is improved, which increases the fossil fuel mileage of the vehicle. In real time application, this type of approach is very useful as the torque demand-based mode control is proposed in this article. The torque supply for both cases is provided in Fig 2. The blue line is the torque demand at the wheel, and the red line presents the wheel torque supply. It can be observed most of the cases the controller able to supply the torque to the wheel. So, the proposed control model can be applied in any series-parallel plugin hybrid electric vehicle.

5. CONCLUSIONS

The model predictive mode control for the series-parallel HEV is designed with recharacterized seven driving modes referred to in table 2. The proposed two-stage control method improves the fossil fuel economy by 7.93% and for a real-time study it exhibits improvement of very high order that is 38.24%. It is inferred that the integrated MPC based HEV powertrain control is able to increase the utilization of electric energy and enhance the fossil fuel mileage. The future scope of research lies in refinement of the designed model predictive controller with consideration of greenhouse gas emission.

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