Online Energy Management Strategy for Hybrid Electric Vehicle

Lok To Mak
The Chinese University of Hong Kong

Minghua Chen
The Chinese University of Hong Kong

Guanglin Zhang
Donghua University

Longbo Huang
Tsinghua University

Haibo Zeng
Virginia Tech

ABSTRACT

In this paper, we present an online energy management strategy for parallel hybrid electric vehicle equipped with two power sources. The strategy orchestrates a fuel-based internal combustion engine and an electric motor to minimize total fuel consumption while meeting driving power demand. A unique feature of our proposed strategy is that it is proven to achieve near-optimal performance without the need of knowing any statistical information of the demand. Simulations based on real-world driving traces corroborate our theoretical findings.

1. INTRODUCTION

Hybrid Electric Vehicle (HEV) is a vehicle equipped with two power sources. One is fuel-based internal combustion engine (ICE) and the other is electric motor (EM) powered by battery. An important problem is to minimize the overall fuel consumption by orchestrating power supply from these two sources to meet the driving power demand, by designing intelligent energy management strategies [5].

Various strategies have been purposed; see [5] for a recent survey. A-ECMS [4] is arguably the state-of-the-art strategy that provides an online algorithm achieves decent performance without requiring any statistical information of the driving trace. However, it is known that A-ECMS does not provide any performance guarantee, the overall fuel consumption may be far from the optimal [3]. In this paper, we apply the Lyapunov drift-plus-penalty method [2] to design an easy-to-implement online energy management strategy with provable near-optimal performance and requires no statistical information of the driving power demand. Our proposed strategy is able to achieve average fuel consumption within $O(1/V)$ to the optimal with an $O(V)$ battery capacity, for any $V > 0$. In the following, we first formulate the problem of energy management strategy design and present our solution. We provide performance guarantee for the proposed solution and carry out simulations based on real-world traces to compare its performance against A-ECMS and an offline optimal assuming complete statistical knowledge.

e-Energy'15, July 14 - 17, 2015, Bangalore, India.

DOI: http://dx.doi.org/10.1145/2768510.2768538 .

2. PROBLEM FORMULATION

We consider parallel HEV, in which ICE and EM can operate in parallel to jointly meet the driving power demand.

Internal combustion engine (ICE): ICE can propel the vehicle and charge battery. $P_e(t)$ denotes the power to satisfy the driving power demand, and it is limited by its ramping constraint $|P_e(t+1)-P_e(t)| \leq P_e^{\max}$. $P_g(t)$ denotes the power to charge the battery. Let the total power output $P_{\text{ice}}(t)$ at time t formulated as $P_{\text{ice}}(t) = P_g(t) + P_e(t)$. We assume $P_{\text{ice}}(t) \leq P_{\text{ice}}^{\max}$. Upon generating $P_{\text{ice}}(t)$ amount of power, the ICE consumes $f(P_{\text{ice}}(t))$ amount of fuel, where $f(\cdot)$ is the fuel consumption function and is assumed to be convex.

Electric Motor (EM): EM draws $b_m(t)$ amount of electricity from battery and outputs power $P_m(t) = g(b_m(t))$ to meet the driving power demand, where $g(\cdot)$ is a power efficiency function and is assumed to be convex. $P_m(t)$ is limited by ramping constraint $|P_m(t+1) - P_m(t)| \leq P_m^{\max}$. We also assume $P_m(t) \leq P_m^{\max}$ for all t.

Power Demand and Braking Power: Given any driving traces, we can obtain the power demand for vehicle acceleration. Let this power demand at time t be $P_d(t)$. It must be jointly satisfied by ICE and EM at any time t; that is, $P_d(t) \leq P_e(t) + P_m(t)$. When the vehicle breaks, certain amount of braking power, denoted by $P_b(t)$, can be harvested to charge the battery.

Battery: State-of-charge of the battery at time t is defined as $q(t)$. Battery discharging power $b_m(t) \leq b_m^{max}$ can provide power to EM. Battery charging power $b_g(t) \leq b_g^{max}$ can charge the battery, which is upper-bounded by the sum of braking power and power from ICE $P_b(t) + P_g(t)$. Let the discharging and charging coefficients be η_m and η_g. The state-of-charge dynamics is then $q(t+1) = q(t) + \eta_g b_g(t) - \eta_m b_m(t)$.

We adopt a discrete-time model where time slot matches the timescale at which the management decisions can be updated. Without loss of generality, we assume there are totally T slots, and each has a unit length. We study the energy management strategy design problem as follows:

$$
\begin{aligned}
\min \quad & \bar{J} = \frac{1}{T}\sum_{t=1}^{T} f\left(P_{\text{ice}}(t)\right) && (1)\\
\text{s.t.} \quad & |P_{\text{ice}}(t) - P_{\text{ice}}(t-1)| \leq P_{\text{ice}}^{\max} && (2)\\
& |P_m(t) - P_m(t-1)| \leq P_m^{\max} && (3)\\
& b_g(t) \leq P_g(t) + P_b(t) && (4)\\
& P_d(t) \leq P_e(t) + P_m(t) && (5)
\end{aligned}
$$

$$0 \le P_{\text{ice}}(t) \le P_{\text{ice}}^{\text{ice}}, 0 \le P_m(t) \le P_m^{\max}$$
$$0 \le b_m(t) \le b_m^{\max}, 0 \le b_g(t) \le b_g^{\max} \tag{6}$$
$$q(t+1) = q(t) + \eta_g b_g(t) - \eta_m b_m(t) \tag{7}$$
$$\text{var} \quad P_{\text{ice}}(t), P_m(t), b_g(t), b_m(t), t \in [1, T]$$

The objective function in (1) represents the average fuel consumption in $[1, T]$. Constraints (2)-(3) capture the constraints of maximum changing rate. Constraint (4) states the maximum of battery charging power. Constraint (5) ensures driving power demand must be satisfied. Constraint (6) captures the upper and lower bounds of the power flow variables. Constraint (7) captures the state-of-charge dynamics. The goal is to minimize average fuel consumption, by controlling total ICE power output $P_{\text{ice}}(t)$, EM power output $P_m(t)$, battery charging power $b_g(t)$ and battery discharging power $b_m(t)$ to satisfy the driving power demand $P_d(t)$ in every time slot t, given driving power demand $P_d(t)$ and braking power $P_b(t)$ as inputs. We do not specify any battery constraints as our proposed strategy provides a safety value for battery capacity and ensures the battery will not underflow/overflow.

3. ALGORITHM DESIGN

To construct the energy management strategy, we adapt the Lyapunov drift-plus-penalty approach expounded in [2]. We first define two control parameters $\theta > 0$ and $V > 0$. V controls the performance optimality gap. θ will be specified later. We construct our energy management algorithm using the "min-drift" principle of Lyapunov optimization: at each time slot, choose a pair of feasible battery charging/discharging actions to minimize the cost. Our proposed **Energy Management Strategy** is as follows: at every time slot t,

1. Observe the state-of-charge $q(t)$ and power demand $P_d(t)$. Define the following weights:

$$W_g(t) = \eta_g(q(t) - \theta) + Vf(P_{\text{ice}}(t))$$
$$W_m(t) = \eta_m(q(t) - \theta) + Vf(P_{\text{ice}}(t))g(b_m(t))$$

2. Solve $\min_{b_g(t), b_m(t)} b_g(t)W_g(t) - b_m(t)W_m(t)$ subject to the constraints (2) - (6).

3. Update the battery according to (7) with the chosen $b_g(t), b_m(t)$, and calculate the corresponding fuel usage.

In the algorithm, we only have to solve a linear program with four variables, and it does not require any statistical knowledge of driving power demand. Hence, the algorithm can be easily implemented and the complexity is low.

4. PERFORMANCE ANALYSIS

We now provide performance guarantee for our proposed energy management strategy. Parameter θ is defined as:

$$\theta \triangleq \eta_m \min\,[P_d^{\max}, b_m^{\max}] + \frac{V f_{\max} g_{\max}}{\eta_g}$$

where $P_d^{\max}, f_{\max}$ and $g_{\max}$ are defined as the maximum driving power demand, maximum fuel consumption rate and maximum EM efficiency, respectively.

THEOREM 1. *(Determine Battery Capacity) Under our proposed energy management strategy, the battery state-of-charge is bounded by:*

$$0 \le q(t) \le \theta + \eta_g b_g^{\max}.$$

Theorem 1 shows the state-of-charge never go underflow and is upper bounded; thus we can size the battery capacity accordingly. Combining Theorem 1 and the definition of θ, we can see that a battery capacity of size $O(V)$ is sufficient.

We have the following performance guarantee on the average fuel consumption.

THEOREM 2. *(Performance guarantee) Let $\bar{J}$ be the average fuel consumption achieved by our strategy, and J^* be the optimal average fuel consumption by solving the problem with full statistical knowledge. We have*

$$\bar{J} \le \frac{B}{V} + J^*$$

where B is a constant.

Theorem 2 guarantees that the fuel consumption is within $O(1/V)$ to the optimal. As we increase the value of V, the battery size increases and the gap to optimal decreases. It shows this strategy forms an $[O(1/V), O(V)]$ optimality gap-battery capacity tradeoff with performance guarantee.

5. SIMULATIONS

Using a real-world driving trace UDDS [1], we evaluate the performance of different algorithms under a reasonable range of battery sizes (0 to 2 kWh) in Fig. 1. We measure the performance of Dynamic Programming (DP), A-ECMS [4] and our proposed strategy. The DP solution with full driving demand knowledge achieve the optimal and serves as a benchmark. The results show that (i) our strategy saves more fuel as battery capacity increases, and (ii) it saves significant amount of fuel even when battery capacity is small. With one kWh battery capacity, our strategy saves about 10% fuel as compared to the state-of-the-art solution A-ECMS.

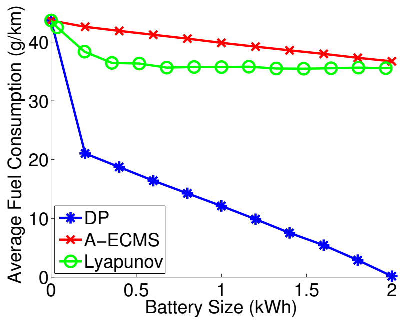

Figure 1: Fuel Efficiency vs. Battery Capacity.

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