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Dynamometer test of a rule-based discharge strategy for plug-in hybrid electric vehicles

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Abstract: This paper presents a rule-based battery discharge strategy for a Plug-in Hybrid Electric Vehicle. The main idea is to exploit results of previous research and synthesize a strategy that mimic optimal battery State of Charge (SoC) discharge behaviour. A subsystem called the Target SoC Optimizer computes a sequence of target SoCs at specified driving distances along a given trip prediction. The Power Limit Optimizer subsystem is then responsible for adapting the engine on/off power limits so that the upcoming target SoC is reached. Simulations and tests in a vehicle dynamometer show that the proposed strategy can decrease fuel consumption with more than 5% compared to the nominal Depletion-Sustain discharge strategy.

Keywords: Plug-in Hybrid Electric Vehicles, Energy Management, Vehicle Dynamometer

1. INTRODUCTION

At the present day there is an ongoing electrification trend within the automotive industry to meet stricter legislative requirements. Several automotive manufacturers are therefore producing Plug-in Hybrid Electric Vehicles (PHEVs) with an electric driving range of 20-60 km, meaning that most short trips can be driven almost exclusively on electrical energy. Nevertheless, if the driving distance exceeds the electric driving range, then there is a possibility to optimize the battery discharge strategy and thereby improve fuel economy. The topic of route optimized discharge strategies has therefore received significant attention from researchers during recent years. The standard assumption in most publications is that the future driving conditions are either predicted from navigation system information or from the historical driving pattern of the vehicle, see for example Zhang and Vahidi (2011); Larsson et al. (2014). The strategy is then typically optimized using optimal control methods such as Dynamic Programming (DP), e.g. Moura et al. (2011), or the Pontryagin Minimum Principle (PMP) [1], e.g. Stockar et al. (2011). However, several published papers have shown that a near optimal discharge strategy can be obtained using relatively simple rule-based methods that does not require a very accurate trip prediction, see for example Tulpule et al. (2010); Zhang and Vahidi (2011); Sivertsson and Eriksson (2015).

The intention of this paper is therefore to exploit the insights provided by previous research on the topic and propose a simple rule-based discharge strategy that is straight forward to implement and validate in a production vehicle. The idea is primarily to address the following aspects: fuel consumption, robustness, computational demand and ease of integration. Furthermore, it is worth to stress that the main idea of the paper is not to present novel results, but rather to illustrate how results of academic research can be transferred into an industrial implementation.

[1] Called Equivalent Consumption Minimization Strategy (ECMS).

Paper Outline PHEV discharge strategies are discussed briefly in next section. The two succeeding sections describes the investigated vehicle(s) and the proposed rule-based discharge strategy. Simulation results and the outcome of the vehicle dynamometer tests are presented in the section thereafter. The paper is ended with conclusions.

2. PHEV DISCHARGE STRATEGIES

The section provides a brief background on PHEV discharge strategies and optimal discharge behaviour.

2.1 Nominal Discharge Strategy

If the future driving conditions are unknown, it is generally fuel cost optimal to use the electrical energy before the expensive liquid fuel is used. The nominal strategy is therefore to operate in charge depletion mode until the battery SoC reaches the lower SoC limit. The vehicle will then proceed in charge sustaining mode, keeping the SoC approximately constant around the lower SoC limit.

2.2 Optimal Discharge Strategy

When there is a prediction of the future driving conditions available it is possible to compute a fuel cost optimal discharge strategy. The typical approach within the academic community is to formulate the problem as an optimal control problem and calculate the control signal trajectory, $u(\cdot)$, that minimizes the cost function, J, given some prediction of the future driving conditions. Eq. (1) provides an example of such a problem formulation,

$$\begin{aligned} J^* = \min_{u(\cdot)} \quad & G(x(t_f)) + \int_{t_0}^{t_f} g(u(t),t)\ dt. \qquad (1) \\ s.t. \quad & \dot{x}(t) = f(x(t),u(t),t) \\ & x(t_0) = x_0 \\ & x(t) \in X \\ & u(t) \in U(x(t),t) \end{aligned}$$

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The state x represents the battery SoC and f defines the non-linear state dynamics. The instantaneous fuel cost of the engine is represented by g and the cost to recharge the battery at the end of the trip is given by the final cost G. The control signal, u, is typically defined by one or several of the following signals: the engine state, the choice of gear and the torque split between the engine and the electrical motor(s).

2.3 Optimal Discharge Behaviour

Most academic studies have used DP or PMP/ECMS to solve the problem defined by Eq. (1). The results indicate that an optimized strategy can improve fuel economy significantly compared to the nominal strategy. The potential improvement is typically 0-15%, much depending on driving distance, speed profile and topography, see for example Tulpule et al. (2010); Moura et al. (2011); Zhang and Vahidi (2011); Larsson et al. (2014).

Several of the published papers have shown similar results in terms of optimal discharge behaviour, some general trends are summarized below.

- A trip with uniform speed profile and minor altitude variations leads to a SoC-trajectory that is roughly linearly decreasing with respect to driving distance, see Kum et al. (2010); Tulpule et al. (2010).
- If there are significant altitude variations throughout the trip, then the SoC-trajectory is influenced by the variations in potential energy, see Zhang and Vahidi (2011); Larsson et al. (2014).
- A high power demand favours engine propulsion, since the efficiency of an engine generally is increasing with higher load, e.g. see Heywood (1988). Electric propulsion is thus favoured at low power demand due to poor engine efficiency.
- If the trip length prediction is uncertain and this uncertainty is considered during the optimization, then the optimal strategy is to have the battery net depleted slightly before the expected end of the trip, see Larsson et al. (2010).

3. THE PLUG-IN HYBRID ELECTRIC VEHICLE

The paper considers the powertrain configuration of the Volvo XC90-T8 and S60L-T6 models, shown in Figure 1. Both powertrains feature a 4-cylinder gasoline Internal Combustion Engine (ICE) with an 8-speed automatic transmission. An Integrated Starter Generator (ISG) is mounted directly at the engine crankshaft and an Electric Rear Axle Drive (ERAD) is coupled to the rear axle through a fixed gear and clutch. The key powertrain data for both models are summarized in Table 1.

The default driving mode in a Volvo PHEV is called *Hybrid* and it contains two distinct phases, *Depletion* and *Sustain*, meaning that the vehicle operates according to the nominal discharge strategy described in Section 2.1. In both the Depletion and the Sustain phases the engine on/off decisions are mainly triggered by the driver's power request according to an hysteresis, i.e. there is a higher power limit to turn on the engine and a lower power limit to turn it off. If the engine is on it is primary provider of traction torque, the ERAD and ISG are then mainly used as torque fill-in during transients. Furthermore, the ISG is only used to charge the battery in the Sustain phase. When the engine is off the ERAD is the sole provider of traction torque. In the default Hybrid mode the engine on/off power limit parameterization is fixed and the battery discharge rate is therefore not really controllable.

Table 1. Official powertrain data for the Volvo XC90-T8 and S60L-T6.

Model Name Vehicle Type	XC90-T8 SUV	S60L-T6 Sedan
ICE	235 kW, 400 Nm	175 kW, 350 Nm
Battery	9.2 kWh	11.2 kWh
Gearbox	8-speed aut	8-speed aut
ERAD	65 kW, 240 Nm	50 kW, 200 Nm
ISG	34 kW, 150Nm	34 kW, 150Nm
Weight	2350 kg	2000 kg

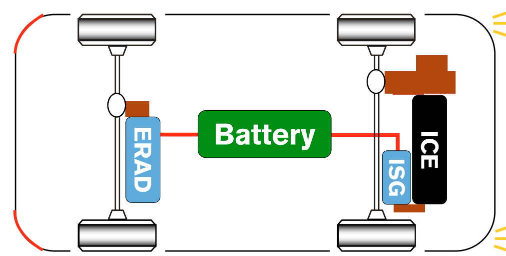

Fig. 1. The PHEV powertrain configuration.

4. THE PROPOSED ECO-DISCHARGE STRATEGY

This section provides some background and briefly describes the different subsystems in the proposed strategy.

4.1 Background

A critical design requirement when developing the new *Eco-Discharge* strategy is that it should be easy to integrate within the existing control system. Hence, if possible, it is desirable to develop a strategy that only requires minor modifications of the current system. Furthermore, it also important to have a strategy with low computational demand that can be used even if the trip prediction is very crude, e.g. if only the expected driving distance is known.

Neither of the two predominant methods in the academic literature, DP and PMP/ECMS, are suitable in the current context. DP is computationally demanding and calls for a relatively detailed trip prediction, i.e. expected driving distance alone is not sufficient. Moreover, to implement a PMP/ECMS-based discharge strategy, as suggested by Tulpule et al. (2010); Zhang and Vahidi (2011), would require relatively profound changes of the current control system. The proposed Eco-Discharge strategy will therefore only override the default engine on/off power limits used in the default Hybrid mode.

The principal idea with the proposed strategy is to mimic the optimal discharge behaviour described in Section 2.3. To accomplish this the Eco-Discharge strategy is divided into two different subsystems, a *Target SoC Optimizer* and a *Power Limit Optimizer*. Figure 2 provides an illustration of the interfaces between the two subsystems, the navigation system and the Hybrid mode. The assumptions and functionality of the different systems are described next.