

Optimization of Rule-Based Control Strategy for a Hydraulic-Electric Hybrid Light Urban Vehicle Based on Dynamic Programming

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ABSTRACT

This paper presents a low-cost path for extending the range of small urban pure electric vehicles by hydraulic hybridization. Energy management strategies are investigated to improve the electric range, component efficiencies, as well as battery usable capacity. As a starting point, a rule-based control strategy is derived by analysis of synergistic effects of lead-acid batteries, high efficient operating region of DC motor and the hydraulic pump/motor. Then, Dynamic Programming (DP) is used as a benchmark to find the optimal control trajectories for DC motor and Hydraulic Pump/Motor. Implementable rules are derived by studying the optimal control trajectories from DP. With new improved rules implemented, simulation results show electric range improvement due to increased battery usable capacity and higher average DC motor operating efficiency.

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INTRODUCTION

This work investigates a novel concept for extending the range of small urban electric vehicles. Light-duty vehicles provide the most common transportation service. Over 85% of travel in the United States is in light-duty vehicles [1, 2]. In recent years, Electric Vehicle manufacturers have been accelerating the Electric Vehicle development. The attractiveness of light-duty EVs stem from zero direct carbon and pollutant emissions, low energy costs, and ability to use diverse energy sources including nuclear power, and renewables such as wind, and solar power. Therefore, large scale EV deployment can significantly reduce the dependence on oil. To achieve low cost, using the mature and simple lead-acid batteries and electric machines such as the brushed DC motor is a good choice for manufacturers aiming at the small-vehicle market. Under these circumstances, the main goal for light-duty EVs is to extend the electric range without compromising vehicle life and while maintaining low cost.

Hydraulic hybridization is a promising way to achieve range improvements through effective regeneration. The hydraulic components are low cost and comparatively high efficiency. Compared with electrochemical battery, hydraulic accumulator has more power density with less energy capacity [3], [4]. Therefore, adding hydraulic system to EV

combines both advantages of high power density and high energy capacity. This holds a promise of significantly improving the electric range of operation, but also opens the question of how to coordinate the operation of these two energy storage systems to better satisfy the power demand and improve the overall efficiency.

The platform used in this study is a light-duty PK truck called Xebra as shown in Fig. 1 from ZAP Jonway, a new automotive manufacturer in electric vehicles (EVs). Based on the existing EV configuration, a low-cost solution for improving the electric range is proposed as shown in Fig. 2. To get the performance and calibration data for vehicle modeling, this Xebra truck was tested for range and efficiency under different driving cycles at the US EPA National Vehicle and Fuel Emissions Lab. Vehicle status data, such as, speed, battery voltage, current, power, charging energy, AC energy from the wall, were recorded over the tests.

The Xebra has a battery pack consisting of six 12V lead-acid batteries, which can provide 4.64 kWh at 1C and costs \$1,050. It takes up to 12 hours to charge the battery pack that is 100% discharged. A 5kW brushed DC series wound motor is coupled to the wheel through the reduction gears with gear ratio 4.5:1. No regenerative braking is allowed in the stock Xebra.

The previous work [5] introduced several energy management options for the hydraulic-electric Xebra. The objective of this paper is to further investigate the energy management options for the hydraulic-electric hybrid light urban vehicle.

The baseline EV uses a Lead-acid battery and a DC motor to minimize cost. Regeneration was not possible. The option to improve the range with more advanced Li-Ion battery is prohibitively costly, as it almost doubles the price of a small urban vehicle. Instead, we propose integration of a compact and low-cost hydraulic regeneration system. As the only energy source in the EVs, battery usable capacity becomes an important factor to the vehicle electric range. In order to better understand the lead-acid battery performance, a high fidelity battery model is developed based on the testing data from the US EPA National Vehicle and Fuel Emissions Lab. Simulation study shows the usable capacity is highly dependent on the usage patterns. This presents a special opportunity to maximize the range by adding a hydraulic regeneration system and coordinate the operation of the two propulsion sub-systems in an optimal manner. Aggressive discharging can significantly decrease battery usable capacity. High power density hydraulic system can avoid high current demands on battery and therefore improve its usable capacity significantly.

The paper is organized as follows. In the first part the modeling effort is presented. Then the intuitive rule based strategy is proposed, based on the analyses of the component efficiencies. In order to explore the best achievable system efficiency, the Dynamic Programming technique is introduced. The near-optimal control rules are extracted from the DP result to be applied in the real world. The results subsequently obtained using the high-fidelity simulation are analyzed to provide insight regarding new modes of operation uncovered by the algorithm and quantify the further improvements achieved by the optimized strategy. The paper ends with a summary and conclusions.



Figure 1. Xebra light-duty pickup truck front ZAP Jonway.

HYDRAULIC ELECTRIC HYBRID SYSTEM

Based on the stock Xebra PK truck, hydraulic system was designed and added to the stock Xebra in order to improve the vehicle electric range. The hydraulic system consists of a 45cc bent-axis pump/motor with variable displacement, a 23 L hydraulic accumulator with maximum pressure of 344 bars and a 30 L hydraulic oil reservoir. The hydraulic Pump Motor (PM) shaft is coupled to the DC motor shaft in parallel through a gear reduction to achieve the gear ratio 2.9:1 from PM shaft to wheel shaft. The gear ratio was selected through a systematic simulation study. The configuration of the Hydraulic-Electric Hybrid Vehicle (HEHV) is shown in Fig. 2. The parameters for electric and hydraulic components are listed in Table 1.

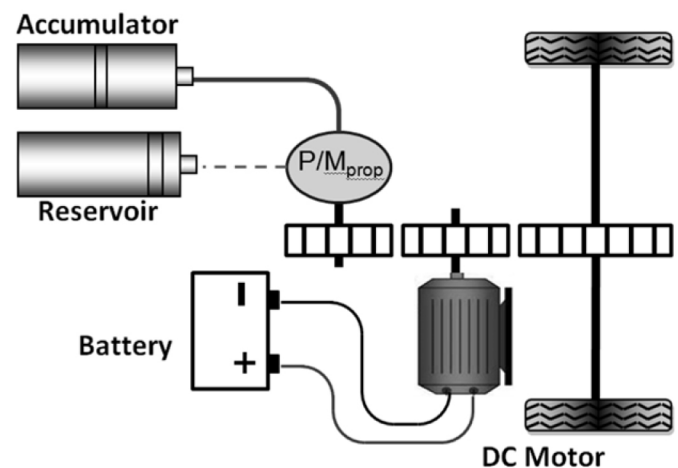


Figure 2. -Hydraulic-Electric Hybrid Vehicle (HEHV) Parallel Configuration.

Table 1. Components Parameters.

DC motor Power Nom.	5.0 kW
Battery Capacity @ 1C	4.64 kWh
Battery Mass	199 kg
Final Drive Ratio	4.5:1
PM to wheel Ratio	2.9:1
Pump Motor	45 cc/rev
Accumulator Vol.	23 L
Max. Pressure	344 bars
Oil Tanks Vol.	30 L
Hybrid Vehicle Mass	895 kg

VEHICLE SYSTEM MODELING

The dynamometer tests conducted at the US EPA NVFEL provided a rich set of data for the system modeling and calibration. A baseline EV model was first developed and used as a platform for the further hybridization and energy management strategy study. This baseline model consists of

battery model, driver model, DC motor model, DC slave controller, and vehicle dynamic model. The preview was added to the driver model to reduce the velocity overshoot. A physics-based DC series wound motor model was developed as the primary power source [5]. The DC motor model is accurate under certain conditions, however, magnetic flux saturation and losses due to commutator switching have a significant impact on the mutual inductance factor. A 3D map was derived from the testing data to predict the mutual inductance factor under varying speed and torque. The testing data from US EPA NVFEL covers most typical driving styles from aggressive stop-go to moderate cruising, and also includes standard UDDS driving cycle, where the maximum speed was limited to 35mph to match the Xebra specifications. Thus, the baseline model was calibrated and validated with a variety of data collected under different driving cycles.

After validating the baseline EV model with actual testing data, hydraulic system was added to build the hybrid model. The hydraulic pump motor model is based on Wilson's equations and work of Purmovahed et al. [6]. The model accounts for both volumetric and torque losses in the pump motor, the volumetric losses include laminar leakage loss, turbulent leakage and the loss due to fluid compressibility. Torque losses include losses due to fluid viscosity and mechanical friction. The hydraulic accumulator is modeled based on the thermodynamic analysis considering the energy conservation for the gas side and Benedict-Webb-Rubin (BWR) equations for real gas properties [6]. The hydraulic accumulator model can predict both the pressure and temperature change during discharging and charging. More details about the DC motor, hydraulic pump motor, vehicle dynamics, driver model are available in references [5]. The whole HEHV model is shown in the Fig. 3.

ENHANCED BATTERY SOC ESTIMATION

Battery state-of-charge (SOC) is vital in the evaluation of the energy saving in this study. The battery capacity is usually specified for a certain discharge time of n hours, for example, $C_n = 200$ Ah means that 200 Ah is delivered if discharged at such a rate that the discharge time is n hours. The discharge rate can be calculated by Eq. (1)

$$I_n = \frac{C_n}{n} \quad (1)$$

According to Peukert's findings [7], the relationship between battery usable capacity C_{n1} and the discharge rate I_{n1} can be expressed as Eq. (2)

$$C_{n1} = C_n \left(\frac{I_n}{I_{n1}} \right)^{pc-1} \quad (2)$$

Where C_{n1} is the usable capacity that the battery will deliver if the discharged at such a rate that the discharge time is n_1 (h). pc is the "Peukert coefficient" (usually between 1 and 2) unique to a battery of a certain make and model [7].

Peukert's findings show the impact of different discharge rates on the battery usable capacity. Eq. (2) can be used to calculate the usable capacity under constant discharging. However, due to the non-uniform power demand over the driving cycle, the discharging current varies all the time through the driving cycle, which causes troubles to use Peukert's equation to calculate the usable capacity. Inaccurate usable capacity estimation leads to poor SOC prediction. Thus, an enhanced battery model was developed in order to improve the SOC estimation under varying discharging rate.

As a starting point, a simplified equivalent circuit model (shown in Fig. 4) for lead-acid pack was used based on the equivalent circuitry introduced by M. Ceraolo [8].

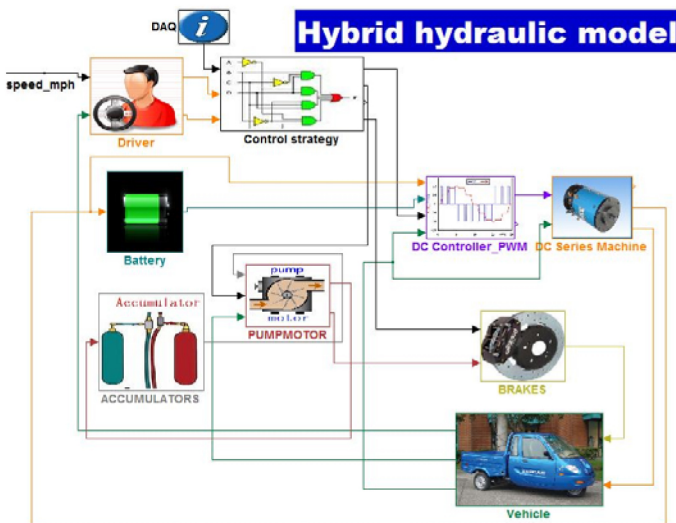


Figure 3. Hydraulic-Electric Hybrid Vehicle (HEHV) Simulation Model.

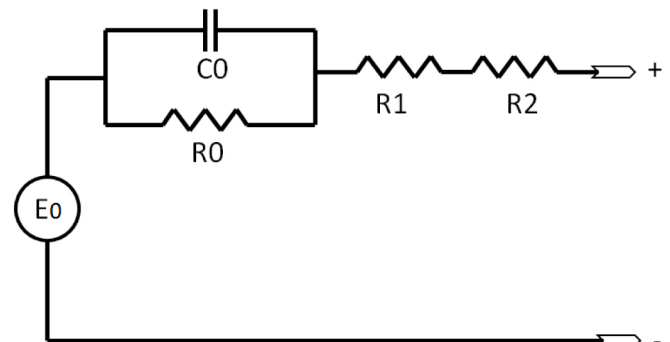


Figure 4. Simplified equivalent circuit model for the lead-acid battery pack. [8]

The governing equations are shown in Eqs. (3), (4), (5), (6), (7). More details are available in the reference [5].

$$E_0 = E_{00} - K_E(1 - \text{SOC}) \quad (3)$$

$$C_0 = \frac{\tau_1}{R_1} \quad (4)$$

$$R_0 = -R_{00} \ln \text{SOC} \quad (5)$$

$$R_1 = R_{10} \frac{\exp[A_{11}(1 - \text{SOC})]}{1 + \exp(A_{12}I/I^*)} \quad (6)$$

$$R_2 = R_{20}[1 + A_2(1 - \text{SOC})] \quad (7)$$

The modeled electromotive force, capacitance, and resistances are represented by E_0 , C_0 , R_0 , R_1 , and R_2 , respectively. These variables are dependent upon parameters which were tuned to fit test data. The detailed parameters are shown in Table 2.

Table 2. Battery Parameters.

E_{00}	78.2 V
K_E	7.56
τ_1	60.082 s
R_{00}	0.027958 Ohm
R_{10}	0.13605 Ohm
A_{11}	-10.694
A_{12}	-3.8789
R_{20}	0.02569 Ohm
A_2	-0.3005

The above equivalent circuit model is very accurate in constant discharging, but has a poor capability to estimate SOC under varying discharge. To solve this problem, an enhanced SOC estimation algorithm is introduced to the battery model [9].

The SOC in the above model is calculated by Eq. (8).

$$\text{SOC} = 1 - \frac{Q}{C} \quad (8)$$

Where C is the battery nominal capacity, Q is the total amount of energy (Ah) discharged. Because the usable capacity changes under different discharging patterns, the C should also be changed accordingly. Rather than changing the denominator C , the enhanced SOC algorithm adjusts the numerator Q according to the discharging patterns. Eq. (9) is used to calculate the Q_e under different discharge patterns.

$$Q_e = \int_0^T \alpha(i) i(t) dt - Q_{reg} \quad (9)$$

Q_{reg} is a term introduced for Ah reactivated by electrolyte diffusion during pauses. Alpha is the penalty factor for different current. More details are available in the reference [5].

Battery Discharge Tests

Battery discharging data was recorded over different driving cycles (including 3 acceleration cycles with different acceleration rates, 3 steady state cycles with different steady speeds), as shown in Fig. 5.

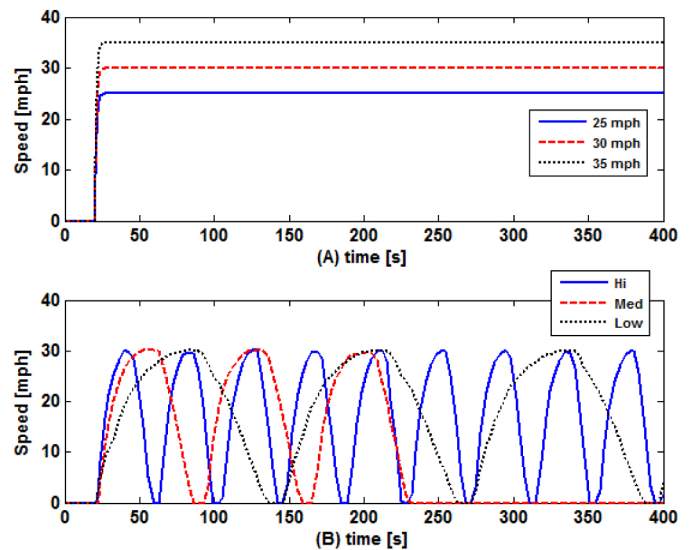


Figure 5. -A) Steady state cycles, and B) acceleration cycles

In Fig. 6, compared with steady state traces, the acceleration traces have many pauses between accelerations. Energy is reactivated by electrolyte diffusion during pauses, which leads to more usable energy from the battery. In both steady state and acceleration traces, the total energy from the battery increases as the average current from the battery decreases. And, higher discharge rate also causes the loss of conductivity between adjacent particles in the active material matrix, which leads to uneven current distributions and higher stress on the cell [10], [11]. This increased stress will likely lead to shorter battery life.

Therefore, in order to get more energy from the lead-acid battery and protect the battery health, one of the objectives of the preliminary rule based control strategy for HEHV is to keep the battery discharge rate as low as possible.