

Low-Cost Pathway to Ultra Efficient City Car: Series Hydraulic Hybrid System with Optimized Supervisory Control

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ABSTRACT

A series hydraulic hybrid concept (SHHV) has been explored as a potential pathway to an ultra-efficient city vehicle. Intended markets would be congested metropolitan areas, particularly in developing countries. The target fuel economy was ~100 mpg or 2.4 l/100km in city driving. Such an ambitious target requires multiple measures, i.e. low mass, favorable aerodynamics and ultra-efficient powertrain. The series hydraulic hybrid powertrain has been designed and analyzed for the selected light and aerodynamic platform with the expectation that (i) series configuration will maximize opportunities for regeneration and optimization of engine operation, (ii) inherent high power density of hydraulic propulsion and storage components will yield small, low-cost components, and (iii) high efficiency and high power limits for accumulator charging/discharging will enable very effective regeneration. The simulation study focused on the SHHV supervisory control development, to address the challenge of the low storage capacity of the accumulator. Two approaches were pursued, i.e. the thermostatic SOC control, and Stochastic Dynamic Programming for horizon optimization. The stochastic dynamic programming was setup using a set of naturalistic driving schedules, recorded in normal traffic. The analysis included additional degree of freedom, as the engine power demand was split into two variables, namely engine torque and speed. The results represent a significant departure from the conventional wisdom of operating the engine near its "sweet spot" and indicate what is preferred from the system stand-point. Predicted fuel economy over the EPA city schedule is ~93 mpg with engine idling, and ~110 mpg with engine shut-downs.

INTRODUCTION

The energy security and climate change challenges provide strong impetus for pursuing ultra-efficient vehicle concepts. The fuel economy of passenger vehicles shows very strong dependency on vehicle mass and aerodynamic drag, but hybridization enables departures from the trend and significant leaps in fuel economy improvements. The mechanisms for improvements include possibility for engine downsizing, optimization of engine operation, regeneration and engine shut-downs when the vehicle is stopped. The relative contribution of each depends on the architecture, e.g. parallel, power-split or series, selection of component and the type of application. In the context of a small passenger vehicle, the series configuration holds a promise of maximizing benefits through flexibility in controlling the engine and effective regeneration, since by default the traction motor will be sized generously. However, larger sizes of components in the hybrid driveline create a cost challenge. Hence, this study explores the potential of the hydraulic hybrid propulsion system, with the expectation that inherently high power density of hydraulic propulsion and storage components will yield compact, low-cost components [1]. While state-of-the art hydraulic pump/motor technology for mobile applications includes very advanced designs, manufacturing is mature and can easily be setup in any region of the world.

The series hydraulic hybrid driveline comprises propulsion pump/motors coupled to front and rear differentials and a hydro-pneumatic accumulator for energy storage. Coupling another hydraulic pump to the engine creates a power generation sub-system. The

particular advantages of hydraulics relevant for series architectures are the high-efficiency of the hydraulic pump/motor and high power limits for accumulator charging/discharging. They both contribute to very effective regeneration, and to some extent mitigate the effect of multiplying efficiencies in the propulsion chain. The comparatively low energy density of the hydraulic accumulator creates a special challenge and requires novel approaches to development of supervisory control.

The features of the parallel and series hydraulic hybrid vehicle architectures have been investigated before, particularly in the context of heavier vehicles [2, 3, 4] and the optimization of the design and control strategies led to impressive fuel economy improvements. However, the application of a series hydraulic hybrid concept to a very small car has only recently caught attention [5, 6, 7]. It is our goal to utilize some of the advanced methodologies previously demonstrated in studies of heavy vehicles to maximize the fuel economy of the SHHV system for a small car. The particular focus is on the supervisory control development. This is of critical importance for SHHV analysis since the low storage capacity of the hydraulic accumulator creates a special challenge for controller development, very different than in the case of electric system. The low-cost objective requires keeping the component sizes as small as possible, therefore emphasizing the impact of power management.

The aim of this paper is to demonstrate a hydraulic hybrid system for an ultra small city car. The target fuel economy is ~100 mpg or 2.4 l/100km in city driving. Hence, the baseline for the study is a first-generation Honda Insight IMA Hybrid Electric Vehicle, as its aluminum structure and aerodynamic body represent the state-of-the-art for a given category. The series hydraulic hybrid powertrain is designed and analyzed for the selected platform using a simulation developed in SIMULINK.

Two approaches for supervisory control development are pursued, i.e. the Thermostatic State-Of-Charge (SOC) control and Stochastic Dynamic Programming (SDP) for horizon optimization of the supervisory policy. In the case of Thermostatic control, we challenge the conventional wisdom of operating the engine at the “sweet spot” and search for optimal $SOC_{threshold}$ and power threshold during charging. In the SDP investigation, we take the notion that system effects dominate over the component-centric approach a step further. Namely, the technique includes selection of engine torque and speed, rather than just the power level, thus allowing departures from the best BSFC line if it benefits the overall powertrain efficiency.

The paper is organized in three major sections. First, we explain the modeling of the baseline Honda Insight HEV. This includes in-depth review of its control strategies and electrical system operation based on data available in literature [8]. The second section proposes the new

series hydraulic hybrid vehicle configuration. Modeling of hydraulic components and integration of the complete SHHV system is included. Detailed description of the two control approaches follows, i.e. the Thermostatic SOC management and SDP horizon-optimization. The stochastic dynamic programming is setup using a set of naturalistic driving schedules, recorded in normal traffic. Results of both supervisory control methodologies are discussed to uncover the mechanism of fuel economy improvements. Finally, we discuss the findings and the compare the fuel economy results of the SHHV vehicle to the baseline IMA HEV. The paper ends with conclusions.

BASLINE ISA HYBRID CONFIGURATION

A low cost city car with very high fuel economy will require a very light body with superb aerodynamics. Honda Insight (first generation) is used as a starting point for a light vehicle platform because it represents the state-of-the art in addressing both the light weight and aerodynamic drag. Honda Insight is a pre-transmission parallel electric hybrid, as shown on the schematic in Figure 1. The motor augments the engine torque under high load and hence is also called Integrated Motor Assist (IMA). Honda Insight does not have a conventional alternator and uses the IMA for other electrical needs.

Honda Insight in North America has a 5 speed manual transmission. Manual transmission offers higher efficiencies at steady state speeds but forces the driver to choose the optimal gearing to keep engine operation near optimal. High fuel economy of Honda Insight is attributed to its small engine and attention to every source of vehicle losses. The impact of hybridization, including the ability to regenerate will be highlighted later in the paper through comparisons with the SHHV.

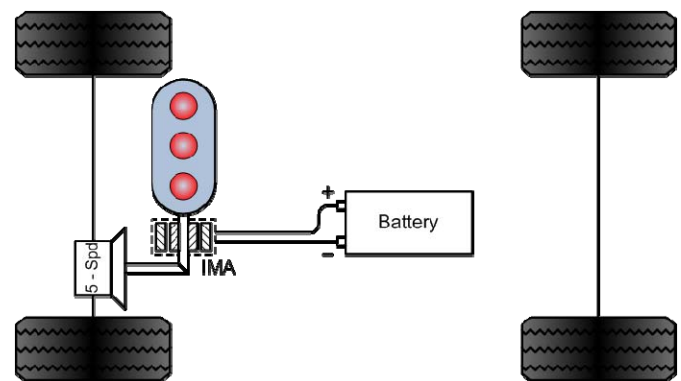


Figure 1 : Hybrid electric vehicle architecture with Integrated Motor Alternator

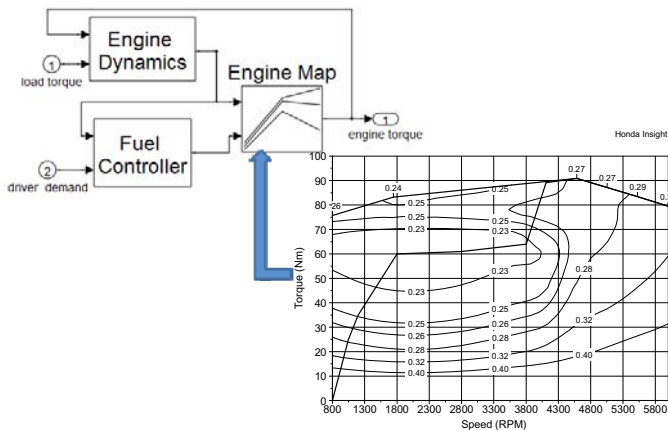
Honda Insight model is used as a baseline vehicle for performance and fuel consumption comparison. The model will be validated using the published results on Honda Insight, [8]. Table 1 gives the specifications of the baseline Honda Insight vehicle.

Table 1 : Honda Insight Specifications

Engine	Description	1L VTEC
	Max. Power	49kW @ 6000 RPM
	Max. Torque	90 Nm @ 4600 RPM
Motor	Design	Brushless Permanent Magnet DC
	Max Power	10 kW
Battery	Design	Nickel Metal Hydride spiral wound cells
	Capacity	0.9 kWhr
Vehicle	Type	Sedan
	Weight	962 kg
	Coeff. of Drag	0.25
	Frontal Area	1.9 m ²
	Tire Radius	0.275 m
	Final Drive Ratio	3.21
Transmission	Design	5 speed Manual
	Gear Ratio	3.46,1.75,1.1,0.86,0.71

ENGINE

The engine model takes driver command and external load torque as input and calculates the engine speed and fuel consumption. The engine model is based on look-up table which outputs engine torque as a function of fuel input and engine speed. The look-up table is obtained from ADVISOR, [9] and is based on testing done by NREL and ANL. Figure 2 give the SIMULINK implementation of engine.

**Figure 2 : Engine model in SIMULINK**

TRANSMISSION AND VEHICLE

Honda Insight has a 5 speed manual transmission. The gearbox is modeled as a finite state machine with different gear being the different states of the system. A blending function is added to simulate inertia and torque phase during gear shift. Blending function provides a fast and fairly accurate way of incorporating these phases. The gear shifting logic is based on vehicle speed, according to test procedures laid out by the EPA.

The clutch is modeled based on the normal pressure theory. The maximum torque transmitted is proportional to the normal force applied. There are two distinct modes of operation in clutch: 1) slipping - the two plates have differing angular velocities and, 2) lockup - the two plates rotate together. Controller logic engages and disengages the clutch to reduce the torque discontinuity during clutch engagement/disengagement.

$$T_{f \max k} = \frac{2}{3} R F_n \mu_k \quad (1)$$

$$T_d = \text{sgn}(\omega_e - \omega_v) T_{f \max k} \quad (2)$$

where ω_e and ω_v are the speeds across clutch, $T_{f \max k}$ is the clutch max torque capacity, R is clutch radius, F_n is the normal force on clutch and μ_k is the friction coefficient.

The vehicle is modeled as point mass system and pitch plane dynamics are ignored. This is deemed sufficient for the fuel economy studies. The resistive forces were modeled as rolling and drag resistance. The vehicle also contains a brake model, which acts as a coulombic friction device.

ELECTRICAL SYSTEM

Electrical sub-systems is composed of a Brushless Permanent Magnet DC motor, and a Nickel Metal Hydride battery. Their characteristics are described in the following.

Battery - is modeled as an equivalent circuit comprising a perfect open circuit voltage source, V_{OC} in series with an effective internal resistance, R_{int} based on ADVISOR data [9]. V_{OC} and R_{int} are computed as piecewise linear functions of SOC. There are two such functions for computing R_{int} , one for discharge power and another for charge power. Equivalent circuit current is solved from the V_{OC} , R_{int} and maximum power battery can deliver. The battery current is then used to update the effective SOC of the battery. The thermal model of the battery calculates the module temperature, which is fed back to be used in determining the performance parameters.

Motor - is modeled as 2D lookup table [9] with efficiency of the motor as function of motor torque and motor speed. The motor dynamics are approximated by a first-order lag. However, due to the battery power and motor torque limit, the final motor dynamics assume the following form

$$T_m = \begin{cases} \min(T_{m_req}, T_{m_max}, T_{m_bat}) \frac{\lambda_m}{s + \lambda_m}, & \text{motor} \\ \max(T_{m_req}, T_{m_max}, T_{m_bat}) \frac{\lambda_m}{s + \lambda_m}, & \text{generator} \end{cases} \quad (3)$$

where T_m is the motor torque, T_{m_req} is the requested motor torque, T_{m_max} is the maximum torque motor can generate at given condition and T_{m_bat} is the max motor torque due to battery limitations. λ_m is the inverse of the motor time constant.

SUPERVISORY CONTROLLER

A rule based control strategy is developed for Insight based on data from testing done by Argonne National Laboratory (ANL) and National Renewable Energy Laboratory (NREL) [8]. Rule-based controller design relies on engineering intuition and is typically component-centric. Our primary goal here is to establish a representative baseline for comparison with the HHV, hence we relied on the published data to achieve behavior observed during testing of the production vehicle [8].

The vehicle power demands are managed through a supervisory controller. The strategy is influenced by the fact that the vehicle with IMA represents a very mild hybrid. During acceleration, the engine is the prime mover and most of the propulsion torque comes from the engine. The motor supplements additional torque to keep the engine operation near the optimal except during 1st gear driving. This is done to keep motor from operating at low efficiency regions. The motor also acts as alternator for the vehicle and provides the energy for accessories. During braking event, the controller commands motor to act as an alternator for recharging the battery. Friction brakes are applied when the power demand exceeds either motor or battery capabilities, or if vehicle speed is below certain speed.

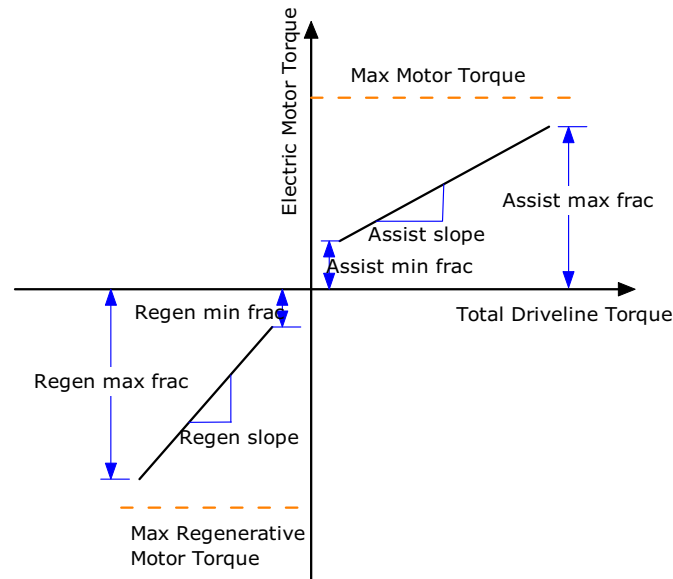


Figure 3 : Honda Insight strategy for controlling motor torque based on total driveline torque [9].

Motor demand during acceleration and deceleration are based on ratio of total driveline torque required by the vehicle. The SOC of battery is maintained near 0.68 to increase battery life. Based on driver commands, the

controller calculates the power demand by the vehicle. Positive power demand is fed to the driving logic which calculates the torque split between engine and motor. Motor torque is calculated based on gear number and total driveline torque required using the logic shown in Figure 3 [9].

Based on the torque and rate of acceleration, the electric motor assists the IC Engine, producing around 10 Nm of torque.

- There is no electric assist in the first gear.
- In case SOC drops below a threshold value, engine provides all the torque.
- If the power demand crosses a predefined value with SOC below threshold, the motor is operated as generator to trickle charge the battery until desired SOC is reached.

In case of negative power demand, the braking logic calculates the ratio between motor braking and friction braking.

- During regeneration, the electric motor provides a portion of the negative torque available to the driveline.
- At low vehicle speeds, typically below 10 mph, the braking is primarily by the friction brakes as the amount of kinetic energy diminishes.

For the Honda Insight, the engine remains *on* in most cases. The following criteria define when the engine is allowed to shut off. The engine in the Insight will only shut down if all of the following conditions are satisfied

- Engine is warm.
- Battery SOC is greater than the low SOC set point.
- Vehicle is decelerating or stopped; no gear shifting

RESULTS – BASELINE HYBRID ELECTRIC VEHICLE (IMA)

The Honda Insight SIMULINK model was simulated over different EPA cycles. Figure 4 to Figure 6 show the engine and motor operation during FUDS cycle. The engine is operated at low speeds to allow higher BSFC region operation. However, the dominant regimes are still characterized by low load, as a result of the relatively mild power requirements during FUDS and constraints imposed by the mechanical driveline. The predicted traces of motor torque vs. driveline torque indicate success in implementing the blending strategy seen in the production IMA vehicle (see Figure 5). The motor runs in a favorable speed range, but at relatively modest loads (see Figure 6). The overall low driveline power requirements, as well as management of a tradeoff between drivability and efficiency, prevents the motor from running at higher loads and closer to maximum efficiency. The electrical machine is used very aggressively during regeneration.

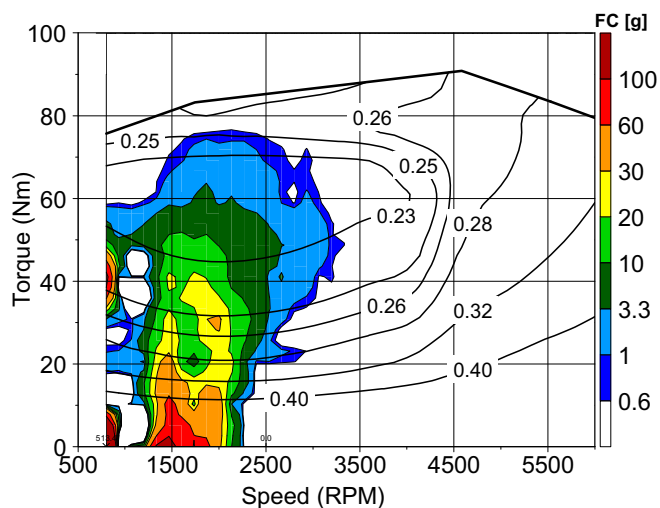


Figure 4 : Engine visitation points on the BSFC map, with color scale indicating the relative amount of fuel consumed in a given zone during FUDS for baseline IMA Hybrid Electric Vehicle

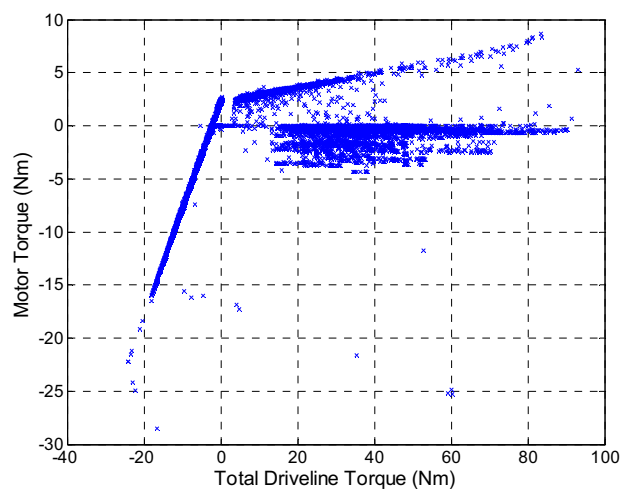


Figure 5 : Predicted IMA torque as a function of total driveline demand, illustrating the IMA control strategy.

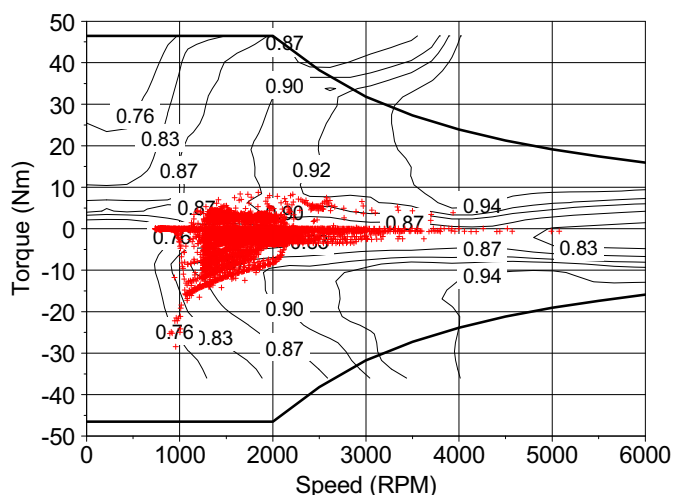


Figure 6 : Motor operation visitation points on the efficiency map during city driving (EPA FUD).

Figure 7 shows engine power, gear number and motor torque histories during part of the FUDS driving schedule. Figure 7b indicates that engine operates relatively close to the load-following mode due to a mild assist from IMA (see Figure 7d). The motor provides zero torque at launch (in 1st gear), as intended by the controller designers. Figure 7d also illustrates capturing of the braking energy around the 180-second mark, and during deceleration down to stand still at the end of this vehicle speed profile.

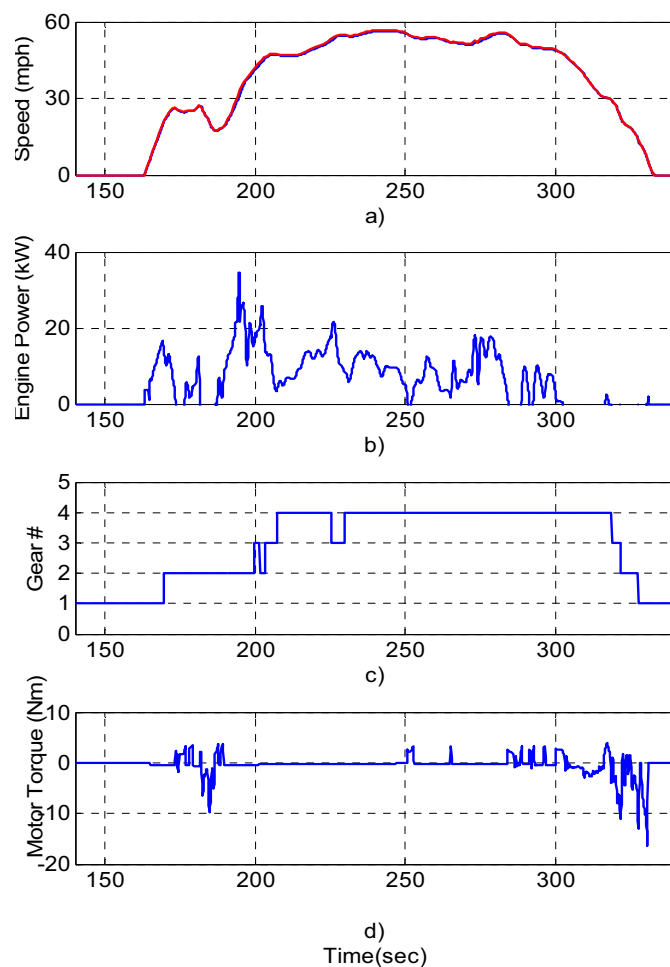


Figure 7 : Predicted interactions in the IMA HEV propulsion system: a) Vehicle Speed, b) Engine Power, c) Gear # and d) Motor Torque, for a section of FUDS cycle from 140 sec to 340 sec

From Table 2, it can be seen that the model over predicts the fuel economy over the published EPA values. This is mostly due to the fact that the model ignores modifications of engine fueling strategies during and after cold start. However, the same assumptions will be used in our subsequent study of the hydraulic hybrid powertrain, hence using the simulated values for IMA HEV fuel economy will ensure the fair comparison.