

Power-Split HEV Control Strategy Development with Refined Engine Transients

John Arata, Michael Leamy and Kenneth Cunefare
Georgia Institute of Technology

ABSTRACT

Power-split hybrid-electric vehicles (HEVs) employ two power paths between the internal combustion (IC) engine and the driven wheels routed through gearing and electric machines (EMs) composing an electrically variable transmission (EVT). The EVT allows IC engine control such that rotational speed can be independent of vehicle speed at all times. By breaking the rigid mechanical connection between the IC engine and the driven wheels, the EVT allows the IC engine to operate in the most efficient region of its characteristic brake specific fuel consumption (BSFC) map. If the most efficient IC engine operating point produces more power than is requested by the driver, the excess IC engine power can be stored in the energy storage system (ESS) and used later. Conversely, if the most efficient IC engine operating point does not meet the power request of the driver, the ESS delivers the difference to the wheels through the EMs. Therefore with an intelligent supervisory control strategy, power-split architectures can advantageously combine traditional series and parallel power paths.

Previous work compared two different power-split HEV powertrains using a 2-term cost function and steady-state backward-looking simulation (BLS). BLS was used to find battery power management strategies resulting in minimized fuel consumption over a user-defined drive-cycle. The supervisory control strategy design approach amounts to an exhaustive search over all kinematically *admissible* engine and EM operating points, leading to a minimized instantaneous cost function. While the approach provides a valuable comparison of two architectures, non-ideal engine speed fluctuations result, preventing the control strategy from being effectively implemented. In the present work, two approaches are investigated for *refining* IC engine state transitions for use in an implemented control strategy: i) smoothing the 2-term cost function optimization results, and ii) introducing a 3-term cost function. These approaches are tested and verified in high-fidelity forward-looking simulations (FLSs). It is found that both refinement approaches effectively reduce engine speed transitions, and result in fuel economy (FE) estimates and component operation which compare well to BLS results. It is further found that the 3-term cost function finds more efficient operating points than the smoothed 2-term cost function approach. From the investigations carried out in this paper, a two-phase control strategy development process is suggested where control strategies are first explored using highly-efficient steady-state BLS models, and then further tested and refined in high-fidelity FLS models. Favorable comparison of BLS and FLS results justify the efficacy of the two-phased process, suggesting rapid and effective development of implementable power-split HEV supervisory control strategies.

CITATION: Arata, J., Leamy, M. and Cunefare, K., "Power-Split HEV Control Strategy Development with Refined Engine Transients," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-0629.

INTRODUCTION

IC engine operation is best suited for steady power delivery (e.g., highway driving at constant cruising speed), as opposed to dynamic power delivery (e.g., stop-and-go or variable speed driving). For dynamic power delivery over a large range of vehicle speeds, conventionally propelled vehicles and their transmissions are limited by a finite number of fixed-gear (FG) ratios, preventing efficient engine operation at all vehicle speeds and power requirements. Stricter Corporate Average Fuel Economy (CAFE) standards

[1] and Tier 2 [2] regulations have presented original equipment manufacturers (OEMs) with renewed design challenges, necessitating the need to more efficiently operate vehicles' IC engines. HEVs are one promising technology for doing so. By reducing IC engine dynamic operation, and by further recovering braking energy, HEVs increase fuel economy and reduce emissions.

The three fundamental HEV architectures in use today are series, parallel and power-split. In series architectures, the IC engine operates independently of the road-load conditions by

driving a generator, providing steady and highly-efficient IC operation. However, the overall system efficiency in a series architecture is limited by electro-mechanical power delivery, which is less efficient than pure mechanical delivery due to energy conversion losses. Parallel architectures employ a highly-efficient mechanical path to transmit IC engine power to the driven wheels, but engine speed and efficiency is still constrained by a finite number of FG ratios. Power-split HEV designs combine the two series and parallel designs by providing two power paths between the IC engine and the driven wheels through an EVT. An EVT allows IC engine control such that rotational speed is independent of vehicle speed at all times. The addition of an on-board energy storage system (ESS), such as a high voltage electric energy buffer, and EMs also allow IC engine power to be chosen independently of wheel power. Thus by breaking the rigid mechanical connection between the IC engine and the driven wheels, EVTs allow the IC engine to be controlled such that it operates in the most efficient region of its characteristic BSFC map. Note that if the most efficient IC engine operating point produces more power than is requested by the driver, the excess IC engine power can be stored in the ESS and advantageously used in the future. Conversely, if the most efficient IC engine operating point does not meet the power request of the driver, the EMs powered by the ESS deliver the difference to the wheels. Therefore with an intelligent supervisory control strategy, power-split architectures can advantageously operate serial and parallel power paths between the vehicle's IC engine and driven wheels.

A number of optimization methods have been used to design HEV supervisory control strategies. Time-horizon *dependent* optimization methods assume *a priori* knowledge of the entire drive-cycle. Dynamic programming (DP) is one approach where the globally optimum solution is found by optimizing numerically with respect to a specific drive-cycle (e.g., DP results can be sub-optimal for another drive-cycle) [3, 4, 5]. Pontryagin's Minimum Principle and Pareto Optimization have also been applied to the HEV supervisory control strategy design challenge [6, 7, 8], providing an analytical formulation that also considers the entire driving cycle. Stochastic dynamic programming (SDP) is yet another approach which does not optimize solutions for a specific drive-cycle, but instead for assumed road-load conditions with known probabilities [9, 10]. However, SDP results can be sub-optimal or charge depleting when applied to a drive-cycle with drastically different road-load conditions than those assumed. Note further that time-horizon *dependent* routines optimize a cost function over an entire driving schedule and are therefore difficult to implement in general.

Time-horizon *independent* optimization approaches have also been used to design HEV supervisory control strategies. Heuristic rule-based methods, and fuzzy logic control with optimized thresholds and transitions, have each been employed to address the supervisory control design problem [11, 12]. Other time-horizon independent techniques require

minimizing an instantaneous cost function to find the most efficient split between on-board energy sources. By translating electric power into an equivalent energy consumption term of the cost function, total consumption can be minimized [13]. Note that instantaneous equivalent minimization strategies have been shown to be close to the optimal DP results and good candidates for developing implementable control algorithms, but lead to scattered engine power commands [14].

In previous work [13], BLS and steady-state equations were used to develop an optimized supervisory control approach and subsequent comparison of the front-wheel drive (FWD) Toyota Hybrid System II (THS-II) with the FWD General Motors Allison Hybrid System II (GM AHS-II). The supervisory control design approach is summarized in Figure 1. At each instant of the drive-cycle, an input-state $\mathbf{S}_{in} = [T_o \ \omega_o \ \text{SOC}]$ is defined containing the road-load condition (transmission output torque T_o and transmission output speed ω_o) and battery state-of-charge (SOC). The road-load condition, constraints on engine and transmission rotational speeds, and the achievable transmission speed ratios (SRs) define kinematically *admissible* regions of the IC engine BSFC and torque maps. Each *admissible* engine operating point then contributes to an output-state $\mathbf{S}_{out} = [\omega_e \ T_e \ T_{M/GB}]$ containing IC engine speed ω_e , IC engine torque T_e , and output motor-generator torque $T_{M/GB}$. The goal of the supervisory controller is to choose an $\mathbf{S}_{out}$ for each $\mathbf{S}_{in}$, which maximizes the efficient operation of the powertrain. Note that this output state may be one requiring excess power storage in the ESS. The approach employed is to then exhaustively search all kinematically *admissible* input operating points and to then minimize a two-term instantaneous cost function. The two-term cost function used is given by,

$$C = P_f + sP_B, \quad (1)$$

where $P_f = H_f \dot{m}_f$ is the power resulting from burning liquid fuel in the IC engine, H_f is the heating value of the fuel, $\dot{m}_f$ is the flow rate of fuel into the engine, and s is the equivalence factor used to weight battery power based on SOC. The electric power equivalence factor s is used to balance fuel and battery power consumption. By varying the form of s , different battery power management strategies can be assessed. In [13], s was varied to find battery power management strategies that resulted in maximized FE.

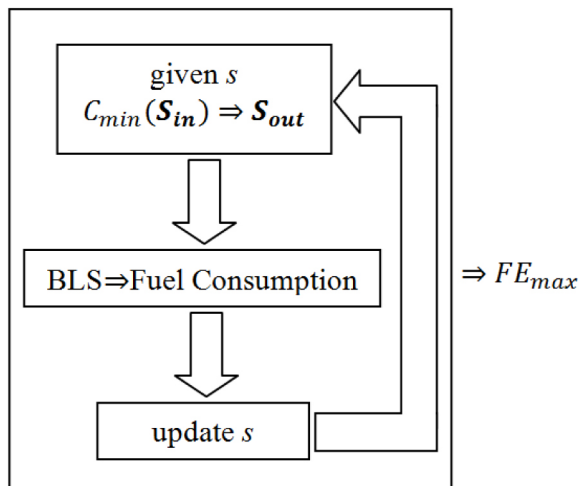


Figure 1. 2-term cost function supervisory control strategy design approach [13]

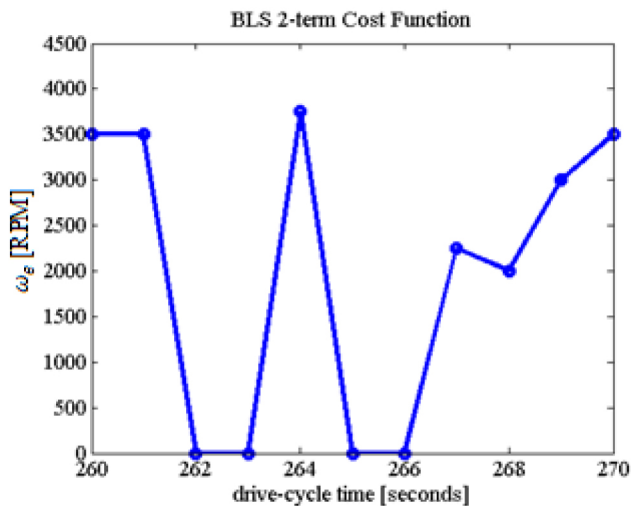


Figure 2. THS-II UDDS 2-term cost function engine speed in BLS

Although the described approach is useful for comparing and contrasting architectures, it does not easily translate to an implementable control strategy since i) the 2-term cost function does not penalize rapid transitions in IC engine speed, and ii) the steady-state model does not reveal detrimental transient behavior due to IC engine rotational inertia. This is consistent with other works which also neglect speed transients of various powertrain components and assume that engine speed can rise as fast as needed [15, 16]. The downside of the BLS 2-term optimization is that it yields *unrefined* state transitions where IC engine speed varies rapidly in time, as evident in Figure 2. This figure plots sample drive cycle simulation results from [13] for the THS-II system where rapid engine speed fluctuations exist. As previously noted, IC engines are best suited for constant speed operation. The IC engine state transitions evident in

Figure 2 are not only difficult to achieve, but due to engine inertia, may also force actual powertrain operation to employ inferior output states while attempting to achieve the engine speed fluctuations. Problematic IC engine state transitions can also jeopardize consumer acceptability with unnecessary powertrain noise, vibration, and harshness (NVH). For these reasons, two methods will be investigated herein for *refining* IC engine state transitions: i) smoothing the 2-term optimization results, and ii) introducing a 3-term cost function.

CONTROL STRATEGY OVERVIEW

An implementable supervisory control strategy, with *refined* engine speed transitions, is developed next using backward-looking and forward-looking simulations. Computationally-efficient BLS employs steady-state modeling equations and explicit following of a drive cycle to compute vehicle acceleration/deceleration and subsequent power required. It is not constrained by the need for a stable time step, is quick to compute, and is straight-forward to program. On the other hand, FLS calculations are carried out in a high-fidelity and forward time-marching fashion using equations of motion. A driver request is derived from a drive cycle and translated into the required energy output demanded of powertrain components (e.g., EMs, IC engine, and the high voltage battery). Importantly, transient behavior of components with non-negligible inertia is captured in a FLS model, and not in a BLS model. FLS captures transient motions using high-order integration schemes with relatively small variable time-steps to solve the following differential equations of motion for each component,

$$\sum F = m \frac{dv}{dt}, \quad (2)$$

$$\sum M = \frac{dH}{dt}. \quad (3)$$

In Equations (2) and (3) F denotes the external force on the component, m its mass, V its velocity, M the resultant external moment, and H the angular momentum. These equations of motion are integrated to yield the vehicle's state from one time-step to the next.

Since BLS is modeled with steady-state equations, it can be used to produce results quickly and easily. More accurate FLS can then be used to verify and tune supervisory control strategies developed in BLS. FLS is particularly desirable for hardware development and detailed control strategy simulation (e.g., frequency analysis) but has slower execution times relative to BLS. For these reasons, this work suggests the two phase development process shown in Figure 3 to design implementable HEV supervisory control strategies.

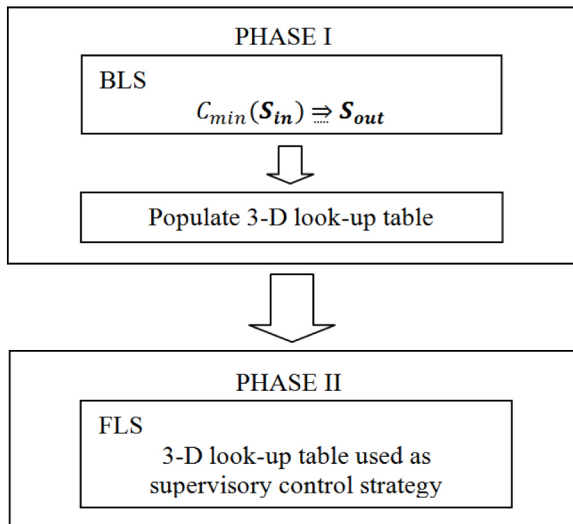


Figure 3. Two phase supervisory control strategy development process

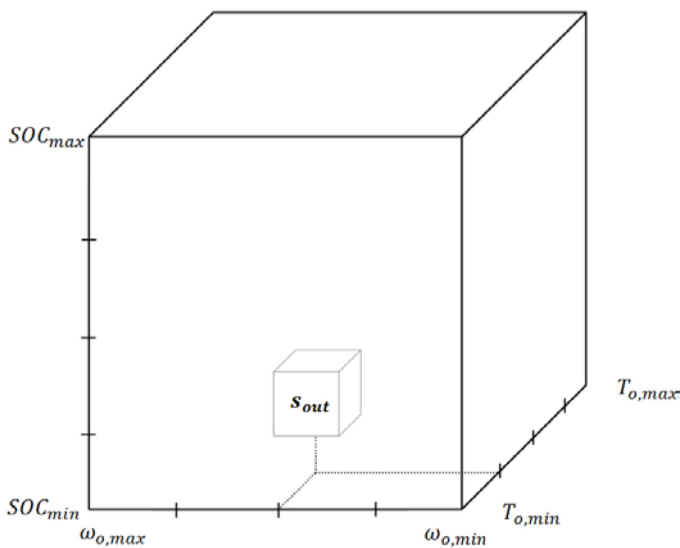


Figure 4. Three-dimensional structure storing pre-computed solutions

In Phase I, all expected road-load conditions, kinematic constraints, and SOC's are used to populate a look-up table which given an input-state S_{in} , returns an optimized output-state S_{out} . In Phase I, the input-state S_{in} implies the output-state S_{out} through the instantaneous minimization of the cost function C , as described in the Introduction. In Phase II, the generated look-up table is implemented as an open-loop control strategy in FLS. The three-dimensional structure in Figure 4 can be used to store the control strategy where S_{in} is the table's input and S_{out} is the table's output. Note that to implement in FLS, each axis in Figure 4 is discretized into a finite number of values. In FLS high-order integration routines require stable time steps as small as nanoseconds

(ns), which is an unnecessarily frequent sampling time for the control strategy. Thus for computational efficiency, control strategy output-states are sampled at a set frequency much lower than that of time stepping, and linear interpolation is used when necessary. The transient response of the steady-state Phase I control strategy is then studied in Phase II and any necessary refinements are carried-out.

POWERTRAIN AND SIMULATION MODELS

This section provides technical background on the operation of the Toyota THS-II architecture and its representation using backward-and forward-looking simulation models. Note that all drive cycle simulations, whether backward-looking or forward-looking, are performed using the UDDS cycle [17]. The *refinement* of engine transients will be considered in the context of the THS-II system, but equally applies to *refining* the engine transients in the GM AHS-II system.

THS-II BACKWARD-LOOKING MODEL

The example power-split architecture considered is based on Toyota's THS-II system, as found in the Prius. The THS-II powertrain is composed of several key components: battery, IC engine, two inverters, two motor-generator EMs (M/GA and M/GB), and a planetary power-split device (PSD). Refer to [13] for a complete definition of THS-II notations used herein. Figure 5 displays the FWD THS-II powertrain along with the positive power conventions assumed throughout this work.

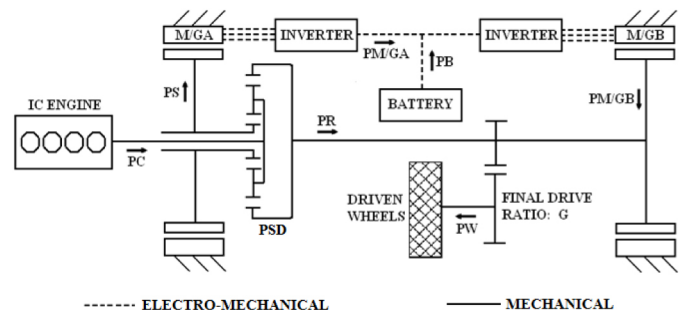


Figure 5. Cut-away of the THS-II powertrain, power of each component and their positive conventions are indicated

Splitting of IC engine power into the electro-mechanical power path is enabled by the PSD. The PSD allows IC engine power to be simultaneously transferred to M/GA and the wheels. The carrier shaft of the PSD is directly linked to the engine and mechanically transmits the motive engine power to the outer ring gear and inner sun gear via pinion gears. M/GA typically generates electricity and is connected to the sun gear, giving rise to the serial power path. The ring gear is directly coupled to the larger propulsive M/GB and the front axle through fixed reduction gearing, giving rise to the

parallel path. The smaller M/GA is controlled such that the machine is capable of dictating the SR (ratio of input engine speed to output ring gear speed) through the transmission using the PSD sun gear [18]. The larger M/GB does not affect the speed ratio as it is connected directly to the wheels. The rotational speed of the common M/GB -output shaft $\omega_{M/GB} = \omega_o$ is proportional to vehicle speed by the final-drive ratio G . Thus for any prescribed vehicle speed, transmission output angular velocity ω_o is known. Both EMs are capable of bi-directional energy flow by operating as either a motor or as a generator; however M/GA converts electric power into mechanical power when its speed is negative or it is boosting engine speed [8]. The battery is an energy buffer that cannot be externally recharged; therefore battery SOC must be maintained within usable limits or the integrity of the battery is jeopardized.

The PSD is a three axis simple planetary gearset with three pinion gears, as shown in Figure 6.

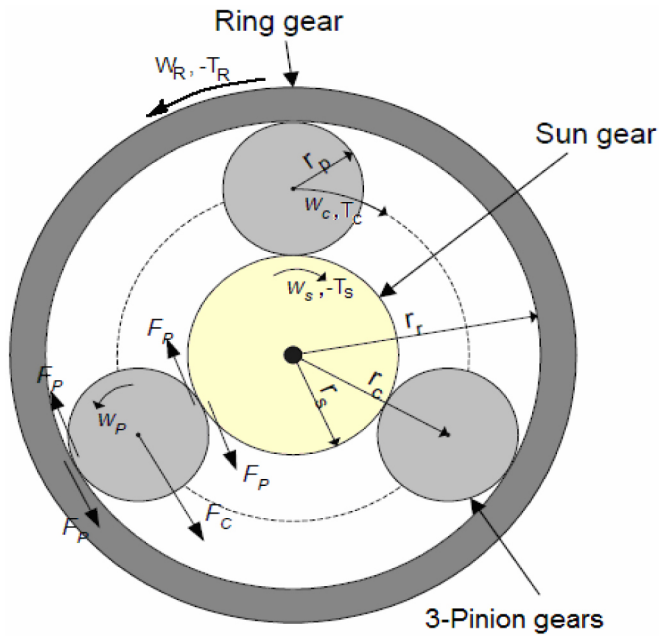


Figure 6. A simple planetary gearset is the PSD in the THS-II powertrain, adopted from [19] and reproduced from [20].

The characteristic ratio for the planetary gearset R is defined as,

$$R = \frac{r_{sun}}{r_{ring}} = \frac{N_{sun}}{N_{ring}}, \quad (4)$$

where r is the radius and N is the number of teeth on the respective gears. Torque constraints on the simple planetary are derived by imposing a power balance neglecting gearset accelerations and losses, reducing to the steady-state torque relationship,

$$T_C = (1 + R)T_R = \frac{1+R}{R}T_S, \quad (5)$$

where T_C , T_R , and T_S are the carrier, ring, and sun gear torques respectively. Kinematic speed constraints based on equal speeds at points of contact where gear meshing occurs,

$$(1 + R)\omega_C - \omega_R - R\omega_S = 0, \quad (6)$$

exist such that ω_C , ω_R , and ω_S are the carrier, ring, and sun gear rotational velocities respectively. The kinematic relationships in Equations (5) and (6) model the steady-state operation of the PSD. From these two equations, it can be noted there are two independent speeds and one independent torque constraining the power delivery through all branches of the THS-II PSD. In what follows we return to using torques T_e and $T_{M/GA}$ for T_C and T_S , respectively, where T_e denotes IC engine torque and $T_{M/GA}$ denotes M/GA torque. Similarly we will use angular velocities ω_e , ω_o , and $\omega_{M/GA}$ for ω_C , ω_R , and ω_S , respectively, where ω_e denotes the IC engine angular velocity and $\omega_{M/GA}$ denotes the angular velocity of EM M/GA . The kinematic torque and speed constraints of the THS-II PSD can therefore be expressed as,

$$T_e = (1 + R)T_R = \frac{1+R}{R}T_{M/GA}, \quad (7)$$

$$(1 + R)\omega_e - \omega_o - R\omega_{M/GA} = 0. \quad (8)$$

Two relevant facts regarding planetary gearsets are: i) when any two terminals are connected together, all three terminals rotate at the same speed in the same direction *i.e.*, the gearset becomes locked-up, and ii) when any terminal is stationary, no power flows through that terminal *i.e.*, the gearset reduces to a conventional two-terminal gearset.

THS-II FORWARD-LOOKING MODEL

The highest level of the THS-II FLS is shown in Figure 7. The vehicle parameters used to define this model are found in [21] and summarized in Table A.1. Of the parameters not found in [21], common values were assumed *i.e.*, EM inertias, IC engine inertia, etc. In the model, the difference between the simulated vehicle's speed and the drive-cycle's speed trace implies the acceleration and power required to follow the cycle. The driver model specifies the throttle position required to follow the user-defined drive-cycle and the controller stores the three-dimensional structure shown in Figure 4. The controller model routes required control signals to the plant's sub-models. As depicted, controller area network (CAN) signals are named System_Signals in the