

Hybrid Electric Vehicle Powertrain and Control Strategy Optimization to Maximize the Synergy with a Gasoline HCCI Engine

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ABSTRACT

This simulation study explores the potential synergy between the HCCI engine system and three hybrid electric vehicle (HEV) configurations, and proposes the supervisory control strategy that maximizes the benefits of combining these two technologies. HCCI operation significantly improves fuel efficiency at part load, while hybridization aims to reduce low load/low speed operation. Therefore, a key question arises: are the effects of these two technologies additive or overlapping? The HEV configurations include two parallel hybrids with varying degrees of electrification, e.g. with a 5kW integrated starter/motor ("Mild") and with a 10 kW electric machine ("Medium"), and a power-split hybrid. The engine is a dual-mode, SI-HCCI system and the engine map reflects the impact of HCCI on brake specific fuel consumption. The new HEV supervisory controller, called e-HCCI, is proposed considering two additional criteria: (i) maximize the time spent in the HCCI operating region, and (ii) minimize SI-HCCI mode transitions. The relative fuel economy improvements of using a dual-mode SI-HCCI engine over an SI engine for a conventional powertrain (non-hybrid) is 17%. When the dual-mode engine is used in the "Mild" HEV using the e-HCCI strategy, the percent improvement jumps to 35%. This indicates a strong synergy, and creates a very compelling case for the "Mild" parallel HEV w/ HCCI. Gains on a relative basis diminish somewhat with the "Medium" hybrid and significantly more with stronger power-split hybrids, as the latter typically moves engine load above the HCCI knock limit.

INTRODUCTION

Strict exhaust emission regulations, fuel economy requirements, and concerns pertaining to greenhouse gas

emissions and climate change stimulate investigations of new powertrain concepts. The newest regulations, such as a CO₂ limit of 120 g-CO₂/km by 2012 in Europe and the stringent fuel economy requirement from CAFE of 35.5 mpg by 2016 in the US, emphasize vehicle fuel efficiency. Such high fuel economy expectations cannot be met with incremental improvements of conventional powertrains; rather, a diverse set of solutions will likely be necessary. Specific technologies include advanced engines (e.g. gasoline HCCI, turbocharged downsized engines, high-boost diesels), light weight structures, advanced 7- or 8-speed transmissions, etc. However, a true vertical leap away from a correlation linking vehicle weight and fuel economy is possible only with hybrid technology [1]. The mechanisms enabling very significant fuel economy improvements without sacrificing vehicle performance or utility include optimization of engine operation, regeneration of braking energy, and engine start-stop. Hybrid electric vehicles (HEV) come in a variety of configurations and degrees of electrification or hybridization. The most prevalent configurations are parallel, such as systems introduced by Honda [2] and Nissan [3], and power-split, favored by Toyota [4], Ford [5], and GM [6]. Hybrid electric vehicles constitute almost 3% of the passenger car market, but that percentage is likely to increase significantly in the future.

The introduction of a larger number of hybrid vehicles and the tightening of fuel economy regulations bring up the question of the engine choice. A modern diesel engine would provide the most fuel-efficient option, but combining a very expensive engine with a hybrid leads to prohibitively high vehicle price. The downsized SI engine has been the choice favored by all major OEMs so far, but new technologies are on the horizon. The most promising of advanced gasoline

technologies is the Homogeneous Charge Compression Ignition (HCCI) engine, a high efficiency and low emissions alternative for conventional spark-ignition (SI) and diesel engines. HCCI engines take advantage of high compression ratios and very lean unthrottled operation, both of which result in higher fuel conversion efficiency [7, 8]. The low temperature homogeneous combustion, which is characteristic of HCCI, reduces NOx and soot emissions to negligible amounts [8]. The biggest challenge is control of ignition due to the lack of a direct trigger, as well as the limited operating range [9]. The high pressure-rise rates lead to an upper load knock-limit, while a misfire-limit prevents operation near idle. In order to cover the full operating range required by an engine in an automotive application, dual-mode operation (e.g. SI-HCCI) will likely be necessary. Nevertheless, this is an attractive package with a price significantly lower than an advanced diesel. The prospect of using the SI-HCCI dual-mode engine in a hybrid raises a fundamental question: are the effects of these two technologies additive or overlapping? If HCCI reduces the fuel consumption at low loads, and HEV systems provide flexibility in controlling the engine, such as load leveling, does pairing the two technologies effectively minimize HCCI operation and have diminishing returns, or is there a synergy between the two technologies? This paper aims to answer this fundamental question.

A recent study was conducted at Argonne National Lab with a similar intention: to observe and understand the effects of pairing a dual-mode SI-HCCI engine with various hybrid electric drivetrains [10]. They explored all types of hybrid electric drivetrains with varying degrees of electrification from a micro parallel to a series plug-in with a 40 mile all electric range. Although their study screens all types of hybrid electric drivetrains, their focus was on stronger hybrids, such as power-splits and plug-ins. Adjustments to the power-split control strategy were made in the case of the power-split systems, but there were no modifications to the parallel hybrid control strategy. The work reported here focuses on the development of a rule-based supervisory control strategy that maximizes the potential synergy between a parallel hybrid electric drivetrain and a dual-mode SI-HCCI engine. It was hypothesized that the combination of a relatively simple parallel HEV system and a dual-mode engine will result in a comparatively low vehicle cost, but that closer examination of engine operating strategies is required to improve the synergy and maximize the benefits.

The main hypothesis in this work is that managing mode transitions, i.e. reducing the transitions from HCCI to SI, will play a critical role in the success or failure of dual-mode engines. Because the operating conditions and engine parameters in SI and HCCI modes are very different, transitions between the two modes can result in combustion instabilities and possible misfire. For this reason, minimizing mode transitions is highly desired. A hybrid-electric

drivetrain could offer the opportunity to suppress a mode transition by keeping the engine at the current operating point and using the motor to provide or absorb the difference in power demand. The goal is to develop a practical way of maximizing the benefits of HCCI combustion and in the process, reduce the burden on the engine controller through advanced multi-objective HEV supervisory control. The emphasis is on parallel systems configured in two different strengths; “Mild” and “Medium”. This enables the determination of the effects of the degree of electrification on the potential synergy between HCCI and HEVs. Simulations are developed in SIMULINK for each of the configurations, interactions in the system are studied to understand the engine duty cycle with a classic HEV supervisory controller, and the insight is subsequently used to propose a new e-HCCI strategy for maximizing synergy.

The organization of this paper is explained in this paragraph. The vehicle modeling is introduced first, followed by a detailed discussion of the rule-based supervisory control strategy and the development of the dual-mode SI-HCCI engine model. Next, the baseline is established through simulation of a conventional vehicle, before assessing the benefits of hybridization alone in the case of the “Medium” parallel HEV. The results of the e-HCCI strategy for minimizing mode transitions and maximizing operation in the HCCI mode are studied in detail for both the “Mild” and “Medium” parallel HEV. The Discussion section offers insight into the system behavior with e-HCCI and quantifies the improvements in order to fully characterize the synergy. Brief remarks regarding the marked difference in behavior of the power-split HEV with a dual-mode engine are offered before the conclusions.

VEHICLE SYSTEM MODELING IN MATLAB/SIMULINK

VEHICLE SYSTEM SIMULATION

A conventional vehicle simulation was developed in SIMULINK using the component models and a feed forward logic described in [11, 12]. Subsequently, the parallel hybrid vehicle was generated by integrating submodels for the battery, power bus, and electric motor [12]. The supervisory control module was introduced within the powertrain submodel to manage the operation of the multiple power sources on board. The top level SIMULINK model of the parallel hybrid vehicle is shown in [Figure 1a](#). The model is comprised of three main submodels; the driver submodel, the powertrain submodel, and the driveline and vehicle submodel. The driver submodel is unchanged from the conventional vehicle model. The driveline and vehicle submodel was updated to include accurate aerodynamic and rolling resistance forces for a typical mid-size passenger car. The vehicle is a 1490 kg sedan with a frontal area of 2.65 square meters and a drag coefficient of 0.31.

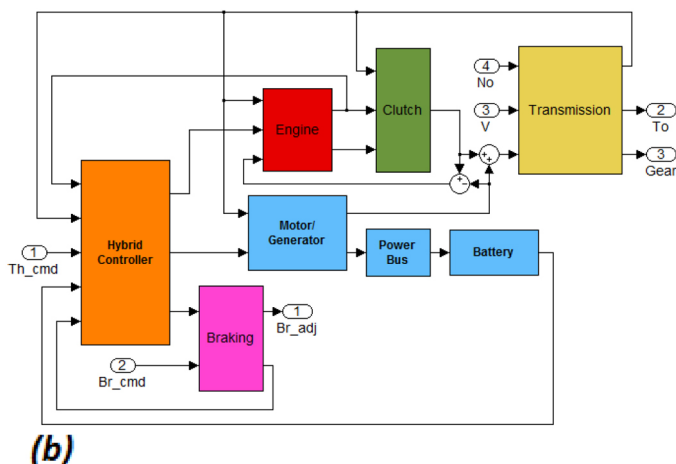
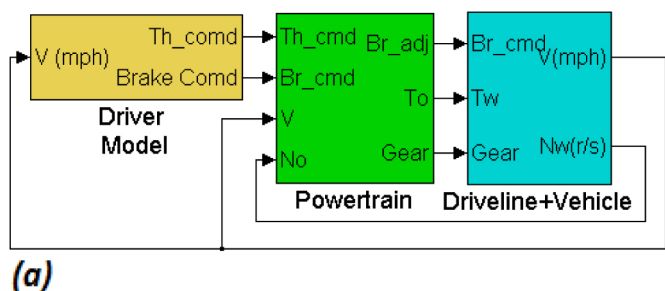


Figure 1. (a) Top Level Parallel Hybrid Vehicle Model and (b) Powertrain Submodel

The motor/generator, power bus, and battery submodels are located in the powertrain submodel, which is shown in [Figure 1b](#). The electric motor is connected after the clutch but before the transmission, i.e. this is a typical integrated starter-alternator configuration. A clutch submodel replaces the torque converter submodel in between the engine and the transmission. A clutch is used in this study rather than a torque converter because clutches are more efficient and can allow engine shut-off. The orange block in [Figure 1b](#) is the hybrid controller submodel. The driver throttle command and requested braking command are sent through the hybrid controller, which decides how to split the power between the engine and the motor/battery and then calculates a modified throttle command to send to the engine, as well as an adjusted braking command and the generator command. This hybrid-controller-modified throttle command will be referred to as the “engine” throttle command for the purposes of this paper. The “driver” throttle command will refer to the throttle command given by the Driver submodel to the Powertrain submodel in an effort to follow the velocity profile.

SUPERVISORY CONTROLLER AND E-HCCI STRATEGY

The inputs to the hybrid controller are driver throttle command, requested braking torque, engine and transmission speed, and battery state of charge (SOC). The outputs are engine throttle command, motor/generator torque command,

and the braking torque required by the friction brakes. The modes of the hybrid controller are torque-assist, engine stop-start, motor only operation, recharging, and regenerative braking. Torque-assist is performed by saturating the driver throttle command at 90% of full load and adding the rest of the requested torque with the motor/generator. Motor only operation is determined by checking if the torque requested by the driver is below the maximum motor torque at that speed. If the motor is capable of supplying the requested torque, then the engine is shut off and the motor is used to drive the vehicle. Given the e-motor characteristics, the torque limit for motor-only operation effectively becomes the power limit above 1000 rpm. Regenerative braking is done by taking the requested brake torque and supplying as much resisting torque as the motor/generator can provide at that speed. The remaining requested torque is supplied by the friction brakes. These are the common features of a parallel hybrid and the hybrid controller in the powertrain model implements this control strategy.

Contained within the hybrid controller is a block named the e-HCCI Controller. The logic within this block performs a hybrid control strategy that is specific to a parallel hybrid with a dual-mode SI-HCCI engine. This logic calculates the difference between the requested torque by the driver and the torque limits of the HCCI operating range. The goal is to minimize the transitions between the HCCI and SI modes, and to maximize the time spent in the HCCI region. If the driver throttle command places the engine operating point just above the upper load limit of HCCI, then the motor will supply the difference in torque between the request torque and the maximum HCCI torque. This shifts the engine operating point down into the HCCI range. If the driver-requested torque is slightly below the lower load limit of HCCI, then the motor supplies a resisting torque so that the engine operating point is shifted up into the HCCI range. With this control strategy, the amount of time for a given cycle spent in HCCI will be maximized. Also, the number of transitions between the SI and HCCI modes will be reduced, which alleviates much of the burden on the engine controller to manage these transitions and makes dual-mode engine operation more robust. [Table 1](#) illustrates the rule-based logic behind in the e-HCCI controller.

Table 1. Rule-Based e-HCCI Control Strategy

Driver Requested Torque, T	e-HCCI Mode	Description
$0 > T$	Regenerative Braking Mode	Motor supplies a resistive torque, which slows the vehicle and charges the battery
$0 < T < \text{Maximum Motor Torque}$	Motor Only Mode	Engine is off, Motor is used to drive the vehicle
$\text{Maximum Motor Torque} < T < \text{Minimum HCCI Torque}$	HCCI with Generator Recharge Mode	Engine is operated in HCCI, Motor supplies a resistive torque
$\text{Minimum HCCI Torque} < T < \text{Maximum HCCI Torque}$	HCCI Mode	Engine is operated in HCCI, Motor is inactive
$\text{Maximum HCCI Torque} < T < \text{Maximum HCCI Torque} + \text{Maximum Motor Torque}$	HCCI with Motor Assist Mode	Engine is operated on the upper load limit of HCCI, Motor supplies an assistive torque to meet driver demand
$\text{Maximum HCCI Torque} + \text{Maximum Motor Torque} < T < 0.90 * \text{Maximum SI Torque}$	SI Mode	Engine is operated in SI mode, Motor is inactive
$0.90 * \text{Maximum SI Torque} < T < \text{Maximum SI Torque} + \text{Maximum Motor Torque}$	Torque Assist Mode	Engine is operated at 90% of full load, Motor supplies an assistive torque to meet driver demand
If battery SOC is less than 0.45	Recharge Mode	Motor supplies maximum resistive torque to recharge the battery upto an SOC of 0.55

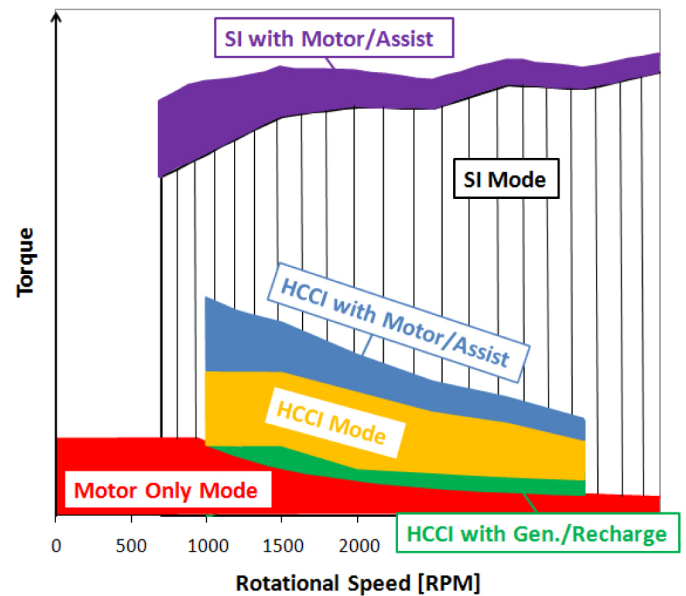


Figure 2. Qualitative Schematic of Torques Limits used for the Rule-Based P-HEV Supervisory Control and e-HCCI Inner Loop

ENGINE-SUBMODEL

The vehicle simulation requires detailed engine performance maps that characterize the brake specific fuel consumption (BSFC) at a given torque and speed, which are used to create a torque look-up table for integration in SIMULINK and eventually determine vehicle fuel economy. The aim of this paper is to study the impact of operating the engine in two modes; conventional SI and HCCI. Therefore, a composite BSFC map is needed to reflect the reduction of fuel consumption within the range of load-speeds attainable in the HCCI mode. To create these maps, comprehensive thermodynamics-based engine models were constructed in GT-Power. Realistic engine geometry and specifications were provided as inputs. SI combustion was modeled using the built-in GT-Power version of the turbulent entrainment combustion model [13] originally proposed by Blizzard and Keck [14] and later refined by Tabaczynski et al. [15, 16]. In the HCCI mode, the ignition is predicted using the auto-ignition integral published by He et al. [17], burn rates are determined using a correlations based on computational studies developed at the University of Michigan [18, 19, 20], and heat transfer is calculated using a correlation developed through in-depth experimental studies of the gasoline HCCI engine by Chang et al. [21]. The HCCI engine employed a symmetric negative valve overlap strategy to trap large amounts of residuals and a common scaling methodology of equally varying lift and duration to vary the load. Reference [22] provides more details on the HCCI engine model validation and map generation procedure. Figure 3 shows the maps that were generated in GT-Power and prepared for subsequent use in the Matlab/SIMULINK vehicle simulation.