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Multimode combustion in a mild hybrid electric vehicle. Part 1: Supervisory control

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ABSTRACT

This is the first of a two-part simulation study that discusses the application of a multimode combustion engine in a mild hybrid electric vehicle (HEV). The torque assist, offered by the electric motor, can be used to extend the residence time in the homogeneous charge compression ignition (HCCI) regime, before returning to spark-ignition (SI) combustion. To enable multimode operation in the HEV, the supervisory control strategy has to maintain the battery's state-of-charge while accounting for the SI/HCCI combustion mode switch. In this study four supervisors are discussed which extend the baseline equivalent consumption minimization strategy by the mode switching decision.

1. Introduction

Since the 1980s homogeneous charge compression ignition (HCCI) combustion has been an active area of research (Najt & Foster, 1983; Thring, 1989). The HCCI principle relies on a homogeneous and highly dilute charge auto-igniting, triggered by compression. This promises high benefits in efficiency due to its ability to operate unthrottled, increased thermal efficiency (Cairns & Blaxill, 2005), and reductions in timing losses (Farrell & Stevens, 2006). Furthermore, its low peak cylinder temperatures result in very low levels of engine-out NO_x. In contrast, however, elevated levels of HC and CO were seen (Dec & Sjöberg, 2003). HCCI operation can be enabled by several methods. In this article recompression HCCI (Willand, Nieberding, Vent, & Enderle, 1998) is applied. Variable valve timing (VVT) allows early closing of the exhaust valves to trap large amounts of highly reactive residual gas, which in turn promotes autoignition of the charge during the succeeding engine cycle. Due to the relatively inexpensive hardware this represents a cost-effective method to implement and control this combustion mode. Transient HCCI control has been discussed by Jade, Hellström, Larimore, Jiang, and Stefanopoulou (2016). They presented experiments for such a configuration, showing very fast and stable engine load and speed transitions while in HCCI mode.

A disadvantage of recompression HCCI, however, is its very narrow operating regime. At midload conditions, the very fast pressure rise rates result in ringing and potential hardware damage (Thring, 1989). On the other hand, at low loads not enough fuel energy is available to maintain stable combustion, resulting in increased occurrences of misfires (Hellström & Stefanopoulou, 2013). During common drive cycles the driver regularly demands engine loads and speeds outside the feasible HCCI regime. This can be resolved by combining HCCI with spark ignition (SI) combustion in a multimode engine as described by Kulzer et al. (2007). To analyze the potential of such an engine in terms of fuel economy, Cairns and Blaxill (2005), Kulzer et al. (2007), Ma, Zhao, Li, and Ladommatos (2001), and Ortiz-Soto, Assanic, and Babajimopoulos (2012) applied steady-state engine maps for SI and HCCI in drive cycle simulations. In addition, to prolong the residence time in HCCI mode while reducing the number of mode switches, this SI/HCCI multimode concept was extended to different types of hybrid electric vehicles (HEV) by Delorme et al. (2010), Lawler, Ortiz-Soto, Gupta, Peng, and Filipi (2011), and Ahn, Whitefoot,

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Abbreviations: ECMS, Equivalent consumption minimization strategy; ECU, Engine control unit; HCCI, Homogeneous charge compression ignition; HEV, Hybrid electric vehicle; ISG, Integrated starter-generator; SI, Spark-ignited; SOC, State-of-charge; *Bsl*, Baseline; *Ext*, Extended; *Max*, Maximum; *Opt*, Optimal; *Ph*, Phase; *Sw*, Switch; *OC*, Open-Circuit; *Des*, Desired; *Al*, Auxiliary Load; *Cl*, Clutch; *Sat*, Saturated; *Act*, Actual

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Babajimopoulos, Ortiz-Soto, and Papalambros (2012). In such a configuration fluctuations in desired torque can be compensated using the electric machine while operating the engine at a constant load in the efficient HCCI regime, resulting in additional fuel economy improvements. However, Cairns and Blaxill (2005), Kulzer et al. (2007), Ma et al. (2001), Ortiz-Soto et al. (2012), Delorme et al. (2010), Lawler et al. (2011), and Ahn et al. (2012) all assumed instantaneous combustion mode switches and neglected any influence by the aftertreatment system. As discussed by Nüesch, Gorzelic, Jiang, Sterniak, and Stefanopoulou (2016), such switches are not instantaneous and they incur dynamics and fuel penalties that need to be addressed by the supervisory controller of the HEV.

Combustion mode switches between SI and HCCI need to be accomplished in very short amount of time and with minimum disturbance in torque. However, during a switch operating conditions are neither optimal for SI and HCCI combustion, thereby resulting in penalties in fuel efficiency. Besides fluctuations in torque during the switch, the delays originating from the mode switch dynamics may also impact the engine's torque response. This has been considered by Nüesch and Stefanopoulou (2015) by incorporating the finite state mode switch model from Nüesch et al. (2016) within the loop of the dynamic vehicle simulation and by implementing a supervisory control structure for a SI/HCCI cam switching strategy.

Mild HEVs based on 48 V-systems with relatively small electric machines and batteries are shown to be a cost-efficient way to achieve reasonable improvements in fuel economy (Rick & Sisk, 2015). In this paper a SI/HCCI multimode engine integrated in a 48 V-system with belt-driven integrated starter-generator (ISG) is discussed. The dynamic drive cycle model from Nüesch and Stefanopoulou (2015) is extended by implementing models of electric machine and battery to allow HEV-operation. A part of this research has been presented by Nüesch and Stefanopoulou (2016b) with a focus on emissions aftertreatment. This article expands on that work by comparing four different supervisory control strategies for SI/HCCI mode switching in terms of fuel economy and engine operation. Three of those strategies are rule-based and one represents an equivalent consumption minimization strategy (ECMS).

This article is organized as follows: In Section 2 an overview of the vehicle model is shown, with additional details in the Appendix. In Section 3 the tested supervisory control strategies are presented. Finally, the associated drive cycle results are discussed in Section 4. The second part of this simulation study that accounts for the emission aftertreatment constraints can be found in Nüesch and Stefanopoulou (2016a).

2. Vehicle model

The longitudinal vehicle model was parameterized for a stock Cadillac CTS 2009 with 6-speed manual transmission, a curb mass of 1700 kg, and conventional powertrain with SI combustion engine (Nüesch, Hellström, Jiang, & Stefanopoulou, 1981). Engine cold-start during the FTP75 cycle (approx. first 5 min) is captured by applying a methodology presented by Gao, Conklin, Daw, and Chakravarthy (2010). It is assumed that during this time period a mode switch from SI to HCCI combustion cannot be achieved. The model was developed in MATLAB/Simulink/Stateflow and a detailed model validation with chassis dynamometer measurements can be found in Nüesch (2015). In general the accuracy of the model in terms of drive cycle fuel economy was ±6%. Fig. 1 depicts the block diagram of the vehicle model. Further descriptions of the model can be found in the Appendix.

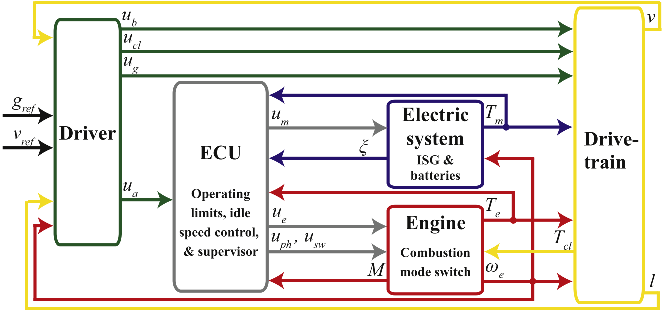

Fig. 1. Block diagram of the vehicle model. For the conventional vehicle the electric system is only used to generate power for the electric auxiliaries.

2.1. Overview and nomenclature

This paper discusses two vehicle configurations. First, the *conventional vehicle* that uses the ISG only as alternator to generate power for the electric auxiliaries without interfering with the SI/HCCI operation. Second, the vehicle denoted *HEV*, which utilizes the ISG's capabilities for torque-assist, regenerative braking, and start/stop. Both vehicles are tested with SI-only as well as with SI/HCCI multimode combustion engine. In case of the HEV, for engine-types, adaptive ECMS is applied to determine the torque split between ISG and engine.

Furthermore, due to the SI/HCCI mode switching dynamics and penalties a supervisory strategy is required to decide when to perform a switch. This decision is not necessarily linked to ECMS and could be solely rule-based. The four tested supervisory strategies for SI/HCCI multimode operation, denoted *Bsl*, *Ext*, *Max*, and *Opt*, represent alternative ways to integrate the mode switching decision into the general HEV torque definition. Due to the number of strategies and the complexity of the system, several variables describing engine torque are used throughout this paper. To help the reader an overview over these variables and the strategies is provided here, before they will be formally introduced later.

The actual torque of the engine plant is denoted T_e. Input to the engine is torque command u_e. The definition of u_e depends on the vehicle configuration. In case of the conventional vehicle, u_e is based on the desired torque of the driver T_{des}. In case of the mild HEV, on the other hand, the optimal engine torque x_T^* is used to determine u_e. Torque variable x_T is the optimization argument within the ECMS. Due to ECMS and torque saturations at the HCCI limits T_e can deviate from T_{des}. The ISG is used to compensate for differences between T_e and $\tilde{T}_e$, representing an ECU-internal variable for the filtered response of T_{des}.

The baseline strategy *Bsl* commands a mode switch based on T_e and T_{des}. Therefore it does not specifically rely on the ISG torque and can be used in both, the conventional vehicle and the HEV. Strategy *Ext* extends residences in HCCI mode by saturating T_e at the limits of the regime while using the ISG to compensate for the difference in torque. The most aggressive strategy *Max* not only extends residences in HCCI, but also moves T_e into the HCCI regime preemptively. In order to do so this strategy relies on the internal ECU-variable T_3, when determining command u_e and initiating the SI-HCCI mode switch. In the rule-based strategies *Ext* and *Max* ECMS and mode switching decision are not connected. This is different in case of optimal strategy *Opt*, where the mode switching decision is integrated within the ECMS optimization.

2.2. Multimode engine

The engine used in this article is a turbocharged 2.0 L I4 multimode engine. Its model is based on steady-state fuel efficiency data for SI and HCCI combustion. The resulting maps are functions of engine torque and speed and can be found in Fig. 2 as well as in