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IFAC-PapersOnLine 49-11 (2016) 034–041

Mild HEV with Multimode Combustion: Benefits of a Small Oxygen Storage

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Abstract: This simulation study discusses the application of a multimode combustion engine in a mild hybrid electric vehicle (HEV) with three-way catalytic converter (TWC). Operation in the lean combustion mode homogeneous charge compression ignition (HCCI) results in oxidation of the oxygen storage capacity (OSC) of the TWC. Thereby, the TWC's ability to convert NOx under lean conditions is removed. Succeeding depletion of the OSC under rich spark-ignition (SI) conditions is required, which results in significant fuel efficiency penalties. In case of a mild HEV the torque assist from the electric motor is able to extend the residence time in HCCI, thereby reducing the number OSC depletion events. The applied supervisory controller, which decides when to switch between SI and HCCI, is based on the equivalent consumption minimization strategy (ECMS) and incorporates the fuel penalties associated with mode switching and OSC depletion. It is shown that, while the impact of the OSC depletion on drive cycle fuel economy of the mild HEV is still significant, it is much smaller than in case of the vehicle without electric motor. The prolonged operation in lean HCCI mode leads to substantial amounts of tailpipe NOx for all drive cycles tested. In a case study two modifications to the system hardware are introduced with counterintuitive results. First, the HCCI regime is further constrained to conditions where engine-out NOx levels are extremely low. Second, the size of the OSC is significantly reduced, allowing a much faster and less inefficient depletion. Associated drive cycle results show a substantial reduction in tailpipe NOx while fuel economy benefits can be maintained.

Keywords: Multimode combustion engine, mild HEV, combustion mode switch, homogeneous charge compression ignition (HCCI) combustion, supervisory control, three-way catalyst.

1. INTRODUCTION

Mild hybrid electric vehicles (HEV) 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 and Sisk (2015). Such a HEV offers the flexibility of choosing the torque-split between electric motor and engine to optimize overall system efficiency. Furthermore, the torque assist provided by the electric motor can be used to tailor the response of a multimode combustion engine, with the goal of increasing the residence time in the beneficial combustion mode while reducing the number of mode switches and their impact on driveability.

One example of such a multimode combustion engine is based on spark-ignition (SI) and homogeneous charge compression ignition (HCCI) combustion, shown by Kulzer et al. (2007). HCCI combustion relies on autoignition of a homogeneous and highly dilute charge, triggered by compression. This promises high benefits in efficiency due to its ability to operate unthrottled, increased thermal efficiency, and reductions in timing losses. Furthermore, its low peak cylinder temperatures results in very low levels of engine-out NO_x. HCCI operation can be enabled by several methods. In this article recompression HCCI is applied, as discussed by Willand et al. (1998), which represents a cost-effective method to implement and control this combustion mode due to the relatively inexpensive hardware.

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, as shown by 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, as seen by Hellström and Stefanopoulou (2013).

To prolong the residence time in HCCI mode, Delorme et al. (2010); Lawler et al. (2011); Ahn et al. (2012) all extended this SI/HCCI multimode concept to different types of HEVs and evaluated the associated fuel economy improvements based on drive cycle simulations. However, in all those articles combustion mode switches were assumed instantaneous and important interactions with the aftertreatment system were neglected. As discussed by Nüesch et al. (2016), such switches are not instantaneous and they exhibit dynamics and fuel penalties.

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

10.1016/j.ifacol.2016.08.006

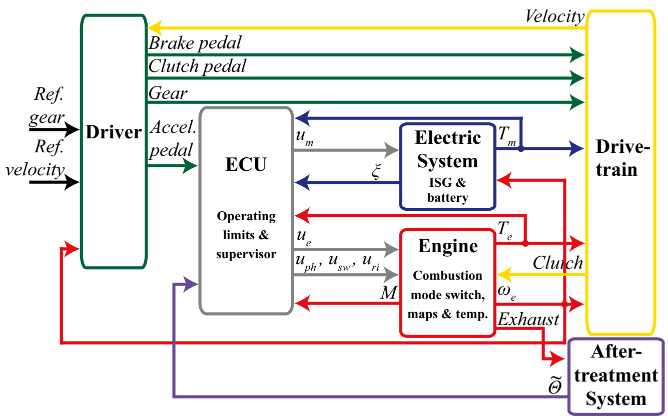

Fig. 1. Block diagram of the vehicle model. For the conventional vehicle the electric system is only used to generate power for the electric auxiliaries.

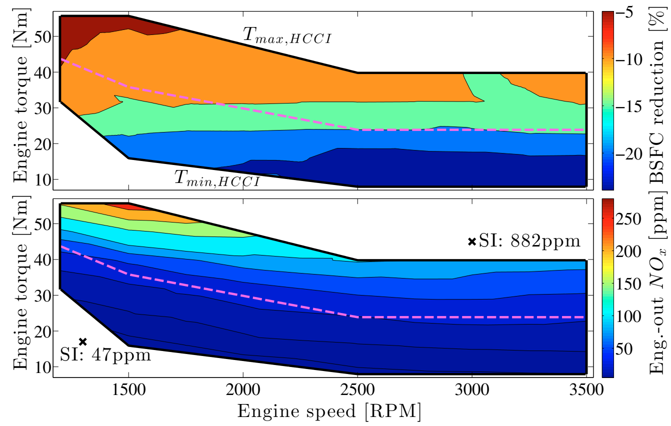

Fig. 2. Steady-state data of the 2.0 L multimode engine in NA HCCI mode. Top: Fuel efficiency improvement of HCCI over SI. Bottom: Engine-out NO_x. Dashed line represents center torque in HCCI regime, used in the case study. Black cross: Exemplary SI conditions.

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 by 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.

However, besides the dynamics and penalties connected to the combustion mode switch it is important to also consider the interaction of the multimode engine with the aftertreatment system in both, drive cycle simulations and supervisory control. Aftertreatment systems for lean engines are generally very expensive. HCCI's low engine-out NO_x offers the potential to use a relatively inexpensive three-way catalytic converter (TWC). In stoichiometric SI the TWC reduces all emissions as usual. In lean HCCI the TWC would still be able to reduce HC and CO while breakthrough of relatively low NO_x might be acceptable. This architecture, however, has two drawbacks. First, the low exhaust temperatures of HCCI might lead to cool-down of the TWC, thereby resulting in low conversion efficiencies for CO and HC. This problem has been addressed in a control strategy by Kulzer et al. (2007). Second, lean HCCI operation results in filling of the TWC's oxygen storage capacity (OSC). In SI operation the OSC represents a buffer for deviations from stoichiometry. To maintain high conversion efficiencies in SI, rich operation is required to deplete the OSC, thereby resulting in large fuel penalties. These penalties have the potential to significantly reduce HCCI's original efficiency benefits, as shown by Nüesch et al. (2015). Experimental results on the OSC dynamics during combustion mode switching have been presented by Chen et al. (2014).

This paper discusses a SI/HCCI multimode engine, running with gasoline, used in a 48 V mild HEV with belt-driven integrated starter-generator (ISG). The presented supervisory control strategy accounts for mode switching penalties. The dynamic drive cycle model by Nüesch and Stefanopoulou (2015) is extended by implementing models of electric machine and battery to allow HEV-operation. The equivalent consumption minimization strategy (ECMS) is implemented as supervisory control strategy, accounting for SI/HCCI mode switching and OSC depletion. An engine exhaust temperature model by Gao et al. (2010) is combined with a TWC model, described by Nüesch et al. (2015) and Nüesch (2015), to simulate the TWC's temperature and OSC dynamics. This simulation is used to analyze drive cycle fuel economy as well as tailpipe NO_x emissions of the system. Further, a case study is presented, outlining the influence of a different hardware design on fuel economy and NO_x emissions.

This paper is organized as follows: In Section 2 the vehicle mode is discussed. In Section 3 the applied supervisory control strategies are explained. The drive cycle results are discussed in Section 4, followed by a case study in Section 5.

2. VEHICLE MODEL

The longitudinal vehicle model was parameterized for a stock Cadillac CTS 2009 with 6-speed manual transmission and a curb mass of 1700 kg. The model was developed in MATLAB/Simulink/Stateflow and validated with chassis dynamometer measurements in Nüesch et al. (2013). Figure 1 depicts the block diagram of the vehicle model.

2.1 Engine

The engine used in this article is a turbocharged 2.0 L I4 multimode engine. Due to its low exhaust enthalpy HCCI operation is naturally aspirated (NA). The engine's model builds on steady-state data for SI and HCCI combustion of fuel, emissions, and exhaust temperature. Based on experimental data the engine's torque response is approximated using a first-order filter with time constant τ_e. The HCCI maps for efficiency improvement over SI mode and engine-out NO_x are shown in Fig. 2. Associated HCCI maps can be found in Nüesch et al. (2016).

The maps of the two combustion modes are connected by the mode switch model, described in Nüesch et al. (2016), and implemented within the dynamic vehicle simulation as in Nüesch and Stefanopoulou (2015). A methodology presented by Gao et al. (2010) was implemented to capture