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Multimode combustion in a mild hybrid electric vehicle. Part 2: Three-way catalyst considerations

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ABSTRACT

This is the second of a two-part study that discusses multimode combustion in a mild hybrid electric vehicle. Homogeneous charge compression ignition (HCCI) combustion oxidizes the oxygen storage capacity (OSC) of the three-way catalyst (TWC), thereby removing the TWC's ability to convert NOx under lean conditions. Despite prolonged operation in HCCI mode, enabled by the electric motor, the depletion of the OSC causes significant penalties in fuel economy and the amounts of tailpipe NOx are substantial. Counter-intuitively, it is seen that decreasing the sizes of both HCCI regime and OSC results in reduced tailpipe NOx while maintaining fuel economy benefits.

1. Introduction

This is the second part of a two-part simulation study on multimode combustion in a hybrid electric vehicle (HEV). In particular it is focused on a SI/HCCI engine integrated in a 48 V-like mild HEV. In the previous paper (Part 1, (Nüesch & Stefanopoulou, 2016)) four different supervisory control strategies are compared in terms of fuel economy. A finite state combustion mode switch model, presented in Nüesch, Gorzelic, Jiang, Sterniak, and Stefanopoulou (2016), is used to describe mode switch dynamics and fuel penalties during the switching. The optimal torque-split between engine and integrated starter-generator (ISG) is based on an equivalent consumption minimization strategy (ECMS) with four supervisors responsible for deciding, when to switch between SI and HCCI mode. It was seen that during the FTP75 drive cycle the relative fuel economy benefit of multimode over SI-only combustion is significantly greater in case of the mild HEV compared to the conventional vehicle. This suggests a great synergy between the ISG's torque assist and HCCI's high efficiency. Further it was concluded that, especially during the HWFET drive cycle, it is necessary to integrate the battery's state-of-charge (SOC) into the mode switching decision. The associated optimal strategy would switch out of HCCI as soon as a low SOC is reached and would not allow to further extend the residence time in the mode.

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 break-through 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, Sauer, Karrelmeyer, and Fischer (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 in Nüesch, Jiang, Sterniak, and Stefanopoulou (2015). Experimental results on the OSC dynamics during combustion mode switching have been presented in Chen, Sima, Lin, Sterniak, and Bohac (2015).

Abbreviation: AFR, air-fuel ratio; ECMS, equivalent consumption minimization strategy; ECU, engine control unit; HCCI, homogeneous charge compression ignition; HEV, hybrid electric vehicle; ISG, integrated starter-generator; OSC, oxygen storage capacity; SI, spark-ignited; SOC, state-of-charge; TWC, three-way catalytic converter; *Bsl*, baseline; *Opt*, optimal; *ph*, phase; *sw*, switch; *OC*, open-circuit; *des*, desired; *al*, auxiliary load; *cl*, clutch; *sat*, saturated; *act*, actual; *cat*, catalyst; *amb*, ambient; *cond*, conduction; *conv*, convection; *geo*, geometric; *ri*, rich; *Sml*, small; *Str*, stratified

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In this paper the mild HEV model with SI/HCCI multimode engine from Nüesch and Stefanopoulou (2016) is extended in two ways, first with an engine exhaust temperature model by Gao, Conklin, Daw, and Chakravarthy (2010) to describe the TWC's temperature and second with a TWC model, described in Nüesch et al. (2015) to simulate the OSC dynamics. This simulation is used to analyze drive cycle fuel economy as well as tailpipe NO_x emissions of the system. Further, two case studies are presented, outlining the influence of different hardware design on fuel economy and NO_x emissions.

Closely related research has been presented in Nüesch et al. (2016). This article expands on that work by providing more details on the TWC model and its validation with experiments. Further a small case study is added which approximates conditions during a stratified HCCI-SI mode switch. This paper is organized as follows: In Section 2 the TWC model is presented. In Section 3 the applied supervisory control strategies are summarized. The drive cycle results are discussed in Section 4, followed by the case studies 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. It is described in detail in Nüesch and Stefanopoulou (2016). Chassis dynamometer data was used to validate the vehicle model qualitatively, e.g., in terms of load profile, and quantitatively, e.g., in terms of drive cycle fuel economy. The differences between measured and simulated fuel economy were: FTP75 (+0.5%), HWFET (−9.4%), and US06 (+4.5%). More details on its validation is provided in Nüesch (2015). In the following section it is focused on required additions to integrate the model of the TWC aftertreatment system.

2.1. Aftertreatment system

A central aspect of the supervisory control of a multimode combustion engine is its interaction with the aftertreatment system. The system used in this article was parameterized based on two TWCs in series. The first TWC is based on two bricks which are located in a single can. Its two substrates are based on *Pd* and *PdRh*. The second TWC is located underfloor and is based on a *PdRh* substrate. The TWCs offer generous OSC based on CeO_2-ZrO_2. More on the experimental setup and the applied hardware can be found in Chen et al. (2015). The close coupled TWC is used for control purposes. Its inputs and outputs are shown in Fig. 1. Its volume V_{cat} is 1.29 L and its gas volume fraction ϵ_{cat} is 0.8. As can be seen, relative AFR is measure up- and downstream of the first TWC using a wide-range and a switching-type λ-sensors, respectively. The measurements are used to estimate the relative OSC $\tilde{\Theta}$. More on this estimation strategy can be found in Nüesch et al. (2015).

2.1.1. Oxygen storage

The excess O_2 during lean HCCI operation leads to saturation of the TWC's OSC. With a full OSC the TWC is unable to reduce the engine-out NO_x when facing lean exhaust gas. This may be acceptable under certain HCCI conditions. However, it cannot be tolerated in SI mode,

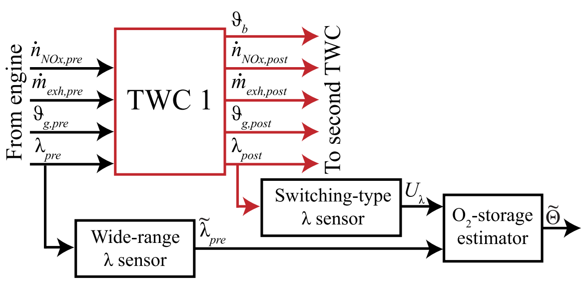

Fig. 1. Block diagram with inputs and outputs of the close coupled TWC.

since AFR-control does not always guarantee operation at exact stoichiometry, especially during transients. Therefore, a full OSC needs to be depleted by operating the engine rich as soon as SI combustion is reached. In this paper a phenomenological OSC model by Brandt, Wang, and Grizzle (2010) is applied. The model is based on a saturated integrator with a single state describing the current relative OSC Θ. The implementation and parameterization of the model as well as strategies to deplete the OSC are described in Nüesch et al. (2015). For the convenience of the reader the equation describing the oxygen storage estimator is repeated here:

$$\dot{\tilde{\Theta}} = \frac{0.\,23 \cdot \dot{m}_{exh}}{\tilde{C}_{0,1}} \cdot \left(1 - \frac{1}{\lambda_{exh}}\right) \tag{1}$$

with $\dot{m}_{exh}$ and λ_{exh} mass flow and relative AFR of the exhaust, respectively, and $\tilde{C}_{0,1}$ the estimated OSC. Model parameters, e.g., $\tilde{C}_{0,1} = 0.7$, were identified in Nüesch et al. (2015) using lean-rich cycling experiments. As can be seen, the applied oxygen storage model neglects the influence of temperature. More detailed models oxygen storage dynamics, e.g., the control-oriented model by Kibitz, Onder, and Guzzella (2012), take into account reaction rates, rather than simplifying the process using an integrator. Temperature directly affects those reaction rates through, as shown in Arrhenius relationships.

2.1.2. Brick temperature

The second way HCCI combustion is able to affect the TWC is its low exhaust temperature. As discussed in Kulzer et al. (2007) prolonged residence in HCCI can lead to decrease in TWC brick temperature, which in turn leads to a reduction in its conversion efficiency for *CO* and *HC*. Therefore the TWC's brick temperature needs to be monitored to initiate a switch back to SI combustion.

For many reasons accurate modeling of TWCs is a demanding task. Various aspects need to be taken into account, e.g., two distinct phases, temperature, mass, chemical composition, temporal and two spatial dimensions. In general, the temperature dynamics of the gas phase are significantly faster than the ones in the solid phase. Solving such coupled differential equations is not trivial. Depending on the application, TWC need to be simplified to allow computation in a reasonable amount of time. A simplified TWC temperature model provided by Guzzella and Onder (2010) distinguishes between the temperature of the gas phase ϑ_g and the brick temperature ϑ_b. However, similar to Sanketi and Hedrick (2005), Kum, Peng, and Kucknor (2011), the model applied in this article has been even further reduced to 0D to allow for fast computation when simulating entire drive cycles. It needs to mentioned that this also significantly reduces the accuracy of the model.

$$\epsilon_{cat} V_{cat} \rho_{exh} c_{v,g} \frac{d}{dt} \vartheta_g = c_{p,g} \dot{m}_{exh} (\vartheta_{pre} - \vartheta_g) - \dot{Q}_{gb} \tag{2}$$

$$m_{cat} c_b \frac{d}{dt} \vartheta_b = \dot{Q}_{gb} + \dot{Q}_R - \dot{Q}_{loss}. \tag{3}$$

Parameters are TWC mass and specific heat capacity m_{cat} and c_b, respectively. ϵ_{cat} denotes the volume fraction of the TWC filled with exhaust gas, V_{cat} the volume of the TWC, c_b the specific heat capacity of the solid phase, and m_{cat} the mass of the TWC. Inputs to the model are exhaust gas mass flow and temperature, ϑ_{pre}, $\dot{m}_{exh}$, respectively. Exhaust gas density and specific heat capacities ρ_{exh}, $c_{v,g}$, and $c_{p,g}$, respectively, are calculated as functions of temperature and composition, approximated as described by Heywood (1988, chapter 4). $\dot{Q}_{gb}$ and $\dot{Q}_{loss}$ describe heat transfers between gas-phase and brick as well as brick and environment, respectively:

$$\dot{Q}_{gb} = \alpha_{cat} A_{geo} V_{cat} (\vartheta_g - \vartheta_b) \tag{4}$$

$$\dot{Q}_{loss} = A_{cat} U_{cat} (\vartheta_b - \vartheta_{amb}) \tag{5}$$