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

S. Nüesch * A.G. Stefanopoulou *

* Department of Mechanical Engineering in the University of Michigan, Ann Arbor, MI 48109, USA (email: snuesch@umich.edu; annastef@umich.edu).

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 of 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.

© 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

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 NOx. 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); Alm 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
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 48V 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 model 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 $\tau_c$. 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...
Operating Regime As discussed above, the feasible operating range of NA HCCI combustion is limited by high pressure rise rates and combustion stability at mid and low loads, respectively. Further limitations originate from allowable NOx emissions and fuel efficiency. Applying these constraints resulted in the HCCI limits shown in Fig. 2. The function $f_f$ indicates the feasibility of HCCI combustion for specific load/speed conditions:

$$f_f(T, T_{\text{min}}(\omega_e), T_{\text{max}}(\omega_e)) = \ldots$$

with:

- HCCI: $T_{\text{min}}(\omega_e) \leq T \leq T_{\text{max}}(\omega_e)$
- SI: $\omega_{\text{min},\text{HCCI}} \leq \omega_e \leq \omega_{\text{max},\text{HCCI}}$

It is used to evaluate if current engine speed $\omega_e$ as well as actual and the desired engine torque, $T_e$ and $T_{\text{des}}$, respectively, lie within the limits of the HCCI regime:

$$R_{\text{act}} = f_f(T_e, T_{\text{min},\text{HCCI}}(\omega_e), T_{\text{max},\text{HCCI}}(\omega_e))$$

Finite state $M$ is the output of the state machine and represents the current combustion mode: Either SI, HCCI, or one of the intermediate mode switch states. Exemplary SI-HCCI and HCCI-SI mode switches during a drive cycle simulation are shown in Fig. 4, left and right side, respectively. A more detailed description of the model can be found in Nüesch and Stefanopoulou (2015).
The combustion mode switch

which distinguishes between 14 finite states

The function

\[ R = \begin{cases} f_1 & \text{if } x, i \in (1, 9) \text{ operate under low valve lift conditions, while } \\ f_2 & \text{if } x, i \in (13, 14) \text{ are at high lift, with the cam switch } \\ f_3 & \text{else} \end{cases} \]

As a simplification, it is assumed that the mode switch fuel penalties can be found in Gorzelic (2015). As a simplification, it is assumed that the mode switch fuel penalties can be found in Gorzelic (2015). As a simplification, it is assumed that the mode switch fuel penalties can be found in Gorzelic (2015).

At the beginning of the HCCI-SI switch, \( M = 8 \), the cams remain in prepared conditions as long as either both \( R_{out,1} \) and \( R_{out,2} \) or \( R_{TWC} \) demand a mode switch to SI mode. Upon entering high lift conditions in \( M \in (10, 11) \), the engine will be operated rich to enable the TWC to reduce the increased levels \( NO_x \), as shown in Fig. 4-right at \( t > 0 \). This results in the relatively high fuel efficiency penalties. After the first two SI-cycles, depending on \( R_{TWC} \), it is decided to either continue to deplete the OSC, \( M \in (13, 14) \), or to operate at stoichiometry, \( M \in (12, 1) \). Alternatively, if requested by \( R_{in} \), another switch to HCCI can be initiated. More details on the scheduling can be found in Nüesch and Stefanopoulos (2015).

Engine Torque Command

The variable \( u_e \) represents the engine torque command. While in SI mode, specifically at high cam lift conditions (lower half of Fig. 3), the entire load range is available and the torque by the engine can be delivered unconditionally. However, in HCCI, specifically as long as the cams are in low lift (upper half of Fig. 3), the torque is constrained by HCCI’s operating limits. Therefore, the command to the engine needs to be saturated, which is emulated by function \( f_{sat} \):

\[
f_{sat}(T, M) = \begin{cases} T_{max,HCCI} & T \geq T_{max,HCCI} \ldots \\ T_{min,HCCI} & T \leq T_{min,HCCI} \ldots \\ T & \text{else} \end{cases} \]

where \( T_{max,HCCI} \) and \( T_{min,HCCI} \) are constants. (4 - 9)

The torque input \( T \) to \( f_{sat} \) depends on the applied supervisory control strategy, see Sec. 3.

2.2 Integrated Starter-Generator (ISG)

The model for a belt-driven ISG is used to evaluate potential synergies between multimode combustion and mild hybridization. The ISG with a maximum continuous power of 5 kW boost and 14 kW regeneration represents a small e-machine as seen in upcoming 48 V-systems. A belt ratio of \( \gamma_b = 2.5 \) is used to connect engine and ISG.

In the conventional vehicle the ISG simply operates as alternator to deliver power for electric auxiliaries. In the HEV, the ISG is additionally used for start/stop operation, torque assist, and regenerative braking. Note that those capabilities have been implemented in the model, however, their description is omitted here for simplicity.

In case of the mild HEV, the optimal torque-split between engine and ISG is computed by the ECMS, described in Sec. 3. Due to this optimization in general \( u_e \neq T_{des} \), resulting in torque gaps which need to be filled by the ISG. The ISG’s time constant \( \tau_j \), based on experimental data, is an order of magnitude faster than engine time constant \( \tau_c \). In addition, the goal is to compare the performance of the HEV powertrain to the conventional vehicle without changing the combined response of engine and ISG. For that reason the time constant of the engine is used to filter the desired driver torque \( T_{des} \) and to compute \( \hat{T}_c \), which represents the virtual engine torque the driver expects from the conventional vehicle:

\[
\hat{T}_c = \frac{1}{\tau_c} (T_{des} - \hat{T}_e). \quad (5)
\]

The ISG is used to compensate for the gap between virtual and actual engine torque, \( T_e \) and \( \hat{T}_c \), respectively. The associated torque command to the ISG \( u_m \) is defined as:

\[
u_m = \frac{1}{\gamma_b} (\hat{T}_e - T_e). \quad (6)
\]

This definition also compensates for torque gaps, e.g., due to torque saturations at the limits of the HCCI regime (22). The efficiency map \( f_m \) of the belt-driven ISG is modeled based on steady-state data. It computes the electric power of the motor \( P_{m,el} \) as a function of mechanical power \( P_m \) and motor speed \( \omega_m \):
\[ \begin{align*}
    P_m &= T_m \cdot \omega_m \\
    P_{m,el} &= f_m(P_m, \omega_m). 
\end{align*} \]

The torque response of the ISG \( T_m \) is modeled as first-order with time constant \( \tau_m \):

\[ \frac{d}{dt} T_m = \frac{1}{\tau_m} (u_m - T_m). \]

### 2.3 Battery

The battery behavior is described by an equivalent circuit model with \( I_c \) and \( U_c \), cell current and voltage, respectively, similar to Guzzella and Sciarretta (2007).

\[ U_c = U_{OC}(\xi) - R_i(\xi, I_c) \cdot I_c \]

\[ I_c = \frac{P_{m,el}}{n_s n_p U_c} \]

The battery consists of \( n_p = 1 \) cells in parallel and \( n_s = 14 \) in series, each cell with a capacity of \( Q_c = 5 \, \text{Ah} \). The open-circuit voltage \( U_{OC} \) and the internal resistance \( R_i \) are implemented as look-up tables based on steady-state data. They are functions of the battery’s state-of-charge (SOC) \( \xi \) and the direction of \( I_c \). The influence of battery temperature on \( U_{OC} \) and \( R_i \) is neglected. The battery’s only state SOC is modeled applying coulomb-counting as in Guzzella and Sciarretta (2007):

\[ 3600 \cdot Q_c \frac{d}{dt} \xi = -I_c. \]

### 2.4 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 \( \text{PdRh} \). The second TWC is located underfloor and is based on a \( \text{Pd} \)-based TWC. The TWCs offer generous OSC based on \( \text{CeO}_2 \)-\( \text{ZrO}_2 \). More on the experimental setup and the applied hardware can be found in Chen et al. (2014). The close coupled TWC is used for control purposes. Its volume \( V_{\text{cat}} \) is 1.29 L and its gas volume fraction \( e_{\text{cat}} \) 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 A-sensors, respectively. The measurements are used to estimate the relative OSC \( \Theta \). More on this estimation strategy can be found in Nüesch et al. (2015).

#### 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, 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 et al. (2010) is applied. The model is based on a saturated integrator with a single state \( \Theta \) describing the current relative OSC. The implementation and parameterization of the model are described in Nüesch et al. (2015).

#### 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 \( HC \). In this paper a 0D model with two states is used to capture the TWC’s main temperature dynamics. More details on this model can be found in Nüesch (2015). Based on simulations of the FTP75, HWFET, and US06 drive cycles it was seen that individual residences in HCCI mode are too short to lead to a significant reduction in temperature, which therefore neither influenced the combustion mode switching nor the fuel economy.

#### TWC Depletion

The variable \( R_{TWC} \) is used to describe constraints posed by the TWC. If the OSC is estimated to be full, rich SI operation is demanded:

\[ R_{TWC} = \begin{cases} 
\text{rich SI} & \Theta \geq 0.9 \text{ and } M \in (1 - 3, 10 - 14) \\
\text{HCCI} & \text{else.}
\end{cases} \]

The implemented OSC-depletion strategy allows operation in HCCI with full OSC and tolerates the associated breakthrough in \( NO_x \). Rich SI is only demanded once high lift conditions are reached during the HCCI-SI mode switch. This depletion strategy as well as an alternative, in which the OSC is never allowed to be full, are described in Nüesch et al. (2015).

### 3. SUPERVISORY CONTROL STRATEGIES

In this section the two supervisory control strategies are discussed. They are responsible for the SI/HCCI mode switching decision in the conventional vehicle and the mild HEV, respectively. The block diagrams of the two strategies are shown in Fig. 5. The rule-based supervisory strategy used in the conventional vehicle commands a mode switch based on current speed and torque conditions. The strategy for the mild HEV makes an optimal mode switching decision, taking into account battery SOC.

#### 3.1 Rule-based Mode Switch in Conventional Vehicle

The first supervisory control strategy has been described in Nüesch and Stefanopoulou (2015). It prepares the SI-HCCI mode switch as soon as \( T_{des} \) enters the HCCI regime, as can be seen in Fig. 4 at \( t = -0.24 \, \text{s} \). The cams are switched to low-lift as soon as the valves reached their switching positions and \( T_e \) enters the HCCI regime. Conversely, in the HCCI-SI direction the mode switch is prepared when \( T_{des} \) exits the HCCI regime, in Fig. 4 at \( t = -0.25 \, \text{s} \). If by the time the valves reach their switching position \( T_{des} \) still lies outside the HCCI boundaries, the cam switch to high-lift is initiated. Therefore the following variables are all equal:

\[ R_{in} = R_{out,1} = R_{out,2} = R_{des}. \]

Finally, in case of the conventional vehicle the torque command \( u_e \) is based on the desired load \( T_{des} \):

\[ u_e = f_{sat}(T_{des}, M). \]
3.2 Optimal Mode Switch in Mild HEV

Instead of making a rule-based decision about when to enter or exit HCCI mode, as done in the previous supervisor, the following strategy integrates the decision into the ECMS control structure. The optimal torque split \( x_T^* \) is determined together with the currently optimal combustion mode \( x_M^* \) by the following minimization:

\[
J(x_T, x_R) = P_f(x_T, x_R) + \alpha \cdot P_b(x_T) \\
(x_T^*, x_R^*) = \arg \min_{x_T \in X, x_R \in \{SI, HCCI\}} J(x_T, x_R)
\]

with the space of admissible controls \( X \) a function of \( x_R \):

\[
X(x_R) = \{ x_T : T_{min}(x_R) \leq x_T \leq T_{max}(x_R) \} \\
T_{m, min} \leq T_m(x_T) \leq T_{m, max}
\]

\[
P_f(x_T) \text{ and } P_b(x_T) \text{ are the power released by the burned fuel and by the battery cells, respectively, as a function of engine torque. Battery power } P_b \text{ is based on equations}\]

(10) and (11). Co-state \( \alpha \), the equivalence factor, is used to compare the two power sources, thereby weighing battery power based on the deviation from the SOC reference, as discussed later. Therefore, rather than from any load commands, the switches from to and from HCCI are ultimately determined by the ECMS equations \( x_R^* \):

\[
R_{in} = R_{out,2} = x_R^* \\
R_{out,1} = f_R(T_{des}, T_{min, HCCI}, T_{max, HCCI})
\]

The engine torque command \( u_e \) is determined by the optimum engine torque \( x_T^* \):

\[
u_e = f_{sat}(x_T^*, M).
\]

**Equivalence Factor** Different alternatives are available on how to determine the equivalence factor \( \alpha \). Onori and Serrao (2011) compare several adaptive approaches, in which \( \alpha \) is defined as a function of battery SOC \( \xi \). In this paper the approach by Chasse et al. (2010) is used, in which a PI controller modifies \( \alpha \) to track a reference SOC \( \xi_{ref} \), in this case \( \xi_{ref} = 50\% \):

\[
\alpha = K_P \cdot (\xi_{ref} - \xi) + K_I \cdot \int_{0}^{\alpha_I} (\xi_{ref} - \xi) \, dt
\]

with controller gains \( K_P = 20 \) and \( K_I = 0.5 \) based on manual tuning.

**Computation of Equivalent Power** The computation of the fuel power incorporates the fuel penalties of mode switching and OSC depletion:

\[
P_f(x_T, x_R) = H_f \cdot m_f(x_T, x_R, M)
\]

\[
m_f(x_T, SI, M) = \begin{cases} f_{SI}(x_T, \omega_c) & M = SI \\ f_{SI}(x_T, \omega_c) \cdot (1 + d_2) & M = HCCI \end{cases}
\]

\[
m_f(x_T, HCCI, M) = \begin{cases} f_{HCCI}(x_T, \omega_c) & M = HCCI \\ f_{HCCI}(x_T, \omega_c) \cdot (1 + d_1) + d_{ei} & M = SI \end{cases}
\]

Equation (25) is used to compute the fuel consumption of remaining in SI and switching to SI from HCCI mode, (26) vice versa. The variables \( d_1 \) and \( d_2 \) represent the total penalties in terms of fuel flow for the SI-HCCI and HCCI-SI mode switches, respectively, and are calculated as follows:

\[
d_1 = \frac{1}{\tau_1} \cdot \sum_{i \in \{2-6\}} d_i \cdot \Delta t_i
\]

\[
d_2 = \frac{1}{\tau_2} \cdot \sum_{i \in \{8-12\}} d_i \cdot \Delta t_i
\]

As can be seen these parameters represent the total fuel penalty divided by tuning parameters \( \tau_1 \) and \( \tau_2 \). These parameters can be interpreted as the average duration to the next mode switch, where larger values encourage and smaller values prevent mode switching. Their optimal choice depends on the applied drive cycle. Here \( \tau_1 = 1 \) s and \( \tau_2 = 6 \) s were chosen. Besides total switching penalties \( d_1 \) and \( d_2 \), the parameter \( d_{ei} \) is used to incorporate the fuel penalty due to OSC-depletion whenever the OSC is estimated to be full:

\[
d_{ei} = \begin{cases} \frac{\lambda_{14} \cdot \Delta \bar{\Theta} \cdot \bar{C}_{0,1}}{\tau_2 \cdot 0.23 \cdot 10^3 \cdot (\lambda_{14} \cdot r_s + 1)} & \bar{\Theta} \geq 0.9 \\ 0 & \text{else} \end{cases}
\]

with relative AFR during depletion \( \lambda_{14} = 0.9 \), fraction of the OSC to deplete \( \Delta \bar{\Theta} = 0.9 \), stoichiometric AFR \( r_s \), and estimated OSC \( \bar{C}_{0,1} \).

4. DRIVE CYCLE RESULTS

In this section the drive cycle results for fuel economy and tailpipe \( NO_x \) emissions are analyzed to compare the performance of the two powertrain configurations. The results are shown in Fig. 6. Note that, since results for the \( NO_x \) emissions are based on steady-state data, the absolute numbers need to be treated with caution and are in reality generally higher due to transients and imperfect AFR control. For the multimode engine three cases are
Fig. 6. Drive cycle results assuming a TWC, which requires OSC depletion. Results for FTP75 (left column), HWFET (center column), and US06 (right column) cycles. Plotted are fuel economy (top row) and average tailpipe NO$_x$ (bottom row). Conventional vehicle (bars on the left) and mild HEV (bars on the right) with results shown for the SI-only engine (black bars) as well as the SI/HCCI multimode engine. Mode switches are assumed instantaneous (green bars), penalized (blue bars), and penalized with OSC depletion (red bars). Results are shown from the original mode switch model as well as the case study with reduced OSC capacity and HCCI regime (grey bars).

distinguished, denoted Orig, in Fig. 6. The first case assumes instantaneous mode switches, the second applies the presented mode switch model and the associated penalties. Both cases assume that the TWC’s OSC does not exhibit any dynamics, i.e., it fills instantaneously when HCCI mode is entered and it returns to a depleted state as soon as stoichiometric SI is reached. Therefore these cases do not incur any fuel penalty from depletion. On the other hand, they also do not have the OSC to delay the NO$_x$ breakthrough when entering HCCI. The third case takes into account both, the mode switch penalties and the TWC aftertreatment system requiring fuel-expensive depletion of the OSC.

As can be seen in the case of the FTP75 cycle, combining the multimode engine operation with the mild HEV results in significant fuel economy synergies. For the other drive cycles synergies exist, however, they are significantly smaller, due to limited operation at low loads and fewer opportunities for regenerative braking. The FTP75 drive cycle is subjected to engine and TWC cold start and therefore during the first 30 seconds the TWC’s temperature lies below light-off. This leads to the relatively high tailpipe NO$_x$ results. However, upon reaching nominal temperatures the applied model assumes perfect AFR control and NO$_x$ conversion in stoichiometric SI mode. For that reason NO$_x$ in the SI-only cases during the HWFET and US06 cycles is equal to zero. As can be seen for the FTP75 and the HWFET drive cycles, extended residence time in HCCI leads to long periods of NO$_x$ breakthrough. The NO$_x$ accumulates to significant amounts which would pose a problem for low emissions certification under LEVIII standards. Since during the US06 cycle HCCI combustion is even in the mild HEV only rarely used, the resulting NO$_x$ emissions are relatively low.

The impact of the OSC dynamics can be seen clearly. For all the drive cycles and both vehicles the requirement of depleting the OSC leads to a significant drop in fuel economy. For the conventional vehicle the depletion overall negates all of HCCI’s efficiency benefits. On the other hand, in case of the HEV and the FTP75 cycle still more than 2.5% improvement in fuel economy is achieved despite the OSC depletion. The important takeaway is twofold. First, hybridization does not lead to a noticeable improvement for the other two drive cycles. Second, focusing on the NO$_x$ emissions it can be seen that based on the applied HCCI-SI mode switch strategy the buffer from the OSC does not lead to a significant reduction in tailpipe NO$_x$.

5. CASE STUDY: SMALL O$_2$-STORAGE & SMALL HCCI REGIME

The following section discusses a case study which applies small, and at first counterintuitive modifications in HCCI-SI control strategy and hardware. First, even if a TWC with generous OSC is used, this storage fills up too fast to lead to a substantial reduction in tailpipe NO$_x$, as can be seen in Fig. 6 when comparing the results of penalized mode switch with and without OSC dynamics. However, it requires large quantities of fuel to deplete the full OSC. Therefore the usage of a TWC with a small rather than a large OSC might be desirable, thereby assuming that in SI-combustion AFR-control is accurate enough. Second, it can be seen that extended operation in HCCI mode results in significant amounts of AFR-control is accurate enough. Therefore simulations were run, assuming only the lower half of the HCCI regime (in Fig. 2 area below purple dashed line) combined with a TWC with a quarter of the original OSC. The associated results are shown in Fig. 6. The smaller HCCI regime leads to a significant reduction
in HCCI operation, e.g., the mild HEV during FTP75, HWFET, and US06 drive cycles exhibits a decrease in HCCI residence time from 35% to 29%, 40% to 22%, and 13% to 8%, respectively. However, as can be seen, the fuel economy of this modified configuration is almost equal or greater than the original results. In addition, tailpipe NO\textsubscript{x} originating from HCCI operation is significantly reduced. Finally, it must be mentioned that a reduction in size of the OSC could have some drawbacks and is likely to require an increased accuracy in AFR control under nominal SI conditions.

6. CONCLUSION

A model of a mild HEV with SI/HCCI multimode engine and TWC aftertreatment is discussed in terms of drive cycle fuel economy and NO\textsubscript{x} emissions. The torque split and the combustion mode are chosen by ECMS which takes into account fuel penalties associated with mode switching and OSC depletion. It is shown that the extended residence time in HCCI due to the ISG’s torque assist reduces the amount of fuel spent on depleting the OSC. The prolonged HCCI operation, however, results in extended periods of time under which the TWC is unable to reduce NO\textsubscript{x}, leading to substantial tailpipe emissions. A case study evaluates the impact of a smaller HCCI regime and a smaller OSC. Even a generous OSC fully oxidizes rapidly under lean HCCI conditions and is therefore unable to maintain NO\textsubscript{x} conversion in a significant way. Therefore it is suggested here, that a TWC with smaller OSC is preferable, since its depletion requires less fuel. Furthermore, the attempt to push the HCCI regime to higher loads gives rise to an increase in combustion temperature and therefore engine-out NO\textsubscript{x}. Constraining the HCCI regime to conditions exhibiting ultra-low NO\textsubscript{x} emissions reduces the associated breakthrough substantially. Due to the ISG’s torque assist even this smaller HCCI regime can be utilized for significant periods of time. Simultaneously, the fuel savings originating from the smaller OSC compensates for reduced HCCI residence time.

ACKNOWLEDGEMENTS

The authors wish to thank a) Dr. Patrick Gorzelic for helpful discussions on SI/HCCI combustion mode switches, b) the company CPT for providing ISG efficiency maps, c) Drs. Kim and Siegel for valuable discussions on battery and HEV modeling, and d) Drs. John Hoard and Galen Fisher for helpful discussions about TWC aftertreatment.

REFERENCES


