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IS IT ECONOMICAL TO IGNORE THE DRIVER? A CASE STUDY ON MULTIMODE COMBUSTION

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ABSTRACT

Ignoring the driver's torque command can be beneficial for fuel economy, especially if it leads to extended residence time at efficient operating conditions. We answered this question for a particular engine, which allows mode switches between spark ignition (SI) and homogeneous charge compression ignition (HCCI) combustion. When operating such a multimode combustion engine it might be required to defer a load command outside the feasible regime of one combustion mode until a mode switch is accomplished. The resulting delays in engine torque response might negatively affect vehicle performance and drivability. In this paper a longitudinal vehicle model is presented, which incorporates dynamics associated with SI/HCCI mode switching. Two exemplary supervisory control strategies were evaluated in terms of fuel economy and torque behavior. It was seen that the duration of a mode switch may be short enough to avoid substantial impairment in torque response. This in turn would lead to the opportunity of purposefully ignoring the driver command. Thereby, the residence time in the beneficial HCCI combustion regime is prolonged and fuel-expensive mode switching avoided. The result is a trade-off between torque deviation and improvements in fuel economy. Finally, based on this trade-off the supervisory control strategy relying on a short-term prediction of engine load was seen to achieve similar fuel economy with slightly improved torque response than a strategy without prediction.

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1 INTRODUCTION

Advanced combustion modes show great potential to improve vehicle fuel economy. One possible implementation of such combustion modes are multimode combustion engines applying spark ignition (SI) and homogeneous charge compression ignition (HCCI) combustion [1]. HCCI combustion improves engine efficiency, is, however, limited to low loads [2]. This disadvantage is resolved by switching to the less efficient SI mode if the driver requests a load outside HCCI's limits.

A supervisory control strategy is required which makes the decision, when a mode switch should be attempted. In [3] instantaneous mode switches are assumed with every visitation of

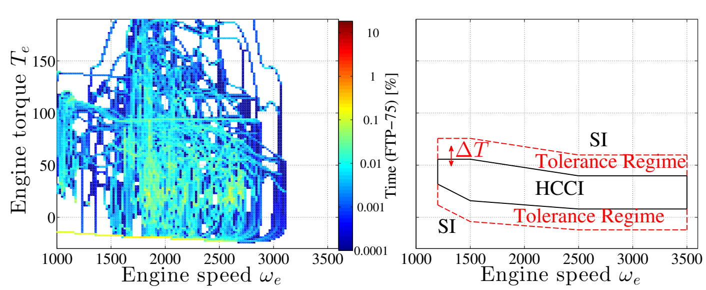

Figure 1: Left: Map of frequently visited operating points during the FTP-75 drive cycle. Right: Boundary of the feasible operating regime of naturally aspirated HCCI combustion (solid black). In HCCI combustion, the tolerance regime (dashed red) represents the load/speed conditions for which a deviation between desired torque and actual engine torque is accepted.

the feasible HCCI operating regime being an actual residence in HCCI combustion mode. Both [1,4] switch combustion modes based on the state of the three-way catalyst, thereby taking into account its temperature [1] and oxygen storage level [4]. The integration of a multimode combustion in a hybrid electric vehicle is discussed in [5,6] with a focus on the power and torque split decisions. However, research on SI-HCCI mode switching has shown that mode switches require a certain amount of time and incur a penalty in fuel [7–9]. Therefore not every visitation of the feasible HCCI operating regime is long enough to result in a benefit for overall fuel economy [10]. Previous work [11] has shown that the large number of combustion mode switches during a drive cycle leads to a short consecutive residence time in HCCI. This in turn results in an accumulation of the associated penalties with a negative impact on overall fuel economy.

In addition, HCCI's load limitations might lead to potential drivability issues. If the driver demands a load far outside HCCI's operating regime, the engine torque response needs to be delayed while the combustion mode is switched from HCCI to SI. Drivability is a subjective measure of vehicle performance as perceived by the driver. Attempts to find an objective drivability measure can be found in [12–14]. A potential measure to quantify the impact of independent events such as mode switches might be jerk, i.e., the derivative of the vehicle's longitudinal acceleration.

This paper discusses the potential increase in residence time in HCCI mode by allowing the engine to temporarily ignore the torque desired by the driver. Thereby small excursions from the HCCI regime are avoided and the number of costly mode switches reduced. The frequently visited engine operating points based on FTP-75 drive cycle simulation and the feasible operating regime of HCCI are shown in Fig. 1. In turn, however, this strategy inherently leads to periods, in which the actual engine torque deviates from what is desired by the driver. Therefore a trade-off can be expected between fuel economy benefits and drivability. A longitudinal vehicle model is introduced which takes into account the delays and penalties associated with combustion mode switching. The model is presented in Sec. 2. In Sec. 3 two supervisory control strategies are presented and evaluated in drive cycle simulations in Sec. 4.

2 MODEL

In the following section the delays and supervisory control of combustion mode switching are incorporated into a vehicle model. In [15] a methodology is presented, modeling the combustion mode switch dynamics in form of a finite state machine. In [9] the model was parameterized with experimental mode switch data. Based on the inputs engine speed ω_e and torque T_e the current combustion mode M was determined. Therefore the model was run in a post-processing scheme without any influence on the dynamic behavior of the vehicle. Here the combustion mode switch dynamics are integrated into a longitudinal vehicle and driver model. A block diagram of the model is shown in Fig. 2. Depending on current combustion mode M and with T_e and ω_e steady-state maps and penalty parameters are used to calculate the fuel mass flow.

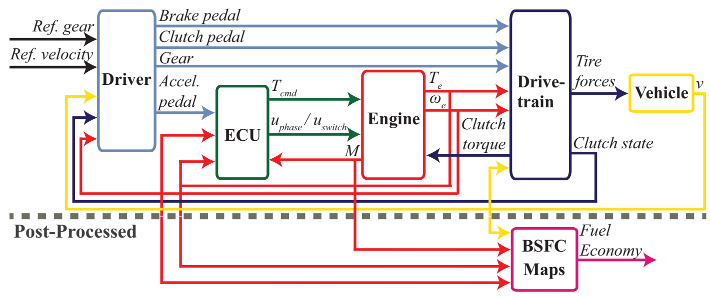

Figure 2: Overview of vehicle model block diagram.

2.1 Engine

The response of actual engine torque T_e to a commanded torque T_{cmd} from the ECU is modeled as a first order system with time constant $\tau_e = 90\,\text{ms}$, identified with throttle snap experiments:

$$\dot{T}_e = \frac{1}{\tau_e}(T_{cmd} - T_e). \tag{1}$$

The SI-HCCI combustion mode switch is modeled using a finite state machine with twelve finite states M, shown in Fig. 3. The applied mode switch control strategy relies on a two-stage cam switching mechanism. Finite states utilizing a high lift cam position (bottom half) can be characterized as SI combustion modes, while states at a low lift cam position (top half) as HCCI modes. Each finite state exhibits a minimum duration in seconds or engine cycles until a transition to the next state is feasible.

Control inputs to the combustion mode switch model are u_{phase} and u_{switch}, originating from the supervisory controller in the engine control unit (ECU). They can be imagined as commands from the supervisory control to the underlying mode switch controller, not discussed in this paper, which takes care of the actual mode switch tasks, such as air path and combustion control as well as misfire prevention. The mode switch preparation, i.e., phasing the cams between nominal and switching conditions, is controlled by u_{phase}. If $u_{phase} = 1$ the cams are phased to prepare the mode switch from SI to HCCI, $u_{phase} = 0$ represents the other direction, from HCCI to SI mode. The second input u_{switch} controls the cam switch command, the point of no return during mode switch. If $u_{switch} = 1$ the command to switch from high to low lift will be sent as soon as the cams reach their target location; vice versa if $u_{switch} = 0$, which represents a cam switch from low to high lift.

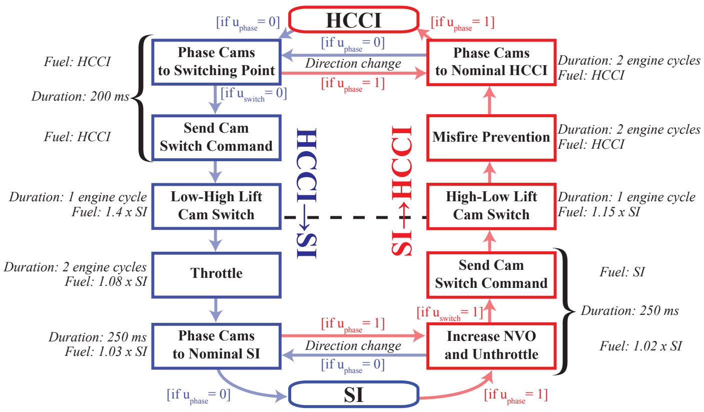

Figure 3: Finite state machine representing mode switch between SI and HCCI combustion. Durations and fuel penalties associated with each finite state are shown on the side. Inputs of the supervisory controller are u_{phase} and u_{switch}.

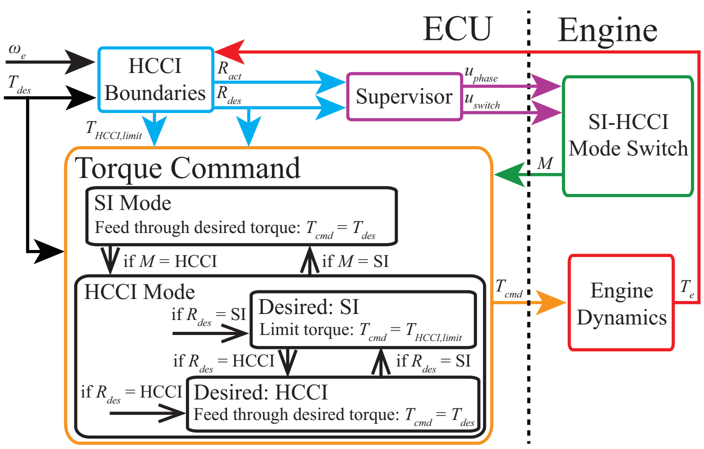

Figure 4: Block diagram of the ECU model and its interaction with combustion mode switch.

Note that the mode switch controller is assumed to perform a torque-neutral switch, i.e., without any substantial deviations from reference torque. Therefore the potential impact of torque fluctuations occurring during the mode switch are neglected.

2.2 Engine Control Unit (ECU)

The supervisory controller of the combustion mode switches is located within the ECU model, shown in Fig. 4. Based on current engine operating conditions the supervisory strategy computes the mode switch commands u_{phase} and u_{switch}. Two different control strategies are presented in Sec. 3. For each engine load/speed condition the function $R_{act}(\omega_e, T_e)$ determines if the engine operates within the feasible range of HCCI combustion:

$$R_{act}(\omega_e, T_e) = \begin{cases} \text{HCCI} & \omega_{HCCI,min} \leq \omega_e \leq \omega_{HCCI,max} \text{ AND} \ldots \\ & T_{HCCI,min}(\omega_e) \leq T_e \leq T_{HCCI,max}(\omega_e) \\ \text{SI} & \text{ELSE.} \end{cases} \quad (2)$$

The function $R_{des}(\omega_e, T_{des}, \Delta T)$ is similar and represents the regime the desired torque lies in:

$$R_{des}(\omega_e, T_{des}, \Delta T) = \begin{cases} \text{HCCI} & \omega_{HCCI,min} \leq \omega_e \leq \omega_{HCCI,max} \cdots \\ & \text{AND } T_{HCCI,min}(\omega_e) - \Delta T \leq T_{des} \\ & \text{AND } T_{des} \leq T_{HCCI,max}(\omega_e) + \Delta T \\ \text{SI} & \text{ELSE.} \end{cases} \quad (3)$$

The HCCI operating regime is extended towards higher and lower loads using parameter ΔT to create a tolerance regime between SI and HCCI mode, shown in Fig. 1. If in $M =$ HCCI mode, excursions of T_{des} into the tolerance bands are ignored and no combustion mode switch is triggered. The operating regimes of actual and desired load are distinguished since the multimode operation leads to certain constraints in load command, as shown in the bottom right of Fig. 4. If the engine operates in $M =$ SI mode the entire load range of the engine is available. Therefore commanded torque is equal to desired torque:

$$T_{cmd} = T_{des}. \quad (4)$$

However, in $M =$ HCCI mode the torque is limited due to high pressure rise rates and combustion instabilities. If the driver desires a load outside the feasible regime of HCCI, this load cannot be achieved before a mode switch from HCCI to SI combustion has been conducted. Therefore the load command T_{cmd} needs to be delayed. As can be seen in Fig. 4, here the T_{cmd} follows T_{des} until the HCCI load limit $T_{HCCI,limit}$ is reached. This can either be the upper or the lower boundary. The command T_{cmd} remains at this value until either the SI mode is reached or T_{des} returns to the HCCI regime.

$$T_{cmd} = \begin{cases} T_{des} & R_{des}(\omega_e, T_{des}, 0) = \text{HCCI} \\ T_{HCCI,limit} & R_{des}(\omega_e, T_{des}, 0) = \text{SI} \end{cases} \quad (5)$$

2.3 Vehicle

The applied longitudinal vehicle model was parameterized for a stock Cadillac CTS 2009 with manual transmission. The model is briefly described and validated in [11]. It considers the lock-up state of the clutch and includes the three following main dynamic states: Vehicle speed v, rotational speed of the wheels, and engine speed ω_e.

3 CONTROL STRATEGIES

In the following section, two different supervisory mode switch control strategies are introduced. The first strategy makes the mode switch decision depending on the current states only. The second strategy applies a prediction in engine torque and speed to anticipate the switch.

3.1 Strategy 1: No Prediction (NoP)

The first strategy NoP is solely based on the current actual and desired combustion regimes, R_{act} and R_{des}, respectively. In SI mode the phasing of the cams is initiated, using u_{phase}, as soon as $R_{des}(\omega_e, T_{des}, 0) = \text{HCCI}$. As can be seen in Fig. 3 the mode switch direction can be changed and the cam movement reversed to nominal SI conditions in case the desired load exits the HCCI regime again.

$$u_{phase} = \begin{cases} 1 & R_{des}(\omega_e, T_{des}, 0) = \text{HCCI} \\ 0 & \text{ELSE} \end{cases} \tag{6}$$

Once the engine torque T_e enters the feasible HCCI combustion regime $u_{switch} = 1$ is commanded:

$$u_{switch} = \begin{cases} 1 & R_{act}(\omega_e, T_e) = \text{HCCI} \\ 0 & \text{ELSE.} \end{cases} \tag{7}$$

At this point the cam switch command will be sent as soon as the cams reach their switching position.

In $M = \text{HCCI}$ mode the mode switch is initiated as soon as the desired torque exits the HCCI regime.

$$u_{phase} = \begin{cases} 0 & R_{des}(\omega_e, T_{des}, 0) = \text{SI} \\ 1 & \text{ELSE} \end{cases} \tag{8}$$

$$u_{switch} = \begin{cases} 0 & R_{des}(\omega_e, T_{des}, \Delta T) = \text{SI} \\ 1 & \text{ELSE} \end{cases} \tag{9}$$

Since this strategy only acts based on the current engine operating conditions, a time delay is incurred upon entering the HCCI regime until the mode switch to HCCI combustion is completed. This therefore reduces the potential residence time in the beneficial HCCI combustion. The opposite is the case during the switch from HCCI to SI combustion, where the residence in HCCI mode is prolonged. However, this is done by temporarily saturating the load command T_{cmd} at HCCI load boundary, leading to potential drivability issues. Finally, it is likely that some visitations of the HCCI operating regimes are very short. Therefore this strategy might allow mode switches which are actually harmful for overall fuel economy, since short stays cannot be predicted.

3.2 Strategy 2: Predict by Linear Extrapolation (LiP)

In order to mitigate the two potential problems of the first control strategy, in the strategy LiP the controller attempts to predict the short-term behavior of engine load and speed. The prediction is used to anticipate entries and exits of the feasible HCCI regime, thereby preparing the mode switches beforehand and mitigating associated delays. In addition the prediction can be used to prevent mode switches during very short visitations of the HCCI operating regime. In [10] different prediction methods were tested on drive cycle measurements and they exhibited poor accuracy in predicting the duration of future visitations of the HCCI regime. However, they were able to correctly identify very short and very long durations, which is applied in this strategy. The prediction method used here applies linear least squares to the h most recent values of desired load and engine speed,

$$\mathbf{T}^k_{hist} = \left(T^{k-h}_{des}, \ldots, T^{k-2}_{des}, T^{k-1}_{des}, T^k_{des}\right)^{\mathrm{T}} \tag{10}$$

$$\boldsymbol{\omega}^k_{hist} = \left(\omega^{k-h}_e, \ldots, \omega^{k-2}_e, \omega^{k-1}_e, \omega^k_e\right)^{\mathrm{T}} \tag{11}$$

using $t_s \cdot h = 0.5\,\text{s}$ with sampling time t_s. The more recent values are weighted more heavily by applying

$$\mathbf{W} = \text{diag}\left(e^{-35\cdot h\cdot t_s}, e^{-35\cdot(h-1)\cdot t_s}, \ldots, e^{-35\cdot t_s}, 1\right). \tag{12}$$

The slopes f_T and f_ω for linear polynomial extrapolations of desired engine torque and speed, respectively, are found by

$$\mathbf{A} = -t_s \cdot (h, h-1, \ldots, 0)^{\mathrm{T}} \tag{13}$$

$$\mathrm{A}^* = \mathbf{A}^{\mathrm{T}} \cdot \mathbf{W} \cdot \mathbf{A} \tag{14}$$

$$\mathbf{b}^* = \mathbf{A}^{\mathrm{T}} \cdot \mathbf{W} \tag{15}$$

$$\mathbf{T}^k_{des} = T^k_{des} \cdot (1, \ldots, 1)^{\mathrm{T}} \tag{16}$$

$$\boldsymbol{\omega}^k_e = \omega^k_e \cdot (1, \ldots, 1)^{\mathrm{T}} \tag{17}$$

$$f_T = \frac{1}{\mathrm{A}^*} \cdot \mathbf{b}^* \cdot (\mathbf{T}^k_{hist} - \mathbf{T}^k_{des}) \tag{18}$$

$$f_\omega = \frac{1}{\mathrm{A}^*} \cdot \mathbf{b}^* \cdot (\boldsymbol{\omega}^k_{hist} - \boldsymbol{\omega}^k_{des}). \tag{19}$$

Desired engine load and speed are predicted over a horizon H with $t_s \cdot H = 1.5\,\text{s}$, leading to vectors

$$\hat{\mathbf{T}}^k_{des} = \mathbf{T}^k_{des} + f_T \cdot t_s \cdot (1, \ldots, H)^{\mathrm{T}} \tag{20}$$

$$= \left(\hat{T}^{k+1}_{des}, \hat{T}^{k+2}_{des}, \ldots, \hat{T}^{k+H}_{des}\right)^{\mathrm{T}} \tag{21}$$

$$\hat{\boldsymbol{\omega}}^k_e = \boldsymbol{\omega}^k_e + f_\omega \cdot t_s \cdot (1, \ldots, H)^{\mathrm{T}} \tag{22}$$

$$= \left(\hat{\omega}^{k+1}_e, \hat{\omega}^{k+2}_e, \ldots, \hat{\omega}^{k+H}_e\right)^{\mathrm{T}}. \tag{23}$$

To predict the actual engine torque the discrete time first order engine dynamics are used

$$\hat{T}_e^{k+i} = \left(1 - \frac{t_s}{\tau_e}\right)^{i-1} + \frac{t_s}{\tau_e} \cdot \sum_{j=1}^{i} \left(1 - \frac{t_s}{\tau_e}\right)^{i-1-j} \cdot \hat{T}_{des}^{k+j} \quad \text{with } i = \{1, ..., H\} \tag{24}$$

leading to the prediction of actual engine torque

$$\hat{\mathbf{T}}_e^k = \left(\hat{T}_e^{k+1}, ... \hat{T}_e^{k+H-1}, \hat{T}_e^{k+H}\right)^{\mathrm{T}}. \tag{25}$$

From prediction vectors $\hat{\mathbf{T}}_{des}^k$, $\hat{\mathbf{T}}_e^k$, and $\hat{\boldsymbol{\omega}}_e^k$ the crossing times of the HCCI operating regime can be calculate. The predicted duration until entry of the HCCI regime is denoted τ_{Entry}:

$$j_{Entry} = \min\left(i \in (1, H) \mid R_{act}(\hat{\omega}_e^{k+i}, \hat{T}_e^{k+i}) = \text{HCCI}\right) \tag{26}$$

$$\tau_{Entry} = j_{Entry} \cdot t_s. \tag{27}$$

The predicted durations until actual torque and desired torque exit the HCCI regime are denoted $\tau_{Exit,act}$ and $\tau_{Exit,des}$, respectively:

$$j_{Exit,act} = \max\left(i \in (1, H) \mid R_{act}(\hat{\omega}_e^{k+i}, \hat{T}_e^{k+i}) = \text{HCCI}\right) \tag{28}$$

$$\tau_{Exit,act} = j_{Exit,act} \cdot t_s \tag{29}$$

$$j_{Exit,des} = \max\left(i \in (1, H) \mid R_{des}(\hat{\omega}_e^{k+i}, \hat{T}_{des}^{k+i}, \Delta T) = \text{HCCI}\right) \tag{30}$$

$$\tau_{Exit,des} = j_{Exit,des} \cdot t_s. \tag{31}$$

The potential visitation duration of the HCCI regime is τ_{Stay}:

$$\tau_{Stay} = \tau_{Exit,act} - \tau_{Entry}. \tag{32}$$

These durations are used to schedule the combustion mode switches. In SI combustion the mode switch to HCCI mode is prepared as soon as τ_{Entry} is smaller than the time requirement to phase the cams. Due to the constraints of the variable valve actuation it requires 250 ms to phase to cams from nominal SI to switching conditions. In addition it requires about one engine cycle to process the cam switching command. However, this command can already be sent beforehand to reduce the overall switching duration, leading to the following condition for u_{phase}:

$$u_{phase} = \begin{cases} 1 & \tau_{Entry} < 250\,\text{ms} - \frac{4\pi}{\omega_e} \text{ AND } \tau_{Stay} > 0.2\,\text{s} \\ 0 & \text{ELSE.} \end{cases} \tag{33}$$

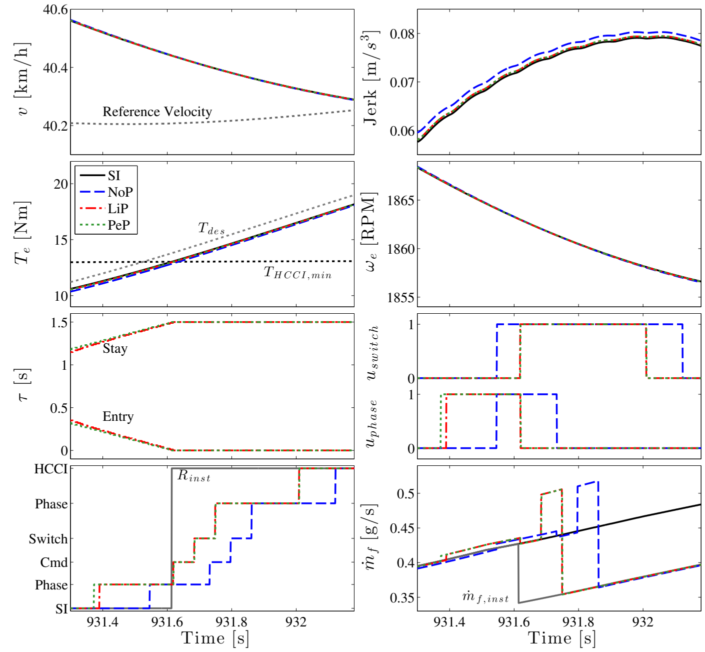

Figure 5: Exemplary SI-HCCI mode switch during the FTP75 drive cycle. SI-only (solid black) and strategies NoP without any prediction (dashed blue), LiP with linear extrapolation (dash-dotted red), and PeP with perfect prediction (dotted green).

As can be seen, in addition the mode switch is only prepared if the visitation duration τ_{Stay} is predicted to be of a certain minimum.

$$u_{switch} = \begin{cases} 1 & R_{act}(\omega_e, T_e) = \text{HCCI AND } \tau_{Stay} > 0.1\,\text{s} \\ 0 & \text{ELSE} \end{cases} \tag{34}$$

In HCCI combustion the mode switch is prepared in a way that allows a cam switch as soon as T_{des} exits the feasible regime.

$$u_{phase} = \begin{cases} 0 & \tau_{Exit,des} < 200\,\text{ms} - \frac{4\pi}{\omega_e} \\ 1 & \text{ELSE} \end{cases} \tag{35}$$

$$u_{switch} = \begin{cases} 0 & R_{des}(\omega_e, T_{des}, \Delta T) = \text{SI} \\ 1 & \text{ELSE} \end{cases} \tag{36}$$

The strategies are compared to the best possible case, referred to as strategy PeP, in which perfect knowledge of the actual and desired torque and engine speed trajectories in a SI-only engine is assumed:

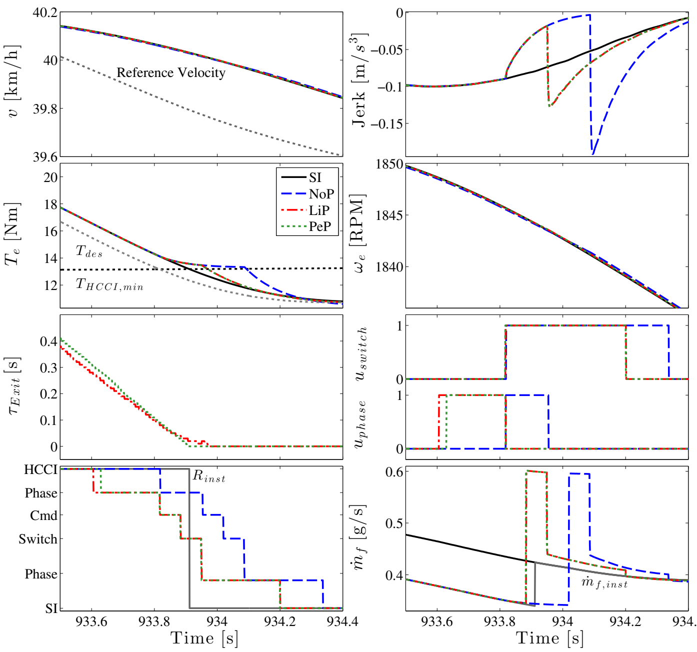

Figure 6: Exemplary HCCI-SI mode switch during the FTP75 drive cycle. SI-only in solid black and strategies NoP without any prediction (dashed blue), LiP with linear extrapolation (dash-dotted red), and PeP with perfect prediction (dotted green).

$$\hat{\mathbf{T}}^k_{des} = \left(T^{k+1}_{des,SI}, \ldots, T^{k+H-1}_{des,SI}, T^{k+H}_{des,SI}\right)^{\mathrm{T}} \tag{37}$$

$$\hat{\mathbf{T}}^k_{e} = \left(T^{k+1}_{e,SI}, \ldots, T^{k+H-1}_{e,SI}, T^{k+H}_{e,SI}\right)^{\mathrm{T}} \tag{38}$$

$$\hat{\boldsymbol{\omega}}^k_{e} = \left(\omega^{k+1}_{e,SI}, \ldots, \omega^{k+H-1}_{e,SI}, \omega^{k+H}_{e,SI}\right)^{\mathrm{T}}. \tag{39}$$

Note that all these trajectories will still differ from the multimode engine results, since they are not subject to the mode switching delays. However, they still allow a very accurate prediction of τ_{Entry}, $\tau_{Exit,act}$, and $\tau_{Exit,des}$ as long as ΔT is small.

4 DRIVE CYCLE SIMULATION

The two supervisory control strategies were evaluated during the FTP75 cycle. They are compared with three cases: An SI-only case, the assumption of instantaneous mode switches between SI and HCCI combustion without any penalties, and the assumption of perfect knowledge of the SI-only load/speed trajectories.

4.1 Without Tolerance Regime

First, the cases are compared without a tolerance regime, i.e., $\Delta T = 0$. Exemplary SI-HCCI and HCCI-SI mode switches are shown in Figs. 5 and 6, respectively. As can be seen in Fig. 5, the strategies relying on prediction are able to anticipate the upcoming

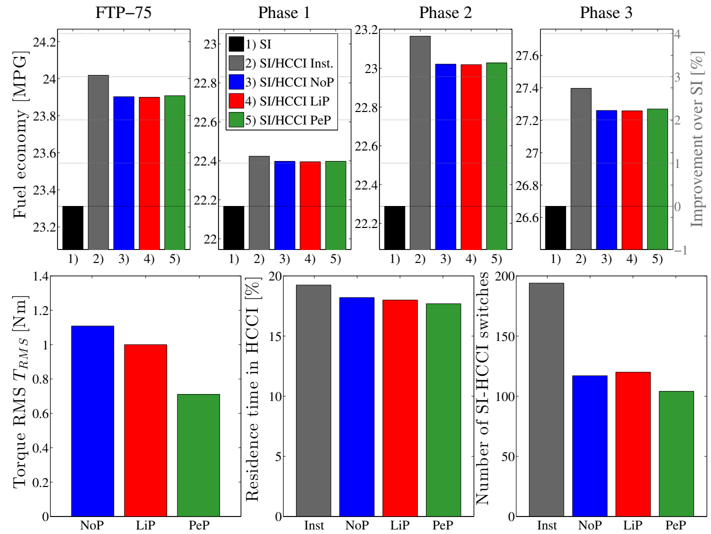

Figure 7: Drive cycle results for the different strategies during the FTP75 drive cycle. SI-only (black), instantaneous switches (grey) and strategies NoP without any prediction (blue), LiP with linear extrapolation (red), and PeP with perfect prediction (green). Top: Fuel economy during three individual phases of FTP75. Bottom-Left: Torque deviation. Bottom-Center: Total residence time in HCCI mode relative to duration of drive cycle. Bottom: Right: Number of cam switches in SI-HCCI direction.

entry of the feasible HCCI regime and prepare the mode switch accordingly. Therefore the cam switch command is sent as soon as the regime is entered. Strategy NoP, on the other hand, starts preparation slightly later, thereby reducing the available time spent in the HCCI regime. The effect of the torque saturation at the HCCI boundary during the HCCI-SI mode switch can be seen in Fig. 6. Strategy NoP initiates the mode switch much later than the other strategies, leading to a longer torque saturation in HCCI mode and resulting in a vehicle jerk motion. However, no effect on velocity is visible. Cases LiP and Pep, due to their prediction of the exit event, are able to send the cam switch command as soon as the desired torque exits the HCCI regime. Therefore the disturbance in torque is mitigated and jerk reduced.

The fuel economy and other drive cycle results for the FTP75 drive cycle are shown in Fig. 7. As can be seen, improvement values are between 1% and 4%. During the first phase of the FTP75 the potential of HCCI combustion is reduced, since a significant part of the phase is subject to engine cold start when a mode switch to HCCI combustion is infeasible. As can be seen, the fuel economy benefits for all penalized cases are substantially smaller, approx. 15%, than if instantaneous switches are assumed. This is due to the accumulated mode switch fuel penalties. However, the three penalized cases show almost identical fuel economy results. Strategy NoP benefits from an extended residence time in HCCI mode, with, however, a potential sacrifice in drivability. The im-

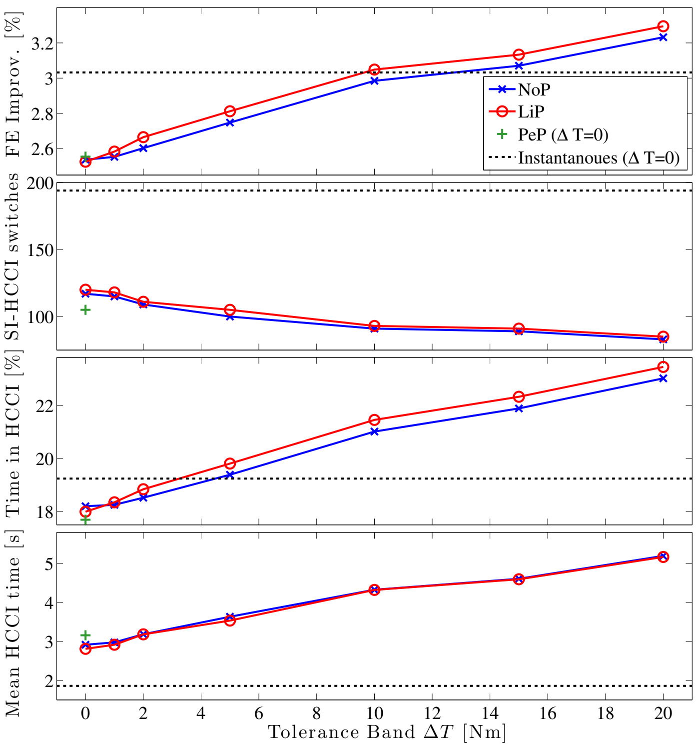

Figure 8: Simulation results for the FTP75 drive cycle with fuel economy improvements compared to a conventional SI engine versus width of the tolerance band ΔT. Strategy NoP without any prediction (red circles) and strategy LiP with linear extrapolation (blue crosses), compared with the fuel economy achieved by instantaneous mode switches (dashed black) and perfect prediction PeP (green pluses). Top: Fuel economy improvement compared to SI-only case. Second: Number of cam switches in SI-HCCI direction. Third: Total residence time in HCCI mode relative to duration of drive cycle phase. Bottom: Residence time in HCCI mode per SI-HCCI cam switch.

pact of the strategy on the overall torque response is measured as RMS error T_{RMS} between the torque T_e of the associated simulation run and the torque result $T_{e,SI}$, based on the conventional SI engine without any mode switching.

$$T_{RMS} = \sqrt{\frac{1}{t_{ph}} \int_0^{t_{ph}} (T_{e,SI} - T_e)^2 dt} \tag{40}$$

with t_{ph} the duration of the associated drive cycle phase. A larger T_{RMS} corresponds to a reduction in drivability. Indeed, it can be seen that the cases applying prediction exhibit a reduction in T_{RMS}. Overall, however, even in case of strategy NoP relatively mild amplitudes of jerk were experienced and velocity was barely affected.

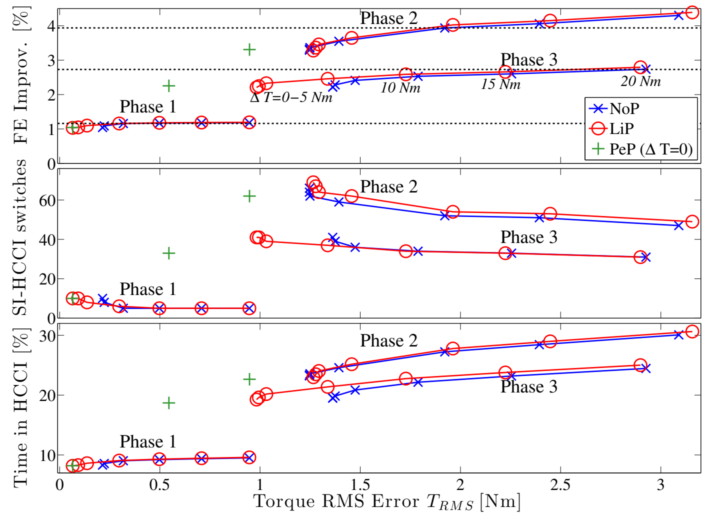

Figure 9: Simulation results for the three phases of the FTP75 drive cycle with fuel economy improvements compared to a conventional SI engine versus drivability as RMS torque error T_{RMS}. Strategy NoP without any prediction (red circles) and strategy LiP with linear extrapolation (blue crosses), compared with the fuel economy achieved by instantaneous mode switches (dashed black) and perfect prediction PeP (green pluses). Top: Fuel economy improvement compared to SI-only case. Center: Number of cam switches in SI-HCCI direction. Bottom: Total residence time in HCCI mode relative to duration of drive cycle phase.

4.2 Variation of Tolerance Regime

Since the occurrences of vehicle jerk in the cases without a tolerance band were acceptable, it may be possible to amplify HCCI's efficiency benefits by temporarily ignoring the driver's commands, thereby increasing HCCI's utilization. In this section, the width ΔT of the tolerance bands is varied from 0 Nm to 20 Nm. The associated simulation results are shown in Fig. 8.

As expected, with increasing tolerance band, fuel economy improvements relative to the SI-only case increase as well, eventually even surpassing the case assuming instantaneous switches. The reasons for this benefit are twofold. The larger tolerance band results in additional residence time in beneficial HCCI conditions. For the entire FTP75 cycle residence time in HCCI mode increased by up to 26% and 30% for strategies NoP and LiP, respectively. In addition, due to the tolerance band, short excursion from the operating regime do not necessarily lead to fuel expensive mode switches. Therefore also the number in cam switches decreased by up to 30% for the two strategies. Together these two effects result in a dramatic increase in residence time in HCCI per cam switch, i.e., by up to 78% and 88% for strategies NoP and LiP, respectively.

Note that even for $\Delta T = 20$ Nm the driver was able to follow the reference velocity without violating the velocity tolerance boundaries. However, with larger ΔT, time periods, during which the engine does not respond to changes in pedal position, become longer. This increasingly impacts drivability and T_{RMS}. The trade-off between fuel economy improvement and drivability can be seen in Fig. 9, split up into the three phases of the FTP75 cycle. By introducing a small band with $\Delta T = 1\,\mathrm{Nm}$ to $5\,\mathrm{Nm}$ the fuel economy benefits are increased without greatly affecting drivability. However, it can be seen that for larger ΔT the trade-off tends to plateau. Eventually, vehicle jerk and the slow engine response would become unacceptable for the driver. Overall, it can be seen that strategy LiP is slightly superior to NoP in a way that at same fuel economy, the impact on drivability is reduced. This is even amplified if perfect prediction is assumed, which at $\Delta T = 0\,\mathrm{Nm}$ shows similar fuel economy, but at significantly reduced deviations in engine torque.

5 CONCLUSION

A finite state model for a SI/HCCI multimode engine was integrated in a vehicle simulation to capture delays in torque associated with combustion mode switching. Two supervisory control strategies were tested. The first one without any prediction, the second one applying linear extrapolation to anticipate entries and exits of the feasible HCCI combustion regime. The HCCI regime was extended by a tolerance band. As long as the driver's desired torque is located within the tolerance regime, the actual engine torque saturates at the HCCI limit, thereby temporarily ignoring the driver's commands. This in turn leads to a degradation in vehicle drivability as perceived by the driver.

The strategies were tested in simulation on the FTP75 drive cycle with varying width of the tolerance regime. It was seen that both strategies showed very similar fuel economy, however, the predictive one accomplishes it with smaller deviations in torque. Applying a tolerance band with small width increases fuel economy by increasing time spent in the HCCI regime while avoiding mode switch fuel penalties due to short excursions. For both strategies a narrow tolerance regime leads to a relatively small impact on torque without significant impact on velocity. Wider tolerance bands increase the positive effect on fuel economy and the driver was still able to follow the reference velocity without violations. However, very long time periods during which a driver command is ignored would lead to a low drivability performance and are unacceptable.

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