2014 American Control Conference (ACC)
June 4-6, 2014. Portland, Oregon, USA

Mode Switches among SI, SACI, and HCCI Combustion and their Influence on Drive Cycle Fuel Economy

Sandro Nüesch[1], Erik Hellström[1], Li Jiang[2] and Anna G. Stefanopoulou[1]

Abstract— **A vehicle and driver model from [1] is here integrated with a finite state model describing mode switches among spark-ignited (SI) combustion and the advanced combustion modes spark assisted compression ignition (SACI) and homogeneous charge compression ignition (HCCI). The model is used to quantify the influence of mode switch fuel penalties on drive cycle fuel economy considering the federal test procedure (FTP-75) and highway fuel economy test (HWFET). The simulation under the assumed fuel penalties and dynamics shows a very small fuel loss due to harmful switches. Harmful switches are mode switches that lead to short stays in the advanced combustion, where the penalty in switching is greater than the benefit achieved after the switch. The simulations also highlight the benefits of integrating the SACI mode. Apart from extending the fuel efficiency improvements beyond the HCCI range, it is postulated that SACI combustion is easier to reach (lower fuel penalty and faster response than the HCCI-SI switch) from both SI and HCCI, creating a bridge and an economic destination in the overall speed-load space. The combined operation of SACI and HCCI leads to substantially higher improvements, especially for the FTP-75 drive cycle, than using either mode individually.**

I. INTRODUCTION

Legislation and industry keep on pushing gasoline engines to their limits to achieve higher fuel economy with reduced emissions. One way towards reaching those goals is the development of advanced combustion technologies such as homogeneous charge compression ignition (HCCI). The homogeneous and highly diluted charge auto-ignites through compression. This leads to low temperature combustion and an increase in thermal efficiency through higher specific heat ratio and reduced wall heat losses [2]. In addition the rapid heat release leads to a reduction in timing losses [3]. The low peak cylinder temperature also gives very low levels of NO_x emissions. Due to the lean charge, throttling the engine is not necessary and pumping losses are reduced. Therefore, Diesel-like efficiencies can be obtained but with significantly lower emissions [4]. The load range in recompression HCCI engines is limited to low and intermediate engine speed and loads [5], [6] due to high cyclic variability and very high pressure rise rates (ringing), respectively.

Typical drive cycles, e.g. federal test procedure (FTP-75), operate frequently in the feasible operating regime of HCCI, but due to its limitations a gasoline HCCI engine will be required to return to traditional spark-ignited (SI) combustion to cover the required range of engine load and speed [7]. Additionally the time spent in the HCCI regime is divided into several shorter stays that would require a large number of combustion mode switches [1].

At a given speed and load, the engine operating conditions and settings in which SI and HCCI combustion are realized are completely different. Conventional SI combustion runs throttled with positive valve overlap (PVO) and a stoichiometric air-fuel ratio (AFR) whereas recompression-based HCCI combustion runs unthrottled with negative valve overlap (NVO), a lean AFR, lower lift cams, and with lower exhaust gas temperatures. During a combustion mode switch a rapid adjustment of the engine parameters is desired while the response times of the physical actuators (such as cam phasing, throttle position and two-stage valve lift) and the air path variables are limited. During the mode switch phase the engine operates at conditions outside the normal range of the departure and the destination mode, hence a mode switch is typically associated with a fuel penalty which could negate part of the fuel economy advantages of HCCI [1]. The exact penalty and duration of the mode switch period depends on the control strategy. Work on combustion mode switch control strategies can be found in [8], [9] and experimental results are shown in [10].

One way of increasing the high load range of advanced combustion is the use of spark and external exhaust gas recirculation (EGR) in a spark assisted compression ignition (SACI) [11]. SACI combines characteristics of SI and HCCI combustion. The spark initiates a pre-mixed flame consuming a portion of the charge, which makes the remainder of the charge auto-ignite. Spark assist can reduce the peak heat release rate since the flame consumes part of the fuel before the fast heat release during auto-ignition. Since SACI cylinder temperatures are normally not sufficiently low to achieve ultra-low NO_x emissions like HCCI, it is in this work chosen to run stoichiometric as in [12] in order to maintain three-way catalyst efficiency. By changing the spark timing and the amount of external and internal EGR, the SACI combustion properties can be varied continuously from SACI-like to SI to HCCI-like as load decreases [13]. Due to their similar properties where the regimes overlap, i.e. at low-load SACI and high-load HCCI, mode switches in-between those two combustion modes are significantly faster and less penalized than switches from and to SI.

The goal of this paper is to develop a methodology for calculating the fuel economy in different drive cycles that can be realistically achieved when accounting for fuel penalties occurring during combustion mode switches. The paper is organized as follows: In Section II the engine

---

[1] S. Nüesch, E. Hellström and A. G. Stefanopoulou are with the Department of Mechanical Engineering in the University of Michigan, Ann Arbor, MI 48109, USA

[2] L. Jiang is with Robert Bosch LLC, Farmington Hills, MI 48331, USA

978-1-4799-3274-0/$31.00 ©2014 AACC

and combustion mode switch models are explained. Then the benefits of the advanced combustion modes are shown assuming instantaneous mode switches in Section III followed by an analysis incorporating fuel penalties in Section IV.

II. ENGINE MODEL

A. *Hardware*

In this paper a turbocharged 2.0L I4 engine is used. To achieve an efficiency gain this engine is modified to a multimode combustion engine by increasing compression ratio, strengthening reciprocating components and adding cooled EGR, 2-step cam profile switching and electric cam phasing for recompression or NVO. This enables lean naturally aspirated (NA) HCCI in a small low-load regime which is generally characterized by lower brake specific fuel consumption (BSFC) compared to SI mode and ultra low NO_x engine-out emissions. The engine is also able to run stoichiometric SACI, which extends the feasible regime of advanced combustion and leads to improvements in efficiency over SI but with comparable NO_x.

The vehicle model is parameterized for a Cadillac CTS 2009 with 6-speed manual transmission.

B. *BSFC Maps and Operating Regions*

The BSFC maps for the 2.0L engine in SI, HCCI and SACI combustion mode, interpolating steady-state experiments, are used to compute engine torque and fuel consumption from acceleration pedal position and engine speed. Hence penalties in fuel consumption associated with transient phenomena on engine level are not accounted for. Since the aim here is to study the influence of the combustion mode switches, only those penalties are considered.

Experiments have been performed to identify the favorable regimes for HCCI and SACI combustion for the particular engine in terms of fuel efficiency gains over SI operation and constraints imposed by emission requirements. Therefore the BSFC map of the SI-only 2.0L I4 is used and modified in this study by including the SACI and the HCCI regime.

The engine torque is mapped over engine speed and acceleration pedal position, as input for the SI BSFC map. If the HCCI mode is enabled, it is first verified that torque and speed lie inside the feasible boundaries for HCCI combustion. If so, the BSFC of the HCCI map is used. The same procedure is used for SACI combustion. The currently most fuel efficient operating mode is denoted by R. Fig. 1 represents the combined BSFC maps of the 2.0L I4 for SI, HCCI and SACI combustion. The solid regime corresponds to HCCI. At low loads HCCI combustion results in up to 25% lower BSFC than SI; at the ringing limit the decrease in BSFC is between 5-12%. SACI shows a 10% increase in efficiency over SI at its lower limit. A BSFC optimal boundary between HCCI and SACI was found at approximately 3bar BMEP, also plotted as a dash-dotted line, where the mode switches between HCCI and SACI are assumed to occur. At its upper limit SACI combustion approaches SI and the benefit in efficiency is reduced to 0-5%.

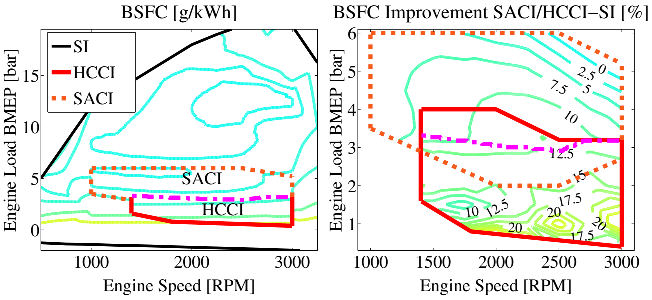

Fig. 1. Left: BSFC map including the operating regimes of lean HCCI with negligible NO_x (red, solid) and SACI (orange, dotted) and the BSFC optimal boundary in between (purple, dash-dotted). Right: Operating regimes of HCCI (red, solid) and SACI (orange, dotted) showing the improvement in BSFC using the advanced modes compared to SI with the BSFC optimal boundary (purple, dash-dotted).

C. *Combustion Mode Switch Model*

The combustion modes are defined as finite states M. The number of engine cycles since entering the current state $M(k)$ is denoted by state $n(k)$, the time in seconds by $\Delta t(k)$. Besides the main modes SI, SACI and HCCI 24 additional intermediate modes i are introduced and combined in a finite state machine. Each of those states features a fuel penalty d_i compared to SI, e.g. $d_t = 1.1$ means 10% higher fuel flow than SI.

Fig. 2 shows a detailed flow chart of the mode switch model representing a low lift (LL) strategy: During a mode switch from SI to HCCI/SACI the cams are switched from high to low lift while still running SI combustion. Then the combustion is gradually modified until autoignition starts. Therefore switching the cams is separated from switching the actual combustion. A different strategy is being referred to as high lift (HL) strategy [8]: The mode switch is prepared in SI. When ready, the cam switch is initiated and the combustion switches to autoignition simultaneously. In Fig. 2 this could be shown by interchanging rows 4 and 5 of the state machine. The figure also shows the assumed parameters for each state.

In realistic drive cycles SI combustion will be the dominant mode. Therefore $M = \text{SI}$ can be interpreted as starting and end point of different combinations of finite state transitions, in the following defined as mode switch cycles. For example a transition from SI to $M = \text{Dwell}$ and back is the shortest possible of these cycles. The most direct mode switch cycle to HCCI and back to SI can be explained in the following way (addition of SACI is explained later):

- Starting in SI mode the state is changed to the **Dwell** mode in rows 1 and 3 of Fig. 2 as soon as the beneficial region $R(k)$ changes from SI to HCCI. During this time combustion is regular SI without any fuel penalties. The number of cycles actually spent in the dwell modes are design parameters. Some stays in the HCCI regime are very short and not worth the fuel penalty of a mode switch [1]. Therefore it may be reasonable to include a dwell time n_w to increase the average duration of a stay.
- In between the dwell modes the **Cams are Phased** from PVO to NVO during the preparation states in row 2. Based

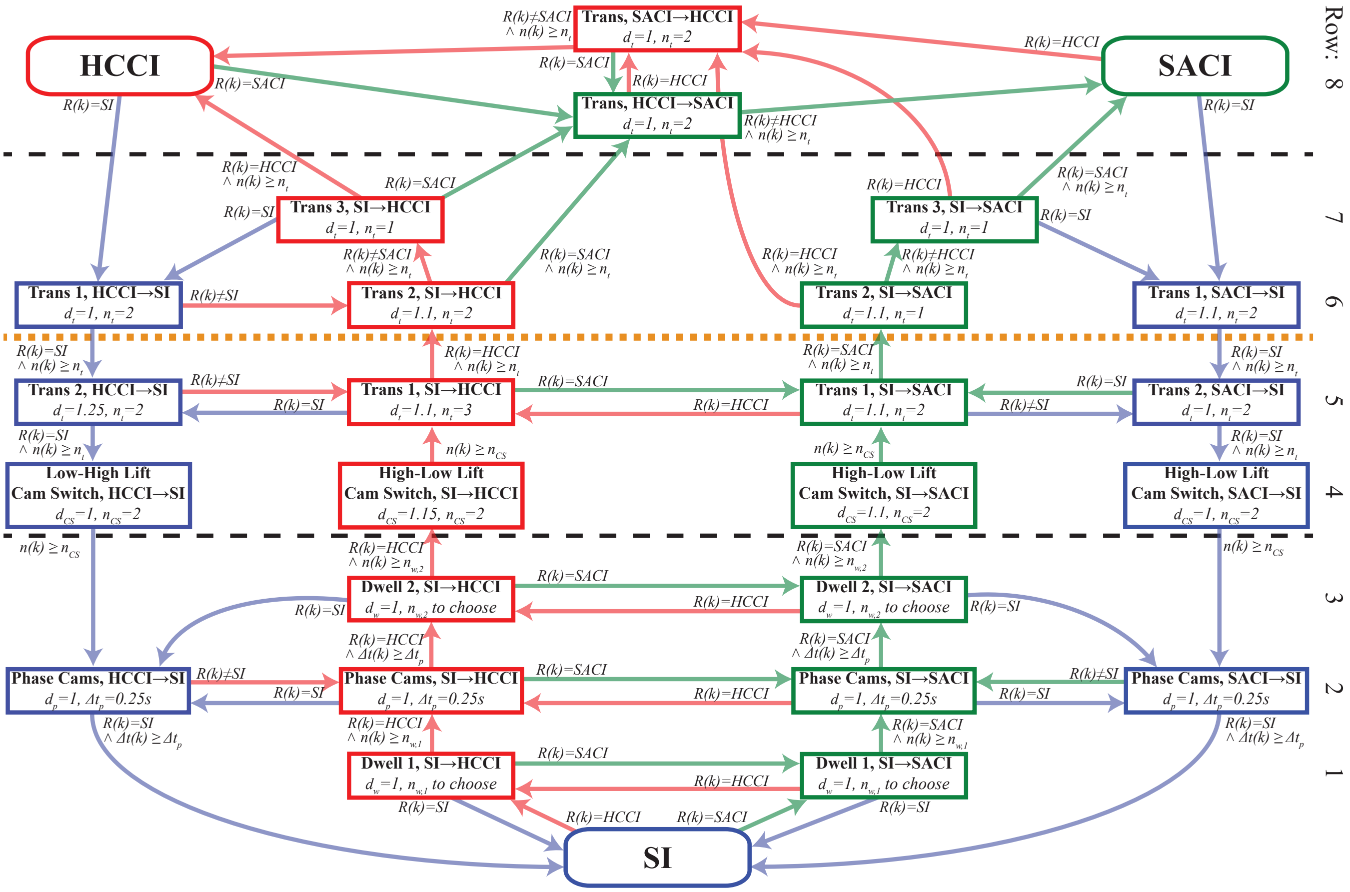

Fig. 2. Finite state model of the combustion mode switch among SI, SACI and HCCI using a low lift SI strategy. Blue paths lead to SI, green paths to SACI and red paths to HCCI. In between the black dashed lines the combustion in changes from SI to an advanced mode. The dotted line represents the start of autoignition. The rows are enumerated on the right. The currently beneficial region is denoted as $R(k)$. The number of cycles and the time since entering the current mode are denoted as states $n(k)$ and $\Delta t(k)$, respectively. Also shown are the assumed parameters for fuel penalties d_i and durations n_i and Δt_i for each finite state i.

on typical actuator phasing dynamics this requires $\Delta t_p = 250\,\text{ms}$ ($n_p \approx 4$ engine cycles @ 1900 RPM) and can be accomplished without fuel penalty. Of course the phasing has to be reversed at the end of the switch from HCCI to SI or if a mode switch is cancelled.

- After the dwell time is exceeded the **Cam Switch** is initiated, shown in row 4. A direct return to SI in case R changes is impossible before the cam switch is completed.
- The actuators are gradually changed during the three **Transition** modes in rows 5-7. Between rows 5 and 6 autoignition conditions are reached. During Transition state 1, i.e. before reaching autoignition, it is possible to directly move back towards SI if R changes. But after moving to Transition state 2 it is necessary to wait until Transition state 3 is reached before combustion can be returned to SI.

Adding the SACI combustion mode closely resembles duplication of the SI-HCCI path. But lag times due to external EGR and manifold dynamics will affect the mode switch strategy. Nevertheless preliminary experiments have shown that switches from HCCI to SACI and back are relatively easy to accomplish and short since they only require to phase spark timing and build external EGR, respectively. Therefore the associated fuel penalties and durations can be assumed slightly smaller than the ones on the HCCI path. In addition, since SACI represents an intermediate combustion mode between SI and HCCI it is assumed to be relatively easy to discontinue a switch and to start targeting SACI instead of HCCI or vice versa. However, we have very limited data on the SI to SACI transition.

The values of d_i and n_i shown in Fig. 2 are assumptions based on simulations using mean value models [8] and preliminary measurements of open-loop combustion mode switches taken during controller development. It is assumed that mode switches are controlled robustly such that the penalty parameters can be determined once for a given operating condition and then remain constant.

D. Vehicle and Driver Model

In order to analyze the engine mode switching behavior during a vehicle drive cycle, the reference velocity of the vehicle has to be translated into engine speed and load. This is done by using a dynamic vehicle and driver model. The model is described and validated in [1]. Chassis dynamometer measurements, taken with the baseline vehicle equipped with the original 3.6L V6 engine were available and used for validation. For this paper the engine maps for the 2.0L I4 multimode engine were applied. A drive cycle shift schedule determined the gear selection.

III. INSTANTANEOUS MODE SWITCHES

The vehicle model was applied to analyze the influence of combustion mode switches and to predict their impact on the fuel economy of the vehicle with the downsized and multimode combustion engine. The torque and speed trajectories are analyzed with respect to the stays in the combustion modes M and according to the regions R. First, mode switches between SI, SACI and HCCI combustion are assumed to be instantaneous and without penalties. This provides the maximum theoretical use of the advanced combustion modes for a particular drive cycle.

A. *Operating Regimes*

Fig. 3 shows the engine operating regimes during federal test procedure (FTP-75) and highway fuel economy test (HWFET) drive cycle. The plots on the left depict the fraction of time; the plots on the right show the fraction of fuel spent at each point on the engine map. As can be seen in the top row, even though the feasible region of HCCI is very limited, during the FTP-75 the engine operates at those lower loads for a significant amount of time. Despite the short time spent in SACI mode during the FTP-75 cycle, the SACI load range involves higher fuel than the HCCI low-load range, hence the fuel spent at SACI (20%) is comparable to the fuel spent at HCCI (22%). As consequence SACI mode is important for the FTP-75 fuel economy. The result is different for the HWFET cycle: The engine operates 51% of the time and 54% of fuel is spent in the SACI region while HCCI plays only a minor role.

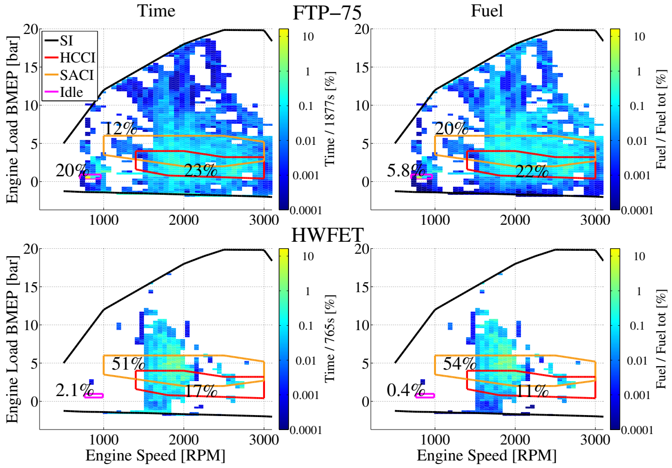

Fig. 3. Maps of frequently visited load/speed points of the 2.0L multimode engine during FTP-75 (top) and HWFET (bottom) cycle. Instantaneous mode switches are assumed. Left plots show distribution according to time, right ones according to fuel. The feasible regions of HCCI (red) and SACI (orange) are highlighted. Also marked is the idle point (purple).

B. *Fuel Economy Results*

Table I summarizes the MPG results for FTP-75 and HWFET drive cycles. As can be seen the improvement in MPG due to the use of the advanced combustion modes HCCI and SACI, assuming instantaneous switches, lies around 6% for both, FTP-75 and HWFET.

TABLE I

MPG COMPARISON OF ORIGINAL, DOWNSIZED AND MULTIMODE ENGINE, APPLYING ASSUMPTIONS FROM FIG. 2

MPG	**FTP-75**		**HWFET**	
SI	22.8		36.1	
Instant. Mode Switch	24.13	*(+5.9%)*	38.30	*(+6.1%)*
LL Strategy	23.84	*(+4.7%)*	38.00	*(+5.2%)*
HL Strategy	23.85	*(+4.7%)*	38.01	*(+5.3%)*

IV. PENALIZED MODE SWITCHES

The previous section described the theoretical potential of HCCI and SACI if instantaneous mode switches are assumed. As explained in the beginning of the paper combustion mode switches are not instantaneous. In the following section the mode switch model introduced in Section II is applied to enable a more thorough analysis. As a case study two versions of the mode switch model are used to compare HL and LL mode switch strategies, as explained above in more detail. At this point it must be mentioned that as of now both strategies are still in an early phase of development and therefore quantitative results and conclusions need to be treated with caution. Nevertheless the same methodology and model structure can easily be applied to represent and account for other mode switch strategies.

A. *Fuel Economy Results*

The MPG results for penalized combustion mode switches, using the parameters listed in Fig. 2, are shown in Table I. As can be seen incorporating the assumed fuel penalty of mode switches reduces the gain in efficiency due to advanced combustion during the FTP-75 and HWFET from 5.9% to 4.7% and from 6.1% to 5.2%. This loss corresponds to around 20% of the improvement due to the advanced combustion modes. Due to the properties of the HL strategy explained in Section II it is possible to abort a mode switch and return back to SI quicker than by using the LL strategy. Theoretically this could lead to an advantage in fuel economy. But as can be seen in Table I under the made assumptions the difference in time actually spent in transition is too small to have an impact on overall fuel economy. Of course this is only true if durations and fuel penalties of the two strategies are actually comparable.

B. *Mode Switch Analysis*

Table II lists the fractions of time and fuel spent in the different mode switch states for the two strategies and drive cycles. We can observe that the time spent during transition is indeed smaller in case of the HL strategy, probably because early cancellations of mode switches are easier. But the differences are very small and, as we saw above, have no impact on fuel economy. It can also be seen that the total time and fuel spent during transition, cam switch etc. lies between 8-10% and reduces the time available in SACI and HCCI to achieve a fuel benefit significantly. The reason for the small difference between the two strategies could be that early cancelled mode switches do not occur as often as expected. To analyze the behavior of those mode switches in greater detail Fig. 4 simplified mode switch cycles for the two drive cycles and switching strategies. The lowest arrows represent the number of complete cam phasings. As we can see during the FTP-75 and the HWFET the cams are phased back and forth around 113 and 46 times, respectively. The second row of arrows shows the cam switches and their corresponding direction e.g. 15 cam switches are performed during transitions towards and 20 starting in HCCI. After the cam switch it is possible to change the target mode e.g. in the FTP-75 LL strategy case we notice that out of 66 cam switches towards SACI, 17 are unnecessery and directly returning back to SI without ever reaching an advanced mode. The number of cases in which the target mode is changed from SACI to HCCI is zero, in the remaining 49 times the switches continue towards SACI. The top row shows the number of mode switches between the two advanced modes.

TABLE II

USE OF DIFFERENT MODES M IN % TIME AND FUEL WHEN APPLYING THE TWO MODE SWITCH STRATEGIES AND ASSUMPTIONS FROM FIG. 2

	FTP-75				HWFET			
	LL Strat.		HL Strat.		LL Strat.		HL Strat.	
	T	F	T	F	T	F	T	F
SI	62	55	62	55	28	31	29	31
Dwell / Phase	3.9	4.8	4.0	4.9	3.9	4.0	4.0	4.0
Cam Switch	1.4	1.7	1.3	1.6	1.7	1.7	1.6	1.7
Transition	3.4	4.2	3.2	4.1	4.2	4.2	3.9	3.9
SACI	9.9	16	9.9	16	47	49	47	49
HCCI	20	19	20	19	15	10	15	10

Again, as expected the LL strategy shows a greater number of cam switches in total (121 to 113 for FTP-75 / 49 to 39 for HWFET) as well as a greater number of unnecessary cam switches (19 to 11 for FTP-75 / 6 to 4 for HWFET). But both differences are very small compared to the total number of mode switches.

C. *Beneficial Mode Switches*

Mode switches which actually reach an advanced combustion mode need to remain there for a certain amount of time in order to ”regain the invested fuel”. If the net fuel gain of a mode switch is positive, the mode switch is beneficial for fuel economy and all others should be minimized. Table III compares the number of beneficial to harmful mode switch cycles. Switches that are cancelled while still in dwell or preparation mode do not show a difference to SI and are therefore enlisted as neutral. As can be seen again the differences between the two strategies are negligible. For FTP-75 and HWFET around 14% and 20% of mode switch cycles, respectively, are counterproductive. The number of harmful mode switches was kept relatively low. Small control values $n_{w,1} = n_{w,2} = 1$ engine cycle were chosen. But due to the time requirement $n_p \approx 4$ engine cycles to phase the cams, the total dwell time of 6 engine cycles was relatively long.

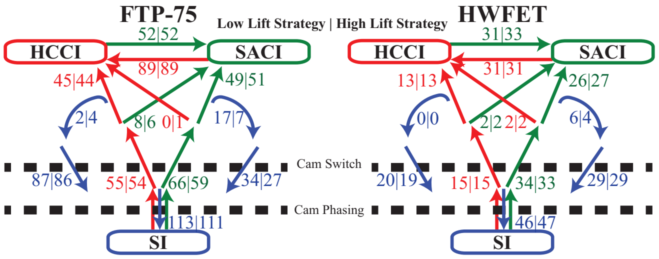

Fig. 4. Combustion mode switch analysis for the two drive cycles and mode switch strategies, applying assumptions from Fig. 2. It is distinguished between complete phasings and switches of the cams, switches between HCCI and SACI and returns to SI before an advanced combustion mode is actually reached.

TABLE III

COMPARISON OF THE NUMBER OF HARMFUL AND BENEFICIAL MODE SWITCHES FOR THE TWO MODE SWITCH STRATEGIES, APPLYING ASSUMPTIONS FROM FIG. 2

	FTP-75		HWFET	
	LL Strat.	HL Strat.	LL Strat.	HL Strat.
Beneficial	78	80	34	36
Harmful	17	19	10	10
Neutral	35	35	5	4

Nevertheless, the number of harmful mode switches is not insignificant; therefore the actual amount of fuel spent in different states was calculated. Since those harmful mode switch cycles are very short, their negative impact on fuel economy is small. When calculated, it was found that for FTP-75 and HWFET drive cycles, only about 3% and 6%, respectively, of the difference between instantaneous and penalized cases originates from those harmful switches. The rest of the fuel simply has to be invested in order to use the advanced combustion modes. Therefore, in this case the hardware delay n_p is large enough to substantially reduce the loss in fuel economy due to harmful mode switch cycles. Longer wait durations $n_{w,1}$ and $n_{w,2}$ would not lead to large improvements. However, if the made assumptions are optimistic and the mode switches are longer and less fuel efficient, there is potential for the use of supervisory control in order to minimize the number of harmful mode switch cycles and to reduce overall fuel penalty.

D. *The Synergy of SACI and HCCI Mode*

The fuel economy results from using both advanced modes combined are compared to the cases when SACI or HCCI are used individually. It is important to note that the two feasible regions overlap substantially. Table IV summarizes the results, assuming the LL strategy for the mode switch. As can be seen for the FTP-75 the benefit from using either mode is significantly smaller than the combined case. SACI and HCCI lead to comparable improvements and are therefore of similar importance when combined. Introducing the mode switch penalty reduces the improvement by approximately one third for all the cases, which is greater than that for the combined case. The results for the HWFET turn out differently: SACI by itself almost achieves the same fuel economy than when combined with HCCI. On the other hand HCCI by itself only leads to minor improvements. Introducing penalties reduces the benefit of SACI and HCCI by 15% and almost 40%, respectively. For both drive cycles it can be seen that when adding up the improvements for the two individual penalized modes the total is similar to the combined penalized cases. This result holds even though the two feasible regions of HCCI and SACI overlap. Therefore, the opportunity to conduct a relatively simple switch in between the two modes would have a strong impact on the overall benefit.

TABLE IV

FUEL ECONOMY COMPARISON IF EITHER SACI OR HCCI IS USED, ASSUMING INSTANTANEOUS MODE SWITCH OR LOW LIFT SI STRATEGY WITH ASSUMPTIONS FROM FIG. 2

MPG		**FTP-75**	**HWFET**
SI		22.8	36.1
SACI	Inst.	23.5 *(+3.2%)*	38.0 *(+5.3%)*
	Pen.	23.25 *(+2.1%)*	37.8 *(+4.5%)*
HCCI	Inst.	23.8 *(+4.3%)*	36.9 *(+2.2%)*
	Pen.	23.40 *(+2.7%)*	36.6 *(+1.3%)*

E. Example of Realtime Implementation

These results propose the possibility of the following realtime implementation. Based on current vehicle and engine operating conditions a supervisory controller could estimate the potential duration of a stay in advanced combustion before initializing a mode switch. By applying a fuel penalty map the controller could evaluate whether a mode switch cycle would potentially be harmful or beneficial. On this basis the controller could initialize the switch or choose an appropriate dwell time.

V. CONCLUSION

A finite state combustion mode switch model was introduced and subsequently applied in combination with a dynamic vehicle and driver model. Assumptions were made about the control strategy and fuel penalties to analyze the influence of combustion mode switches on fuel consumption during FTP-75 and HWFET drive cycles. With the presented methodology we could quantify the overall degradation of the achievable fuel improvement by the use of HCCI and SACI due to the mode switch penalties. As a case study two different mode switch strategies were compared and showed similar impact on fuel economy. Also it was shown that combining the two advanced modes makes it possible to exploit the relatively fuel cheap switches between SACI and HCCI, which leads to greater fuel benefits than by using each mode individually. In addition, a time requirement for preparing the mode switch, i.e. to phase the cams, reduces the number of unnecessary mode switches naturally. In future work the combustion mode switch model will be parameterized using measurements of different switching strategies and represent more accurately the dynamics and fuel penalties during the mode switch at different operating points. Optimized gear selection and control could lead to additional fuel economy improvements. The methodology will be extended to account for constraints due to emissions and aftertreatment system.

ACKNOWLEDGMENT

This material is based upon work supported by the Department of Energy (National Energy Technology Laboratory) under award number DE-EE0003533 and performed as a part of the ACCESS project consortium (Robert Bosch LLC, AVL Inc., Emitec Inc.) with direction from Hakan Yilmaz and Oliver Miersch-Wiemers, Robert Bosch LLC.

REFERENCES

[1] S. Nüesch, E. Hellström, J. Li, and A. Stefanopoulou, "Influence of transitions between SI and HCCI combustion on driving cycle fuel consumption," in *ECC*, 2013, pp. 1976–1981.

[2] A. Cairns and H. Blaxill, "The effects of combined internal and external exhaust gas recirculation," in *SAE*, no. 2005-01-0133.

[3] J. Farrell and J. Stevens, "Second law analysis of high efficiency low emission gasoline engine concepts," in *SAE*, no. 2006-01-0491.

[4] F. Zhao, T. Asmus, D. Assanis, J. Dec, J. Eng, and P. Najt, "Homogeneous charge compression ignition (HCCI) engine: Key research and development issues," *Warrendale, PA: Society of Automotive Engineers*, 2003.

[5] R. Thring, "Homogeneous charge compression ignition (HCCI) engines," in *SAE Int. Fall Fuels and Lubricants Meeting and Exhibition*, 1989.

[6] E. Hellström and A. Stefanopoulou, "Cyclic variability and dynamical instabilities in autoignition engines with high residuals," *IEEE Trans. Contr. Syst. Technol.*, vol. 21, no. 5, pp. 1527–1536, 2013.

[7] A. Kulzer, J.-P. Hathout, C. Sauer, R. Karrelmeyer, W. Fischer, and A. Christ, "Multi-mode combustion strategies with CAI for a GDI engine," in *SAE*, no. 2007-01-0214.

[8] P. Gorzelic, E. Hellström, L. Jiang, and A. Stefanopoulou, "Model-based feedback control for an automated transfer out of SI operation during SI to HCCI transitions in gasoline engines," in *DSCC*, 2012.

[9] Y. Zhang, Y. Xie, and H. Zhao, "Investigation of SI-HCCI hybrid combustion control strategies for combustion mode switching in a four-stroke gasoline engine," *Combust. Sci. and Technol.*, vol. 181, pp. 782–799, 2009.

[10] H. Wu, N. Collings, S. Regitz, J. Etheridge, and M. Kraft, "Experimental investigation of a control method for SI-HCCI-SI transition in a multi-cylinder gasoline engine," in *SAE*, no. 2010-01-1245.

[11] G. Lavoie, J. Martz, M. Wooldridge, and D. Assanis, "A multi-mode combustion diagram for spark assisted compression ignition," *Comb. Flame*, vol. 157, pp. 1106–1110, 2010.

[12] D. Manofsky, J. Vavra, D. Assanis, and A. Babjimopoulou, "Bridging the gap between HCCI and SI: Spark-assisted compression ignition," in *SAE*, no. 2011-01-1179.

[13] C. Daw, K. Edwards, R. Wagner, and J. Green, "Modeling cyclic variability in spark-assisted HCCI," *J. Eng. Gas Turbines Power*, vol. 130, no. 5, 2008.