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CRADA Final Report
For
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Expanding Robust HCCI Operation with Advanced Valve and Fuel Control Technologies

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Expanding Robust HCCI Operation with Advanced Valve and Fuel Control Technologies

CRADA Final Report

Office of Energy Efficiency and Renewable Energy

Department of Energy

By

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OAK RIDGE NATIONAL LABORATORY

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Abstract

Delphi Automotive Systems and ORNL established this CRADA to advance the commercialization potential of the homogeneous charge compression ignition (HCCI) advanced combustion strategy for gasoline engine platforms. HCCI combustion has been shown by others to produce high diesel-like efficiency on a gasoline engine platform while simultaneously producing low NO_X and particulate matter emissions. However, the commercialization barriers that face HCCI combustion are significant, with requirements for a more active engine control system, likely with next-cycle closed-loop feedback control, and with advanced valve train technologies to enable negative valve overlap conditions.

In the partnership between Delphi and ORNL, each organization brought a unique and complementary set of skills to the project. Delphi has made a number of breakthroughs with production-intent valve train technologies and controls in recent years to make a part time production-intent HCCI engine plausible. ORNL has extensive knowledge and expertise with HCCI combustion, and also has a versatile research engine with hydraulic valve actuation (HVA) that is useful for guiding production of a cam-based HCCI system. Partnering these knowledge bases and capabilities was essential towards making progress to better understand HCCI combustion and the commercialization barriers that it faces.

ORNL and Delphi maintained strong collaboration throughout the project. Meetings were held regularly, with additional reports, presentations, and meetings as necessary to maintain progress. Delphi provided guidance to ORNL regarding operational strategies to investigate on their single-cylinder research engine with HVA and data from their experimental multi-cylinder engine for modeling. ORNL provided single-cylinder engine data and modeling results.

1. Statement of Objectives

- Perform parametric investigations to quantify the effects of engine controls on HCCI combustion, efficiency, and NO_X emissions. Engine control parameters include valve strategy, charge motion, fuel injection timing, spark timing, boost, and external EGR.
- Expand the low load limit of HCCI combustion.
- Expand the high load limit of HCCI combustion.

2. Benefits to the Funding DOE Office's Mission

Advanced combustion strategies for internal combustion engines offer the potential to produce high efficiency while simultaneously emitting low levels of NO_X and particulate matter emissions. As a result, the Office of Vehicle Technologies within DOE has invested in technologies and studies that are aimed at developing advanced combustion strategies on both gasoline and diesel engine platforms. Commercialization of advanced combustion strategies is challenging, however, because it is difficult to control. Additionally, the demands of the HCCI advanced combustion strategy include a significantly more versatile valve train than what is found in current production vehicles in order to operate with a negative valve overlap (NVO) valve strategy.

In this project, we worked toward making HCCI combustion more commercially viable for production engines with a cam-based valve train. Specifically, Delphi's 2-step valve train with high authority cam phasers may allow the engine to switch between one cam profile for conventional SI combustion and another profile for when HCCI combustion is applicable. ORNL's role in the project was to help guide development of the multi-cylinder cam profile through experiments with a highly versatile single-cylinder engine with hydraulic valve actuation (HVA) and through GT-Power modeling. Specifically, experimental investigations were focused on performing parametric studies of the effects of engine controls on combustion, and expanding both the high and low load limits of HCCI combustion.

The outcome of the project is a much more thorough understanding of how HCCI combustion, NO_X emissions, and efficiency are impacted by fuel injection timing, spark, NVO duration, charge motion, boost, and external EGR. There remains a significant amount of development before this technology can be commercialized, but the work done under this CRADA project provides some fundamental knowledge that brings production HCCI one step closer to reality.

3. Technical Discussion of Work Performed by All Parties

The experimental work in this CRADA project was separated into three single-cylinder campaigns at ORNL and an extensive multi-cylinder campaign at Delphi. Modeling activities at ORNL included the use of GT-Power throughout each of the ORNL experimental campaigns and the Delphi multi-cylinder campaign to evaluate the trapped residual levels and gain further insight into the gas exchange processes. The following subsections correspond to the three ORNL experimental campaigns, but modeling and experimental overlap with Delphi are discussed as appropriate.

<u>Experimental Campaign 1.</u>

The purposes of the initial experimental campaign during this CRADA were to baseline HCCI operation and identify the sensitivity of each of the engine controls available (spark timing, injection timing, NVO duration). This study was performed on a highly modified version of the 2007 GM 2.0 L Ecotec engine with direct injection fueling. This engine is turbocharged in its OEM configuration, but was operated naturally aspirated for the first two experimental campaigns in this project. Modifications to the single-cylinder engine include disabling cylinders 1-3, equipping cylinder 4 with a Sturman hydraulic valve actuation (HVA) valve train, as shown in Figure 1, and increasing the compression ratio from 9.2:1 to 11.85:1 by using a piston provided from Delphi as part of an earlier project.

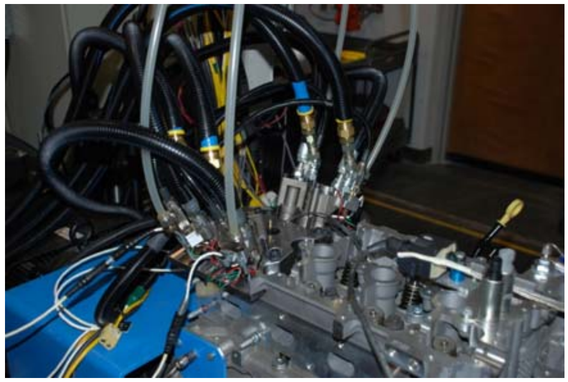

Figure 1. ORNL single-cylinder research engine equipped with a hydraulic variable valve actuation system.

Parametric studies were performed at 2000 rpm and 5 different fueling rates, representing the operable load range. The effects of fuel injection timing on engine load and NOx emissions are shown in Figure 2 for three different fueling rates, both with and without spark. Fuel injection timing has a strong impact on combustion phasing and stability which impacts power, efficiency, and emissions. These sweeps show that each fueling rate has a different optimum fuel injection timing, but it also shows that fuel injection timing can be used to control combustion stability over a fairly wide range.

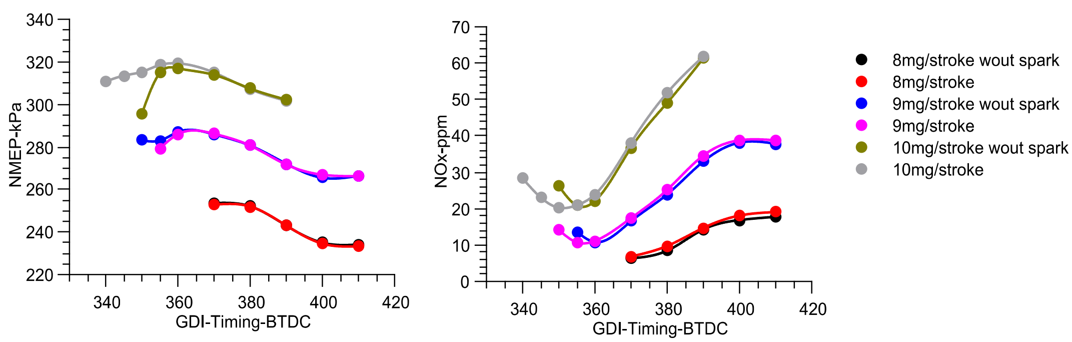

Figure 2. The effect of fuel injection timing on NMEP and NOx emissions for single injection HCCI combustion.

The effects of spark timing on engine load and NOx emissions for various fueling rates and NVO duration were also examined during this phase. The presence of the spark between 25 and 40 deg BTDC did have a stabilizing effect over the combustion event, measurably reducing the coefficient of variance and increasing power depending on operating point characteristics. Nevertheless, for the majority of the operating map this was not required, instead it was found to be effective at increasing the operating range only at the outside limits of the operating map.

To illustrate this, Figure 2 shows that for the most retarded fuel injection timing, the points are only operable when spark is present. Thus, while spark does not have a large impact on fuel consumption or emissions, it does act as a stabilizer that can enable a wider range of operation.

The effect of three different NVO durations on HCCI operating load and NOx emissions are shown in Figure 3. Knowing the range of NVO durations where a given engine point is operable is necessary to enable a cam-based valvetrain because valve lift durations are considerably less flexible compared to an HVA valvetrain. Figure 3 shows that the engine can achieve nearly identical operating load at a constant fuel rate for these three different NVO durations. Importantly, each NVO duration has a unique optimal fuel injection timing. While the trends in NOx emission are similar for the three NVO durations, the shorter NVO duration results in a lower concentration of NOx emissions.

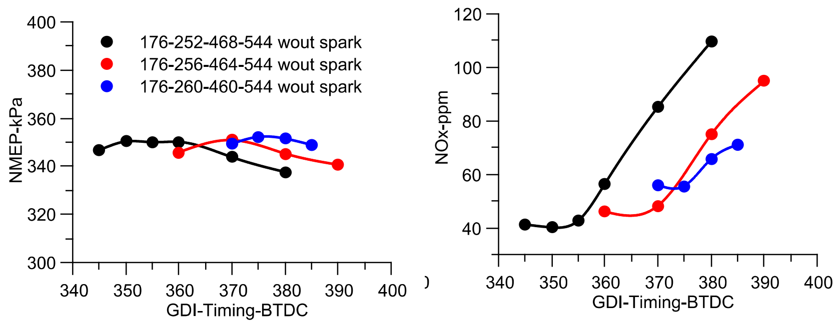

Figure 3. Effect of fuel injection timing for three different NVO durations at a constant fueling rate of 11 mg/stroke. Numbers in the legend describe the exhaust valve opening angle, exhaust valve closing angle, intake valve opening angle, and intake valve closing angle.

Despite differences in engine load, NVO duration and fuel injection timing, the best indicated specific fuel consumption (ISFC) consistently collapses to the same value of approximately 225 g/kW-h, as shown in Figure 4. This is valuable information because it illuminates that by using fuel injection to control the combustion event, the engine efficiency is not degraded over the operable HCCI range of the engine as long as combustion phasing can be maintained.

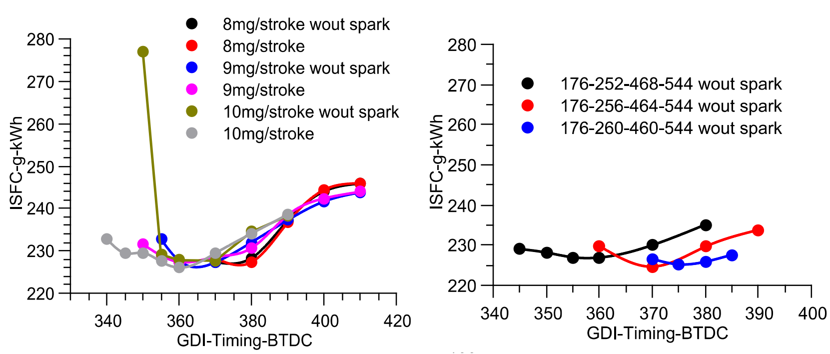

Figure 4. ISFC as a function of fuel injection timing for fueling rates of 8, 9 and 10 mg/stroke (left) and for 3 different NVO durations at 11 mg/stroke (right).

In summary, the first phase of experimental HCCI work consisted of parametric studies to determine the operable regions of HCCI combustion, as well as the sensitivity to available engine controls. Results showed that spark timing has only a minimal impact on engine load and emissions, and its effect is mainly to increased engine stability. Fuel injection timing exhibits a stronger control authority over HCCI combustion, and each engine operating condition has an optimal fuel injection timing for best efficiency. Importantly, many of the engine operating conditions can be reproduced with several different NVO durations, with each having its own optimal fuel injection timing. Complete details of this experimental campaign were presented at the 2011 DOE Annual Merit Review [1].

Experimental Campaign 2.

The purpose of the second experimental campaign was to expand the low load limit of HCCI combustion. Low load operation in HCCI combustion regimes is typically limited by combustion instability and misfire. In this campaign we worked to use fuel injection and air handling strategies to expand the low load limit. Complete details of this experimental campaign were published in the SAE International Journal of Engine Research and presented at the 2012 SAE World Congress [2].

Experimental studies on this engine were conducted on the same engine platform as discussed above. The valve strategies used on the HVA engine as part of this project were limited to approximate the capabilities of Delphi's cam-based variable valve actuation (VVA) valve train. An example of the comparison of valve profiles can be seen in Figure 5. Results from the single-cylinder HVA engine were modeled with GT-Power for translation onto a multi-cylinder engine platform.

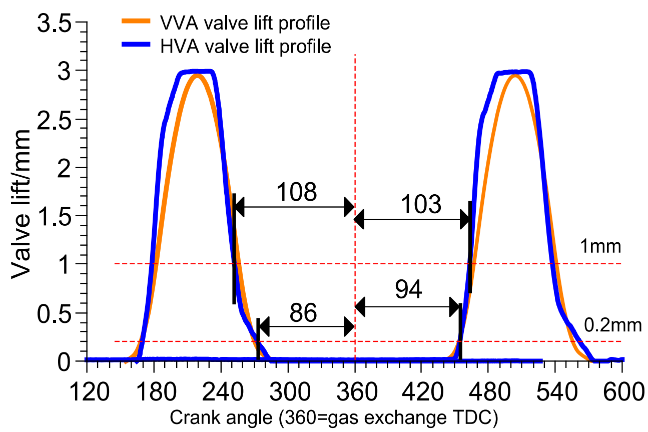

Figure 5. Comparison of HVA valve profile and cam-based HCCI valve profile.

One of the central findings of this study was that a pilot injection is beneficial for engine loads below 3 bar $IMEP_{net}$ because it provides a better stability-to-ISFC tradeoff compared to a single injection strategy. Pilot injection timing and the mass of fuel injected during the pilot injection are both effective controls on combustion. Pilot injection timing may actually be more useful because of the difficulty of controlling pilot injection mass in the non-linear response regime of GDI fuel injectors. In addition to pilot injection, deactivation of one of the intake valves helps to improve combustion stability with no adverse impacts on ISFC or NO_X emissions. The improved stability is attributed to richer operation and possible benefits of charge motion. The effect of pilot injection mass and intake valve deactivation at 2 bar $IMEP_{net}$ on combustion stability, fuel consumption, combustion phasing, NO_X emissions, and lambda are shown in Figure 6.

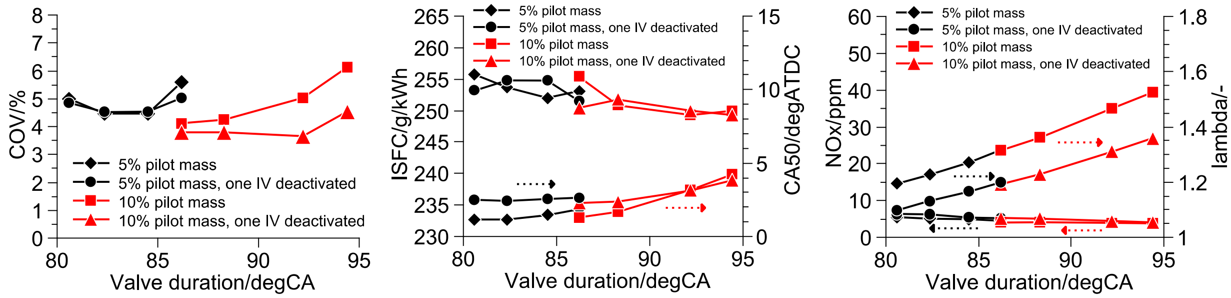

Figure 6. Effect of injected pilot mass and intake valve deactivation on combustion stability, fuel consumption, combustion phasing, NO_X emissions, and lambda.

In order to reduce engine load from 2.0 to 1.6 bar $IMEP_{net}$, the pilot fuel injection strategy was required and a total of 50% of the fuel mass had to be injected into the pilot event. Additionally, deactivation of one of the intake valves was also required to provide a richer air/fuel mixture. With the NVO duration used, GT-Power simulations calculate that the exhaust residual fraction for this operating strategy is 35%. Even with these measures combustion stability was just outside of the targeted range, with COV of $IMEP_{net}$ being 5.4% rather than 5.0%. The operating conditions for 1.6 bar $IMEP_{net}$ are shown in Table 1.

Table 1. Operating conditions at 1.6 bar $IMEP_{net}$.

Main SOI	-240degATDC
Pilot SOI	-375degATDC
Pilot fraction/mass %	50
ISFC/g/kWh	272
COV IMEP/%	5.4
RGF/%	35
Lambda/-	1.36
Spark timing	-25deg ATDC

In contrast to the lowest operating loads where pilot injection was beneficial or even necessary, it was found that pilot injection did not provide significant benefit at operating loads of 3.0 bar $IMEP_{net}$ or higher, and can even be detrimental to stability or ISFC. Additional conclusions for this study are that fuel injection strategy and timing can reproduce similar operating conditions over a range of valve strategies, which is an important consideration for production-intent valve trains that are less flexible than the HVA system used here. Additionally, the high load limit for HCCI was 3.9 bar $IMEP_{net}$ under naturally aspirated conditions. HCCI combustion did provide a substantial fuel consumption benefit compared to conventional SI combustion at comparable load conditions, as shown in Figure 7.

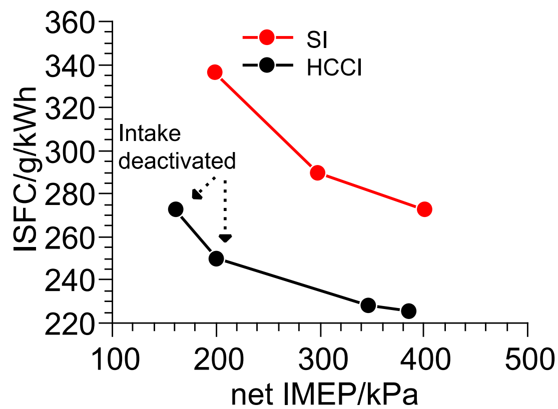

Figure 7. $ISFC_{net}$ as a function of engine load for conventional SI combustion and HCCI combustion at 2000 rpm.

It was during this portion of the project that a significant effort was made to use GT-Power simulations to bridge the gap between Delphi's multi-cylinder HCCI engine and ORNL's single-cylinder HVA engine. Unfortunately, attempts to match the behavior of the multi-cylinder engine with the model and the ORNL HVA single-cylinder engine were unsuccessful for both fired and motored cases. Directly applying operating parameters from the multi-cylinder data to the model and single-cylinder engine produced much higher cylinder pressures and mass air flow (MAF) rates that were as much as double those reported per cylinder of the multi-cylinder engine. Matching multi-cylinder engine MAF with the single-cylinder engine required reducing valve duration and lift by almost half.

Minor calibration tweaks of the model were insufficient to bridge the drastic differences in behavior observed in the multi-cylinder engine and predicted by the model. Further efforts focused on applying several modeling strategies to simulate potential physical or operational differences with the multi-cylinder which could account for the discrepancies in behavior. Strategies which succeeded in matching MAF often also matched peak cylinder pressures but not peak NVO pressure. These strategies also failed to match cylinder pressure during gas exchange events and often resulted in changes to other parameters such as intake and exhaust manifold pressures. No modeling strategy was found which could accurately match the measured cylinder pressure during the intake stroke. The most successful modeling strategies involved simulating flow restrictions in the manifolds or changes in valve timing or lift.

One such strategy involved retarding intake valve opening (IVO) to limit the intake of fresh charge. Matching peak cylinder pressure with this strategy required opening the intake valve up to 80CAD after IVO for the multi-cylinder engine. However predicted MAF was 25% higher, peak NVO pressure was 30% lower, and cylinder pressure did not match well during the gas exchange events. Another strategy involved increasing intake valve lash by as much as 1.75 mm (half the total valve lift) to drastically reduce both the valve lift and duration. This approach produced similar results as retarding IVO, but manual measurements of the valve motion seemed to indicate that they were operating properly without such high amounts of lash. Applying throttling restrictions on the intake and exhaust manifolds allowed matching of both peak pressure and peak NVO pressure, but MAF remained ~14% high, cylinder pressure did not match well during gas exchange, and intake and exhaust manifold pressures varied significantly from measured values. None of the strategies employed were able to satisfactorily match the behavior of the multi-cylinder engine (MCE) with either the model or the single-cylinder engine (SCE), nor were we able to find any physical difference between the two engines which could explain the difference in behavior.

Experimental Campaign 3.

The purpose of the third experimental campaign was to expand the high load limit of HCCI combustion. It was evident from the results during the second campaign and reported results in the literature that it would not be possible to provide substantial high load expansion under naturally aspirated condition, so the air handling system on ORNL's single cylinder HVA engine was modified to have external boost and cooled external EGR capabilities, as shown in Figure 8.

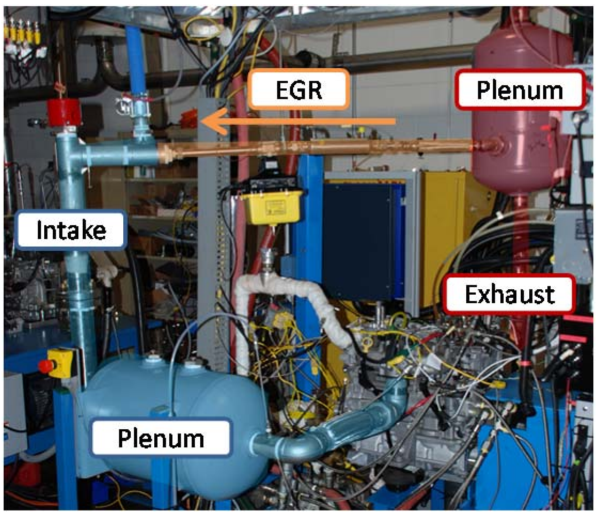

Figure 8. ORNL's single cylinder research engine with an HVA valve train, boost, and cooled external EGR.

Both external EGR and boost were enablers to being able to operate at higher engine loads under lean-burn conditions. Using boost up to 190 kPaa with 25% external EGR, engine loads as high as 6.5 bar $IMEP_{net}$ were investigated at 2000 rpm. The required intake manifold pressure, indicated thermal efficiency, and NO_X emissions are shown in Figure 9 as a function of engine load. It can be seen that the intake pressure requirement rises sharply with engine load as does indicated thermal efficiency. NO_X emissions are highest for the naturally aspirated condition, but are very low at the higher loads under boosted conditions.

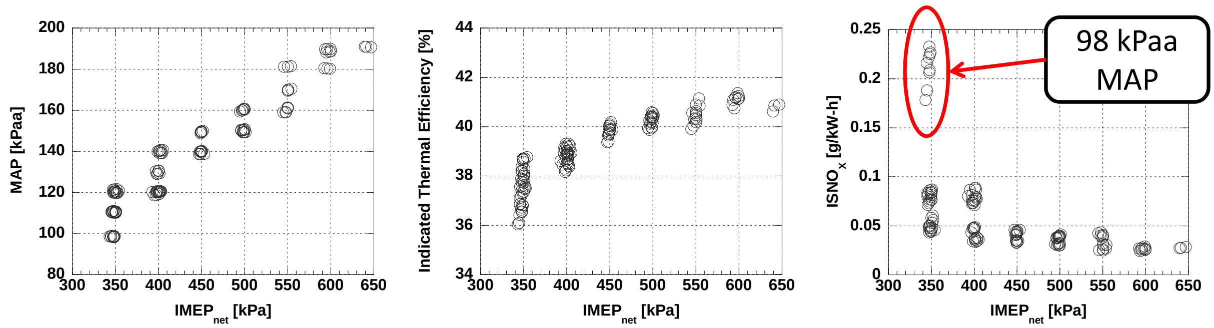

Figure 9. Intake manifold pressure, indicated thermal efficiency, and NO_X emissions as a function of HCCI engine load at 2000 rpm.

The effect of external EGR on the HCCI combustion process is shown in Figure 10 for a boost pressure of 120 kPaa and an engine load of 4.0 bar $IMEP_{net}$ at an engine speed of 2000 rpm. As EGR increases, advancement of fuel injection timing is required to maintain combustion phasing. However, when noise, NO_X emissions, combustion stability, maximum heat release rate, and many other parameters are compared as a function of combustion phasing, the EGR fraction has little difference. Interestingly, exhaust temperature is one area where there was a repeatable trend with external cooled EGR, and that was that exhaust temperature increased with EGR. In this case, external EGR is replacing air dilution of the charge, so there is a reduction in the ratio of specific heat (gamma) of the gas mixture that causes exhaust temperature to increase.

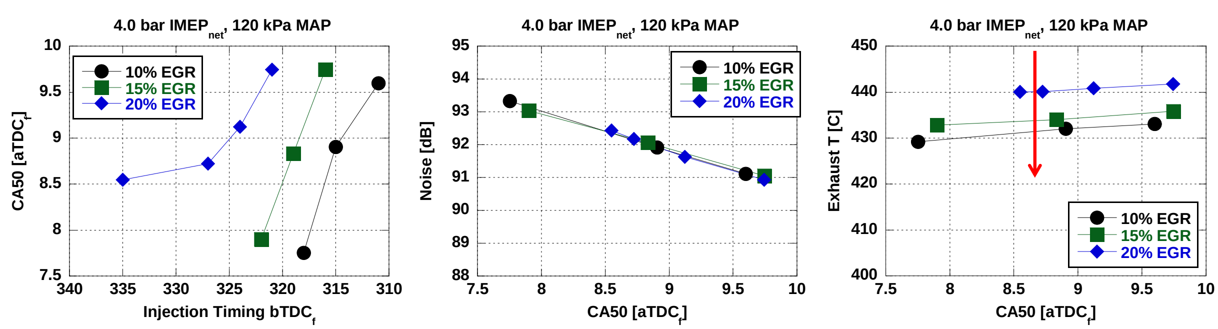

Figure 10. Combustion phasing as a function of injection timing, and noise and exhaust temperature as a function of combustion phasing for three different levels of external EGR for a load of 4.0 bar $IMEP_{net}$ and a boost pressure of 120 kPaa.

The effect of boost at a constant load and external EGR fraction is shown in Figure 11. Similar to the effect observed with increasing EGR in Figure 10, increasing boost requires that injection timing be advanced to maintain a constant combustion phasing. However, unlike the effect observed with increasing EGR, a higher level of boost leads to a reduction in combustion noise and a reduction in NO_X emissions. There was no impact of higher boost on thermal efficiency for a given engine load observed in this study.

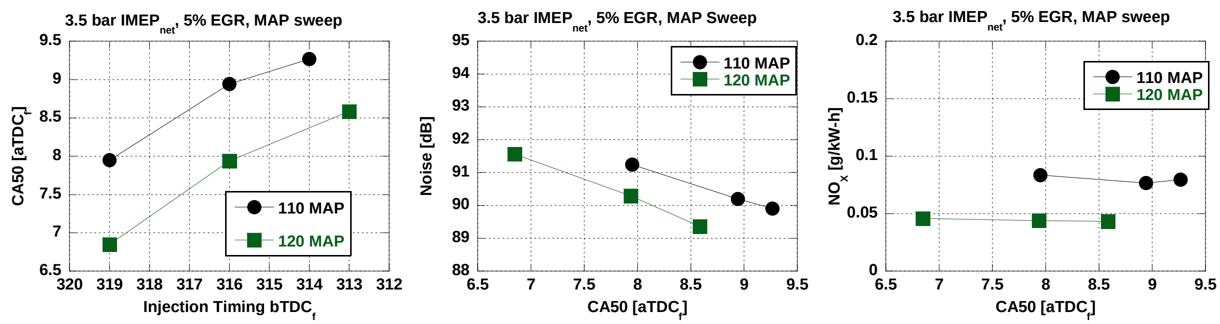

Figure 11. Effect of manifold pressure on combustion phasing, noise, and NO_X emissions at an engine load of 3.5 bar $IMEP_{net}$ and 2000 rpm.

The duration of the negative valve overlap, and specifically the exhaust valve closing angle, was a highly sensitive parameter in terms of controlling combustion phasing. Figure 12 shows the relationships between combustion phasing and start of injection timing. At a relatively light load of 4.0 bar $IMEP_{net}$, a change in exhaust valve closing angle of 5 CA degrees requires a change in the start of injection timing of 20 CA degrees. This relationship becomes much more sensitive as load increases where, at an engine load of 6.0 bar $IMEP_{net}$, a change in exhaust valve closing angle of 1 CA degree requires a change in injection timing of 10 CA degrees. This illustrates that although stable HCCI combustion is possible at these relatively high load conditions with low NOX emissions and high efficiency, combustion phasing and overall operation becomes more sensitive to engine controls.

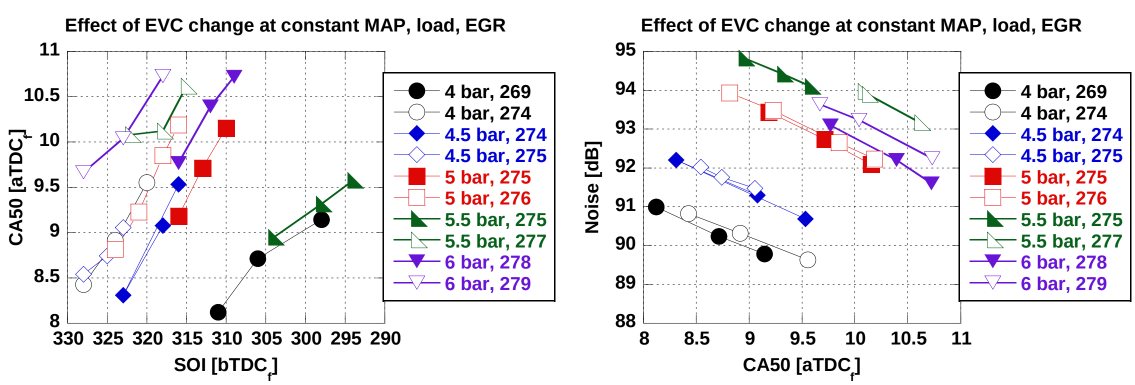

Figure 12. Effect of exhaust valve closing angle on combustion phasing and noise.

The final findings from the third experimental campaign at ORNL have to do with measured engine noise. The parameter used to quantify engine noise has not been standardized for researchers studying different advanced combustion regimes. Commonly cited metrics include maximum pressure rise rate, ringing intensity, and combustion noise, as measured by an AVL noise meter. However, a consensus is beginning to form that the AVL noise meter provides the best metric for combustion noise, and it is supported by data from noise chambers. Figure 13 shows the maximum pressure rise rate and the ringing intensity as functions of noise as measured by the AVL noise meter. In all cases, there is trend-wise agreement that noise increases with both the maximum pressure rise rate and ringing intensity. However, there is a great deal of discrepancy about the effect of manifold pressure. Particularly, the ringing intensity parameter is much more sensitive to manifold pressure than the AVL noise meter is. Thus, if ringing intensity is the only noise metric being used, it's likely that combustion noise will be under-predicted.

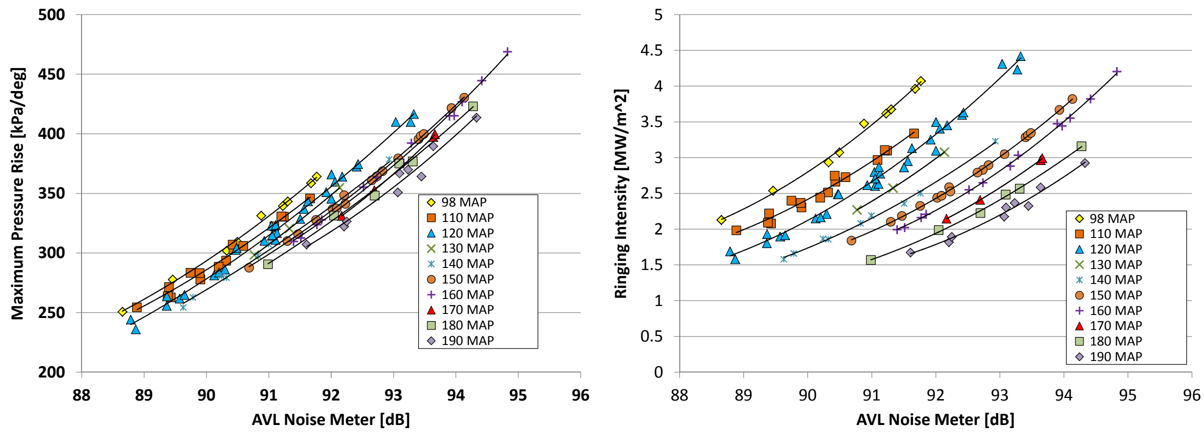

Figure 13. Maximum pressure rise rate and ringing intensity as functions of noise as measured by the AVL noise meter.

To summarize, the parametric sweeps conducted in the third experimental campaign revealed a great deal of information about the sensitivity of EGR, boost, injection timing, and manifold pressure on HCCI combustion. And, while previous researchers have exceeded the engine loads achieved in this study, this investigation provides the most in-depth publically-available study on the ability to control HCCI combustion with the available engine controls.

Details on the high load expansion of HCCI combustion will be detailed at the 2013 SAE World Congress [3].

4. Subject Inventions

No Inventions were filed under this CRADA.

5. Commercialization Possibilities

No new product was developed as a direct result of this CRADA project.

6. Plans for Future Collaborations

Participants in this CRADA are interested in continuing collaborations in future CRADAs, including a new CRADA project proposed for FY13 on characterizing efficiency/emission tradeoffs with a wide array of combustion technologies on gasoline-platform engines. Discussions for additional collaboration will continue as research needs and opportunities present themselves.

7. Conclusions

A CRADA project was successfully conducted for the purposes of further developing HCCI combustion strategies to be compatible with production-intent valve train. Commercialization of HCCI combustion in a robust manner would allow the high efficiency and low emission potential of HCCI to be realized. The team member from ORNL and Delphi each brought a unique set of complementary skills to the project, and progress was made in understanding the effects of engine controls on HCCI combustion, and on expanding both the high and low load limits of HCCI. A significant amount of work remains in developing HCCI combustion, as was underscored by some of the difficulties encountered with cylinder-to-cylinder dynamics on the multi-cylinder engine experiment at Delphi's facility.

The progress made in understanding the effects of engine controls on HCCI load expansion provides a more thorough understanding of the relative effectiveness of engine controls than was previously available in the open literature. Specifically, the tradeoff between fuel injection timing exhaust valve closing angle under boosted conditions adds to the fundamental knowledgebase of HCCI combustion.

ORNL also upgraded the capabilities of its single-cylinder engine research facility by adding an air handling system capable of simulated boost, exhaust backpressure, real external EGR, and thermal control of the intake. This experimental upgrade enabled the high load portion of the study to be conducted (engine loads greater than 3.5 bar $IMEP_{net}$).

ORNL and Delphi maintained a good working relationship throughout the project. The CRADA participants are interested in continuing collaborations in the future, and proposed a follow-on CRADA for FY13. Discussion for additional collaboration will continue as research needs and opportunities present themselves.

8. References

1. Szybist, J., K. Confer, A. Weall, M. Foster, K.D. Edwards, and W. Moore. "*Expanding Robust HCCI Operation*" Presented at the 2011 DOE Vehicle Technologies Program Annual Merit Review, Presentation Number ACE053.

2. Weall, A.J., J.P. Szybist, K.D. Edwards, M. Foster, K. Confer, and W. Moore. "*HCCI Load Expansion Opportunities Using a Fully Variable HVA Research Engine to Guide Development of a Production Intent Cam-Based VVA Engine: The Low Load Limit*." SAE International Journal of Engines, 2012, vol 5(3), pp. 1149-1162.

3. Szybist, J.P., K.D. Edwards, M. Foster, K. Confer, and W. Moore. "*Load Expansion Opportunities Using a Fully Variable HVA Research Engine to Guide Development of a Production Intent Cam-Based VVA Engine: The High Load Limit.* To be presented at the 2013 SAE World Congress.