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Development of High Efficiency Clean Combustion Engine Designs for Spark-Ignition and Compression-Ignition Internal Combustion Engines,

Final Report

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EXECUTIVE SUMMARY

This report summarizes activities related to the revised STATEMENT OF PROJECT OBJECTIVES (SOPO) dated June 2010 for the Development of High-Efficiency Clean Combustion engine Designs for Spark-Ignition and Compression-Ignition Internal Combustion Engines (COOPERATIVE AGREEMENT NUMBER DE-FC26-05NT42415) project.

In both the spark- (SI) and compression-ignition (CI) development activities covered in this program, the goal was to develop potential production-viable internal combustion engine system technologies that both reduce fuel consumption and simultaneously met exhaust emission targets. To be production-viable, engine technologies were also evaluated to determine if they would meet customer expectations of refinement in terms of noise, vibration, performance, driveability, etc. in addition to having an attractive business case and value. Prior to this activity, only proprietary theoretical / laboratory knowledge existed on the combustion technologies explored The research reported here expands and develops this knowledge to determine series-production viability.

Significant SI and CI engine development occurred during this program within General Motors, LLC over more than five years. In the SI program, several engines were designed and developed that used both a relatively simple multi-lift valve train system and a Fully Flexible Valve Actuation (FFVA) system to enable a Homogeneous Charge Compression Ignition (HCCI) combustion process. Many technical challenges, which were unknown at the start of this program, were identified and systematically resolved through analysis, test and development. This report documents the challenges and solutions for each SOPO deliverable.

As a result of the project activities, the production viability of the developed clean combustion technologies has been determined. At this time, HCCI combustion for SI engines is not considered production-viable for several reasons. HCCI combustion is excessively sensitive to control variables such as internal dilution level and charge temperature. As a result, HCCI combustion has limited robustness when variables exceed the required narrow ranges determined in this program. HCCI combustion is also not available for the entire range of production engine speeds and loads, (i.e., the dynamic range is limited). Thus, regular SI combustion must be employed for a majority of the full dynamic range of the engine. This degrades the potential fuel economy impact of HCCI combustion. Currently-available combustion control actuators for the simple valve train system engine do not have the authority for continuous air - fuel or torque control for managing the combustion mode transitions between SI and HCCI and thus, require further refinement to meet customer refinement expectations. HCCI combustion control sensors require further development to enable robust long-term HCCI combustion control. Finally, the added technologies required to effectively manage HCCI combustion such as electric cam phasers, central direct fuel injection, cylinder pressure sensing, high-flow exhaust gas recirculation system, etc. add excessive on-engine cost and complexity that erodes the production-viability business

case. In particular, the added cost of the FFVA system did not justify the modest additional fuel economy improvement when compared to the simple valve train system.

In the CI program, a single cylinder diesel engine was designed and developed with a FFVA system. The single cylinder program primarily focused on exploring three applications of a Variable Valve Actuation (VVA) system to a diesel engine. The first application investigated the effect of the intake valve closing timing as a method to reduce Nitrogen Oxide (NOx) and smoke and to extend the operating load range possible with a low temperature combustion mode. The second application was the use of VVA in order to increase residual gas in the cylinder as a means to reduce hydrocarbon (HC) and Carbon Monoxide (CO) emissions under light load and cold operating conditions. The third focus area was an investigation of exhaust valve opening timing as a means to increase exhaust temperature for improved after-treatment warm-up. For all three applications, benefits were shown to be possible through the use of VVA and the costs and tradeoffs associated with the benefits were quantified.

The overall program goal for the multi-cylinder CI engine was to optimize fuel consumption while reducing engine-out emissions to meet Tier 2 Bin 5 tailpipe levels with an exhaust after-treatment system for a pickup truck chassis certification. Prototype versions of a V8 4.5L multi-cylinder were designed and developed with a simple CI valve actuation system. Two enabling valve train technologies were implemented. The first was Late Intake Valve Closing (LIVC) for variable effective compression ratio control to extend the early premixed charge compression ignition combustion process for High Efficiency Clean Combustion. The second was exhaust valve secondary opening during the intake stroke for Internal Exhaust Gas Recirculation (EGR). Experimental work helped down-select the enabling valve train technologies by focusing on fuel efficiency, engine-out and tailpipe emissions as well as exhaust gas temperature management. Exhaust gas recirculation, turbochargers (both single- or two-stage configurations), close couple after-treatment system were installed on the base engine and the costs associated with these technologies were assessed.

The value of automotive diesel VVA technologies depends on the cylinder head design impact to incorporate the technology; the additional cost, manufacturing and assembly impact of the new valve train components; required engine control module upgrades; required turbocharger system upgrade from single- to two-stages and the impact to the after-treatment system architecture. The value of VVA also depends on the enhancements to diesel engine combustion to improve fuel economy and reduce emissions. As a result of this project, the value of diesel VVA based on technical merit, fuel economy and emissions potential has been quantified. In addition, this project also helped identify the valve train features and capabilities required for future diesel engines.

Several technologies that were developed as part of this project to enable HCCI combustion, that have independent value for fuel economy and performance improvement, could potentially be introduced in vehicle production with further development. These include 2-Step valve train; FFVA, electric cam phasing; concentric cam LIVC; cylinder pressure sensing; central gasoline direct fuel injection; advanced actuator controls, calibration and diagnostics; high flow exhaust gas recirculation, etc. These technologies offer improved fuel economy, reduced emissions, performance and improved refinement that regulators and customers expect and require.

ACCOMPLISHMENTS vs. OBJECTIVES

The following is a comparison of actual accomplishments to the goals and objectives of the project. The overall program objective was to develop prototype engine hardware and actuator controls software to enable HCCI combustion for improving fuel efficiency for both SI and CI engines while meeting Tier 2 Bin 5 emission specifications as validated via the installation and testing of a gasoline-fueled 2.2L I4 engine in a mid-size car and a new Diesel-fueled 4.5L dual overhead cam V8 engine in a mid-size sport utility vehicle. The project was to focus on variable valve timing technologies for short-term and long-term applications to allow implementation of HCCI combustion approaches. (Note: these objectives were modified when some of the vehicle demonstrations were removed from the Phase 4 deliverables as the project team and the DOE became aware of the significant challenges associated with a full vehicle demonstration.)

SI Systems Goals:

The goal of the SI program was to develop potential production-viable technologies that both reduce fuel consumption and simultaneously met exhaust emission targets. At every stage of the project, the developing technologies were to be evaluated to determine if they would meet customer expectations of refinement in terms of noise, vibration, performance, driveability, etc. in addition to having an attractive business case and value for series production when considering the established fuel economy potential.

SI Systems Accomplishments:

- Identified required technology sets required to enable HCCI combustion in SI engines,
- Identified and evaluated market-availability of HCCI-required technology systems and components,
- Selected and evaluated HCCI enabling technologies from suppliers,
- Identified HCCI-enabling technologies not available in the market,
- Partnered with specialized engineering companies to develop required HCCI-enabling technologies not available in the market,
- Designed, constructed and assembled simple and FFVA SI and HCCI engines,
- Demonstrated FFVA capabilities on spin rigs, test bed engines, and on non-fired and fired engines,

- Developed FFVA system capabilities including demonstrated controlled valve seating velocity over a range of hydraulic fluid viscosity, engine speed and load on both intake and exhaust valve train systems. Demonstrated reliable FFVA operation at 20°C – 110°C, 300 - 7,000 rpm, and 0 - 14 Bar BMEP engine load,
- Demonstrated simple valve train-enabled HCCI on dynamometer engines and in vehicles,
- Demonstrated FFVA-enabled HCCI combustion on dynamometer engines,
- Determined fuel economy reduction potential of simple and FFVA vs. the baseline SI combustion system:
    - Recorded US EPA fuel economy certification test cycle composite 10.0 - 10.2% fuel economy improvement with the simple HCCI system relative to the baseline SI engine,
    - Recorded US EPA fuel economy certification test cycle composite 11.2 - 12.8% fuel economy improvement with the FFVA HCCI system relative to the baseline simple engine,
- Developed control algorithms and calibrations to manage HCCI-to-SI and SI-to-HCCI combustion mode transients,
- Identified limitations of torque and air-fuel control disturbances during combustion mode transitions of simple mechanical valve train system,
- Determined that seamless continuous combustion mode transitions were possible with an FFVA valve train,
- Determined the value (benefit vs. cost) of both the simple HCCI and FFVA HCCI technologies,
- Demonstrated simple / FFVA increased engine and vehicle performance relative to the baseline engine. Also demonstrated 10% increased low-end torque.
- In addition to the program accomplishments, several spin-off technologies were also developed such as simple Variable Valve Actuation (VVA) technologies, cylinder pressure sensing, increased efficiency high-pressure hydraulic pumps, FFVA valve train systems, electric cam phasers, central direct injection technology, control system algorithms and calibration for complex transient combustion, etc. Many of these technologies could be developed further individually as part of non-HCCI product programs.
- Based on this list of accomplishments, the deliverables of the revised Statement of Project Objectives were achieved by demonstrating production-viable technologies required to enable high-efficiency clean combustion in SI engines including quantifying the fuel economy benefit while monitoring system cost and emissions. Furthermore, these objectives were demonstrated with transient vehicle and engine operation.

<u>CI Systems Goals:</u>

Phases 1 and 2 of the CI program had two primary goals. The first was to use a FFVA system on a single cylinder research engine along with 1-D and 3-D modeling tools to explore the possibility of using VVA to improve the performance of a light duty Diesel engine. Specifically, the first goal was to investigate several different VVA strategies including LIVC, IEGR and early exhaust valve opening as potential methods for improving the fuel consumption and emissions of the engine. The FFVA system and research engine allow this type of work to proceed quickly and cover a wider range of parameter variations. This investigation would yield recommendations for further study on the multi-cylinder engine in Phases 3 and 4.

The second primary goal of Phases 1 and 2 was to utilize the FFVA system to simulate the operation of several simpler, production-viable VVA systems in order to evaluate the benefits and limitations of the simple systems. This investigation would determine the pros and cons of each production-viable system and yield a preliminary recommendation for the prototype multi-cylinder engine.

The first goal for Phase 3 was to develop and test a simple valve train mechanism in a prototype V8 4.5L multi-cylinder Diesel engine. The mechanism was designed specifically for LIVC of one valve per cylinder. A second goal was to investigate exhaust rebreathing for IEGR in the multi-cylinder engine via a secondary opening of the exhaust valves during the intake stroke. Using these two valve train strategies, the goal was to operate the engine under low temperature combustion conditions through control of the effective compression ratio and to expand the useful range of the Early Premixed Charge Compression Ignition combustion mode. These strategies were expected to reduce fuel consumption and engine-out emissions and also to raise exhaust gas temperature for catalyst efficiency and regeneration.

To achieve LIVC, a concentric camshaft system and electro-hydraulically operated phaser were applied. This required design modifications to the cylinder head with lubrication features and the single stage turbocharger was replace with a two-stage turbocharging system. Several different exhaust valve events were tested in the exhaust rebreathing under several different engine operating regimes.

For these strategies, the goals were to understand the:

- Design and fabrication of the prototype system, functional performance and response characteristics of the simple CI system,
- Implications on the cylinder head packaging for the added valve train functionality to the base multi-cylinder engine design,
- Cost of modifications and added hardware to a prototype Diesel engine,
- interactions between multi-cylinder engine components of the added and modified hardware,
- Methods to incorporate component controls in coordination with other engine systems,
- Component and system improvement recommendations, and
- Impact on fuel efficiency improvements and emissions reductions in various engine operating ranges and combustion regimes using a multi-cylinder engine dynamometer test bed.

The goal of Phase 4 was to continue the development program with GM-internal funds to identify common valve train technology solutions. The goal was to develop a simple CI VVA mechanical design and to implement the hardware and controls in order to quantify the cost and effectiveness of VVA technology on engine efficiency and emissions targets for a new prototype Diesel engine.

CI Systems Accomplishments:

In Phases 1 and 2, the following accomplishes were achieved:

- Assessed the brake thermal efficiency and emission benefits of a FFVA system and three simple VVA mechanisms for enabling LIVC,
- Quantified the benefits of a simple VVA mechanism for reducing HC and CO emissions at idle / low loads using IEGR,
- Assessed the benefits and limitations of Early Exhaust Valve Opening for controlling exhaust temperature,
- Assessed the potential application of combining recompression and fuel reforming for NOx reduction,
- FFVA system Design for independent control of each valve in a single-cylinder engine with packaging analysis in a base multi-cylinder engine head, and
- VVA hardware preliminary packaging for intake and exhaust valve trains into a prototype multi-cylinder engine.

In Phases 3 and 4, the following accomplishes were achieved:

- Determined the kinematic and dynamic requirements of a 2-Step system to enable intake valve phasing and exhaust valve re-opening events,
- Determined the brake thermal efficiency and emission benefits of IEGR at key warm-up phase operating points of the of the Federal Test Procedure (FTP) driving cycle,
- Determined the benefits and limitations of IEGR for controlling exhaust temperature,
- Determined the brake thermal efficiency and emission benefits of LIVC at key hot phase operating points of the of the FTP driving cycle,
- Assessed the technical characteristics and capabilities of a concentric camshaft system for Variable Effective Compression Ratio control,
- Assessed the potential contribution of a two-stage turbocharging system for charging requirements of VVA in a multi-cylinder Diesel engine, and
- Assessed the cost-benefit of 2-Step and some continuous VVA system alternatives for Diesel engines.

Overall CI systems summary statements:

- LIVC and Exhaust rebreathing are effective valve train strategies for controlling Diesel engine effective compression ratio and IEGR respectively.
- The technical merit of the applying various valve train strategies to a prototype V8, 4.5L Diesel engine to reduce fuel consumption and exhaust emissions was determined.
- A potential prototype Diesel engine design concept including package protection for advanced valve train systems was developed.

Activities performed with the multi-cylinder V8 4.5L Diesel engine in the joint sponsored GM-DOE Agreement, and activities in-progress with internal GM funds with VVA technologies in a prototype Diesel engine, complete the deliverables for the CI systems activities according to the revised SOPO for the program.

DETAILED ACTIVITIES AND RESULTS SUMMARY

The following is a summary of the activities, approaches used, problems encountered and departure from planned methodology and an assessment of their impact on the project results for each project phase.

Phase 1 – Applied Research
SI Summary:

In the SI engine part of this first phase, several simulation and analysis tools were used to determine the component and system requirements of the simple and FFVA valve train systems to meet HCCI combustion control. Some of the tools used were Simulink / Matlab, MS EXCEL, CFD, GT-Power, conjugate heat transfer analysis and AEMSim. Some of the analyses performed were simple valve train system switching window and oil control valve response time analysis, fuel injection multiple small injection pulse capability, central injector heat flux analysis, FFVA operating capability over the expected engine speed, load, temperature range, etc. while meeting standard production engine valve seating velocity noise, durability and energy requirements, etc.

The requirements established were used to evaluate commercially available technologies, which showed some areas would challenge the capabilities of the combustion system enabling technologies. Typically, these technologies were not able to meet the accuracy, repeatability, or design integration requirements and thus, this evaluation revealed the need for component and subsystem development during this program. In particular, significant simple mechanical and FFVA develop would be required during the following phases of the project.

Due to packaging limitations, the supply base was only able to provide switchable rocker arm solutions that have only one roller-type cam follower interface, while the other cam follower interface of the same switching element was a sliding type. The sliding type follower thus incurred higher friction losses when compared to the baseline engine that is equipped with roller element finger followers. In order to minimize this friction impact, the roller element of the switchable follower arm was applied to the short duration (low-lift) profile that is required to enable HCCI combustion. This minimized the resultant fuel consumption increase associated with the slider follower element. However, only an all-roller switchable valvetrain could meet the valvetrain friction levels of the baseline engine. Therefore a new all-roller cam follower would have to be developed as part of the project with Meta Motoren-und Energie-Technik and Hitchiner Manufacturing Co., as collaborative engineering partners.

The FFVA system would need to include the favorable attributes of established technology features including an electro-hydraulic system with force-based valve event flexibility and minimum energy consumption using a 2-stage actuator. However, critical features needed to be developed to address the hydraulic pump efficiency, valve lift sensor accuracy, as well as a means to enable acceptable valve closing velocity control throughout the fluid viscosity range. All of these features needed to be developed as part of the project while addressing system cost to enable production potential. These features thus became the focus of a newly defined system based on a GM-unique valve seating control method with Sturman Industries identified as a collaborative engineering development partner, as defined in this US DOE awarded program.

CI Summary

The purpose of this CI engine phase of the program was to assess the potential performance improvements possible for a Diesel engine through the implementation of a FFVA system based upon existing experimental hardware and modeling work. In order to achieve low emissions levels and maintain high efficiency, a low temperature Diesel combustion mode will be required. Therefore this phase investigated the ability of a FFVA system to aid the achievement of low temperature combustion in a Diesel engine.

At the outset, the plan for the program was to look at two different VVA strategies for improving and controlling low temperature combustion in the Diesel engine. These were 1) controlling the effective compression ratio through variation of the intake valve closing timing and 2) increasing the IEGR or residual using VVA in order to reduce either NOx or unburned HC emissions. Later in the program, two additional strategies were also investigated; 3) controlling exhaust temperature through early exhaust valve opening and 4) combining recompression and fuel reforming for NOx reduction.

A limited set of experiments were conducted in Phase 1 utilizing an existing lost-motion VVA system for a preliminary investigation of the effect of varying the effective compression ratio via LIVC (Miller cycle) and increasing the IEGR via early exhaust valve closing (recompression).

Both 3-D (KIVA) and 1-D (GT-Power) modeling tools were used to analyze the initial test results from the lost motion VVA system on the Diesel single-cylinder engine in order to better understand the result and to confirm the viability of a multi-cylinder capable VVA system. The 3-D modeling was useful for developing an understanding of the NOx and soot formation processes and how they were affected by the various VVA strategies. The 1-D cycle simulation work investigated the air handling and exhaust gas recirculation system requirements for a multi-cylinder engine using LIVC. The preliminary conclusion was that LIVC was feasible but that it would require a 2 stage turbo-charging system to be effective.

A predictive NOx model was developed for use in 1-D cycle simulations codes. The model was validated using data from the single-cylinder research engine and used for modeling the multi-cylinder engine. The purpose of developing the NOx correlation was to better understand the key parameters that affect NOx emissions and the relationship between them. The correlation can be used to investigate the sensitivity of the NOx emissions to each parameter at different NOx levels. Also, it provides a simple method to predict NOx from GT-Power modeling results.

Phase 2 – Exploratory Development
<u>SI Summary:</u>

In the exploratory development phase of this project, technologies identified in the first phase were evaluated and down-selected. In some cases, the available technologies could not meet the advanced combustion system requirements and GM partnered with specialized engineering companies for subsystem development. For the simple mechanical HCCI engine, synchronous electric cam phasers, all-roller switchable valve train elements, central mount direct injection with small pulse operation, direct cylinder pressure sensing, and external EGR, were the key elements that were obtained from the supply base.

A cylinder head was designed to integrate all these key elements for HCCI combustion. Special features were also incorporated in the cylinder head such as a dual plane water jacket to target cool the central direct injector areas. Dual passage lash adjuster oil galleries were also created to allow hydraulic control of the switching roller finger followers independent of the other engine oil functions (cam bearings and lash control parts of the lash adjusters). Qualified machined surfaces on the sides of cam bearing towers provided adequate packaging space for the switching roller finger followers.

The engine front cover assembly was redesigned to accommodate a variable displacement engine oil pump in place of the production fixed displacement engine oil pump. The variable displacement pump enabled reliable hot, low-speed simple valve train switching while not compromising high-speed fuel economy due to wasted pump work.

Some initial system evaluations also occurred in this project phase. Much of this initial evaluation was focused on the switching roller finger follow valve train system including switching and durability evaluations. This early evaluation identified inadequate performance of the all-roller switching roller finger follower concept. Switching reliability testing identified variation outside of the system requirements and an excessive failure rate for adequate HCCI / SI combustion mode switching control. Thus, this component was replaced with another follower that had both roller and slider cam interfaces. The replacement arm had improved performance and durability, though, as is discussed in later sections of this report, it also required further development to meet requirements.

The FFVA valve actuation systems available on the market did not meet GM’s HCCI engine control requirements. In particular, valve seating velocity and system viscosity sensitivity lead to the GM-unique internal valve position feedback system concept and development. An application-specific variable displacement axial piston pump addressed issues of the market-available pump component. An integrated variable-inductance valve lift sensor located within the valve actuator addressed sensor challenges identified in Phase 1.

The FFVA cylinder head design concept displaced most of the conventional valve train system content. While combustion chamber features of spark plug, combustion pressure sensor and injector locations as well as the unique coolant jacket design features were carried over from the simple cylinder head design, the camshafts, cam support towers, cam phasers, cam position sensors, cam drive train, etc. were replace by the hydraulic system components. FFVA system specific items like reservoirs, accumulators, filter, cooler, lift pump, high-pressure pump, sensors, hydraulic hoses, etc. were added to the head and block.

Initial component level evaluation of the FFVA system also took place in this project phase. The high-pressure pump performance was evaluated on a specialized test stand. Pressure, flow and drive torque measurements were used to evaluate pump performance and efficiency. The testing also demonstrated that the pump could operate at high speed without cavitation for normal operating temperatures. The testing revealed poor low-speed performance though.

A single valve actuator assembly was fabricated and tested. The testing revealed the need to tune the internal feedback spool opening area relationships to control the damping, over-shoot and valve seating bounce characteristics. Once these characteristics were understood, multi-cylinder actuators were installed on a test engine without pistons to determine system performance and reliability. This test rig was also used to provide initial calibration information and system performance. Energy consumption and initial durability analysis were also assessed. Based on this early testing, actuator material condition recommendations were developed.

<u>CI Summary</u>

The purpose of this CI engine phase of the program was to investigate several different VVA strategies using a FFVA system on a single-cylinder research engine. This process would help reveal fundamental understandings that enabled the concept and design selections necessary to expand pre-mixed compression-ignition in a light duty Diesel engine.

A FFVA system was designed and built for the single cylinder Diesel research engine. This system was capable of independent control of all four valves with variable opening and closing timing, variable lift and the ability to execute multiple valve openings per cycle.

Initial testing focused on LIVC and its effects on performance and emissions. In this valve lift strategy, the intake valve is left open longer than in conventional engines. This results in a lower effective compression ratio, and thus lower compression temperatures. LIVC was investigated over a wide range of operating speeds and loads using several different valve lift strategies. LIVC was found to be a useful strategy over the range from low- to mid-loads. The most significant benefit of LIVC is a reduction in particulates due to the longer ignition delay time and a subsequent reduction in local fuel-rich combustion zones. It can also reduce the EGR requirement for a given NOx level. However, LIVC significantly increases the boost pressure requirements on the engine.

The second strategy that was investigated was increasing IEGR for HC and CO control at light loads and under cold operating conditions. Based on extensive testing and analysis of several IEGR strategies, exhaust re-breathing was found to be the most promising strategy for achieving IEGR at idle / low loads. In the exhaust re-breathing strategy hot exhaust gas is reintroduced into the cylinder by reopening the exhaust valve during the intake stroke. Exhaust re-breathing was found to reduce HC and CO emissions as well as improve combustion stability under idle and light load conditions.

Other VVA strategies were investigated with the FFVA system including early exhaust valve opening for controlling exhaust temperature and the combination of recompression and fuel reforming for NOx reduction. These strategies showed some potential benefits but also drawbacks. The test work was able to quantify the capabilities of all of these VVA strategies.

An additional task in Phase 2 of the program was to use the FFVA system to mimic the valve lift profiles of three different simple VVA systems: 1) the concentric cam system, 2) the 2-step roller finger follower system, and 3) the variable valve lift and duration system. These were the systems being considered for use on the multi-cylinder engine in Phases 3 and 4 of the program. Although all three systems were capable of expanding the early premixed charge CI operation range, the concentric cam system achieved the widest range of operation at most engine speeds. The major advantage of the concentric cam system was that it improved the swirl flow in the cylinder at light to medium loads, which promoted air - fuel mixing and soot oxidation.

Phase 3 – Advanced Development
<u>SI Summary:</u>

In the development stage of this project, hardware designs were created and constructed and function tested. In preparation for the next phase, bench testing of components, subsystems, non-fired and fired engine test properties for both the simple and FFVA configurations took place to verify component and system features and effectiveness.

A set of computer-aided design models and drawings were made of all modified engine components for both the simple and FFVA valve train systems. In addition, the FFVA actuator sub-component models and drawings, which were jointly developed by Sturman Industries and GMPT were created. Bill of Materials, which are lists of all engine and support system components (valve train, fuel injection, cylinder pressure sensing, etc.) used to organize engine builds, were made for both the simple and FFVA test properties.

Start cart (which is a low-cost engine test bed) testing was used to identify and correct any engine component or assembly issues prior to installation in higher cost and complexity test beds. More sophisticated testing took place next in dynamometer test cells to initially develop control systems and calibrate sub-systems and data acquisition systems.

These initial hardware and system empirical analyses revealed areas of required improvements in function and durability. For example, as previously discussed, the initial switching roller finger follower design was an all-roller concept that unfortunately did not have the required durability and consistency to reliably control the advanced combustion system. This component was replaced by another that was more reliable, but also had more friction. As another example, the lubrication system was also modified to improve high temperature issues to improve valve event switching dynamic range. Not only were valve train components developed, but also the fuel system was improved based on this initial testing. In particular, component material selection and component volumes were modified to improve fuel compatibility and response time respectively. The fuel pump capacity was also increased to improve engine start times and reduce cold-start emissions.

The FFVA system also went through significant development in this phase. A second crankshaft position sensor was added to improve system reliability and crankshaft position resolution. Actuator O-ring stability and seal reliability was developed as a result of failures. The actuator bias spring was replaced with fixed thickness shims to address O-ring failure and valve positional variation. The FFVA control system was developed during this phase also. For example, the system hydraulic pressure was modified to include an engine load variable that enabled the hydraulic system pressure to be modified to address the effect of higher cylinder pressure at the point of exhaust valve opening.

Finally, fired engine testing and durability spin-rig testing was the last step in preparing and developing the hardware and systems for the next phase. Durability issues such as the sliding pad cam interface of the switching roller finger follower and piston pins were identified. The sliding pad failed within 800 hours of high-lift operation and piston pins failed prematurely during HCCI operation. In both case, extensive development and design refinements were required to bring these failures under control. Significant FFVA control system development also took place in this phase. The first hardware test properties did not have pistons installed to prevent piston-to-valve interference while the control systems were developed. Over time, the number of “virtual” piston-to-valve hits significantly dropped until the later fired testing (with pistons installed) had no impacts after more than 1,000 hours of operation.

CI Summary

The purpose of this CI engine Phase of the program was to implement a simple CI valve actuation system to optimize multi-cylinder CI engine fuel consumption while reducing engine-out emissions. Program targets aimed to meet Tier 2 Bin 5 tailpipe levels with an exhaust after-treatment system for a pickup truck chassis certification. Two prototype versions of a V8 4.5 L multi-cylinder Diesel engines were developed with simple CI VVA systems for LIVC for variable effective compression ratio control. Single- or two-stage turbochargers configurations along with a close-couple after-treatment system were installed on the base engine and the costs associated with these technologies were assessed. Modeling, design and experimental activities included incorporating the concentric camshaft system into the cylinder head package to enable LIVC of one valve per cylinder. LIVC strategy requires turbocharger system optimization for boost ratio capability with a unique cylinder head and lubrication system design. A two-stage turbocharging system was selected based on 1D modeling using variable nozzle turbochargers. Valve lift profiles with secondary opening during the intake stroke were designed for controlled amounts of exhaust gases to flow back into the cylinder leading to IEGR for emissions and exhaust gas temperature control.

The significant soot reduction capability combined with lower NOx emissions with LIVC resulting in a potential calibration method for optimizing emissions reductions within smoke limits. LIVC allows extending the early premixed charge compression ignition combustion process for improved efficiency. There also is brake specific fuel consumption reduction with optimized LIVC due to lower friction and heat transfer as a result of the lower peak combustion temperatures from the lower effective compression ratio. Combining LIVC engine-out test bed data with weighting factors from vehicle data to determine the overall FTP cycle fuel economy revealed a brake specific fuel consumption reduction of ~ 0.5%; reduced particulate matter of ~ 25%, reaching as high as 50% for some of the key test points; and a HC increase of more than17%. However, when applying LIVC in the hot fraction of the FTP cycle there is limited impact on HC tailpipe emissions. The ability to increase combustion stability and turbine inlet temperature over the entire operating range by using IEGR was determined. IEGR also can enable early Diesel oxidation catalyst light-off and higher conversion efficiency to after treatment catalysts by higher operating temperature. Smoke emissions levels limit the engine operating range because of the air - fuel ratio drop with increasing IEGR. By combining IEGR test bed data with weighting factors obtained from vehicle drive data for the overall FTP cycle, the estimated brake specific fuel consumption increased by 0.3%, decreased HC by 20% and NOx emissions by 17%. Thus, IEGR increased fuel consumption, but when exhaust temperature increase from exhaust rebreathing and retarded injection timing is matched, less fuel is required with lower engine-out HC emissions using the exhaust rebreathing strategy.

Gasoline engine 2-Step switching roller finger followers require some modifications for Diesel engine applications. The main component issue is durability and involves the roller and sliding pad geometry and material limitations vs. the intended or desired valve events. Switching roller finger followers controlled by an oil control valve and appropriate control algorithms combined with modulating the exhaust pressure considering the interactions between cylinders in the engine can help optimize IEGR.

Phase 4 – Engineering Development (System Integration)
SI Summary:

In the SI engine part of Phase 3, there were efforts to improve the range of the HCCI combustion mode by engine hydraulic system development for the simple valve train system. In particular, increasing available oil pressure and flow to lower engine speeds enabled controlled valve train switching dynamic range and increased HCCI operation dynamic range. Other development efforts beyond the simple valve train system such as noise and vibration and HCCI-to-SI mode switching refinement were explored. HCCI combustion was noisier than regular SI combustion and this was particularly evident during combustion mode switching. Vehicle performance and drive quality were inferred from engine performance testing (note: the SOPO was revised in June 2010 to not include actual vehicle performance evaluations). The HCCI engine exceeded the power and torque performance of the baseline production engine (peak torque increased by approximately 10%) though some of the gains are also attributed to non–HCCI technologies such as dual independent cam phasing and direct fuel injection added technologies. HCCI combustion also improved the FTP fuel economy by approximately 4.5% relative to the production SI engine and there potentially could be further improvements if transmission gear ratios are optimized for the improved low end torque and by some additional valve lift event development. Engine-out NOx emissions for the HCCI engine were lower than for the SI engine, but tail pipe emissions were lower for the SI engine which had greater catalytic convertor efficiency. Thus, HCCI operation could jeopardize SULEV emissions capability. Limited extreme temperature testing revealed that the ability of the vehicle system to support stable HCCI combustion was constrained by temperature, engine speed and engine load. While the engine control system was able to control HCCI combustion within these constraints, the transient operation driveability was affected by the mode switch delays, particularly the mode transition from HCCI to SI during increasing load transients. The HCCI combustion mode also exhibited other driveability-related issues such as mis-fire and stalling that were related to HCCI combustion robustness.

For the SI FFVA engine, the calibration resources to optimize this engine were outside the scope of this project, so the simple valve train engine calibration was leveraged. The control algorithm results in a valve closing timing variation of approximately ±2.5 crank degrees, which exceeded the initial goals, but did not significantly impact the ability of the valve train system to optimize HCCI combustion phasing or variation. Noise analysis revealed that this valve train system has substantially more noise than the baseline SI engine at speeds below 3,500 rpm. However, the addition valve train noisy was masked by general engine noise at higher speeds. This engine configuration produced approximately an additional 2.6% FTP fuel economy improvement compared to the simple valve train HCCI engine. Much of this improvement came from improved SI and idle combustion conditions. This engine configuration also realized increase power relative to the baseline engine, but not relative to a modern engine with direct injection and variable valve timing. The FFVA engine also enabled a continuous combustion mode transition from HCCI to SI and vice versa with combustion noise and variation as primary constraints. In general, the maximum load that could be sustained in the HCCI mode was limited by acoustic ringing intensity. With regard to extreme temperature operation, this engine and valve train system was predominantly dependent on hydraulic fluid effective bulk modulus and viscosity. -40°C operation was predicted by simulation methods to limit engine speed to less than 2,000 rpm. Conversely, at extreme high temperatures (150°C), engine valves would not be able to open at cranking speeds below 100 rpm. Finally, there is a delay of the valve train system reaching normal operating temperature of approximately 400 seconds after a cold-temperature engine start which would not affect certification test cycles, but would impede extreme temperature operation.

<u>CI Summary</u>

Activities in the CI engine part of Phase 4 are based on the approved revised SOPO where vehicle development was replaced with GM-internally funded application of a simple CI system to a new prototype engine. This project is scheduled to extend beyond this 2011 calendar year so the activities are still in-progress. The goal of this CI engine phase is to assess the potential performance improvements of a prototype Diesel engine through the application of a simple CI valve actuation system. Another goal is to fully explore the potential of applying common valve train components and systems to multiple engines and to build on what was learned in this GM-DOE program.

PROJECT PRODUCTS

Several products were developed as a result of this program. In particular, publications, collaborations, patents and data bases were generated.

This is a list of publications generated as a result of this project:

1. Sun, Z. and He, X., “Development and Control of electrohydraulic fully flexible valve actuation System for Diesel Combustion Research,” SAE paper no. 2007-01-4021.
2. He, X., Durrett, R. P., and Sun, Z., “Late Intake Valve Closing as an Emissions Control Strategy at Tier 2 Bin 5 Engine-Out NOx level,” SAE Int. J. Engines 1(1): 427-443.2008 (also SAE paper # 2008-01-0637).
3. Sun, Z. and He, X., “Development and Control of electrohydraulic fully flexible valve actuation System for Diesel Combustion Research,” GM R&D Report PSR-159, 2007.
4. He, X., Durrett, R. P., and Sun, Z., “Late Intake Valve Closing as an Emissions Control Strategy at Tier 2 Bin 5 Engine-Out NOx levels,” GM R&D Report PSR-175, 2007.
5. He, X., Durrett, R. P., “An Investigation of Late Intake Valve Closing in Improving Fuel Economy and Reducing Emissions at Tier 2 Bin 5 Engine-Out NOx Levels,” GM R&D Report, to be released.

6. He, X., Durrett, R. P., “Reducing UHC and CO Emissions at Idle/Low Loads Using Variable Valve Actuation at Tier 2 Bin 5 Engine-Out NOx Levels,” GM R&D Report, to be released.
7. He, X., Durrett, R. P., “Assessing the Efficiency and Emission Benefits of the Miller Cycle Using a Simple VVA Mechanism in a Diesel Engine,” GM R&D Report, to be released.
8. He, X., Durrett, R. P., “Assessing the Benefits and Limitation of Early Exhaust Valve Opening and Recompression with Fuel Reforming,” GM R&D Report, to be released.
9. Gonzalez D, Manuel A., “LIVC and Exhaust Rebreathing in a V8 Diesel Engine for High Efficiency Clean Combustion”, Directions in Engine-Efficiency and Emissions Research (DEER) Conference. September 2010. Presentation also available at: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2010/wednesday/presentations/deer10_gonzalez.pdf

Some collaboration activities took place; in particular, a collaborative team including members from Meta Motoren-und Energie-Technik, Hitchiner Manufacturing Co., Inc. and GM LLC developed a low-friction, all-roller switching roller finger follower that enables cam profile switching (2-Step and valve deactivation). Sturman Industries, Inc. collaborated with GM LLC to develop the FFVA system that was used to enable HCCI SI combustion research. Mechadyne International, Ltd. developed a concentric camshaft system with the GM Diesel development team that enabled LIVC.

Several inventions were created as a result of this project. Here is a list of awarded US patents, patent applications and Records of Inventions:

1. 7,644,688 “Center-Biased Dual Action Internal Feedback Spool Valve with Detent”, Craig Marriott and Zongxuan Sun
2. 7,665,431 “Boost Drive Piston for Engine Valve Actuation”, Zongxuan Sun
3. “Seating Control of the Engine Valve Actuation System”, Zongxuan Sun, USPTO patent application 2008-0066701-A1
4. “Integrated Hydraulic Cooler and Return Rail in Camless Cylinder Head”, Craig Marriott, Timothy Neal and Jeffrey Swain, USPTO patent application 2010-0064990-A1
5. “A Method For Improving Fuel Economy, Reducing Emissions, and Reducing Combustion Noise Using a Simple Variable Valve Actuation System”, Xin He, Russell Durrett, Patrick Szymkowicz and Gerald Malta, Record of Invention submitted, January 26, 2009, GM reference number P008328
6. “In-Cylinder Pressure based Method for Variable Valve Lift (VVL) Mechanism Failure Detection”, Matthew Wiles, USPTO patent application 2011-0196567-A1
7. “A Method of Reducing Combustion Noise and Smoke Emissions at Medium and High Loads”, Xin He, Russell Durrett, Patrick Szymkowicz and Gerald Malta, Record of Invention submitted, February 24, 2009, GM reference number P008683
8. “A Method of Reducing Diesel Engine-Out Pollutant Emissions at Low Load”, Xin He, Russell Durrett, Patrick Szymkowicz and Gerald Malta, Record of Invention submitted, GM reference number: P008684

9. “Diesel Engine With Switching Roller Finger Followers for Internal EGR Control”, Manuel Gonzalez, Robert Moran, Sameer Bhargava, Ronald Pierik and Jonathan Burton, USPTO patent application 2011-0114067-A1
10. “Extended Valve Lift Duration at Reduced Lift Amplitude With FFVA Valvetrain”, Joel Cowgill, USPTO patent application 2011-0168111-A1
11. “Use Of Valve Lift To Conserve Control Oil Flow During Valve Enable/Disable Of a Electrohydraulic Camless Valve Control System”, Daniel Brennan, Craig Marriott, Joel Cowgill, Matthew Wiles and Kenneth Patton, USPTO patent application 12/910212
12. “Individual Cylinder Spark Knock Control Via Load Control With Electrohydraulic Valve Control In A Camless Engine”, Daniel Brennan, USPTO patent application 12/850930
13. “Immediate Torque Control With Electrohydraulic Camless Engine”, Daniel Brennan, Record of Invention submitted, December 16, 2009, GM reference number P011310
14. “Exhaust Helical Port To Support Swirl Motion During Exhaust Rebreathing Timing Strategies”, Paolo Di Martino, Record of Invention submitted, March 22, 2010, GM reference number P012232
15. “Independent Internal Feed-back Spools for Hydraulic Engine Valve Actuation”, Craig Marriott, USPTO patent application 12/984233
16. “Improved Backup Torque In a 2 Mode Hybrid EVT With a Fully Flexible Valve Actuation(FFVA) Camless Engine”, Daniel Brennan, Record of Invention submitted, November 19, 2010, GM reference number P015042
17. “Simultaneously Firing Two Cylinders Of an Even Firing FFVA Camless Engine”, Danniel Brennan, USPTO patent application 13/238388
18. “Using a FFVA Camless System to Prevent Diesel Engine Runaway”, Daniel Brennan, patent application pending, November 19, 2010, GM reference number P0015067
19. “Using a Camless FFVA System To Control Engine Stop Position”, Daniel Brennan, Record of Invention submitted, November 19, 2010, GM reference number P015066
20. “Individual Cylinder Combustion Phasing Control for HCCI Through Modulation of Trapped Internal Residual Quantity”, Joel Cowgill, Record of Invention submitted, August 3, 2011, GM reference number P013920
21. “Individual Cylinder Combustion Phasing Control For HCCI Through Modulation of Effective Compression Ratio”, Joel Cowgill, patent application pending, August 3, 2011, GM reference number P015275

Several analytical and empirical data collections were compiled. The databases include empirical data from all engine testing, component and assembly drawings, modeling activities such as GT-POWER, KIVA, FEA, valve train simulation, CFD, dynamic system modeling, etc. More details of these data bases have been provided separately to the DoE.

Since the scope of this project did not include the development of any new computer models or software, but only the application of existing commercially-available software and code, no additional computer modeling detail is reported above.