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UNIVERSITY
COLLEGE OF ENGINEERING

Advanced Start of Combustion Sensor

Phases I and II-A: Feasibility Demonstration, Design and Optimization

Final Report

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TIAX, LLC
15 Acorn Park
Cambridge, Massachusetts
02140-2390 U.S.A.

TIAX Contact:
Chad Smutzer (Project Director)
+1 (617) 498-6187
smutzer.chad@tiaxllc.com

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Nomenclature

HCCI	Homogeneous Compressed Charge Ignition
SOC	Start of Combustion
LPP	Location of Peak Pressure
θ	Crank Angle
$\Delta\theta$	Change in Crank Angle
b	Weibe Parameter
m	Weibe Parameter
CAD	Crank Angle Degrees
ϕ	Phi, Relative Fuel-Air Ratio
TDC	Top Dead Center
HP	High Pass [filter]
SI	Spark Ignition
IVC	Intake Valve Close
IMEP	Indicated Mean Effective Pressure
MBT	Maximum Brake Torque
PCCI	Premixed Charge Compression Ignition

1 Executive Summary

Homogeneous Compressed Charge Ignition (HCCI) has elevated the need for Start of Combustion (SOC) sensors. HCCI engines have been the exciting focus of engine research recently, primarily because HCCI offers higher thermal efficiency than the conventional Spark Ignition (SI) engines and significantly lower NO_x and soot emissions than conventional Compression Ignition (CI) engines, and could be fuel neutral. HCCI has the potential to unify all the internal combustion engine technology to achieve the high-efficiency, low-emission goal. However, these advantages do not come easy. It is well known that the problems encountered with HCCI combustion center on the difficulty of controlling the Start of Combustion. TIAX has an SOC sensor under development which has shown promise. In previous work, including a DOE-sponsored SBIR project, TIAX has developed an accelerometer-based method which was able to determine SOC within a few degrees crank angle for a range of operating conditions. A signal processing protocol allows reconstruction of the combustion pressure event signal imbedded in the background engine vibration recorded by the accelerometer. From this reconstructed pressure trace, an algorithm locates the SOC. This SOC sensor approach is non-intrusive, rugged, and is particularly robust when the pressure event is strong relative to background engine vibration (at medium to high engine load). Phase I of this project refined the previously developed technology with an engine-generic and robust algorithm.

The objective of the Phase I research was to answer two fundamental questions: Can the accelerometer-based SOC sensor provide adequate SOC event capture to control an HCCI engine in a feedback loop? And, will the sensor system meet cost, durability, and software efficiency (speed) targets? Based upon the results, the answer to both questions was “YES”.

The objective of Phase II-A was to complete the parameter optimization of the SOC sensor prototype in order to reach a juncture where plans can be and are discussed with an industry partner for how best to perform a more detailed implementation of the TIAX SOC technology on an HCCI engine system. This occurred, as evidenced the number of potential commercialization partners shown in Table 4. Potential Commercialization Partners Contacted (up to date as of January 31, 2010).

During the two phases, a robust, engine-generic algorithm was developed that met the desired targets and was shown to work extremely well for HCCI engine operation.

2 Project Approach

2.1 Project Background

An affordable and rugged SOC sensor for ordinary automotive spark-ignition engines was intensely pursued by the automotive engineering community during the 1980s and 1990s; the various efforts to develop such a sensor have been summarized in the excellent review by Sellnau, Matekunas, Battiston, Chang, and Lancaster [19]. The primary types of sensors which were explored in that era included the following:

- Low-cost durable cylinder pressure transducers
- Ion sensors
- Knock sensors
- Torque fluctuation on the crank
- Strain gauges on the head bolts
- Spark Plug washer transducers
- Microphones (accelerometers)

The intended benefits for SI engines were primarily a few valuable percentage points in BSFC, moderate NO_x reduction, and preventing misfire. In the end there was no sensor system developed in that era which met the rigorous cost and durability targets for light duty vehicles. Since that time a durable cylinder pressure sensor for heavy duty NG engines has appeared on the market, but it is prohibitive costly for vehicle applications.

The advent of the Homogeneous-Charge Compression-Ignition (HCCI) and “low temperature combustion” engine designs has elevated the need for SOC sensors. The SOC sensor is a “sine qua non” for HCCI; this type of engine will not function properly without some form of effective combustion phasing control for reasons given below. Novel HCCI engine designs are currently under development by most major manufacturers with government collaboration and support, and promise to revolutionize and replace both conventional spark-ignition and diesel injected engines for both heavy duty and light duty segments. Most observers expect that engines with at least partial HCCI might appear first in the heavy-duty diesel segment (truck and bus engines) in the 2010-2015 timeframe, followed by light duty diesels somewhat later. Once the LD diesel fuel HCCI is introduced, the gasoline direct injection HCCI engines will follow quite rapidly.

HCCI is inherently near-premixed and therefore exhibits a “sweet spot” of desired behavior within those in-cylinder conditions where the mixture readily ignites on a reproducible basis (limited range A/F mixture and compression temperature conditions). This HCCI sweet spot is shown in Figure 1 on a typical load-speed diagram [1]. The practical reality is that most real vehicle drive cycles take the engine outside this sweet spot, as shown in Figure 2 [1]. Most HCCI engines will probably have a second mode which switches to stoichiometric outside the sweet spot.

Figure 1. Typical HCCI Operating Zone [1]

Figure 2. Drive Cycle Requires Transitions in and out of HCCI Mode [1]

Combustion phasing becomes a problem, then, during transient engine operation in and out of the HCCI mode, as the engine moves to different speed-load combinations. A similar challenge occurs in dilute-combustion SI Engines with high EGR, because cycle-to-cycle the combustion event can be delayed severely. When this happens, the engine can exhibit alternatively over-dilute (high HC/CO) and under-dilute (high NO_x) combustion events. A successful or robust transition is shown in

Figure 3 [2]. This is the behavior desired as a result of using feedback control with an SOC sensor.

Figure 3. Transition Sequence of Cylinder Pressure Traces [2]

HCCI engines have been the exciting focus of ICE research recently primarily because, with lean fuel/air mixtures, they can obtain higher thermal efficiency than the conventional SI engines and significantly lower NO_x and soot emissions than conventional CI engines [3~12]. HCCI could be fuel neutral or fuel-flexible. It also has the potential to unify all the IC engine technology to achieve the high-efficiency low-emission goal; however, these advantages do not come easy. It is well known now that the problems encountered with HCCI combustion center on the difficulty in control [13~18]; e.g., controlling the start of combustion, rate of heat release, mitigating HC and CO emissions, improving the power density, and controlling the transition in and out of HCCI modes.

Enabled by the recent advances in actuation and model-based control technologies developed in the past decade, engineers have many tools to choose and have applied them to HCCI engine operation in the laboratory; e.g., Direct Injection Timing, Mixture Homogeneity Control, Internal or External Gas Recirculation Control, Variable Valve Actuation, Variable Compression Ratio, Inlet and Charge Temperature Control, Boost Pressure, Fuel Property or Blending Control, etc. Among all the control parameters, the control of ignition timing or Start of Combustion (SOC) is probably not the most basic but also the most difficult subject. HCCI operation critically depends on the chemical composition and the sensible enthalpy of the trapped charge during compression. Since the onset of HCCI combustion depends on the auto-ignition of the fuel-air mixture, it is very hard to directly control it both thermodynamically and chemically. In addition, transient operation can change the onset timing of HCCI combustion in response to the

instantaneous change of the engine load and speed. Dynamic control requires management of load/speed change within the HCCI regime as well CI or SI high-load operation into and out of it. A stable HCCI operating point, however, does not imply a robust SI to HCCI transition at that point. The mode change and load-trajectory following is very complicated with inter-cycle coupling in HCCI engine operation through heat transfer, residual gas, and fuel/air excursion in mode transition. The engine torque output is governed by many parameters including charge composition, combustion phasing, and pumping loss. Transitions between HCCI and CI/SI modes can be frequent with short residence time in the HCCI region which can be quite unpredictable; therefore, the engine requires rapid and robust transition management even if drive mode has been statistically optimized.

Before we can apply directly or indirectly any of the actuation technology or load-following, multi-variable control strategy, a robust sensor must be implemented to provide this most important process variable for cylinder-pressure-based model control [e.g., 19]. A non-intrusive sensor is also preferred than an intrusive ones, such as ionization sensing [20, 21] because of better robustness, survivability, linearity, and thermal management. Therefore, a robust non-intrusive TIAX accelerometer-based SOC sensor with proven signal processing to filter out the combustion pressure noise [22, 23] is proposed to meet these challenges.

Significant challenges remain for HCCI engines to meet commercialization threshold targets, including light load HC/CO, cylinder to cylinder variability, noise, and transition between modes of operation. The root cause of many of these challenges is controlling combustion phasing so that the combustion event occurs at the desired time each cycle, for all cylinders (there is no external triggering mechanism as there is for conventional diesel or spark engines). Given a functional SOC sensor such as the one to be developed here, feedback control of the combustion event would be possible using VVT or fuel injection adjustments.

2.2 TIAX Sensor Concept

The various concepts for sensing SOC fall into two categories: sensors having physical access to the engine cylinder and sensors mounted externally on the engine. Sensors mounted externally have the obvious advantage of not taking up valuable cylinder head “real estate” (i.e., valves, injectors, ignition devices may be placed in optimum configurations) as well as not having to be exposed to the high-temperature in-cylinder environment. For large stationary gas engines there are commercial cylinder pressure sensors (reference GE), but these would be prohibitively expensive for the transportation sector. The accelerometer-based sensor concept under development by TIAX has the advantage of using a low-cost accelerometer that, in combination with signal processing, will distinguish the combustion event from the background engine noise and allow determination of the SOC.

TIAX has demonstrated the accelerometer sensor in previous work “Accelerometer-Based Feedback for the Control of an HCCI Engine.” DOE SBIR Final Scientific/Technical Report. March 2, 2006.). A schematic of how the accelerometer signal is acquired and processed is shown below:

Figure 4. Schematic of Accelerometer-based SOC Process

As shown in Figure 4, the accelerometer serves as an indirect SOC sensor. For research purposes, the accelerometer is mounted on a carefully selected location on the engine head or block. The signal from the accelerometer is fed to appropriate amplifiers and then into advanced signal processing algorithms. These algorithms allow reconstruction of the source term (the combustion pressure event signal which is imbedded in the background engine vibration that the accelerometer picks up). From this re-constructed pressure trace, the data is fed into an algorithm to locate the SOC. This SOC value can then be fed into the Engine Control Unit (ECU) and feedback adjustments may be made depending on whether SOC was at the desired crank angle location or was found to be advanced or retarded.

In previous work, TIAX has shown that this method is promising for a range of operating conditions. For that study, TIAX used a spark-ignition engine with retarded spark timing to generate HCCI-like cylinder pressures (where SOC started at or after Top Dead Center). An accelerometer was mounted on the block of the engine, and this signal was recorded along with actual in-cylinder pressure traces (from a pressure transducer). Using signal processing techniques, the pressure was reconstructed and then fed into a variety of algorithms to determine SOC for the various cycles. The results of this are shown in Table 1.

Table 1. Comparison of the Accuracy of Two SOC Methods Used in Previous TIAX Work (degrees)

Condition	Method 1 (error in SOC)	Method 2 (error in SOC)
Regular SI	2.7	-5.5
HCCI-like Medium Load (SOC After TDC)	5.8	-0.4
HCCI-like Low Load (SOC After TDC)	7.3	0.6
HCCI-like Medium Load (SOC Before TDC)	0.7	-5.5
HCCI-like Low Load (SOC Before TDC)	0.6	-3.5

Method 1 is a filtering method which highlights the SOC by using a band pass filter. This method encounters some difficulty when the SOC is after TDC, but does well for the other data. Method 2 is a method of taking the third derivative of the pressure trace. This method does well

where Method 1 does not, but has some inaccuracies at other locations. However, Method 2 performed better in all cases when the data was smoothed and filtered, so this Method has great promise for improvement. A third method based on a Neural Network was tested and also proved to be promising. However, the Neural Network was trained only over limited conditions, and more work needs to be done to evaluate its ability to recover SOC accurately. The methods discussed above show promise, and Method 2 and Method 3 both have room for improvement as well as need for further exploration.

Improvements/Next Steps: Based on the earlier work at TIAX there are three areas for improvement which were investigated in the proposed work: (1) Improving the S/N of the raw signal by means of accelerometer model selection, custom sensor designs, better placements on the engine, custom lower-noise engine attachment schemes, and the like. (2) Improving the recovered pressure trace fidelity by trying improved signal processing algorithms. For example, in addition to Cepstral windowing (which is promising but has limitations), TIAX will investigate LMS Adaptive Filtering (using two independent accelerometer signals to find the imbedded combustion event of interest). (3) Improving the effectiveness of SOC determination from the pressure trace especially at lower engine load when there are “two peaks”. In the proposed project the SOC algorithms will be developed further over a wider set of data taken from actual HCCI combustion. These approaches were investigated, but found to have limitations in the Cepstral reconstruction method, so a new approach was devised.

2.3 Technical Discussion and Development Risks of Indirect SOC Detection

In the ideal situation, a method of finding SOC would use a direct in-cylinder measurement, such as a pressure transducer. However, as discussed earlier, this is impractical outside of the laboratory due to cost, cylinder-head space, and durability issues. These constraints lead to the fact that an ideal sensor location would be one located externally on the block or head of the engine. Thus, the accelerometer is an ideal basis for a sensor to determine SOC. However, it has to be noted that while there are many benefits, there are some risks of using an accelerometer.

The development risks fall into six categories:

- Signal-to Noise (S/N) Ratio of Pressure Trace
- Reliable Algorithms for Identification of SOC from Pressure Trace
- Processing code efficiency (response time of control system)
- Interface with HCCI actuation/control mechanism (VVT, Fuel injection, etc)
- Durability
- Cost of the control system

Signal-to Noise Ratio of Pressure Trace: The first risk is the signal to noise ratio of the accelerometer signal. Engines are noisy by nature; in addition to the combustion noise, there are bearing noises, belt noises, etc. At high engine loads the combustion noise dominates over the other engine noises, but at low loads, it can often be difficult to distinguish the combustion noise from the other engine noises. This is evident by a comparison of engine load points and the pressure traces for each engine load point. Figure 5, shown below, highlights the difficulty as the load is decreased.

Figure 5. HCCI Pressure Traces with Varying Load Conditions Showing “Two Peaks”

Shown in Figure 5 is data from TIAX’s previous work. This data is from modeled HCCI conditions. As the load is lowered (in this case by the reduction of fueling with the same amount of air), the peak combustion pressure becomes lower. When there are two peaks as shown above, reconstructing a pressure trace does present some challenges. However, in the previous body of work, it has been shown that at the lower loads, reconstruction of the pressure trace is possible, and from this reconstruction, SOC may be identified. This area does need to be explored further, as this is important in the overall goal of having a robust SOC determination method for all load and speed conditions, but the results to date have been encouraging.

The approach used in the previous work to reconstruct the pressure trace from the accelerometer data was based upon Cepstral windowing. This method is a well-published and robust method that had original use in the field of speech recognition and has been applied to machinery diagnostics. In this method, a transfer function is calculated to represent the path from the accelerometer to the cylinder to the block. This is an inverse method of filtering. To obtain the transfer function, the source and response waveforms have to be monitored simultaneously. The response and source is windowed, and then returned to the frequency domain. The ratio of the two spectra is the transfer function. The next step is to record only the accelerometer signals. Using the window function spoken of earlier, the accelerometer signal is smoothed, and then the transfer function is subtracted. The result is a reconstruction of the actual pressure signal [23]. This method is what was used to reconstruct the pressure trace, which was then used to obtain the SOC results. Cepstral windowing is a powerful tool but has drawbacks in terms of signal magnitude. Therefore, in addition to Cepstral windowing TIAX investigated LMS Adaptive Filtering (using two independent accelerometer signals to find the embedded combustion event of interest) during this project, but chose another method altogether that did not involve Cepstral windowing.

Reliable Algorithms for Identification of SOC from Pressure Trace: Further developed in this body of work are methods aimed at improving the effectiveness of SOC determination from the pressure trace, especially at lower engine load when there are “two peaks”. The SOC algorithms

were developed over a data set taken from actual HCCI combustion. These accelerometer signals were processed using the methods described above, and each of the processed wave forms were processed by various SOC algorithms to further expand the detection range and determine a robust method which is applicable for a range of load cases.

Also of investigation are the computing requirements of the algorithms to be tried. Once the optimum algorithms have been determined, then consideration will be given to understanding the computing time needed for the algorithms such that the implementation of the algorithm is feasible using current or next-generation ECU hardware and software.

Processing code efficiency (response time of control system): Assuming a six cylinder engine operating up to 3600 rpm (60Hz), a cylinder fires every 120 degrees or 1/180 sec. The portion of each combustion event which will be of interest will be nominally 40 degrees or just under 2 milliseconds in duration. So the signal acquisition and processing requirements will be 10 microseconds time resolution or 100,000 Hz sampling rate. The code must be efficient enough to derive and send SOC information to the feedback system before the next fuel/air mixing actuation event of that cylinder, or well under 10 milliseconds. As we evaluate the various reconstruction algorithms as well as the SOC determination algorithms for accuracy, we simultaneously evaluated them for code efficiency.

Interface with an effective HCCI actuation/control mechanism (VVT, Fuel injection, etc): Once the SOC has been determined from the algorithms to be developed, that value must be fed into the engine controller and adjustments made to the engine so that the desired change may occur. The algorithms developed must provide accurate information rapidly enough such that the engine controller can determine what change to make and implement that change. In the literature, work has been done with using actual measured cylinder pressure as a feedback to make a successfully make change on an HCCI engine. In the literature study, the change occurred over 50 cycles, which is much too slow for production use. The reason for the slow response was the use of inlet air control for the HCCI load regulation mechanism (the thermodynamics of heating the air limit the response), the fact that the pressure data had a heat release analysis performed upon it, and the controller limitations [24]. The majority of the delay was the actuation mechanism, rather than the feedback control. Great care was taken throughout the project to ensure that the code can effectively interface with the ECU to minimize the response time.

Durability: The accelerometer as mounted externally on the engine (along with harness) must survive the lifetime of the vehicle with no degradation of signal. Here the stresses include vibration, thermal shock, corrosion, ice build up, and electrical noise. Knock sensors, which are an integral part of modern SI engines, are a version of accelerometers that have proven to be extremely robust and durable. Consideration was given during the performance of this project whether the sensor needed to determine SOC needs to be more sensitive than a typical knock sensor, and this will give an excellent picture of future durability. Using this as a durability projection method has the advantage of the years of actual field use that accelerometers in the form of knock sensors have undergone.

Cost of the control system: Since the cost target for the complete HCCI advanced engine is \$150 per kW we have set a preliminary cost target for the SOC sensor (complete system) at \$1 to 2 per kW ex-factory. This is an aggressive target but the accelerometer cost is quite low (\$2-3 range).

Consideration was given throughout the project to minimize the final cost of the SOC sensor by determining the minimum resolution needed (lower resolution which still gives accurate results is a cost savings), streamlined algorithms (these will lower the computing cost, which could translate into lower hardware cost), and using the minimum amount of sensors possible.

2.4 Objectives - Phase I Feasibility Demonstration

The objective of the Phase I research is to answer two fundamental questions: Can the accelerometer-based SOC sensor provide adequate SOC event capture to control an HCCI engine in a feedback loop? And will the sensor system meet cost, durability, and software efficiency (speed) targets? For successful completion of Phase I, the accelerometer-based combustion sensor must provide enough discernable signal resolution at low load conditions (where the lowest signal-to-noise ratio exists) such that the SOC may be readily identified to the required accuracy. During Phase I, reliable algorithms for identification of SOC from the reconstructed pressure trace must be developed to meet accuracy and speed specifications. The processing code efficiency (response time of control system) must be rapid enough (meeting the specifications determined in the initial task) that control decisions may be made and implemented. The interface with the HCCI actuation/control mechanism (VVT, Fuel injection, etc) must be rapid and robust enough to allow the control mechanisms an opportunity to change engine conditions. The sensor(s) must be durable enough to meet all conditions of the engine operating regime and still provide accurate data for the life of the engine. The detailed specifications for each of these six criteria will be determined in the initial task of the project.

2.5 Program Approach - Phase I

The objective of the Phase I research was to answer two fundamental questions: Can the accelerometer based SOC sensor provide adequate SOC event capture to control an HCCI engine in a feedback loop, and will the sensor system meet cost, durability, and software efficiency (speed) targets? For successful completion of Phase I, the accelerometer-based combustion sensor must provide enough discernable signal resolution at low load conditions (where the lowest signal-to-noise ratio exists) such that the SOC may be readily identified to the required accuracy. During Phase I, reliable algorithms for identification of SOC from the reconstructed pressure trace must be developed to meet accuracy and speed specifications. The processing code efficiency (response time of control system) must be rapid enough (meeting the specifications determined in the initial task) that control decisions may be made and implemented. The interface with the HCCI actuation/control mechanism (Variable Valve Timing (VVT)/Fuel injection, etc) must be rapid and robust enough to allow the control mechanisms an opportunity to change engine conditions. The sensor(s) must be durable enough to meet all conditions of the engine operating regime and still provide accurate data for the life of the engine. The sensor and algorithm must also demonstrate “technology robustness” in application across engines of the same type (same model, different serial number) as a measure of production and commercial feasibility. The detailed specifications for each of these six criteria will be determined in the initial task of the project.

The objective of Phase II is to develop a pre-production prototype which implements the algorithms into a functional control system ready for vehicle testing. Phase II is contingent upon Phase I meeting the success criteria detailed above, in which case we assume that The Tier 1 will be heavily involved in Phase II. The team will design and optimize the SOC sensor as a system

to meet commercialization targets. Phase II will address left over issues not resolved in Phase I. From Phase I, the two best algorithms will be selected, as well as the two best accelerometer sensor designs and engine mounting packages. These packages and algorithms will be down-selected and optimized. The Tier 1 will be heavily involved through this process, and from this selection process pre-production prototypes will be made.

A schematic of the Phase I workflow is shown below in Figure 6, which highlights the approach which the team is proposing to ensure successful technology development.

Figure 6. Schematic of Work Flow

C. PERFORMED TASKS

Phase I: Feasibility Demonstration (Time period: Month 1-12)

Task 1.1: System Design Targets and Specifications. Duration: 1 month

The project commenced with a 1-day kickoff meeting, held at a mutually convenient time and location. The first task of the project was to determine the Start of Combustion (SOC) system design targets such as SOC accuracy, cost, curability, algorithm speed, and Engine Control Unit (ECU) interface. This was accomplished by looking at the target engine families and determining the performance parameters needed from a SOC system to provide the desired control. From this in-depth examination of the design targets, specifications for the SOC system were compiled to provide a framework for the rest of the project.

Task 1.2: Setup Engine to Operate as Test Bed for Novel Hardware. Duration: 4 months

This task began in parallel to Task 1.1, and involved the installation and setup of three test engines: and two multi-cylinder engines in and one vehicle mounted engine. TIAX's Engine Test Facility has the flexibility needed to act as a multi-cylinder test bed for novel sensor technologies. Since engine-to-engine repeatability is an important issue with SOC sensing, two multi-cylinder Diesel engines (one of which will be modified to run HCCI-like later in the project) was outfitted with sensors. Once instrumented, the engines were tested in sequence and run over a range of operating points and accelerometer data will be recorded while in a standard diesel mode. Following the testing of the second engine, it was modified to run as an HCCI-like

diesel engine and verified to ensure that the engine is operating correctly so as to simulate HCCI (this occurred at Wayne State). The two engines were the same model but different serial numbers. This data will have the algorithms developed in Task 1.4 applied to it to determine if the transfer functions are applicable to both engines (thus giving a measure of technology robustness).

Task 1.3: Design Novel Sensor Configuration. Duration: 3 months

This task began subsequent to Task 1.1 and in parallel to Task 1.2. This task took the design specification results developed in Task 1.1 and started the design of the novel sensor, building on the successful configurations that TIAX has already demonstrated. For the first pass at the design, this was an off-the-shelf item. Also examined in this task is the optimum sensor location on the engine and the number of sensors needed for adequate SOC sensing. These parameters will be considered in the context of past work, and the concepts will be tested in Task 1.5: Test Feasibility.

Task 1.3.1: Fluxgate Sensor Investigation. Duration: 3 months

As a complement to the use of accelerometers for the detection of combustion events, TIAX proposes to explore the feasibility of using fluxgate sensors to measure crankshaft rotation dynamics. The proposed fluxgate sensor task will be focused on analytical and modeling studies. A minimal amount of experimental work will be done to determine key empirical values that are required for the analysis. *This investigation was not undertaken as the team felt the developed algorithm was robust enough without additional means of SOC detection.*

Task 1.4: Develop Software For Pressure Reconstruction and SOC Determination. Duration: 2.5 months.

This task began subsequent to Task 1.3. This task focused on the intellectual fabrication of the algorithms that will process the data from the novel sensor. This task also focused on the requirements (e.g. the processing power needed) to use the signal from the novel sensor and return useful information to the engine controller. Also of interest during this task was the interface of the Controller with the ECU.

Task 1.5: Test Feasibility. Duration: 4.5 months

This task will begin after Task 1.4 and Task 1.2. The Test Feasibility Task focuses on using the engine testbed installed in Task 1.2 to test the schemes that were generated in Task 1.3. This included running the engine at representative load points and recording data from the novel sensors as well as the standard engine parameters (e.g., cylinder pressure, exhaust temperature). This Task tested the assumptions and conclusions made in Task 1.3 regarding the number of sensors as well as the sensor locations.

Task 1.6: Reduce Data/Evaluate Results. Duration: 2 months

From the detailed data generated in Task 1.5, conclusions were drawn to assess how well the SOC system is meeting the targets set in Task 1.1, and to determine the optimum configuration and number of sensors needed to determine the SOC. The data was put into context of the market need, available computing power, and the prototype controller capabilities/limitations for the purposes of determining the next steps.

Task 1.7: Commercialization Plan/Path Forward. Duration: 2 months

In this task TIAX summarized the results of the previous tasks and assess the SOC development status in market context. Conclusions from Task 1.6 regarding the number of sensors needed and their respective locations were tied together with the results from Task 1.4 to piece together an overall system schematic for SOC sensing. Recommendations for Phase II, including a detailed work Plan, were developed.

Task 1.8: Phase I Project Management and Reporting. Duration: 9 months

This task covers the project management and reporting requirements of project as well as oversight and management of the team. This task included the reporting requirements of the DOE, as well as the communication necessary to ensure the team is working constructively together. Also included is the budget tracking and resource allocation for the project.

Figure 7 shows the duration of the project as well as the expected duration of each subtask. The entire project was expected to take approximately 260 working days, or one year to complete.

Figure 7. Project Timeline by Task

The following were the success criteria for the Phase I effort. They were successfully met, as the project proceeded to the second phase.

1. For successful completion of Phase I, the accelerometer-based combustion sensor must provide enough discernable signal resolution at low load conditions (where the lowest signal-to-noise ratio exists) such that the SOC may be readily identified to the accuracy determined in Task 1.
2. During Phase I, reliable algorithms for identification of SOC from the reconstructed pressure trace must be developed to meet the accuracy and speed specifications set forth during Task 1.

3. The processing code efficiency (response time of control system) must be rapid enough (meeting the specifications determined in the initial task) that control decisions may be made and implemented.
4. The interface with the HCCI actuation/control mechanism (VVT, Fuel injection, etc) must be rapid and robust enough to allow the control mechanisms an opportunity to change engine conditions.
5. The sensor(s) must be durable enough to meet all conditions of the engine operating regime and still provide accurate data for the life of the engine. The detailed specifications will be determined in the initial task of the project.
6. The projected cost of the control system (including the sensor and the electronics hardware) must be low enough to allow implementation of the package for wide-spread use. The cut-off point for this will be determined in the project.

Table 2. Comparison of Phase I Results with Objectives

<i>Phase I Success Criteria</i>	<i>Outcome</i>
The accelerometer-based combustion sensor must provide enough discernable signal resolution at low load conditions (where the lowest signal-to-noise ratio exists) such that the SOC may be readily identified	An algorithm was developed that was able to capture enough signal strength to determine the start of combustion at low loads.
Reliable algorithms for identification of SOC from the reconstructed pressure trace must be developed	Preliminary results show promise when compare to SOC data from laboratory grade pressure transducers.
The processing code efficiency (response time of control system) must be rapid enough	Speed looks promising.
The interface with the HCCI actuation/control mechanism (VVT, Fuel injection, etc) must be rapid and robust	Algorithm speed looks to be fast enough to execute in a fraction of a cycle.
The sensor(s) must be durable enough to meet all conditions of the engine operating regime and still provide accurate data	Based upon knock sensors, which are well-proven for durability and robustness in millions of current underhood applications.
The projected cost of the control system (including the sensor and the electronics hardware) must be low enough	Knock sensors are the main hardware cost, and they are much more economical than pressure transducers.

2.6 Program Approach Phase II-A

Phase II-A

The objective of Phase II was to develop a pre-production prototype which implements the algorithms into a functional control system ready for vehicle testing. Phase II will also address left over issues not resolved in Phase I. At the end of Phase II we expect to have a working prototype. The prototype will be “works-like, looks-like” and will meet cost, durability, and software efficiency targets as specified in Phase I of the project and evolved through the project. To meet these objectives, Phase II was divided into Phase II-A and II-B. The objective of Phase II-A is to complete the parameter optimization of the SOC sensor prototype in order to reach a juncture where plans can be and are discussed with an industry partner for how best to perform a more detailed implementation of the TIAX SOC technology on an HCCI engine system. At the end of Phase II-B we expect to have the working prototype developed in concert with our commercialization partner (TBD). The prototype will be “works-like, looks-like” and will meet cost, durability, and software efficiency targets as specified in Phase I.

Task 2.1: Algorithm/sensor Selection and Optimization.

Using the best algorithms and best sensor packages as recommended in Phase I, we selected the most promising based on the Engine Control Specifications. Additional accelerometer types were purchased based upon the recommendations from the signal processing done in Phase I, including commercially available knock sensors. Transient testing and further load point testing was done to ensure the robustness of the algorithm. The algorithm was compiled to be real-time rapid prototyping hardware ready during this task.

Task 2.3: Engine Testing of the Prototype.

The prototype was installed on the engine and engine run in PCCI combustion mode. Evaluation occurred over a range of load points and conditions (feasible for PCCI operation) to determine the accuracy and the time of SOC determination. These response times and accuracies were compared to the specifications and found to be in good agreement.

Task 2.7: Phase II Project Management and Reporting.

This task covered the project management and reporting requirements of project as well as oversight and management of the team. This task included the reporting requirements of the DOE, as well as the communication necessary to ensure the team is working constructively together. Also included is the budget tracking and resource allocation for the project.

The following were success criteria for the Phase II-A effort, which were met on a technical front but not a business development front, as a commercialization partner was not obtained in time.

1. The algorithm must robustly detect SOC during transient engine operation as well as handle detecting SOC for multiple cylinders.
2. Real-time operation on rapid prototyping platform must occur well before next combustion cycle.
3. SOC system must be able to detect PCCI start of combustion.

Table 3. Comparison of Phase II-A results with Objectives

<i>Phase II-A Objective</i>	<i>Outcome</i>
Confirm engine to engine repeatability	Proven by running the same 5 load/speed points on 3 different engine platforms (WSU dyno, TIAX dyno, and TIAX Jeep)
Determine algorithm feasibility with knock sensor	Knock sensor data works well with the algorithm
HCCI combustion	Algorithm was shown to work well for HCCI combustion using HCCI data taken at WSU (4 load/speed combinations)
Real time algorithm feasibility	Written but not run yet due to software/hardware uncertainty (currently being addressed by TIAX)
Firm up IP position (requirement from TIAX management to approach potential partner)	HCCI, transient, engine to engine repeatability, and real-time algorithm know- how all contribute to IP
Obtain commercialization partner	Initial contact made with many Tier 1s.

Figure 8 highlights the actual timeline of Phase II-A. The technical work of developing the SOC sensor system was completed in December 2008, and the results were communicated to the DOE in January 2009. After that time, technical work halted and efforts were focused on obtaining a commercialization partner.

Figure 8: Phase II-A Project Timeline

The overall program plan of the entire project from Phase I to commercialization is shown in Figure 9. One caveat of such a plan is the acceptance of HCCI engines as a viable technology. Although SOC sensing is a key component to enable HCCI, the surround technology (such as powerful ECUs, variable valve mechanisms, and fast response EGR) that makes HCCI a reality has to be in place. The five year plan shown in the Figure assumes that the surround technology is in place.

Major Steps	Year					Goal
	Y 1	Y 2	Y 3	Y 4	Y 5	
Completed Phase I and II						SOC Sensor and Feedback Control unit that is ready for dyno demonstration and testing.
Transition from prototype to first HD engine platform						Develop an engine-specific SOC application by designing components and embedded controller for min. cost and max. robustness
Limited run of six vehicles tested by OEM customers						Support OEM's new HCCI vehicle platform by establishing SOC system as a market leader with HCCI as a competitive advantage
Expand SOC to other HD engine models						Proliferate SOC technology to other HD engine platforms and seek potential licensees
Expand SOC to light duty engine platforms						Implement SOC technology on automotive HCCI platforms

We are here
(Phase II-A)

Figure 9. Overall goals and timeline of project

4.1. Commercialization Path for SOC Sensor

A successful SOC prototype will attract attention of HCCI engine developers. Using externally mounted accelerometers represents a new opportunity to develop a practical and non-intrusive combustion feedback approach for Homogeneous Charge Compression Ignition (HCCI) engines, the control of which represents a major technical hurdle to the widespread use of HCCI combustion. Looking ahead to the end of Phase 2 of this project, let us assume that the team will have demonstrated a fully functional low-cost SOC sensor based on signals picked up by accelerometers mounted on the engine casing. Assuming the successful development of a SOC sensor after Phase 2 of this program, what comes next? Obviously the HCCI engine will require several other challenges to be overcome beyond just the means to control combustion phasing. Therefore, in parallel to this program, it can be assumed that the engine manufacturers will be intensely attempting to solve such problems as light load HC/CO, cylinder to cylinder variability, noise, and transition between modes of operation. During our project we will conduct regular briefings to the industry on the SOC sensor status and progress. The engine manufacturers will be in need of a functional SOC sensor such as the one to be developed here, since it would enable feedback control of the combustion event using VVT or fuel injection adjustments.

The reason the HCCI engine is so important is the impact it might have on both fuel economy and low emissions. The concept of HCCI combustion has been in existence and researched for well over 25 years, with the first paper on the subject published in 1979 by Nippon Clean Engine Research Institute Co members [34]. This technology was identified to have the potential for fuel economy improvement as well as NO_x reduction. HCCI is essentially a hybrid between Diesel and Gasoline Combustion processes, and in well-controlled instances combines the positive aspects of both combustion methods. HCCI can have Diesel-like thermal efficiency without the Diesel particulate emissions (because there is no locally fuel rich combustion), and low NO_x emissions due to low in-cylinder temperatures. The significance of this opportunity is that HCCI could be successfully implemented on the millions of cars and trucks on the road in the United States (after full market penetration). This could save 10-15% of gasoline used in the automotive sector while still allowing US automakers to keep gasoline and diesel engines and save multi-billion capital investments in hybrid cars and other less efficient solutions.

The sequence of steps that a Tier One supplier would follow is described next.

(1) Implementation of prototype SOC on Initial HD Engine Platform:

Following the Phase 2 program, the supplier will dedicate the necessary resources required to develop a pre-production version of the SOC prototype feedback control system suitable for a specific OEM or HD diesel engine supplier who was in the process of rolling out HCCI and needed the SOC as a critical enabler. In particular, The Tier 1 will provide the technical expertise required for designing the SOC sensor components and converting the prototype controller to an embedded control system. This effort will be focused on minimizing production, installation, and maintenance costs while maximizing robustness on the engine.

The Tier 1 will then arrange for production of these sensor components and the embedded controller. Once components are produced, The Tier 1 will assemble and test the units on a dyno and work with the first customer (OEM or engine supplier) to define key operating regimes on the torque-speed map and tune the EMS to meet emission and bsfc goals. This would lead to a limited “beta” test run with the sensor installed on four to six vehicles. Once that was successful, The Tier 1 would help the engine supplier get the HCCI engine certified by the EPA and other agencies. The total time expected for this portion of the commercialization process is approximately two years including vehicle endurance testing.

The next step would be installation of the HCCI package including the SOC sensor system on a production run of a certain HD engine model (say 5000 HD units).

These initial installations will also allow The Tier 1 to be first to market with SOC technology and, therefore, gain a competitive advantage over other first-tier suppliers. As a matter of natural course, this will spawn competition among the other suppliers, who will seek to remain competitive in this market by either developing their own SOC technology or licensing the technology developed here. In either case, the establishment of The Tier 1 as a market leader with a significant competitive advantage as a result of SOC will result in a proliferation of this technology within this HD market segment. The total time expected for this portion of the commercialization process is approximately two years from the introduction of an HCCI engine.

(2) Success in the HD Truck Engine market would position the SOC sensor for automobiles:

Most observers expect heavy-duty HCCI engines for trucks and buses to emerge first, perhaps in the 2010-2015 timeframe. Then somewhat later the HCCI engine may become feasible (including affordable price points) for light-duty vehicles (perhaps in 2012-2020 timeframe). The impact of phasing in HCCI engines in the HD and light-duty automotive sectors over the next twenty plus years would be quite significant; since these sectors currently accounts for more than half of all U.S. petroleum consumption. Higher fuel prices combined with new CAFÉ standards (and perhaps the proposed state greenhouse gas reduction legislation), combined with the 2010 emission standards (and future even tighter standards) will prompt engine researchers to implement hybrid powertrains and HCCI advanced engine systems. The realization of the economic benefits offered by HCCI technology in the automotive sector is quite likely because the market pathway for HCCI will be straightforward and near-term in comparison to other options. Specifically, the capital commitment required to convert an existing engine assembly line to HCCI is modest. Not only does this reduce the risk for the OEMs, but it will also foster rapid adoption and competition from small and large companies alike. We plan to take advantage

of the pre-existing infrastructure for engine and automobile manufacturing. This approach will minimize the timeframe for realizing the economic benefits of HCCI.

The commercialization sequence for SOC sensors (see above) will be readily implementable at low risk. As an add-on to new HCCI engines, the SOC sensor feedback control system will have a low incremental ex-factory cost (perhaps \$1 to 2 per kW) even at modest sales volumes. The low cost will open the market for HCCI to companies of all sizes, ensuring that the penetration and economic benefits of HCCI will not be limited by the availability of HCCI engines from a few large companies. Instead, the cost-benefit trade-off associated with HCCI for automotive applications will enable companies of all sizes to compete in the marketplace. This will ensure that the penetration and, thus, the economic benefits of HCCI are maximized.

By leveraging the existing engine-production factory infrastructure for conventional reciprocating engines, the economic benefits of HCCI will be realized in a near-term timeframe. Such use of the existing infrastructure circumvents the “chicken-and-egg” dilemma that has limited the penetration of fuel cells and other alternative technologies, which require unique manufacturing methods, distribution, maintenance, and/or unique fuel additives. Thus, we expect that the economic benefits associated with SOC sensor and HCCI technology will begin to be realized within two years of introduction. Once proven in use, the compelling economics outlined above will serve as the impetus for further penetration and realization of significant and widespread economic benefits.

We have anticipated certain potential risks and, working with The Tier 1, we can adapt the commercialization strategy to overcome these risks. The principal risks we face are that:

- Breakthrough advances in spark-ignition and diesel-injected engines eventually might displace HCCI or diminish its attractiveness. In any case, the market for DG is so vast that there will be room for several technologies.
- Competing SOC technologies including advanced low-cost durable cylinder pressure sensors might be developed in the same timeframe.

Once the HCCI technology has been successfully integrated into the first HD diesel engine platform, The Tier 1's position as a market leader will be leveraged to distribute SOC sensor feedback controls to other HD diesel HCCI engine platforms. Following such HD vehicle demonstrations, the SOC technology will be taken to the light duty automotive sector (not only diesel fuel HCCI engines but also GDI engines with HCCI). The timeline indicating the expected duration of each of these commercialization phases is shown in Table 3, and a description of each phase is also included below.

Table 3. Commercialization Timeline for SOC Feedback Control Technology

Major Steps	Year					Goal
	Y 1	Y 2	Y 3	Y 4	Y 5	
Proposed program						SOC Sensor and Feedback Control unit that is ready for dyno HCCI demonstration and testing.
Transition from prototype to first HD engine platform						Develop an engine-specific SOC application by designing components and embedded controller for min. cost and max. robustness
Limited run of six vehicles tested by OEM customers						Support OEM's new HCCI vehicle platform by establishing The Tier 1 SOC system as a market leader with HCCI as a competitive advantage
Expand SOC to other HD engine models						Proliferate SOC technology to other HD engine platforms and seek potential licensees
Expand SOC to light duty engine platforms						Implement SOC technology on automotive HCCI platforms

(3) Diffuse SOC Technology Through Licensing:

Building upon the establishment of The Tier 1's competitive advantage and the subsequent market demand for proliferation of the technology, the team will license the SOC technology to industry stakeholders. This approach will provide stakeholders with the fastest path to market by obviating the need for an HCCI technology development program. A dedicated effort to license SOC technology will further ensure that the supply of HCCI-based engine units will keep pace with the growth of the market.

Finally, through this aspect of the commercialization plan, The Tier 1 will actively seek to extend the technology beyond the currently envisioned vehicle application. Specifically, we will approach potential licensees in the marine, construction and locomotive industries. HCCI technology is currently being considered as a low emission, fuel efficient alternative in each of these applications, and it is anticipated that the technology developed under the proposed program will be extensible to these areas.

4.2. Benefits to the Nation If Successful***Energy Savings from HCCI Engines enabled by SOC Sensors***

HCCI engines are remarkable in that they potentially can meet future emission standards with an increase in fuel economy and with lower exhaust after-treatment costs (systems such as SCR may not be needed or could be downsized). It can be assumed that if successful HCCI engine platforms become available, sales would ramp up faster than recent hybrid vehicle sales and reach 40% of HD engine sales (approximately 1.2 million per year) and 20% of light duty engine sales (approximately 3 million per year) by 2015. Based on this scenario, the installed base of HCCI vehicles in the target applications would reach 21 million vehicles in the U.S. by the year 2020. Even recognizing the high range of uncertainties associated with such projections, it can

be reliably projected that the successful HCCI engine development would greatly enhance the prospects for approaching such market penetrations. On a national basis, the fuel savings associated with the increase in HCCI-equipped vehicles (due to the higher efficiency of HCCI technology) could be well in excess of 10% of the nation's transportation fuel usage (i.e., 10% of 17 quadrillion BTU) by the year 2020.

Environmental Benefits from HCCI Engines enabled by SOC Sensors

It is likely that 2010 emission standards will somehow be met on schedule by the industry, but it is not a foregone conclusion. The future availability of an SOC sensor would greatly enhance that prospect as well as positioning the engine suppliers to phase in superior HCCI technology in the 2012-2020 timeframe. Using the penetration scenario assumed above, successful HCCI engines enabled by the proposed SOC sensor could achieve or exceed the most stringent emission targets which are in place today. This achievement would translate to 90% reduction in NOx emissions and over 95% reduction in particulate for the HCCI-equipped subset of the fleet.

Economic Benefits

There is a widespread view in the transportation industry that the transition to HCCI engines in trucks and automobiles could lead to major economic benefits to the nation, OEMs, and consumers. Our analysis indicates, however, that for these benefits to be realized in practice the HCCI (and SOC) technologies must achieve stringent cost/performance targets – the two most important being:

1. Achieving affordable cost (under \$150/kW for HCCI and \$1-2/ kW for SOC sensor) on a vehicle ex-factory installed basis (some niche markets can support somewhat higher costs); and
2. A fuel conversion efficiency in excess of 35 % for light-duty engine markets and 45-50% for HD engines to achieve large markets with substantial impacts.

Currently advanced HCCI engine technologies are close to achieving these requirements, but a key barrier among others is controlling start of combustion. The team fully expects the SOC technology to position and enable HCCI engine platforms to achieve these targets in the timeframe of interest.

The economic benefits associated with high-efficiency HCCI engines could be in excess of \$2 billion annually by the year 2020. On a national basis, the increase in HCCI-equipped vehicles due to the higher efficiency of HCCI technology could be well in excess of 20 million by year 2020 (shared by multiple industry participants). The associated direct economic benefits for the US would include:

- Approximately \$6 billion in cumulative SOC control system sales;
- \$2 to \$3 billion in annual energy cost savings to consumers;
- Annual reductions of ~140 trillion Btu in energy consumption and 3 million metric tons in carbon emissions – these benefits would not exist for conventional engines; and
- Large, but difficult to quantify, benefits in enhanced energy security.

The Tier 1 would adjust its business model to ensure it shares in a significant portion of the equipment sales and energy savings benefits. Clearly the stakes are high, providing major incentives to accelerate the HCCI development program.

Savings in aggregate health care costs would be expected from achieving regional air quality targets. As part of the 2010 Emissions Standards setting process for vehicles, the EPA provided estimates of billions of dollars in benefits related to lowering respiratory problems caused by particulate emissions in non-compliant urban regions. These benefits relate to correcting lost work hours, raising productivity and lowering medical costs.

Successful commercialization of HCCI for vehicle engines will be “pathbreaking” and have substantial economic benefits to the rail and marine industry and to U.S. export markets. Once the HCCI challenges are met using SOC sensors for diesel engines for truck, bus, and automobile applications, the benefits could become available for rail and marine engines. Therefore, the potential economic benefits is significant, especially when taking into account the boost to U.S. engine exports.

4.3. Economic Viability and Customer Attractiveness

The shift in sales away from low mileage models following the run up in gasoline prices in late 2005 showed that customers are not completely oblivious to fuel economy. The market for new cars will readily embrace HCCI engines that boost fuel economy by 15-20% and thereby save customers \$150 to \$250 per year in fuel (assuming in 2006 dollars the fuel price at the pump is about \$2.50 to \$3.00 per gallon when HCCI engine equipped vehicles are offered). The fuel for HCCI may be gasoline, diesel or a new “HCCI”-fuel. The SOC sensor must be able to be implemented at prices comparable to the knock sensor, and if so the economic viability should be compelling. In the heavy duty sector, HCCI diesels when offered in 2010-2015 are expected to create immediate demand even at modest premiums because fleet owners and operators are intently focused on improvements in truck mileage, and purchase decisions are made with other factors such as style and vehicle image ranked lower than economics.

TIAX has contacted twenty three OEMs and Tier 1 suppliers, as summarized in Table 4. Three have expressed definite interest and sample support letters have been sent, seven are still being contacted for further discussion, and the other thirteen has stated they have no interest or have not replied.

Table 4. Potential Commercialization Partners Contacted (up to date as of January 31, 2010)

[Table contained in Appendix A—Limited Rights Data]

3 Project Activities

3.1 Phase I—Feasibility Assessment

In the initial portions of the effort, TIAX worked to develop and improve algorithms to take the accelerometer data and convert it back to the forcing function which caused it. An example of one such algorithm is shown in Figure 10. This data is from an engine block, and the forcing function is shown on the left which shows the impulse function used to generate the vibration.

The vibration through the block is picked up via the accelerometer, the signal of which is shown in the center picture. The final picture on the right shows the results of the developed algorithm being applied to the accelerometer signal. The reconstructed signal has the key main features of the forcing function.

Figure 10. Application of developed algorithm

3.1.1 TIAX Experimental Setup

Once initial algorithms had been generated, the next steps of the program were to record engine data and investigate promising ways to determine the SOC. If possible, it was desired to greatly improve the accuracy of the algorithm or change the algorithm to more accurately determine the SOC. This desire was realized, as the initial algorithm developed in the prior work was found not to be robust as desired across engine platforms or as accurate.

To accomplish the testing needs of the project, an engine was needed that would be able to run in HCCI mode. Since the aim of the project was not to design an HCCI engine but focus on an accelerometer based SOC detection method, the path of least resistance to an HCCI engine (which is not commercially available) is a Diesel engine. Diesel engines have a high compression ratio, which readily fosters HCCI, as well as the capability for high rates of EGR, which aid in increasing the cylinder charge temperature and enabling the auto-ignition of HCCI to occur. Originally Wayne State University was planning to use a single cylinder research engine, but due to a hardware failure on that engine, the test engine was shifted to another model. TIAX and Wayne State looked at the available engines, and decided upon a VM Motori Diesel Engine. The specifications for the engine are shown in Figure 11. Jeep Liberty Diesel Engine Specifications. This engine has a high compression ratio, EGR capability, and is a multi-cylinder model that allowed for the team to test the SOC sensing capability on multiple cylinders.

	Specification
Engine type	VM Motori I4
Bore and Stroke, mm (in)	94 x 100 (3.7 x 3.9)
Displacement, L (CID)	2.8 (171)
Compression ratio	17.5:1
Valve train	Belt Drive DOHC 16 valve
Fueling System	1600 bar Common Rail Direct Injection

Figure 11. Jeep Liberty Diesel Engine Specifications

A Jeep Liberty Common Rail Diesel (CRD) engine was purchased by TIAX, and Wayne State was able to use its industry contacts to obtain an engine as well as have access to a development ECU. Because of IP reasons, TIAX was not able to obtain access to a development ECU, which meant that parameters could not be changed on the TIAX engine to allow it to run in HCCI mode. This engine is the same model engine that Wayne State University has set up in parallel, allowing testing for the engine to engine repeatability of the SOC detection system. A photograph of the engine setup at TIAX is shown below in the TIAX Engine Test Facility. Because of TIAX not being able to access the ECU, a further difficulty was found in the engine installation. A stock engine controller was used, and because of the vehicle security features, the engine would idle for about 30 seconds, then shut down. Upon further investigation, it was determined that either a development controller had to be obtained, or a vehicle had to be purchased. Reaching out to OEM contacts (including our Tier 1 subcontractor who has had experience with similar engine controllers) to determine the root of the controller problem (with DOE input and aid), it was determined that the only available option was to obtain a vehicle. TIAX purchased a Jeep Liberty diesel-equipped vehicle to instrument and provide test data to complete the project, as well as use to overcome the security system barrier.

¹ Figure from Jeep Liberty Website.

Figure 12. Photograph of Jeep Liberty Engine in TIAX's Engine Test Facility

The final TIAX dynamometer setup included the body control module, the ECU, and required a key transponder to run. These electronics are shown in Figure 13. The interface between the engine controller and the body control module is over the Controller Area Network (CAN), which adds complexity to the system and complicates the setup.

Figure 13. Engine Control Unit (ECU) and Body Control Module

The Jeep Liberty vehicle equipped with a diesel engine served as a third testbed, as well as providing access to the modules necessary to solve the security system issues with the engine mounted on the TIAX dynamometer. The engine in the vehicle has been instrumented with accelerometers (see Figure 14). In parallel, the modules were used to “clone” the vehicle on the testbed to get the dynamometer-mounted engine to operate.

Figure 14. Labeled instrumentation of vehicle testbed

Mounting instrumentation in the vehicle testbed also gave valuable insight as to performance of the SOC algorithm during realistic driving conditions with the additional vibrations associated with the vehicle itself. The SOC sensor instrumentation itself is difficult to see in Figure 14 as it is mounted out of sight on the exhaust side of the engine block two inches below the manifold opposite cylinder #4 (please refer to Figure 16 as well).

3.1.2 Wayne State Experimental Setup

In their test facility in Detroit, MI, WSU used their identical test engine to generate diesel data that has been sent to TIAX for analysis to test the various algorithms. A photograph of the WSU engine is shown in Figure 15.

Figure 15. Photograph of Jeep Liberty Engine in Wayne State University's Engine Test Facility

For reference, the instrumentation of the WSU engine is shown in the diagram in Figure 16. These sensor placements have been duplicated in the TIAX setup (vehicle engine), as well as a third accelerometer to further compliment the data gathered.

Figure 16. Schematic of Accelerometer Locations on the WSU Engine²

While TIAX was involved in setting up the dynamometer engine as well as instrumenting the Jeep Liberty vehicle, Wayne State University generated data using their commissioned engine, and TIAX worked with the reconstruction algorithms. A sample of the data is shown below, where a pressure trace is shown in the top graph, and data from the accelerometers is shown in the graphs below the pressure. It may be seen from that not only are the combustion events linked to the cylinder pressure traces (from cylinder 4) shown up in the accelerometer traces, but the combustion events from the other cylinders show up as well in the accelerometer traces. This bodes well for the sensor placement, and TIAX is currently examining the data algorithmically to test the algorithms described above.

At the request of TIAX, Wayne State generated the following test matrix of points representative of standard engine operation (shown in Table 5). The motoring trace was useful during the baselining of the engine noise as recorded with the accelerometers as well as during the heat release analysis.

² Diagram provided by Wayne State University

Table 5. Wayne State Engine Test Matrix

Engine Speed (RPM)	Engine Load (% maximum torque)				
	Motored (-)	Idle (0%)	20%	40%	60%
1100		✓			
1200	✓		✓	✓	
1550	✓		✓	✓	✓
1650	✓		✓	✓	✓

3.1.3 Heat Release Analysis of Combustion Traces for SOC Determination

For comparison of the SOC results from the accelerometers, the pressure traces recorded during the engine testing were processed by first law analysis for the heat release. In this engine, there are two pilot injections and then a main injection. Based upon these heat-release shaping injection events, the main combustion actually occurs later in the cycle, making the combustion more HCCI-like.

Figure 17. Example of heat release analysis

Shown in Figure 17 is the process completed for each cycle of the data to determine the SOC from the pressure trace as a comparison to the SOC determined from the accelerometer data, which is computed completely independently. There are two pilot injections prior to the main

injection event, and the SOC (shown by the black triangle at 1% MFB) occurs slightly before Top Dead Center (TDC). The combustion is late combustion, as evidenced by the second “hump” in the pressure trace, and the rate shaping of the combustion may be seen from the inflection in the mass fraction burned curve.

3.1.4 Start of Combustion Determination from Accelerometers

[Text contained in Appendix A—Limited Rights Data]

Examples of applying this method to both high-load (60%) and low-load (20%) load cases are shown in Figure 18 and Figure 19, respectively. The Start of Combustion calculated from the heat release analysis (chosen to be 1% Mass Fraction Burned) is shown with the red circle on all three curves. The green circle, shown on the accelerometer plots, is the SOC determined from the method described above. The pressure trace was only used in the heat release analysis; only the accelerometer data was used to determine the green circle SOC. As may be seen, there is good agreement between the two methods for both high and low load.

Figure 18. 60% Load Pressure and Accelerometer Traces with SOC identified

Figure 19. 20% Load Pressure and Accelerometer Traces with SOC identified

Applying this method over many cycles shows it to be a robust method. A histogram of the high load points is shown in Figure 20, and this Figure highlights excellent accuracy and shows promise for a feedback control method. The vast majority of the points fell only two crank angle degrees from the actual value.

Figure 20. Histogram of the high load SOC error

Lower load will obviously present more of a challenge, as the signal to noise ratio of combustion to background noise is much lower. Despite this, the algorithm (power amplitude change) still shows promise, as evidenced in Figure 21. The error amounts shows promise to still provide valuable feedback to the engine controller to determine when the combustion event occurred.

Figure 21. Histogram of the low load SOC error

(Note: Error is systematically positive by ~ 2-4 degrees)

A special concern with acoustically based SOC detection systems is the interference of acoustical noise as well as false detection from other noise producing events, such as valve closings. Plotting out the valve events for the inline four cylinder used in this program, it is seen that the valve events of other cylinders do not interfere with SOC detection. This is highlighted in Figure 22.

Figure 22. Comparison of SOC detection with valve events of other cylinders

Because of small changes in RPM, temperature, and airflow, the injection timing varies slightly as the ECU interpolates in the injection timing map. This causes some variation in injection timing, even at steady-state points. It is interesting to look at an overlay of many cycles, as shown in Figure 23, as the variation in injection timing can be seen as a spread in data points. The robustness of the SOC detection method is highlighted from the spread of the SOC detection points echoing the spread of the injection timing points. The difference in Crank Angle of the two points is from the fact that the SOC from accelerometers is detecting the combustion noise of the combustion event, and the Heat Release analysis is detecting the point at which 5% of the fuel has already been combusted.

Figure 23. Comparison of SOC and 5% Burned over 90 engine cycles

The algorithm also shows promise to work for detection of SOC in all of the cylinders of the engine. This is important to minimize the cost of the system, as the less sensors that are used, the less the system will cost. Conversely, there must be enough sensors on the engine to accurately detect the SOC event. Based upon the results, it appears that for an inline engine, there can be one less accelerometer than cylinder. So for an inline four cylinder engine, three sensors appear to be adequate. This value may change for the specific engine type. Shown in Figure 24 is the detection of four cylinder SOC events from three sensors.

Figure 24. SOC detection in four cylinders from a set of three accelerometers

Applying this system to SOC detection for the engine at a variety of speed and load points is shown below in Figure 26. The results are excellent for 1100, 1400, and 1600 RPM. However, the 1800 RPM point was taken at a very low load condition, so the combustion signal to external engine noise ratio is very low. Better hardware filtering (as done in Phase II-A resulting in an improvement in SOC detection) and an adaptive filter will likely improve the results. Also, the source of error exists in the SOC taken from the pressure trace, as even the 5% MFB point has an estimated error of 1-2 CAD.

Figure 25. SOC detection system results for multiple speed and load points

3.1.4.1 Application of Algorithm for Multiple Engines

The robustness of this algorithm was tested by feeding accelerometer data from the WSU engine and the TIAX engine into the same algorithm. It was found that the algorithm was able to detect the Start of Combustion for both engines. An example of such data is shown in Figure 26. The top two graphs are the pressure traces measured with pressure transducers (for similar data points), and the bottom graph is the accelerometer data. The top graph has green circles highlighting the SOC derived from the algorithm (the red asterisk is the SOC determined from the heat release rate), and the middle graph contains green circles highlighting the SOC. Comparing the two pressure curves (which are different cycles from similar operating points, so are not exact matches), the green circles (the SOC determined from algorithm fed with accelerometer data) show SOC to be at the correct location for both engines.

Figure 26. Comparison of algorithm for multiple engine platforms (TIAX in-vehicle engine, top graph; WSU engine, middle graph; WSU accelerometer, bottom graph)

The next step of the project is to take the algorithm to a real-time platform to evaluate the response time and accuracy of the system as the engine is running. Shown below is the Simulink block diagram of the algorithm. During Phase II, this algorithm will continue to be improved and vetted, as there were some minor changes in taking the algorithm from an offline to an online version. The Simulink code can readily be compiled to run on real-time rapid prototyping hardware.

[Figure contained in Appendix A—Limited Rights Data]

Figure 27. Simulink block diagram of the real-time algorithm

3.2 Phase II-A HCCI and Multiple Engine Testing

The second Phase of the project followed the project plan and took the technology one step closer to commercialization. During this phase, PCCI combustion was achieved, as well as robust comparison between three engine platforms operating at the same load point in Diesel mode. The algorithm was further refined during this Phase as well, resulting in even higher accuracy than shown in Phase I.

Figure 28. Locations and types of accelerometers tested

TIAX has mounted accelerometers as well as a commercially available knock sensor on the engine to record a full range of data to ensure algorithm robustness. Using the knock sensor allows the team to determine the production feasibility of the system, as the prototype would be similar to a knock sensor. The mounted sensors are shown in Figure 29.

Figure 29. Photograph of the mounted accelerometers and knock sensor. NOTE: front of engine to the right

The testing of the commercially available knock sensor showed the excellent commercialization potential of this SOC detection system. A broadband knock sensor was used, the specifications of which are shown in Figure 28, and was mounted as shown in Figure 29. The engine was run and the resulting accelerometer traces were recorded. The excellent agreement both in location and duration of the vibration event is shown visually in Figure 30. The algorithm agrees with the visual comparison—it is able to process raw data from both the research-grade accelerometer and the knock sensor equally well.

Figure 30. Comparison of knock sensor signal to research grade accelerometer signal

The final technical aspect of Phase II-A was to test the SOC detection system using PCCI combustion as opposed to the diesel combustion that had been used up to this point. It was also desired to address the limitations shown in the work done before this project, that of using lower-load points where the signal to noise ratio of the combustion event to the background engine noise was relatively low. At the same time, it was desired that these points be realistic and representative of actual points that would be seen over realistic drive cycles. Based upon modeling work done by TIAX of the diesel Jeep Liberty over the FTP-75, points were chosen that fell into the operating map of the engine during this drive cycle. Both the diesel points highlighted earlier in this report as well as the PCCI points fit that criterion. Shown in Figure 31 is the model generated engine operating map and where the engine operates during the drive cycle (on the left side of the figure). Shown on the right side of the figure is where the points fall that were tested during both Phases. The Tables included in the Figure explicitly reference the speed and load conditions.

Figure 31. Data points tested on both engines and shown on engine operating map

As mentioned earlier, careful selection of the engine was done to readily enable PCCI operation. As TIAX did not have access to the proprietary development ECU but Wayne State did, the PCCI operation was carried out at Wayne State University. TIAX traveled to the test cell and oversaw the testing. Hardware limitations were minimal—Wayne State had earlier modified the EGR system inlet to a point further upstream to promote better mixing with the intake air and minimize cylinder to cylinder variation, but the EGR valve remained the same as the stock configuration. PCCI operation was accomplished but large amounts of EGR to raise the intake air temperature and using early injection (20 deg BTDC). Injection any earlier than this point resulted in high amounts of wall wetting as evidenced by excessive amounts of hydrocarbons in the exhaust stream. This was due to the design of the fuel injectors having a very shallow cone pattern. Figure 32 highlights the minor hardware differences in the EGR inlet, as well as a table highlighting key parameters of the PCCI operating points. Of note are the extremely low NO_x emissions as well as the relatively high efficiency. It should be noted that a different injector design would greatly reduce the excess hydrocarbon production, as there is still a small amount of wall wetting that quenches the hydrocarbons and stops their oxidation.

Figure 32. HCCI engine setup and emissions and efficiency results of HCCI points.

Digging deeper in the data highlights the differences between PCCI/HCCI and standard diesel combustion. These differences are highlighted in Figure 33 by comparing pressure traces and heat release curves for two similar speed/load points. The diesel mode, shown on the left, has the two pilot injections used for rate shaping of the combustion event to reduce noise. It is seen from the heat release curve that it has a very shallow slope during these two events, then after the main injection event, the heat release rate rapidly rises. The accelerometer trace, shown below the other two curves, follows the trend. As the first two pilot injections ignite, there is a spike in the noise, and then as the main injection event occurs there is a large noise event. PCCI, on the other hand, has all of the fuel introduced early in the stroke before the temperature is high enough for autoignition (as done in this project—rate shaping via injections is also possible with PCCI). When that temperature is reached, there is a large ignition event, resulting in a much higher rate of heat release than seen in diesel combustion. This higher rate of heat release is seen both in the slope of the MFB curve as well as the amplitude of the accelerometer trace.

Figure 33. Comparison of diesel and PCCI operation for similar speed/load points

In addition to the PCCI combustion aspect of Phase II-A, careful testing was done with diesel combustion to replicate the same speed/load point for all three engines: the TIAX Jeep, the TIAX dynamometer engine, and the Wayne State dynamometer mounted engine. The Jeep was the initial starting point for the measurements, as the Jeep speed/load points were a function of over the road driving points, and then the two dynamometer setups could easily mimic the points. The same research grade accelerometers were used in the three setups and were mounted in approximately the same positions on the engines. The same algorithm with the same threshold limits was used for all three sets of data, ensuring a fair comparison. These results are shown in Figure 34 through Figure 37. As may be seen from comparing both the points as well as the histogram curves, there is good agreement across all three engines. As in the earlier work in Phase I, the SOC detected by the accelerometers is a few degrees before that of the 5% MFB point simply because the accelerometers detect the noise generated by combustion at its first event, and the 5% burn point is slightly time delayed from the initial onset of combustion. Also, from looking at the offset pressure traces overlaid with the SOC points, it is seen that the SOC system often detects the combustion starting from just the pilot injection, which highlights its sensitivity. Future work would involve tailoring the thresholds to find exactly what event the ECU programmers wanted—the SOC from the pilot injections or the SOC from the main injection.

Figure 34. Comparison of results for three diesel engines at 1122 RPM, 1.4 bar BMEP

Figure 35. Comparison of results for three diesel engines at 1260 RPM, 1.4 bar BMEP

Figure 36. Comparison of results for three diesel engines at 1482 RPM, 3.6 bar BMEP

Figure 37. Comparison of results for three diesel engines at 1572 RPM, 6 bar BMEP

Figure 38. SOC detection for diesel combustion during transient operation.

Of interest as well is the SOC performance during transient operation, as this is the state the engine is always operating in during normal driving—rarely is the engine in a steady state point. Shown in Figure 38 is one such transient event for the engine in diesel operation (programming the engine to work in a transient PCCI mode was beyond the scope of this project). Again, since this is diesel, there are a few crank and degrees between the SOC and the point of 5 % MFB (in this case, about 5 CAD). But it is seen from the height and narrowness of the histogram that the SOC detection method is very robust for this transient.

The final set of results to be discussed is the results for the PCCI testing. Since the PCCI combustion event is much noisier than the diesel event, the SOC detection method worked extremely well, giving 1 CAD accuracy (when the 5% MFB point error is accounted for) over the points tested. This is highlighted in Figure 39.

Figure 39. SOC detection histograms for PCCI combustion

A final concern over the technical feasibility of the developed algorithm is the processor requirements and whether the algorithm would be able to run on a representative automotive grade ECU. As shown in Figure 40, the time appears feasible to allow for rapid actuation of whatever is needed to change engine operating parameters for the next cycle.

By comparing a simple matrix multiplication in MATLAB to the developed algorithm, it is ESTIMATED to require 80-100 million multiplies per second. For an advanced automotive processor, this works out to about 12.5 ms.

Even at a speed of 3000 RPM, this leaves an actuation time of 17 ms

Figure 40. Estimated algorithm actuation time for a representative ECU processor

4 Products Developed

Homogeneous Compressed Charge Ignition (HCCI) has elevated the need for Start of Combustion (SOC) sensors. HCCI engines have been the exciting focus of engine research recently, primarily because HCCI offers higher thermal efficiency than the conventional Spark Ignition (SI) engines and significantly lower NO_x and soot emissions than conventional Compression Ignition (CI) engines, and could be fuel neutral. HCCI has the potential to unify all the internal combustion engine technology to achieve the high-efficiency low-emission goal. However, these advantages do not come easy. It is well known that the problems encountered with HCCI combustion center on the difficulty of controlling the start of combustion.

TIAX has an SOC sensor under development which has shown promise. In previous work, including a DOE-sponsored SBIR project, TIAX has developed an accelerometer-based method which was able to determine SOC within a few degrees crank angle for a range of operating conditions. A signal processing protocol allows reconstruction of the combustion pressure event signal imbedded in the background engine vibration recorded by the accelerometer. From this reconstructed pressure trace, an algorithm locates the SOC. This SOC sensor approach is non-intrusive, rugged, and is particularly robust when the pressure event is strong relative to background engine vibration (at medium to high engine load).

The objective of the Phase I research was to answer two fundamental questions: Can the accelerometer-based SOC sensor provide adequate SOC event capture to control an HCCI engine in a feedback loop? And, will the sensor system meet cost, durability, and software efficiency (speed) targets? Based upon the results the answer to both questions was “YES”.

The objective of Phase II-A was to complete the parameter optimization of the SOC sensor prototype in order to reach a juncture where plans can be and are discussed with an industry partner for how best to perform a more detailed implementation of the TIAX SOC technology on an HCCI engine system. This occurred, as evidenced the number of potential commercialization partners shown in Table 4. Potential Commercialization Partners Contacted (up to date as of January 31, 2010).

This has resulted in a algorithm sensor package that is ready to be tested on a real-time platform for a variety of engines and an expanded operating range than explored during these two Phases.

5 Problems Encountered During the Project and Their Resolution

The engine actual cost was approximately twice as much as had been estimated at the proposal stage, so TIAX could not purchase a second engine to assess engine-to-engine SOC repeatability. The team has devised a work around solution: Wayne State University had a Jeep Liberty CRD engine on hand, and TIAX purchased the same model. This change allows the engine to engine repeatability testing without the requirement of TIAX purchasing two engines. The Wayne State portion of the testing was conducted using the multi-cylinder Jeep diesel engine at their test facility.

The project has been delayed both by hardware procurement delays and funding delays, but was technically on track with data being actively generated and algorithms analyzed, but with the actual end dates being pushed back.

Delays were encountered with both engine setups. Despite these many technical hurdles, the team has generated data and found an SOC algorithm which shows promise. Wayne State encountered a drive shaft failure, and TIAX had difficulty overcoming the security features of the ECU. Wayne State overcame the drive shaft failure by inserting a dual mass flywheel in the driveline. TIAX purchased a diesel-equipped Jeep Liberty vehicle, and successfully cloned the vehicle in the test cell. They also used the vehicle to generate useful test data. The program was brought to a close due to the length of time used in finding a commercialization partner. Internal TIAX decision-making as well as the difficult economic climate contributed to this result.

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