

Steady-State Combustion Development of a Downsized Multi-Cylinder Engine with Range Extended HCCI/SACI Capability

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ABSTRACT

This paper focuses on the combustion development portion of the Advanced Combustion Controls Enabling Systems and Solutions (ACCESS) project, a joint research project partially funded by a Department of Energy grant. The main goal of the project is to improve fuel economy in a gasoline fueled light-duty vehicle by 30% while maintaining similar performance and meeting SULEV emission standards for the Federal Test Procedure (FTP) cycle.

In this study, several combustion modes Spark Ignited (SI), Homogeneous Charge Compression Ignition (HCCI), Spark-Assisted Compression Ignition (SACI) were compared under various conditions (naturally aspirated, boosted, lean, and stoichiometric) to compare the methods of controlled auto-ignition on a downsized, boosted multi-cylinder engine with an advanced valvetrain system capable of operating under wide negative valve overlap (NVO) conditions. The engine was operated under steady state conditions at a constant engine speed of 1500rpm and various loads (2.0 - 6.0 bar BMEP) to investigate the impact of extending the HCCI/SACI operating range and compare the results to traditional SI combustion modes. The HCCI operating mode was tested under lean conditions both naturally aspirated and with mechanically supercharged operation to increase the load range. SACI combustion was examined at both lean and stoichiometric operating conditions, with the use of external cooled Exhaust Gas Recirculation (EGR) for mitigation of combustion noise at high loads.

It was found that the effective load range of naturally aspirated lean HCCI is limited but provides good combustion stability with significant improvements in BSFC compared to the optimized SI combustion mode. Extending the lean HCCI range via forced induction improves the lean capability at higher loads but exacerbates loss mechanisms that reduce overall brake thermal efficiency. Extending the operating range through stoichiometric SACI combustion modes resulted in BSFC improvements at the mid and high load points tested.

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INTRODUCTION

With both emissions standards and fuel economy mandates becoming more stringent in the US in the upcoming years, utilizing the efficiency benefits from advanced combustion concepts becomes important when attempting to improve overall powertrain efficiencies. In recent years, downsizing of engine displacement with turbocharging and direct injection has been a prime-path for many automakers to reduce overall powertrain fuel consumption for traditional SI engines, mainly by operating at higher specific loads to reduce operation in heavily throttled regions and reduce the specific contribution of engine friction. In the US, the

traditional downsized SI concept continues to utilize a stoichiometric and homogeneous mixture due to the high conversion efficiency of three-way catalytic (TWC) convertors and the relatively high costs of lean-NO_x aftertreatment systems required for lean concepts.

It is also well known that HCCI concepts have potential to mitigate pumping losses while maintaining relatively low NO_x emissions during lean operation. However, HCCI operation has typically been limited by combustion stability at low loads less than 1.5 bar net mean effective pressure (NMEP). Ringing intensity (RI) and increasing NO_x emissions at high loads, generally limit HCCI operation to

~4.0 - 5.0 bar NMEP in naturally aspirated engines [1]. To couple the downsized and HCCI concepts, the HCCI operating range needs to be increased significantly in order to capture the benefits in the high frequency operating region during a typical drive cycle, while still maintaining a compression ratio in a range that can allow for high turbocharged specific torque outputs that are traditionally limited by engine knock in SI combustion modes. NO_x emissions and RI must also be carefully managed such that the higher load operation does not exceed the identified system limits.

Early HCCI concepts were mainly concentrated on utilizing external EGR and elevated inlet air temperatures under wide-open throttle (WOT) conditions [2, 3] to achieve high thermal efficiencies at part load conditions. Some recent studies have looked at optimizing the HCCI load range through careful control system management with this approach as well [6], looking at parameter optimization over wide ranges with good success in increasing HCCI load capability. However, many recent efforts have revolved around using variable valve actuation (VVA) systems in order to utilize NVO and early exhaust valve closing to manage the trapped residual gas content [7, 8, 9, 10, 11, 12]. Methods for increasing the high load limit using the NVO HCCI concept have also been recently investigated through means of utilizing boosted air through turbocharging or supercharging [10, 11, 12, 13, 14, 15, 16] and implementing SACI methods [10, 17]. Utilizing boosted air for load extension can help to achieve ultra-lean operation at high load to reduce RI and NO_x emissions to manageable system levels. This study focuses on mechanically driven supercharging rather than exhaust gas turbocharging. Turbocharging was considered in the hardware development, but was not utilized due to the increase in thermal exhaust mass which can increase TWC light-off time, the increased controls complexity of a dual-turbocharged system, the increased transient response times of turbocharged operation, and the increase in system backpressure due to turbocharging.

The SACI combustion mode, with the aid of air dilution or cooled EGR, is effective in reducing peak heat release at higher loads by increasing burn durations and therefore reducing RI [1, 10]. The SACI combustion mode has also shown stable combustion at stoichiometric conditions, and has the added advantage of potentially utilizing the TWC while sacrificing some of the benefit of lean operation. Investigating the air boosting method and SACI method were a large part of the study presented in this paper. Other internal EGR methods include using a re-breathing strategy in which the exhaust valve is opened during the intake stroke to allow for a re-breathing of exhaust gases [18, 19] and positive valve overlap SACI (PVO SACI) [10], which are not included in this study but may be the subject of further investigation.

The goal of the research in this paper is to extend the load range of HCCI operation on a multi-cylinder engine using a NVO strategy to trap residual exhaust gases. This approach is also coupled with the benefit of downsizing and boosting the system to high specific torque outputs, which has not been widely explored but also increases the importance of the load range extension of the HCCI combustion mode to a wider range of the operating map. This system characteristic also forces compromises on increasing compression ratio at the high specific torque outputs due to engine knock in SI mode.

The target application for the ACCESS engine is to replace a naturally aspirated 3.6L port fuel injected (PFI) engine in a Cadillac CTS with a 6-speed transmission. Early drive cycle simulations produced an operating region within 1200 - 2500 rpm and 2 - 6 bar BMEP in which the ACCESS engine will operate most frequently (ignoring idle operating points) over the Federal Test Procedure (FTP) city cycle. The research presented in this paper explores the range of the engine operating map shown in focusing on the following:

- Naturally-aspirated HCCI lean of stoichiometry at WOT conditions using a two-step valvetrain to achieve NVO conditions, with a focus on improving brake specific fuel consumption (BSFC) while maintaining RI and NO_x emissions below system limits.
- Utilizing a mechanically driven supercharger to achieve highly dilute conditions in order to reduce RI and NO_x emissions in HCCI operating mode while minimizing BSFC increases due to mechanical energy losses to the supercharger.
- Comparing range extension of lean boosted and naturally-aspirated HCCI operation with that of the SACI combustion mode in both lean and stoichiometric conditions at WOT, and with the use of cooled EGR as a diluent for RI control.
- Investigating the full load capability of the downsized engine in order to evaluate the acceptability of the target vehicle performance.

These investigations were all performed on the same multi-cylinder, downsized, turbocharged direct-injection engine equipped with a two-step valve train. The majority of testing was performed using Indolene fuel, however the effects of using a lower octane 87 AKI E10 fuel was also investigated.

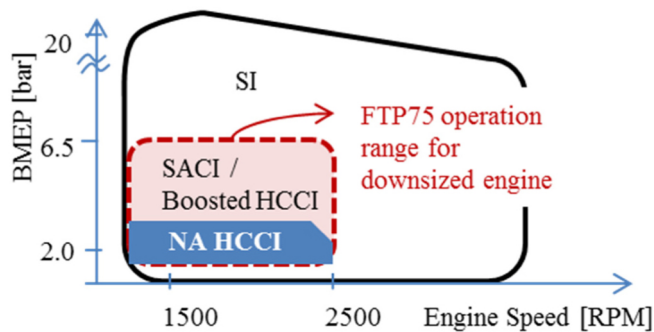


Figure 1. Operating Range of Optimization Based on FTP Drive Cycle Analysis of ACCESS engine in Cadillac CTS

The various results sections in this paper focus on the following topics which address each of the combustion modes found in and the integration of these modes into an overall strategy:

- Multi-Mode Combustion Heat Release Characteristics
- Naturally-Aspirated HCCI Combustion Strategy
- Boosted HCCI Combustion Strategy
- SACI Combustion Strategy
- Full Load SI Capability
- Multi-Mode Combustion Strategy

EXPERIMENTAL SETUP

Engine Hardware

All of the experiments performed in this study used a modified General Motors 2.0L in-line four-cylinder Ecotec turbocharged engine equipped with direct injection. The engine geometry is listed in [Table 1](#).

The cylinder head was modified from the production configuration to accommodate a two-step valvetrain system provided by Delphi, to move the direct injection location to centrally mounted in the combustion chamber, and to add a wide-range Denso electric cam phaser. The Delphi two-step hardware includes oil control valves and roller finger followers to enable variation of the cam lift via a 3-lobe cam. The center lobe on each cam consists of the traditional SI high lift cam profile and the two outer lobes are the much lower valve lift profiles required to achieve NVO for HCCI combustion. The valve lifts and durations are shown in [Table 1](#) and [Figure 2](#) for both high and low lifts and for both intake and exhaust valve lift profiles. The Delphi roller-finger follower mechanism includes a slider follower in the center and roller followers on the outside of the follower arm. For this project, the roller-finger followers are configured such that the low lift cams are operated by the outside roller followers in standard operation and default pressure mode. The high lift cam is inactive since the slider follower is not

fixed in place. When high lift is desired, oil pressure is increased to the RFF through the hydraulic lash adjuster via the oil control valve solenoid. A locking pin within the body of the follower arm then fixes the slider follower such that only the high lift cam is functional.

Table 1. Engine Geometry and Specifications

Displacement Volume (L)	2.0
# of Cylinders	4
Number of Valves per Cylinder	4
Head Design	Pent-roof
Bore (mm)	86.0
Stroke (mm)	86.0
Connecting Rod Length (mm)	145.0
Compression Ratio	10.8:1
Valvetrain	DOHC + 2-step
Intake Valve Lift – High/Low (mm)	10.3 / 4.0
Exhaust Valve Lift – High/Low (mm)	10.0 / 4.0
Intake Valve Opening Duration – High/Low (CAD)	276 / 134 @ 0.1524mm lift
Exhaust Valve Opening Duration – High/Low (CAD)	262 / 132 @ 0.1524mm lift
Injector Type	Multi-Hole Solenoid
Number of Fuel Injection Nozzles	6
Injector Static Flow Rate @ 100bar n-Heptane (cc/sec)	15.0
Maximum Injection Pressure (bar)	200
Direct Injector Location	Central

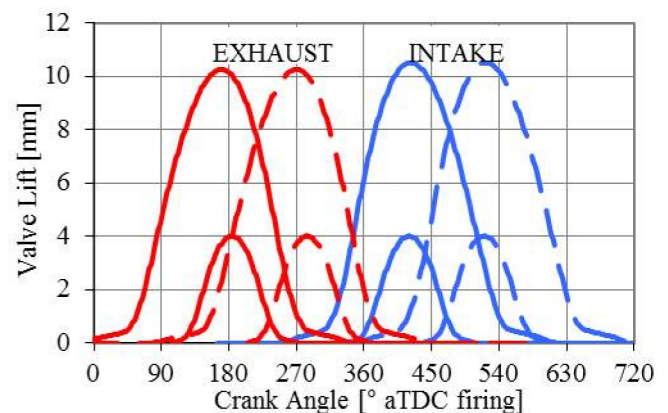


Figure 2. Valve Lift Profiles for Low and High Lift Cam used with the 2-Step Valvetrain and Electric Cam Phasers

The electric cam phasers on both intake and exhaust enable a 100°crank angle phasing range which is required for the extreme differences in cam phasing angles for high lift and low lift modes. The valve profiles for both high lift and

low lift cams, as well as their respective phasing range are shown in [Figure 2](#). This is now becoming commonly accepted as a highly complex, but production feasible valvetrain system [20] and has been employed previously on NVO HCCI combustion systems [22].

The injector was relocated from the original side mounted position beneath the intake valves to a central location in the combustion chamber mainly to enable optimum split injection strategies during the cold start catalyst heating phase of the drive cycle. The central mount location has also been used in similar previous direct injected HCCI concepts [10, 13, 15] with acceptable homogeneous mixture preparation. The injector used was a 6-hole solenoid HDEV5 direct injector supplied by Robert Bosch, LLC and spray cone targeting was designed specifically for this combustion system and piston bowl design. Fuel injection pressure ranged between 50-150 bar depending on the operating condition and was supplied by the original production cam-driven Bosch high pressure pump. Due to the restrictions of packaging space within the valve bridge cooling jacket area because of the injector relocation, the spark plug size was reduced to 10 mm to remain centrally mounted. Other modifications include integration of a low-pressure EGR system and high-pressure EGR systems, of which only low-pressure EGR was used in this study. The low-pressure EGR system was created by taking the exhaust downstream of the empty TWC canister into the intake system upstream of the turbo-compressor. Flow was adjusted by increasing exhaust backpressure with an electrically-actuated valve downstream of the empty canister.

An Eaton R410 supercharger was integrated into the air system for boosting HCCI at part load conditions and was driven by a belt and pulley system to a crank-driven pulley. The supercharger was integrated downstream of the turbocharger, but also faced a butterfly valve downstream of the supercharger connection to the charge air system, which functioned as a bypass system for the supercharger. The production fixed geometry Borg Warner K04 turbocharger with pneumatically controlled wastegate was used for high output boosting. The exhaust downpipe from the turbocharger to the catalyst was from a 2010 Pontiac Solstice, with the TWC canister emptied to eliminate any risk of catalyst damage resulting from misfire during HCCI development. A manually adjusted butterfly valve was installed downstream of the empty catalyst to simulate system backpressure for a 2.0L turbocharged Ecotec engine previously benchmarked in the laboratory with a vehicle exhaust system. A schematic of the fresh boosted air system is shown in [Figure 3](#).

The engine was controlled by a prototype MED17 engine management system (EMS) controller provided by Robert Bosch, LLC which was used for control of the variable two-step system, electric cam phasing, ignition, fuel injection and throttle control. The ECU communication was configured with an ETAS ES1232.1A card over ETK connection with INCA 6.2 EMS calibration software. The EMS strategy was also complete with closed-loop HCCI load and combustion

phasing control using in-cylinder pressure feedback. The engine electrical harness was highly modified from a 2.0L Ecotec electrical engine harness to incorporate the modified actuators and sensors as well as to allow for non-vehicle operation.

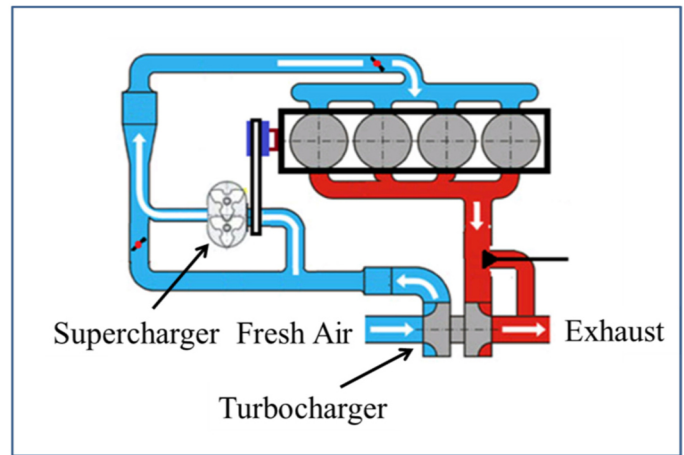


Figure 3. Boosted Air System Configuration

Data Acquisition Systems

In-cylinder gas pressure measurements were collected with AVL GU22CK piezoelectric pressure transducers mounted beneath the intake valves through the cylinder head without any type of flame arresting components. Charge amplification was performed with an AVL MicroIFEM system and signal conditioning was performed with an AVL Indimodul. The crank angle resolved data was collected using an AVL 365C crank angle encoder at 0.2 ° CA intervals for 300 consecutive cycles on each cylinder. All crank-angle resolved cylinder pressure data analysis was completed by applying a 5.5kHz filter on the measured pressure trace. Injector pulse width and ignition coil signal feedback were measured with FLUKE current measurement clamps, which were located on cylinder 1. The intake and exhaust runners of cylinder 4 were instrumented with high-speed KULITE LP11DA piezoresistive pressure transducers, with a cooling adapter on the exhaust side to prevent overheating of the transducer structure.

Exhaust emissions were measured with a sample probe located just downstream of the turbocharger and upstream of the empty catalyst canister. NO_x measurements were completed using a chemiluminescence analyzer, CO was measured with infrared analyzers, and hydrocarbons were measured with a flame ionization detector (FID). Smoke measurements were collected with an AVL415S Smoke Meter to obtain a measure of filter smoke number (FSN). Two wideband exhaust lambda sensors were used for air-to-fuel ratio (AFR) measurements, one for the EMS system control feedback and an independent measurement for the laboratory data acquisition system. AFR was also measured and calculated with gaseous emissions measurements, which

were used for the AFR and lambda measurements reported in this paper. CO₂ in the intake manifold was measured and EGR rate was determined by the ratio of molar fractions of CO₂ in the intake and exhaust samples.

Torque was measured with a 500 Nm full scale HBM torque measurement flange installed in line with the drive shaft to the engine dynamometer. Air mass flow was measured with a laminar element flow device. Fuel flow was measured with an AVL 734 twin balance gravimetric fuel measurement system. Fuel temperature was regulated with an AVL 753 conditioning system to 18°C and coolant temperature was maintained at 90°C water outlet temperature. The intake air system was conditioned to 45% relative humidity and 25°C inlet air temperature. Boosted air temperature was maintained with a BEHR water-to-air charge air cooler and controlled to maintain 45°C inlet manifold temperature at rated power (6300rpm, 168 kW).

Fuel Properties

Two fuels were used for the research presented in this paper: Indolene and 87 AKI E10 (10 %v ethanol) pump grade fuel. Indolene was chosen as it has repeatable tailpipe emissions from a test vehicle and is the certification reference fuel used for the FTP cycle emissions tests. The fuel properties for these fuels are shown in Table 2.

Table 2. Test Fuel Properties

Fuel	Indolene	E10
Research Octane Number	96.5	92.2
Motor Octane Number	88.4	84.4
Carbon (wt%)	86.6	82.6
Hydrogen (wt%)	13.4	13.5
Oxygen (wt%)	0	3.9
H/C Atomic Ratio	1.85	1.94
Stoichiometric AFR	14.57	13.97
Lower heating value (MJ/kg)	42.98	41.19
Ethanol Content (vol%)	0	10
Density (kg/L)	0.743	0.748

Test Procedure

The test procedure consisted of steady state engine operation at the operating points shown in Table 3 with the prototype ACCESS engine. These steady state conditions were selected as falling within the high frequency operating range over the FTP cycle, using a simple drive cycle simulation of the Cadillac CTS equipped with the proposed 2.0L engine in this study. The main combustion modes that were investigated were: lean naturally-aspirated homogeneous charge compression ignition (NAHCCI); lean, air-boosted HCCI (BHCCI); stoichiometric spark-assisted compression ignition (SACI); and traditional spark-ignition (SI). The NAHCCI, BHCCI, and SACI combustion modes

were all performed under wide-open throttle (WOT) conditions. The goal of the testing was to minimize measured BSFC in each of the operating modes while maintaining some of the critical operation limitations.

Table 3. Engine Operating Conditions

Engine Speed (rpm)	BMEP (bar)	Combustion Mode
1500	2.0	NAHCCI, SACI, SI
1500	4.0	NAHCCI, SACI, BHCCI, SI
1500	6.0	SACI, SI
2000	3.0	BHCCI, SI

HCCI was limited primarily to the lower loads due to excessive RI at the higher loads. The RI (MW/m²) limit for this engine was established at a maximum intensity of 5 MW/m², defined by the relation [10, 12] shown below.

$$RI = 2.88 \times 10^{-8} \times \frac{(R_{MAX} \times N)^2}{P_{MAX}} \quad (1)$$

Where R_{MAX} (kPa/degree) is the maximum rise rate of cylinder pressure, N (rev/min) is the engine speed and P_{MAX} (kPa) is the nominal maximum cylinder pressure. This is a generally accepted restriction [10, 12, 21] on pressure rise rate for a production engine based on structural and noise limits using this definition of RI. The maximum coefficient of variance (COV) of NMEP (as measured by integrating over the 720° CA cycle) was limited to 3.0% for an accepted operating condition. Maximum cylinder pressure was limited to within three standard deviations of a 90 bar mean cylinder pressure over 100 cycle measurements, although most operating conditions did not reach this magnitude of cylinder pressure. NO_x emissions for the optimized points were limited to 1g NO_x/kg fuel, in order to minimize the lean-NO_x aftertreatment system required while operating in lean fuel conditions. It was assumed that a TWC had a sufficiently high NO_x conversion efficiency that no NO_x limitations were required at stoichiometric operation. Emission index NO_x (EINO_x) is reported throughout this paper to offer a better comparison to previous light duty HCCI work. [13,14]

RESULTS

Multi-Mode Combustion Heat Release Characteristics

Residual estimation was carried out using an in-house one-dimensional (1D) analysis of the intake, exhaust, and in-cylinder pressures as boundary conditions to the combustion chamber of the instrumented cylinder. The 1D software uses thermodynamic and mass conservation principles to model the gas exchange process, using measured cylinder head port