

Design of a 4-Cylinder GTDI Engine with Part-Load HCCI Capability

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ABSTRACT

This paper focuses on the engine design 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 25% while maintaining similar performance and meeting SULEV emission standards.

A Cadillac CTS with a high-feature naturally-aspirated 3.6L V6 engine was chosen as the baseline vehicle. To achieve the target fuel economy improvement over the baseline engine configuration, gasoline turbocharged direct-injection (GTDI) technology was utilized for engine downsizing in combination with part-load lean homogeneous charge compression ignition (HCCI) operation for further fuel economy gains. The GM 2.0L I4 GTDI Ecotec engine was used as the platform for the basis of this design. The production engine hardware was redesigned to support various combustion system options to be investigated during the engine development portion of this program.

One-dimensional (1D) modeling was used to determine the optimal valve lift profiles, compression ratio and boosting configuration. Fuel economy improvements expected from the new engine design and advanced combustion controls were determined using vehicle simulation.

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INTRODUCTION

Project Objectives

Due to availability and security of energy resources, environmental concerns, and costs factors, the automotive industry is facing the challenge of improving fuel economy and reducing emissions without sacrificing performance. Although there are promising developments in electrification of powertrains with hybrids systems, battery electric vehicles and fuel cell electric vehicles, internal combustions engines are expected to be the mainstream power source of future vehicles for the next few decades. Especially with increased production volume of renewable fuels and optimized powertrain solutions for flexible fuel vehicles, there is a chance for combustion engines to not only remain in the market but also be sustainable for future vehicles. Future advanced engine and powertrain configurations must address emission and fuel economy requirements for worldwide

applications, transition to bio-fuels, and synergies with future powertrain trends.

The ACCESS project addresses the technical barriers in fundamental research, technology application, and system implementation to accelerate the development of the next-generation powertrain system for light-duty vehicles. Developed based on the state-of-the-art combustion concepts and automotive technologies, this work focuses on:

- Coordinating multi-mode combustion events to optimize engine performance with improved thermal efficiency and reduced emissions over the entire drive-cycle operating conditions.
- Developing robust and flexible control algorithms, on the basis of a universal modular platform, to coordinate various actuators, especially during combustion mode transitions.
- Designing a powertrain system to enable the proposed advanced combustion and control strategies, which include air-fuel path, combustion system, after-treatment system, and vehicle platform.

- Implementing the proposed approach and demonstrating its associated fuel efficiency benefits on engine dynamometer and on full-scale vehicles.

Technical Approach

Downsizing, during the past two decades, has been recognized as one promising method of improving fuel economy in gasoline engines [1],[2],[3]. A downsized engine with a reduced displacement runs a larger proportion of operation at higher loads, thus significantly reducing pumping loss and the percentage of indicated work used to overcome mechanical friction for a given load requirement [4]. In order to avoid knock caused by the associated rise in cylinder peak pressure and temperatures, conventional control strategies involve retarding spark timing and/or cooling the cylinder mixture with excess fuel, which results in increased fuel consumption. The latter also dramatically increases emissions due to inefficient oxygen available for catalyst conversion. The most promising approach for mid-term engine technology roadmap adopted by several major light duty vehicle manufacturers today is the downsizing concept based on the synergistic configuration of turbocharging [5], direct injection [6][7], variable valve timing, external EGR [8], and dual fuelling.

The dual-stage boosting system is commonly used in light-duty diesel engine vehicle applications due to its ability to achieve much higher intake boost pressure, thus resulting in higher Brake Mean Effective Pressure (BMEP) while retaining high efficiency [9][10]. It has also been shown in [11][12] that the combined use of a small High Pressure (HP) turbocharger and a much larger Low Pressure (LP) turbocharger, can improve transient engine behavior because the small HP turbocharger has quicker response to sudden changes of speed/load, improving low-end-torque. Moreover, the use of a HP turbocharger in gasoline applications also enables the extension of lean boosted HCCI operation range. Electric boosting systems or superchargers have also been investigated in place of the HP turbocharger for improved transient operation and simpler control algorithms.

Compared with the conventional methods, the presence of some EGR (<10%) in a turbocharged engine is more effective in reducing exhaust gas temperatures than fuel enrichment or air dilution [4][8]. It has been shown in previous simulation and experimental results that the use of EGR can significantly improve fuel economy and reduce emissions over a wide range of engine operation [13]. The use of cooled EGR at low-speed, high-load improves fuel economy by reducing the need for spark retard for knock avoidance, which enables potential for further turbocharging and downsizing. At part-load conditions, EGR reduces or even eliminates the pumping loss, and also results in lower burned gas temperatures and consequently reduced heat losses.

Previous work has also shown that different EGR configurations work better at some operation points than others. In particular, the high pressure loop (HPL) EGR system, where the exhaust gas flows from the exhaust

manifold pre-turbine into the intake manifold post-throttle, has demonstrated superior performance at low loads. However, the HPL EGR system is not effective at low-speed, high-loads when the engine has a positive pressure gradient from intake to exhaust. Although increasing the backpressure can help improve the performance of the HPL EGR system, it imposes a negative effect on turbocharger efficiency and increases knock propensity due to the increased amount of hot residual gases trapped in the cylinders, and is thus counter-productive. Therefore, the low pressure loop (LPL) EGR system, where the exhaust gas flows from the exhaust system post-turbine into the intake system pre-compressor, has shown to be more effective at low speed, high-load conditions. However, this system can be more challenging for transient operation.

Compared to electro-hydraulic valve train systems, electric dual cam-phasing and two-position cam profile switching (CPS) provides a more cost-effective and less complex solution to cycle-to-cycle control of the amount of trapped residual gas. Both the range of authority and actuation speed are improved with use of electric phasers. Such an advanced variable valvetrain system not only enables robust control of HCCI combustion, especially during mode switches, but also improves the peak torque capability of spark ignition (SI) combustion by enabling scavenging of residual burned gas at high-load operation.

The concept of dual-fuel dual-injection (port fuel injection and direct injection, PDI) with the use of alternative fuels is not new in compression ignition diesel engine research, for instance, compressed natural gas (CNG) [14], hydrogen [15], and bio-fuels [16]. In SI combustion, the combination of PFI and DI dual injection strategies with a single fuel improves charge homogeneity and results in more complete combustion, which reduces particle and CO emissions and fuel consumption at part-load conditions. In addition, PDI also increases system robustness and on-board diagnostic capability by adding redundancy into the fuel delivery system. The potential of the dual injection PDI concept for SI engines is summarized in Table 1. This strategy for both single and dual fuel concepts will be explored in this project.

Table 1. Potential of Dual-Fuel Port assisted Direct Injection Strategy in SI Engines

Requirements $\lambda=1$, t/c		DI	PFI	DI+PFI
Low end torque	→ Scavenging	++	o	++
	→ Downsizing			
Fuel economy	→ Increased compr. ratio	+	o	+
Fuel economy at part load	→ Homogenization	o	+	+
	→ Complete combustion			
Particle emissions	→ Homogenization	o	+	+
Effective catalyst heating (w/o SAI)		++	o	++
Cranking at low temperature (e.g. E85)		+	o	++
Risk oil dilution		o	+	+
Noise level at idle		o	+	+

+, ++ = Benefits, o = Basis

One of the advanced combustion concepts to be investigated in this research is HCCI combustion which offers a large opportunity to improve fuel economy as well as maintain low-level NO_x and particulate matter (PM) emissions. HCCI is a lean strategy, which is capable of running at low-to-mid loads, and hence it is currently complemented with SI combustion to cover the operating map. Multi-mode engine operation using lean HCCI strategies combined with homogeneous direct injection offers a promising opportunity for gasoline engines for meeting the efficiency requirements as well as the emission regulations with only a moderate increase in cost compared to current production engines, while keeping the gasoline vehicle's advantage in cost-effectiveness and simplicity compared to diesels and hybrid electric vehicles. Such a combustion strategy combined with homogeneous DI can offer up to 16% fuel consumption decrease over the Federal Test Procedure 75 (FTP75) drive cycle, compared to running the engine only with PFI and spark ignition. This is in the same range of fuel economy of a stratified DI concept without the complexity and cost of a special lean NO_x aftertreatment system. While turbocharged downsizing and HCCI were understood as competing approaches before, studies carried out within Bosch showed that an intelligent combination of both technologies results in a beneficial technology package. An illustration of the original concept engine system is shown in the [Appendix](#).

1D THERMODYNAMIC MODELING

Model

A 1D GTPOWER model was constructed and validated for an in-line 4-cylinder (I4) GTDI baseline engine using 93 AKI E10 gasoline. The model was then modified to include additional hardware required for part load HCCI operation. This modified model is illustrated in [Figure 1](#).

Initially, the simulations were to be used to define the basic engine hardware, including the following parameters:

- Engine displacement
- Compression ratio
- Valve lift profiles
- External EGR circuit design
- Air system specification and turbocharger matching

In addition, the following effects were to be investigated:

- Benefits of cooled EGR on full load operation
- Benefits of dual-fuel operation on efficiency and performance
- EGR and boost requirements for HCCI operation

However, in order to minimize the scope of the simulations and engine hardware changes, some basic assumptions were made. Engine displacement was defined as

2.0L and the EGR circuit was specified to be high pressure loop cooled EGR in order to maximize the benefit for mid-to-high speed full-load performance and fuel economy. In addition, the charging system was assumed to be a 2-stage series sequential turbocharger using a very small high-pressure (HP) stage turbo for part-load HCCI range extension. (Ultimately, a supercharger was chosen for the HP stage boosting system, however at the time of the 1D work, the series sequential turbocharger was being pursued as the main design path.) To improve transient operation, twin-independent, electrically controlled variable cam timing (VCT) was assumed. The high lift valve profiles were assumed to be the same as the production engine. The baseline low lift profiles were chosen based on experience with HCCI combustion.

The purpose of the 1D simulation was thus to define the remaining parameters to be used to achieve the project objectives. Simulated engine maps created using the optimized model were used as inputs for the vehicle simulations. Exhaust temperature and emissions predictions were used for after-treatment system design. In the latter phases of the ACCESS project, the 1D model will be updated and correlated with engine dynamometer data to provide a higher degree of fidelity and allow further optimization.

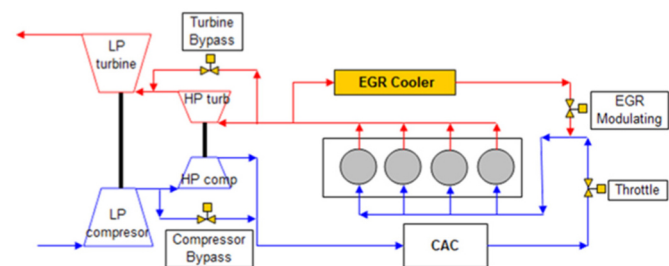


Figure 1. Diagram of 1D GTPOWER Model

Methodology

After the baseline model was created, a full set of engine data for a 2.0L I4 GTDI engine was used to validate the model to fuel flow, air flow and resultant torque. Then an HCCI combustion model similar to the model found in Babajimopoulos et al. [17] was developed which used correlated HCCI combustion data similar to the approach taken in Babajimopoulos et al. [18]. This was incorporated along with the necessary hardware assumption modifications detailed in the previous sections and a full-factorial design of experiments (DOE) was performed to help determine an optimum configuration for the engine.

Engine load sweeps were performed at various speeds from 1000 rpm to 3500 rpm. Both SI and HCCI operation were examined for each engine operating point. A DOE variation simulation was performed for each operating mode in order to optimize fuel economy. For SI operation the following variables were considered in the DOE:

- Compression ratio

- VCT positions for intake and exhaust
- Cooled External EGR rate
- Wastegate and bypass positions

To account for the influence of these variables on the end gas knocking behavior of the combustion process, a controller was applied to combustion phasing during the DOE. As the simulation converged to a solution for each set of actuator inputs, combustion phasing was automatically modified to limit the peak unburned gas temperature to a level empirically observed to occur at borderline knock. By doing so, the thermodynamic benefits of a particular system configuration can be more realistically assessed. For HCCI operation, external EGR was not used, however, optimization of the cam lobe profiles was of interest and lean operation was also considered. Therefore, the following variables were used to develop the DOE for the HCCI operation mode:

- Compression ratio
- Valve profiles for intake and exhaust
- VCT positions for intake and exhaust
- Lambda
- Wastegate and bypass positions

1D Results

The results of the simulations suggested that a compression ratio (CR) of 11.0:1 should be used to achieve acceptable full load characteristics to meet the peak torque target, and to enable efficient HCCI combustion. In addition, optimal low lift intake and exhaust valve profiles were determined. The final valve lift profiles are shown in [Figure 2](#). The remaining variables used in the DOE have been defined as functions of the engine operating point for each operating mode: SI and HCCI.

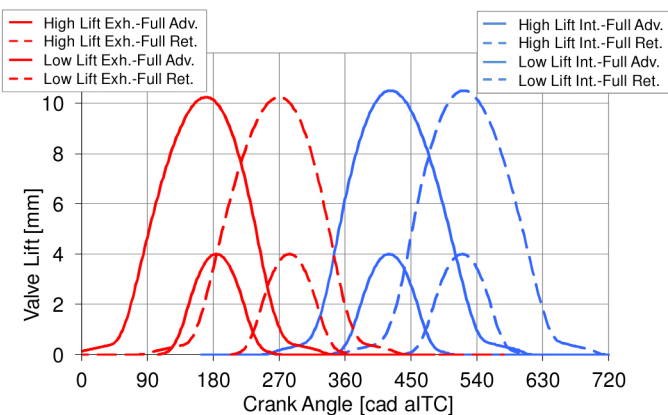


Figure 2. High and Low Valve Lift Profiles

The benefit of adding cooled external EGR to a boosted SI engine is substantial. For the purposes of this study EGR rate was limited to 15% at lower loads, since higher EGR

rates create a significant challenge for transient operation. EGR rate at higher loads was driven primarily by the pressure differential between pre-turbine exhaust pressure and the post-compressor intake pressure. As intake manifold pressure increases, this differential decreases and prevents high rates of external EGR. For example, at 8 bar the EGR rate was approximately 11%. The results for 1500 rpm using this strategy are shown in [Figure 3](#).

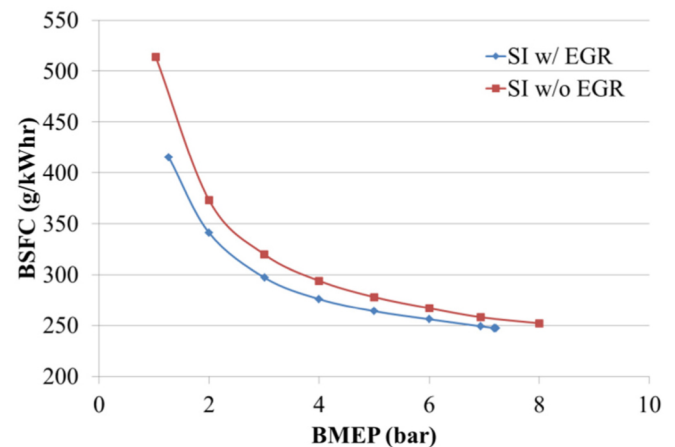


Figure 3. Simulated SI BSFC for 1500 rpm with and without EGR.

The optimal engine maps for each operating mode were compared to predict the approximate part-load HCCI operating range within 1.0 - 8.0 bar BMEP. This range is defined as the area of the engine map where HCCI operation provides a fuel economy benefit over SI operation with EGR and a highly focused region for the FTP75 drive cycle frequency. Additionally, rates of pressure rise, peak cylinder pressure and excessive NO_x emissions in lean operating conditions may prohibit the use of HCCI in the high load regions of this operating map. [Figure 4](#) shows the estimated benefit of HCCI operation over SI operation with cooled external EGR. At low loads the benefit is substantial, however as speed and load are increased the benefit decreases considerably. The resulting optimal brake specific fuel consumption (BSFC) values predicted by the model using combined HCCI and SI operation are illustrated in [Figure 5](#). Throughout the part-load operating range, combustion phasing was set for best BSFC. For points with high rates of external or internal EGR this is typically quite early and can range from 2 to 8°CA aTDC for the 50% mass fraction burned (MFB) location with low load HCCI requiring early combustion phasing to ensure robust combustion, as estimated by monitoring the peak unburned gas temperature. Since knocking and pressure rise rate become issues at the higher load points, peak unburned gas temperature and pressure rise rate are again limited by retarding combustion phasing as necessary to maintain this specified level.