Low Temperature Combustion Exploration with Negative Valve Overlap

Shengrong Zhu, Nahm Roh Joo, Jeffrey Hollowell, Kyoung-Pyo Ha, Mark Shirley, Nickolas Fantin, and Mayuri Wagh

Hyundai-Kia America Technical Center, Inc.

Abstract

Progressively stringent emission regulations and increasing regulatory demands on fuel economy have led to advanced combustion development. Low temperature combustion (LTC), specifically homogenous charge compression ignition (HCCI), is a promising technology for reducing exhaust emissions and improving efficiency. However, its operating range is limited to low load without boosting and EGR, due to low volumetric efficiency and high pressure rise rates. In addition, effectively controlling the combustion phasing is another challenge in realizing the associated combustion gains.

In this work, advanced valve control mechanisms known as continuously variable valve duration (CVVD) and continuously variable valve timing (CVVT) were used for both intake and exhaust valvetrains to enable negative valve overlap (NVO) for trapping hot exhaust residuals and to promote multipoint simultaneous ignition. Heat release phasing was controlled by varying the fueling scheme and by adjusting the amount of NVO. Parametric studies on valve timing and duration, fueling strategy, lambda, spark assist, etc., were carried out first. Afterwards the LTC strategy was proposed and then LTC operation was explored at different engine speeds. Various approaches for extending load limits were summarized and discussed. Finally, combustion performance was compared to that of spark ignition combustion, demonstrating the combustion gains of LTC.

Introduction

Lately many automotive OEMs have been gradually adopting electric vehicles, as emission regulations become ever more stringent and the world demands a cleaner environment. However, internal combustion engines are not expected to disappear any time soon. One indication is that the electrified vehicles (EV) class also includes hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs) that contain internal combustion engines, to meet the ever-increasing transport needs of goods and people for modern society. Therefore, to reduce environmental impact and improve in internal combustion engines for higher energy efficiency and reduced exhaust emissions is critical.

Low temperature combustion (LTC) has the combined benefits of low nitrogen oxides (NOx) and soot emissions like a spark-ignited gasoline engine with three-way catalyst and the high efficiency of a compression-ignition diesel engine. In LTC mode, fuel is injected very early so that the air-fuel mixture is well mixed prior to autoignition. Through mixture dilution with EGR or air, combustion temperatures are low, preventing nitrogen oxides (NOx) formation. Thus, the most problematic emissions for the internal combustion engine: soot and NOx can be significantly reduced. However, LTC is dictated by the chemical kinetics of the mixture. In other words, the spontaneous auto-ignition of LTC is determined by mixture reactivity and thermodynamic conditions. As a result, controlling the combustion phasing becomes difficult [1]. Another challenge is the high maximum pressure right rate (MPPR) which results from the rapid heat release of simultaneous combustion, leading to high levels of combustion noise [2], especially at higher loads. Additionally, the charge dilution requirements to slow the mixture reaction rate decreases the effective volumetric efficiency of the engine. An air-charge boost system such as turbocharger [3] is needed to extend the LTC load range.

To achieve controllable LTC, several different methods were developed and can be further categorized into two main groups: changing charge air thermodynamic conditions and mixture reactivity. The first group includes elevated intake temperature [4], trapping hot exhaust gas residuals [5], variable compression ratio [6], multiple fuel injections to create mixture stratification [7] and spark assist technology [8]. The second group mainly includes in-cylinder blending by using two different reactivity fuels such as gasoline-diesel [9], adding fuel additives [10], in-cylinder mixture stratification with multiple injections [11], and fuel reforming [12].

To extend LTC operation range, boosting intake charge flow can be used to increase the LTC high load limit along with late direct injection (DI) or/and EGR for suppressing the high MPRR [13, 14]. 16.34bar gross IMEP was achieved in LTC mode with 325kPa absolute boost pressure and external EGR [14].

Using NVO has shown to be a promising method to realize controllable LTC [4, 5, 12]. By advancing exhaust valve closing (EVC) and retarding intake valve opening (IVO), high temperature combusted gas can be trapped in cylinder as internal exhaust gas recirculation, providing the needed thermal conditions to promote auto-ignition of high-octane number fuels such as gasoline that has a high auto-ignition temperature. However, the amount of NVO used is somewhat limited in current public literature than desired, and elevated intake temperatures still must be used.

In this paper, LTC was achieved by varying the extents of NVO with our CVVD technology (continuously variable valve duration) for both intake and exhaust valves, and without additional intake air heating. CVVD allows the valve opening duration to be changed in quite a large range, while maintaining the same valve lift. We have successfully used CVVD & CVVT (continuously variable valve timing) to enable LTC in our six-stroke engine development project [15, 16] and a HCCI/LTC feasibility study with a four-stroke engine. CVVD technology has been utilized in Hyundai production engines since 2019. More information can be found in [17-20].

Experimental Setup and Methods

Engine Setup

The engine used for this study was Hyundai's 2nd generation of gasoline compression ignition engine (GCI-02) for our DOE funded project "Co-Optimized Mixed-Mode Engine & Fuel Demonstrator for Improved Fuel Economy while Meeting Emissions Requirements."[21] It is a four-cylinder 2.2L turbocharged engine equipped with dual CVVD & CVVT mechanisms for both intake and exhaust valvetrains. The engine has a compression ratio (CR) of 16:1, and is outfitted with both port and direct fuel injection systems, both high and low pressure cooled EGR loops, and a spark-ignition system. The high pressure gasoline fuel system, developed by Hyundai Motor Europe Technical Center, consists of an engine-oil lubricated injection pump, common rail, and modified diesel injectors. Table 1 summarizes the basic engine specifications. Figure 1 shows the schematic diagram of the engine layout.

This GCI-02 engine is capable of running multimode combustion with intention of spark ignition for cold start, LTC for low load, and GCI for mid to high loads. The LTC here refers to HCCI combustion mode with early fuel injection before or during intake stroke, and HCCI-like combustion with the majority of fuel injected early and one small injection (up to 20% of total fuel mass) around firing TDC. GCI mode is gasoline compression-ignition combustion with all fuel injections taking place late in the compression stroke and near firing TDC, burning fuel as in a diesel engine, as reported in our previous work [22]. The GCI mode typically requires higher direct injection pressure (e.g. greater than 250bar) and higher boost levels (e.g., greater than 140kPa) than LTC, to ensure sufficient fuel-air mixing, and consistent and reliable auto-ignition. In terms of combustion characteristics, LTC is a prevalently fully premixed combustion, while GCI is a partially premixed or stratified combustion, in between fully premixed and fully diffusion combustion. In this study, LTC is the focus.

To realize LTC without additional intake heating, the NVO approach was used by controlling the duration and timing of intake and exhaust valves to trap high temperature combusted gases and increase in-cylinder gas temperature for fuel auto-ignition. All or a majority (80%) of fuel was introduced into the cylinders during NVO or early in the intake stroke, e.g., 300 deg. crank angle BTDC, for homogenous fuel distribution.

With this GCI-02 engine, engine tests confirmed that LTC mode can be run at higher engine load points than 5bar BMEP, but the GCI mode shows more benefits in fuel economy and combustion controllability at higher loads. Hence, LTC mode testing is included up to 5bar BMEP.

Regarding the experimental instrumentation, measurement and data analysis, more details can be found in our previous publication [22]. In brief, all four cylinders used AVL GP15DK pressure sensors. Engine emissions were measured by using a Horiba MEXA 7500HEGR emissions bench and AVL 415S smoke meter, including total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO_x), soot concentration and filter smoke number (FSN). AVL PUMA 2.0 was used for low speed data acquisition, and AVL Indi-Com was used for high speed data acquisition and analysis.

Table 1. Engine Specification (GCI-02)

Engine	GCI-02
Displacement [L]	2.2 (4-Cylinder)
Bore [mm]	85.4
Compression Ratio [-]	16
Piston	Stepped-Lip Bowl
Fuel Injection	1. Port Fuel Injection - 5bar Max 2. Direct Injection - 1800bar Max
Valve System	CVVD & CVVT for Intake and Exhaust
Turbocharger	Variable Inlet compressor & Variable Geometry Turbine
EGR	High/Low Pressure Cooled EGR Loops

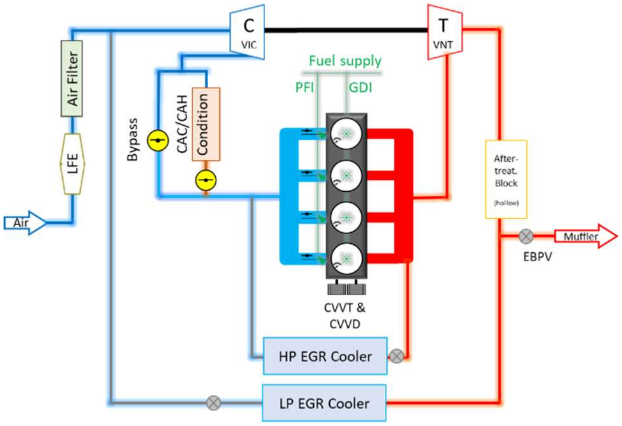

Figure 1. Engine schematic layout

CVVD & CVVT Range

Figure 2 shows the ranges of CVVD &CVVT for both intake and exhaust valvetrains. The adjustable valve duration ranges from 116 to 197 CAD for intake, and 125-200 CAD for exhaust. The valve phasing can be changed up to 100CAD for both intake and exhaust. In order to avoid interference with the piston, the intake valve has a fixed earliest opening point and the exhaust has a fixed latest closing point, which yields a minimum NVO of 28CAD. CVVT allows the intake valvetrain to move in the retard direction and the exhaust CVVT to move in the advance direction, resulting in maximum NVO of 228CAD.

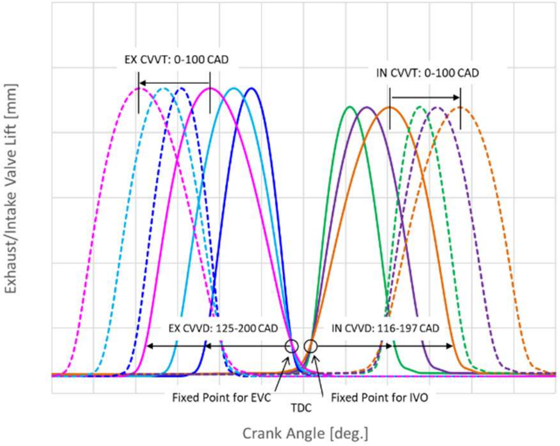

Figure 2. CVVD & CVVT range

Test Conditions

Conventional E10 gasoline fuel was used with an anti-knock index (AKI) of 87. The engine tests with LTC mode were conducted at engine speeds of 1200-3500 rpm and BMEP of approximately 1-5bar. Intake air temperature was around 25^{0}C; no intake heating was applied. Fuel injection pressure was 4.5bar for PFI, and 250bar for DI. SOI was swept from -300 to -180 deg. crank angle ATDC for PFI, and -380 to -180 deg. ATDC for DI single injection. At engine loads greater than 3.5bar BMEP, double DI injections were used to reduce the MPRR. The SOI was around -300 and -10 deg. ATDC for the 1st and 2nd injections, respectively. Fuel quantity for the 2nd injection was up to 20% of total injected fuel.

Results and Discussion

SOI Sweep with Different NVO

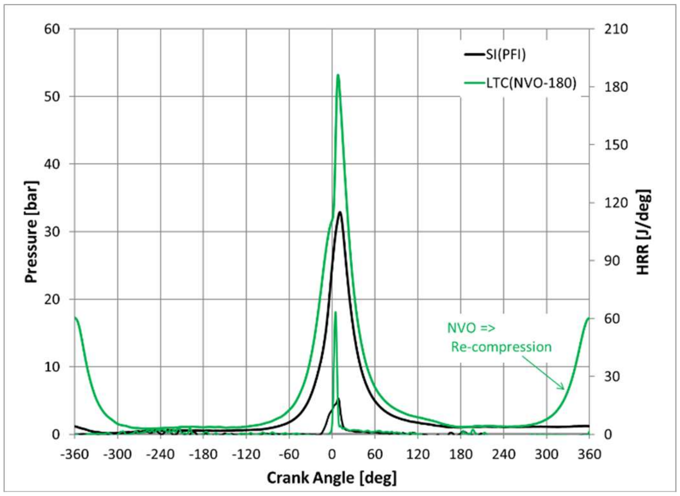

Figure 3. Combustion pressure and heat release rate for LTC (with DI SOI-360) and SI (with PFI SOI-340) modes at 1500rpm and ~2.6bar BMEP

To study the effects of fuel injection timing and NVO on LTC, SOI timing was swept along with different NVO settings. For this parametric study, engine operating conditions were 1500rpm engine speed and approximately 2.6bar BMEP. Fuel mass flow rates were kept constant, and the throttle was fully open for all cases. The NVO reported here is symmetric NVO. Symmetric NVO means the retard angle of intake valve opening is the same as the advance angle of exhaust valve closing, with respect to the gas exchange TDC. The NVO was varied while the exhaust valve opening and intake valve closing were kept constant.

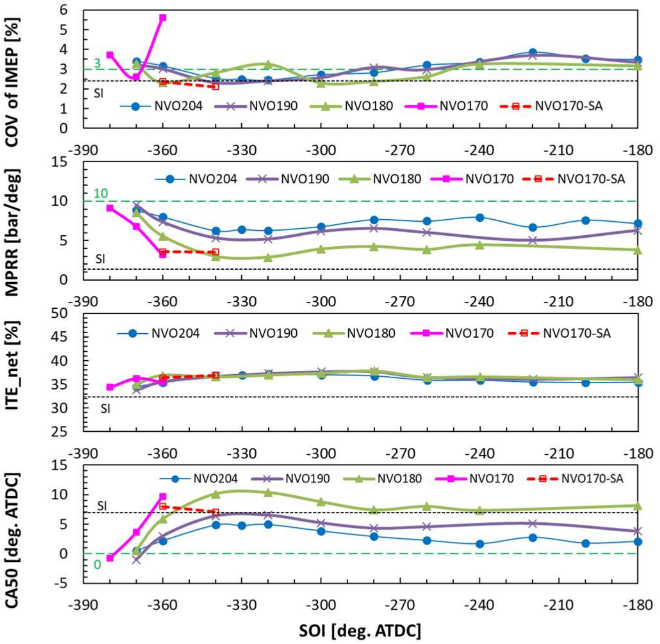

Figure 4. COV of IMEP, MPRR, net ITE, and CA50 for LTC at 1500rpm and ~2.6bar BMEP.

Figure 3 shows a comparison of pressure traces and combustion heat release rates between SI mode and LTC mode with this GCI-02 engine. Since LTC mode has NVO of 180CAD, the re-compression process resulting from NVO can be easily seen by another pressure peak of 17bar at 360 deg. crank angle BTDC, in addition to 53bar at 9deg. crank angle ATDC. In comparison with SI mode, LTC has higher compression pressure due to higher intake pressure without throttling and higher effective compression ratio because of earlier IVC. LTC also shows very fast combustion with a high peak of heat release rate and a short duration, which results in better thermal efficiency.

Figure 4 shows COV of IMEP, MPRR, net ITE, and CA50 of LTC for different DI SOI timings under different NVO settings. For comparison, corresponding data of SI combustion at the same engine operating condition is provided. Four different NVOs were studied, 204, 190, 180 and 170CAD. NVO170-SA represents the spark assist case for NVO170. The SOI timing of direct injection was varied from -380 to -180 deg. crank angle ATDC. For COV of IMEP, all LTC cases have similar or slightly worse COV of IMEP as compared to SI, except the case with NVO170 and SOI-360, where the high COV of IMEP of ~5.7% was reduced significantly to 2.6% by using spark assist. The effect of spark assist will be discussed later. MPRR and CA50 show a non-monotonic relationship with SOI timing for a given NVO, but a clear trend is observed as the SOI timing is early and between -330deg to -380deg: more advanced SOI timing, more advanced CA50, and higher MPRR. With such early SOI, fuel is injected during NVO when the in-cylinder gas temperature is high. Some chemical reactions may take place since overall the engine is running at lean conditions where oxygen is available in the internally trapped residuals. The oxygen availability in the residuals is confirmed by overall lean air-fuel ratio (AFR), as shown in Figure 5 for different NVO cases. With the NVO increased, the mixture is richened due to more trapped residuals and less fresh air entering the cylinders. But all cases were operating in overall lean conditions, with AFR higher than 14.7. Meanwhile, more NVO also indicates higher in-cylinder gas temperatures since the ratio of hot residuals to fresh air is higher, leading to even earlier and faster combustion, and in turn, higher MPRR for a same SOI timing. All LTC cases have combustion duration BD1090 around 10deg CA, compared to 32deg crank angle of BD1090 for SI. The net ITE varies a little for different SOI, and it appears to be dependent on the resultant combustion phasing. Additionally, the net ITE of LTC is about 6-17% higher than that of SI mode, due to the much faster combustion, and reduced pumping loss.

The approach used to determine the optimum configuration is to have the best efficiency while the following criteria are met:

1) COV of IMEP ≤ 3%
2) MPRR ≤10bar/deg.
3) NOx emissions ≤ 800ppm
4) Soot emissions FSN ≤1

With these criteria, the best configuration in Figure 4 is NVO=180 and SOI=-280, with a 37.8% ITE while all criteria are met.

Additionally, the effect of NVO on combustion phasing can be seen in the CA50 plot in Figure 4. Figure 6 replots the CA50 against NVO for two SOIs, SOI-360 and SOI-280. Different SOI affects combustion phasing a little, but clearly, less NVO leads to retarded CA50. Therefore, NVO along with fuel injection can be used to control the combustion phasing of LTC.

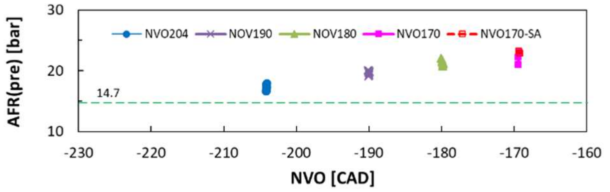

Figure 5. NVO effect on air-fuel ratio for LTC at 1500rpm and ~2.6bar BMEP

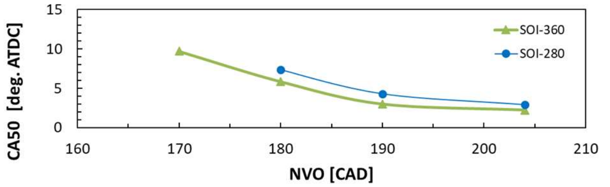

Figure 6. NVO effect on CA50 for LTC at 1500rpm and ~2.6bar BMEP as Figure 4

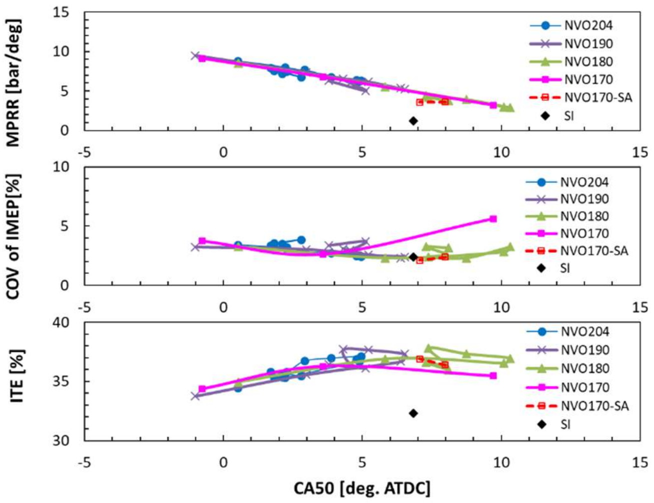

Figure 7. Correlation of MPRR, COV of IMEP, and net ITE with CA50 for LTC at 1500rpm and ~2.6bar BMEP

Figure 7 replots the MPRR, COV of IMEP, and net ITE against CA50 from Figure 4. MPRR directly correlates to CA50, regardless of NVO. Early CA50 leads to high MPRR. However, it should be noted that too retarded CA50 can result in misfiring, and the CA50 retard limit is determined by the combined effects of the expansion cooling and the heating of autoignition reactions. Different in-cylinder thermal and chemical conditions lead to different reaction rates and heating effects, thus, can result in different CA50 retard limit. Within the allowable CA50 range for each case, retarding CA50 can be used to reduce MPRR. COV of IMEP reaches its minimum value when CA50 is located between about 3 to 7 deg. crank angle ATDC. Net ITE reaches its maximum with CA50 around 4 to 5 deg. crank angle ATDC.

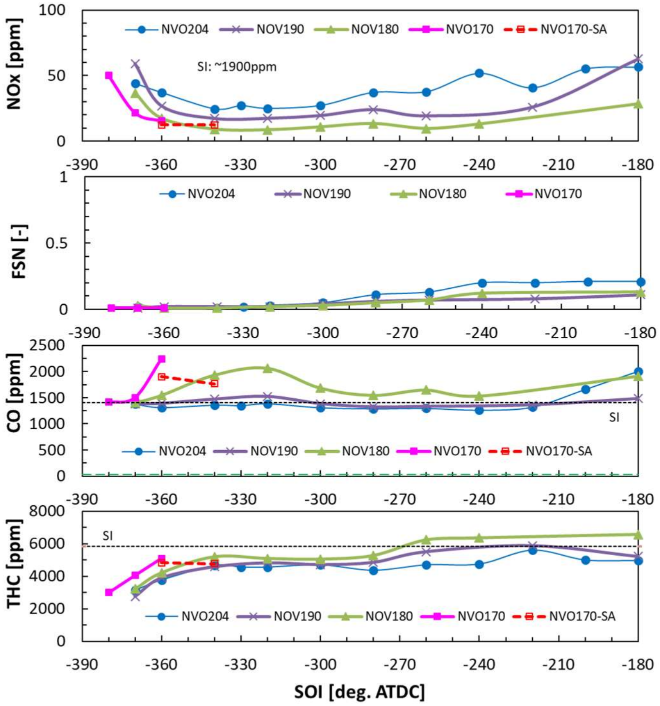

Figure 8. Emissions of LTC at 1500rpm and ~2.6bar BMEP

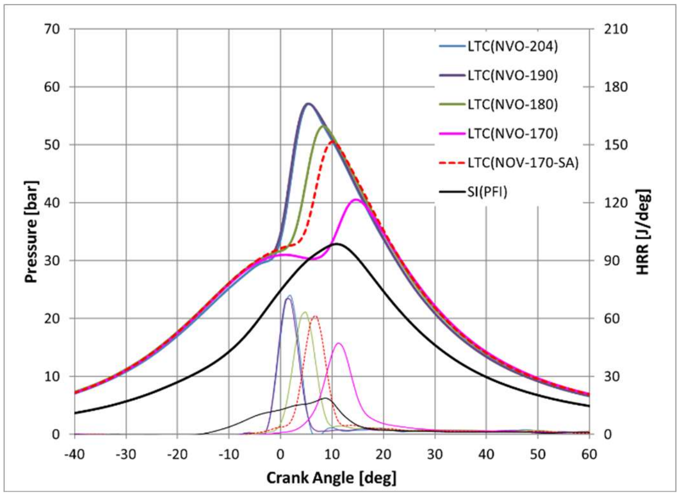

Figure 9. Combustion pressure and heat release for LTC (with DI SOI-360) and SI (with PFI SOI-340) at 1500rpm and ~2.6bar BMEP

Figure 8 shows the corresponding emissions data of NOx, soot (FSN), CO, and total hydrocarbons from the measurement points shown in Figure 4. It can be seen that NOx is significantly lower than that of SI mode, under 50ppm vs. ~ 1900ppm in SI mode, which is the result of low temperature combustion. Additionally, for the same SOI, the NOx emissions increase slightly with NVO for the cases studied. This is believed to be caused by the relatively richer mixture as NVO increases, as shown in Figure 5. FSN is very low for all cases, close to zero for SOI earlier than -280 deg. crank angle ATDC, implying that the injected fuels are fully vaporized and participate in combustion with wall wetting minimized. CO emission levels can be very similar to that of SI mode, depending on amount of NVO used. For example, CO emissions are similar to that of SI for NVO durations of 204 and 190, regardless of the SOI timing. When NVO duration is reduced down to 180 or 170CAD, CO emission level depends on the SOI timing and in turn LTC combustion quality. THC emissions can even be lower than that of SI mode. Additionally, the exhaust temperature of LTC at this operating condition is about 320 ^{0}C. A potential exhaust aftertreatment system could be an oxidation catalyst + lean NOx trap.

Figure 9 shows the combustion pressure and heat release rate for all LTC cases with DI SOI-360 along with those from SI case with PFI SOI-340. The fast combustion of LTC is clearly seen from the narrow and high heat release profile. The combustion duration BD1090 of LTC is about 10deg CA, vs. 32deg CA of SI.

These results of SOI sweeps with different NVOs indicate LTC can have higher combustion efficiency and lower emissions than SI. CVVD technologies enable NVO to alter in-cylinder mixture thermodynamic conditions by regulating the ratio of hot residuals and fresh air, which in turn can be used to control LTC. The NVO adjustment can be done in real time, significantly improving LTC phasing control, and thus the search for improvement in fuel economy and emissions reductions from LTC mode can be achieved.

Effect of Spark Assist

Figure 4 shows the COV of IMEP is relatively high around 3% at ~2.6bar BMEP. As the load is further reduced, the combustion cycle-to-cycle variation becomes even higher. To study the impact of spark assist on LTC, a low load of 1.1bar BMEP was tested with and without spark assist. Figure 10 shows the results of spark timing sweeps from 10 to 40 deg. crank angle BTDC. Compared to the case without spark assist, the spark contributes to an earlier start of combustion, that is, CA5 taking place slightly earlier, resulting an earlier combustion phasing of CA50. The COV of IMEP was then reduced from 4.8% to about 4%, while the combustion duration did not have noticeable changes. Earlier spark timing did not lead to earlier start of combustion or combustion phasing. No considerable change was observed in the net ITE or emissions. But it is clear that the spark assist reduces the COV of IMEP and extends the LTC operating window as shown in both Figure 10 and Figure 4.

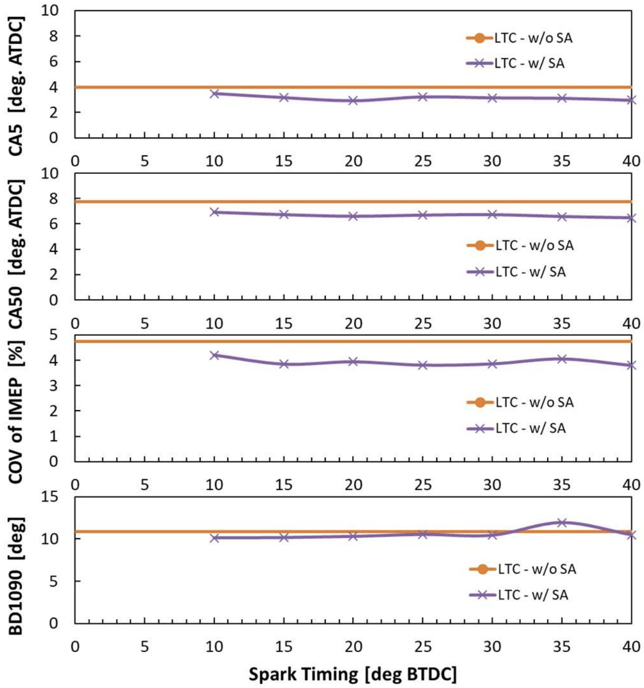

Figure 10: LTC without and with Spark Assist at 1500rpm and 1.1bar BMEP (NVO=200CAD, SOI=-250 CAD ATDC)

Effect of PFI and DI at Low Load

At low loads, fuel injection quantities are small. The DI injector is designed for high injection pressure and high flow rate. Injecting small amounts of fuel through the DI injector with low injection pressures can potentially lead to large shot-to-shot fuel injection variation, which compounds the complexity and difficulty of low load operation. Therefore, the effects of port fuel injection and direct injection on LTC mode were investigated for LTC at low loads.

Figure 11 shows COV of IMEP, CA50, BD1090, THC and net ITE for the SOI sweeps of PFI and DI at 1500rpm and 1.1bar BMEP. Spark assist was used since it helped in reducing COV of IMEP. The spark timing used was 30 degrees crank angle before TDC. The NVO was 200CAD. Using DI leads to higher COV of IMEP than using PFI. Additionally, the SOI timing had to be earlier than -260deg. crank angle before TDC to have enough time for the injected fuels to be fully mixed with trapped gases, otherwise the COV of IMEP increases significantly. DI leads to slightly earlier combustion phasing and shorter combustion duration, but the higher THC emissions lead to a worse net ITE. For PFI, injection timing earlier than IVO timing, that is, SOI-300 and SOI-270, injects fuel before charge flow is established and without any contact with hot residual gas, resulting in more wall wetting on the intake port and valves, and in turn, slow fuel atomization. THC emissions have shown to be high for these two early SOIs, decreasing as SOI is retarded after IVO. The net ITE increases along with THC emissions improving when SOI is retarded.

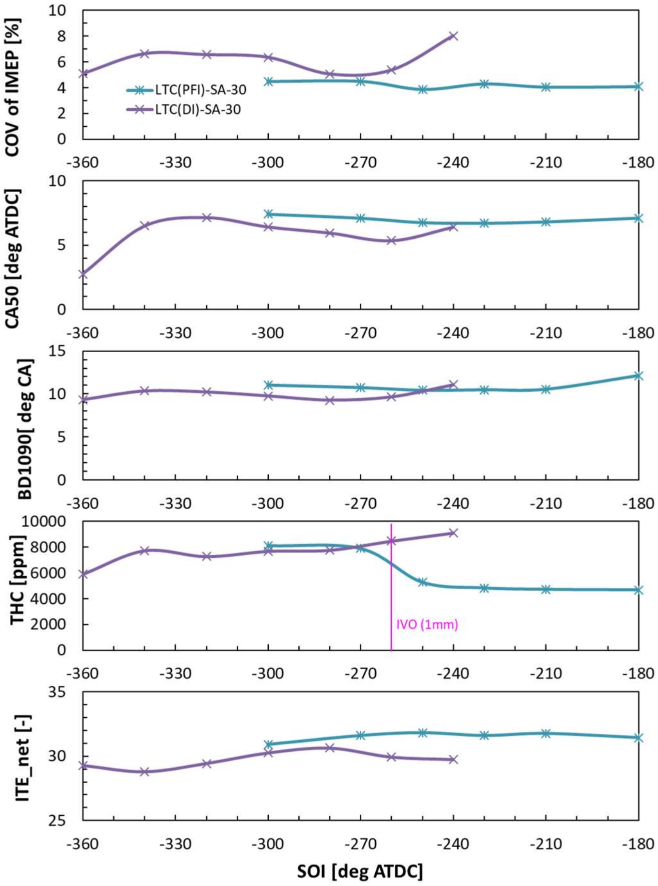

Figure 11. LTC at 1500rpm and ~1.1bar BMEP with spark assist (spark timing 30deg BTDC): PFI vs. DI

Strategies for LTC

As a result of the parametric study on NVO, spark assist, and fueling strategies (SOI, PFI, DI), several combustion strategies for LTC were proposed. Figure 12 shows the main LTC strategies for high combustion efficiency and low emissions. Spark assist is used for low load, and can be turned off as the load increases. PFI is used for low loads to reduce the cycle-to-cycle variation. As load increases, single and early DI can be used to accommodate the need of increased fuel flow rate if any. As load increases, double DI with one late DI should be used to suppress the increasing MPRR. NVO is used to regulate the in-cylinder thermodynamic conditions to promote auto-ignition and should be reduced to suppress the unacceptable MPRR at higher load, where in-cylinder condition becomes better suited for auto-ignition.

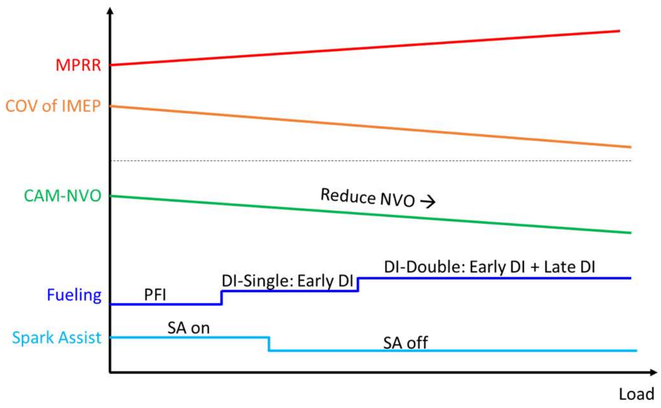

Figure 12. Proposed strategy for LTC

With the strategies in Figure 12, LTC was explored for engine speeds of 1200-3500rpm and BMEP of about 1-5bar. Figure 13 shows the LTC contours of NVO, MPRR, COV of IMEP, net ITE, FSN and NOx emissions. NVO decreases as engine loads and speeds increase. The net ITE shows it gradually increases with engine speed and load, and peaks at 43.7% under 3000rpm and 5bar BMEP. MPPR increases as the engine load increases. The soot/FSN is very low, below 0.1 for BMEP under 4bar, while increasing at higher BMEP, around 0.6 at 5bar BMEP. COV of IMEP is high - around 4% at 1bar BMEP, and gradually decreases to about 1% at 5bar BMEP. NOx is low, on the order of tens of ppm at low loads, increasing with engine load, although still lower than 500ppm. As engine load increases, in-cylinder pressure increases, reducing ignition delay. As a result the combustion phasing is advanced and MPRR is increased. To maintain the MPRR lower than 10bar/deg., the direct fuel injection was changed from an early single injection with SOI around 300deg BTDC into double injections with one late injection of SOI around 10deg BTDC and fuel split up to 20%. This late fuel injection creates a fuel stratification, increasing local high combustion temperature and leading to relatively high NOx emissions. It also increases FSN due to reduced mixing time for the 2nd injection.

Continued optimization of CAM timing such as asymmetric NVO vs. symmetric NVO as used in this study, external EGR, fuel injection timing and split, etc., is expected to further improve the combustion performance of LTC mode. To extend LTC operating range, throttling can be an additional lever in extending the low load limit, and using boost and external EGR can increase LTC high load limit.

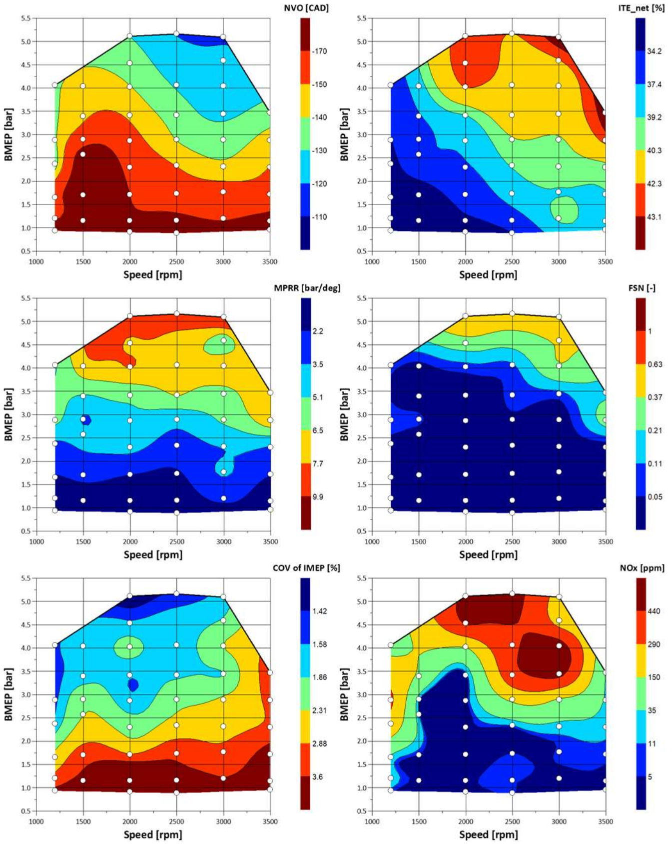

Figure 13. LTC contours of NVO, MPRR, COV of IMEP, ITE_net, FSN and NOx.

Summary and Conclusions

Experiments have been conducted on a Hyundai 2.2L gasoline compression ignition engine to investigate the low temperature combustion mode enabled by NVO. This NVO was realized by using Hyundai's CVVD technology, which can be adjusted in real time, providing flexibility in achieving controllable LTC. The effects on LTC performance from fuel injection timing, symmetric negative valve overlap, spark assist, port fuel injection and direct injection, were studied first. Then a strategy for controllable LTC by using NVO was developed, and the LTC operating range was explored without using external EGR. The findings of this study are summarized as follows:

- NVO traps hot residuals, and can be used to vary the in-cylinder thermodynamic conditions by changing the ratio of hot residuals to fresh air to promote auto-ignition for LTC as well as to control the combustion phasing.
- Increased NVO induces higher percentage of hot residuals and higher in-cylinder gas temperatures, and promotes auto-ignition.
- With early direct fuel injection during NVO, the injected fuel can undergo chemical reformation if oxygen is available in the residuals since the temperature of in-cylinder gas is high due to pure hot residuals and recompression. This increases mixture reactivity during the main compression and facilitates compression ignition, thus a shorter NVO can be used.
- Spark assist helps in reducing the COV of IMEP, especially at low loads, while the ignition angle does not affect the LTC combustion phasing.
- At idle or low loads, port fuel injection appears to have more consistent cycle-to-cycle variation as compared to direct injection. It's assumed due to the DI injector's as-designed high flow rates at high pressures characteristics, so using it for lean burn at low fuel flow rate leads to high shot-to-shot fuel injection variation.
- When PFI is used for LTC, the SOI timing should be around or slightly after IVO, to avoid wall wetting with poor fuel atomization, as well as to attain better fuel economy and low emissions.
- For LTC at higher loads, NVO should be reduced to avoid excessive pressure rise rate or/and too-advanced combustion phasing.
- With dual CVVT & CVVD for both intake and exhaust valvetrains, changing NVO in real time becomes possible, enabling LTC operation over different speeds and loads, and realizing a fuel economy gain along with an emissions reduction.
- Dual CVVT & CVVD mechanism for both intake and exhaust valvetrains appears to be a very promising technology to address the low load challenges faced with GCI concept and develop advanced multimode combustion engines.

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Corresponding Author

Shengrong Zhu,
Principal Investigator and Senior Engineer
szhu@hatci.com

Definitions/Abbreviations

AFR	Air-Fuel Ratio
ATDC	After Top Dead Center
BD1090	Burn Duration of 10% to 90% Fuel Mass Burned
BMEP	Brake Mean Effective Pressure
BTDC	Before Top Dead Center
CA	Crank Angle
CA5	Crank-angle location of 5% fuel mass burned
CA50	Crank-angle location of 50% fuel mass burned
CAD	Crank Angle Degree
CI	Compression Ignition
CR	Compression Ratio
CVVD	Continuously Variable Valve Duration
CVVT	Continuously Variable Valve Timing
DI	Direct Injection
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve Closing
FRP	Fuel Rail Pressure
FSN	Filter Smoke Number
GCI	Gasoline Compression Ignition
HCCI	Homogenous Charge Compression Ignition
HRR	Heat Release Rate
ITE	Indicated Thermal Efficiency
IVO	Intake Valve Opening
LTC	Low Temperature Combustion
MPRR	Max Pressure Rise Rate
PFI	Port Fuel Injection
RON	Research Octane Number
SOI	Start of Injection
TDC	Top Dead Center