

The Effects of Piston Crevices and Injection Strategy on Low-Speed Pre-Ignition in Boosted SI Engines

Manfred Amann, Terrence Alger, Barry Westmoreland and Andreas Rothmaier
Southwest Research Institute

ABSTRACT

The spark ignition (SI) engine has been known to exhibit several different abnormal combustion phenomena, such as knock or pre-ignition, which have been addressed with improved engine design or control schemes. However, in highly boosted SI engines, Low-Speed Pre-Ignition (LSPI), a pre-ignition event typically followed by heavy knock, has developed into a topic of major interest due to its potential for engine damage. Previous experiments associated increases in hydrocarbon emissions with the blowdown event of an LSPI cycle [1]. Also, the same experiments showed that there was a dependency of the LSPI activity on fuel and/or lubricant compositions [1]. Based on these findings it was hypothesized that accumulated hydrocarbons play a role in LSPI and are consumed during LSPI events. A potential source for accumulated HC is the top land piston crevice. Since the top land crevice is a quench zone, a series of experiments was undertaken to increase the clearance in the top land region to promote flame propagation into that region. The results indicate that increasing the size of the crevice volume reduced the incidence of LSPI significantly. Further experiments were conducted to determine the sensitivity of the effect of the shape and size of the crevice volume on the LSPI rate, yielding significant changes in the LSPI frequency. In addition to the piston hardware study, it was found that the LSPI behavior is strongly dependent on the mixture formation, particularly the injection strategy and type of injection system used (PFI versus GDI). It was hypothesized that by varying the amount of liquid fuel that impinges with the cylinder wall, the oil and fuel mixture is influenced, which in turn affects the top land accumulation rate as well as the release timing.

CITATION: Amann, M., Alger, T., Westmoreland, B. and Rothmaier, A., "The Effects of Piston Crevices and Injection Strategy on Low-Speed Pre-Ignition in Boosted SI Engines," *SAE Int. J. Engines* 5(3):2012, doi:10.4271/2012-01-1148.

INTRODUCTION

The present challenge for spark ignition engines is to reduce fuel consumption and meet the current tailpipe emissions standards while maintaining driveability. Several solutions are being pursued by automotive manufacturers and a downsized (smaller displacement and/or fewer cylinders), boosted (high specific power) engine in combination with direct fuel injection (GDI) is regarded as one of the most promising solutions. However, when operating boosted SI engines at high loads (e.g. 12bar BMEP and higher) and low engine speeds (e.g. less than 2000rpm), the occurrence of Low-Speed Pre-Ignition or LSPI is now being recognized as one of the key limiting factors for further downsizing and improvement in engine efficiency. LSPI is characterized as the stochastic occurrence of pre-ignition that result in a rapid transformation of a normal propagating flame to heavy knock. This heavy knock can quickly damage the engine. Figure 1 shows the in-cylinder pressure traces and corresponding peak combustion pressures for a typical LSPI event. LSPI events occur randomly and suddenly and usually

consist of 1 to 20 pre-igniting engine cycles. Based on in-cylinder pressure measurements, engine cycles preceding LSPI events show no indications that a pre-ignition event is imminent. Furthermore, the engine often operates with 'normal' combustion, where combustion is initiated by the spark followed by a propagating flame without knock, for an extended period (i.e. several thousand engine cycles) between LSPI events without any changes in engine operating conditions such as BMEP, MAT, spark timing and cam timing.

Significant resources are currently being devoted to investigate this phenomenon and its causes and influencing factors and to develop means to prevent it or to mitigate against it [1,2,3,10,11,12]. One of the leading hypotheses is that high molecular weight hydro-carbons, oil and/or fuel based, are being accumulated in the top land crevice volume between the piston, liner wall and piston top ring. This accumulation is believed to take place at different rates, depending on in-cylinder conditions, piston ring position and movement, fuel injection parameters and various properties

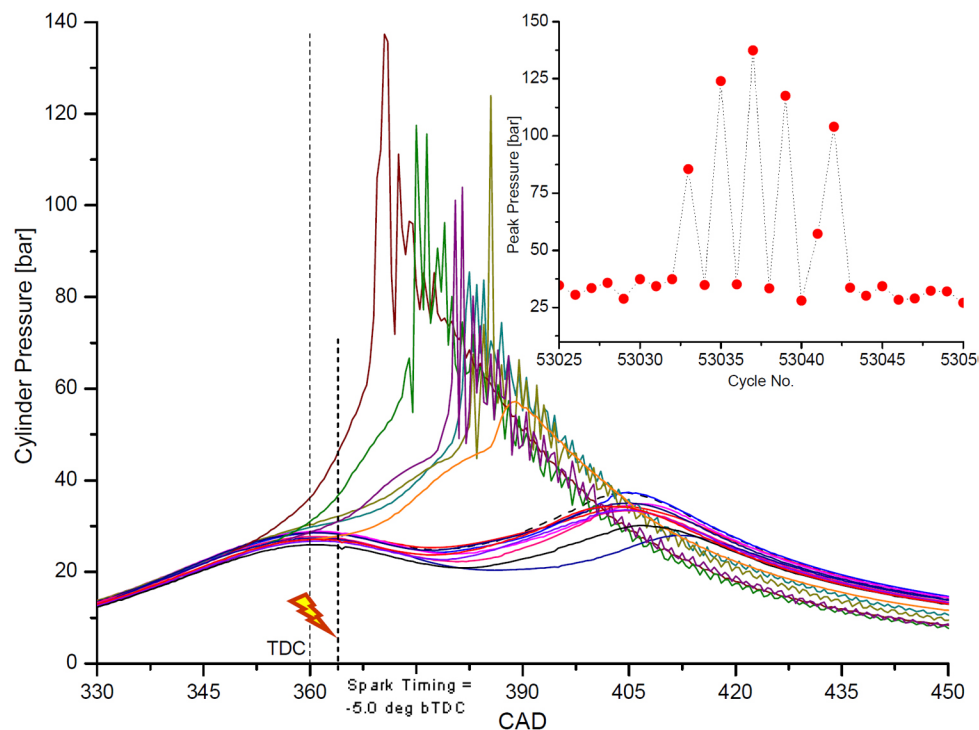


Figure 1. Typical LSPI Event with Multiple LSPI Engine Cycles and Corresponding Peak Combustion Pressure

of the fuel and oil. Once a critical mass has accumulated, some of this accumulation is released occasionally and auto-ignites during the compression stroke causing a pre-ignition. The pre-ignition is followed by severe knock due to the effective advance of ignition from the pre-ignition event. Very high in-cylinder pressures associated with the rapid heat release during knock can stress the in-cylinder components to the point of breakage quickly. Even though this theory of HC accumulation and release has not been fully proven, several observations have been made that indicate that it is, at a minimum, one of the sources of pre-ignition [1,2]. Besides the observations that there is an unnatural amount of increase in HC emissions associated with LSPI and the recognition that the chemical and physical properties of the fuel have a strong effect on LSPI [1], strong correlations between LSPI and fuel injection strategies [2], lubricants [2], and charge air motion [3] have been described. For the work described in this paper, the hypotheses was that if this theory of HC accumulation and release from the top land crevices holds true, geometrical changes to the piston crown and top land crevices should directly impact these accumulation and release mechanisms and, thus, alter the observed LSPI characteristics. In particular, decreasing the quench area by increasing the clearance between the piston and cylinder wall should allow improved flame propagation in the crevice, slowing the accumulation of the HCs that are believed to lead to LSPI. In addition to the piston hardware modifications, experiments were carried out to study effects of different fuel injection systems and strategies on LSPI. The purpose of this study was to significantly alter the amount of liquid and

gaseous fuel present in the combustion chamber and explore their potential impact on LSPI.

EXPERIMENTAL SETUP

A modern boosted, direct-injection gasoline engine was installed in an engine dynamometer test facility. The high speed data acquisition system was programmed to continuously store cylinder pressure data to a circular buffer and trigger data recording as soon as a LSPI event was detected. Even though many different combustion parameters were available to trigger the data acquisition, peak firing pressure was found to be a fairly reliable parameter and was deemed to be sufficient for this study. Nonetheless, because of this choice, the potential exists that pre-ignition events that did not result in high cylinder pressures were not captured. However, since the majority of LSPI events resulted in peak cylinder pressures well above the trigger threshold, the likelihood of missing a significant number of events was considered to be negligible. The 3.5 liter V-6 engine has two turbochargers in a parallel arrangement and a compression ratio of approximately 10:1. A picture of the test engine is shown in Figure 2. Since the speeds and loads where LSPI is most likely are often only achieved transiently in typical drive cycles, which would produce LSPI very infrequently, accelerated testing was chosen. Fixed engine operating conditions were identified where LSPI can be observed much more frequently than normal driving, but allowing extended testing without engine degradation. The following operating conditions were chosen to be of primary focus:

- Engine speed = 1250 rpm

- BMEP = ~ 13 bar
- Fuel mass flow rate = 13.6 kg/hr
- Intake manifold temperatures (MAT) = 60 degC
- Intake valve opening = 33 bTDC
- Lambda = 1.0 (stoich)
- Spark timing = knock limited spark advance
- Test duration: 30,000 consecutive engine cycles (approx. 48 min); steady-state
- Number of test repeats for each configuration/condition: 5-10 repeats



Figure 2. Experimental Setup

The fuel used for this testing was a standard winter blend pump gasoline without ethanol with an Octane rating (R+M/2) of 87 ON. The OEM recommended lubricant, labeled as synthetic blend, with a viscosity of 5W20 was used.

Many engine OEMs who are utilizing the downsized and boosted strategy to achieve higher engine efficiency and lower greenhouse gas emissions have experienced LSPI with their engine platforms. The majority of these engines also are equipped with a direct injection system. It is known that fuel impingement on the piston crown and, presumably, on the cylinder wall is largely increased by using direct injection. However, reports of LSPI occurring in turbo-charged, port fuel injection (PFI) engines as well as recent literature [1] describing the LSPI phenomenon observed on PFI engine suggests that LSPI is not only related to direct injection engines. Quite to the contrary, Zaccardi et. al. [4] determined that a large increase in LSPI activity can be observed when operating the engine with PFI. To study the differences between direct and port fuel injection on LSPI in more detail, the test engine was converted to operate with both injection methods. Open valve injection (PFI injection during intake stroke) and closed valve injection (PFI injection shortly after

intake valve closes) strategies were utilized when operating on PFI as well as tests with different GDI injection timings were carried out. Additionally, experiments where both injection systems were utilized simultaneously and at different fuel amount ratios were conducted. A picture of the test engine modified to accept a PFI system is shown in Figure 3. Even though every attempt was made to place the injectors with the injection spray targeting the intake valves, geometric constraints resulted in the spray to impinging at least in part on the intake runners.

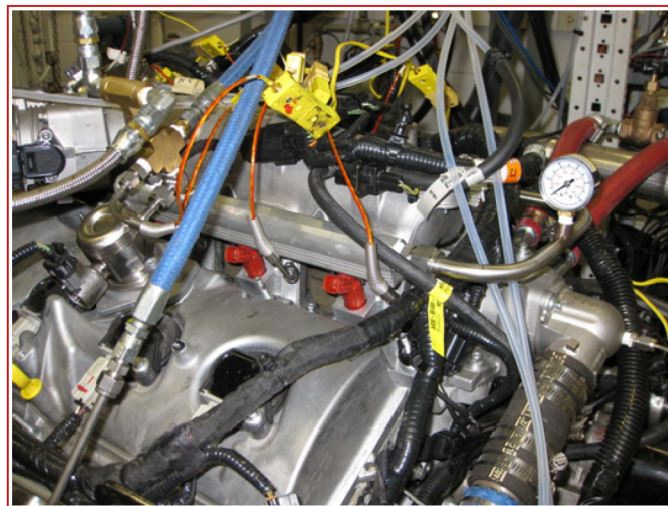


Figure 3. GDI Engine with PFI Manifold

Due to the reduction in charge air cooling from PFI (heat from intake valve is used to aid fuel evaporation when using PFI thus reducing the amount of intake air cooling due to fuel evaporation), differences in compression temperature could influence the LSPI activity. To reduce this potential temperature effect, one dimensional engine simulation using GT-Suite™ was carried out to determine the differences in in-cylinder compression temperature and to calculate intake air manifold temperatures required to achieve similar in-cylinder compression temperatures for both PFI and GDI operation. Based on these simulations, reducing the intake air manifold temperature from 50°C to 37°C would yield similar in-cylinder compression temperatures. Figure 4 shows the simulation results for in-cylinder temperature and pressures for GDI and PFI cases.

To investigate the validity of the theory that oil and/or fuel mixture accumulation in the top land crevice is a primary source of LSPI, the top land crevice of several OEM pistons were modified by means of altering the piston crown shape. As a first step, the piston top land was chamfered to effectively increase the top land crevice volume. Pictures and dimensions of the chamfered piston crown are shown in Figure 5. For this first iteration, this chamfer size and depth was chosen to allow flame penetration into the crevices. A remaining top land height of 1.04 mm was determined to provide sufficient structural integrity to support the rings for the duration of this project. The total removed volume was

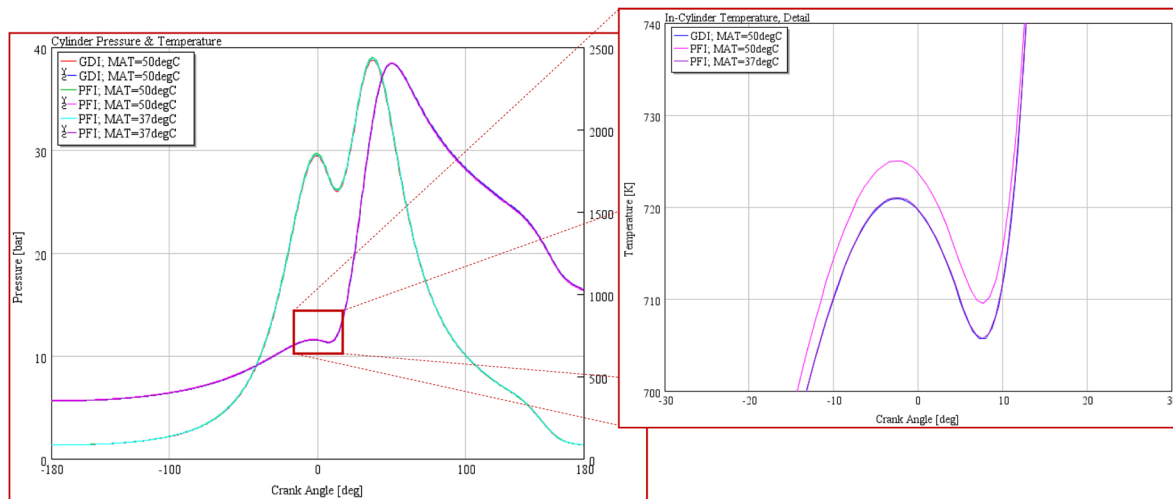


Figure 4. Simulation In-Cylinder Pressure and Temperature



Figure 5. Original and modified (chamfered) piston crown

1.95cc which resulted in a reduction in compression ratio of 0.25.

EXPERIMENTAL RESULTS AND DISCUSSION

Similarly to observations published previously [4], a large increase in LSPI frequency was observed when operating the engine on PFI. As shown in Figure 6, the number of LSPI events observed when operating on PFI increased by an order of magnitude in comparison to GDI cases.

As described previously, one of the reasons for such a large increase in LSPI activity may be the differences in in-cylinder temperatures, due to the reduction in charge air cooling from PFI when operating the engine at constant intake manifold air temperatures. However, even when reducing the intake manifold air temperatures to yield similar in-cylinder compression temperatures as with GDI, only a small effect on the LSPI frequency was observed (Figure 6). One might argue that the amount of liquid fuel droplets present in the combustion chamber and during the compression stroke has a strong influence on the LSPI behavior. To further study this hypotheses, open-valve and closed-valve PFI injection strategies were employed to vary the amount of liquid fuel entering the chamber. Since the

evaporation period for the open-valve injection case was much shorter, more liquid droplets are potentially entering the combustion chamber and, given the intake flow, may even impinge on the cylinder wall. In addition, the injection pressures were varied to alter the droplet size, with the intent to alter the evaporation rate of the liquid. However, none of these strategies yielded any significant variation in LSPI behavior. When looking at other LSPI specific parameters such as number of LSPI engine cycles per LSPI event, LSPI peak-cylinder firing pressures (in bar) and LSPI knock intensity (based in integrated knock pressure measurement), no significant differences between PFI and GDI could be detected either (Figure 7). Knock intensity values for LSPI cycles when operating on GDI appear to be somewhat higher despite similar peak-cylinder pressures suggesting that knock pressure waves are somewhat stronger with GDI than PFI although the reason why is unclear at this time and may be an area for future study.

Since the engine was set up with both injection systems working, tests were carried out where the fueling was split between PFI and GDI at different ratios. The injection timings for PFI were set to closed-valve injection and for the GDI system the stock calibration timing (approximately 68 CAD aTDC) was chosen. Constant combustion phasing