

The Effect of EGR on Low-Speed Pre-Ignition in Boosted SI Engines

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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 - where the engine displacement is reduced and turbocharging is employed to increase specific power - a new combustion phenomenon, described as Low-Speed Pre-Ignition (LSPI), has been exhibited. LSPI is characterized as a pre-ignition event typically followed by heavy knock, which has the potential to cause degradation of the engine. However, because LSPI events occur only sporadically and in an uncontrolled fashion, it is difficult to identify the causes for this phenomenon and to develop solutions to suppress it. Some countermeasures exist that OEMs can use to avoid LSPI, such as load limiting, but these have drawbacks. As an alternative measure to suppress LSPI, the benefits of operating the engine with various levels of Exhaust Gas Recirculation (EGR) have been explored. Besides a reduction in general engine knock tendencies, recent engine tests indicate that light to moderate levels of EGR (5 - 10%) reduce the incidence of LSPI dramatically. Additionally it was recognized that the addition of about 6% EGR allows an increase in fueling amount of 5-10% and an increase in engine torque of 10-13% (when operating with knock limited spark advance) without increasing the frequency and severity of LSPI. By operating the engine with 10% EGR an increase in fueling rates of 15% and engine torque of 17% was possible while reducing LSPI frequency by roughly 80% and LSPI intensity by approximately 30% over non-EGR conditions.

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. A highly boosted, small displacement 4 cylinder engine can potentially offer the same performance as a naturally aspirated, larger displacement V-6 engine. More importantly, due to the reduction in friction and pumping losses for the smaller engine, significant improvements in fuel economy can be realized. However, operating at high levels of specific power can be stressful on engine components and can lead to an increase in knock, reducing efficiency by forcing either a reduction in compression ratio or retarded spark timing or both [1].

In a spark ignition (SI) engine, a combustible air/fuel mixture is introduced to the combustion chamber during the intake stroke. Since the air/fuel mixture is highly combustible, only very little energy is necessary to ignite it. For normal SI combustion, ignition is accomplished by an electrically induced spark and is followed by a flame propagating uniformly through the combustion chamber. Besides this standard process, two other combustion mechanisms may occur that result in uncontrolled combustion which may lead to degradation of the engine:

Spontaneous ignition (autoignition)

This is generally governed by the temperature and pressure history of the air/fuel mixture. During the compression stroke, the air/fuel mixture can react and burn spontaneously after the "ignition delay", which corresponds to the time

necessary to initiate oxidation reactions. For normal SI combustion, the exhibited temperature and pressure history yields ignition delay times that are far greater than the engine cycle duration, requiring ignition to be initiated by means of electrical spark. However, boosted engines show significantly increased in-cylinder pressures and temperatures during compression, consequentially shortening the ignition delay time of the air/fuel mixture such that autoignition might occur prior to spark induced combustion. Because autoignition occurs at the bulk level, consuming the majority of the air/fuel mixture simultaneously, in-cylinder pressures can reach very high levels and exceed the mechanical limits of the engine components. However, bulk autoignition tends to be out of the operating range even for modern boosted engines.

An alternate version of autoignition in an SI engine occurs during SI engine knock. In this case, autoignition occurs after a normal mixture reaction is initiated through the electrical spark. Since the in-cylinder pressure and temperature increase quickly while the flame propagates through the combustion chamber, autoignition can take place in the unburned mixture regions. This “end gas” autoignition also causes high cylinder pressures. In addition to high pressure levels, the rapid increase in pressure generates high frequency pressure waves. The pressure waves disrupt the boundary layer around engine components and heat transfer from the hot combustion gases into engine components, such as the piston, increases substantially causing material fatigue or melting under extreme conditions.

Surface ignition or pre-ignition

In the case of pre-ignition, ignition is caused by some other source inside the combustion chamber instead of initiating combustion by a controlled electrical spark. The sources for pre-ignition can be hot spots, i.e. an overheated spark plug or valve, hot chamber deposits, or ignition enhancing components such as an oil mist introduced into the combustion chamber. Since pre-ignition initiates combustion prior to the target ignition timing, combustion phasing is often advanced and the possibility of knock is greatly increased. Also, premature initiation of combustion can result in pressures and temperatures that are high enough to degrade the engine, even in the absence of knock.

For boosted engines, these two general abnormal combustion mechanisms can be present together or separately. Different symptoms can be observed when the source of abnormal combustion differs. Recent observations by various researchers appear to include both mechanisms, pre-ignition and knock, which in some cases led to test engine degradation [2,3,4,5,6]. This style of combustion is often called Low-Speed Pre-ignition (LSPI) or sometimes “superknock”, “megaknock” or “rumble”. The adjective “Low Speed” is used to differentiate this mode from more typical pre-ignition, which occurs at high power levels, most

often due to hot spots in the combustion chamber. LSPI combustion is often described as an audible event that exhibits sharp noise resulting from very high peak in-cylinder pressures when the engine is operating at low engine speeds (< 3000 rpm) and high loads (> 10 bar bmep). Vangreghschèpe and Zaccardi [2] characterized this kind of combustion as follows:

- Very early beginning of combustion (before spark was triggered - pre-ignition)
- Initial combustion is relatively slow and similar to normal SI combustion
- A sudden increase in combustion speed, similar to severe end gas knock

Figure 1 illustrates the in-cylinder pressure and heat release information of normal combustion, light SI engine knock cycles and heavy knock caused by LSPI:

LSPI events appear sporadically and sometimes disappear without the user or engine control system changing any of the engine control parameters (ignition timing, fuel injection control, boost pressures, etc.). The causes for this LSPI are not fully understood even though various studies, including optical measurements, have been carried out [2,3,4,5,6].

Figure 2 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. Additionally, LSPI events are often characterized by the alternation between ‘normal’ combustion cycles and LSPI cycles. One theory for this behavior is that, since the combustion event during LSPI cycles occur earlier (with reference to TDC) and with faster heat release rates, exhaust dynamics as well as gas exchange dynamics are disturbed to the point where factors such as the amount of trapped residuals are altered strongly. Because of the variation in trapped residuals and, thus, temperatures and pressures during the following compression stroke, in-cylinder conditions are not favorable for pre-ignition (i.e. cooler temperatures, reduced trapped mass resulting in enriched A/F mixture, differences in mixture composition). However, since the source of LSPI is still present, a pre-ignition cycle will again follow this ‘normal’ combustion cycle. This alternation between LSPI cycles and ‘normal’ combustion cycles takes place until the source for LSPI is depleted.

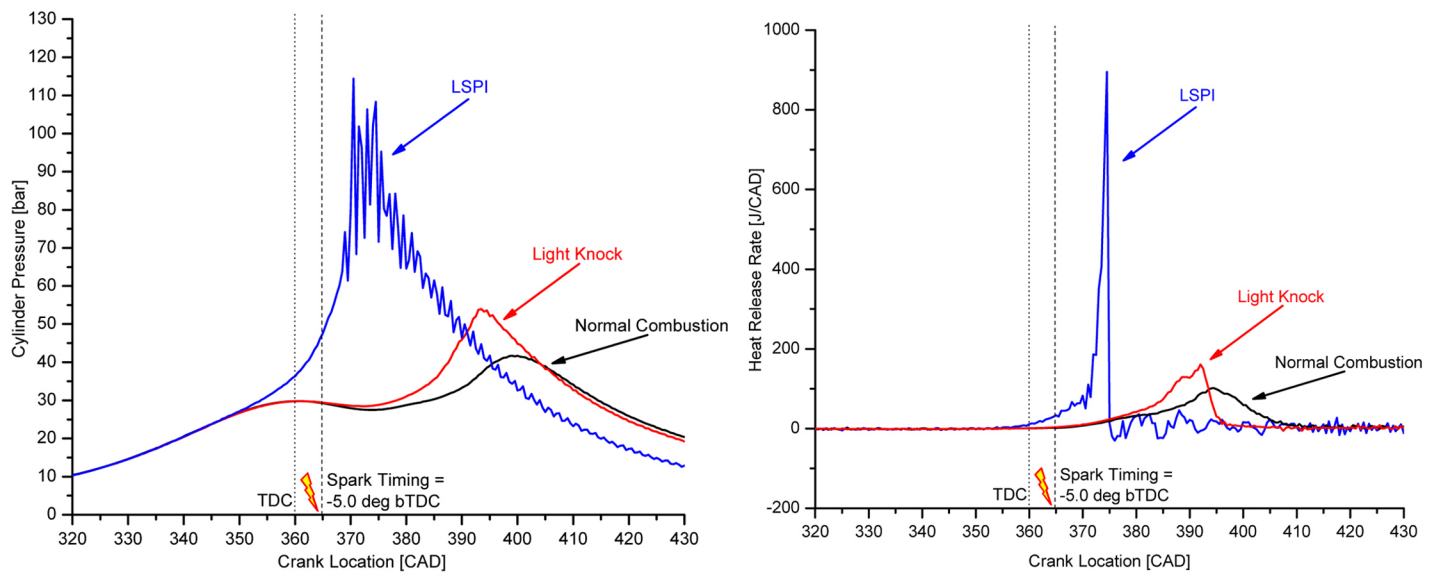


Figure 1. In-cylinder pressure and heat release rates, normal combustion, light knock & LSPI

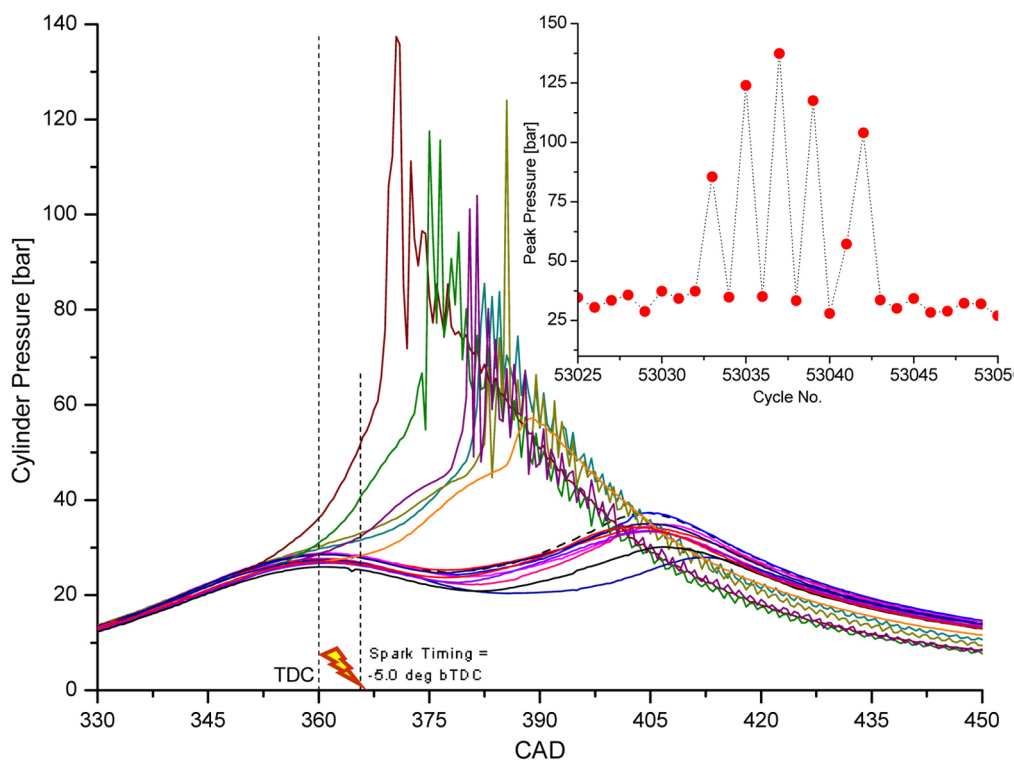


Figure 2. Typical LSPI Event with Multiple LSPI Engine Cycles and Corresponding Peak Combustion Pressure

To prevent boosted engines from knocking under adverse conditions, very late ignition timing, sometimes well after Top Dead Center (TDC), is generally required. This results in combustion initiation during the expansion stroke, which is bad for efficiency but necessary to reduce the incidence of knock. If there is a source for pre-ignition, which initiates combustion earlier than intended, engine knock is inevitable. The magnitude of knock will be shown later in this paper and

it is obvious from the heat release rates that the pre-ignited air/fuel mixture advances to bulk gas auto-ignition after only a short flame propagation phase - in some cases over 50% of the fuel is consumed by the auto-ignition event. Several different actions have been proposed to reduce / prevent the occurrence of LSPI, including:

- Prevention of pre-ignition:

- Eliminating in-cylinder hot spots
- Prevention/reduction of in-cylinder deposits by optimizing injector targeting and injection strategy and by minimizing over-fueling
- Prevention/reduction of in-cylinder deposits by improving fuel and lubricant additives
- Prevention/reduction of ingested oil
- Prevention/ mitigation of knock
 - Change of pressure and temperature history during compression, i.e. by utilizing lower compression ratios or by reducing engine torque
 - Change air/fuel mixture sensitivity to auto-ignition.

Many of the items above that are believed to result in reduced LSPI frequency have not been proven to definitively be the source of LSPI and thus the utility of altering the engine design to reduce the frequency of LSPI is questionable. However, researchers have shown that the use of EGR can result in a significant reduction in the knock tendency of SI engines [7,8,9,10,11,12], and has been used to control the autoignition in HCCI applications as well [13, 14]. The objective of this project was to demonstrate the potential of limiting the occurrence and/or eliminating it by using low to mid levels of cooled-EGR.

EXPERIMENTAL SETUP

A modern boosted, direct-injection gasoline engine was installed in an engine dynamometer test facility. The engine setup was modified to include a low-pressure loop, cooled EGR system and high speed in-cylinder pressure data acquisitions system. 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 is detected. This strategy allowed capture of engine cycles leading up a LSPI event while minimizing the amount of data recorded during the rather long test duration of 30,000 cycles (roughly 45 minutes). In addition to the EGR system, an externally driven supercharger was added to the engine intake system to provide additional boost pressure when operating the engine at increased levels of EGR (greater than 5%) as the engine's turbochargers were not designed to provide sufficient boost pressures at elevated EGR levels. The 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 3](#).



Figure 3. Experimental Setup

Using the in-cylinder pressure data acquisition, the detection of LSPI events is based on statistical analysis of the following parameters:

- Peak firing cylinder pressure (PP): Max cylinder pressure during combustion event (typically shortly after firing TDC during expansion stroke)
- Location of peak pressure (LPP): Crank angle location of peak cylinder pressure
- Maximum rate of pressure rise (MRPR):
- Location maximum rate of pressure rise (LMRPR)
- Knock Intensity; based on integrated knock pressure waves (in-cylinder pressure measurement filtered for knock frequency)
- Location of CA2 or CA10: Crank angle location of 2% and 10% Mass Fraction Burn Point in reference to ignition timing. Some researchers define a pre-ignition event as a cycle where the CA2 or CA10 point occurs prior to the ignition point (in crank angle domain)[4, 6].

Generally, each observed LSPI event (or LSPI burst) consisted of multiple (1-20) LSPI engine cycles. As described earlier, for each of the LSPI events, the LSPI engine cycles are often not consecutive where an alteration between LSPI cycle and 'normal' combustion cycle was observed. During the initial engine test runs, it was recognized that using a peak-pressure measurement to detect LSPI events in real-time is sufficient as LSPI events result in significantly higher peak cylinder pressures in comparison to 'normal' combustion pressures ([Figure 1](#)). To simplify and automate the data acquisition, setting the trigger limit approximately 20% above the average peak pressure values measured while operating