

Engine Operating Condition and Gasoline Fuel Composition Effects on Low-Speed Pre-Ignition in High-Performance Spark Ignited Gasoline Engines

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ABSTRACT

Downsizing is an important concept to reduce fuel consumption as well as emissions of spark ignition engines. Engine displacement is reduced in order to shift operating points from lower part load into regions of the operating map with higher efficiency and thus lower specific fuel consumption [1]. Since maximum power in full load operation decreases due to the reduction of displacement, engines are boosted (turbocharging or supercharging), which leads to a higher specific loading of the engines. Hence, a new combustion phenomenon has been observed at high loads and low engine speed and is referred to as Low-Speed Pre-Ignition or LSPI. In cycles with LSPI, the air/fuel mixture is ignited prior to the spark which results in the initial flame propagation quickly transforming into heavy engine knock. Very high pressure rise rates and peak cylinder pressures could exceed design pressure limits, which in turn could lead to degradation of the engine. Due to this potential, LSPI is considered a key consideration for further downsizing and improvement in engine efficiency. While some countermeasures exist that OEMs can use to avoid LSPI, such as load limiting, further study is required to formulate better countermeasures.

In the attempt to gain a better understanding of the causes of and potential mitigation methods for LSPI, several engine controls factors and operating conditions were investigated with respect to their effects on LSPI. It was recognized that the two dominant factors in influencing the LSPI occurrence frequency are engine load as governed by fueling rate (energy flux) and in-cylinder air/fuel ratio. When maintaining a constant fueling rate (not BMEP or torque), all other factors such as spark timing, MAT, coolant temp, etc. only played a

minor but not necessarily eliding role in their effect on LSPI activity.

From exhaust emission and exhaust port air/fuel ratio measurements it was also recognized that a spike in HC emissions and a significant increase in Lambda (air/fuel ratio enrichment) was associated with LSPI. Furthermore, when inducing a LSPI-like combustion event by using large spark advance for a short duration, HC emission and exhaust port Lambda were significantly lower than during 'true' LSPI events. It was concluded that a hydrocarbon based accumulation occurs in the combustion chamber over time. These additional HC are consumed during LSPI events. When combined with the results of other researchers in this field [8 , 2 , 5 , 6], one might conclude that the leading cause of LSPI is lubricant and/or fuel based HC accumulation in the top land piston crevices volume.

To investigate the source for LSPI from a fuels' perspective, four gasoline fuel blends with similar properties, such as Octane rating, boiling point distribution and RVP but vastly different composition were tested for their effects on LSPI in a modern turbo-charged, DI gasoline engine. From this study, it was recognized that the fuel chemical composition strongly influences the likelihood and magnitude of LSPI. Fuel blends with high levels of aromatics increase the frequency at which LSPI occurs somewhat where as oxygenated fuels and, especially, low aromatic blends reduced the LSPI frequency. It was also learned that despite very similar RON & MON ratings, the knock and auto-ignition characteristics of the test fuels in the DISI engine were different. In particular the low-aromatics fuel blends showed an increase tendency to auto-ignition and knock (traditional SI engine knock or end-gas knock) characterized by the presence of a low-temperature heat release regime prior to the main combustion phase.

INTRODUCTION

The spark ignition engine has been known to exhibit several different abnormal combustion phenomena, most of which have been addressed with improved engine design or control schemes. However, in the next generation of SI engines - where turbocharging and direct injection technology are employed to increase brake power at low engine speeds for improved efficiency - a new combustion phenomenon, described as Low-Speed Pre-Ignition (LSPI), has been exhibited. However, because LSPI events occur only sporadically and in an uncontrolled fashion, the causes for this phenomenon still need further investigation and solutions to suppress or prevent it need to be improved.

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, a relatively small amount of 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, known as spontaneous ignition (auto-ignition generally seen with end-gas knock) and surface ignition (hot-spot pre-ignition), can occur that result in uncontrolled combustion which may lead to engine degradation. For a modern, high performance engine, these two general abnormal combustion mechanisms can be present together or separately. Different symptoms can be observed when the source differs. Phenomena that been observed recently by various researchers appears to include both mechanisms, pre-ignition and knock, [2, 3, 4, 5, 6, 7, 8]. LSPI combustion is described as an event that exhibits sharp noise with high peak in-cylinder pressures. In his studies, F. Vangrešchêpe [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 heavy end gas knock

LSPI events appear sporadically and disappears 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 pre-ignition are not fully understood even though various studies, including optical measurements, have been carried out. [2, 4, 5, 6, 8]

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 load, MAT, spark timing, cam timing, etc. Additionally, LSPI events are often characterized by the alternation between “normal” combustion cycles and LSPI cycles. It is believed, 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 due to LSPI favorable in-cylinder conditions following the “normal” combustion cycle. This alternation between LSPI cycles and “normal” combustion cycles takes place until the source for LSPI is “consumed” or “removed”.

OBJECTIVE

The objective of this project was to study engine controls and operating conditions for their effects on Low-speed Pre-Ignition (LSPI) and to gain an initial understanding of gasoline fuel composition effects on LSPI.

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). The engine has two turbochargers in a parallel arrangement and a compression ratio of approximately 10:1. A picture of the test engine setup is shown in Figure 2:

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

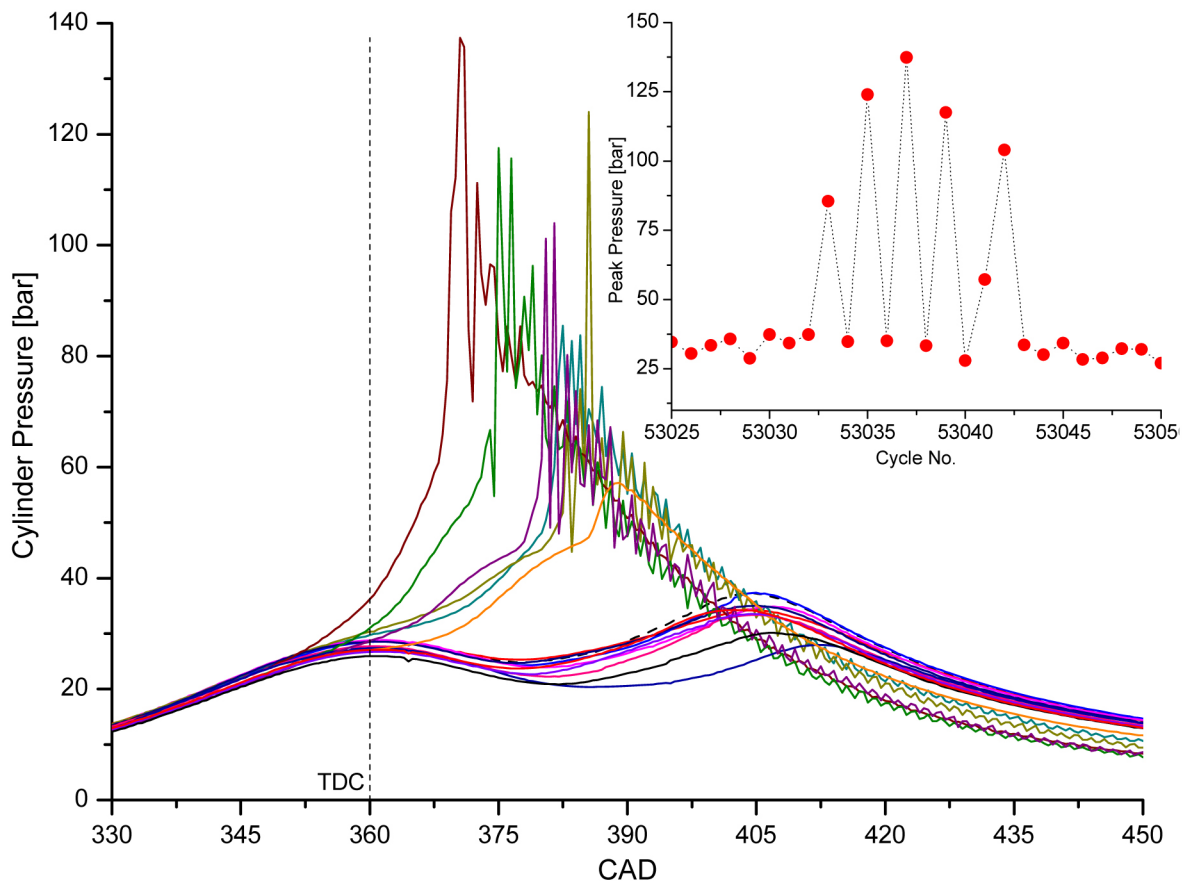


Figure 1. Typical LSPI Event with Multiple LSPI Engine Cycles and Corresponding Peak Combustion Pressure

- 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
- Location of CA2 or CA10: Crank angle location of 2% and 10% Mass Fraction Burn Point in reference to ignition timing. A pre-ignition event is present when the CA2 or CA10 point occurs prior to the ignition point (in crank angle domain) [4], [6]

During the initial engine test runs, it was recognized that using Peak-Pressure measurement to detect LSPI events in real-time is sufficient as LSPI event result in significantly higher peak cylinder combustion pressures in comparison to 'normal' combustion pressures, as indicated in [Figure 1](#). To simplify and automate the data acquisition, setting the trigger limit approximately 20% above the average peak pressure values measured while operating the engine was deemed sufficient to trigger recording when a LSPI event was

detected. The drawback of this simplified method is that "small" single cycle pre-ignition events where start of combustion was advanced by only a few degrees over the spark location and where peak cylinder pressures were only slightly above the average peak pressures for 'normal' combustion were ignored. However, the majority of LSPI events resulted in very high peak firing pressures with multiple LSPI cycles per event which were the focal point of this study.

RESULTS AND DISCUSSION

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. To study the effects of varying engine control parameters and temperatures the following ranges where tested:

- Engine Speed: 1250 rpm
- Manifold Temperature: 40 - 65 degC
- Coolant Temperature: 65 degC - 90 degC



Figure 2. Experimental Setup

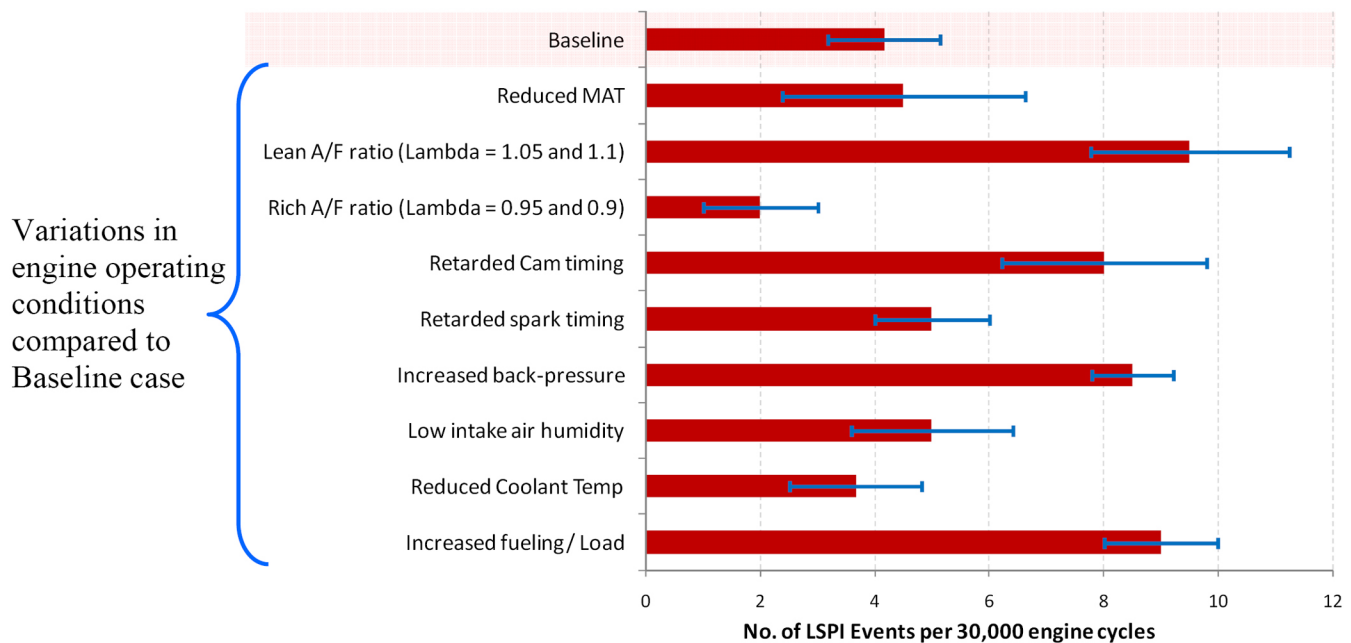


Figure 3. Engine Operating Condition Effects on LSPI

- Exhaust Air/Fuel Ratio, Lambda: 0.9 - 1.15
- Intake cam timing (IVO): 33 deg bTDC - 20 deg bTDC
- Spark timing: -8.0 deg bTDC - -3.0 deg bTDC
- Back pressure (turbine out pressure): 2 kPa - 20 kPa
- Intake air dew point (rel. humidity): ~0 degC - 15 degC (~0% - 60%).
- Fuel flow rate (Load or energy flux; corrected for fuel specific LHV): 13.6 kg/hr - 15.3 kg/hr

Figure 3 summarizes the results from this testing. The “Baseline” case is highlighted in red with a number of observed LSPI events per 30,000 engine cycles of approximately 4. As indicated in Figure 3, varying engine control parameters such as spark timing, manifold temperature and coolant temperature appears to have only a limited impact on the frequency at which LSPI occurs. It is important to note, however, that this observation is only true when a constant energy flux or fuel injection quantity (fuel flow rate) is maintained. Particularly, when varying spark timing, engine load (BMEP) varies greatly with spark timing