

Measuring the Impact of Engine Oils and Fuels on Low-Speed Pre-Ignition in Downsized Engines

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ABSTRACT

One of the limits on the maximum fuel efficiency benefit to be gained from turbocharged, downsized gasoline engines is the occurrence of low speed pre-ignition (LSPI). LSPI may lead to high pressures and extreme knock (megaknock or superknock) which can cause severe engine damage. Though the mechanism leading to megaknock is not completely resolved, LSPI is thought to arise from local auto-ignition of areas in the cylinder which are rich in low ignition delay "contaminants" such as engine oil and/or heavy ends of gasoline. These contaminants are introduced to the combustion chamber at various points in the engine cycle (e.g. entering from the top land crevice during blow-down or washed from the cylinder walls during DI wall impingement).

This paper describes a method for testing the propensity of different contaminants to cause a local pre-ignition in a gasoline engine. During one cycle, a small amount of contaminant is injected into one cylinder of a 4 cylinder engine. The spark is suppressed during this or the following cycle to allow detection of local pre-ignition events after spark timing. If the contaminant is injected on the cycle before, it is the cycle following the injection that has the missed spark. By detecting auto-ignition events before and after spark timing, it is possible to compare contaminants over a broad range of ignition tendencies. Sensitivities of pre-ignition tendencies to intake pressures and temperatures, the amount of contaminant introduced, and fuelling ratios are discussed. Additionally, the importance of contaminant stratification is shown, and pre-ignition is demonstrated to result from the introduction of contaminant as early as the beginning of blow-down of the preceding cycle.

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INTRODUCTION

Engine downsizing through turbocharging or supercharging is a strategy to improve vehicle efficiency by reducing engine displacement volume, while at the same time maintaining acceptable levels of performance. Through the ensuing reductions in friction, pumping losses, and vehicle weight, downsizing, when combined with direct injection, could reduce the fuel consumption of gasoline engines by 12-15% compared to naturally aspirated engines of similar performance [1, 2, 3, 4].

The extent to which downsizing can currently be implemented is limited by irregular combustion at low engine speeds (under 3000 rpm) and high load (at least 10 bar BMEP, but often more than 20 bar) [5, 6, 7, 8, 9, 10, 11]. This irregular combustion is intermittent and unpredictable, and leads to high peak pressures (250-350 bar) and high-intensity knock (up to 130 bar peak-to-peak), which have the potential to cause severe engine damage in a single cycle [1,3,6,9,12,13]. This irregular combustion phenomenon has become known as superknock or megaknock ("megaknock" will be used in this paper).

A megaknock event consists of three steps: an early pre-ignition (often referred to as low-speed pre-ignition, or LSPI [14]), a period of flame propagation, and a bulk auto-ignition of the end gas resulting in high-intensity knock [3,6,11,15]. The three steps can be seen in the pressure trace of a typical megaknock cycle, which is shown in Figure 1 along with a conventional knocking cycle and a non-knocking cycle. The late ignition of the non-knocking cycle typifies the very late knock limited spark advance at operating points affected by megaknock. The methods presented in this paper focus on developing the understanding of the first step in the process: the pre-ignition.

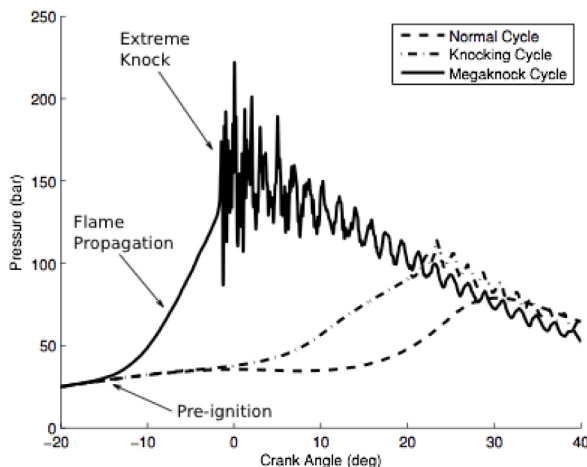


Figure 1. Pressure trace of megaknock, conventional knock, and normal cycles. The late ignition of the non-knocking cycle typifies the very late knock limited spark advance at operating points affected by megaknock. Figure adapted from Kalghatgi et al. [12]

Pre-ignition at a hot surface, such as the spark plug or squish edges, is known to occur in some engines and has been a problem in the past. However, the low-speed pre-ignition observed in downsized engines appears to have a different source. Engine tests have shown decreased pre-ignition frequency with increased cylinder wall temperatures [11]. Additionally, low-speed pre-ignition is often seen to occur in short sequences (typically 2-7 pre-ignitions) with every other cycle pre-igniting, rather than continuously with earlier ignition timing each cycle which is often observed with surface ignition [5,11]. And perhaps the most convincing evidence that surface ignition is not the primary source: pre-ignition sites have been optically observed to originate inside the combustion volume away from any surface [11].

At the point of pre-ignition in these downsized engines an auto-ignition of gasoline would not be predicted from the mean temperature and pressure history making it unlikely that a bulk auto-ignition of the gasoline itself is the root cause [13]. Instead, it is thought that droplets of low ignition delay components, such as engine lubricants or fuel-lubricant mixtures (henceforth referred to simply as contaminants), enter the combustion chamber and act as a pre-ignition source through a local auto-ignition event [10,11,16]. A strong dependence of pre-ignition tendency on volume of the top land

crevice [10] and on ring tension [13] suggest that the lubricant enters the cylinder past the piston rings. Furthermore, an increase in pre-ignition tendency with heavy cylinder wall wetting from a GDI injector suggests that contaminants formed from mixtures of fuel and lubricant could be more detrimental than lubricant alone [10].

If these low ignition-delay contaminants are in fact the source of LSPI, two clear pathways to a solution present themselves: 1. engine design could be modified to reduce or eliminate the ingress or formation of the contaminants in the combustion chamber, or 2. lubricant and/or fuel properties could be modified to change the reactivity of the contaminants, or to change the physical presentation of the contaminants to a form less susceptible to becoming an ignition source. These solution pathways have received research attention, yet gaps remain in our understanding of them. The experiment presented in this paper aims to further understanding of the second solution pathway by assessing the impact of the chemical and physical properties of contaminants on LSPI.

A study by Zahdeh et al. has already begun to investigate the impact of engine lubricant composition on LSPI. Four lubricants were tested including two with hydrocracked base oils and two with polyalphaolephin base oils. Within each type, one of the lubricants was treated with a "normal" additive package, and one was treated with an additive package of relatively reduced mass. It was found that the synthetic (polyalphaolephin) oils and the oils with reduced additive mass performed relatively better than the others. The synthetic, low additive mass lubricant had the lowest LSPI frequency of the four [13].

In a typical downsized engine, large parametric studies of the effects of lubricant composition are time consuming; the oil must be drained and re-filled between each test and long run times are required to capture a few LSPI events. Comparing the previous results to fundamental reactivity data for lubricants, such as from rapid compression machines or combustion bombs, would be insightful. Unfortunately, little such data exists to date. Crude reactivity estimations such as the Calculated Ignition Index (CII) often used for residual fuel oil can provide some insight, but these are empirically based and miss the underlying chemistry. For example, a metric such as the CII cannot provide any insight about lubricant additives.

This paper describes an alternate, faster and easier method for testing the LSPI impact of various contaminants, and presents examples of experiments that can be conducted with this method.

The method uses an engine with a supplementary GDI injector to introduce small amounts of contaminant into the combustion chamber on selected cycles (an induced LSPI engine). Test contaminants can be quickly changed in a small sample line and control over the rate and timing of contaminant introduction allows significant data to be collected over a relatively short run time. The total time required to test a contaminant can be as little as 20 minutes.

THE INDUCED LSPI ENGINE

An in-line four cylinder Ford Sigma Zetec-SE engine (2002, stock specifications are shown in [Table 1](#)) was modified to achieve induced LSPI. The Sigma is originally unboosted, and has a high compression ratio (11:1) compared to many production boosted engines. However, as manufactures are increasingly pushing for higher fuel efficiency from down-sized engines, the compression ratio is rising from the lower levels which have typically been associated with boosted engines. Previous LSPI studies have used engines with compression ratios ranging from 9.2:1 [10] to 10.5:1 [11].

Table 1. Stock specifications of Sigma Zetec-SE [17].

Displaced volume	1596 cc
Stroke	81.4 mm
Bore	79.0 mm
Compression ratio	11.0:1
Max Power	75 kW @ 6000 rpm
Max Torque	147 Nm @ 4000 rpm

The engine uses port fuel injection to increase charge homogeneity and avoid wetting of the cylinder walls with fuel, both factors in the occurrence of LSPI. Despite the increasing use of gasoline direct injection in boosted, downsized engines, it was thought that such factors could potentially interfere with measurements of contaminants' impact in the induced LSPI engine.

Test Cylinder Modifications

All tests are conducted in a single cylinder of the engine (#4). The remaining three cylinders are run to balance the engine and to keep the block warm. The intake and exhaust of the test cylinder was separated from the main manifold to allow independent control of the intake temperature and pressure, and the exhaust back-pressure. Boost for the test cylinder is provided by an external compressor capable of providing 2.5 bar_a intake air with the engine running at 2000 rpm and 3 bar_a at 1500 rpm. An in-line air heater was placed between the compressor and the test cylinder. The exhaust back pressure is provided by an exhaust brake. A 20 liter silencer was placed between the test cylinder exhaust port and the exhaust brake to reduce pressure fluctuations in the single cylinder exhaust manifold.

Sample injection is achieved with a swirl nozzle GDI fuel injector (Bosch 103092933) installed in the test cylinder. [Figure 2](#) shows the installation position in the cylinder head, which was chosen to simulate detachment of contaminant droplets from the top land crevice when the piston is near top dead centre. Since the design of this engine, it has been suggested that droplet detachment from the crevice could instead occur around exhaust valve opening when the pressure in the ring pack is higher than the cylinder pressure and the piston is close to bottom dead centre [13]. Tests on the induced pre-ignition engine have verified that introduction of small amounts

of contaminant around exhaust valve opening can cause a pre-ignition in the following cycle. Future researchers may wish to attempt introduction of the contaminant lower in the cylinder to more accurately simulate droplet detachment from the crevice near to bottom dead centre.

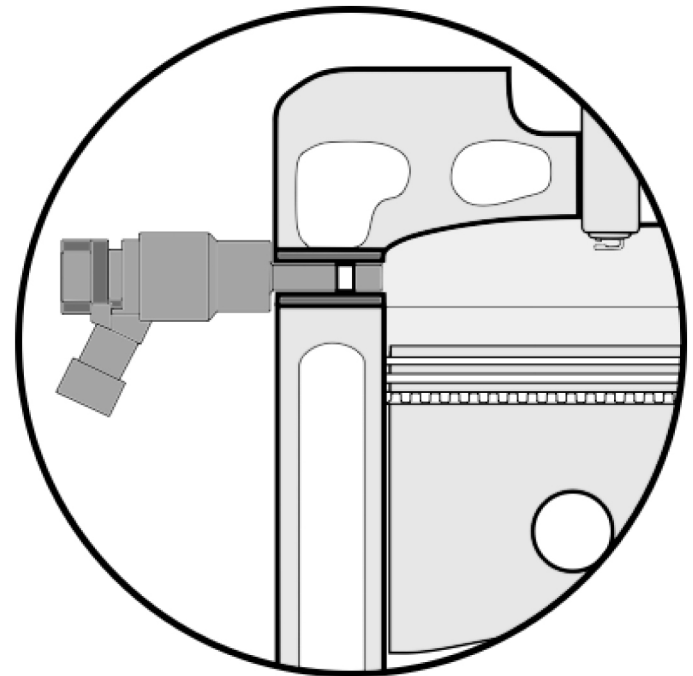


Figure 2. The GDI injector used for test sample injection is located in the cylinder head just above the head gasket in a horizontal orientation.

For all tests, the manufacturer recommended lubricant is used for lubrication of the test engine. It is possible, therefore, that some pre-ignition events could arise from auto-ignition of the engine lubricant rather than the injected sample contaminant. However, in previous studies natural LSPI occurred once in 1,000 or even once in 10,000 cycles [11,13]. Compared to a target mean of around one pre-ignition for every two contaminant injected cycles with the induced LSPI engine, the number of natural pre-ignition events would be statistically insignificant amongst the induced pre-ignitions. Even so, precautions were taken to reduce erroneous LSPI events: the crank case breather was connected to the separate manifold of cylinders 1-3 so engine lubricant could not enter the test cylinder through this pathway, and an oil trap was installed on the external compressor to reduce the chance of compressor oil entering the test cylinder.

Sample Injection System

Measuring the impact of lubricants on LSPI tendency in a typical engine is time consuming. Each time a new lubricant is to be tested, the sump must be drained and the filter changed and long run times are required to collect a sufficient number of LSPI events. The induced pre-ignition engine uses a small, 30 ml contaminant sample line (schematic shown in [Figure 3](#)) which can be quickly drained, rinsed, and filled with the next sample while the engine is still running. Additionally, precise