

Investigation of Engine Oil Base Stock Effects on Low Speed Pre-Ignition in a Turbocharged Direct Injection SI Engine

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ABSTRACT

Low speed pre-ignition (LSPI) is a type of engine knocking specific to turbocharged direct injection engines. There are numerous factors that affect the amount of LSPI produced by an engine. Some of these factors are related to engine hardware; others are specific to the fuel and engine oil. In this paper we focus on the effect of the engine oil base stock on LSPI. We conducted experiments in a stationary engine operating at conditions chosen to accentuate pre-ignition. Our results indicate that base stock viscosity has a statistically significant effect on the amount of low speed pre-ignition. Directionally, we found that engine oils formulated with higher viscosity base stocks produced more pre-ignition events. We measured the effect of base stock quality (defined by either Viscosity Index or concentration of aromatic species) to be small and statistically insignificant in our experimental data. In the course of our experimentation we detected a drift in the LSPI results from our test engines, and instituted an engine-hours correction on our results to compensate. We recommend that other researchers be wary of such a drift.

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INTRODUCTION

Automotive manufacturers have realized vehicle fuel economy benefits in recent years by downsizing engines and employing turbocharged direct injection technology. Downsizing the engine increases fuel economy by reducing the vehicle weight, frictional losses, and pumping losses in the engine. To compensate for the loss in power associated with engine downsizing, manufacturers have employed turbocharged direct injection. It is reasonable to expect these engine designs will continue to find favor with automotive manufacturers and consumers.

While the performance benefits of turbocharged direct injection are significant, this technology presents new challenges for fuel and lubricant manufacturers. One challenge of great importance is low speed pre-ignition (LSPI). LSPI occurs when some fraction of the fuel-air mixture in the combustion chamber ignites prior to the spark plug firing. This pre-ignition disrupts the engine timing and can create dangerously high pressures in the combustion chamber as the piston compresses the expanding combustion products. The high pressures and disrupted timing can lead to knocking in the engine, and in the worst case, produce catastrophic engine failure after only a few LSPI events. Turbocharged direct injected engines are particularly susceptible to LSPI when operating at low engine speeds (RPM typically < 3000) and high brake mean effective pressures (BMEP).

LSPI differs from conventional knocking in several ways. Principally, LSPI refers to pre-ignition that occurs at low engine speeds and high loads. Furthermore, unlike conventional end-gas knock, LSPI is random in nature and occurs unpredictably even while the engine

operates at LPSI-prone conditions. Several reports have been published aiming to determine the exact causes of LSPI and yet no single cause has been conclusively identified. Factors such as fuel quality, engine operating conditions, and lubricant formulation have all been shown to influence the frequency and severity of LSPI events. Because of the unique nature of LSPI and the potential damaging impact it can have on engine hardware, the next generation International Lubricants Specification Advisory Committee (ILSAC) GF-6 and General Motors (GM) dexos1® engine oil specifications will include testing to ensure robust LSPI performance for licensed lubricants.

STUDIES OF LSPI ROOT CAUSES AND THE ROLE OF ENGINE OIL

There have been many investigations into LSPI published in the past five years. These studies have generally employed similar methodologies for generating LSPI in the laboratory and identifying its causes. Most research follows the following protocol. The researchers fit a test engine with pressure transducers in the cylinders and operated the engine in low speed, high load conditions. The researchers collect pressure data over time, identifying pre-ignition events by transient periods of extremely high pressure. (One technical challenge is the lack of a single definition or threshold for distinguishing LSPI from other abnormal combustion events.) The researchers may supplement data collection with high-speed imaging of the combustion and may compare imaging data to computer simulations of combustion chemical kinetics and fluid dynamics. The researchers vary some conditions of the experiment and measure the effect on the frequency of pre-ignition events. Some examples of

conditions explored in these studies are spark plug timing, fuel injection strategy, fuel chemical composition, engine oil composition, and engine coolant temperature.

The investigations most relevant to this paper are those that explored the influence of the engine oil on LSPI. We will summarize the most relevant research here.

Dahnz et al. [1] found that LSPI events are intermittent and alternate with regular combustion cycles. Combining this evidence with observations from combustion chamber imaging, they concluded that pre-ignition is related not to persistent hot spots in the engine (which would lead to consecutive rather than intermittent pre-ignition events), but rather shorter-lived contaminants entering the combustion chamber and initiating combustion. The authors hypothesized that the LSPI mechanism begins with fuel impinging on the cylinder walls and mixing with the lubricant film that coats its surface. The resulting fuel-oil mixture has different physical properties than the pure engine oil that make it more able to form droplets that eject from the wall or the piston grooves and enter the combustion chamber. Because fuel-oil mixture has a lower ignition temperature than the fuel itself, these droplets ignite prematurely. An unexpended finding in this paper was that decreasing the engine coolant temperature (thereby lowering temperature at the cylinder walls) had the effect of increasing pre-ignition frequency.

Zahdeh et al. [2] proposed a similar hypothesis for LSPI cases based on their experimental results. They found that fuel injection strategies meant to minimize fuel impingement reduced the frequency of pre-ignition events. This seems to support the hypothesis described above. Similar to Dahnz et al., they found that lower coolant temperatures increase pre-ignition frequency. The authors tested three different engine oils formulated with various base stocks (hydrocracked petroleum-based stocks and synthetic PAO stocks) and various concentrations of lubricant additives. The engine oil with PAO base stock and lower concentrations of additives produced the least amount of pre-ignition, although it is difficult to conclude whether this is due to the base stock, the additives, or some combination of both.

Takeuchi et al. [3] focused their studies on engine oil effects on LSPI. The authors blended and tested a variety of engine oils with various base stocks and varying concentrations of detergent, friction modifier, and antiwear additives. The authors identified two trends that characterize the base stock effect on pre-ignition event frequency. First, the base stocks' pre-ignition tendencies ranked in order of their API group. The Group I base stock produced the most pre-ignition events and Group IV the least, and the results ordered as Group I > Group II > Group III > Group IV. Second, a higher viscosity Group IV base stock produced more pre-ignition than a lower viscosity Group IV. Seeking a more fundamental explanation for these observations, the authors found that the auto-ignition temperature (measured by calorimetry) of the base stocks at 10 atm pressure correlates well with pre-ignition event frequency. This led the authors to hypothesize that the engine oil effect on LSPI is a better described as a chemical (combustion-related) phenomenon than a physical (evaporation or otherwise) one.

Welling et al. [4] further explored LSPI and its relationship to fuel and engine oil ejection into the combustion chamber. The authors modified an engine to directly inject engine oil into the combustion chamber to more easily produce pre-ignition events. The authors found no significant correlation between base oil group and pre-ignition event frequency. Other attempts to classify the physical properties of the lubricants' influence on LSPI produced results that are difficult to interpret.

To summarize, there are numerous factors that appear to affect LSPI. Some of these factors are mechanical, such as engine speed and load, fuel injection strategy, and engine cooling. In fact it is possible that purely mechanical solutions to LSPI exist. Other factors involve the fuel and the lubricant properties and chemistry. Because the science of LSPI is still developing, it is difficult to synthesize the various experimental findings into one comprehensive hypothesis. Nevertheless, it is useful to find common themes in the work and collect them to form a conceptual model: A mixture of fuel and engine oil collects in the piston crown land crevice over a period of time during engine operation. This collection mechanism is accompanied by sporadic ejection of small (~ 100 μm) droplets of some composition that have sufficient character to auto-ignite, thus causing premature ignition of the fuel-air mixture already present in-cylinder. This "droplet-hypothesis", as well as other theories involving deposit formation, forms the basis of understanding the causes of LSPI in the engine.

EXPERIMENTAL APPARATUS

Our experimental apparatus was the LSPI stationary engine test developed by Southwest Research Institute (SwRI) for the Pre-ignition Prevention Program (P3). This test method employs a GM Spark Ignited L4 2.0 L Ecotec® turbocharged gasoline direct injection engine. Our test protocol identified low speed pre-ignition events from in-cylinder pressure data obtained during prescribed engine speed and load set points, and included analyses of both peak in-cylinder pressures as well as 2% Mass Fraction Burned metric derived from the calculated heat release rate. The protocol identifies a pressure or heat release excursion greater than 4.7 standard deviations from the mean as an LSPI event. The exact operating procedure used in the experiment is proprietary to the P3 consortium.

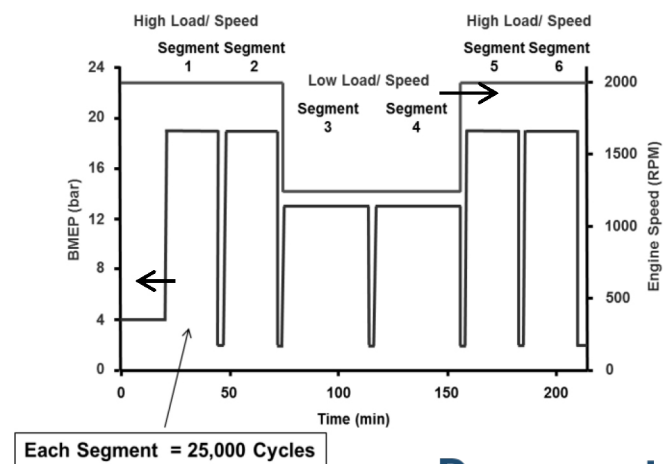


Figure 1. This figure shows the engine operating cycle over time. The cycle consists of several high load and low load segments.

Figure 1 describes the engine speed and load set points in the protocol. The test protocol repeats these test conditions four times, giving a total of 16 separate “counts” of the LSPI frequency per 25,000 engine cycles for each lubricant composition. The “Low Load/Speed” conditions generated too few LSPI events for our test oils to warrant a detailed analysis. Therefore this study considers only the data obtained at the “High Load/Speed” conditions. We typically observed between 0-60 pre-ignition events over the duration of a test.

The goal for this apparatus is to produce an experimental setup for producing and measuring LSPI in the laboratory. Because LSPI is highly sensitive to engine design and engine operating conditions, quantitative results are specific to the particular engine and protocol. However by employing a real production engine, we hope that the results of our experiments are qualitatively descriptive of LSPI in real driving conditions in the field.

ENGINE HOURS CORRECTION

In our research we observed that LPSI frequency can vary over time in a test engine even as test oil and engine conditions are held constant (Figure 2). We also observed bias in results from different engines.

It is not uncommon in engine testing for test results to drift over time even when the test protocol includes careful measures to break in the engine and flush the oil between runs. To address this bias, industry standard ASTM tests implement a statistical control system employing reference oils run periodically in test engines [5] and/or engine hour correction factors [6] to account for engine hours bias (“engine hours” refers to the number of operating hours logged on an engine).

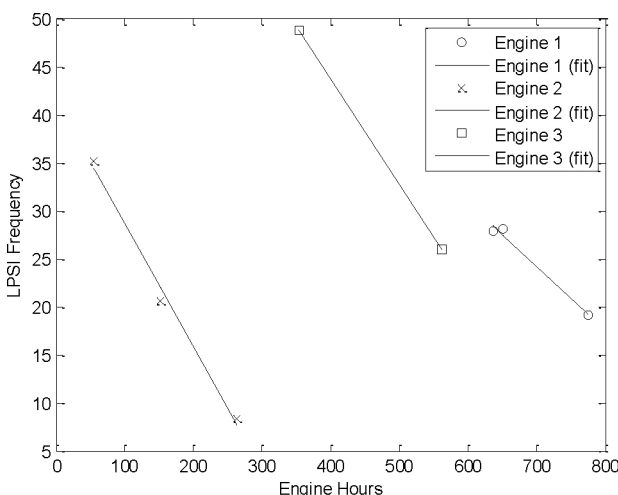


Figure 2. This figure shows the LSPI Frequency measured in reference oil tests on 3 separate engines. In each engine there is a severity shift over time towards fewer LSPI events. There also appears to be some bias among the three engines. These observations lead us to apply a normalization to our results to remove the bias of measurements collected at various engine hours and in different engines.

It is outside the scope of this study to implement such a formal statistical control system. However we choose to test a reference oil at periodic intervals during our experiments to benchmark engine

severity over time. This reference oil is a fully-formulated oil similar to the test oils in our experiments. We observed enough variation of reference oil results to justify implementing a correction factor to normalize our LSPI results. The goal of this correction factor is to correct for the observed engine hours effect and engine-to-engine bias.

Equation 1 shows the equation we used to normalize LSPI results based on reference oil results. The term in the denominator of Equation 1 is the expected value of the reference oil LSPI frequency at the appropriate engine hours of the test oil run. We calculated this number by linear interpolation of the reference oil LSPI results collected before and after the test oil in the particular test engine. The numerator in Equation 1 is the calculated mean of all observations of the baseline oil (128 data points), and is what we consider as the reference level performance for the baseline oil. The units of Raw LSPI Frequency in this equation are number of LSPI events per 25,000 engine cycles.

$$\text{LPSI Frequency} = (\text{Raw LPSI Frequency}) \times \frac{26.8}{\text{interpolated reference oil LPSI frequency}} \quad (1)$$

The cause of test engine drift is uncertain. One possible cause is gradual wear in the cylinder liners. Cylinder liners are typically honed with a cross hatched pattern to help retain oil for proper lubrication. As the engine wears this hone reduces in capability to hold engine oil, therefore leading to reduced LSPI due to less available oil entering the combustion chamber to contribute to LSPI. Furthermore, the test method itself may have a significant impact on the drift observed in the engine. The engine operates in a regime that is designed to cause LSPI, which can lead to gradual damage to the engine with time. While the exact causes of the engine drift are unclear, accounting for this effect is a critical step before attempting to draw conclusions from the data.

One unfortunate byproduct of this engine hours correction is that it leaves us without a way to estimate test precision - we had initially intended the reference oil runs as repeat data points for this purpose. With the reference oil results now serving as the source of a correction factor, we are left with no repeat runs. Therefore it is impossible to place error bars on our data. Instead, we will rely on a statistical analysis to judge the significance of base stock property effects on LSPI.

TEST OILS AND EXPERIMENTAL RESULTS

To measure the effect of lubricant base stock choice on LSPI we blended 11 engine oils consisting of various base stocks and base stock blends with a common set of lubricant additives. The additive chemistry in these oils is similar to that found in many commercially available premium engine oils, and is identical in all the test oils. Additionally, we kept the viscosity modifier type and concentration constant in all these oils. Table A1 summarizes the properties of the base stocks in our study and the LSPI results for their corresponding finished oil.