

Controlling Low-Speed Pre-Ignition in Modern Automotive Equipment Part 3: Identification of Key Additive Component Types and Other Lubricant Composition Effects on Low-Speed Pre-Ignition

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ABSTRACT

Market demand and evolving global legislation are forcing OEMs to improve fuel consumption and reduce CO₂ emissions. Downsizing in direct injection gasoline engines has been a common strategy towards achieving this goal, but this requires increased boost pressures to maintain power. The increased boost pressures are creating a new abnormal combustion phenomenon known as Low-Speed Pre-Ignition (LSPI).

Lubricants and fuels have been implicated as significant influencers of LSPI frequency and intensity. Part 1 of the series described the development of a statistical approach for measuring and quantifying LSPI activity. This statistical approach was shown to be consistent and repeatable. Part 2 of the series further refined the methodology from Part 1 to reduce the frequency of false positives and negatives. A baseline lubricant was used in both of these papers to demonstrate the robustness of this methodology.

This paper explores major lubricant components in order to assess their impact on LSPI activity as promoters, quenchers or having no effect (neutral) on LSPI based on this baseline lubricant, with a strong focus on the most common metal detergent cations used in modern automotive lubricants. It also raises concerns about using general LSPI prediction equations, particularly concerning their accuracy with poor quality fuels.

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BACKGROUND AND INTRODUCTION

In recent years there has been an intense effort to establish a methodology for evaluating lubricant- and fuel-related influences on the number of Low-Speed Pre-Ignition (LSPI) events which occur in downsized turbocharged gasoline direct-injected equipment. It is now commonly recognized that lubricant and fuel type and quality have a significant influence on the occurrence of LSPI [1-2]. To that end, a number of recent studies have looked at the process for setting up the equipment and collecting and analyzing the data. LSPI is amenable to a statistical approach to its study. In Part 1 and 2 of this series of papers [3-4], the methodology for studying LSPI was described, and a detailed description of statistical approaches for studying the data was defined.

As discussed in Part 1 of this series of papers [3], each test performed included four higher speed and load segments and two lower speed and load segments. Though the trends were, in general, directionally the same, the LSPI count for the higher speed and load segments was much higher and yielded better discrimination. Therefore, in this paper, the results plotted relate to the sum of the four higher speed and load segments.

In this part of the series, these data analysis techniques are applied to provide a statistical analysis of the effects of Calcium and Magnesium detergents on LSPI, as well as the responses of the other key components in modern lubricants. Based on the results, components will be divided into one of three primary categories - Quenchers, Promoters, or Neutral, depending on whether the components inhibit, promote or have no effect, respectively, on the level of LSPI in the engines being investigated. LSPI Quenchers will be given the designation LSPI-Q, LSPI Promoters will be designated as LSPI-P, and those components which have no effect on LSPI will be designated as LSPI-N. Based on some of the previous studies of LSPI, LSPI Quenchers (LSPI-Q) include the Zinc Dialkyl Dithiophosphates (ZDDP)s and Molybdenum, whereas Calcium has been identified as a Promoter (LSPI-P). [5, 6, 7, 8] However, there is little or no indication of the precision of the results in these studies, or whether the findings are statistically valid, and, if so, to what degree. In the work reported here, the responses of ZDDP types and levels, detergent types and levels, antioxidant types and viscosity modifier types are also investigated, but in a statistically rigorous manner. An LSPI-Q is a component with a negative statistically significant coefficient resulting from a regression analysis of LSPI count on

1)] on the components and other formulation variables tested as well as operational factors including test number, segment, etc. Likewise, an LSPI-P is a component with a positive statistically significant coefficient. Some formulation-related variables, such as SAE viscosity grade and ZDDP type, were modeled as fixed effect categorical factors for which the statistical significance of the group effect is determined via analysis of variance. For this paper, statistical significance is determined relative to the threshold, or significance level, of 0.05.

The responses of the LSPI-Q components pose key questions around the future directions and choices concerning the composition of the next generation of lubricants formulated to reduce and ideally eliminate the occurrence of LSPI events, as well as providing the types of performance and protection expected from a modern lubricant. Some of these questions, as well as the implications of moving in various directions in future lubricant formulation, are also discussed here.

EXPERIMENTAL APPROACH AND ANALYSIS METHODOLOGY

Any approach to studying the lubricant effects on LSPI requires a careful methodology to be followed, as detailed in Part 1 of this study [3], including the use of Baseline fluids. All of the work presented here involved the use of the Baseline Oil 1 reported in Part 1. It has the characteristics listed in [Table 1](#).

Table 1. Characteristics of Baseline Oil 1

Property	Baseline Oil 1
Viscosity Grade	SAE 5W-30
Ash, %	0.72
B, %	0
Ca, %	0.19
Mg, %	0
Na, %	0
P, %	0.054
Zn, %	0.06
KV100, cSt	10.36
HTHS150, cP	3.04
CCS @ -30C, cP	6129
NOACK, %	14

The data reported here were collected from six different GM 2012-2013 MY 2.0L Ecotec LHU engines operating in two different test cells. These are the same 6 GM engines used and described in Part 1 of this series of papers [3]. All LSPI and/or knock suppression strategies, including fuel cylinder enrichment, were disabled in the engine management systems of these 6 engines. This is an important item because these LSPI suppression strategies have been seen to disrupt the form of the data in the presence of significant LSPI promoters (LSPI-P) [3, 9].

The work in Part 3 of this series of papers (as well as in Part 1[3]) was conducted exclusively in the engine just described. A common question is how applicable the findings in this study would be to other

OEM equipment, particularly the Ford engine which will be used in an ASTM standard test being developed to measure LSPI for ILSAC GF-6. The authors will cover this subject in Part 4 of this series (to be published at a later date), but it is clear that the LSPI lubricant responses in the broad categories of LSPI-Q, LSPI-P and LSPI-N are recognizable in the other engine types. The authors have, however, noted differences in both the size and type of the responses in other OEM equipment and, therefore, caution the need to test for optimized lubricant solutions in the specific equipment the lubricants are intended for. The authors further caution that, extrapolation of the conclusions beyond the formulation space and conditions tested may not be appropriate.

A tightly controlled standard fuel is critical to an effective lubricant study of the type presented here, and the fuel used in all of this work was Haltermann EEE test fuel. This fuel has a low aromatic content and is known to be relatively mild towards LSPI compared to bad fuel. Recent LSPI field issues may have arisen when OEM equipment encountered poor quality fuels. Lubricant solutions required to address these situations should always be evaluated with these poor quality fuels to assure understating the effectiveness of the lubricant solution when it meets these types of fuels in the field. Testing with a 'bad LSPI fuel' [10-11] is the best way to draw out the benefits of the best lubricants for LSPI, rather than using a general LSPI prediction equation which may have been developed based on data obtained with a better fuel. Several of these equations have appeared in the literature recently [12]. Further comments will be made about the use of such equations in the following section.

To date the authors have not been able to record a 'zero' LSPI count with their best lubricant tested with the worst fuel, but they will continue to test the hypothesis that a lubricant could totally eliminate LSPI events even with the worst fuel. [Table 2](#) below illustrates the authors' general experiences to date

Table 2. Fuel-Lubricant Interaction Effects on LSPI

	Bad Fuel	Mid Fuel	Good Fuel
	LSPI Relative Count		
Bad Oil	High	High	Mid
Mid Oil	High	Low	Low
Good Oil	Mid	Low	Low

The fuel composition has a significant impact on LSPI counts, and, therefore, it is absolutely crucial that the test fuel is carefully controlled. For this reason, we used the ILSAC industry standard Haltermann EEE fuel with the specification properties listed in [Table 3](#). The authors' experience is that this fuel is relatively benign to LSPI counts, even though the aromatic content can be as high as 32.5%. Reports of high event counts in certain regions, particularly China [11], are we believe most likely connected to higher aromatic fuel content, which can rise above 40%. Ethanol has been reported to reduce LSPI counts [10] and is often seasonally adjusted. When ethanol is added, the overall fuel composition is also adjusted and may confound any direct fuel-related observations. Using an uncontrolled fuel, which can affect LSPI counts, disrupts studies of the type reported here which are centered on measuring lubricant-related effects.

Table 3. Haltermann EEE test fuel specification

Test	Method	Units	Min	Target	Max
Distillation - IBP	ASTM D86	°C	23.9		35.0
10%		°C	48.9		57.2
50%		°C	93.3		110.0
90%		°C	151.7		162.8
Distillation - EP		°C			212.8
Gravity @ 60°F/60°F	ASTM D4052	°API	58.7		61.2
Density @ 15° C	ASTM D4052	Kg/l	0.734		0.744
Reid Vapor Pressure	ASTM D5191	kPa	60.1		6.4
Oxygen	ASTM D4815	wt%			0.05
Sulfur	ASTM D5453	mg/kg	3		15
Lead	ASTM D3237	mg/l			2.6
Phosphorous	ASTM D3231	mg/l			1.3
Composition, aromatics	ASTM D1319	vol %	26.0		32.5
Composition, olefins	ASTM D1319	vol %			10.0
Particulate matter	ASTM D5452	mg/l			1
Oxidation Stability	ASTM D525	mins	1000		
Copper Corrosion	ASTM D130				1
Gum content, washed	ASTM D381	mg/100mls			5.0
Fuel economy Numerator/C Density	ASTM E191		2401		2441
Research Octane Number	ASTM D2699		96.0		
Sensitivity			7.5		
Color	Visual	1.75 ptb		Red	

Results and Discussion

Detergent Effects

As noted, some recent publications have reported the negative influence of Calcium on LSPI [2, 7-8, 13, 14, 15, 16]. In this work, the authors took the opportunity to study, for the first time in a statistically rigorous manner, the effect of various levels of Calcium on LSPI in the GM engine. The data obtained are shown in Figure 1.

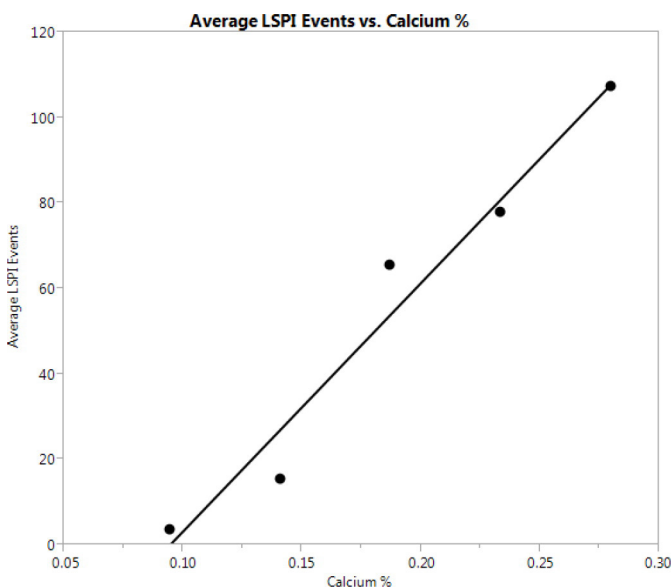


Figure 1. Effect of increasing concentrations of Calcium on LSPI

The data are plotted as the number of LSPI events recorded averaged across the four tests (1 test set) run at each concentration (y-axis) versus the Calcium concentration as a mass percent in the oil (x-axis).

(Note: All concentrations expressed as a percent (%) in this paper are mass percent.) Five different concentrations of Calcium Sulfonate, covering the range of normal commercial use, were used to blend the oils for this particular phase of the study. The oils were run consecutively in the same engine. The oils did not contain any other detergent metals. The authors note the striking linear nature of the Calcium response. It should also be noted, however, that the first of the four tests of the oil with a Calcium concentration of approximately 0.18% had an LSPI count much higher than the remaining three tests. If that test were omitted, the curve would be relatively flat at low concentrations and then increase with increasing Calcium concentration. Although no concentrations lower than the 0.095% point shown in Figure 1 were investigated, it appears from this figure that concentrations below about 0.08% Calcium would cause only a minimal number of LSPI events, although this will likely vary with each individual engine and depend to some extent on the other components in the formulation. Above about 0.10%, Calcium is certainly an LSPI Promoter (LSPI-P).

Next, the effect of Magnesium-based detergents was investigated. In striking contrast to the effect of Calcium, the curve in Figure 2 showing the effect of various levels of Magnesium on LSPI is essentially flat. It should be noted, however, that Figure 2 is shown on the same y-axis scale for LSPI counts as Figure 1, and, while there appears to be no LSPI response to changes in Magnesium concentration in Figure 2, there was actually some change, if we look at the LSPI response on a more restricted scale, as shown in Figure 3. Here we see that a very small number of LSPI counts occur within the range of Magnesium concentrations studied (0.07 - 0.22% Mg). While it appears in Figure 3 that there might be a curve descending towards 0 LSPI events at concentrations above about 0.25% Mg, the fact that 0 events were found for the 0.11% Mg oil suggests that the other non-zero values for LSPI events shown in Figure 3 could be random scatter.

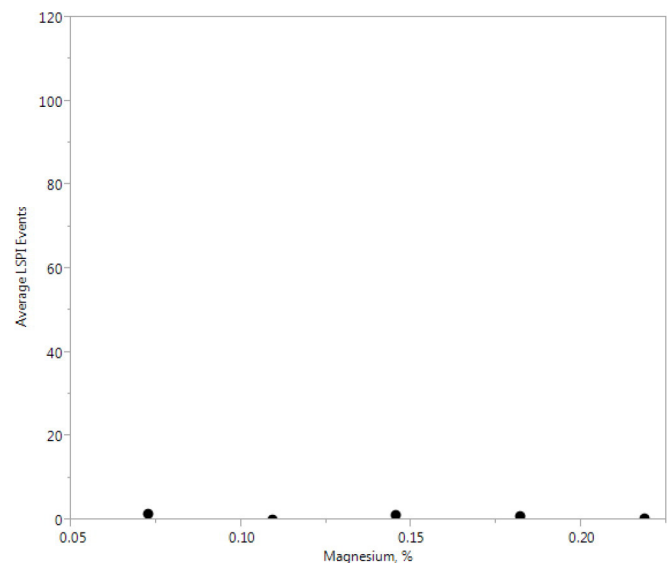


Figure 2. Effect of increasing concentrations of Magnesium on LSPI