

Engine Oil Additive Impacts on Low Speed Pre-Ignition

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ABSTRACT

Low speed pre-ignition (LSPI) is an undesirable combustion phenomenon that limits the fuel economy, drivability, emissions and durability performance of modern turbocharged engines. Because of the potential to catastrophically damage an engine after only a single pre-ignition event, the ability to reduce LSPI frequency has grown in importance over the last several years. This is evident in the significant increase in industry publications. It became apparent that certain engine oil components impact the frequency of LSPI events when evaluated in engine tests, notably calcium detergent, molybdenum and phosphorus. However, a close examination of the impact of other formulation additives is lacking. A systematic evaluation of the impact of the detergent package, including single-metal and bimetal detergent systems, ashless and ash-containing additives has been undertaken using a GM 2.0L Ecotec engine installed on a conventional engine dynamometer test stand. Consistent with previous reports, the detergent system was found to have the largest impact on LSPI frequency. Furthermore, once a balanced detergent system was identified and its LSPI impact was minimized, the effect of other additives, ash-containing as well as ashless, became apparent. In order to develop a robust additive package that maintains performance in critical bench and engine tests while offering optimal LSPI protection, consideration must be given to the impact of all lubricant additives not simply the detergent type and treat rate.

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INTRODUCTION

Low speed pre-ignition (LSPI) is a type of abnormal combustion observed in modern turbocharged engines which has been attributed to modifications in engine designs and operating conditions [1, 2, 3]. Although early research focused on engine operating conditions as a method to reduce LSPI frequency, ongoing research continues to explore possible sources of this type of abnormal combustion [4, 5, 6, 7]. Theories include consideration of a liquid fuel/oil droplet, solid combustion chamber deposit, or some combination thereof.

Although fuel has been shown to have a profound impact on LSPI frequency [8,9], far more reports describe how lubricant components affect LSPI [10, 11, 12, 13, 14, 15]. In very general terms, increasing calcium-based detergent treat rates in a lubricant has been found to increase LSPI under the conditions reported, while molybdenum and phosphorus containing components can be beneficial to LSPI. The absolute number of LSPI events may vary in different studies, but these general trends have been reported for lubricants tested in a number of engine platforms operated under a range of conditions. Other than detergent type, specific formulation information is rarely disclosed beyond base oil group, calcium, molybdenum, phosphorus and perhaps magnesium concentration in fresh oil.

Single cylinder engine tests are very useful tools to investigate the impact of injecting fuel, oil or a fuel/oil mixture directly into the combustion chamber. Oftentimes fuel surrogates or individual

lubricant additives are injected to monitor the effect on pre-ignition timing [16, 17, 18, 19]. These studies support the observation that lubricant contributes to LSPI.

Reducing the frequency of LSPI is closely linked to the enablement of engine operation to maximize the efficiency of modern downsized, turbocharged direct injection gasoline (TGDI) engine designs. As a result, minimizing the likelihood of LSPI events through engine oil formulation continues to be an active research area. Typical ILSAC GF-5 oils have been shown to provide insufficient LSPI protection [20], and detergent continues to be identified as the major contributor to LSPI from the lubricant. Therefore, next generation passenger car engine oils will need to utilize a modified detergent system in order to protect against engine damage that can result from LSPI while maintaining engine performance and oil life. There remains a great deal of ambiguity related to specific benefits or debits other lubricant components offer once the effect of detergent is reduced.

In this paper we consider the variability in the LSPI response of a high event baseline oil and methods to treat data in order to reduce engine and stand effects. We then systematically investigate the effect of single-metal and mixed-metal detergent systems as well as molybdenum and zinc dithiophosphate (ZnDTP) type and treat rate on LSPI frequency. Finally, we consider the impact of dispersant.

EXPERIMENTAL METHODOLOGY

All LSPI tests were conducted in a MY 2012-2013 GM 2.0L TGDI I4 Ecotec (LHU) engine that has been modified in such a way to facilitate both the generation and identification of LSPI events. [Table 1](#) lists select engine and operational parameters. For a complete 16 hour test, the engine is operated for a series of segments designed to generate LSPI events: a high load / high speed segment repeated a total of 16 times, and a lower load / lower speed segment repeated a total of 8 times. Under the applied operating conditions, statistically significant LSPI events were only generated for the high load / high speed segments. As a result, all data presented here summarize LSPI events recorded during valid high load / high speed segments.

Table 1. Engine Conditions at High Speed and Load

Engine	GM 2.0L I4 TGDI Ecotec (LHU)
BMEP, bar	19
Engine Speed, rpm	2000
Air-fuel ratio	fixed
Ignition timing	fixed
Camshaft phasing	fixed

To minimize the impact of fuel quality on LSPI, standard Haltermann EEE fuel was used for all tests. It is common to observe a shift in engine response as an engine ages, between engines and between stands. In order to monitor and assess the degree of shift in LSPI responsiveness, two baseline oils were included in the test plan: a high incident baseline oil, BL-HIGH, designed to generate a relatively high number of LSPI events, and a low incident baseline oil, BL-LOW, designed to generate a number of LSPI events similar to experimental oils. Both baseline oils were blended using Group III base stock. Select properties of the baseline oils are listed in [Table 2](#).

Table 2. Properties of Baseline Oils

Property	BL-HIGH	BL-LOW
Viscosity Grade	5W-30	5W-30
KV 100, cSt	10.9	10.4
HTHS-150, cP	3.3	3.1
Ca, wt%	0.24	0.16
Mg, wt%	0	0
P, wt%	0.075	0.075
Mo, wt%	0.008	0.008
TBN, mg KOH / g	8.9	6.6

A series of experimental oils were blended as SAE 5W-30 viscosity grade using Group III base stocks to evaluate the impact of detergent metal type and treat rate, detergent soap type, molybdenum type and treat rate, ZnDTP and dispersant treat rate on normalized LSPI frequency. When investigating the impact of the detergent system, all oils were blended to include approximately 0.008 wt% molybdenum and 0.076 wt% phosphorus from ZnDTP. The remaining experimental oils were blended using the same detergent system, overbased calcium sulfonate treated to deliver about 0.16 wt% calcium to the finished fluid. For the sake of clarity, specific modifications necessary to study the desired additive impact are described in the section discussing the results of that study.

RESULTS AND DISCUSSION

Engine and Stand Effects

Understanding the variability in engine response will increase confidence that observed differences in LSPI frequency arise from changes in fluid composition rather than from shifts in engine response. Data were generated over more than two years in 11 engines across 3 test stands. During this timeframe BL-HIGH was repeated 48 times and its response was used to evaluate stand and engine effects. A comparison of the sum of LSPI events observed for all valid high load / high speed segments could be misleading because, on occasion, one or more high load / high speed segment(s) was determined to be operationally invalid and omitted from further analysis. Using the average LSPI frequency per 25000 engine cycles naturally accounts for any invalid high load / high speed segments.

BL-HIGH data were treated in two ways to evaluate engine and stand effects at the 95% confidence level. For Data Treatment 1, the average number of LSPI events per 25000 engine cycles was analyzed. For Data Treatment 2, the data set was transformed by a normalization process to adjust for stand and engine variability. A typical run sequence consisted of BL-HIGH followed by a block of up to ten candidate oils and another BL-HIGH run. The candidate oil LSPI response was normalized by dividing by a BL-HIGH moving average calculated from initial and final BL-HIGH average LSPI counts per 25000 engine cycles.

Both data treatment methods resulted in normally distributed data sets. An examination of [Figure 1](#) clearly demonstrates that Data Treatment 2 reduces the impact of observed engine and stand variability on LSPI response.

Using Data Treatment 1, an analysis of the BL-HIGH data suggested that stand and engine model effects were statistically significant at the $\alpha = 0.05$ level. However, an analysis using Data Treatment 2, where BL-HIGH data was normalized, suggested that stand and engine model effects were not statistically significant at the $\alpha = 0.05$ level. [Table 3](#) lists the P-values from the statistical models that were used to evaluate the stand and engine effects on LSPI frequency.

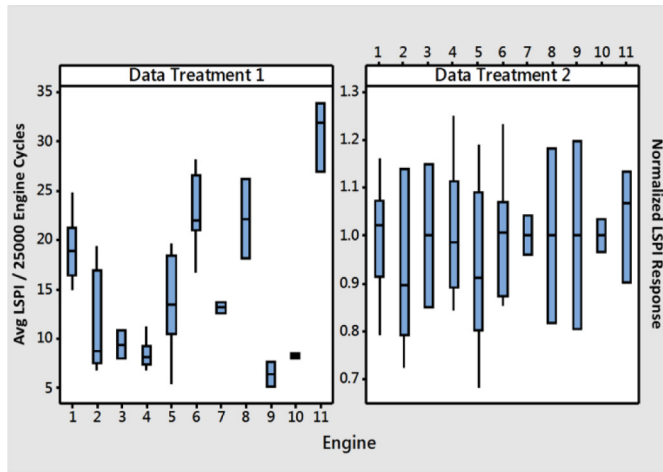


Figure 1. Effect of Data Treatment on LSPI Response

Table 3. Engine and Stand Effects at the $\alpha = 0.05$ Level

	Data Treatment 1 Avg LSPI per 25,000 Cycles	Data Treatment 2 Normalized LSPI
P-Value		
Stand	0.006	0.9797
Engine (Stand)	< 0.0001	0.5355

To further evaluate the applicability of the two data treatment methods, a smaller BL-LOW data set was analyzed. Figure 2 illustrates the LSPI response of BL-LOW calculated using Data Treatment 1 (Figure 2A) and Data Treatment 2 (Figure 2B). For both plots, 95% confidence intervals around the true mean test response of BL-LOW are indicated by the dashed lines.

For this limited data set, one oil repeated in two engines on a single stand, a higher percentage of BL-LOW data analyzed using Data Treatment 2 falls within the 95% confidence interval. Again, Data Treatment 2 seems to reduce the observed engine effects that could hinder an assessment of the lubricant impact on LSPI. For example, refer to the two oils indicated by an asterisk in Figure 2A. These two oils look very different from each other and different from the average BL-LOW response as they are outside the bounds of the 95% confidence interval for the mean BL-LOW test response. The results shown for these two oils in Figure 2A could erroneously be considered different, when, in fact, they are the same oil repeated more than once. The differences in test response for these two oils are reduced by the normalization process. Using Data Treatment 2, the two oils indicated by an asterisk in Figure 2B now fall within the 95% confidence interval for the mean response of BL-LOW. This shows that after the normalization process, these oils both fall within the expected range for the true BL-LOW test response.

A recent report [21] also normalized the LSPI response of experimental oils by a baseline oil in order to, at least in part, account for shifting engine response. No data treatment method can eliminate all observed engine and stand effects. However, the normalization process suggested here increases confidence that observed differences in LSPI response are correctly attributed to formulation changes. Subsequent data for experimental oils were transformed using Data Treatment 2 in order to more accurately assess formulation impacts on observed differences in LSPI response.

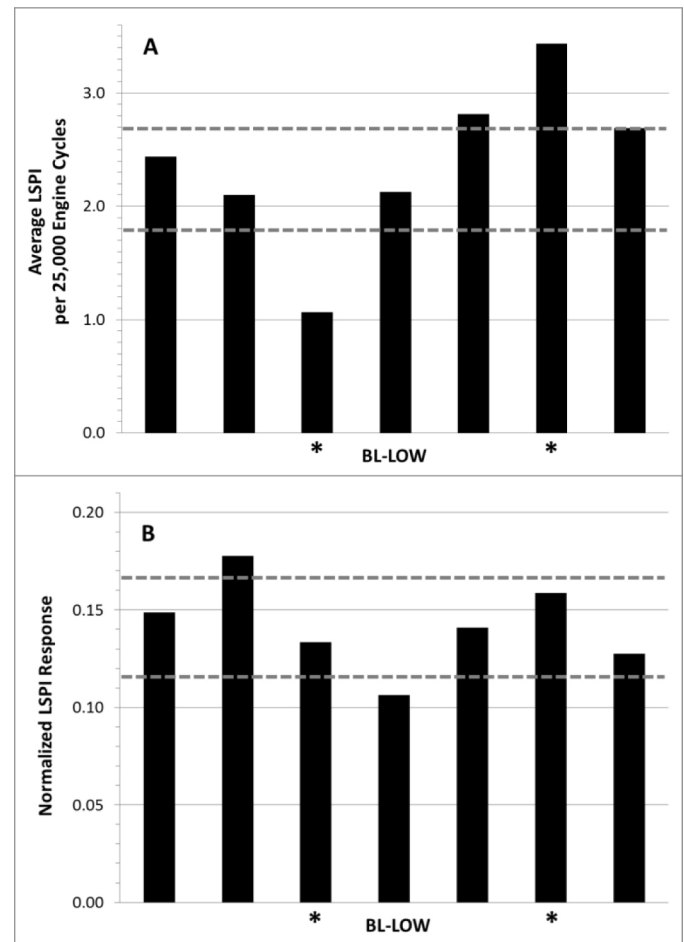


Figure 2. LSPI Frequency and 95% Confidence Interval (dashed lines) of BL-LOW Following (A) Data Treatment 1 and (B) Data Treatment 2

Additive Impact: Effect of Detergent System

As mentioned in Background, many references report the impact of calcium on LSPI frequency. In this study we examine the effect of the detergent system on LSPI frequency: single-metal, calcium-based systems made up of overbased detergents or combinations of overbased and low base / neutral detergents, and mixed-metal detergent systems. All other additive components remained constant for this series of oils. Table 4 describes how the detergent system was varied in this study and includes finished fluid TBN measured using ASTM method D-2896.