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Full Length Article

Effect of market variations in gasoline composition on aspects of stochastic pre-ignition

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HIGHLIGHTS

- Marketplace variation in fuel composition caused large variation in SPI frequency.
- Sum of aromatic and olefin concentrations most accurate predictor of SPI frequency.
- Chain-reaction SPI events observed, with groups of SPI events in rapid succession.
- SPI frequency increase corresponds primarily to increase in number of groups.
- Results strongly connect fuel properties, deposit dynamics, and SPI frequency.

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ABSTRACT

The sensitivity of stochastic pre-ignition (SPI) behavior to commercial variations in fuel composition in the United States was systematically evaluated in a typical modern 2.0 L downsized boosted engine. In-cylinder pressure time history measurements made during a prescribed speed-load test sequence were used to determine the frequency and pattern of SPI occurrence and the resulting in-cylinder peak pressures. Ten fuels in total were evaluated all with "regular" commercial octane ratings and broad variation in paraffin, olefin, and aromatic concentrations. The engine was operated using a production calibration, and air conditions in the intake manifold were held constant at approximately two bar and 35 °C. A wide range of SPI frequency results was indeed observed, between zero and 45 events in 135,000 engine cycles; whereas, variation in peak pressures during SPI across all fuels was minimal. Analysis of the present results combined with those from a previous study indicated that the sum of aromatic and olefin concentrations in each fuel, represented in an exponential model, is the most accurate predictor of SPI frequency. SPI behaviors were often observed in groups of "chain-reaction" events in rapid succession and increases in SPI frequency corresponded chiefly to a rapid increase in the number of groups not the number of events in each group. Collectively the present results support the hypothesis that increases in SPI frequency for high aromatic and olefin fuels are driven by enhanced engine deposit formation and dynamics, not an heightening of local reactivity as has often been proposed in previous literature.

1. Introduction

As fuel economy focused downsized boosted gasoline engine architectures are becoming more prevalent the relative impact of stochastic pre-ignition (SPI) behaviors is likewise increasing. These undesired behaviors are characterized by a random and uncontrolled early local ignition, which can lead to abnormally early heat release and large magnitude destructive auto-ignition, also called "super-knock." SPI occurs most often at low-speed high-load highly boosted conditions where the chemical time scales driving ignition and pre-spark in-cylinder residence times are similar. With this in mind it is critical to develop viable mitigation strategies for SPI, to enable the broader implementation of highly boosted combustion strategies aimed at fuel economy and emissions improvements.

It has been well established throughout the current and historical literature that the occurrence of SPI is highly dependent on fuel composition, see Haenel et al. [1], Amann et al. [2], Sturgis [3], and Pless [4] and the references therein; with aromatic content generally well correlated to increased propensity for SPI behavior.

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Considering the wide variations in domestic and international gasoline fuel composition [5], it follows that differences in SPI behaviors in vehicles resulting from these compositional variations is very likely. In practical terms, a customer with the same vehicle could experience drastically different SPI behaviors simply by filling up at one gas station versus another. In reviewing the current literature, it is presently not possible to meaningfully predict the magnitude and manifestation of these expected SPI behavior differences, given that nearly all studies of fuel effects have focused on neat fuels or synthetic fuel blends and few if any quantitative relationships between fuel composition and SPI behaviors have been established. Furthermore, while the qualitative correlation between aromatic content and increased SPI activity is well established the precise mechanism through which these compounds act to stimulate SPI are not well understood. As discussed in Mansfield et al. [6] there are both chemical and physical attributes of aromatic compounds that are feasible pathways of impact on SPI behaviors.

To address these needs the primary goal of the present work was to evaluate the effects of compositional variation of commercially available pump gasolines in the United States on SPI behaviors; frequency and patterns of occurrence, as well as impact of events (peak in-cylinder pressure). This goal was accomplished by stimulating, quantifying, and comparing the SPI tendencies of nine different fuels sampled from consumer gas station pumps across the continental United States marketed as “regular octane”, described in detail in Table 1, in a typical modern downsized boosted 2.0 L in-line 4 cylinder engine operated at a typical condition. Note that all these pump fuels were rated as 87 average knock index (AKI). These data were then combined with those for two other regular octane fuels, one synthetic blend and one certification fuel, from a study by Mansfield et al. [6], in order to create a larger database of SPI results. The properties of these two additional fuels are also described in detail in Table 1. The distillation curves of all fuels considered here are given in Fig. A1 of the Appendix, measured using the ASTM D86 procedure. With this comprehensive data set in hand, the secondary goals of this work were to identify any significant quantitative relationships between fuel composition and SPI behaviors, and then leverage these findings to gain insight into the fundamental pathways for fuel effects on SPI. This includes an investigation of chain-reaction SPI behaviors, where an initial events spurs several follow on events in close succession. In this work an SPI event is defined as an engine cycle which exhibited SPI behaviors, which are described specifically later.

2. Methods

For each fuel under consideration in this work two major observations were made during each experiment, the number of SPI events and the peak in-cylinder pressure during them, hereafter referred to as SPI frequency and peak pressure. Additional specific details of the combustion process and SPI patterns were also determined and used for more in depth analysis and interpretation of the results as appropriate.

2.1. Experimental

All experiments were conducted using a modern production 2.0 L direct injected turbocharged 4-cylinder engine with a production intent calibration. The engine operation and all boundary conditions were controlled using an AVL Puma system. Each cylinder was instrumented with one centrally-located pressure transducer, type AVL GH14D or GH14DK, indexed to the manifold air pressure, and sampled at 20 kHz frequency. Uncertainty in the raw pressure measurements was conservatively estimated at ±1–2%. The raw readings from the pressure transducers was recorded and processed directly in a custom post-processor (discussed in a later section), where a three-point smoothing algorithm was applied to reduce artifact noise. The engine thermal boundary conditions were held constant throughout the testing with: $T_{\mathrm{coolant,engine\ out}} = 95\ ^\circ\mathrm{C}$, $T_{\mathrm{oil,\ engine\ sump}} = 85\ ^\circ\mathrm{C}$, $T_{\mathrm{air,\ intake\ manifold\ in}} = 35\ ^\circ\mathrm{C}$. The dynamometer control system was able to hold these values within reasonable bounds (±5–15%) during the test sequence. Dexos 1 Generation 1 5W-30 oil was used throughout the testing with a specific systematic oil break-in procedure implemented in order to ensure uniform oil condition at the start of testing. Using a fixed and retarded spark timing from typical operation, air intake manifold air pressure (MAP) and CA50 (Crank angle degrees after

Table 1
Test fuel composition and basic properties.

Fuel name/station location	AKI[a]	RVP[b]	FBP[i]	Paraffin	Aromatic[c]	Napthene	Olefin
	–	psi	°C		vol%[d]		
Test fuels, from Mansfield et al. [1][h]							
Synthetic 4[h]	88	9.3	234	40.0	32.4	8.6	8.6
Tier III Cert.[j]	88	8.9	208	45.6	24.6	9.2	10.8
Commercial pump fuels (present work)[f,g]							
Great Falls, MT	“Regular”	9.9	191	53.9	17.3	8.2	10.1
Martinez, CA		7.5	194	46.5	21.1	13.0	8.6
LaPlace, LA		9.7	202	55.3	16.8	7.1	10.1
Lake Charles, LA		8.4	206	45.2	23.2	7.9	12.6
Anacortes, WA		9.8	216	50.3	22.1	9.6	7.7
Corpus Christi, TX		7.5	203	58.2	7.2	7.8	16.4
Richmond, CA		7.5	191	47.0	21.1	12.9	8.2
Baton Rouge, LA		8.3	213	44.3	20.1	7.0	16.6
Wilmington, CA		7.3	196	53.6	22.7	8.9	4.9

[a] Average Knock Index = (RON + MON)/2.
[b] Reid vapor pressure, per ASTM D5191.
[c] Includes naphthalenes.
[d] Concentrations per ASTM D6730. Remainder primarily water and ethanol, approx. 10 vol%.
[f] Detergent additives at “Lowest Allowable Concentration”.
[g] All fuels have 87 average knock index (AKI) rating.
[h] Synthetic 4 and Tier III Cert. fuel contain no detergent additives.
[i] Final boiling point, per ASTM D86, temperature at which 96–98% volume fraction evaporated.
[j] Environmental Protection Agency. Control of air pollution from motor vehicles: Tier 3 motor vehicle emission and fuel standards. Fed Regist 2014;79:23414–886.