

Fuel Octane and Volatility Effects on the Stochastic Pre-Ignition Behavior of a 2.0L Gasoline Turbocharged DI Engine

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ABSTRACT

Classic, hot-spot induced pre-ignition is a phenomenon that has been observed in gasoline spark ignited engines over the past 60-70 years. With the development of turbocharged, direct-injected (DI) gasoline engines, a new pre-ignition phenomenon occurring at low engine speeds and high loads has been encountered. Termed Stochastic Pre-ignition (SPI), it has become a significant issue to address in allowing for the full potential of gasoline turbo DI technology to improve powertrain efficiency. Many researchers are studying all aspects of the causes of Stochastic Pre-ignition, including causes by oil, fuel and engine hardware systems. The focus of this specific research was to study the relationship of fuel octane and volatility to Stochastic Pre-ignition behavior utilizing a GM 2.0L Gasoline Turbocharged DI engine (LHU).

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INTRODUCTION

Abnormal combustion phenomenon, Stochastic Pre-Ignition in particular, have become more critical in modern engines which are more commonly downsized and boosted with direct injection. As compared to conventional engine knocking due to rapid auto-ignition of fuel/air mixture (end gas) ahead of the flame front, SPI is considered uncontrollable by traditional knock control algorithms in vehicle ECMs (Engine Control Module). SPI is caused or influenced by engine design, operating conditions, droplets or deposits, and fuel and lubricant chemistry [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

Previously, Dahnz and co-workers studied the SPI frequency of various fuels [9]. Specifically, they noted the differences in the Research Octane Number (RON) number of the fuels. [Figure 1](#) shows the results of their study. Initially, they showed a decrease in the SPI rate with an increase in the RON of the fuel. However, when the RON 100 fuel that had the lowest SPI rate was retested, it then showed the highest SPI rate. They concluded that octane number (RON) was not the correct or only fuel property to use to correlate to SPI tendency. This change in SPI frequency was attributed to the aging of the fuel and a subsequent change in fuel properties due to the storage.

The effect of aging on fuel volatility was suggested as having an important role. Fuel volatility is the composite property of several hundreds of compounds in a typical gasoline, and measured by vapor pressure and the distillation temperature curve. The distillation curves for the original and old (aged) RON 100 fuels from [Figure 1](#) are shown in [Figure 2](#). While both fuels had about the same T90 temperature, the fuel's overall volatility was

lowered after extended storage. The conclusion drawn was that low volatility fuel tends to have more pre-ignition than fuels with higher volatility. It should be noted, though, that other fuel property and chemistry changes may have resulted from the fuel aging. From the Dahnz work, only the resulting distillation curve of the RON 100 Old was verified. It is unknown if the fuel octane (RON) or other characteristics had also changed, because those fuel properties were not presented.

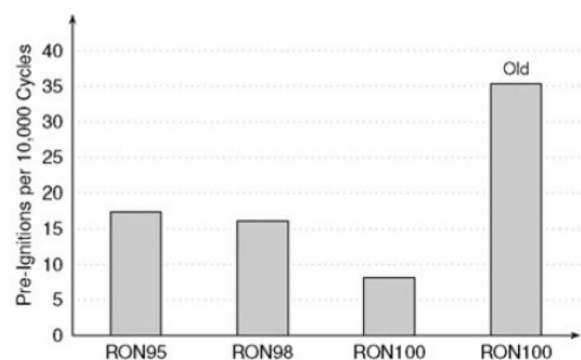


Figure 1. SPI frequency for different fuels from Dahnz study [9]

In another, more recent study, Zahdeh and co-workers also preformed SPI testing with various fuels in two different turbocharged, direct-injected (DI) engines [1]. In their work, they noted some of the fuel properties of interest for the fuels as shown in [Table 1](#). [Figure 3](#) shows the distillation curves for the various fuels tested while the SPI rate plotted against RON is presented in [Figure 4](#).

As shown in [Figure 4](#), the observed trends of the fuel RON number and the SPI rate do not correlate. Comparison to Spark Advance and MAP were also analyzed. While there seemed to be some trending, the data did not correlate with all fuels. This appeared to be due to a change to the boost pressure in the engine test condition [1]. As the author notes, this is related to the way that the engine torque was controlled. Higher RON fuels allowed the spark to be advanced and boost compensated (lowered) in order to maintain torque. This change in boost also influenced the SPI frequency and convoluted correlation of SPI frequency to fuel RON.

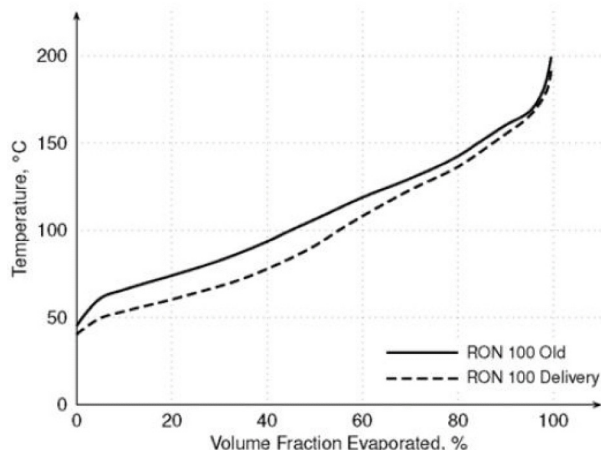


Figure 2. Boiling curves of fuels used during fuel variations from Dahnz study [9]

The two fuels with the lowest SPI rate were the High DVPE (Dry Vapor Pressure Equivalent) fuel and the RON 100 fuel [1]. These fuels had a lower end of boiling temperature by 10° C compared to the rest of the group. The two fuels also had the lowest volume percent of high boiling aromatics. The authors note that a common denominator for both the fuels is the high volatility in the temperature regime between 130° C (266° F) and 150° C (302° F). Notice, that the two fuels with the lowest SPI rate were also the lowest in T60 through the End of Boiling Temperature, as the authors also observed. Also, it should be noted that the E10 fuel did not follow the same trend in volatility and SPI rate, even though it had a lower T50 like the High DVPE fuel.

Other authors have studied various aspects of fuels that they hypothesize are impacting SPI. These include fuels containing higher concentrations of compounds with low minimum ignition energy [2], fuels lower in laminar flame thickness [3], and fuels with varying chemical kinetics [6]. Ricardo and Helpson produced data for the preignition resistance (PR) of single component fuel compounds with a heated wire used to start the pre-ignition [11]. They were able to rate the single components as having higher or lower PR, with a higher PR number being more prone to preignition, and a lower or negative PR number less prone to preignition. With the Ricardo data, Kalghatgi plotted this data against the laminar flame speed of the fuel and the RON and MON [12]. A correlation was established with the single component compound's PR

and laminar flame speed, but no correlation was found with RON and MON. There are additional aspects of the literature to be reviewed in greater details with links to SPI, but this paper will only focus on a few properties.

Recent hypotheses and experiments involving the stochastic pre-ignition issue have focused on the fluids used in modern engines, including the oil, fuel, and the resulting partial combustion of the oil and fuel mixtures developing into droplets, deposits and particles. To sort out the impact of each of the fluids separately, engine dynamometer tests have been developed to show the impacts of the oil and the fuels. However, the papers in the literature have been conflicting with regard to various fuel properties, and tend to focus on single component fuels rather than blended fuels. To try to answer some of those questions, this paper focuses specifically on the influence of fuel volatility and octane number on SPI using a set of fuels blended with a majority of normal gasoline components.

APPROACH, EXPERIMENTAL SET UP AND TEST PLAN

To confirm and further understand the observations previously shown in the literature, an experiment was devised with a parametric fuel set. A turbocharged DI engine was selected and set up on an engine dynamometer and a SPI test was established.

Approach

The approach to this project was to develop a set of fuels with various Research Octane Number (RON), Motor Octane Number (MON), and volatility characteristics and then to test those fuels in a turbocharged DI engine at a fixed set of operating conditions. The test procedure was comprised of a fixed speed and load condition and SPI events are recorded over 16 segments of 15 minutes each. The results shown are the total number of SPI events that were detected.

Experimental Set Up

A description of the GM 2.0L turbocharged, spark-ignition, direct-injection engine used in the project is shown in [Table 2](#).

Test Plan

Each of the fuels was tested on the same engine installation and in a specific sequence of testing. That engine sequence is shown in [Figure 5](#). The engine test was run with a total of 16 repetitions for 15 minutes each. Because of the length of the test, the repetitions occurred over a 2 day period, with 8 on each day. The engine was run at a fixed, steady-state set of conditions as shown in [Table 3](#).

Table 1. Fuel specification for the 7 test fuels from Zahdeh study [1]

Metrics \ fuel names →	RON 95	RON 91	RON 98	High DVPE	Low DVPE	E 10	RON 100
RON	95,3	92,5	98,0	90,3	99,1	98,1	100,9
Density (15°C) [g/l]	750,7	743,4	750,5	723,8	765,9	763,2	746,1
Evaporation residue (unwashed) [mg/100ml]	33	33	34	6	11	2	48
Start of Boiling [°C]	35,5	34,1	33,2	28,0	37,9	39,7	34,9
End of Boiling [°C]	200,3	206,6	200,4	189,6	200,8	196,8	190,0
Ethanol [Vol.%]	0,2	<0,1	0,2	<0,1	0,1	9,7	0,2
Methanol [Vol.%]	<0,1	0,4	<0,1	<0,1	<0,1	0,4	<0,1
High Boiling Aromatics [Vol.%]	1,21	1,04	0,52	0,44	0,61	0,48	0,38
Oxygen [%]	1,1	1,2	2,4	0,0	2,1	3,9	1,8
DVPE at 37,8°C [kPa]	55,5	55,8	57,2	98,0	47,9	58,9	54,7
Heating Value [MJ/kg]	42,7	42,9	42,2	43,4	42,2	41,7	42,5

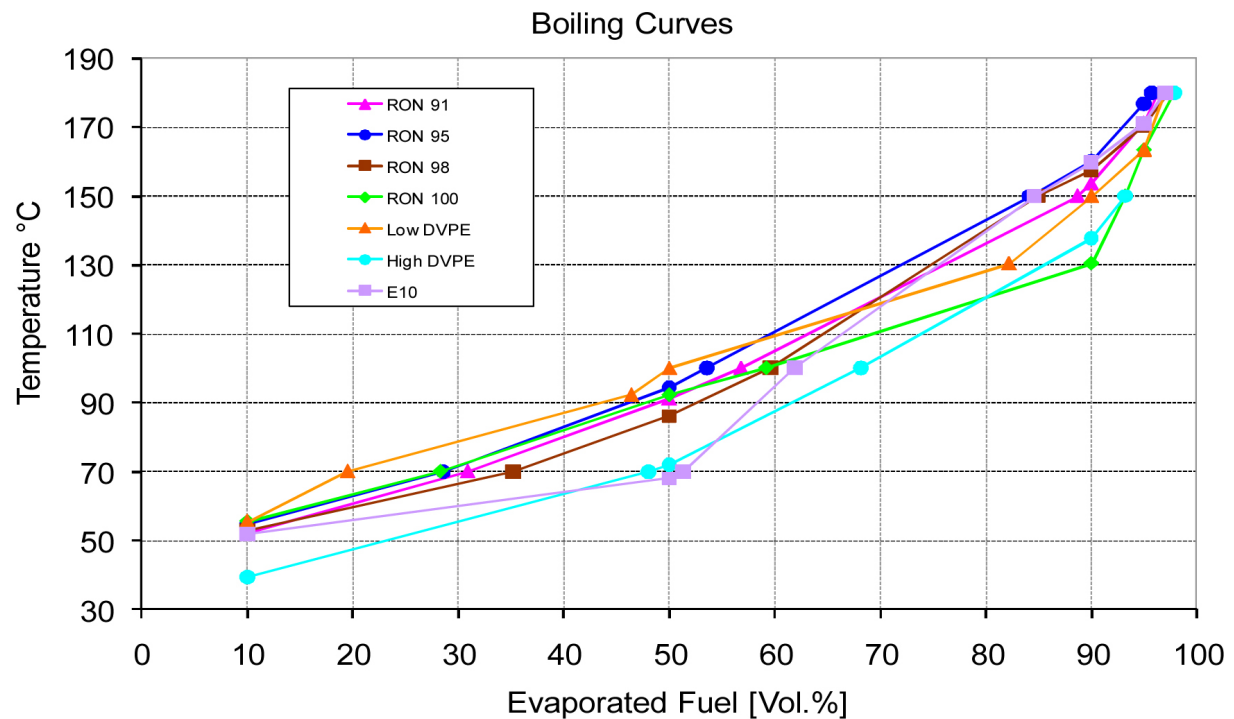


Figure 3. Distillation curves for the different fuels tested from Zahdeh study [1]

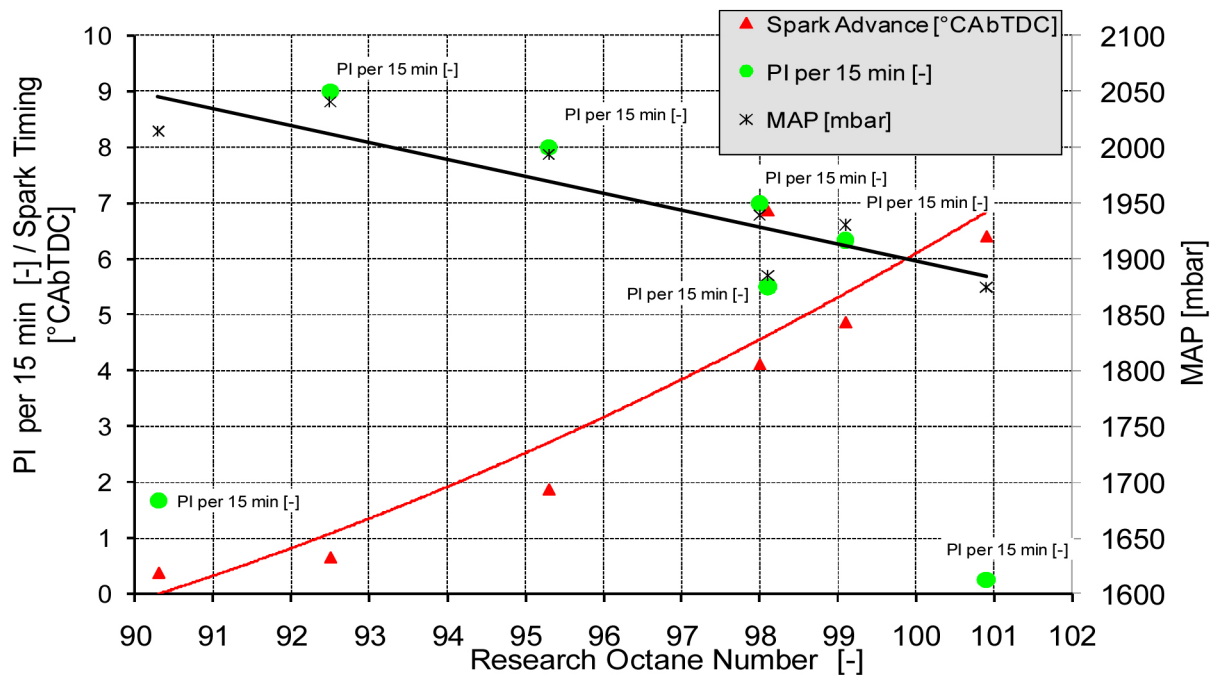


Figure 4. Comparison of Research Octane Number to SPI Events from Zahdeh study [1]

Table 2. GM 2.0L turbocharged, spark-ignition, direct-injection engine (LHU) specifications

Displacement	1998 cc
Bore	86.0 mm
Stroke	86.0 mm
Compression Ratio	9.2:1
Fuel Injection System	Direct Injection
Injector Location	Side Mounted
Injector Type	Multi-hole
Valvetrain	DOHC RFF with Hydraulic Lash Adjusters
Cam Drive	Dual, Continuously Variable Phasing
Cam Phasing Authority	50° Crank (Intake and Exhaust)
Turbocharger	Twin-Scroll
Power *	164 – 201 kW **
Torque *	350 – 400 Nm **
Peak BMEP *	22 – 25 Bar **
Recommended Fuel Quality	Premium Recommended (but not required)

* SAE Certified; ** Varies by Vehicle Application

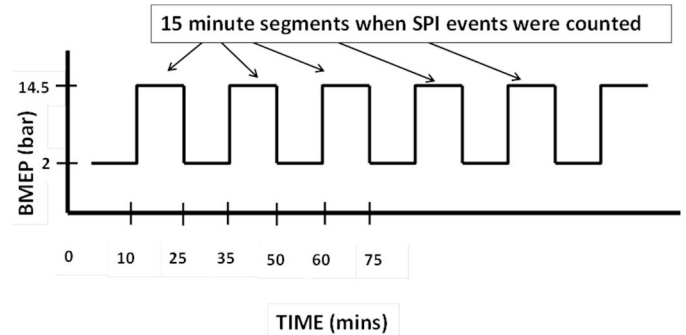


Figure 5. SPI test procedure with 5 fifteen minutes segments showing of the total of 16 segments.

Table 3. Test conditions for the GM 2.0L turbocharged, spark-ignition, direct-injection engine (LHU)

Data Description	Set Point
Engine Speed (rpm)	2000
Load (BMEP)	14.5 bar
Exhaust Equivalence Ratio	0.9:1 (lean of stoichiometric)
CA50 (Ignition Timing adjusted as needed)	33.5° ATDC
Engine Coolant Temperature	70°C
Intake Manifold Air Temperature	35°C
Intake Manifold Air Temperature – Fuel G	50°C
Engine Oil Temperature	100°C
Intake Manifold Pressure	Adjusted to set desired equivalence ratio
Fuel Flow Rate	Adjusted to set desired BMEP
Supply Air Conditions	Standard per SAE J1349