

Influence of Ethanol Blends on Low Speed Pre-Ignition in Turbocharged, Direct-Injection Gasoline Engines

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ABSTRACT

Modern combustion engines must meet increasingly higher requirements concerning emission standards, fuel economy, performance characteristics and comfort. Especially fuel consumption and the related CO₂ emissions were moved into public focus within the last years. One possibility to meet those requirements is downsizing. Engine downsizing is intended to achieve a reduction of fuel consumption through measures that allow reducing displacement while simultaneously keeping or increasing power and torque output. However, to reach that goal, downsized engines need high brake mean effective pressure levels which are well in excess of 20bar. When targeting these high output levels at low engine speeds, undesired combustion events with high cylinder peak pressures can occur that can severely damage the engine. These phenomena, typically called low speed pre-ignition (LSPI), set currently an undesired limit to downsizing.

This study analyzes the influence of ethanol fuel content on low speed pre-ignition events in a direct-injection turbo charged gasoline engine with a homogeneous ($\lambda = 1$) common rail high pressure injection system, side mounted multi-hole injectors and dual variable valve timing. All experiments were conducted on a steady state engine test bench with intake air, coolant, oil and fuel conditioning to be able to separate fuel effects from boundary condition influences. In addition, the engine was equipped with a prototype engine controller that allows to negate the influence of control algorithms on combustion. Four ethanol fuels containing different levels of ethanol were blended using the same base fuel and denatured ethanol. The investigated blends included E10, E20, E30 and E50 fuels. Subsequently, test runs were performed to understand the impact of different ethanol blends on occurrence, number and pressure characteristics of LSPI.

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INTRODUCTION

Low Speed Pre-Ignition

Downsized, highly boosted direct-injection gasoline (GTDI) engines are one way to meet today's increased demands regarding improved fuel economy and reduced CO₂ emissions. In the past years however, several OEM have reported an abnormal combustion phenomenon that challenges further downsizing efforts. This phenomenon is characterized as a stochastic, premature ignition of the cylinder charge under low engine speed and high engine load conditions (see Figure 1) which often also leads to violent and destructive knock events. The phenomenon can occur in isolated, single events or in characteristic bursts which often occur in intermittent pattern (see Figure 2). The phenomenon is generally called low speed pre-ignition (LSPI) or stochastic pre ignition (SPI) in literature due to its characteristics and area of occurrence. Figure 3 displays examples for two pre-ignition events with and without knock as well as a regular combustion cycle.

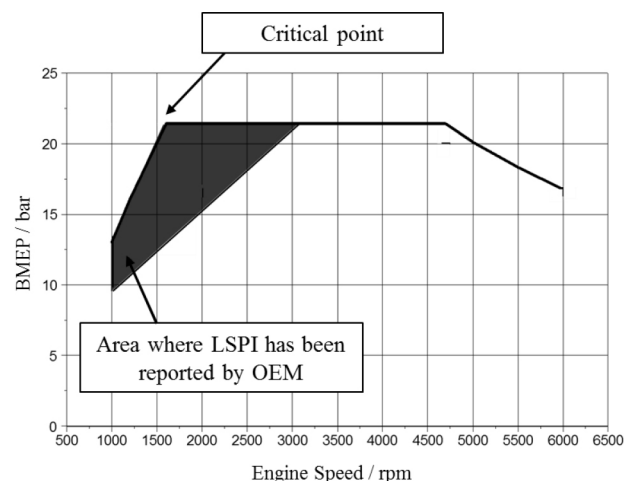


Figure 1. Operating range example where LSPI has been reported by OEM

Many studies have been conducted and published in recent years to analyze the potential root cause and possible impact factors of low speed pre-ignition. Even though the causing mechanism has been narrowed down significantly, a detailed mechanism has still not been established yet.

Optical investigations have determined though that pre-ignition events in modern GTDI engines are not usually localized on combustion chamber surfaces but seem to be instead initiated in various seemingly random locations inside the combustion chamber [e.g. 1, 2, 3, 4]. In addition, a strong dependency of LSPI occurrence on oil composition - especially on metallic oil additives such as e.g. calcium based additives - could be found by several research groups [e.g. 5, 6, 7, 8]. Other investigated dependencies include the impact of fuel properties such as e.g. fuel volatility [9] or deposit formation [e.g. 10, 11, 27], calibration characteristics such as e.g. enrichment, injection timing or exhaust gas recirculation (EGR) [e.g. 3, 10] or design parameters such as e.g. piston and ring designs [12].

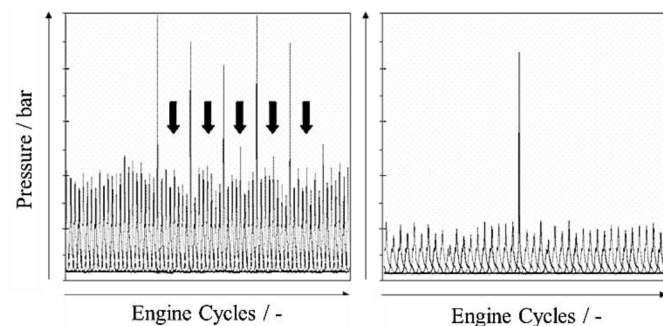


Figure 2. Examples for a characteristic LSPI burst (left) and a single isolated event (right)

The following mechanism has been suggested to combine above observations [2, 13, 14]:

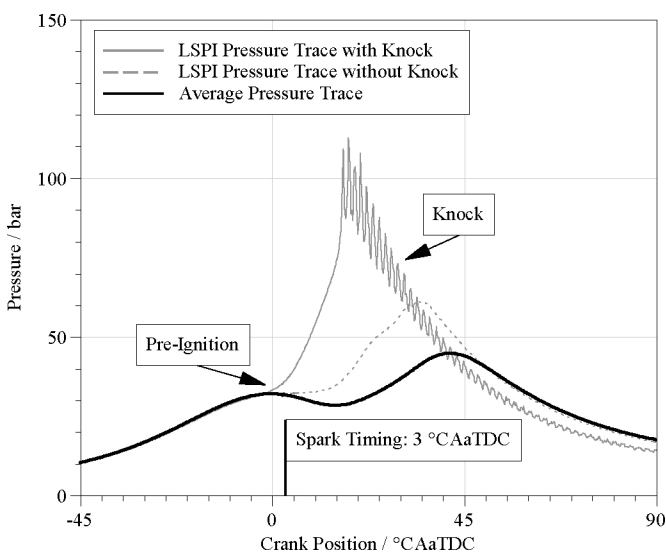


Figure 3. Comparison of LSPI pressure trace examples with and without knock

Oil, oil-fuel mixture or oil and oil-fuel based deposits that accumulate on the cylinder wall and crevice volume of the top ring land area can get thrown, blown or vaporize into the combustion chamber during

the gas exchange or compression stroke of the engine. These droplets can then further mix with oxygen and auto-ignite thus leading to a flame initiation and deflagration. Due to the often early flame initiation and start of deflagration LSPI events can subsequently lead to engine knock and detonation.

Ethanol Fuel Blends and LSPI

The use of alcohol fuels in spark ignited engines has been researched extensively in the past and the results of such alcohol fuel studies are well documented. Especially during the energy crisis in the early 1970's interest in alcohol fuels was high. Testing was however performed with engines using the hardware available at the time and is therefore of limited relevance today. In the early 2000's the interest in biofuels increased again and several studies have been published since. Since the last ten years however, DI fuel injection and turbo charging have gone from a niche technology to mainstream hardware. Few studies have been performed to analyze the impact of ethanol blend fuels on auto-ignition or low speed pre-ignition in this context.

The actual impact of ethanol on pre-ignition is still controversial at this point. Results of our first study evaluating LSPI impact factors from 2011 indicated an unexpected increase of LSPI occurrence with ethanol fuel blends [10]. In the following years, Kalghatgi has correlated pre-ignition resistance to laminar flame speeds and concluded that the increased pre-ignition occurrence with ethanol fuels is due to the high laminar flame speed of such blends [13]. Ebersole et al. quantified the increased surface ignition likelihood of ethanol blends that also leads to the need to utilize colder spark plugs in engine applications using ethanol blends [16]. Hamilton et al. [17] and Menrad et al. [18] similarly reported worse behavior than iso-octane and other gasoline components in PFI engines when using (high-level) ethanol blends. Studies focusing on turbo DI engines and low- or mid-level ethanol blends that supported our finding in 2011 were and are still sparse though.

Several studies performed in this time frame that investigated ethanol blend impact on pre-ignition came however to different conclusions. Bobicic et al. found that pre-ignition numbers reduce with increased ethanol content [19]. Similarly, Kieberger et al. reported an increase in indicated mean effective pressure before occurrence of LSPI when running low- and mid- level ethanol blends [20]. Guenther et al. investigated the impact of biofuel components on surface ignition and gas-phase auto-ignition. The study concluded that ethanol blends reduced LSPI occurrence with both mechanisms [21].

EXPERIMENTAL SETUP

Engine Specifications

The impact of fuel ethanol content on LSPI was tested in a production turbocharged direct-injection inline-4-cylinder engine. The engine is equipped with four valves per cylinder, dual overhead camshaft and continuous variable valve timing on both the intake and exhaust side. The fueling system is a side injected DI system with a maximum injection pressure of 150bar and 7-hole solenoid injectors. The engine features oil cooling jets, which were not active during the performed tests. Like many turbocharged

DI engines, this engine is designed as a high tumble concept with a comparably low intake flow coefficient but high charge motion. On the exhaust side the engine features an integrated, water cooled exhaust manifold (“headerfold”) with a single scroll turbo charger. Both cylinder head and block are made of aluminum. The piston assembly is an aluminum piston with a cast iron connecting rod. One of FEV’s prototype engine control units (ECU) was used in order to control spark timing, throttle position, injection timing, injection settings, valve timing of the intake and exhaust camshaft and enrichment. The use of this prototype engine controller ensured that all engine settings could be manually adjusted to fixed set points and were not automatically altered by vehicle control algorithms. Specifically, the use of the prototype ECU ensured that no vehicle algorithms such as cylinder balancing or engine knock and LSPI mitigation control functions were interfering with the statistical integrity of the performed testing. Some key engine characteristics are summarized in [Table 1](#).

Table 1. Selected test engine specifications

Property	Unit	
Engine type	-	4-cylinder, I-4
Injection type	-	SI-DI, 7-hole-solenoid-injector, side DI
Aspiration	-	turbocharged, integrated exhaust manifold
Ignition system	-	symmetrical, 1 - 3 - 4 - 2, central spark plug
Gas exchange	-	4 vlv/cyl, DOHC, cont. variable valve timing
Displacement	l	1.999
Bore	mm	87.5
Stroke	mm	83.1
Stroke / Bore	-	0.95
Compression ratio	-	9.3 : 1
Power output	kW	179
Specific power	kW/l	89.5
Max. injection pressure	bar	150
Max. torque	Nm	360
Specific torque	Nm/l	180
Miscellaneous	-	piston oil jet cooling

Test Cell Setup

The engine was set up in a steady state dynamometer test cell. The test cell setup allowed closed loop control of all boundary conditions including inlet air temperature, pressure and humidity, fuel temperature and pressure, coolant and oil temperature as well as exhaust backpressure. The engine’s production intercooler was removed and replaced by a test cell intercooler that allowed additional closed loop control of intake manifold conditions. All control parameters and operation characteristics were continuously monitored with a frequency of 10Hz.

In an effort to minimize the influence of externally fed oil residue on combustion and to be able to isolate fuel-oil interactions from inside the combustion chamber, the blow-by gas was instead discharged and measured during the LSPI test runs rather than being returned to the intake manifold. Lambda measurements and calculations were used as quality check and to detect possible measurement equipment issues. Since the lambda calculation according to Spindt [22] is based on exhaust constituent measurements while the volumetric lambda measurement is based on air and fuel flow measurements a

comparison of these two independent measurements indicates equipment, setup or engine issues immediately. An additional pressure corrected lambda probe was installed upstream of the turbine for the use of the prototype ECU.

All four cylinders of the engine were equipped with flush mounted water cooled piezoelectric relative pressure transducers (Kistler 6041A) with an additional absolute low pressure transducer (Kistler 4005BA5FA0) in intake runner one for pressure pegging. For each measurement point continuous cylinder pressure cycles were measured at a frequency of 1800 signals per revolution (0.2°CA resolution) and subsequently analyzed. The measurement position of the cylinder pressure transducers was located between intake and exhaust valves towards the front of the engine at the side of the combustion chamber. This location was chosen to be able to capture the more prominent circumferential pressure oscillation modes during knocking combustion and thus to avoid to under-estimate the severity of knocking combustion.

To capture the LSPI predicting THC spike during gas exchange [24] a Combustion HFR500 fast flame ionization detector (FFID) was included into the exhaust manifold upstream turbo. Due to the design of this engine with an integrated “headerfold” exhaust manifold and a single scroll turbo charger a single FFID was capable to capture all four exhaust pulses. The FFID was fed into the combustion analyzer at a frequency of 1800 signals per revolution (0.2°CA resolution). With a response time as low as 0.7ms T10-90 the HFR500 can distinguish between two adjacent firing cycles and offer information about the variation in HC concentration during a single exhaust stroke.

Lubricant Properties

Lubricant selection and ageing status are major impact factors when performing LSPI testing. To avoid interference of lubricant oxidation and fuel dilution with test results, an oil change was performed before each test run. The utilized lubricant was a commercially available 5W30 engine oil and was selected based on its behavior of leading to above-average numbers of LSPI events.

Fuel Properties

Four ethanol fuels containing different levels of ethanol were blended using the same baseline fuel and denatured ethanol. The investigated blends included E10, E20, E30 and E50 fuels. The four test fuels were splash blended using a common Regular E10 gasoline and denatured Ethanol with an ethanol content of 96.6%. The blending procedure took the denaturant and the thus reduced ethanol content of the denatured ethanol into consideration to reach the exact blend levels. [Table 2](#) summarizes some analysis results of the baseline fuel used for splash blending.

By choosing this blending approach important fuel characteristics such as fuel volatility, the evaporative curve and octane rating obviously differ between the ethanol blends. The approach allowed however to keep the chemical composition of the baseline gasoline constant.

Table 2. Results of the fuel analysis for the base fuel used for splash blending

Fuel Property	Test Method	Unit	
Specific Gravity at 60degF	ASTM D4052	-	0.744
RVP at 100degF	ASTM D5191	kPa	67.30
Research Octane Number	ASTM D2699	RON	92.4
Motor Octane Number	ASTM D2700	MON	83.3
Octane Rating	Calculated	(R+M)/2	87.85
Octane Sensitivity	Calculated	R-M	9.1
Aromatic Content	ASTM D1319	vol. %	22.9
Olefins Content	ASTM D1319	vol. %	8.0
Saturates Content	ASTM D1319	vol. %	59.2
Ethanol Content	Gas Chrom.	vol. %	9.8

Figure 4 shows the evaporative curve of the baseline fuel.

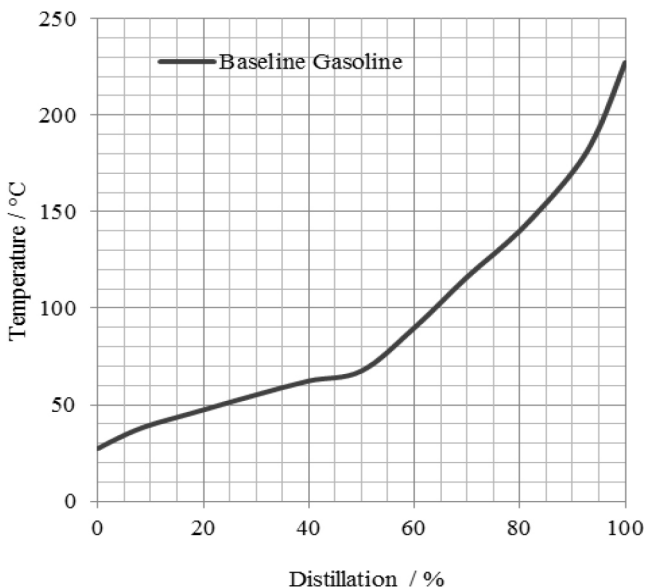


Figure 4. Evaporative curve of baseline test fuel

EXPERIMENTAL PROCEDURE

LSPI Test Procedure

Various different steady state or transient LSPI test procedures can be found in the industry and in literature depending on the scope and application of the respective project or study. However, when analyzing the essence of the different procedures three main types can be identified:

1. Steady State LSPI Characterization Procedures

Steady state characterization procedures currently define the industry standard in LSPI test efforts. This type of procedure focusses mainly on qualitative (ideally also quantitative) characterization of impact factors on LSPI during defined operating settings. The procedures typically contain extended and/or repetitive operation in the LSPI occurrence area of the respective engine operating map potentially interrupted by conditioning points. Due to their repetitive nature, steady state characterization procedures can offer decent result

repeatability and have the potential to allow statistical separation of test results with different settings or boundaries. The steady nature leads however to the characteristic shortcoming that these procedures are typically not representative of relevant passenger car operation modes customers would really experience in the field.

2. Transient or Quasi Transient Calibration Procedures

To address the shortcomings of the steady state characterization procedures, transient or quasi transient procedures can be used. Transient LSPI test procedures typically target specific characteristic coasting and acceleration situations a customer may actually experience in real-world drive cycles. Sufficiently high numbers of repeats of the targeted transient sections as well as accurate engine control during the transient operation sections are necessary to allow a statistically sound data analysis though. Main shortcomings of transient procedures are therefore either the difficulties to scientifically quantify root causes and impact factors when changing various factors simultaneously or the resulting time effort necessary to allow repeatability and statistical separation of test runs with different settings. Due to the necessary effort to overcome said shortcomings, transient procedures are often only used during engine calibration or for real-life validation purposes in conjunction with steady state procedures.

3. Research Procedures with Induced Events

The third group of test procedures includes research procedures with triggered LSPI events. In literature, the utilized trigger has been e.g. externally heated hot spots or artificially induced deposits and oil droplets. While triggered research procedures have their obvious value and allow to fundamentally investigate pre-ignition characteristics in short and predictable time frames, the transfer of the obtained results into the field is challenging. The very nature of triggered procedures can make the results very vulnerable to bias since the ability to generate an event similar to LSPI with external triggers does not necessarily mean that the triggered mechanism is in fact comparable to un-triggered conditions.

For this study a steady state characterization procedure was selected.

Figure 5 shows the overall layout of the procedure while Table 3 summarizes some key engine operating variables.

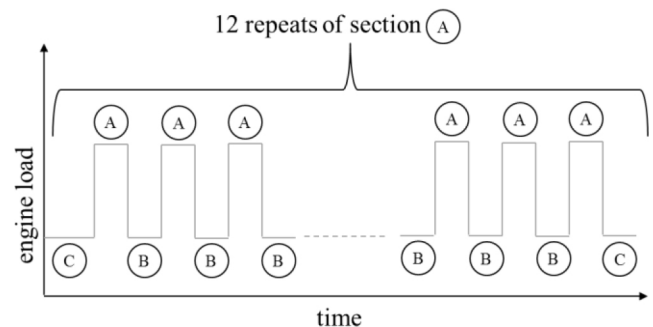


Figure 5. Schematic of the utilized test procedure