

Influence of Different Fuel Properties and Gasoline - Ethanol Blends on Low-Speed Pre-Ignition in Turbocharged Direct Injection Spark Ignition Engines

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Abstract

In recent years a new combustion phenomenon called Low-Speed Pre-Ignition (LSPI) occurred, which is the most important limiting factor to exploit further downsizing potential due to the associated peak pressures and thus the huge damage potential. In the past there were already several triggers for pre-ignitions identified, whereat engine oil seems to have an important influence. Other studies have reported that detached oil droplets from the piston crevice volume lead to auto-ignition prior to spark ignition. However, wall wetting and subsequently oil dilution and changes in the oil properties by impinging fuel on the cylinder wall seem to have a significant influence in terms of accumulation and detachment of oil-fuel droplets in the combustion chamber. For this reason, the influence of test fuels with different volatility were investigated in order to verify their influence on wall wetting, detachment and pre-ignition tendency. During these investigations also different ethanol fuels were investigated to analyse the influence of various alcohol blends on pre-ignitions.

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INTRODUCTION

Future CO₂ emissions targets represent a major challenge for gasoline engines. For this reason, the trend today is towards even smaller engine displacement with simultaneously increased specific performance, so called downsized engines. Downsized gasoline engines with adapted gear ratios are an important concept for the reduction of fuel consumption and emissions. In this case, the engine displacement is reduced and the operating points are shifted to more fuel-efficient regions. In order to ensure no loss of power, due to this displacement reduction turbochargers are used. Due to the resulting higher specific performance of the engines, it can, however - especially at full load and low speeds - encourage the occurrence of a new combustion anomaly referred to as Low-Speed Pre-Ignitions (LSPI) which may result in mega-knock. In contrast to conventional knocking combustion pre-ignition cannot be avoided by the engagement of the knock control, as their initiation takes place prior to the spark ignition. One possible measure to prevent follow-up pre-ignitions after the occurrence of an initial pre-ignition is the deactivation of the fuel supply for this cylinder.

Figure 1 illustrates the pressure traces of a pre-ignition and knocking combustion compared with a cycle of normal combustion.

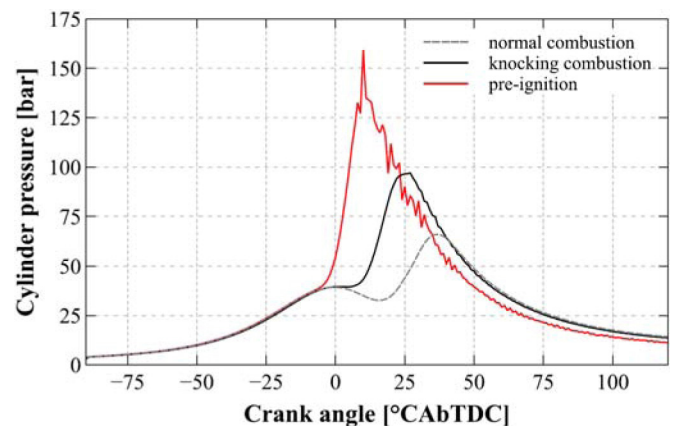


Figure 1. Pressure traces of a pre-ignition, knocking combustion and a cycle of normal combustion [1]

The premature ignition of the air-fuel mixture prior the spark ignition leads to a significant increase in pressure and temperature of the end gas, thus increasing the risk of end gas mega-knock. Due to the spontaneous character of pre-ignition the understanding of possible triggers is essential. The occurrence of pre-ignitions mostly takes place in the form of intermittent series each interrupted by at least one cycle of normal combustion, which recently could be associated with the detachment of combustion chamber deposits [2], [3], [4].

Dahnz et al. [5] postulated the detachment of oil droplets from the piston crevice volume during the rapid piston deceleration immediately before the top dead centre. For this reason, wall wetting, oil dilution and subsequently changes in the oil properties by impinging fuel seem to have a significant influence in terms of accumulation and detachment of oil-fuel droplets. Figure 2 shows the current hypothesis [5], [6] for the detachment of oil-fuel droplets from the piston crevice volume which subsequently can cause a pre-ignition.

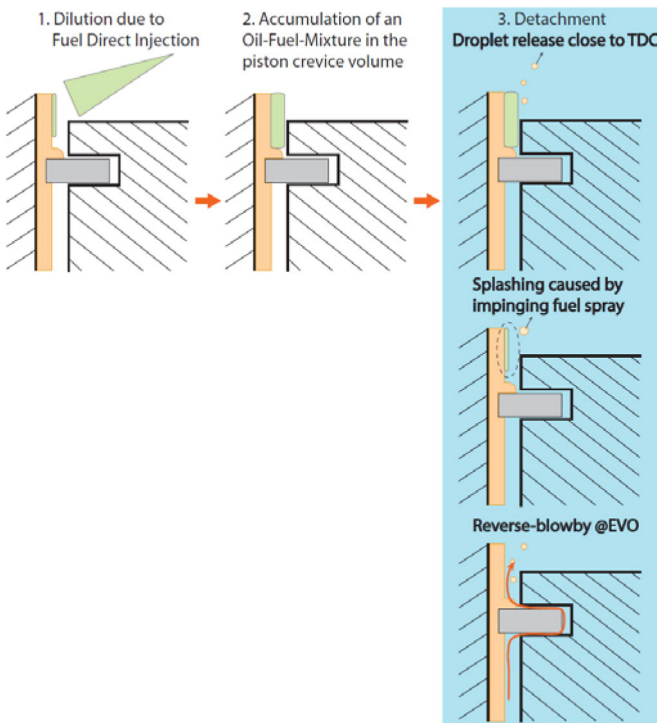


Figure 2. Hypothesis for the detachment of oil-fuel droplets

Step 1 and 2 are essential for the subsequent detachment of droplets, which is why the fuel impact is considered as significant driver due to possible wall wetting. In addition to oil dilution associated with reduced viscosity also changes in wettability, surface tension and flashpoint are possible. For these reasons fuel impingement on the cylinder walls, depending on the present boundary conditions at the cylinder walls, has significant influence on the release mechanism of droplets from the piston crevice volume, which was the motivation for the following fuel investigations. Step 3 shows a number of release possibilities of droplets into the combustion chamber starting with droplet release close to TDC [5], splashing [6] and reverse blowby at EVO [7].

Palaveev et al. [8] showed the behaviour of fuels with low and high boiling curves in regard to the pre-ignition frequency. Especially for the low volatile fuel compounds a delayed evaporation due to increased wall wetting caused an increased propensity to pre-ignite.

The motivation of this work, according to the current state of the art, is to obtain a better understanding of the effects of different fuels regarding volatility and ethanol content on the release mechanism of oil-induced pre-ignitions in a turbocharged direct-injection gasoline engine.

TEST BENCH SETUP

Test Engine

Table 1 lists the specifications of the test engine used for this investigations.

Table 1. Test engine specifications

Description	Unit	
Engine type		4-Cyl Inline
Injector position		lateral
Combustion process		stoichiometric, wall guided
Injector		7-hole Bosch high-pressure injector
Displacement	cm ³	1598
Stroke / Bore	mm	85.8 / 77.0
Compression ratio		1:10.5
Legislation		EU5 / ULEV II

As test engine a current representative of the downsizing concept with gasoline direct injection, twin-scroll turbocharging and variable valve train was used for the investigations. Apart from pressure sensors for in-cylinder measurements and intake manifold pressure an externally powered supercharger upstream of the turbocharger was used to provide the necessary boost level for the investigations.

Test Procedure

Because there are several possible influences for pre-ignition such as deposits, particles or hot residual gas a suitable methodology was initially developed to investigate pre-ignitions caused by released oil-fuel droplets from the piston crevice volume. After several necessary adjustments ultimately an adaptation of the test cycle proposed by Takeuchi et al. [6] was selected with the appropriate operating conditions proposed by AVL. This test cycle showed an outstanding reproducibility considering the duration of the test cycle of less than two hours. Due to this high reproducibility in spite of the stochastic nature a standard deviation of less than one pre-ignition for a mean value of 4,57 pre-ignition events / h over 20 test runs with the reference oil could be achieved.

Figure 3 shows engine load and speed of the adapted preignition test cycle. Due to the chosen engine operating conditions hardly any build-up of deposits or coking occurred, as could be shown by periodic combustion chamber endoscopy.

The conditioning phase of the combustion chamber at 4000rpm for 30 minutes allows an almost complete removal of deposits and particles. This conditioning phase was followed by one hour of pre-ignition operation at 1750rpm and WOT. The selected operating conditions with large valve overlap and thus sufficient scavenging causes a significant reduction in the residual gas content. The pre-ignition phase of one hour was used for evaluation. In each test condition and the least two test runs were performed.

results were averaged. Before each test run an oil change was conducted to exclude any cross influences due to increased oil dilution and degradation.

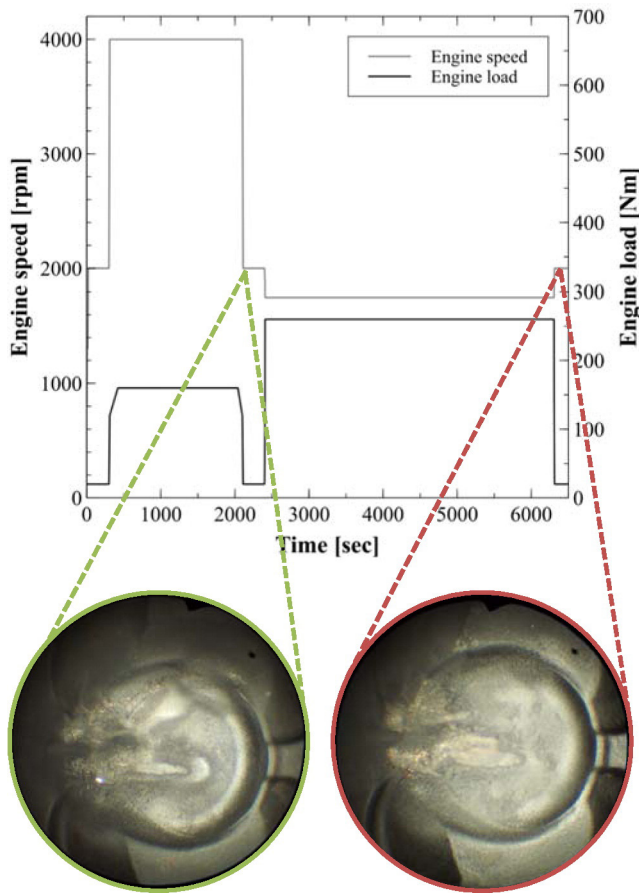


Figure 3. Adapted pre-ignition test cycle

As a limit for the pre-ignition detection, a cylinder pressure of 100bar was used. Taking into account an average peak pressure of around 60bar and process-related cyclic variations, the selected pressure limit shows sufficient distance of three times the standard deviation to avoid false detections. As criterion for mega-knocks a knock peak limit of 20bar was used. During the entire project duration a fully formulated 5W-30 engine oil was used as reference oil.

Test Fuels

To get a holistic overview of a possible impact of different fuel properties on pre-ignitions ethanol fuels (splash and “on-spec” blends) as well as fuels with different volatility were examined. While in the ethanol studies, the main focus was on the properties heat of vaporization and stoichiometric air-to-fuel ratio, the influence of the distillation characteristics primarily associated with wall wetting and subsequently oil dilution was studied with test fuels of different volatility. Table 2 shows the specifications of the ethanol fuels.

Table 2. Specifications of the “on-spec” blended ethanol test fuels

Description	Unit	E0	E10	E20	E30	E50
RON	-	95.5	95.9	96.4	96.7	97.8
MON	-	86.0	85.5	86.0	86.2	86.4
Aromatics	%v	33.1	23.2	20.2	14.3	3.3
Olefins	%v	5.2	8.0	4.3	0.2	0.3
Saturates	%v	61.7	59.2	55.8	53.5	44.9
Ethanol	%v	0	9.6	19.7	32.0	51.5
T80	°C	123	136	139	140	78

In the context of the fuel investigations different ethanol fuels were tested for their effect on pre-ignitions. Bobicic et al. [9] and Martin et al. [10] already showed that the pre-ignition tendency can be significantly reduced by ethanol fuels. In contrast to previous studies on splash blends, the focus in these measurements was on so-called economic blends. In contrast to splash blends high octane fuel fractions [11] (naphthenes and aromatics) are successively substituted in these blends with increasing ethanol content in order to meet specification in the most cost effective manner, and thus significantly influences the composition of the base fuel. Test fuel E0 was also used as reference fuel over the entire project duration. Table 3 shows the specifications of the test fuels with different volatility.

Table 3. Specifications of the test fuels with different volatility

Description	Unit	low	low-mid	mid	high
RON	-	97.0	96.5	97.3	97.2
MON	-	87.1	86.7	87.4	87.2
Aromatics	%v	23.9	31.1	29.5	28.8
Olefins	%v	7.5	9.8	8.8	8.8
Saturates	%v	63.8	54.4	56.9	57.8
Ethanol	%v	4.8	4.7	4.9	4.7
V150	%v	82.3	82.7	88.1	95.0
IBP	°C	32.2	31.5	32.2	30.4
T80	°C	141.4	141.7	129.0	113.1
FBP	°C	226.3	200.3	193.7	174.4

The test fuels shown in Table 3 are RON and MON matched and have nearly constant ratio of aromatics, olefins and saturates. The front-end distillation was almost identical up to 50% of volume evaporated, whereas the back-end distillation varied to investigate the influence of increased wall wetting on preignition. Figure 4 shows the boiling curves of the test fuels with different back-end distillation.