# Using Fuel Figures to Evaluate Pre-ignition in Gasoline Engines

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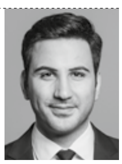

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Due to the increasing power density of modern downsized gasoline engines, they sporadically exhibit combustion anomalies, known as pre-ignition, particularly in the low-end torque region. In addition to the variety of causes of pre-ignition the fuel plays an essential role in this regard. As part of a cooperative FVV project, two experimental methods have been developed at the Vienna University of Technology and the RWTH Aachen University, which evaluate the pre-ignition resistance of a fuel due to thermodynamically critical conditions in the gas phase.


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## 1 MOTIVATION

The combination of direct injection, downsizing and turbocharging in gasoline engines has gained acceptance in recent years as a globally deployable technology for achieving the required reductions in consumption. Using biofuels also offers significant potential for further $CO_2$ reduction and is increasingly becoming the focus of research and development. Both optimization paths, biofuels and downsizing, lead to new challenges caused by the attendant combustion anomalies. In addition, the increased use of alcohol additives necessitates a modification of basic gasoline in order to produce a fuel which conforms to standards (EN228). For example, the increased proportion of volatile hydrocarbon components when adjusting the distillation range of ethanol-based fuels. It is reasonable to expect that such a measure can have a significant influence on pre-ignition behavior. In this regard, a large number of studies have previously confirmed that the current standardized fuel indicators – Research Octane Number (RON) and Motor Octane Number (MON) – do not adequately indicate a fuel's pre-ignition behavior [1, 2]. Based on the findings of the previous FVV projects Downsizing Fuel and Characteristic Fuel Number Biofuels, two potential fuel assessment methods were developed which calculate the tendency of pre-ignition as a consequence of critical thermodynamic conditions in the gas phase [3, 4].

## 2 SELECTION OF FUELS

The fuel matrix tested provides mixtures of various pure hydrocarbons with an E0 gasoline conforming to EN228. The admixed fuel components represent the following substance groups:
– iso-paraffins (isohexane, isooctane)
– alkenes (n-hexene)
– cycloalkanes (cyclohexane)
– aromatics (toluene)
– alcohols (ethanol or methanol)
– ethers (ETBE).

They were mixed at a molar concentration of 20 % (methanol also at 40 %) of the base fuel. In addition, the fuel matrix contains five further market gasolines which comply with EN228 in order to provide information on the influence of different standards-compliant basic fuel compositions. An important aspect of mixed fuels is the distinction between match blends and splash blends. Match blends are fuel compositions that are adjusted to a defined RON by adding knock-resistant components (here: isooctane with a RON of 100) or, if the RON is too high, by adding components with low knock resistance (here: n-heptane with a RON of 0). A target RON of 95 was defined for match blends at the outset of this FVV project. Furthermore, 3-component 95 RON fuels were mixed based on isooctane and n-heptane, which were used for simulation studies.

## 3 METHODS

The test methods developed to quantify tendency to pre-ignition were based on two different experimental engines. Test method 1 uses a CFR test engine which was already modified in the Downsizing Fuel FVV project, whereas test method 2 is based on a heated constant-volume combustion chamber for the analysis of the chemical-physical ignition delay time (AFIDA – Advanced Fuel Ignition Delay Analyzer). Extensive numerical research and analyses of the reaction kinetics were carried out during the project to gain a detailed understanding of a fuel's auto-ignition process. Validation of the predictive test methods took place both on a modern single-cylinder research engine and on a modern 1.0 l three-cylinder production unit. For the single-cylinder research engine the experimental procedure of the gas-phase ignition is based on varying boost pressure at a constant intake air temperature. As a result of the analysis, a critical boost pressure is found which leads to a pre-ignition frequency of at least 2 %. This value is then compared with the pre-ignition number of the respective test method. The methodology used for the three-cylinder standard engine differs from that of the single-cylinder research engine, as the parameter variable is intake air temperature under constant boost pressure. **FIGURE 1** gives a schematic overview of the experimental methods used.

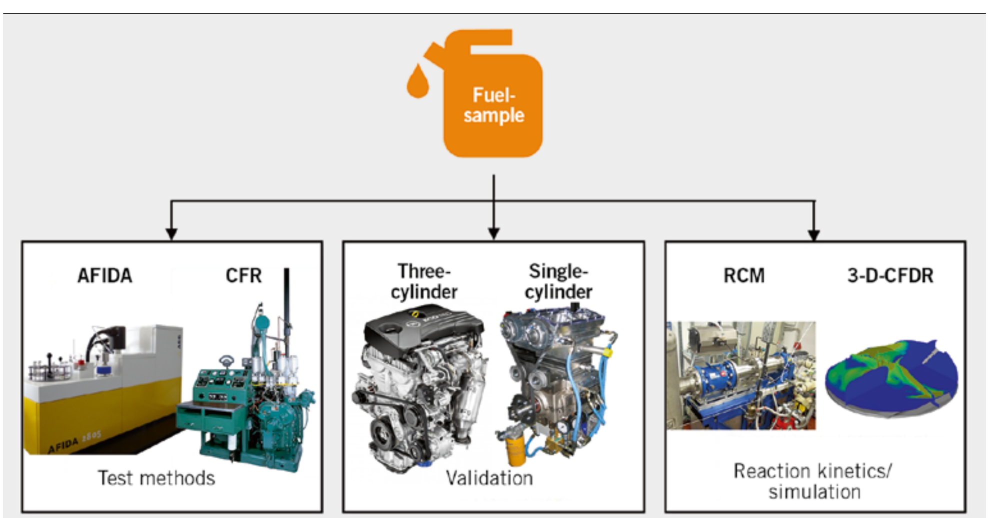


**FIGURE 1** Overview of the analysis methods used (© IFA)

| Operating conditions | RON | MON | CPI |
|---|---|---|---|
| Mixture formation [-] | carburetor | carburetor | DI |
| Engine speed [rpm] | 600 | 900 | 900 |
| Ignition timing (IT) [°CA before TDC] | constant | f(ε) | f(MBF50%) |
| MBF50% [°CA after TDC] | f(IT) | f(IT) | 35 |
| Intake air temperature [°C] | 52 | 38 | 30 |
| Mixture temperature [°C] | – | 149 | – |
| Boost pressure [mbar absolut] | – | – | 1100 |
| Air-fuel ratio (λ) [-] | variable | variable | 1 |
| End of ignition [°CA before TDC] | – | – | 203 |
| Rail pressure [bar] | – | – | 60 |
| Compression ratio (ε) [-] | variable | variable | variable |

**TABLE 1** RON, MON and CPI operating condition on the CFR test engine (© IFA)

### 3.1 ANALYSIS WITH CRF MOTOR

The continued use of the standardized CFR test engine for measuring RON and MON is the basis for the potential industry acceptance of the new figures. A prerequisite for any necessary modification of the CFR unit is the possibility of changing from the operating conditions of the standardized procedures (RON, MON) to the new procedures in an acceptable timeframe. A detailed insight into the previously implemented measures is available in the pre-project on the CFR engine [3]. In addition to [3] provision was made to integrate a compressor with intercooling as a major optimization measure during the course of this project.

The method for measuring the CPI (compression pre-ignition number) is based on the variable compression ratio of the CFR test engine and quantifies pre-ignition resistance due to critical gas phase conditions. The evaluation criterion used is the compression ratio which leads to pre-ignition of the fuel and is given a CPI according to Eq. 1 [3]. Pure isooctane is the reference substance used. **TABLE 1** compares the CPI operating conditions with those of the RON or MON.

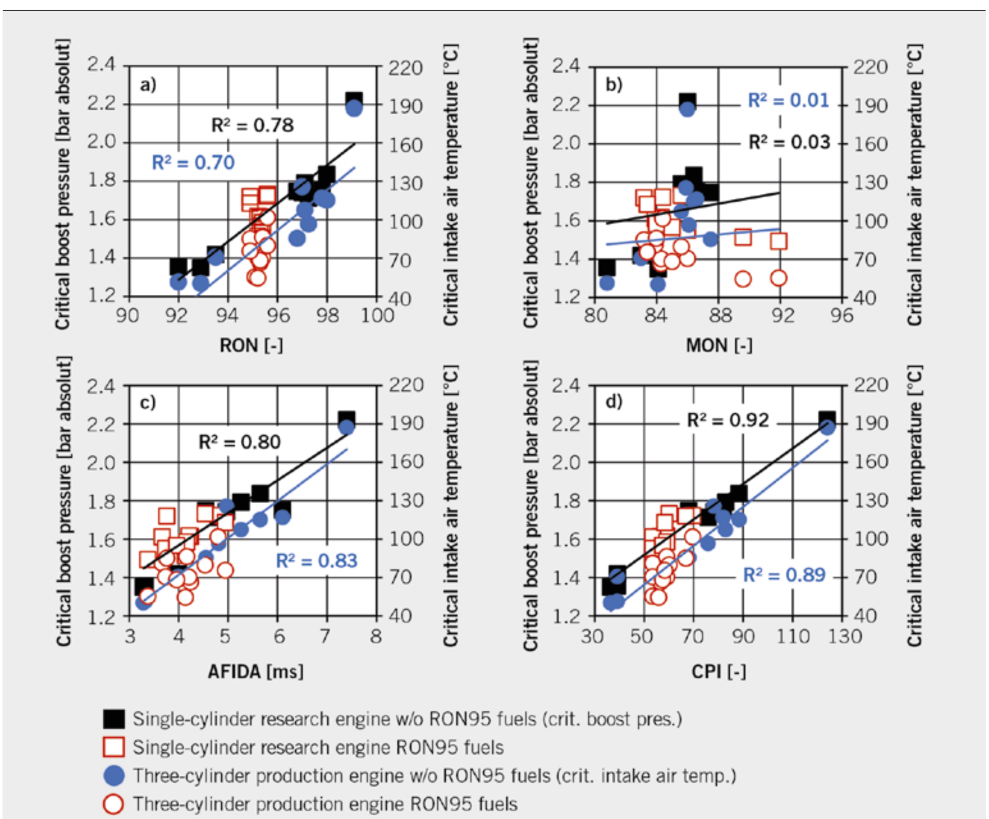


**FIGURE 2** Validation of the relevant test methods using a single-cylinder research engine and three-cylinder standard unit based on 20 fuels (red: fuels of similar RON or MON) (© IFA)

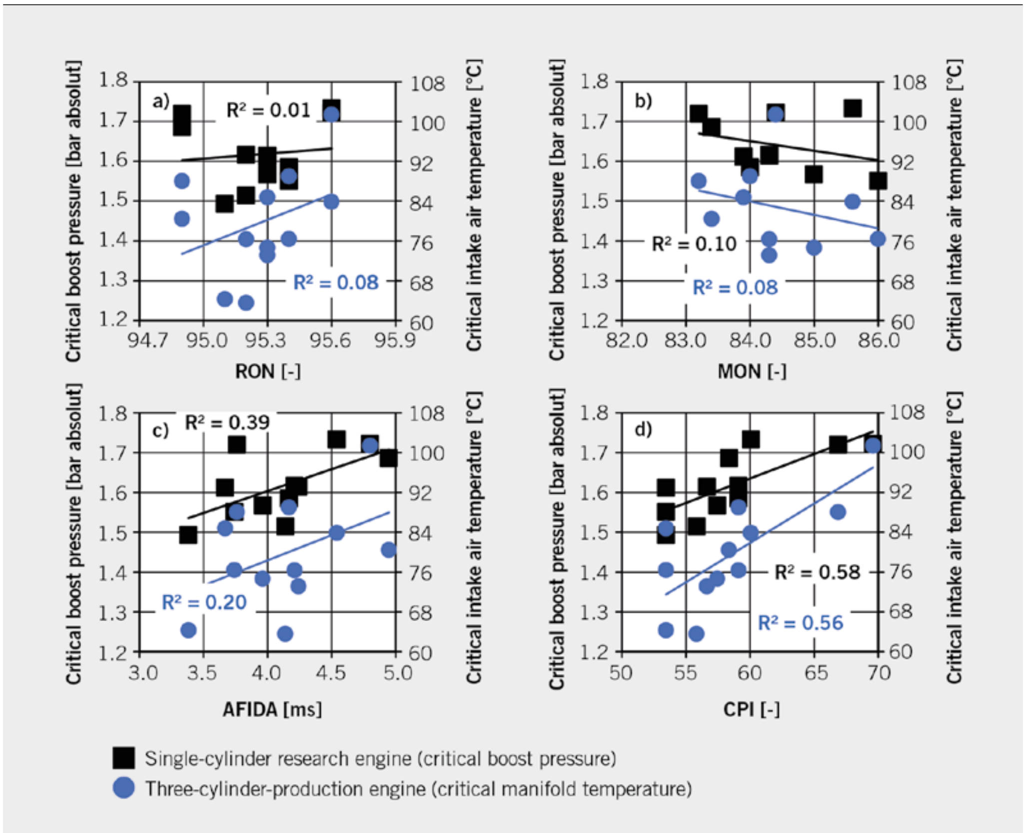


**FIGURE 3** Result of the pre-ignition analysis of fuels of similar RON or MON on the single-cylinder research engine and the three-cylinder production engine (© IFA)

**Eq. 1** $CPI_{sample} = CPI_{isooctane} + (\varepsilon_{sample} - \varepsilon_{isooctane}) * 20$

**Eq. 2** $CPI_{isooctane} = 100$

Here $\varepsilon_{Isooctane}$ is the compression ratio in pre-ignition of isooctane, and $\varepsilon_{sample}$ is the compression ratio with pre-ignition of the fuel sample.

### 3.2 ANALYSIS WITH AFIDA

The AFIDA methodology provides fuel injection by means of a piezo injector with a 1000 bar metering pressure into a constant-volume combustion chamber heated to 650 °C and a defined pressure of 50 bar. At these boundary conditions the petrol ignites spontaneously and an external ignition source in the form of a spark plug is unnecessary. A fixed pressure threshold is used to evaluate the pressure curve measured during injection and combustion. If the combustion chamber pressure exceeds this threshold, the time interval between the start of injection and reaching the defined pressure limit is recorded as the ignition delay time, and used as the basis for evaluating the pre-ignition tendency. An essential difference in the ignition delay time measurement in this method, in comparison to using of an RCM (Rapid Compression Machine), is (inter alia) in the process of fuel-mixture combination. With the AFIDA, the physical ignition delay as a result of the mixture formation is recorded as well as the chemical ignition delay.

## 4 RESULTS OF THE PRE-IGNITION EVALUATION

Based on the reaction kinetic analyses, and the numerical examination of the single-cylinder research engine, it has been shown that the auto-ignition behavior of fuels, especially paraffins, is extremely sensitive to pressure and temperature. The chemical ignition behavior of the fuels leads to significantly different self-ignition tendencies, depending on thermodynamic boundary conditions. It has already been shown in [4] that the pressure and temperature profile in the CFR combustion chamber during compression deviates significantly from that in modern engines. Accordingly, the pressure and temperature levels of the CFR engine is approximated to modern conditions by adaption with an external compressor with intercooling, with the aim of high comparability to modern units. **FIGURE 2** covers the correlation analyses of real fuels with a RON of 92 to 99. In this diagram, the results of the single-cylinder and three-cylinder analyses are compared with the associated fuel-specific values of the RON (a), MON (b), the AFIDA ignition delay time (c) and the CPI (d). Although **FIGURE 2** (a) shows a correlation between knock resistance and pre-ignition tendency, fuels of similar RON (marked red in **FIGURE 2**) also show significantly different self-ignition behavior. The MON method can give no assessment of pre-ignition tendency. In comparison, the newly developed assessment methods in **FIGURE 2** (c) and **FIGURE 2** (d) deliver very promising results for the predictive pre-ignition characterization of real fuel blends. Both methods exhibit a comparably good result based on the analysis of 20 fuels.

**FIGURE 3** contains only the pre-ignition analysis of the fuel group with similar RON or MON from **FIGURE 2** (measurement tolerance of the test methods +/- 0.3 ON [5, 6]. **FIGURE 3** (a) and **FIGURE 3**

| „Fuel-component“ | Fraction | Blend | | RON | | MON | | CPI | | AFIDA [ms] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | [% mol.] | M | S | M | S | M | S | M | S | M | S |
| **Isohexane** | 20 | √ | √ | 95.1 | 92.9 | 91.9 | 84.1 | 53.4 | 36.4 | 3.4 | 3.3 |
| **Toluene** | 20 | √ | √ | 95.3 | 97.8 | 84.3 | 86.6 | 56.6 | 81.9 | 4.2 | 6.1 |
| **Cyclohexane** | 20 | √ | √ | 95.2 | 95.5 | 89.6 | 83.0 | 55.8 | 39.2 | 4.1 | 4.0 |
| **n-hexene** | 20 | – | √ | – | 92.0 | – | 80.6 | – | 39.2 | – | 3.3 |
| **Ethanol** | 20 | √ | √ | 95.2 | 98.0 | 84.3 | 86.4 | 59.1 | 88.4 | 4.2 | 5.7 |
| **Methanol** | 20 | √ | √ | 95.3 | 97.1 | 83.9 | 85.6 | 53.4 | 83.0 | 3.7 | 5.3 |
| **ETBE** | 20 | √ | – | 95.4 | – | 86.0 | – | 53.4 | – | 3.7 | – |
| **Isooctane** | 20 | – | √ | | 96.8 | – | 87.5 | | 68.1 | – | 4.6 |
| **Methanol** | 40 | √ | √ | 94.9 | 99.1 | 83.2 | 86.0 | 66.9 | 124.1 | 3.8 | 7.4 |

**TABLE 2** Result of fuel characterization for the Match (M) and Splash Blend (S) mixtures analyzed (© IFA)

(b) clearly show the limited potential of current standard test procedures for evaluating the pre-ignition of fuels. It should be noted that significantly different self-ignition behaviors occur in modern engines despite similar RON or MON. If, on the other hand, the result of the CPI analysis in **FIGURE 3** (d) is considered, a significantly higher characterization potential can be identified within this fuel group. The AFIDA test methods in **FIGURE 3** (c) also show an improved degree of correlation with regard to the validation on the single-cylinder research engine. However, both newly developed test methods evaluate over a wide ignition delay time range and CPI range and thus offer the possibility of a reproducible evaluation of fuels with similar or equal RON. **TABLE 2** and **TABLE 3** provide a detailed overview of the fuels analyzed and their fuel numbers.

## 5 SUMMARY

With the aim of a predictive fuel assessment methodology for the pre-ignition characterization of gasoline fuels, two potential test methods were developed in the course of this FVV project. Test method 1 involves the modification of a standardized CFR test engine for measurement of the CPI (compression pre-ignition number). Test method 2 is based on a heated constant-volume combustion chamber with direct injection for measuring the chemical-physical ignition delay. Based on extensive research, it was possible to set experimental boundary conditions for both test methods with which a promisingly accurate prediction of a fuel’s pre-ignition tendency can be made.

| Market-fuel | Paraffin | Naphthene | Olefin | Cyc.-olefin | Aromatic | Oxygenate | RON | MON | CPI | AFIDA |
|---|---|---|---|---|---|---|---|---|---|---|
| | [% volume] | [% volume] | [% volume] | [% volume] | [% volume] | [% volume] | [–] | [–] | [–] | [ms] |
| **E5 EN228** | 44.8 | 5.7 | 5.1 | 1.3 | 33.9 | 9.2 | 97.3 | 86.1 | 75.8 | 4.8 |
| **E5 EN228** | 41.6 | 5.2 | 8.3 | 0.9 | 35.1 | 8.9 | 95.4 | 84.0 | 59.1 | 4.2 |
| **E5 EN228** | 50.1 | 3.9 | 16.8 | 0.8 | 20.7 | 7.6 | 95.3 | 85.0 | 57.5 | 4.0 |
| **E5 EN228** | 43.4 | 5.5 | 7.1 | 1.2 | 37.9 | 4.8 | 95.6 | 85.6 | 60.1 | 4.5 |
| **E10 EN228** | 45.5 | 3.7 | 6.9 | 0.7 | 34.0 | 9.3 | 97.0 | 85.9 | 78.2 | 5.0 |

**TABLE 3** Composition and characterization of the market fuels examined (© IFA)

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