

Tomorrows Diesel Fuel Diversity – Challenges and Solutions

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ABSTRACT

Regulated emissions, CO₂-values, comfort, good driveability, high reliability and costs, this is the main frame for all future powertrain developments.

In this frame, the diesel powertrain, not only for passenger cars, but also for commercial vehicle applications, faces some challenges in order to fulfil the future European and current US emission legislations while keeping the fuel consumption benefit, good driveability and an acceptable cost frame.

One of these challenges is the varying fuel qualities of diesel fuel in different countries including different cetane number, volatility, sulphur content and different molecular composition. In addition to that in the future, more and more alternative fuels with various fuel qualities and properties will be launched into the market for economical and environmental reasons.

At present, the control algorithms of the injection system applied in most diesel engines is open loop control. With this approach, the varying fuel qualities will increase the difficulty and duration of calibration; at the same time, it also decreases the robustness of combustion and emissions.

A possible solution to manage the combustion with different fuels is to use a closed loop combustion control. Once this supposition is verified by engine tests, the calibrations for fuels with different qualities will become faster and easier. Also an online adaptation of the calibration during vehicle use is possible to avoid engine malfunction and assure the appropriate drivability and emission performance.

In this paper an innovative method to compensate the varying fuel qualities will be shown. Based on two typical fuel qualities already available on the market, EN590 EU Diesel and low cetane number US diesel, the combustion is analyzed to find out the influence on combustion behaviour and emissions.

Based on these data and results, an innovative closed loop combustion control strategy to compensate varying fuel qualities will be shown.

INTRODUCTION

When we take a look at the combustion process in diesel engines, we will see that the integration of fuel properties will be of considerably greater importance in the future. This has various reasons. For one thing, there is the desire to replace at least part of the fuel that is based on fossil crude oil with a regenerative produced portion. This is due to the problem of global warming and the demand for a massive reduction in CO₂ emissions. It is not yet fully clear, which strategy for substitution should and can be pursued. At first, a partial substitution of diesel fuel seems to make the most sense, because the proportion of diesel fuel that is consumed by vehicles on the road is already significantly higher today than that of gasoline fuel, at least in Europe. It seems that this will not change in the future either [1]. One consequence is that diesel and gasoline fuel is moved within regions with a different proportion of gasoline and diesel engines in order to keep the efficiency of the manufacturing process in the refinery at a high level. A much higher proportion of diesel vehicles in other markets would limit this practice significantly and, when looking at the overall system, lead to a great loss in efficiency and thus to higher CO₂ emissions during the manufacturing process.

However, a further increase of the portion of diesel substitutes of the so-called first generation (rape seed methyl ester, vegetable oil) will not lead to the desired goal, as the savings potential with regard to production and CO₂ is limited [2]. Diesel substitutes of the 2nd generation (Fischer Tropsch fuels) demonstrate a much higher potential here and also have fewer problems when it comes to longterm stability. However, these fuels will in mid term not be available in large quantities.

But all in all we can say that there will be a further substitution of fossil diesel fuels. Depending on the fuel characteristics, this will also have an impact on combustion as well as on exhaust aftertreatment.

Another aspect already mentioned earlier is the probable or the intended expansion of the market share of vehicles with diesel engines in other markets such as China, India, USA, and Russia. The fuel grades sometimes differ greatly between these countries. In the US, a market where vehicles with the most advanced diesel engines will be increasingly offered in the next few years, the fuel grades and properties fluctuate greatly even within the individual states.

These considerations show that future combustion systems must be very robust in spite of further reduced emission limits. Additional control algorithms for the regulation of combustion must at least in part be able to compensate the influence of the fuel within the scope of the particular specified fuel standardization.

As part of this article, we will take a look at basic, currently known influences of different fuel grades on the combustion process in diesel engines. We will use two fuels with clearly different specifications as an example to show possible compensation measures through intelligent, self-learning control functionalities.

FUNDAMENTALS OF DIESEL ENGINE FUELS

Petroleum-based fuels consist of a variety of hydrocarbons. They are commonly divided into four main groups [3]:

- Saturated acyclic (aliphatic) hydrocarbons (paraffins or alkanes)
- Unsaturated hydrocarbons with double bonds (olefins or alkenes) or triple bonds (acetylene or alkynes).
- Acyclic (aliphatic) hydrocarbons, either saturated (cycloalkanes = naphthenes) or unsaturated (cycloalkenes or cycloalkynes).
- Aromatic hydrocarbons (arenes)

Figure 1 shows the boiling temperature and the cetane number for hydrocarbons depending on the number of C atoms. We can see a clear correlation between the number of C atoms and the boiling temperature. In contrast to this, the cetane number correlates with the number of C atoms only in comparison with the own group. The influence of the structure is substantially more pronounced. In particular with paraffins, the cetane number depends to a large extent on the degree of isomerization. While n-octane with a cetane number of approx. 65 is clearly more prone to ignition than conventional diesel fuel, ISO-octane is the standard for knock-resistant fuels and thus fuel with poor ignition quality (with an octane number of 100 or a cetane number of 12.5). The major influence on the combustion behavior results from the different binding forces between hydrogen and the carbon atoms. The lower number of primary bonds in unbranched molecules leads to an increased reactivity, since the likelihood that the weak secondary bonds are breaking up earlier is substantially greater [7].

Due to the thermodynamic principles of the combustion process in diesel engines, the fuel that is being used is an important factor in the entire energy transformation process.

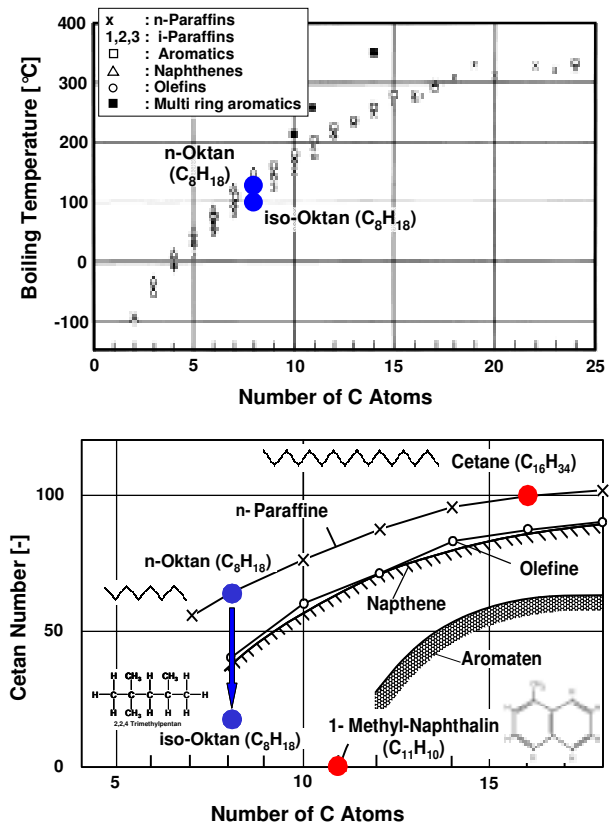


Figure 1: Fuel properties depending on molecular structure [3]

As we know, diesel fuel is injected into the cylinder near top dead center (TDC) at the end of the compression phase in engines with compression ignition when the thermodynamic boundary conditions of the cylinder charge (pressure and temperature) are suitable for mixture formation. As soon as the first fuel quantities enter the cylinder, chemical reactions start and continue as long as more fuel quantities are added, while at the same time the remaining liquid fuel and the fuel/air vapour are intermixed. Auto ignition occurs when this mixture is present in a relatively rich air/fuel ratio of approximately 0.25. After this premixed combustion, the remaining fuel is converted in a diffusion flame, when the injection period is longer than the ignition delay.

The fuel composition and properties are inextricably linked and, due to the various combinations and dependencies, have a direct impact on the combustion-relevant process parameters. In general a description of the fuel only with the help of the cetane number is problematic. The boiling characteristics in particular have a great impact on mixture formation and due to this on combustion as well. A low boiling temperature

contributes to a quick mixture formation and thus promotes a reduction in particulate emissions [4], [8]. A low aromatic content is preferable not only because of a possible health threat, but is generally described as an option for reducing HC, CO, and particulate emissions [9].

BASIC INVESTIGATIONS

Two fuels with very different properties are used as a basis for the following studies (Table 1).

Table 1: Characteristics of investigated fuels

	FUEL 1	FUEL 2
Density at 15 °C [kg/m ³]	831.4	852.3
Cetane number	53.6	42.1
Boiling characteristics up to 250 °C [percent by volume]	37.4	36,4
Boiling characteristics up to 350 °C [percent by volume]	94	>99
Aromatics ratio [percent by volume]	25.6	34.5

Both fuels are available in the US while fuel 1 represents also a typical European fuel and have representative minimum and maximum values in terms of the cetane number. The aromatics content of fuel 2 with a value of 34.5 percent is also to be regarded as a maximum (maximum aromatics content as per ASTM [minimum fuel requirements for diesel engines] D 975-05 Grade 2-D S15: 35%), whereby the 25.6 percent value of fuel 1 characterizes the average in Europe.

The results shown in the following were conducted on a full size engine with a cylinder displacement of appr. 500 cm³.

To illustrate the influence of the greatly differing fuels on the combustion as a function of the load point, we will take a look in the following at the example of the partial load points $n = 1500$ rpm, $p_{me} = 4.5$ bar, as well as $n = 2200$ rpm, $p_{me} = 13$ bar. Table 2 shows the calibration parameters which are identically at first for both fuels and have been determined for fuel 1. The settings represent an Euro V calibration.

The pressure curve and burn rate of the different fuels in the illustrated load points are shown in Figure 2. It can be observed, that in particular in the lowest load point, the pressure curve and burn rate are clearly different. Combustion takes place later due to the significantly longer ignition delay. This is caused by the lower ignition performance of fuel 2 which leads to the effect that the pilot injection is not burning, with the consequence of a longer ignition delay. The burning of the main injection itself is also retarded.

Table 2: Investigated load points and calibration

	1500 rpm BMEP 4.5 bar	2200 rpm BMEP 13 bar
Pilot injection quantity [mg/stroke]	1.9	2.2
Pilot injection start [μs]	1700	1400
Main injection start [°CA BTDC]	2.4	2
Rail pressure [bar]	1050	1460
Air-mass flow [mg/stroke]	345	760

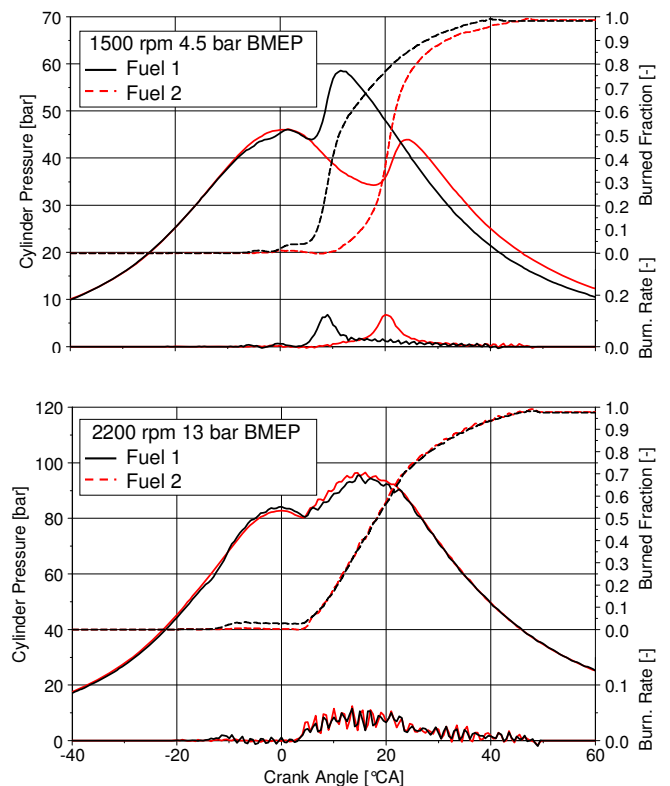


Figure 2: Difference of Combustion, investigated fuels

By comparison, the pressure curve and the combustion at high loads are only marginally affected. Here too, the pilot injection is barely converted in spite of an identical pilot injection quantity. Nevertheless, the combustion during main injection as well as the rate of combustion differs only slightly for the investigated fuels, since, at high loads, the boundary conditions in the combustion chamber in terms of pressure and temperature lead to a clearly shorter ignition delay for both fuels [3]. As a consequence, the ignition delay of the main injection is nearly independent from the pilot quantity, and the conversion rates and burn rates are almost the same.

This shows that the description of fuel characteristic interaction with combustion only via cetane number is limited to low load engine conditions, or more general to the pressures and temperatures prevailing in the