

Cold Start on Diesel Engines: Effect of Fuel Characteristics

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ABSTRACT

Faced with the need to reduce greenhouse gas emissions, Diesel engines present the advantage of having low CO₂ emission levels compared to spark ignited engines. Nevertheless, Diesel engines still suffer from the fact that they emit pollutants and, particularly nitrogen oxides (NO_x) and particulates (PM). One of the most promising ways to meet this challenge is to reduce the compression ratio (CR). However a current limitation in reducing the diesel CR is cold start requirements.

In this context, the fuel characteristics such as the cetane number, which represents ignition, and volatility could impact cold start. That is why a matrix of 8 fuels was tested. The cetane number ranges from 47.3 to 70.9 and the volatility, represented by the temperature necessary to distillate 5% of the product (T5%), ranges from 173 to 198°C. The engine tests were carried out at -25°C, on a Common rail 4-cylinder Diesel engine. Two engine configurations were studied: a nominal CR of 16:1 and a reduced CR of 14:1. Operating points were run with the same settings for all the fuels. Moreover a statistical analysis of the results was used in order to highlight the fuel impacts on cold behaviour (start and idle).

The main results show that the difference between tests operated with CR equal to 16:1 and 14:1 appears only during the idle phase. The impact of volatility is not clear, but the increase in cetane number means better performances on cold start.

INTRODUCTION

Diesel engines are now a vital component of the transport sector especially because of their high thermal efficiency and low CO₂ emissions.

Diesel engines are even more interesting since further progress can still be expected via downsizing: fuel consumption reduction is approximately 9 % with a displacement reduction from 2 to 1,6 L [1].

The most common way to keep the same performances (specific torque and power) on downsized engines is to use a high supercharging. Reduction of the volumetric compression ratio (CR) can avoid higher mechanical and thermal loads [2] and this means that the significant downsizing is possible with a reasonable level of constraints. Moreover, the use of new combustion modes is improved with the reduction of CR on a larger load and speed range, which leads to a reduction of NO_x raw emissions, another huge challenge for Diesel engines [3, 4]. Therefore reduction of CR clearly appears to be a key point in the evolution of Diesel Engines.

Nonetheless this reduction of the CR to values between 14:1 and 16:1 leads to another limitation [5, 6] which is the behavior in cold operation (start and idle) in extreme low temperatures (-20°C and below). In previous papers [7, 8, 9], the consequences of the reduced CR from 17:1 to 14:1 and the optimization of the injection settings in order to obtain good start capabilities, were investigated. Cold operation of a Diesel engine is also linked to the characteristics of the fuel used such as cetane number, volatility [10]. Consequently bad cold flow properties of the fuel can greatly damage engine performances in cold operation.

This is why the objective of this work is to study the fuel impact (cetane number and volatility) on cold start on Diesel engines. A matrix of 8 fuels is tested. The cetane number ranges from 47.3 to 70.9 and the volatility, represented by the temperature when 5% of the product is distilled (T5%), ranges from 173 to 198°C. Two engine configurations were studied: a nominal CR of 16:1 and a reduced CR of 14:1. The tests were carried out at the same engine settings.

Moreover a multidimensional statistical analysis was used in order to highlight the fuel impact on cold start using a rigorous method. This statistical analysis was applied for several reasons: the interdependency of the fuel properties, the poor repeatability of the cold operation tests and the large number of criteria obtained during a test to evaluate the performance of the engine.

FUELS AND EXPERIMENTAL SET UP

FUEL MATRIX

The fuel matrix is built on the variation of two characteristics which are the auto-inflammation property and the volatility (Figure 1). Auto-inflammation is defined by cetane number and volatility is represented by the temperatures necessary to distillate the product. Four levels of cetane number and three levels of volatility, represented by T5% (Temperature at which 5% of the product was distilled), were targeted. The fuel matrix is finally composed of 8 products (GO1 to GO8). The levels of T5% are around 175, 185 and 200°C. The levels of cetane number are around 47 (low), 55 (usual), 63 (high) and 70 (very high). The distillation curve of a conventional diesel fuel is from 180 to 300°C and the cetane number is 51. GO1 represents the conventional diesel fuel. Notice that only four fuels (GO1, GO3, GO4 et GO5) were tested with the engine configuration with a nominal CR of 16:1. Whereas the whole fuel matrix was tested with the engine configuration with a reduced CR of 14:1.

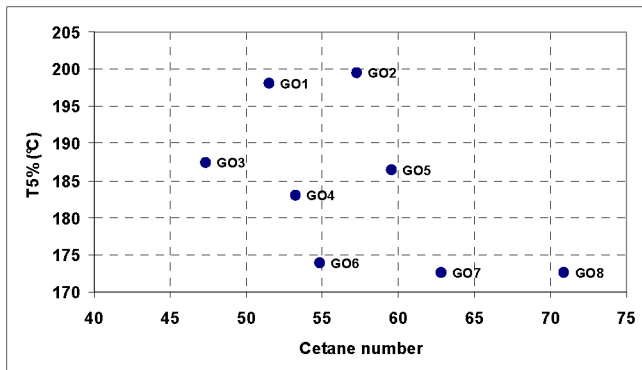


Figure 1. Schematic representation of the fuel matrix according to the main properties which are the volatility and the cetane number

TEST CELL AND MEASURING EQUIPMENT

The engine was installed in a cold and dehumidified room, the ambient temperature of which can be controlled to -30°C. During test operation, ECU data were acquired by ETAS Inca System. Moreover, classical engine data such as: air,

lubricant, water, exhaust gas temperatures, air fuel ratio in the exhaust line, voltage and intensity of starter and glow plugs, were recorded. Exhaust gas Opacity was given by AVL 439 system. Each cylinder was instrumented with an AVL GU12P pressure transducer to measure the gas pressure into the combustion chamber. In addition, an optical shaft encoder determined the engine crank angle inside the cycle.

SOAKING AND STARTING PROCEDURE

Before a test, the engine, the battery and the fuel tank were soaked in the cold test cell for at least 8 hours. At the end of this preglowing period, the engine's electric starter was used to crank the engine which was declutched for the test. After the start, the engine was run at idle in order to characterize idle behavior in such conditions, and the test was stopped after 2min. Then engine temperature and load were increased progressively in order to clean the engine before stopping it and starting a new soaking procedure.

ENGINE TEST

The engine tests were performed on a 4-cylinder Diesel engine RENAULT M9R. The main specifications of the engine are listed in Table 1. Two Volumetric Compression Ratios (CR) were studied: a nominal CR of 16:1 and a reduced CR of 14:1.

(See Table 1 after last section of paper.)

Firstly, operating points are done with the same settings for all the fuels to compare the impact of the fuel properties on the engine performance.

Secondly, a simple methodology is used to look for the optimal engine settings with each fuel. This methodology is described in Figure 2 and it consists of two stages. The first stage consists of a variation of the start of injection (SOI). This variation is done by a step of 3°CA around the standard settings and is applied to the whole injection train. At the end, the optimized SOI can be selected. The second stage consists of a variation of the fuel injected quantity during the starting phase and is done with the optimized SOI. Finally, we determine the optimized engine settings (SOI and injected quantity). A test is repeated with these setting to confirm the tendency. Notice that some tests are impossible to do because the operating settings do not allow a good combustion quality. Finally, the total number of tests is 143, taking into account the number of fuels tested, the engine settings variation and the repeated tests.

(See Figure 2 after last section of paper.)

FUEL EVALUATION METHODOLOGY

Main criteria for evaluation

As illustrated in [Figure 3](#), several criteria were used in order to qualify engine behavior in cold operation. The following list shows the criteria used during the starting phase:

- Rail pressure increase delay (referred to as “RailPD”): defined as the duration between the moment when the starter is switched on and the moment when the rail pressure reaches 20MPa, which gives the authorization of the injection.
- First combustion delay (referred to as “FirstCombD”): defined as the duration between the first fuel injection and the first combustion occurrence.
- Speed increase delay (referred to as “SpdIncD”): defined as the duration between the first combustion occurrence and the moment when the idle mode is reached (at the end of starting phase, also corresponding to “StartBit fall”).
- Exhaust gas opacity during start (referred to as “OpStart”): evaluated by averaging gas opacity during 2s from the moment when the opacity signal increases.

The next list shows the criteria used during the idle phase:

- Stable idle delay (referred to as “StabIdleD”): defined as the duration necessary to reach “stable idle”, corresponding to an engine speed standard deviation lower than 20rpm.
- Engine speed stability after 20s (referred to as “StabIdle20s”): evaluated by averaging engine speed standard deviation during 1s, 20s after the moment when the “idle mode” is reached.
- Engine speed standard deviation in idle (referred to as “SpdStdevIdle”): evaluated by averaging standard deviation from the moment when the “idle mode” is reached and until the end of the test.
- Exhaust gas opacity in idle (referred to as “Op_Idle”): evaluated by averaging gas opacity from 20s after the moment when idle mode is reached and during 60s.

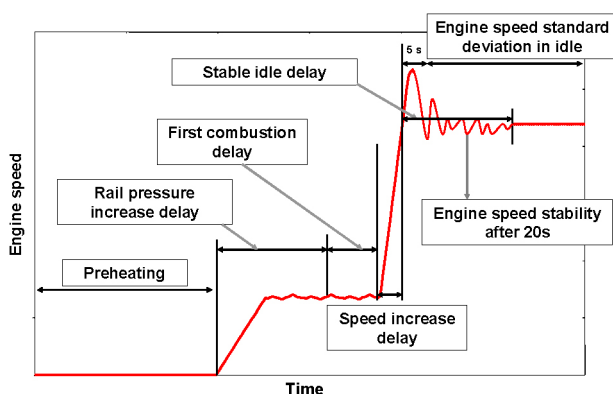


Figure 3. Illustration of the main criteria used to qualify a cold-start

MULTIDIMENSIONAL DATA ANALYSIS

The data studied can be summarized in a table of 143 rows (individuals) - each one presenting an engine test - and several columns (variables) associated with the fuel characteristics (cetane number and volatility), the engine configurations (nominal and reduced CR, settings), and 8 responses which are the criteria defined above (rail pressure increase delay, first combustion delay, speed increase delay, exhaust gas opacity during start, stable idle delay, engine speed stability after 20s, engine speed standard deviation in idle, exhaust gas opacity in idle). The aim of the study is to examine the impact on cold start of the fuel characteristics under different engine configurations. A multidimensional exploratory data analysis of the 8 responses was carried out using Principal Component Analysis.

Principal Component Analysis (PCA) [[11](#), [12](#), [13](#)] is a method which offers both time mathematical tools to reduce data space dimensions and graphic tools to represent and interpret the intrinsic structures within the data (see equations in [appendix](#)). It consists in seeking the directions of space which better represent the correlations between several variables measured on a large number of individuals. PCA is often used in order to provide a transformation of data of large dimensions to describe their subjacent multidimensional structures. The data analysed by PCA are classically represented in the form of $N \times J$ tables, the N lines of which are called individuals (the 143 engine tests in our case) and the J columns are called variables (here, the 8 responses). Data can then be represented as a cloud of N points (individuals) in a space of dimension J (variables are represented by vectors). To highlight the structure of the cloud of points associated with the table, PCA computes, by maximizing their variance, linear combinations of the initial variables, which indicate privileged directions of the space of the individuals. These new variables, which are independent (uncorrelated) two by two, are called principal components (PCs). The PCs are ordered by decreasing variance: the first PC accounts for the highest variance in the data, and each succeeding component accounts for as much of the remaining variance as possible. If the variance load on the last PCs is very low, they can be considered to provide insufficient information (noise) and can then be removed to reduce the dimensionality of the data space. Only the first (informative) PCs are used to describe data.

RESULTS AND DISCUSSION

At a first step in our study, the 8 responses (variables) of the 143 engine tests (individuals) were analysed by PCA. The responses are considered as the coordinates of the 143 individuals in an 8 dimensional space where the dimensions are vectors corresponding to the responses. From the original set of the 8 correlated responses, a set of 8 uncorrelated