

Development of a Fuel System Cleanliness Test Method in a Euro 4 Direct-Injection Gasoline Engine (VW 1.4 L TSI 90 kW)

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ABSTRACT

Driven by increasingly stringent tailpipe CO₂ and fuel economy regulations, gasoline direct injection (GDI) engines are enjoying rapidly increasing market penetration. Already more than 50% of newly produced vehicles in the US and western Europe employ direct-injection technology and many markets in Asia are also seeing an increasingly rapid uptake.

However, with the adoption of GDI engine technology, which is able to push the boundaries of engine efficiency, new challenges are starting to arise such as injector nozzle deposits, which can adversely affect performance. Multi-hole solenoid actuated fuel injectors are particularly vulnerable to deposits formed when operated on some market fuels. In order to address this challenge, the development of a reliable industry test platform for injector cleanliness in GDI engines is currently underway in both the US and Europe.

This study shows the successful application of a mass produced GDI bench engine test platform (VW 1.4 L TSI 90 kW; engine code CAXA; engine family EA111) to differentiate different fuel formulations, at a 99% statistical confidence level, based on an engine metric correlated to injector cleanliness. In this study, a European (EN228 compliant) market representative test fuel was used throughout the entire investigation -i.e. no pro-fouling dirty-up fuel components were required to accelerated deposit formation within a reasonable test duration. The study makes two cross-comparisons between three different fuel formulations and the bench engine deployed is shown to be a highly sensitive test platform to differentiate fuels with different levels of deposit control additive (DCA). Fuels formulated with appropriate DCAs help restore fouled injectors to their original performance level.

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INTRODUCTION

The purpose of this study was to develop a test platform for evaluating the effect of different fuel formulations on the cleanliness of fuel injectors in a mass production GDI engine (VW 1.4 L TSI). The sensitivity of the test platform needed to be able to differentiate fuel formulations with high statistical confidence in a market representative, EN228 compliant basefuel in a reasonable timeframe, while seeking to avoid pro-fouling fuel components (e.g. Zinc as used in the industry standard diesel DW10 nozzle coking test). [1] Furthermore, it had to be able to provide data in a test scenario where injector deposits were built up initially and then subsequently shown to be removed again ('clean-up').

As a result of increasingly stringent tailpipe CO₂ regulations, GDI engines are enjoying rapidly increasing market penetration. [2] The efficiency gains, transient response and cold-start hydrocarbon emission levels are just some of the underlying arguments that drive this development. [3] When compared to the established Port Fuel Injected Technology (PFI), downsized, single turbo GDI engines were shown to provide between 10-17% drive cycle fuel economy benefits. [4] These engine efficiency gains are enabled by direct injection allowing a relatively high compression ratio versus otherwise equivalent PFI technology. Through latent heat of vaporization of the fuel, direct injection technology enables a reduced charge temperature in the cylinder, increasing charge density along with volumetric efficiency and the knock resistance of the engine. More than 50% of newly produced vehicles in the US and western Europe already employ direct-injection technology, and many markets in Asia are also seeing an increasingly rapid uptake.

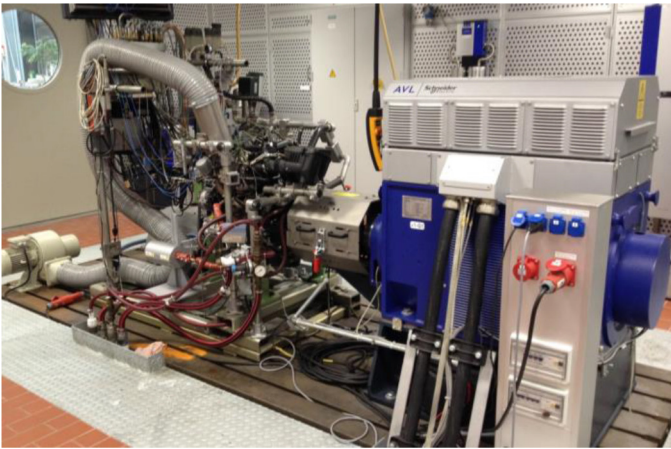


Figure 1. The VW 1.4 L TSI, a Euro 4 direct injection bench engine installed at Shell Technology Centre Hamburg.

This study uses the VW TSI engine, which is a downsized, turbocharged, inline-four, 1.4 L GDI engine prominent in the European marketplace and meeting the Euro 4 emissions standards. This engine (shown in [Figure 1](#)) features side mounted solenoid driven 6-hole injectors and is set up for homogeneous direct injection operation. Equipped with a partially open engine management system (EMS), this setup allowed for engine metrics to be obtained directly from the engine control unit (ECU), including the key metric for this investigation: injection duration.

Engines based on GDI technology feature components that are potentially vulnerable to deposit formation. Most importantly, addition of complex fuel injection equipment results in new parts that need to be protected from the build-up of deposits in order to ensure the 'as designed' performance and efficiency is maintained over the lifetime of the vehicle. The complexity of the fuel injection equipment is set to further increase in future:

- Current gasoline fuel injectors already have to deliver 80 to 200 bar injection pressure, more than 20 times higher pressures than in PFI technology, which is 2.5 to 5 bar. [5]
- Future gasoline direct injectors will have to sustain beyond 350 bar injection pressure to meet increasingly stringent emission legislations. [6]

Deposits in the fuel injector nozzles of direct-injection engines have been proposed to form via the following kinetic model: [5]

- Unstable hydrocarbons such as reactive olefins and aromatics undergo oxidation and form the precursors of injector deposits.
- At higher temperatures, these precursors "stick" together (polymerization/condensation) and start to adhere to the surface inside the injector hole.
- This primary layer will then continue to grow further forming carbonaceous deposits that will reduce the size of the injector hole and negatively impact the fuel flow rate as a result.

The formation of injector deposits can have several negative consequences including deviation from optimum spray patterns, altering engine-out emissions and reducing fuel flow rate through the injector. More specifically injector deposits have been shown to alter fuel spray and to negatively impact fuel/air charge formation. [7] Spray imaging and analysis using a Phase Doppler Particle Analyzer revealed an increased rate of wall wetting caused by a 30% higher initial pre-jet velocity and 5% larger drop mean diameter when an injector with deposits was compared to a new injector. This increase in wall wetting could be correlated with increased engine-out hydrocarbon emissions. A similar observation in terms of increased emissions due to heavy injector deposits was made in a bench engine based investigation in 2012. [8] During the dirty-up phase an increase in carbon monoxide (CO) and total hydrocarbon (THC) emissions was observed, an effect that could be reversed on clean-up of the injector using a fuel borne deposit control additive (DCA).

Incomplete combustion means that the engine is unable to fully convert the available chemical energy of the fuel into thermodynamic work on the pistons, leading to a loss of efficiency. It was found that the increased engine-out emissions correlated with increased fuel consumption. More recently, the negative effects of injector deposits on engine-out particle emissions in the form of particle mass (PM) and particle number (PN) have been explored. [9] [10] Fuel impingement and fuel absorption on deposits near the injector tip are believed to be the cause for diffuse combustion resulting in up to ten-fold increases in PM emissions. In a set of three vehicles featuring GDI engines it was possible to show a reduction in PM emissions upon switching to a fuel formulation capable of removing injector deposits. [11]

A number of previous investigations have made use of the fact that injector deposits lead to a reduction in fuel-flow rate due to clogging of the injector holes, and some examples are outlined below. This effect on fuel flow correlates with the injector cleanliness status and was also used as the key metric in this study. In a vehicle based investigation on a chassis dynamometer (CD) long-term fuel trim data (LTFT), a parameter influenced by the flow rate, was extracted from the on-board diagnostic interface in order to differentiate between poor and high performing DCAs. [12] During this study, splash blended 10% ethanol content in the test fuel was providing a challenge to distinguish between fuels with different level of DCA content and LTFT shifts provided by market fuels were regarded as insufficient to obtain a reliable injector fouling signal. Results were therefore acquired using a proprietary fuel formulation emulating a typical USA specification fuel. A similar approach was used in a study involving a larger number of vehicles and was able to obtain notable clean-up data sets with DCA content in the basefuel. [13] As early as 1999 studies into gasoline injector fouling were performed, using bench engines converted for DI operation, and the nozzle tip temperature was identified as one of the key parameters influencing injector fouling. [14] Learnings regarding basefuel composition (Howell EEE) for dirty-up were used to successfully probe the clean-up potential of new Mannich type DCA molecules in a follow-on study. [15] A bench engine study also employed a pro-fouling fuel formulation to gather emissions and further engine

metrics in order to establish the impact of injector deposits on vehicle performance. [8] Most recently a study using a 1.2 L in-line 3-cylinder GDI engine was successfully used to differentiate a fuel matrix containing both regular and premium Japan market fuels based on different levels of DCA content in a series of keep clean tests. [16] Besides collecting Scanning Electron Microscope (SEM) images of the deposit containing injector holes, this study used the already mentioned kinetic model of deposit formation to explain the results for different DCA content.

Besides further improvements in physical injector design, fuels with DCA could provide part of the solution to the challenges of injector deposits described above. Fuels containing DCA have been used successfully in the marketplace for decades. The DCA therefore plays a critical part in maintaining engine cleanliness and in keeping the engine working according to the manufacturer specifications. In order to keep up with the evolution of engine technology, differentiated and additivated fuels must also continue to adapt. Therefore, a benchmarking method for determining the performance of different fuel formulations in this setting is required to help design a fuel able to restore injector cleanliness.

There is therefore an industry need for a standard test method to evaluate the impact of different fuel formulations on gasoline injector cleanliness. Industry bodies in Europe and the USA in form of the Coordinating European Council (CEC) and the Coordinating Research Council (CRC) are evaluating options for developing an industry standard test (CEC TDG-F-113, [17]; CRC Project No. CM-136 [18]). Once developed, there is a desire by the TOP-TIER Licensing program covering USA, USA Territories and Canada, to integrate such a test developed by the CRC into their fuel selection criterion. [19] The CEC industry standard gasoline injector fouling test under development plans to feature the VW 1.4 L TSI engine with a 125 kW power rating (engine code BLG), which is part of the EA111 engine family, like the 90 kW 1.4 L engine used in this study. [20]

This paper describes the experimental setup including engine and fuel selection, statistical experimental design considerations and provides a summary of the overall test protocol. This is followed by the results, which were obtained in a market relevant VW 1.4 L TSI production GDI engine using a Dirty-up/Clean-up protocol. The dataset obtained for this study is comprised of the results from 11 experiments conducted sequentially over an approximate duration of 3 months. This dataset was statistically evaluated at two points during the clean-up period:

- End of the overall clean up period (ca. 35 hours)
- Point at which one tank fill of clean-up fuel is consumed. (ca. 55 liters of fuel).

Based on the results obtained it was possible to differentiate the two candidate fuels at a 99% confidence interval from a reference corresponding to a defined European/Asian market-average regular DCA treat rate. A single basefuel was used throughout the entire test program, which was an EN228 compliant E10 ULG-95 fuel, obtained directly from a commercial European refinery.

EXPERIMENTAL PROCEDURE

The experimental details of this bench engine based investigation of gasoline injector cleanliness are listed in the sections below.

Statistical Design of Test Matrix

For this study, involving two candidate fuels and one reference fuel the overall test sequence (see Figure 2) was designed based on the following two guidelines listed below:

- Randomized order of test fuels (avoided having the same sequence of fuels)
- Test fuels equally distributed throughout sequence (avoided testing a fuel only during one time-segment of the matrix)

Each individual experiment consisted of a 55 h Dirty-Up (DU) and a 35 h Clean-Up (CU) period, meaning each experiment was 90 hours in total duration.

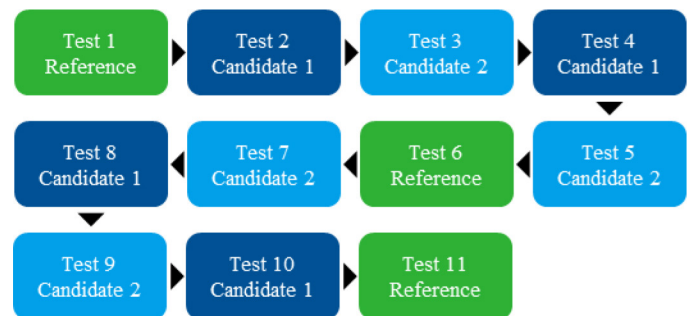


Figure 2. Statistical design of the test sequence for the 11 experiments included in this study.

Engine and Test Bench Setup Details

Details of the VW 1.4 L TSI GDI bench engine used in this investigation are provided in Table 1, including the details of the specific direct injection setup. A special feature of this engine setup was a partially open EMS, which allowed for engine metrics to be obtained directly from the ECU.

Table 1. Details of Euro 4 VW 1.4L TSI GDI bench engine.

Parameter	Details
Manufacturer	Volkswagen AG
Engine model	1.4 L TSI (EA111)
Engine code	CAXA
Displacement	1390 cc
Emission Class	Euro 4
Cylinders	4
Aspiration	Turbo charged (single turbo) with intercooler
Injection	Homogeneous direct injection up to 150 bar, solenoid driven 6 hole injector; side mounted injectors
Compression ratio	10:1
Maximum Power	90 kW at 5000 rpm
Maximum Torque	200 Nm at 1500 – 4000 rpm
Other features	Knock sensor; variable intake valve timing