

Formation and Removal of Injector Nozzle Deposits in Modern Diesel Cars

Rod Williams, Alastair Smith and Ian Buttery
Shell Global Solutions (UK)

ABSTRACT

Deposits forming in the injector nozzle holes of modern diesel cars can reduce and disrupt the fuel injected into the combustion chamber, causing reduced or less efficient combustion, resulting in power loss and increased fuel consumption.

A study of the factors affecting injector nozzle tip temperature, a parameter critical to nozzle deposit formation, has been conducted in a Peugeot DW10 passenger car bench engine, as used in the industry standard CEC F-098 injector nozzle deposit test, [1].

The findings of the bench engine study were applied in the development of a Chassis Dynamometer (CD) based vehicle test method using Euro 5 compliant vehicles. The developed test method was refined to tune the conditions as far as practicable towards a realistic driving pattern whilst maintaining sufficient deposit forming tendency to enable test duration to be limited to a reasonable period.

The test method developed was applied to a fleet of Euro 4 and 5 compliant vehicles enabling the relative deposit sensitivity of the fleet to be assessed. Subsequently the deposit removal performance of conventional and novel diesel detergents was evaluated using the method developed.

Most of the fleet selected was susceptible to nozzle hole deposit formation and in all cases where deposit formation was detected, the novel diesel detergent outperformed the conventional detergent in recovering power and fuel efficiency losses due to deposit formation.

This work has provided insights into the susceptibility of modern diesel passenger vehicles to injector nozzle deposit formation and removal using a test method that is more realistic and widely applicable than industry standard methods.

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INTRODUCTION

Deposits forming in the injector nozzle holes of modern diesel cars fitted with direct-injection fuel systems can reduce and disrupt the fuel injected into the combustion chamber. This can lead to reduced or less efficient combustion, resulting in reduction in power and increased fuel consumption and emissions [2,3,4]; therefore there is a great deal of interest in studying these deposits with the ultimate aim of controlling them.

From prior studies in this field [5,6,7,8] it can be concluded that the propensity for formation of such deposits is influenced primarily by operating conditions (driving pattern and style), fuel quality and the inherent sensitivity of the vehicle hardware.

The CEC Direct Injection Common Rail Diesel Engine Nozzle Coking Test, CEC F-098 (DW10 test) [1] is the industry standard test for evaluating fuel and additive effects

on injector nozzle coking (fouling) in European diesel passenger cars with Direct Injection (DI) engines. The test uses a Peugeot DW10B Euro 4 build common rail engine and relies on three key factors for its baseline injector nozzle deposit sensitivity: -

- it is fitted with non-standard injector nozzles designed to be sensitive to deposit formation;
- requires zinc to be added to the reference fuel (at 1mg/kg) to provide a high deposit baseline;
- features a cycle dominated by high load running.

The objective of the program outlined in this paper was to develop a more realistic and flexible test method for determining the injector nozzle fouling propensity for fuel and additives, whilst drawing on the benefit of experience with the DW10 test as a foundation to the development.

This paper describes the three stages of the test development, contextualizes the finalized method in terms of

realistic road driving and draws conclusions based on the data generated about the possible extent of injector nozzle deposits in the market.

DW10 PROGRAM

CEC Test Overview

The work based around the CEC DW10 engine test comprised measurements on the engine bench in order to compare conditions in the industry standard test to a matrix of conditions mapping across those used in the test to conditions more akin to real world driving in an equivalent vehicle. It was planned to apply the learning from this exercise to define the set points for a vehicle based injector nozzle fouling test optimized to be both realistic and sensitive enough to produce measurable fouling in a reasonable test duration. Some details of the engine are given below in [Table 1](#).

Table 1. Particulars of DW10 engine used in the CEC F-098 test

Engine code	DW10BTED4
Donor Vehicle	Peugeot 407 2.0 HDi 16v
Chassis number series	21010347
Displacement/layout	1998 cc / I4
Output	100kW at 4000 rev/min
Peak torque	320Nm at 2000 rev/min
EMS	Continental/Siemens
Injection system	Common rail, 1600 Bar peak pressure, piezo actuated injectors, 6 hole nozzles
Emissions	Normally certified to Euro 4 (vehicle uses Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF))

Table 2. CEC DW10 test cycle overview

Step	Duration (min)	Engine Speed (rev/min) $\pm$ 20 rev/min	Load (%)	Torque (Nm) $\pm$ 5Nm
1	2	1750	(20)	62
2	7	3000	(60)	173
3	2	1750	(20)	62
4	7	3500	(80)	212
5	2	1750	(20)	62
6	10	4000	100	*
7	2	1250	(10)	25
8	7	3000	100	*
9	2	1250	(10)	25
10	10	2000	100	*
11	2	1250	(10)	25
12	7	4000	100	*
	$\Sigma = 60$			

The DW10 test cycle comprises 12 stages spanning 1 hour. In the industry standard keep clean test four blocks of eight cycles are run, with each block separated by a 4 hour engine off soak period; i.e. 32 hours engine running time and 44 hours in total. The test cycle is dominated by high load, as illustrated in [Table 2](#) and excludes EGR.

Injector Nozzle Tip Temperature

Injector nozzle tip temperature (NTT) was used as a parameter to estimate likely effects on varying operating conditions.

Nozzle tip temperature has been cited in many publications as a key predictor of nozzle fouling severity, [6,7,8,9]. In [8] NTT was shown to correlate strongly with injector nozzle deposit formation over a range of loads and NTTs. In [6] it was concluded that higher NTT led to higher deposit formation rates and that NTT correlated with engine power output.

To enable NTT to be measured, a fuel injector was instrumented with a miniature thermocouple having the hot junction positioned as close to the injector nozzle tip as deemed possible without risking interference with the nozzle exit holes.



Figure 1. Injector nozzle fitted with miniature thermocouple, the upper circled area contains the thermocouple hot junction and in the lower circle is a nozzle exit hole

Nozzle Tip Temperatures in the CEC DW10 Test Cycle

The CEC F-098 test cycle was run with the injector instrumented for injector Nozzle Tip Temperature to determine typical NTTs in the CEC DW10 test. A total of four cycles were run to ensure that NTTs did not increase with successive cycles. The engine was fuelled with the CEC DF79-07 non-fouling reference fuel to ensure that typical deposit-free NTTs were recorded.

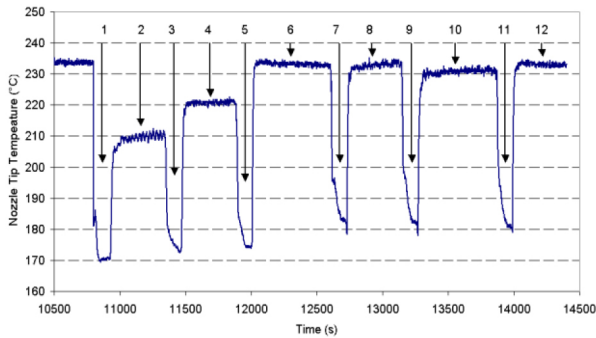


Figure 2. Injector Nozzle Tip Temperature (NTT) measured over the CEC F-098 (DW10) test cycle, with arrows denoting the cycle stage numbers

The data in [Figure 2](#) illustrate that NTT peaks between 230 and 240°C in the full load stages 6, 8, 10 and 12. Temperatures are lower in the high part load stages 2 and 4 and are lower still in the low load odd number stages and in most of the low load stages NTT is still falling at the end of the stage, suggesting that NTT is substantially affected by the preceding stage rather than by the conditions used in the low load stages. Given the weight of evidence from prior publications linking high NTT to conditions conducive to injector nozzle deposits, it is assumed that deposits form in the full and high part load stages, but the propensity for deposits to form in the low load stages is uncertain.

Nozzle Tip Temperature Mapping with Speed and Load

Injector NTT was mapped over a range of speed and load combinations to evaluate the effect of these parameters on NTT in the upper part of the speed/load map where conditions conducive to nozzle fouling were expected. The conditions are detailed in [Table 3](#) below.

Table 3. Speed Load settings for NTT mapping

Equivalent road speed (km/h)	113	127	140
Engine speed (rev/min)	2078	2331	2567
Road load	X	X	X
60% load	X	X	X
80% load	X	X	X
100% load	X	X	X

The data illustrated in [Figure 3](#) indicate a strong correlation between NTT and load (BMEP), but suggest little dependency of NTT on engine speed. Within each subset at a given engine speed, higher load correlates with higher NTT. The two overlapping data points in the 140km/h dataset are at road and 60% load, where the load values are very similar. It can be seen that there are 3 distinct populations in the data, comprising road load and 60% load data, 80% load data and 100% load data. There is little difference in NTT between the

80 and 100% load populations despite the relatively large difference in BMEP of around 5 Bar.

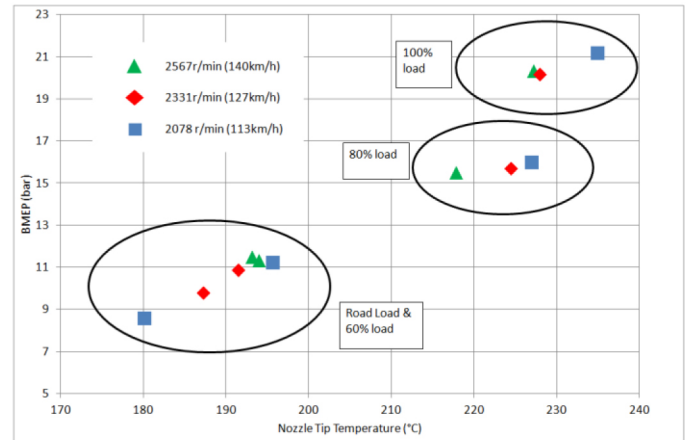


Figure 3. Injector Nozzle Tip Temperature as a function of BMEP at 3 engine speeds x 4 load settings

Rationale for Selection of Primary Vehicle Test Condition

In the interests of sustaining NTT to retain sufficient nozzle fouling propensity optimized with the requirement for road realistic loads, the 80% load point was selected as the basis for development of a CD based injector nozzle fouling vehicle test. It was expected that testing at conditions in the lower NTT population (road load and 60% load), although more representative of the majority of real world driving, would not constitute high enough NTTs to generate sufficiently measurable deposits in a reasonable test duration. The choice of a fixed (80%) load instead of a fixed BMEP was based on the assumption that for other engine and vehicle types, NTT was likely to be similar at given percentage loads rather than at given BMEP values due to higher BMEP engines employing higher capacity cooling regimes to limit combustion chamber material temperature maxima. Also, using a fixed percent load would result in a more consistent loading in terms of ratio to road load, given that high road load vehicles tend to have higher output engines.

TEST DEVELOPMENT AND FOULING FUEL SENSITIVITY IN EURO 5 COMPLIANT CARS

Experimental

Vehicles

The test development phase employed two Euro 5 compliant passenger vehicles representing high selling models in the European market.

Table 4. Test Vehicle Details

	Vehicle A	Vehicle B
Engine: displacement, layout	2.0L / I4	1.6L / I4
Rated power:	125kW	77kW
Fuel Injection Equipment (FIE):	Common rail	Common rail

Chassis dynamometer and measurements

A Chassis Dynamometer (CD) designed for performance measurement, equipped with single 48" roller and electrical inertia simulation was used for all the vehicle work. The CD can run un-manned following a pre-programmed test protocol employing a robot driver to control Accelerator Pedal Position (APP), clutch, brake and gear selection. Fuel is supplied to the vehicle from IBCs (Intermediate Bulk Containers) via an automated fuel switching system and a temperature control and flow measurement device. The test chamber has air temperature and humidity control.

Primary metrics used to evaluate nozzle fouling were power at the driven wheels and mass fuel consumption. Various physical temperature and pressure parameters were monitored via transducers and vehicle control parameters were monitored via the OBD (On Board Diagnostic) interface.

Test fuels

During the test development phase, two pro-fouling fuels were trialed, one relying on the addition of 1mg/kg of zinc for boosting fouling propensity and one relying on the addition of components which could be found in poor quality off-EN14214 specification FAME. Variants of these fuels treated with a novel detergent additive package were also used for stabilization and clean up purposes. The fuels are described in Table 5, below.

Table 5. Fuels used during test development & subsequent fleet testing

Fuel	Zinc free pro-fouling B7	B7 + 1mg/kg zinc
Fuel descriptor	B7	Zinc
	93%v CEC DF79-07	93%v CEC DF79-07
	7%v EN14214 compliant FAME dosed with 2.5%v glycerides	7%v EN14214 compliant FAME
	168mg/kg fatty acid	1mg/kg zinc

Two detergents were employed during the program, being blended into the 'B7' and 'Zinc' fuels for some stabilization and clean up test phases: -

- Detergent (a): conventional detergent package at premium fuel dose rate

- Detergent (b): novel detergent package at premium fuel dose rate.

Initial test protocol

Following some initial running to establish acceptable test boundary conditions including thermal and injection strategy stability, an initial working test protocol that produced meaningful test results was applied in the two Euro 5 compliant cars described in Table 4. This initial scouting test applied slightly differing protocols to the two cars as is described in Table 6, below. These tests used zinc free pro-fouling 'B7' and were run entirely in fourth gear.

Table 6. Initial Test Protocols

		Vehicle A	Vehicle B
	Pre-test	Fit new injectors	
	Warm up	30 mins at 120km/h and road load – zinc free pro-fouling B7 DU fuel	
Test cycle 1	SOT power measure	1 min at 125km/h and full APP	1 min at 120km/h and full APP
	Road load measure	10 mins at 120km/h and road load	
	Deposit form	12 hours at 120km/h and 80% load	12 hours at 120km/h and 90% load
	Repeat test cycle	Total 4 cycles	Total 6 cycles
	EODU power measurement	1 min at 125km/h and full APP	1 min at 120km/h and full APP
	Fuel change	zinc free pro-fouling B7 DU fuel + Novel detergent	
	CU cycles	Total 3 cycles	Total 3 cycles
	EOCU power measurement	1 min at 125km/h and full APP	1 min at 120km/h and full APP

The 120km/h set point was chosen as representative of many markets. The power measurement at the higher speed of 125km/h in vehicle A was selected due to 120km/h being in proximity to an EMS 'trip point' meaning that one of two different injection strategies could be encountered when running at 120km/h, whereas running at full load and 125km/h was clear of the EMS trip point and gave a repeatable condition. Using the 80% load set point for the primary test condition for vehicle A was a direct learning from the bench engine work. The higher load set point of 90% applied to vehicle B resulted from a desire in this formative phase to determine if higher fouling rates would result from higher loads in the 80% plus range.