



Impact of Deposit Control Additives on Particulate Emissions and Fuel Consumption in Pre-used Vehicles with Gasoline Direct Injection Engines

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Abstract

Injector nozzle deposits can have a profound effect on particulate emissions from vehicles fitted with Gasoline Direct Injection (GDI) engines. Several recent publications acknowledge the benefits of using Deposit Control Additives (DCA) to maintain or restore injector cleanliness and in turn minimise particulates, but others claim that high levels of DCA could have detrimental effects due to the direct contribution of DCA to particulates, that outweigh the benefits of injector cleanliness.

Much of the aforementioned work was conducted in laboratory scenarios with model fuels. In this investigation a fleet of 7 used GDI vehicles were taken from the field to determine the net impact of DCAs on particulates in real-world scenarios. The vehicles tested comprised a range of vehicles from different manufacturers that were certified to Euro 5 and Euro 6 emissions standards. In a first phase, the vehicles were fuelled on EN228 compliant gasoline treated with a high dose of DCA and were driven

on a chassis dynamometer over 4750km and in two cases over 5800km with periodic WLTC emissions measurements to determine the potential for particulate emissions and fuel consumption and CO₂ reduction attributable to injector clean-up.

In a second phase, a series of WLTC tests were conducted while the fuel was alternated between the high-DCA fuel and the same fuel excluding the DCA to determine the instantaneous effect of the DCA on particulate emissions.

A fleet-average reduction in particulate emissions, fuel consumption and tailpipe CO₂ emissions were observed with the continuous use of high-DCA fuel whereas no statistically significant differences were observed from the tests alternating between the high-DCA and unadditivated fuels. Therefore, the injector cleanliness benefits of operating these real-world vehicles on high-DCA fuel far exceeded any detriments due to the instantaneous impact of the DCA.

Introduction

Particulate matter (PM) and particle number (PN) limits have been increasingly adopted into emissions legislation to limit the impact of vehicle emissions on air quality [1]. It has been widely observed that injector fouling and intake valve deposits contribute heavily to PM emissions in Gasoline Direct Injection (GDI) engines. The tips of fuel injectors in GDI engines are located within the combustion chamber which causes the injector to be directly exposed to the combustion process, making them particularly prone to deposit formation [1]. Deposit Control Additives (DCAs) are commonly added to gasoline to control the build-up of these detrimental deposits [2].

A previous study conducted by Zhang et al. investigated the effect that the presence of various compounds including DCAs had on the formation of deposits on GDI engine injectors [3]. Fuels with higher olefins, aromatics, and C9/C9+ aromatics were observed to both form a higher level of injector deposits and produce higher particulate emissions. Addition of DCA to the fuels at the beginning of the test was seen to suppress the deposit formation which therefore resulted in lower PN emissions [1, 3]. Wiese et al. observed similar behaviour of both C9/C9+ aromatics contributing to injector deposit formation with an increase in PN and the addition of DCA within the fuel effectively reducing both injector deposits and PN

emissions [4]. Wiese et al. also demonstrated that injector deposit formation can be reduced by increasing fuel injection pressures [4]. According to Monroe et al., formation of deposits on the tips of fuel injectors in GDI engines have also been shown to contribute to an increase in vehicle PN and PM emissions in other studies [1, 3, 4, 5, 6, 7].

The impact of GDI injector tip deposit formation on PM and PN emissions was also investigated by Henkel et al. who found that the presence of deposits on the injectors affected the fuel spray pattern and resulted in an increase of two orders of magnitude in PM and PN emissions [1, 8]. This substantial increase in PM and PN emissions was shown in the same study to be reversible when a gasoline containing DCA was used to remove the deposits and was completely avoided when DCA's were present from the beginning of the test [8].

It is proven that DCAs can keep fuel injectors clean, so that the spray pattern remains as designed, resulting in the PN emissions remaining consistent over time. It is also reported that when DCAs are applied in dirty injectors, the deposits are removed leading to a reduction in the PN emissions [8]. One example mechanism of how particulate emissions increase due to injector tip deposits is described in an SAE paper by Imaoka et al. [9]; the proposed hypothesis for tip soot formation process as shown in Figure 1 is clear evidence of how DCAs contribute to lower particulate emissions. In addition, DCAs keep the injector bores and counterbores free of deposits ensuring a stable and as-designed spray.

In JSAE20239092, Chijiwa et al [10] reported that no significant differences in instantaneous PN emissions were observed when testing a vehicle on fuels with and without a high dose of DCA, both in configurations with and without a GPF. These tests were conducted on a chassis dynamometer over both a WLTC drive cycle and an RTS95 cycle, which is a surrogate cycle used in European RDE development work [10].

A recent study conducted by Monroe et al. proposed that effects of various DCAs chemistries had not been sufficiently investigated and that the potential exists for an increasing concentration of DCA in gasoline to result in higher PM emissions [1]. The study was conducted on a bench engine and one cold and 3 hot FTP95 and US06

drive cycles were simulated. In this relatively short test duration the authors elected to omit the long-term effect of DCAs and instead focussed on instantaneous PM emissions only. The results showed an increase at both very low and very high DCA concentrations. The paper then concluded that this implies the existence of an optimal DCA concentration, however this assumes instantaneous PM emissions are the basis for optimal fuel composition without taking into account the longer-term beneficial effects of DCAs on PM related to injector cleanliness.

The limited scope of the Monroe [1] study combined with the use of a bench engine to collect the data presents a knowledge gap in the behaviour of particulate emissions in real consumer vehicles over time.

The work reported herein was therefore commissioned to determine the net impact of a high DCA dose rate on PM and PN emissions (as well as other effects) in real world vehicles and fuels under consumer-relevant driving conditions.

Experimental Setup

Test Vehicles

The aim of this study was to investigate the behaviour of real-world vehicles, using real-world fuels containing high levels of DCA, under consumer-relevant driving conditions. To achieve this, the following criteria for the test vehicle selection were set: a minimum age of 5 years and approximate mileage of ~100,000km to ~150,000km; a mix of vehicles certified to Euro 5 and Euro 6 emissions standards; representation of various configurations of GDI engines (e.g. side- or centrally- mounted injectors) and manufacturers; some deposits should be evident on the injectors. A further aim was to include two vehicles, which engines are similar to current bench engine test developments for injector cleanliness, e.g. CEC F-113 and from the Top Tier™ group.

Target market for vehicle sourcing was Central/Eastern Europe as these markets were in proximity to the independent test house. Following the selection criteria, more than 20 vehicles were inspected for their technical conditions and readiness for testing by the independent test house prior to testing on the chassis dynamometer (CD). Additionally, in-situ inspection of the injectors was carried out with the aid of a borescope. Almost all vehicles had signs of injector deposits, but no correlation to mileage or age was evident. Finally, seven vehicles were selected for testing. Vehicle details can be found in Table 1.

Fuels

In line with the overall test approach to be as close as possible to the real market, an additive-free E10 gasoline directly from a European refinery was purchased for this project. Key properties of the fuel are shown in Table 2.

FIGURE 1 Hypothesis for tip soot formation process
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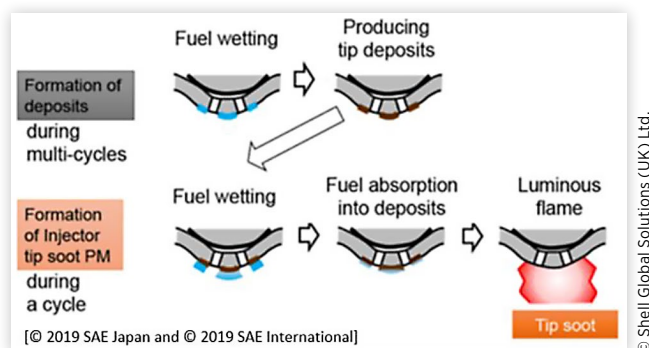


TABLE 1 Overview of Tested Vehicles

Vehicle	1	2	3	4	5	6	7
1 st registration	25.05.2010	2015	30.11.2015	10.07.2014	18.02.2014	03.02.2010	2019
Mileage at SOT (km)	148,722	118,350	94,200	121,400	96,000	151,958	96,949
Emission Standard	EU5	EU6b	EU6b	EU5	EU5	EU5	EU6d-temp
GPF	No	No	No	No	No	No	Yes
Fuel Delivery	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Direct Injection	Direct Injection
Injector type / mounting	Multi-hole / side	Slit / side	Multi-hole / central	Multi-hole / side	Multi-hole / central	Multi-hole / side	Multi-hole / central
Engine Displacement [L]	2.0	1.2	2.0	2.4	1.0	1.4	1.4
Max. power [kW@rpm]	162 @ 5300	85 @ 5200	135 @ 5000	141 @ 6300	74 @ 6000	90 @ 5000	110 @ 5000-5600
Max. torque [Nm@rpm]	350 @ 2000-4000	185 @ 1500-4800	270 @ 1250-4500	242 @ 4250	170 @ 1400-4500	200 @ 1500-4000	230 @ 2000-4000
Number of Cylinders/ valves	4 / 16	4 / 16	4 / 16	4 / 16	3 / 12	4 / 16	4 / 16
Turbocharger [Y/N]	Y	Y	Y	Y	Y	Y	Y
Driveline	2WD	2WD	2WD	4WD	2WD	2WD	2WD

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TABLE 2 Key base fuel properties and SGS Fuel Surveys median values [11]

Fuel property	Results – base fuel	SGS Fuel Survey median values
RON	97.2	96.1
MON	85.0	85.1
Density at 15°C (kg/m ³)	741.8	749.2
DVPE (kPa)	76.9	69.8
Distillation		
IBP (°C)	30.0	37.2
T90 (°C)	153.6	153.2
FBP (°C)	185.8	190.4
E70 / E100 / E150 (%vol)	50.3 / 58.8 / 88.4	38.4 / 58.1 / 88.7
Sulfur (mg/kg)	6	3.7
Ethanol (%vol)	9.9	8.6
Aromatics (%vol)	29.1	30.6
C9 / C10+ Aromatics (%vol)	7.1 / 3.9	8.4 / 2.0
Olefins (%vol)	10.4	10.1
Unwashed gum (mg/100mL)	1.0	16.8
Washed gum (mg/100mL)	<0.5	0.5

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Comparing the test fuel properties with their respective median of more than 400 European E10 gasoline samples from the SGS Worldwide Fuel Surveys analysed between 2020-2023, it is observed that the test fuel is representative of a typical European E10 gasoline and is fully compliant with EN228.

The base fuel is an additive-free gasoline as sourced from the refinery and was used in the 2nd test phase as reference fuel.

DCA Fuel: The additive-free base fuel was used to prepare the test fuel (DCA Fuel) to which a high amount of deposit control additive (DCA) was added.

The DCA was part of an additive package, which mainly consists of the DCA itself and solvents. The package and the additive technology within have been for many years in the market without any major market issues. For the outcome of this study, it was important not to use a complex additive package, as it would be then not possible to put the results into context with other publications, such as from Monroe. [1].

A high dose rate of the additive was chosen in order to represent a premium gasoline. The unwashed gum of the additivated test fuel (DCA Fuel) was 80.5mg/100mL. Referring to the same SGS Fuel Survey data (as shown in Table 1), this dose rate is within the upper quartile of the data and even above the 97.5% quantile. So, the dose rate is close to the highest dose rates to be found in the European fuel market.

Another fuel aspect is often referred to when measuring particulate tailpipe emissions: particulate indices. Two different particulate indices of test fuels have been calculated; the PN index according to Leach [12] and the PM index according to Aikawa [13]. The PN index of both fuels is 2.90 and the PM index is 1.18. As the fuels just differ by the additivation, the indices are identical.

Test Design

In [Figure 2](#) the principal overview of the test layout per vehicle is shown. The detailed activity overview is shown in Appendix, Table.

Vehicle Preparation After receipt all vehicles had been prepared for use on the chassis dynamometer. A vehicle safety inspection was conducted ensuring a safe operation condition and the suitability of the vehicle for testing on chassis dynamometer. Observed malfunctions, which were important for safe and reliable operation, were repaired upfront.

In order to conduct the quick fuel switches during the alternating fuel testing, each vehicle was installed with a 2nd vehicle specific fuel tank in the boot. The installation of the 2nd fuel tank included a 2nd low pressure fuel pump.

Before starting the testing, the original fuel in the original fuel tank was drained, flushed and then filled with the DCA Fuel. The additive-free base fuel was always filled into the additional fuel tank in the boot. As part of the preparations 3 WLTC tests were conducted on base fuel to ensure that the vehicles were operating repeatably within norms.

An engine oil change, including oil filter change, was done before SOT. Only vehicle specific OEM approved engine oils were used, and those lubricants had been previously “de-greened”. De-greening in this context means, that the engine oils, which were used in the test vehicles, ran for 5 hours on a separate GDI bench engine while using a mild drive cycle of a few steady-state load points. This de-greening has the purpose to stabilize the viscosity of the engine oil (shearing of initially present macro molecules) as it has been observed that the viscosity of an engine oil decreases in the first hours of engine operation. The initial viscosity change can have impacts on fuel consumption measurements and in order

to avoid any disruptions of injector deposits in the test vehicles, the de-greening was conducted on a separate bench engine.

Test Cycle – WLTCs Balancing the needs for market realistic data and comparable data to that in the literature, it was elected to run WLTC cycles. Each WLTC test was carried out by a human driver in accordance with the Regulation (EC) 715/2007 – Regulation (EU) 2017/1151 with focus on exhaust emissions and fuel consumption measurements (Type 1 test, WLTP test procedure).

In line with the WLTP test procedure the tests were conducted following at least 8 hours of vehicle thermal soaking at an ambient temperature of approximately 23°C.

Two deviations from the official WLTP procedure have been made in order to reduce test-to-test variability. Firstly, the vehicle battery was fully charged before each cold start WLTC and secondly the start/stop system (where fitted) was disabled.

Mileage Accumulation / Clean-up Phase The aim of this test phase was to observe the PM and PN reduction and any other meaningful effects, over the mileage accumulation with the DCA-additivated test fuel.

Overall, 22 WLTCs were driven per day by human drivers. As emissions measurements were the important part of this project, once per day a cold WLTC and a hot WLTC (after a vehicle stabilization period where the vehicle was driven at 80km/h in the 5th gear) were recorded to document the change of PN and PM emissions, while during the other 20 WLTC the emissions were not recorded. So, a mileage of ~530km were driven per day and overall ~4,750km throughout the whole mileage accumulation. Exceptions were made with vehicle 2 and 4, where a further ~1,500 km were driven to investigate if the PN emissions had stabilized.

The very first WLTC on the 1st test day in the mileage accumulation phase marks the start-of-test (SOT) result and is reported later as result at 0 km.

Alternating Tests In this phase a direct comparison between both test fuels was made. To have statistical confidence in the results the tests have been conducted in the style “BABABAB”. Starting with the additivated fuel had operational advantages in that one fuel change was avoided. In between, the fuel was switched between the two tanks and the remaining fuel in the line was partly drained and partly used-up during the following conditioning phase before each WLTC.

Test Equipment Depending on the vehicle, the tests were conducted on 2WD or 4WD AVL Zoellner chassis dynamometers (CD) at an accredited independent test facility. Each vehicle was consistently tested only on the same CD. The gaseous emissions were collected in bags via a CVS dilution unit.

One CD was equipped with an AVL system (incl. a CVS i60 LD LE and a PSS i60 SD system) where the

FIGURE 2 Overview of Test Design per Vehicle

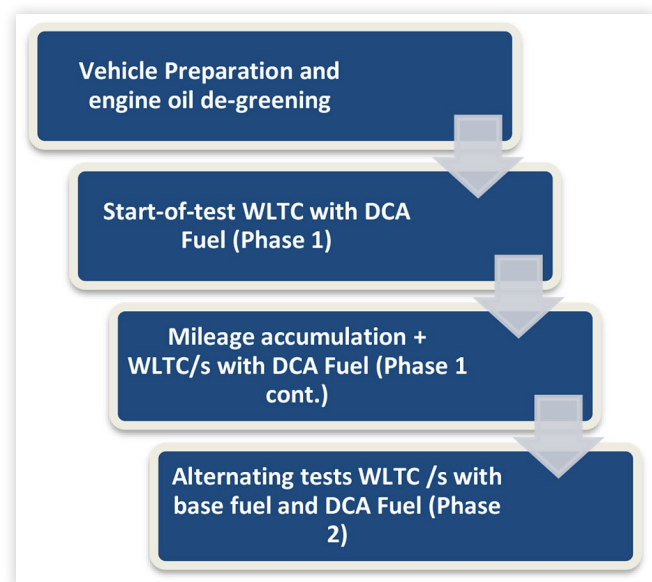
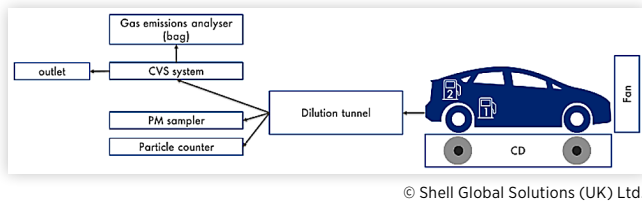


FIGURE 3 Overview of Test Set-up.

gaseous emissions were measured with an AVL AMA i60 system and the particles counted with APC 489 particle counter.

The 2nd CD was using a CVS7400 S sampling system. The gaseous emissions were analysed with a Horiba MEXA 7400 HTRLE system and the particle counter was a Horiba MEXA 2000 SPCS system (23nm minimum particle size limit). The principal set-up of the equipment is shown in [Figure 3](#).

The CD coefficients (F0, F1 and F2) were determined by coast downs and along with vehicle mass were used to develop the road load models. This was done in accordance with the EU regulation 2017/1151.

Results

Events Perturbing Results

When testing pre-used vehicles there is always a certain risk associated with it, that undiscovered technical issues during vehicle pre-checks can turn up later during the testing. Here, some technical issues occurred during the testing of vehicle 4.

During testing on the CD it was noted that the vehicle's internal resistance to motion was unstable, leading to coast-down results being out of tolerance (also visible in the unstable IWR data of the WLTC tests). Since tyre pressures were closely controlled before each emissions test, it was firstly assumed that the primary cause of this was related to the vehicle's brakes, although inspections of the brakes revealed no evident problems. However, the issue could not be solved during testing, but the impact of the increasing internal inertia was clearly visible as the fuel consumption increased steadily during the clean-up test phase. Therefore, the fuel consumption results from this vehicle are not reported in this study.

During the testing of the same vehicle (4) another technical issue arose – a defect of one of the lambda sensors. The exchange of the lambda sensor marked a step change in the gaseous emissions (CO, THC and NO_x) and thus they were not evaluated further. While the PM emissions were not evidently affected, the PN emissions increased somewhat after the exchange, dropping quickly again to a similar level than before the exchange, thus both PN and PM emissions remained in the evaluation as these were the key parameters this study evaluated. Due to the uncertainty on the measurement results of vehicle 4, individual results for the vehicle are shown but the results were excluded from any averaging.

Injector Cleanliness

Clean injectors are important for optimal spray formation and engine performance. With un-additized or low-quality fuels, deposits on injector tips and in bores and counter-bores can be quickly built-up [2, 8, 14] and thus reduce the engine performance.

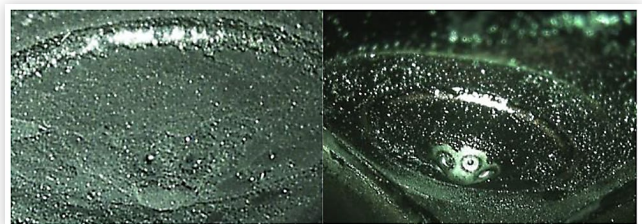
Before the start of the testing and at the end of the testing, in-situ images of the fuel injectors have been made with a borescope. At start-of-test the injectors have not been dismantled in order not to lose any deposits due to potential deposit disturbance during removal and handling. At EOT all fuel injectors have been dismantled and microscope images have been made in addition.

Across the fleet, the amount of deposits within the bores and on the nozzle tip have been reduced. Due to the in-situ imaging at the start-of-test a detailed ranking of the amount of deposit within the bores was not possible as the resolution of the borescope and the access to the fuel injectors was not equal for all vehicles. Two examples are given here to illustrate the clean-up of the fuel injectors ([Figure 4](#) and [Figure 5](#)), further images are included in the Appendix in [Table A2](#).

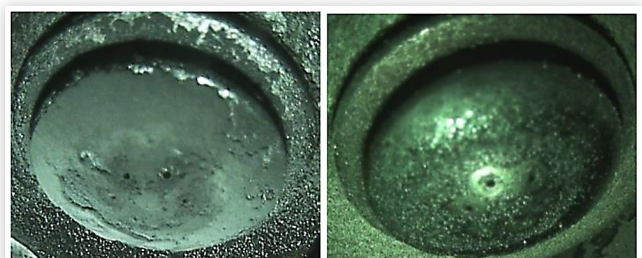
Particulate Emissions

Vehicles 1 to 6 have been homologated against the NEDC and not WLTP, so they must not necessarily comply with the emissions measured here with the WLTC. The limits shown in the figure are thus only of an indicative nature. The "relaxed" Euro 6 PN limit was available for Euro 6b GDI vehicles for up to 3 years after the date for TA/FR.

As laid out in the test description, the gaseous and particulate emissions have been measured once each test

FIGURE 4 In-situ fuel injector within cylinder 2 of vehicle 3 (left before SOT and on the right after EOT)

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FIGURE 5 In-situ fuel injector within cylinder 1 of vehicle 7 (left before SOT and on the right after EOT)

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day using cold WLTC cycles during the clean-up phase (phase 1). This section focuses on the PM and PN emissions, while a following section details out the gaseous emissions. The PM results for all vehicles are shown in Figure 6 and the PN emissions Figure 7. The PN results presented in this section are of PN23, meaning that in line with the Euro 6 legislation only particles larger than 23nm diameter are counted.

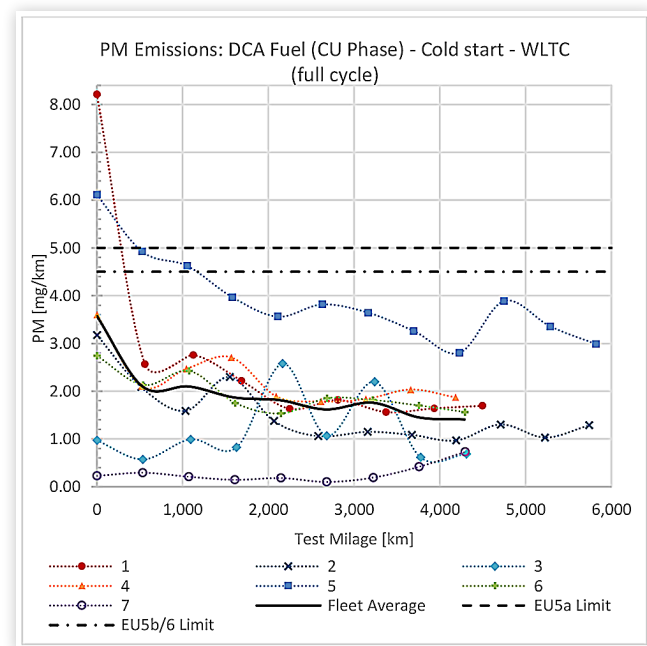
The particulate emissions of the daily measurements are plotted against the vehicle mileage progression in the clean-up phase. The graph clearly illustrates the downward trends in PM emissions as soon as the vehicles start to run on the additivated fuel (DCA Fuel).

Figure 6 clearly illustrates the downward trends in PM emissions as soon as the vehicles start to run on the additivated fuel (DCA Fuel). Greatest PM reductions have been achieved, where the PM emissions were the highest at SOT. The high PM emissions of two vehicles at SOT were even above the Euro 5 emissions legislation limit [15].

PM emissions from vehicle 3 undulated over the mileage and no overall downward trend was apparent. It is postulated that in this case, the deposits on the injector tips (evident from the optical images) were not impairing injection spray formation and therefore no benefit in PM emissions was observed over the clean-up.

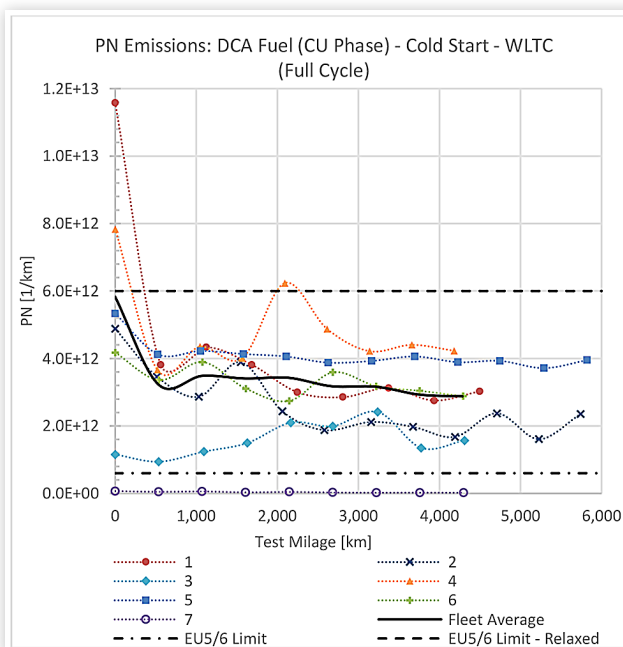
As seen with the PM emissions, the PN count (Figure 7) rapidly decreases over the initial 500km of the test of the test, with the two vehicles that initially exceeded the relaxed Euro 6 limit [15], decreasing below this value. It should be noted that for Euro 5 vehicles the indicative PN limit is not applicable. Again, across all vehicles, the greatest reduction in PN emissions are achieved at SOT when the fuel injectors have the highest amount of deposits.

FIGURE 6 PM results during the clean-up phase



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FIGURE 7 PN results during the clean-up phase

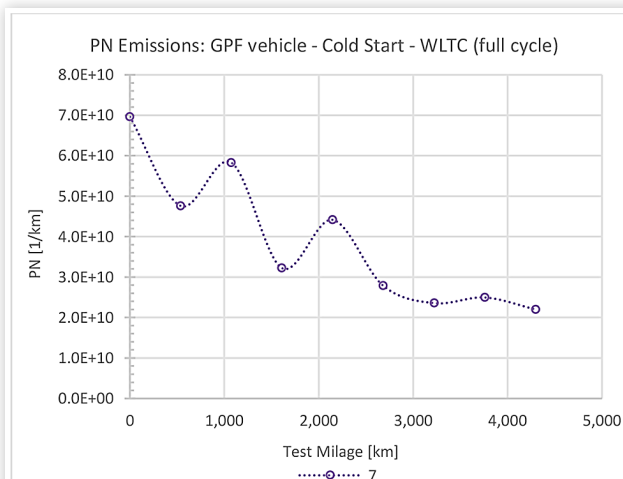


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Vehicle 7, which was equipped with a GPF, had at the end of mileage accumulation slightly higher PM emissions, but were consistently below 1 mg/kg, this is around the detection limit for this measurement and therefore there is uncertainty around any signals in the data. Due to the GPF installed and the scale used in Figure 7, the actual change cannot be observed. From Figure 8 it can be seen that substantial reduction in PN emissions was observed with this vehicle, which is even above the fleet average reduction (see Figure 7).

Due to the DCA within the additivated fuel, the fuel injectors have been cleaned and the particulate emissions become lower in most vehicles. As the injectors are cleaned and deposits removed, the DCA in the fuel has a smaller gross cleaning effect, simply due to fewer deposits available for potential removal. This supports the observed trends seen in Figure 6 and Figure 7. The

FIGURE 8 PN emissions of the GPF vehicle (7)



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initially steep reduction in particulate emissions plateaus as the engine is cleaned to the point where no further emission decrease will occur due to engine cleaning, as the engine has been sufficiently cleaned.

In [Figure 9](#) and [Figure 10](#) the relative reduction of the particulate emissions over the whole clean-up phase are shown. The reductions were calculated according to Equation 1.

$$PM \text{ Reduction } (\%) = \frac{PM_{SoT} - PM_{EoT}}{PM_{SoT}} * 100$$

Equation 1 PM/PN reduction calculation

Vehicle 4, whilst displaying typical values for the fleet, is excluded from the PM and PN fleet averages due to the technical issues observed during testing and thus the uncertainty in the results. For the calculation of the average PM fleet reduction, the GPF vehicle (7) was also excluded as its absolute values were low (around the limits of the measurement) and thus a change, here an increase, in percentage were extremely high (~220%). So, across the remainder of the fleet a reduction in PM of more than

FIGURE 9 Reduction of PM emissions during the clean-up phase (fleet average without vehicle 4, or vehicle 7 - GPF)

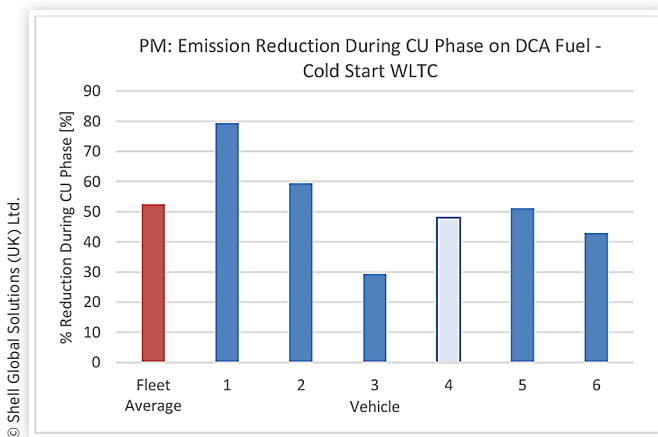
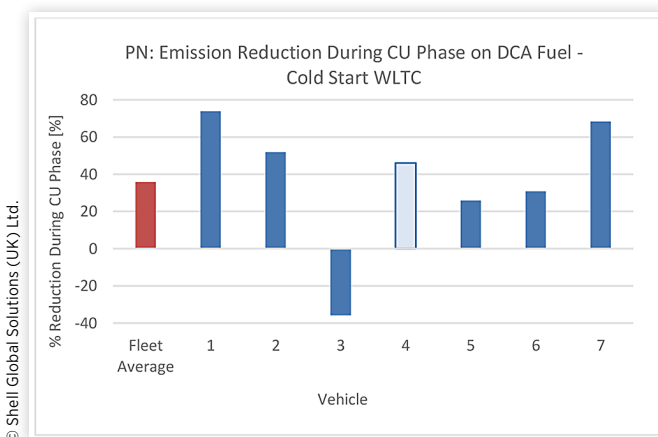


FIGURE 10 Reduction of PN emissions during the clean-up phase (fleet average without vehicle 4)



50% was achieved. The fleet reduction in PN was decrease of ~36%, here the fleet includes vehicle 7.

Vehicle 3 shows no improvement in PN emissions, although the clean-up of the fuel injectors was evident. Through studies of [Figure 7](#) and [Figure 12](#), the very low PN emissions for a non-GPF vehicle at the start of phase 1 ($1.15 \times 10^{12}/\text{km}$) indicate the relative cleanliness of the vehicle at the start of the test even if the injectors were visually dirty, leaving low potential for deposit removal and associated reduction in PN emissions.

Alternating Tests

In the 2nd test phase, the immediate impact on particulate emissions of the additive within the DCA fuel has been investigated. Single WLTC tests have been conducted each day with fuel switches in between. At least 3 WLTC tests per fuel have been conducted while alternating the test fuels each day. The mean values for each fuel and vehicle are plotted for PM emissions in [Figure 11](#) and for PN emissions in [Figure 12](#) (hatched bars). For comparison the start-of-test result before the CU is shown (solid bars). The error bars on the shaded bars are the 95% confidence limits of those tests. Again, the results for vehicle 4 are despite the technical issues included in the chart.

As expected, the highest PM and PN emissions are observed at the beginning of the CU phase. The alternating tests are of comparable values to the end of the CU phase, a result to be expected due to no intermediary use of the vehicles between tests. The differences in PM and PN values between fuels A and B in the alternating tests are not statistically different, meaning that the presence of the DCA in the fuel has no significant negative instantaneous impact on particulate emissions.

FIGURE 11 PM results of the alternating phase in comparison to start-of clean-up results

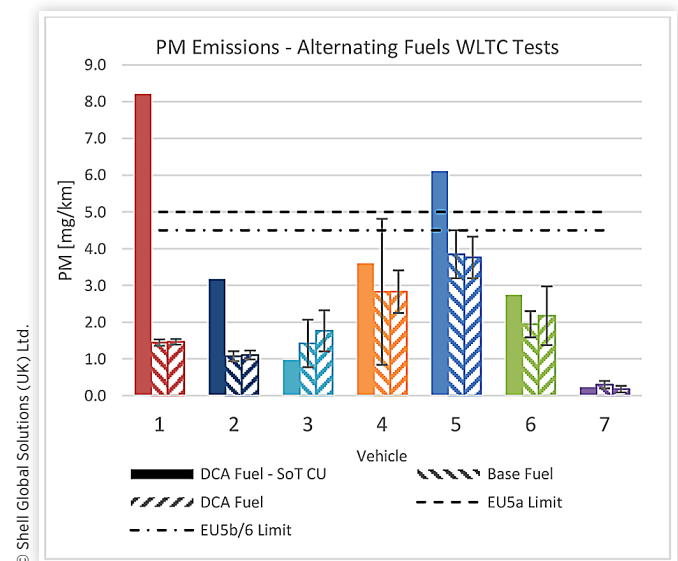
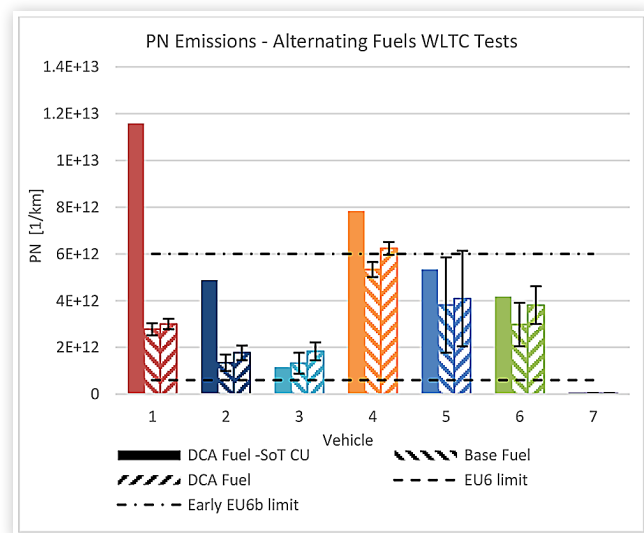


FIGURE 12 PN results of the alternating phase in comparison to start-of clean-up results



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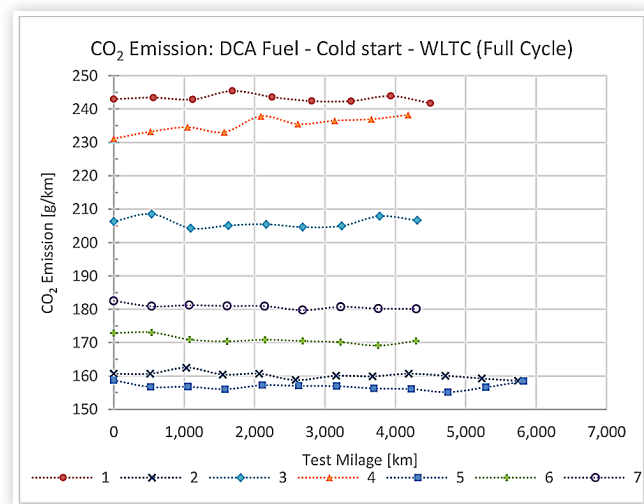
Fuel Consumption and CO₂

The fuel consumption was calculated on basis of the carbon balance of the measured gaseous emissions.

CO₂ and fuel consumption (FC) have been evaluated due to the interest in identifying trends with injector cleanliness related to efficiency. The use of de-greened engine oil enabled a stable viscosity across the whole test procedure. A stable viscosity is highly important to avoid impacts from viscosity on fuel consumption and CO₂ emissions. The measured kinematic viscosity changes at 40°C and 100° were low (see Figure and Figure A2. in the Appendix).

In Figure 13 the CO₂ emissions of all vehicles during the CU are shown. As mentioned earlier, vehicle number 4 had an unstable internal inertia and thus CO₂ and FC increased over mileage. For this technical reason vehicle

FIGURE 13 CO₂ emissions of the vehicles during clean-up



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4 was taken out of the fleet average results but for completeness results of vehicle 4 are shown in the Figure 14 and Figure 15.

At the end of the clean-up phase 4 vehicles had a lower fuel consumption, while vehicles 3 and 5 had no change or a slight increase in FC. This led to fleet average reductions in CO₂ and FC of ~0.7%.

Joedicke et al [14] found that cleaner fuel injectors lead to an increased engine efficiency. In this study the reduction in fuel consumption confirmed the findings of Joedicke in real vehicles which were taken from the second-hand market. However, it should be acknowledged that the size of the effect varies depending on the amount of injector deposits and the drive cycle/pattern.

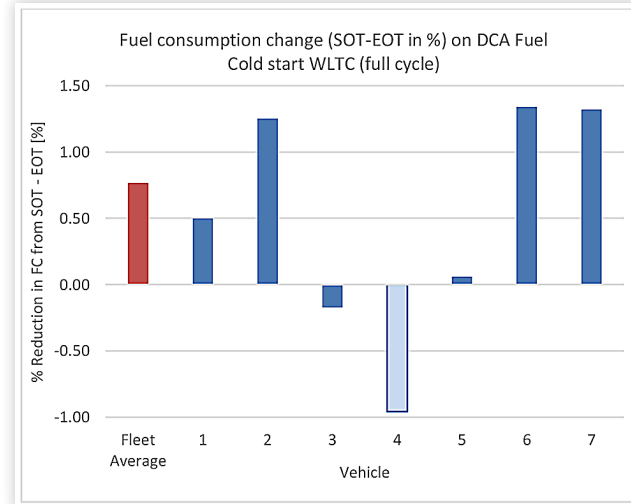
As the fuel consumption was calculated from the measured gaseous emissions, the same trends and almost the same results for CO₂ changes during clean-up were found – see Figure 14 and Figure 15. In both figures the fleet average is shown in red and vehicle 4 in a light blue colour. It can be observed that there is a substantial difference in FC and CO₂ change over test for vehicle 4. This is attributed to poor combustion efficiency in this vehicle as evidenced by the high CO emissions (Figure 18).

Other Gaseous Emissions

It should be noted again, that with the exception of the GPF vehicle (7), none of the vehicles were homologated against the WLTC, but instead the NEDC, thus it was not expected that these vehicles would meet the emissions limits over the higher duty and more transient WLTC.

In line with the WLTP, measurements of THC, NMHC, CO and NO_x emissions for each tested vehicle were taken daily. Analysis of the data proved no sign of distinct trends in gaseous emissions. Due to the transient nature of the WLTC, the “real world” driving simulation results in constantly changing engine load through acceleration and deceleration. Although the quality values of each

FIGURE 14 Fuel consumption change during clean-up phase (fleet average without vehicle 4)



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FIGURE 15 CO₂ change during clean-up phase (fleet average without vehicle 4)

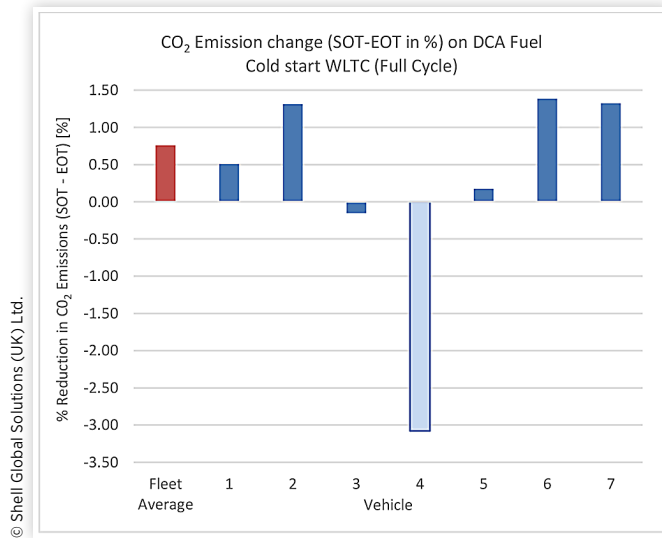
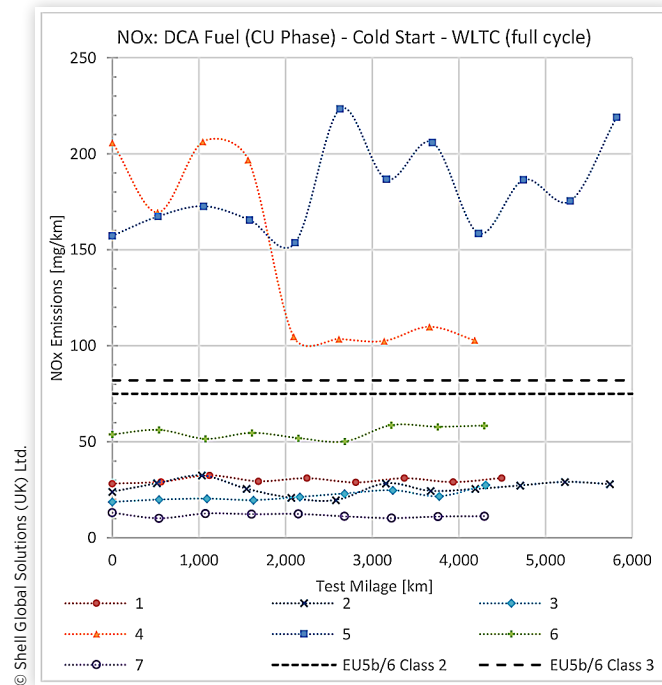


FIGURE 16 THC Emission Results during the clean-up phase



conducted WLTC (IWR and RMSSE) were within limits (except for vehicle 4), slight changes in the driving pattern results in a slight change in emissions, unrelated to the change in injector cleanliness. Whilst the CU phase was not completed running the engine at steady state, the exact driving pattern was repeated through use of the same test cycle, thus the average emissions per cycle could be compared to assess the effect of injector CU on gaseous emissions. In practice, with the gross values of the emissions being low (relative to the limits), additional minor changes to the experimental set-up caused e.g., by re-fitting the vehicle to the CD between tests, due

to other vehicles being tested in the interim, results in relatively noisy data.

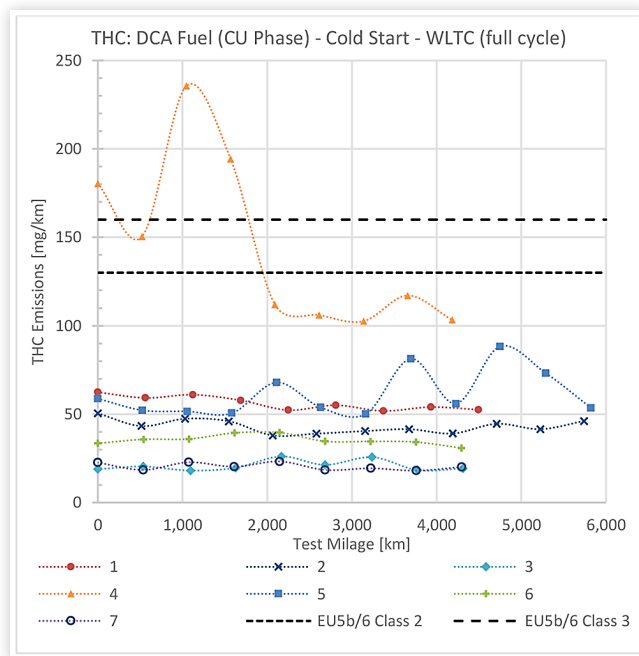
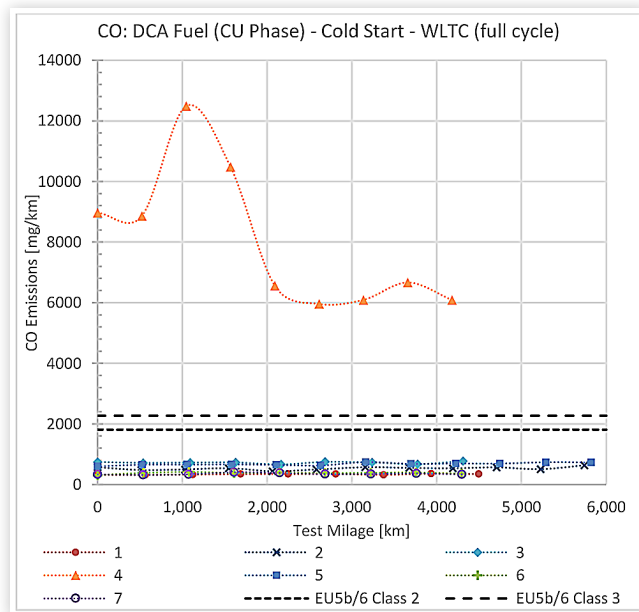
As illustrated [Figure 16](#) the absolute values of THC emissions for the fleet are distinctly below the EU limits for all vehicles, except vehicle 4. It should be noted, that a figure displaying the NMHC emissions of the fleet would be identical in shape. The difference would occur in the absolute values, which would be typically 20 mg/km lower, accounting for the removal of methane from the count.

The step change in emissions seen for vehicle 4 occurs due to a sensor change during testing. The change occurred following the WLTC test beginning at 1568 km and pre the WLTC occurring at 2091 km of test mileage. Following the swap of the downstream lambda sensor, a step change is observed as the false readings are no longer counted and the emissions fall below the EU limit. The still significantly above average readings are a result of the other issues experienced by vehicle 4 during testing. Despite a sharp decrease, this is not a trend replicated across the fleet and as such is attributed to experimental set up and sensor changes, rather than the cleaning of the injectors due to the DCA fuel.

The second vehicle of interest is vehicle 5. Whilst unaffected in all other tests (PM/PN, FC and CO₂), the gaseous emissions and in particular NO_x emissions were affected by both lambda sensors and the three-way catalyst (3WC). When setting up vehicle 5 in the test house, the emissions were measured and found to be far exceeding the limit. Following a period of trouble shooting, everything in the exhaust system was exchanged including both lambda sensors and the three-way catalyst (3WC). The 3WC was de-greened on a bench engine prior to use to fully activate the catalyst prior to testing. To ensure this was the case, a NEDC was conducted determining "normal" levels of all gaseous emissions, except NO_x. Following this single NEDC test, it was accepted that the issues with the system had not been fully resolved, but it was accepted for further testing. Despite the changes to the exhaust system, across all emission types, the data increased in noise as the CU phase was completed and the NO_x did not decrease below the Euro 6 limits until EOT (it should be noted that this vehicle was homologated against the NEDC and a final NEDC test was not conducted).

[Figure 17](#) and [Figure 18](#) show similar trends to [Figure 16](#), of no distinct increase or decrease in emissions across the fleet (excluding vehicles 4 and 5). Any potential change in emission values is insignificant in relation to the EU limits. The fleet contains a mixture of class 2 and 3 vehicles, however all vehicles (again excluding vehicles 4 and 5) are far below the limits for both classes.

Whilst the figures present as flat profiles, there is noise in the data as explained by the changes in experimental set-up and vehicle refitting. Due to the variance in the measurements, using the last data point of the CU phase to calculate the change in emissions achieved due to clean up, would not be truly representative of the effect of the DCA fuel. For some vehicles, the last data point would imply an increase, contrary to the trend across other data points, whilst for other vehicles this effect is the opposite. Whilst the start and end values do not

FIGURE 17 NO_x Emission Results during the clean-up phase**FIGURE 18** CO Emission Results during the clean-up phase

present an opportunity to accurately calculate the effect of injector cleaning on gaseous emissions, from the flat profiles of the fleet across all emission types it can be concluded that the presence of the DCA has no significant net benefit or negative impact on gaseous emissions.

As expected, the initial deposit levels in the engines of the test vehicles had not resulted in high gaseous pollutant emissions and thus following clean up and the location of the sensors after the 3WC, the signals were very small, thus no indication of clean up was observed.

An opportunity was missed to measure emissions before the catalyst, where changes in gaseous emissions due to injector deposits may have become apparent.

Further to the conclusion of no net benefit or detriment (post catalyst) achieved during the CU phase, Figures A3 to A5 in the appendix display no detrimental effect on gaseous emissions noted during the alternating tests. On the contrary, observation of the absolute values of gaseous emissions would indicate a reduction in emissions resulting from the use of the DCA fuel. As mentioned however, the very small signals and noise during testing reduces the confidence in such a conclusion.

Hot WLTC Tests

As mentioned in the test design section, hot WLTC tests have been conducted as part of the procedure. Detailed results are not given here, but the trends observed in the cold WLTC tests are similar for PN and PM emissions, but all on a lower level.

Since the three-way catalyst has been fully warmed-up by the time running these hot WLTC tests, the absolute level of the gaseous emissions was for all vehicles very low (except CO emissions of vehicle 4).

Summary and Conclusions

In this work 7 pre-used vehicles from the market have been sourced, having varying ages, mileages and emission classes. The deposits found on and in the fuel injectors were “real-world” deposits as they have been built during normal vehicle operations by the pre-owners and have not being built during artificial dirty-up cycles on special fouling fuels.

The vehicles underwent operation on DCA-additivated fuel, followed by the alternating fuel test phase in order to determine the long-term and short-term effect of DCA in high dose rates over the long and short term, respectively.

Based on the above results and observations, the following conclusions can be made:

1.) Reduction of particulate tailpipe emissions with DCA-treated fuel

In this study it was demonstrated that a fuel with a premium dose rate of DCA is able to reduce particulate emissions (both by mass and number) in almost all tested vehicles. Furthermore, the PN emissions of the GPF vehicle could be even further reduced, while already being on a very low absolute level. The reduction of the particulate tailpipe emissions is linked to the injector nozzle deposit removal when premium fuels are used.

2.) The alternating test series confirmed that there is no statistically significant difference between two identical fuels, which only differ by their DCA additive content.

3.) Cleaning the injector nozzles of used GDI vehicles by the application of DCA-additivated fuel can improve their efficiency, resulting in reduced fuel consumption and CO₂.

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Acronyms / Definitions

2WD - 2-wheel drive

3WC - Three-Way catalyst

4WD - 4-wheel drive

C10/C10+ - All aromatics with 10 or more C-atoms

C9 - All aromatics with nine C-atoms

CD - Chassis dynamometer

CEC - Coordinating European Council

CO - Carbon monoxide

CO₂ - Carbon dioxide

CU - Clean-up

DCA - Deposit control additive

DI - Direct injection

EOT - End of test

EU - European Union

FBP - Final boiling point

FC - Fuel consumption

FR - First registration

FTP95 - Federal Test Procedure (specific drive cycle)

GDI - Gasoline direct injection

GPF - Gasoline particulate filter

IBP - Initial boiling point

IWR - Inertial work ratio

MON - Motor octane number

NEDC - New European Driving Cycle

NMHC - Non-methane hydrocarbon emissions

NO_x - Nitrogen oxides

OEM - Original equipment manufacturer

PM - Particulate mass

PN - Particulate number

RDE - Real driving emissions

RMSSE - root mean squared speed error

RON - Research octane number

SOT - Start of test

T90 - Temperature at which 90 volume % of fuel have been distilled

TA - Type approval

THC - Total hydrocarbon emissions

US06 - Supplemental Federal Test Procedure (a specific drive cycle)

UWG - Unwashed gum

WLTC - Worldwide harmonized Light-duty vehicles Test Cycle

WLTP - Worldwide harmonized Light-duty vehicles Test Procedure

Appendix

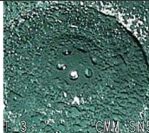
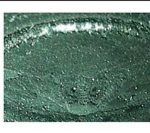
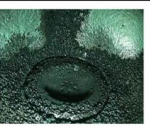
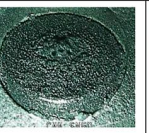
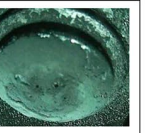
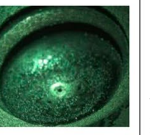
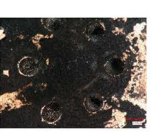
TABLE A1 Schematic summary of the test program

Phase	Test Day	Activity
Vehicle preparation	1-3	Vehicle prepared for CD testing, engine oil de-greening, 3 WLTC tests on base fuel to check vehicles
Clean-up and mileage accumulation		
1	4-12 ¹	Each day 1 cold WLTC (with measured emissions) and 21 WLTC for mileage accumulation + cool down and soaking time
Alternating (back-to-back) fuel tests		
2	13	1 cold WLTC on DCA Fuel
2	14	1 cold WLTC on Base Fuel
2	15	1 cold WLTC on DCA Fuel
2	16	1 cold WLTC on Base Fuel
2	17	1 cold WLTC on DCA Fuel
2	18	1 cold WLTC on Base Fuel
2	19	1 cold WLTC on DCA Fuel

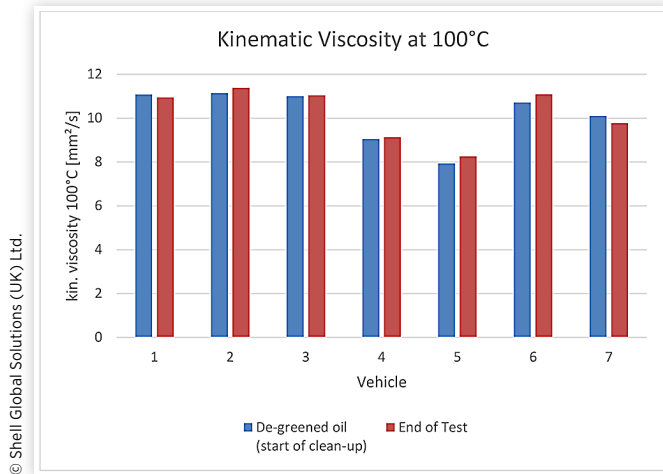
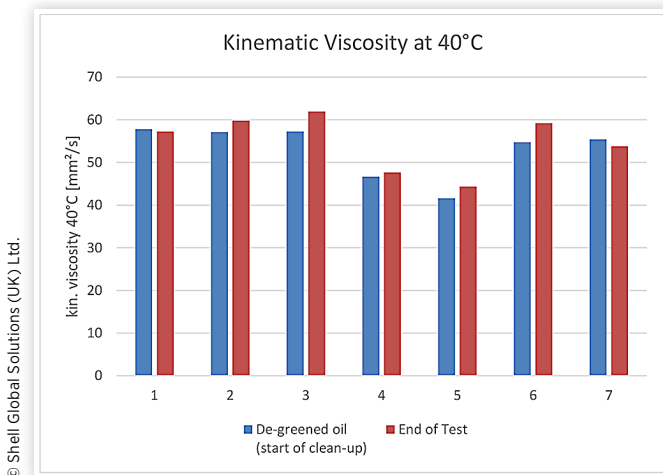
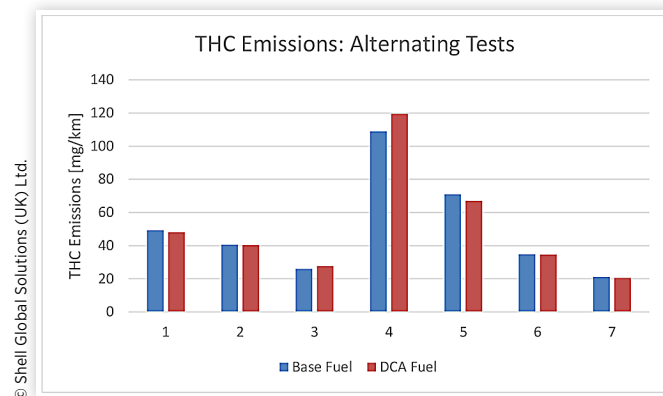
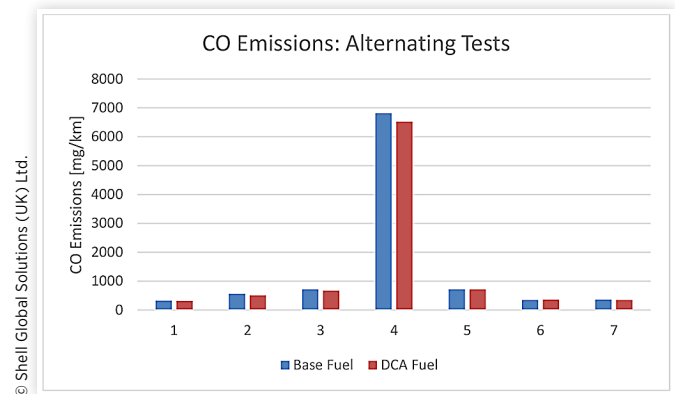
¹ For vehicle 2 and 5 the clean-up test phase has been extended by 3 further test days

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TABLE A2 In-situ borescope images from start and end of test as well as Microscope images at EOT

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7
Start of test							
End of test							
Microscope image							

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FIGURE A1 Engine oil – kinematic viscosity at 100°C**FIGURE A2** Engine oil – kinematic viscosity at 40°C**FIGURE A3** Average THC emissions during the alternating tests**FIGURE A4** Average CO emissions during the alternating tests**FIGURE A5** Average NO_x emissions during the alternating tests