

## On-Road Testing and PEMS Data Analysis for two Euro 6 Diesel Vehicles

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### Introduction

Work by the European Commission's Joint Research Centre (Weiss et al, 2011 & 2012) has indicated that real-world emissions of light-duty vehicles may be significantly greater than results obtained over the Type Approval test, particularly for NO<sub>x</sub> emissions from diesel vehicles. As a result of this, and per Regulation (EC) No. 715/2007, the European Commission has stated (CARS 2020 Action Plan, 2012) their intention to introduce an additional Type Approval test procedure for the measurement of Real Driving Emissions (RDE).

An expert group of stakeholders (RDE-LDV group) has therefore been involved in examining and developing potential test methods (Weiss et al, 2013). During this process, EU Member States and the European Commission have expressed a strong preference for the use of Portable Emissions Measurements Systems (PEMS) to assess real on-road driving, rather than chassis dynamometer tests, with an additional fixed test cycle or cycles produced by a Random Cycle Generator. Alternative methods for the analysis of PEMS data have also been put forward.

In view of these developments, AECC and Ricardo UK Ltd., collaborated on a test programme to conduct a range of chassis dynamometer and RDE tests on two modern Diesel production cars. The aim of this work was to evaluate the real-life emissions performances of the vehicles when using PEMS systems, and to identify and help understand the differences in emissions that may arise between the various test procedures. Gaseous emissions, Particulate Mass (PM) and Particle Numbers (PN) were measured. For the PEMS tests, the measurement system incorporated a new electrical mobility based system for measurement of PN – one of the first test programmes to utilise the new instrumentation being put forward for RDE testing.

### Test vehicles

For these tests two series-production vehicles Type Approved to Euro 6b emissions requirements were procured. Both incorporated Diesel Particulate Filters (DPFs) to achieve Euro 6 PM/PN levels, preceded by a Diesel Oxidation Catalyst (DOC). For NO<sub>x</sub> control, one, "dEGR", relied on a combination of High-pressure and Low-pressure (post-DPF) Exhaust Gas Recirculation (EGR). The other, "SCR", used urea-SCR (Selective Catalytic Reduction) as the prime NO<sub>x</sub> control mechanism.

All tests were conducted using the same batch of <10 ppm sulfur UK pump-grade diesel fuel, compliant with EN590:2009. Both vehicles were tested with as-received lubricants, expected to be the manufacturers' initial fill in view of the low vehicle mileages at test start.

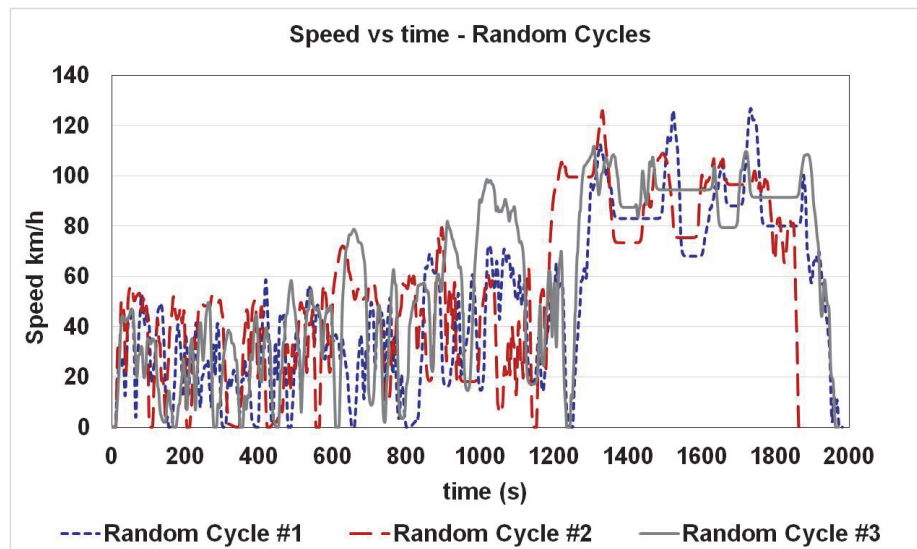
**Table 1:** Test vehicles

	SCR Vehicle	dEGR Vehicle
Cylinders	4	4
Max Power (kW)	103	125
Capacity (litres)	2.0	2.1
Engine technology	Turbocharged Direct Injection	Turbocharged Direct Injection
Transmission	Manual, 6-speed	Semi-auto 7-speed dual-
Emissions control technology	EGR, DOC, DPF, SCR	Engine measures, long and short route EGR, DOC, DPF
Odometer at start (km)	~12 000	~11 000

## Chassis dynamometer testing

Both vehicles were tested over the following chassis dynamometer cycles:

- New European Drive Cycle (NEDC), the current legislative test procedure;
- The Worldwide Light-duty Test Cycle (WLTC), which forms the basis of the Worldwide harmonized Light vehicles Test Procedure (UNECE Global Technical Regulation No.15, 2014; WLTP) that is expected to be used for Type Approvals in the future;
- The Common Artemis Drive Cycle (CADC) (André, 2004) which incorporates more transient operating modes derived from real-world driving and is used as the basis of emissions factors determination for modelling by EU Member States;
- 3 different 'Random cycles' created using a specific cycle generator that was made available to the European Commission's working group on RDE-LDV. This produces test cycles based on 'short trip' segments from the EU database used to construct WLTC. The resulting cycles for this programme are shown in Figure 1.



**Figure 1:** speed vs. time plots for the 3 different Random Cycles.

The NEDC and WLTC were tested as 'cold-start' cycles following an overnight soak. The CADC and random cycles used 'hot-starts' following a standardized warm-up procedure. 3 repeats were run for each of the NEDC, CADC and WLTC cycles. For the Random Cycles it was decided to test three different cycles singly, to assess the degree of variability seen and to increase the database for comparative purposes. For the SCR vehicle, disabling the stop-start system to achieve more repeatable results was considered, but in order to assess the most representative operation the tests were conducted in standard user mode.

The WLTC tests were conducted using the procedures appropriate to WLTP Class 3b vehicles (power to mass ratio  $>34$  W/kg and  $v_{max} > 120$  km/h). The cycle used for this test program was therefore the 4-phase test comprising low-, medium-, high-, and extra high-speed phases.

The CADC tests, with Urban, Extra-Urban and Highway phases, originally had non-sampled portions at the start and end of the cycle. However, as some authorities were understood to evaluate emissions over the whole cycle, this latter variant was used for all the test work.

Changes to the procedures for setting vehicle test inertia between NEDC and WLTP mean that test masses for the WLTC will often be higher than for the NEDC. In this work test masses for the WLTC and random cycles were calculated according to WLTP ( $TM_H$ ), and those for the NEDC and CADC came from current European regulations. To provide a comparator, a one-off test on both vehicles was performed with the CADC at WLTP inertia.

## PEMS testing of Real Driving Emissions

The PEMS instrument used in this work was a Semtech ECOSTAR unit supplied by Sensors Europe GmbH. The modules supplied enabled the measurement of CO and CO<sub>2</sub> by Non-Dispersive Infra-Red (NDIR), THC by Flame Ionisation Detector (FID), NO<sub>x</sub> and NO<sub>2</sub> by Non-Dispersive Ultra-Violet (NDUV), a filter-based PM measurement and a PN metric based on particle mobility. A pitot flow meter enables determination of raw exhaust flow and the downstream proportional dilution system thus

enables a representative PM sample to be collected. It also allowed PN to be measured from diluted exhaust, as in the laboratory procedure. The lower mobility particle size cut-off was set to a nominal ~23 nm, as for the regulatory PN equipment. However, the PN system did not incorporate a Volatile Particle Remover (VPR) that is a feature of the PMP system used in the laboratory. As a result, some volatile particles may be detected by the PEMS PN.

To compare the emissions measured by this PEMS instrument with conventional lab equipment, a correlation exercise was first undertaken. Good correlation was established for the gaseous pollutant measurements. The initial correlation data for PN indicated that emissions profiles were similar between PEMS PN and the PMP system, but a simple background correction needed to be applied to both systems to converge the profiles of the two instruments.

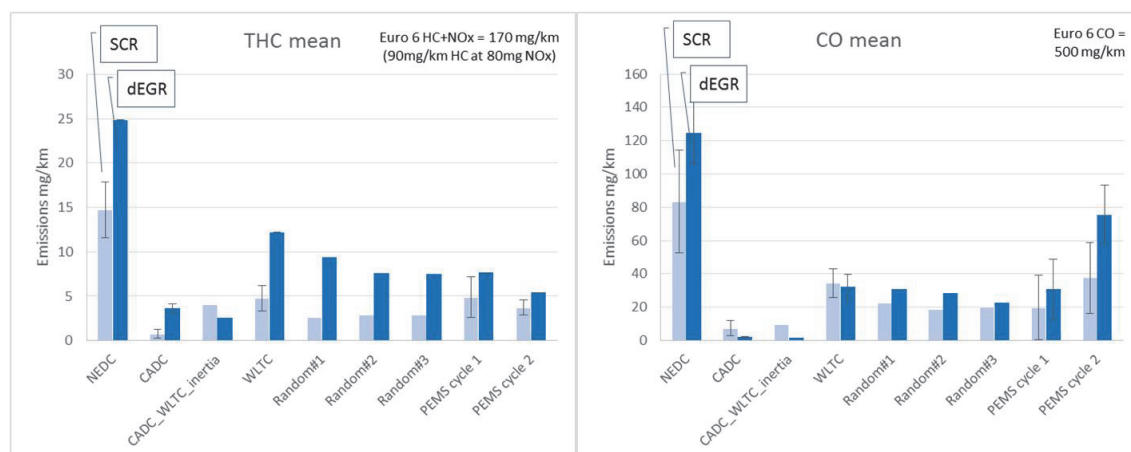
Two real-driving test routes were used. Both incorporated urban, rural and motorway segments. To differentiate the vehicle operating effects on the emissions control systems the routes were to be broadly similar: commencing and completing at the sea-level Ricardo site. Route 1 commenced with motorway driving, (66% of the trip distance), moved to the city (11%) and then completed on rural roads. Route 2 started with urban driving (33%), then motorway (38%), but again completed with rural road operation. Each trip was run 3 times for each vehicle.

Following a ≥6 hour soak, the PEMS equipment was powered well before the engine to enable it to achieve stability. Measurement was started before the engine, thus ensuring that cranking and warm-up emissions were captured. All test results were recorded over the complete test.

## Test results

Emissions data from both the chassis dyno cycles and the PEMS tests on both test vehicles are reported below. The charts presented show the emissions from entire chassis dyno test cycles, and on-road routes, with each bar representing the mean of three repeat tests, except for the CADC at WLTP inertia, where there was only a single test for each vehicle. The error bars indicate one standard deviation. The PEMS data are shown without any additional processing.

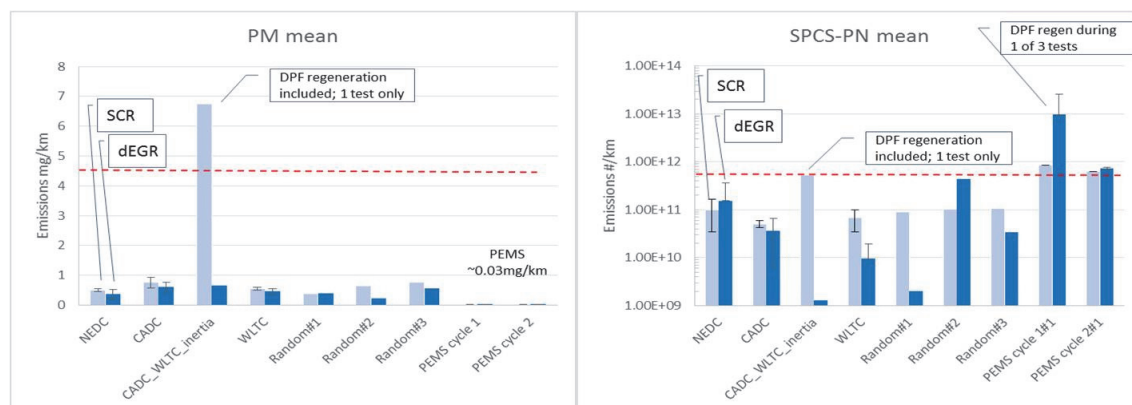
Emissions of total hydrocarbons and carbon monoxide (Figure 2) for both vehicles were less than 30% of the Euro 6 limit on all tests. Highest THC and CO emissions were seen on the NEDC, with substantially lower levels on the WLTC. This is a clear indication of the cold start effect. THC and CO are elevated before DOC light-off, and this has a proportionally greater impact on the NEDC g/km results than on the longer WLTC. As the RDE tests are even longer, the important impact of the cold-start is diminished by assessing only the whole-test PEMS results.



**Figure 2:** Total hydrocarbons (THC) and CO results for both vehicles.

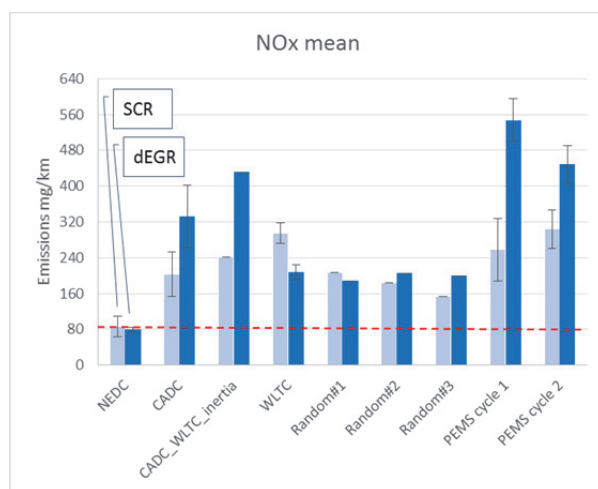
As may be expected from vehicles equipped with DPFs, Particulate Mass emissions (Figure 3) were below 1 mg/km from all chassis dynamometer and PEMS tests except for one CADC at WLTC inertia on the SCR vehicle, where an active DPF regeneration was observed. In this test, the PM mass approached 7 mg/km. However, with regeneration frequency taken into account, PM emissions were well below the 4.5 mg/km Euro 6 limit. Visual inspection of the PM filter paper revealed no obvious sign of elemental carbon, so this additional mass is presumed to be predominantly volatiles. On-road (PEMS) gravimetric PM emissions were approximately an order of magnitude below chassis dyno levels, at <0.3 mg/km, but the collected filter masses were broadly similar (10 µg to 30 µg) from both chassis dyno and PEMS tests. This may be as a result of the collection and removal of semi-volatile materials during the longer PEMS test, so the lower mg/km PM emissions are most likely a simple function of dividing the same mass by a longer distance.

Chassis dyno tests produced PN emissions below the Euro 6 limit of  $6 \times 10^{11}/\text{km}$ , although the CADC that included an active regeneration was borderline. PEMS PN results were in general slightly above the Euro 6 limit, although on one test of the dEGR vehicle a DPF regeneration occurred, resulting in higher measured PN emissions – this result has been included in the mean results for this route. The slightly higher PEMS PN results compared to the chassis dyno tests may be a result of the lack of a specific volatile particle remover in the PEMS instrument used, particularly in the case of the test where a regeneration occurred. Post-DPF PM has previously been shown to be dominated by volatiles with as little as 0.5% of the mass measureable as non-volatile particle numbers. (Andersson et al., 2007)



**Figure 3:** PM and PN results for both vehicles.

NOx emissions of both vehicles are given in Figure 4. Both showed mean NOx emissions close to the 80 mg/km Euro 6 limit on the NEDC, while on other cycles and the PEMS routes they ranged from 2 to almost 6 times these levels. Mean NOx emissions of the dual-EGR vehicle were higher than those from the SCR vehicle over the long-duration CADC (>3000 s) and both PEMS routes, where NOx emissions ranged up to ~600 mg/km on route 1 and nearly 500 mg/km on route 2. NOx emissions over the shorter (~1800 s) WLTC and random cycles were lower but still well in excess of the Euro 6 limit.



NOx emissions from the SCR-equipped vehicle were generally lower than those from the dEGR vehicle, except for the WLTC and one random cycle. Highest emissions were those on the WLTC and PEMS routes, with maximum NOx emissions at ~330 mg/km, <4x the NEDC levels. Mean PEMS emissions from this vehicle were higher from Route 2, which started with urban driving, than Route 1: indicating a delay in optimum NOx control as the SCR system climbs to its operational temperature of ~200°C. Lowest emissions were seen from the hot-start tests, where SCR operational temperature was achieved most rapidly

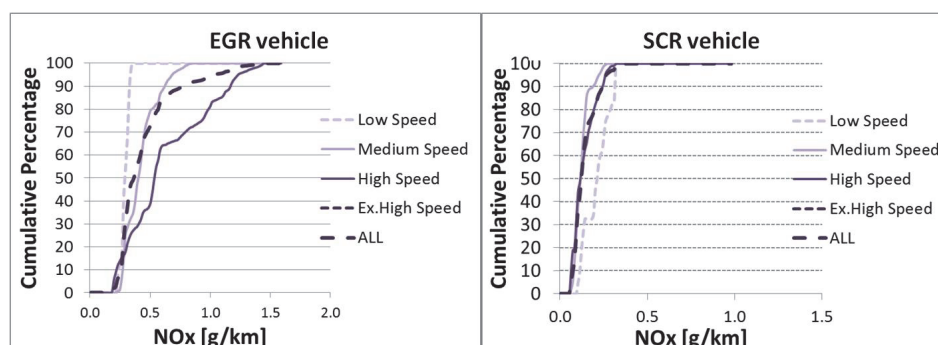
**Figure 4:** NOx emissions for both vehicles

## PEMS data analysis

PEMS data were initially processed using EMROAD Version 5.60 Build 2, produced by the European Commission's Joint Research Centre (JRC). The basis of EMROAD processing is to use a Moving Average Window (MAW) technique with, for this work, 1 kg CO<sub>2</sub> forming the reference quantity for a window. When the vehicle has travelled sufficient distance to produce 1 kg of CO<sub>2</sub> all data within that window is averaged to produce one MAW value. Several windows can overlap and data can contribute to more than one 'window', as long as data is valid for the whole window. The approach can be used to identify 'normal', 'soft', 'severe' and 'extreme' driving conditions by comparison with those obtained from the same test vehicle driving the WLTC on the chassis dynamometer. EMROAD also allows for certain conditions (e.g. cold start and DPF regenerations) to be excluded from the data set. Whilst the impact of cold start in terms of a test of approximately 2 hours is small, many real-life

journeys are quite short and so the impact is greater. In the case of DPF regeneration, this is also a factor in real-world operation. From the experience with these two vehicles, the exclusion of such events can result in significant proportions of the emissions being excluded.

One of the outputs of EMROAD is a graph showing the cumulative percentage of windows in the 'normal' driving band, separated into low, medium, high and extra high-speed sectors. Whilst the CO<sub>2</sub> windows for these speed categories agreed well for both the vehicles, the NO<sub>x</sub> windows (Figure 5) highlight the importance of the higher speeds for proper assessment of real-life NO<sub>x</sub> emissions.

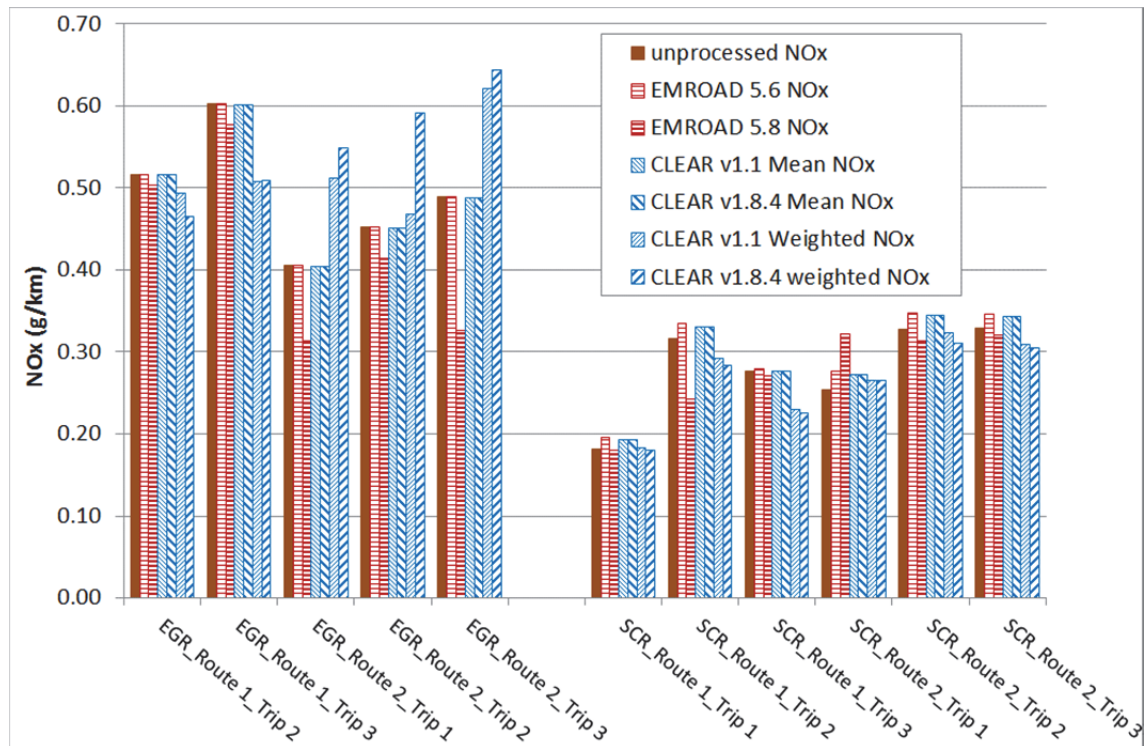


**Figure 5:** Cumulative NO<sub>x</sub> percentages for both vehicles.

The alternative method of PEMS data analysis available at the time of the test programme was version 1.1 of the CLEAR tool developed by TU Graz. In this approach a 'goal pattern' is set that describes a drive cycle in terms of the time spent with the engine operating in different power bands. The test data are then analysed to determine the time spent operating in each of the power bands defined by the goal pattern. The output provides various parameters including mean and weighted emissions (including both g/km and g/h) and emissions related to CO<sub>2</sub> output. Using this approach the initial analysis indicated that the weighted g/h mass emissions results for most tests were ~25% lower than the actual integrated drive cycle emissions, suggesting that portions of the cycle where significant emissions were being produced had been excluded by the weighting process. The weighted g/km emissions, though, were generally much closer to the mean cycle results, because the calculation also weights the distance.

Since these evaluations were first conducted, new versions of both analysis tools have been developed. EMROAD version 5.80B8 for instance now reportedly adjusts the WLTC CO<sub>2</sub> points that form the basis of the 'normal' driving band to allow for the additional mass of the PEMS equipment and uses windows within the 'normal' ( $\pm 25\%$ ) band plus windows within the 'soft' and 'severe' bands (25 to 50%). In addition, weighted average instead of percentiles have been chosen to report emissions. A new analysis of the test data has been conducted using this version. CLEAR has also been updated and TU Graz kindly provided an analysis of the data using the revised version 1.8.4 which, at the time of writing, has yet to be released. The outcomes of these various analyses are shown below in Figure 6. In general, the newer version of EMROAD appears to result in lower NO<sub>x</sub> emissions than the previous version, whilst the newer version of CLEAR appears to give similar or higher results compared to the original version.





**Figure 6:** Comparison of different PEMS analysis methods for the two vehicles.

## Conclusions

A test programme conducted on two Euro 6 Diesel vehicles reinforced concerns that Diesel NOx emissions in real driving may substantially exceed the emissions levels certified during the Type Approval test. Methods proposed for the evaluation of the results from such Real Driving Emissions tests were examined as part of the test work. Concerns remain on possible exclusions – especially DPF regeneration – from the data sets. Whilst the methods are continuing to develop, it is clear that the two main candidates can, in some cases, give significantly different results.

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