

On-Road and Chassis Dynamometer Evaluations of Emissions from Two Euro 6 Diesel Vehicles

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ABSTRACT

The exhaust emissions of two Euro 6 diesel cars with different emissions control systems have been evaluated both on the road and over various chassis dynamometer test cycles. European emissions limits are currently set using the New European Driving Cycle (NEDC), but the European Commission is preparing additional test procedures to ensure that emissions are well controlled both in real-world use and over the legislative test cycle. The main focus of this work on 'Real Driving Emissions' (RDE) is on measurements using Portable Emissions Measurement Systems (PEMS) in truly representative, on-road, driving. A key focus of the test programme, undertaken as a collaboration between AECC (the Association for Emissions Control by Catalyst) and Ricardo UK, was therefore the use of PEMS systems to measure on-road emissions of both gaseous pollutants and particulate matter. This included measurement of particle number emissions with a new candidate system for this type of measurement.

The results from this testing are compared with emissions measured over four different chassis dynamometer test cycles - the current legislative cycle (New European Driving Cycle, NEDC); the Common Artemis suite of test cycles (CADC) that is widely used in emissions modelling; the new Worldwide Light-duty Test Cycle (WLTC) defined by the UN Working Party on Pollution and Energy (GRPE) as part of the development of the Worldwide harmonised Light vehicles Test Procedure (WLTP); and a set of cycles produced by a Random Cycle Generator based on 'short trip' segments from the EU database used to construct WLTC. This Random Cycle (RC) approach was originally considered by the European Commission and Member States as an alternative to PEMS measurements, but remains an option for particle number measurement should PEMS instrumentation not be fully available by the time such measurements are required by legislation.

The aim of this test programme was to evaluate the emissions performance of two different vehicles when using PEMS systems in real-life driving, and to identify and help understand the differences in emissions that may arise between the various test procedures. The test results show the differing vehicle emissions performances that may be encountered in real-driving for two vehicles that both meet the Euro 6 limits in Type-Approval laboratory testing. The results show that in some cases the on-road PEMS-measured emissions for complete test routes can exceed Type-Approval limits, and indicate that real-world conditions require more robust control strategies over those needed to satisfy existing legislation.

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INTRODUCTION

Euro 6, the next stage of European emissions regulations for light-duty vehicles, becomes mandatory from 1 September 2014 for the Type Approval of new passenger cars and the smaller light commercial vehicles (categories M and N1 Class 1), and 1 year later for all other commercial vehicles not

exceeding 3.5 tonnes maximum mass (categories N1 Class II and N1 Class III). One year after these dates, Euro 6 becomes mandatory for all new registrations.

A number of papers and reports have raised concerns over the emissions performance - especially diesel - of current and future light duty-vehicles in real, and in particular

urban, driving conditions, compared to the emissions results obtained in the legislative test procedure on a chassis dynamometer [1,2,3]. The European Commission has therefore announced in its 'CARS 2020 Action Plan' [4] and its Clean Air Programme for Europe [5] its intention to include an additional test for 'Real Driving Emissions of Light-Duty Vehicles (RDE-LDV)' from the start of Euro 6. The Commission has indicated [6] that this will take the form of on-road emissions measurements using Portable Emissions Measurement Systems (PEMS) and the EU's Joint Research Centre (JRC) has been leading the development of appropriate procedures [7,8]. It is planned that test procedures for RDE-LDV will be implemented in the Euro 6 Regulation from 2014, with the introduction of 'Conformity Factors' proposed from the Euro 6c stage starting in 2017.

AECC has previously conducted chassis dynamometer tests emissions over various chassis dynamometer test cycles [9, 10], but these tests did not include the RDE-LDV proposals. To fill this knowledge gap, AECC and Ricardo collaborated on a project conducting emissions tests on two modern light-duty diesel cars. The main aims of the work were to help identify and understand the differences in emissions that may arise between the various test procedures including real driving emissions measurements using PEMS, and to understand the practical and experimental aspects of using these measurement systems. Both of the cars were Type Approved to the Euro 6b emissions requirements and incorporated a Diesel Particulate Filter for PM and PN control. To assist in understanding how different vehicle systems might respond, one of the vehicles used a urea-SCR system for NO_x control, selected as being typical of most current Euro 6 vehicles. The other vehicle provided a view of alternative emission control architecture by its use of a dual EGR to avoid using NO_x-specific aftertreatment.

WORK SCOPE

The programme of work proceeded in a number of stages:

- Two vehicles were identified and located in continental Europe and shipped to the Ricardo UK Shoreham Technical Centre.
- Following PEMS manufacturer-supported installation of their system on the SCR vehicle, a correlation between the on-board and lab-based emissions measurement systems was undertaken.
- After investigation and resolution of any PEMS measurement issues, the on-road measurement campaign was conducted.
- The PEMS was then switched to the dual-EGR vehicle and a second measurement campaign, on the same on-road routes, was conducted.

- In parallel, the SCR vehicle's exhaust system was instrumented and it was then subjected to chassis dyno tests.
- To complete the scheduled test programme, chassis dyno tests were also conducted on the dual-EGR vehicle
- The instrumented exhaust systems were then removed, replaced with identical new OEM systems, and the vehicles returned to the market.

Test Vehicles and Emissions Control Systems

The two light-duty diesel test vehicles employed in this work were sourced from the European market, with both certified to Euro 6b standards. The two vehicles used alternative approaches for meeting the regulatory NO_x targets: the SCR vehicle was selected as an early application of Selective Catalytic Reduction (SCR) into the European market; the dual-EGR vehicle identified as employing combustion and engine hardware (both long-route and short-route Exhaust Gas Recirculation (EGR)) measures for NO_x reduction, and both employed Diesel Particulate Filters (DPFs) for Particulate Mass (PM) and Particle Number (PN) control. A brief classification of the test vehicles is given in [Table 1](#).

The SCR vehicle was equipped with a close-coupled Diesel Oxidation Catalyst (DOC) and DPF. The urea injection system was placed close to the outlet of the Diesel Particulate Filter (DPF), with the SCR placed underfloor. The SCR system was split into two parts as shown in [Figure 1](#).

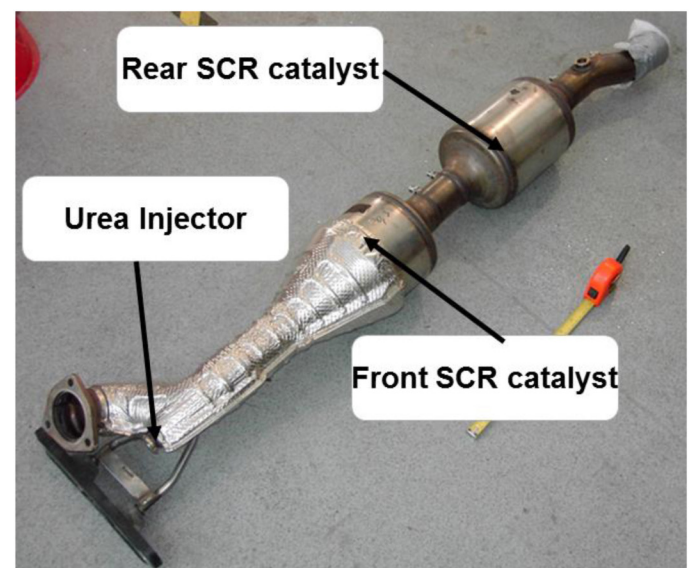


Figure 1. Configuration of the SCR Vehicle's SCR system

The dual-EGR vehicle also included a close-coupled DOC-DPF system with the low pressure EGR loop drawing from a location just downstream of the DPF-exit ([Figure 2](#)).

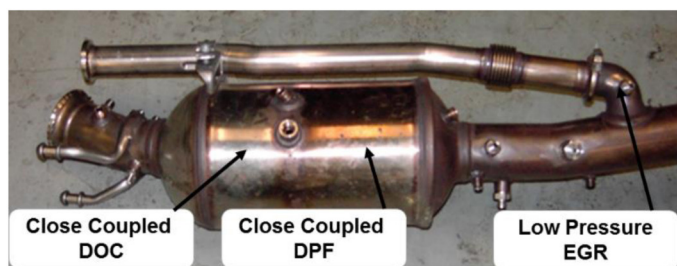


Figure 2. Configuration of the dual-EGR vehicle's exhaust system

Table 1. Test Vehicles' Data

Property	SCR Vehicle	Dual-EGR Vehicle (d-EGR)
Cylinders	4	4
Max Power, kW	103	125
Capacity, cm ³	1968	2143
Transmission	M6	Semi-auto 7, DCT
NOx control strategies	EGR, SCR	Engine measures, long and short route EGR
Certification CO ₂ , g/km	132	115
Certification NO _x , mg/km	68	65
PM/PN Control	DPF	DPF
Odometer at start of test programme, km	~12 000	~11 000

For operation on UK highways both vehicles were equipped with trade registration plates and driven by Ricardo employees with advanced driving qualifications and experience.

Fuel and Lubricant

A batch of <10 ppm sulfur UK pump-grade diesel fuel, compliant with EN590:2009, was set-aside and employed for both chassis dynamometer and on-road PEMS testing in this work. The fuel specification is provided as [Appendix 1](#).

Both vehicles were tested with as-received lubricants. Due to low mileage (<12 000 km) of these vehicles it is expected that these lubricants were the manufacturer's factory-fill product.

PEMS Testing

PEMS System, Analytes and Methods

The PEMS used in this work was an ECOSTAR unit supplied by Sensors Europe GmbH. The ECOSTAR modules enabled the measurement of CO, CO₂, THC, NO_x, NO₂, filter-based PM and a PN metric based on particle mobility. With the exception of NO and NO₂, gaseous emissions were measured using the analytical approaches prescribed for certification testing in the emissions laboratory, and most commonly used. NO/NO₂ were measured using non-dispersive ultra-violet (NDUV) analysis, which has recently been permitted for certification testing in Europe, rather than the chemiluminescence analysis (CLA)

technique subject to longer-term prescription in European legislation. The PEMS employs a pitot flow meter to determine raw exhaust flow, and a downstream proportional dilution system enables a representative PM sample to be collected on-board and this also allows PN to be measured from diluted exhaust - as in a Constant Volume Sampler (CVS) in the laboratory. The PN system incorporated a feature to limit the lower particle size measured to ~23 nm, thus mimicking the performance of regulatory PN equipment. Measurement techniques are summarised in [Table 2](#). However, it did not incorporate a system for removal of volatile particles.

Table 2. ECOSTAR Emissions Measurements

Analyte	Technique
CO	NDIR
CO ₂	NDIR
THC	FID
NO _x and NO ₂	NDUV
PM	Proportional dilution + filter sampling
PN	Modified diffusion charger (DC)
Exhaust flow	Pitot flow meter

Installation

The PEMS was initially installed on the SCR Vehicle by Sensors' technicians, witnessed by Ricardo personnel. After testing, the PEMS was then uninstalled by Ricardo and installed on the dual-EGR vehicle. Similar installation layouts were used for both vehicles. Span gases were employed to verify analyzer performance. These gases were not placed on the vehicle - cylinders were situated in the garage and spans performed prior to vehicle departure and immediately on return.

The complete PEMS installation included requirements for combining exhaust flow from dual exhaust, a cycle rack to mount the exhaust dilution system and flow meter on the vehicle tailgate, and warning stickers indicating flammable gases, hot surfaces and a mobile hazard. Tubes for routing sample gases to in-car analysers ran from the tailgate to the rear windows and were anchored using clamps and adhesive tape. In both vehicles the PEMS system was installed inside the void created with the rear seats down. Even so, the majority of the space was used. The front of the analysers faced the back of the driver's seat to receive the sample transfer lines entering through the rear window. Two sample lines entered - one for gases, one for PM and PN. Large battery packs, able to power the FID and multiple heated lines, were installed rear-most in the vehicle and secured. The H₂/He fuel for the FID (HC measurement) was procured in small, easy to handle bottles and secured to the analysers.

Following testing, and prior to final uninstall of the PEMS equipment, the SCR vehicle was weighed. After uninstallation the vehicle was weighed again, and it was determined that the entire weight of the PEMS equipment, batteries, PCs and necessary ancillaries was ~345 kg - equivalent to 3-4 passengers. The measured weight of the PEMS is applicable to both SCR vehicle and Dual-EGR vehicle's on-road tests.

Risk Assessment

Detailed risk assessments addressing chemical & heat releases, road safety and driver competence were performed prior to on-road testing and relevant documentation carried on-board the vehicles during testing.

On-Board Data Acquisition

In addition to the regulated emissions measurements of the PEMS, other data were logged either into the PEMS software, or via independent data loggers.

- Exhaust temperatures were measured using 3 mm K-type thermocouples.
- Exhaust pressures were measured using Druck ± 200 mbar differential transducers and Druck -1 to +4 bar gauge pressure transducers.
- Both thermocouples and pressure transducers were connected to a CSM dualscan module and logged by ETAS INCA version 5.4.1

OBD information was logged by different software for each vehicle:

- SCR vehicle - Gendan HEX+CAN OBD interface and other specialist software.
- Dual-EGR vehicle - Gendan EOBD interface and Gendan Engine Check Pro v3.1 software

Real-World Drive Cycles

Two PEMS Routes were developed by Ricardo, based upon criteria developed with AECC, with one route to be 60% urban, the other to be 60% motorway and both routes to include 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, but with one route commencing with urban driving, the other with motorway driving. The minimum duration of the route was to be 60 minutes.

Parts of existing drive cycles around the urban and city localities of Shoreham-by-Sea, Hove and Brighton were employed, with the close proximity of dual-carriageways and the Brighton to London motorway exploited. Two 3-segment routes (urban, rural, motorway) were adopted for use in the test work:

- Route 1 commenced with motorway operation, moved to the city and then completed on rural roads
- Route 2 commenced with city operation, then motorway, but again completed with rural road operation.

Testing Overview

To mirror chassis dynamometer measurements, each route commenced following a ≥ 6 h soak. Emissions were logged continuously including key-on. Key-on was preceded by analyser warm-up, span and operational safety checks.

Three repeats of each PEMS route were undertaken on each vehicle. For example, for the SCR vehicle, speed vs time drive traces for Route 1 are shown in Figure 3, with similar traces for Route 2 in Figure 4.

Excepting one occasion when asked to adopt a more aggressive style, the driver was instructed to follow each PEMS route using his normal style of driving. The driver had advanced driving qualifications and chassis dynamometer experience, so given the variability in traffic flow, especially in the urban section of each route, it was considered that driver consistency would have a minor impact on test-to-test 'repeatability'.

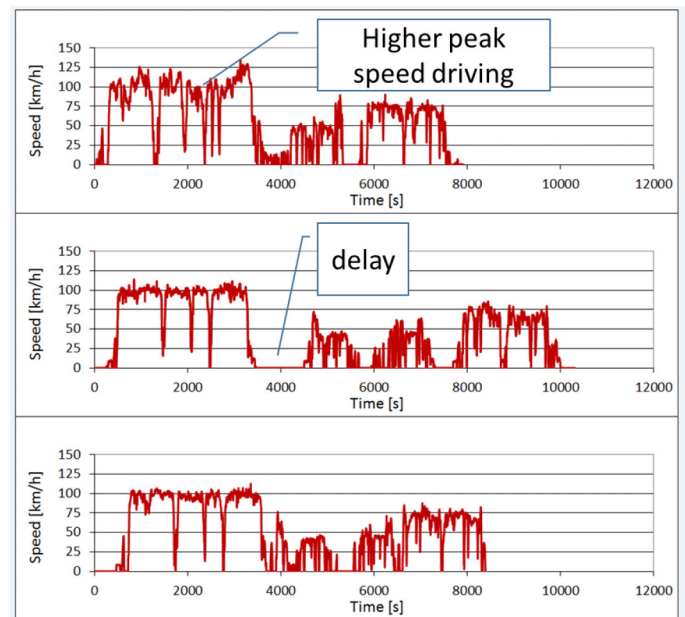


Figure 3. Speed v time traces, 3 repeats PEMS Route 1

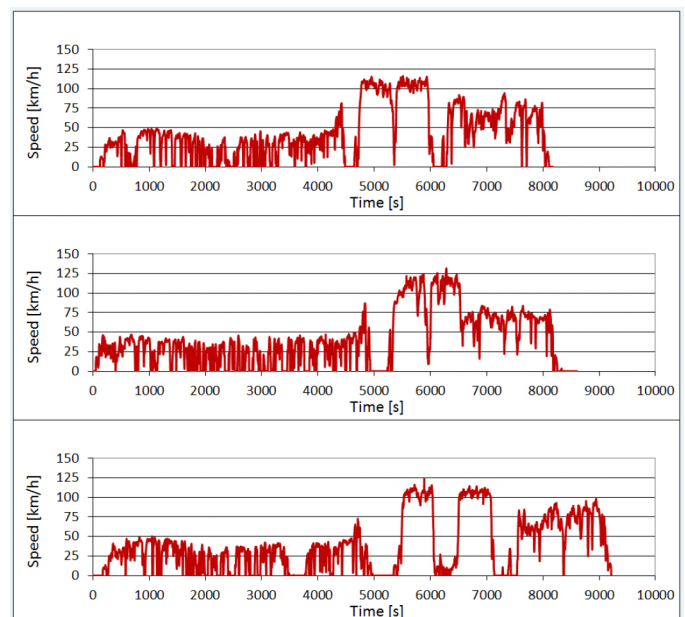


Figure 4. Speed v time traces, 3 repeats PEMS Route 2

Data Processing and Analysis

PEMS data were processed using EMROAD Version 5.60 Build 2, an Excel-based post-processing software tool produced by the European Commission's Joint Research Centre (JRC). EMROAD is supplied in the form of a macro based "add-in" for MS Excel and contains templates suitable for Light-duty, Heavy-duty and Non-Road Mobile Machinery (NRMM).

The basis of EMROAD processing is to use a Moving Average Window technique (MAW) and is comprised of four stages

- Segmentation of the data (identification and exclusion of non-standard operation).
- Averaging emissions data by sub-sets (Window creation).
- Identification of normal testing conditions based on CO₂ curve.
- Sensitivity of the emissions for different driving conditions (speed-based bins).

For the segmentation task, cold start emissions (based upon coolant temperatures below 70°C) and DPF regenerations (elevated temperature events highlighted by inspection of data from on-board logging) were identified as possible exclusions, based on current European Commission discussions.

Following identification and elimination of exclusions, the remaining data is broken down into subset "windows" which are then averaged to produce a data value. Each window is based on a reference quantity, which based on JRC experience was set to be 1 kg of CO₂. When the vehicle has travelled sufficient distance to produce 1 kg of CO₂ all data within that window is averaged to produce one MAW value. Several windows can overlap and data can contribute to more than one MAW window, as long as data is valid for the whole window based on the exclusion conditions. Selection of the reference quantity and value is a trade-off between retaining a small enough window so as not to lose detail but retaining sufficiently long duration to smooth large instantaneous changes arising from transient conditions. Once averaged the MAW approach can be used to identify normal driving conditions by comparison with those obtained from the same test vehicle driving the WLTC on the chassis dynamometer. The sensitivity of a vehicle's emissions to different road speeds can then be assessed. This approach allows a comparison of the emissions behaviour of different vehicles on different drive cycles on-road, and is a candidate for future RDE regulations.

EMROAD also produces tables of emissions results for a whole PEMS route, with calculated emissions including concentration (ppm), total mass (g/test), distance-specific mass emissions (g/km) and fuel specific emissions output. In this work the g/km emissions from each PEMS route, with and without exclusions, were extracted from EMROAD for analysis and comparison with chassis dynamometer test results.

Chassis Dynamometer Testing

Drive Cycles

Six different drive cycles were tested on both vehicles. These included the New European Drive Cycle (NEDC), Common Artemis Drive Cycle (CADC), Worldwide Light-duty Test Cycle (WLTC) and 3 'Random cycles' created using a specific cycle generator. This random cycle generator produces emissions cycles based on 'short trip' segments from the EU database used to construct WLTC. NEDC, CADC and WLTC cycles were each tested in triplicate, while 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.

On each vehicle the chassis dynamometer test programme lasted 6 days. The NEDC and WLTC were tested as 'cold-start' cycles following an overnight soak, with the CADC and random cycles tested as 'hot-starts' following a standardized warm-up procedure that incorporated prior tests in a well-defined daily test sequence (Table 3).

Table 3. Sequence of Chassis Dynamometer Testing for each Vehicle

	Vehicle Event	Notes
Day 0	150kph, 60 mins	Passive regen
Day 0	3 x EUDC	3 x EUDC
Day 1	NEDC#1	Normal inertia
Day 1	CADC#1	Normal inertia
Day 1	WLTC as precon	1800s
Day 2	WLTC#1	WLTP inertia
Day 2	WLTC as precon	
Day 2	Random#1	WLTP inertia
Day 2	120kph, 20 mins; 3 x EUDC	
Day 3	NEDC#2	Normal inertia
Day 3	CADC#2	Normal inertia
Day 3	WLTC as precon	1800s
Day 4	WLTC#2	WLTP inertia
Day 4	WLTC as precon	
Day 4	Random#2	WLTP inertia
Day 4	120kph, 20 mins; 3 x EUDC	
Day 5	NEDC#3	Normal inertia
Day 5	CADC#3	Normal inertia
Day 5	WLTC as precon	1800s
Day 6	WLTC#3	WLTP inertia
Day 6	WLTC as precon	
Day 6	Random#3	WLTP inertia
Day 6	CADC#4	WLTP inertia

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. In addition, a one-off test on both vehicles was performed with the CADC at WLTP inertia. Preconditioning for each test cycle was undertaken at the inertia required for the test, as shown in Table 4.