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A COMPARISON OF LIGHT-DUTY VEHICLE EMISSIONS OVER DIFFERENT TEST CYCLES AND IN REAL DRIVING CONDITIONS

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ABSTRACT

The European Commission is examining test procedures to ensure that light-duty vehicle emissions are well controlled both in real use and over the legislative test cycle. At the same time, the UN Working Party on Pollution and Energy (GRPE) has developed a Worldwide harmonised Light vehicles Test Procedure (WLTP) that is expected to be used for Type Approval in the EU in the future. To identify and understand the differences in emissions that may arise between these new methodologies and between them and existing procedures, AECC has conducted a series of tests on modern light-duty vehicles using both on-road emissions measurements and chassis dynamometer tests. For the on-road measurements Portable Emissions Measurement Systems were used to measure emissions over pre-selected routes. Chassis dynamometer emissions tests were conducted over the current legislative test cycle (NEDC - New European Driving Cycle), the Common Artemis suite of test cycles (CADC), the new Worldwide Light-duty Test Cycle (WLTC – the test cycle for WLTP) and a set of cycles produced by a Random Cycle Generator based on ‘short trip’ segments from the EU driving database that was used to construct WLTC. This paper examines the results of these tests and highlights the key differences between the various chassis dynamometer test cycles and between them and the on-road measurements using PEMS equipment. The test results show that there can be substantial differences for some pollutants measured as ‘real driving emissions’ (RDE) using PEMS equipment, compared to the test cycles.

INTRODUCTION

Since 1992, EU legislation on the Type Approval of light-duty vehicles’ tailpipe emissions has been based on a chassis dynamometer test conducted whilst the vehicle is driven over the ‘New European Driving Cycle (NEDC) defined in European and UN regulations [1]. It is expected that in the future, this highly stylised driving cycle will be replaced by a more transient cycle developed from data gathered on global driving patterns. This new cycle, the Worldwide Light-duty Test Cycle (WLTC) has been developed as part of the development of a global technical regulation (gtr) [2] under the auspices of the UN Economic Commission for Europe (ECE).

Following concerns over the ‘real world’ performance of vehicles approved using the chassis dynamometer test – in particular the NOx emissions of diesel light-duty vehicles [3] - the European Commission announced in its ‘CARS 2020 Action Plan [4] that it intends to include an additional test for ‘Real Driving Emissions of Light-Duty Vehicles (RDE-LDV)’ from the start of the Euro 6 stage. This stage will become mandatory for Type Approval of new car types on 1 September 2014 and 1 year later for all new car registrations (Note both dates are 1 year later for light commercial vehicles – all dates in this paper refer to the dates applicable to passenger cars, category M1). The Commission currently plans to introduce the test procedures at or close to the start of Euro 6 with ‘Not-to-Exceed’ values or Conformity Factors in place 3 years later at the Euro 6c stage.

As a result of the conclusions of a European Commission working group [5], it is expected that this RDE-LDV test will take the form of on-road emissions measurements using Portable Emissions Measurement Systems (PEMS) for gaseous regulated emissions. For particulate mass and/or particle number emissions, EU Member States have stated their interest in applying the same RDE-LDV method to all pollutants, if appropriate and technically feasible. However, PEMS systems for light-duty PN measurement are at an earlier stage of development and so ‘Random Cycles’ currently remains an option for this aspect. An initial method to generate such cycles was based on combinations of the ‘short trips’ (idle to idle) from the development of WLTC, but work is under way for the Commission to develop a final method for the generation of such cycles.

A further set of test cycles that is widely used in Europe is the ‘Artemis suite’ (Common Artemis Driving Cycles; CADC) [6]. This incorporates more transient operating modes derived from real-world driving. It is not a legislative test cycle but is used as the basis of emissions factors determination for modelling of emissions in Member States that need to comply with European Air Quality legislation.

AECC has previously conducted tests comparing the NEDC, CADC and WLTC [7] as part of the validation program for WLTP, but these tests did not include the RDE-LDV proposals. To identify and understand the differences in emissions that may arise between these new methodologies and between them and existing procedures, AECC therefore commissioned tests on four modern light-duty vehicles. The first of these was a Euro 5 gasoline vehicle and the others were Euro 6 diesel vehicles using different emissions control technologies. All tests were conducted for AECC by independent laboratories. Tests on the gasoline vehicle and diesel vehicle 1 were conducted in Germany and tests on diesel 2 and 3 in the UK.

TEST VEHICLES

All test vehicles were normal production vehicles taken from the EU market.
The three diesel vehicles used different emissions control technologies. All three incorporated a Diesel Oxidation Catalyst (DOC) and a Diesel Particulate Filter (DPF). For NOx control, the first used a combination of a Lean NOx Trap (LNT; NOx adsorber) combined with urea-based Selective Catalytic Reduction (SCR), the second used urea-SCR only, and the third relied on a combination of High-pressure and Low-pressure (post-DPF) Exhaust Gas Recirculation (EGR). A summary of key characteristics is shown in table 1.

	Engine size (litres)	Power (kw)	Euro standard	Engine technology	Emissions control technology	Transmission	Mileage at start of testing (km)
Gasoline	1.8	125	Euro 5b	Port Fuel Injection + Direct Injection	Three-way catalyst (TWC)	6-speed manual	4 000
Diesel 1	3.0	180	Euro 6b	Turbocharged Direct Injection Diesel	DOC + DPF + LNT + urea-SCR	8-speed automatic	22 900
Diesel 2	2.0	103	Euro 6b	Turbocharged Direct Injection Diesel	DOC + DPF + urea-SCR	6-speed manual	13 500
Diesel 3	2.1	125	Euro 6b	Turbocharged Direct Injection Diesel	High pressure EGR + DOC + DPF + + Low pressure EGR	7-speed semi-auto	11 000

Table 1: Summary of test vehicle characteristics

TEST CYCLES & INSTRUMENTATION

On-Road Testing

For the on-road testing the vehicles were each parked overnight in an unheated garage. For the first vehicle tested (the gasoline vehicle), 3 days of PEMS testing were conducted over a fixed route, with 4 tests per day, each lasting approximately 1 hour. Only the first test of each day could therefore be considered as fully cold start. For the following vehicles it was decided that all PEMS tests should be cold-start, in line with the most recent guidance from the European Commission. Two tests per day could be conducted in this way.

The tests route comprised sections equating to urban, rural and motorway driving and are summarised in Table 2. For the first (gasoline) vehicle all tests were run over the same route. When tests on the first diesel vehicle were conducted, the guidance from the European Commission’s RDE-LDV group suggested use of 2 different routes, one with a greater proportion of motorway driving. The tests on all the diesel vehicles therefore used two related routes with the motorway proportion differing between the two. In the case of diesel vehicle 1, the first route (A) was the same as that used for the gasoline vehicle, whilst the second route (B) was a modification of this to achieve the different balance of operational conditions. The tests on diesel vehicles 2 and 3 were conducted at a different laboratory, so the routes were different from the previous vehicles. As with diesel vehicle 1, though, the two routes (C and D) were designed to use common sections whilst giving a different balance of the operational conditions. For the three diesel vehicles, a total of 3 PEMS tests were conducted on each of the two routes.

	Route A	Route B	Route C	Route D
Total distance (km)	46	52	120	92
Of which approximately				
Urban (km)	21	16	14	30
Rural (km)	9	6	27	27
Motorway (km)	16	30	79	35
Max. altitude (m)	260	260	140	140

Table 2: Summary of PEMS route characteristics.

Over the testing periods different driving conditions were experienced, ranging from a fluid traffic flow to a total traffic jam. The range of speeds and stop times for the tests are shown in Table 3.

	Route	Average vehicle speed per test		Max. vehicle speed per test		Stop duration per test	
		Mean (km/h)	Range (km/h)	Mean (km/h)	Range (km/h)	Mean (s)	Range (s)
Gasoline vehicle	A	36.5	21.7 - 44.0	126.3	125.0-130.4	948	448 – 2182
Diesel vehicle 1	A	42.6	41.8 – 43.2	126.9	126.5 – 127.5	576	480 – 722
	B	48.2	46.5 – 51.5	127.1	126.5 – 127.6	595	483 – 675
Diesel vehicle 2	C	51.4	43.1 – 58.8	113.1	100.6 – 137.0	2030	1480 - 2971
	D	41.53	39.9 – 43.4	107.2	101.4 – 118.1	1620	1169 - 1926
Diesel vehicle 3	C	60.3	57.6 – 64.1	113.3	107.3 – 121.5	867	508 - 1082
	D	40.7	38.4 – 43.1	110.3	107.6 – 115.7	1670	1313 - 1999

Table 3: Mean and range of speeds and stop times for the repeated PEMS tests.

For the tests on the gasoline vehicle and diesel vehicle 1, the Portable Emissions Measurement System used) was used to measure emissions during real driving comprised a Semtech-D (Sensors) system for measurement of CO, HC, NO, NO_2, CO_2 and O_2 together with an AVL photoacoustic Micro Soot Sensor. This sensor provides a measure of the soot content of particulate mass (PM) but not a measure of particle number (PN). At the time of this part of the testing PEMS equipment for measurement of PN was not available. For the tests on diesel vehicles 2 and 3, a Sensors Semtech Ecostar system was used, comprising modules to measure CO, HC, NO, NO_2, and CO_2 together with a filter-based system for PM and a new system based on particle mobility to provide a PN metric. The system was set to have a 23 nm particle size cut-off so as to be comparable to the PMP system. However, it should be noted that unlike the lab-based PMP system for PN, the PEMS PN methodology did not include a system for the removal of volatile particles before the number count. In the absence of a fully traceable calibration, a correlation exercise was undertaken on diesel vehicle 2 to compare all emissions measured by this PEMS system with conventional lab equipment. The correlation test used a cold-start NEDC together with several different hot-start cycles. 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, with the relationship between the two responses indicating the possibility of scaling the PEMS PN to replicate the PMP data. A simple background correction applied to both systems, converged the profiles of the two instruments. Data shows that both report the same transient events, though some volatile particles from the cold start may be detected by the PEMS PN.

For each of the PEMS tests at both laboratories 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 run.

Chassis Dynamometer Tests

Four different test cycles were run on the chassis dynamometer – the current legislative New European Driving Cycle (NEDC), the Common Artemis suite of cycles (CADC), the new Worldwide Light-duty Test Cycle (WLTC) and a set of cycles produced by a Random Cycle Generator that was made available to the European Commission's working group on RDE-LDV. This produced cycles based on 'short trip' segments from the EU database used to construct WLTC. Three repeats were run for each of the test cycles.

The NEDC tests were performed to the current regulatory standards, with separate gaseous emissions samples collected for the 1st and 2nd elementary ECE urban cycles ('cold urban cycles'), the 3rd and 4th elementary ECE urban cycles ('warm urban cycles') and the Extra Urban Cycle (EUDC). For diesel vehicle 2, the test laboratory advised disabling the stop-start system to achieve repeatable results, as they had previously noted unpredictable behaviour of this vehicle in the test, which they believed to be related to this. However AECC concluded that the vehicle should be tested 'as received' to assess the level of variability.

The WLTC tests were conducted to the WLTP procedures, with cold start tests following a soak period. After successive rounds of discussion amongst UNECE Contracting Parties, the final version of WLTP incorporates variations of the test cycle for three classes of vehicles power-to-mass ratio. All vehicles tested were in the highest (Class 3) power to mass ratio (>34 W/kg), which is typical of European-market vehicles. This class is divided into two, depending on the vehicle's maximum speed (v_{max}). All fell into the higher Class 3b, with 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, comprising an Urban, Extra-Urban and a Highway phase, were conducted as hot-start tests as is normally the case for CADC. Generally, each of these three CADC phases includes portions at the start and

end of the cycle in which the emissions are not sampled. However, as some authorities were understood to evaluate emissions over the whole cycle, this variant was used for all AECC test work.

For the Random Cycles, rather than running 3 repeats of the same cycle to assess repeatability it was decided to test three different random cycles produced by the Random Cycle Generator to assess the degree of variability seen. For the gasoline vehicle and diesel vehicle 1, the Random Cycle Generator was run separately for each vehicle. For diesel vehicles 2 and 3 new random cycles were generated but the same set of three cycles were used for both vehicles. The resultant cycles for each of the vehicles are shown in Figure 1. As may be seen from these three figures, there were substantial differences between the generated cycles in parameters such as maximum speed and the length of steady-state periods.

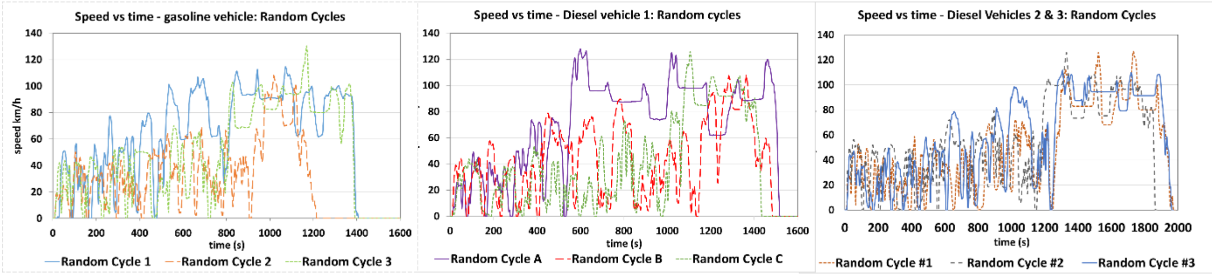

Figure 1: Speed vs time plots for the Random Cycles

One area of significant difference between the current (NEDC) test procedures and the WLTP is the determination of road load and setting of the test (inertia) masses.
For WLTP, the relevant characteristics of the vehicle including aerodynamic drag and tyre rolling resistance are taken into account, and, unlike the current procedures, the vehicle test mass for regulated pollutants has to include the mass of optional equipment. As a result, the test masses for WLTP will often be higher than that for the current regulatory test. The resulting test inertia masses for the four vehicles are shown in Table 4.

	Gasoline vehicle	Diesel vehicle 1	Diesel vehicle 2	Diesel vehicle 3
NEDC-based test inertia	1590 kg	2150 kg	1700 kg	1470 kg
WLTP-based test inertia	1930 kg	2460 kg	1810 kg	1590 kg

Table 4: NEDC-based and WLTP-based test inertia masses for the four vehicles

It was decided that all tests on the gasoline vehicle should be run at the higher (WLTP) inertia. However, to give a comparison with the current regulatory procedure, a single NEDC test was run at the lower (standard NEDC) inertia. When further vehicles were to be tested, this approach was reconsidered. As a result, for the diesel vehicles the NEDC and CADC tests were run at the lower inertia weight, as this is what would normally be used in current testing. The WLTC and Random Cycle tests used the higher inertia as this is what would be expected for future test regimes. To provide a direct comparison of the effect of the two settings, an additional CADC test was run at the higher inertia setting for each vehicle.

Emissions of carbon monoxide (CO), total hydrocarbons (HC), non-methane hydrocarbons (NMHC), oxides of nitrogen (NOx), particulate mass (PM) and particle numbers (PN) were made during each test using the types of analysers specified in current regulations. All test results were recorded over the complete cycle.

RESULTS AND DISCUSSION

Particulate Mass Emissions

It should be noted that the PEMS results for the gasoline vehicle and diesel vehicle 1 relate to soot measurement using the photoacoustic sensor (PASS), rather than filter measurements of particulate mass (PM), but good correlation has been shown between this measurement and the Black Carbon content of PM [8].

As might be expected for a gasoline-engined vehicle, all results for particulate mass measured on the chassis dyno tests were well below the Euro 5/6 limit value of 4.5 mg/km, as was the soot mass measured on the PEMS trips. As shown in Figure 2, the highest result obtained was only 0.8 mg/km.

For the three diesel vehicles the particulate mass (chassis dyno tests) and soot content of particulate mass (PEMS tests) are very much in line with what would be expected from vehicles equipped with a Diesel Particulate Filter (DPF). All results were below 1 mg/km except for the CADC test at high inertia, when a regeneration occurred leading to higher PM emissions, approaching 7 mg/km. Particle Numbers were also substantially elevated from this test. At this level of PM emissions, though, the vehicle would meet the Euro 6 PM limits even if the DPF was actively regenerated every other test. The PEMS tests using the PASS instrument to measure soot mass yielded the lowest PM results for diesel vehicle 1, with average emissions of 0.1 mg/km on both routes. There were no regenerations during these tests. The filter-based PEMS method used for diesel vehicles 2 and 3 also gave very low PM results (< 0.1 mg/km). This is possibly the consequence of the long drive cycle for on-road testing combined with the low mass of particulate from a DPF-equipped vehicle. It may be that volatiles are collected but also removed during the cycle. As only the final mass is divided by the whole cycle distance, this would result in very low g/km figures.

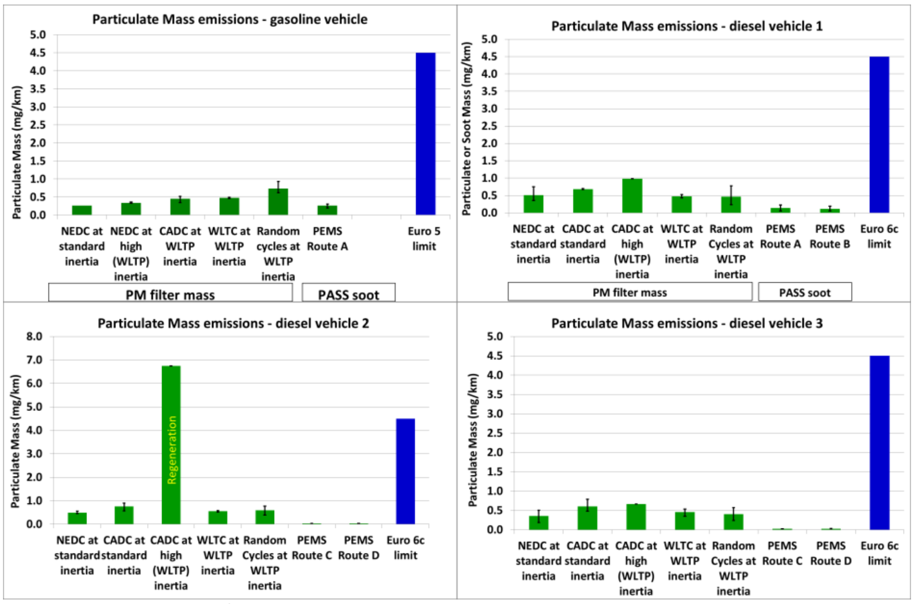

Figure 2: Particulate Mass (PM) emissions for the 4 vehicles, all tests.

Particle Number Emissions

A particle number (PN) limit has been applicable to compression ignition light-duty vehicles since the start of Euro 5.From Euro 6, direct injection gasoline vehicles will also have to meet a limit for PN emissions. The limit value is to be $6x10^{11}$ particles/km, the same as that for diesel vehicles, but for a period of three years (i.e. until 1 September 2017 for new Type Approvals, 1 September 2018 for all registrations) the manufacturer has the option to request approval to a limit of $6x10^{12}$ particles/km. From this 'Euro 6c' date, the European Commission also has the obligation to implement a test method ensuring the effective limitation of the number of particles emitted by vehicles under real driving conditions. A number of studies have indicated that PN emissions from current direct injection gasoline vehicles are greater than the Euro 6c limit of $6x10^{11}$ particles/km limit [12], [13], [14]. In most cases, they can, though, meet the interim limit of $6x10^{12}$ particles/km. There is currently no PN limit for port Fuel Injection (PFI) vehicles in the EU but in most cases such vehicles emit PN at levels below $6x10^{11}$ particles/km.

The PN emissions results for the 4 vehicles tested are shown in Figure 3. As noted earlier, no PEMS PN equipment was available at the time that the gasoline vehicle and diesel vehicle 1 were tested. The PEMS system used for diesel vehicles 3 and 4 incorporated a particle mobility-based system for PN measurement. Although a method of correlation with laboratory (PMP) equipment had been established, it has to be recognised that the system did not include a volatile particle remover, so the presence of volatile materials may have had a further influence on the results.

The gasoline vehicle tested in this program used a combination of direct injection and port fuel injection. On the single test to the current (NEDC) test procedure the PN result was close to, but within, the EU's final $6x10^{11}$ particles/km Type Approval limit value. Interestingly, in the tests conducted using the NEDC but at the higher inertia, there was a greater margin, with the average emissions of the 3 tests being $3.7x10^{11}$/km with a small level of variability. Data from the separate phases of this cycle indicate that the largest difference was seen in the EUDC phase, with average PN emissions of $4.5x10^{11}$ /km in the standard test and $8.6x10^{10}$ /km in the high inertia version. Results in urban cycles 3+4 were also lower in the higher inertia tests, but this was somewhat balanced by higher results in ECE 1+2. For all cycles, the results were highest in the cold-start phases, with emissions above $1x10^{12}$ particles/km. This includes the result from a single additional cold-start CADC urban cycle, where emissions were $2.1x10^{12}$ /km, compared to an average of $8.1x10^{11}$ /km on the normal warm-start test. These results may indicate that factors such as cold quench result in higher particle formation. For the full CADC tests, the results were also within the final Euro 6 limit value. For the WLTC tests, though, the results consistently exceeded this limit value. As with other tests, the results were highest on the first phase of the test and then reduced through the subsequent phases. As might be expected from the nature of the cycles, the test results for the Random Cycles were more varied, but all were above the EU final limit.

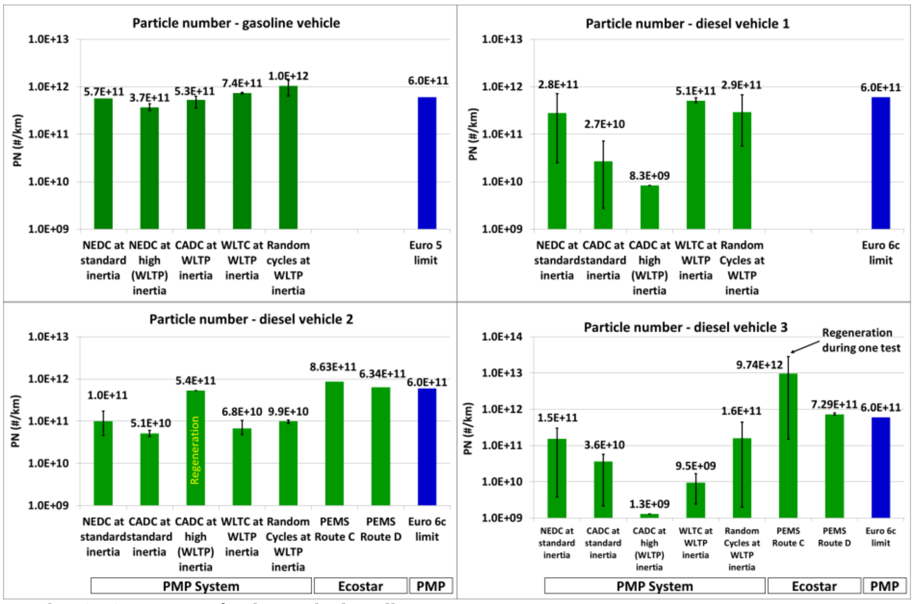

Figure 3: Particle Number (PN) emissions for the 4 vehicles, all tests.

For diesel vehicle 1, although a single Random Cycle test marginally exceeded the Type Approval limit for PN, the average particle number emissions for all tests were below the particle number limit, demonstrating the effectiveness of the DPF under a range of operating conditions.

In the case of diesel vehicle 2, the regeneration experienced during the CADC test at the higher inertia resulted in higher PN emissions than on the other chassis dyno cycles, but still within the Type Approval limit. Due to problems experienced in the main series of tests, only a single PN result is available for each of the on-road tests on this vehicle. Both of these gave results a little above the Type Approval limit. This could be the result of the presence of volatile particles, but further experience will be needed with this instrument to identify whether this effect is significant.

Diesel vehicle 3 similarly consistently produced PN emissions below the Type Approval limit for all chassis dyno test cycles, For PEMS Route C, two of the three results were below the Euro 6 limit, but a regeneration during the third run resulted in higher emissions and raised the average of the three tests. For the second route, results were consistently slightly above the Euro 6 limit value when measured with this equipment. As with diesel vehicle 2, the effect of volatile particles on this instrument will need to be further investigated.

CO and Hydrocarbon Emissions

The CO and HC emissions for all four vehicles are shown in Figures 4 (CO) and 5 (Total HC). Both average and individual results were well below the Euro 6 legislative (NEDC) limits for all tests with the exception of CO in two of the twelve PEMS tests on the gasoline vehicle and one of the three ‘route B’ tests for diesel vehicle 1.

For the gasoline vehicle, although the CO results over the various chassis dyno cycles were at or below 20% of the Type Approval limit value, there was substantial CO variability over the PEMS tests. The majority of trips produced CO emissions in the range of 500 to 900 mg/km (50 to 90% of the Euro 5/6 limit), but one trip gave a very low result of 206 mg/km, whilst two tests showed CO emissions above the Euro 5/6 limit, at 1236 mg/km and 1085 mg/km. Further analysis of the second-by-second data suggests that the differences relate to λ variability during (and particularly at the start of) significant accelerations. For diesel vehicle 1, both PEMS routes gave higher CO emissions than on any of the chassis dyno cycles, but those over route B, which had the higher proportion of motorway driving, were higher and more variable than those on Route A. The other two diesel vehicles did not exhibit significantly higher CO results in on-road driving than in the chassis dyno tests – indeed for both vehicles the NEDC tests gave the highest CO emissions.

The total hydrocarbon results for all four vehicles were well within legislative limits, with the highest (diesel vehicle 1, CADC test) being only 54% of the Euro 6 limit.

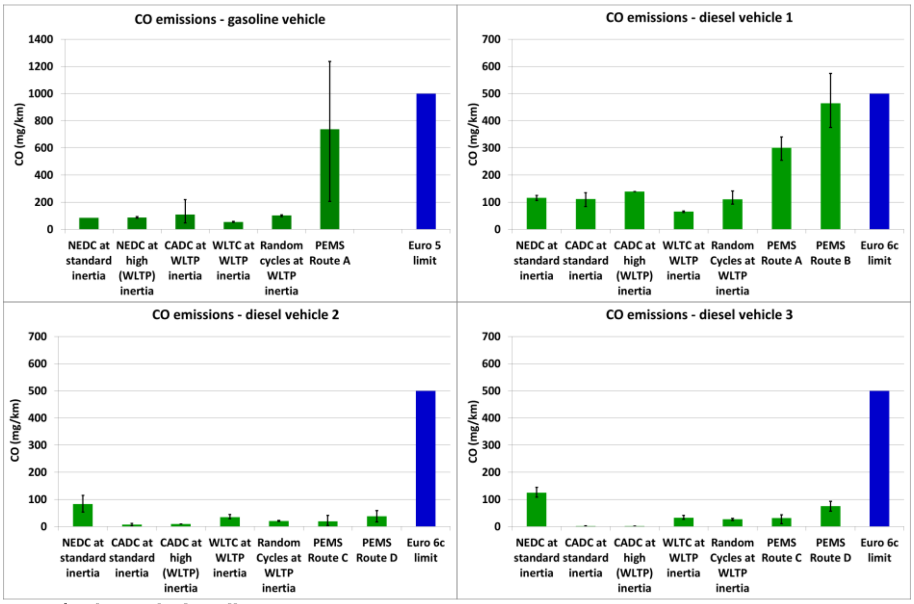

Figure 4: CO emissions for the 4 vehicles, all tests.

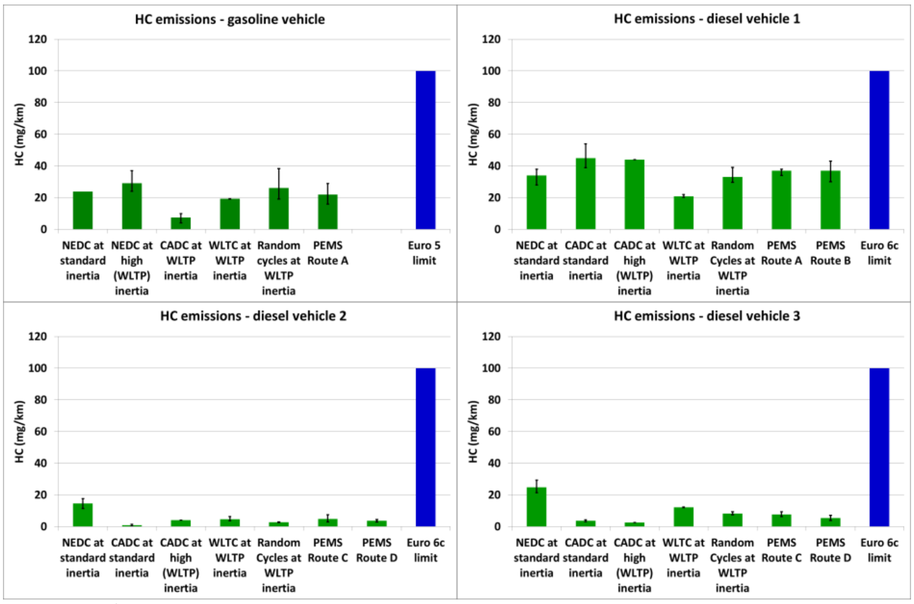

Figure 5: Total HC emissions for the 4 vehicles, all tests.

NOx Emissions

The NOx emissions for all tests are summarised in Figure 6. The chassis dyno test results for the gasoline vehicle were all below the Euro 5/6 limit of 60 mg/km. Both the WLTC and Random Cycle tests produced higher results than the standard NEDC test, although still well within the Type Approval limits. The NOx results were also marginally higher on the high-inertia NEDC tests than in the single test with standard inertia. The NOx emissions over the CADC tests, though, were very similar to the NEDC tests (an average of 20 mg/km on the CADC compared to 24 mg/km on the NEDC at the same inertia and 22 mg/km on the NEDC at current inertia). The CADC, WLTC and Random Cycle tests are, of course, more transient than the NEDC – the lower results for the CADC test may be attributable to this being a hot-start test – HC results were also lower on this test. The NOx results from the on-road testing were significantly higher than the dynamometer cycles and, on average, some 23% higher than the Euro 5/6 limit value. Only one PEMS trip gave NOx emissions marginally below the limit, at 58.4 mg/km. The individual PEMS test results ranged from this to 82 mg/km.

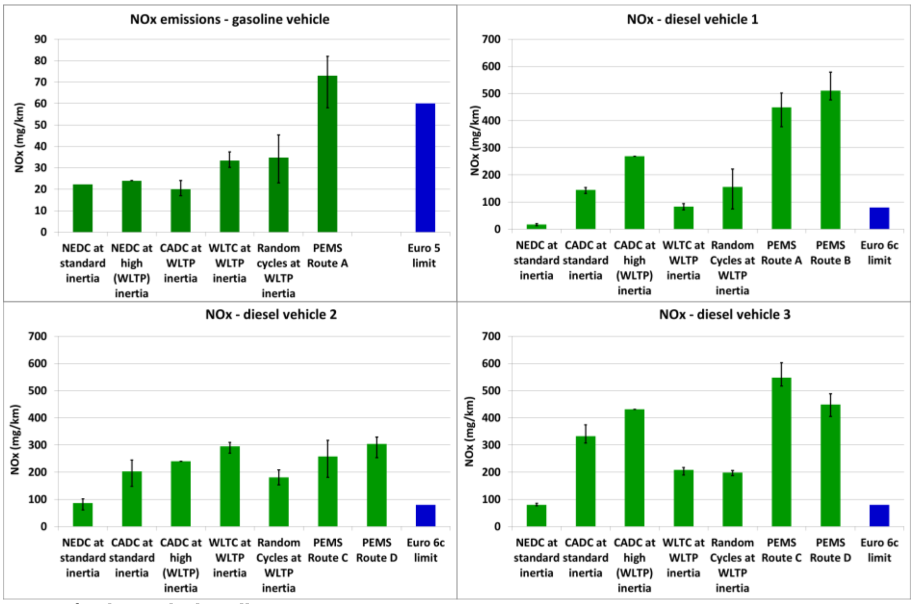

Figure 6: NOx emissions for the 4 vehicles, all tests.

All three diesel vehicles exhibited very substantial difference between the on-road PEMS results and the NOx emissions achieved on the legislative NEDC test. The results on chassis dyno cycles other than the NEDC were also higher than the Type Approval limits. Other studies [3], [7], [9] have shown a similar trend for NOx emissions from modern diesel vehicles to be substantially higher than the Type Approval values in real-world driving and in tests on cycles other than the NEDC.

For diesel vehicle 1 the results on the standard NEDC tests averaged 17 mg/km (range 13 to 20 mg/km), well within the Euro 6 limit of 80 mg/km for compression-ignition vehicles. For the PEMS tests, though, the results for this vehicle ranged from 378 to 579 mg/km (4.7 to 7.2 times the Type Approval limit), with the route having the higher proportion of motorway driving showing somewhat higher results than the other route. This is despite the fitment of a comprehensive NOx aftertreatment system. The WLTC NOx results slightly exceeded the Type Approval limit value, at an average figure of 83 mg/km. The CADC tests significantly exceeded the Euro 6 (NEDC) limit for NOx at both inertia settings - 145 mg/km for the lower inertia and 269 mg/km for the single test at the higher inertia. The results for the Random Cycles were quite variable: test 1 gave a NOx result of 222 mg/km, test 2 met the Type Approval limit at 74 mg/m, but test 3 again exceeded it at172 mg/km. The results suggest that NOx emissions for this vehicle are affected by a combination of inertia and drive cycle/operating conditions with PEMS providing substantially higher emissions than the dynamometer cycles. Relatively high NOx emissions originated from the highway phase of the CADC, which reaches 150 km/h. Similarly, the extra high-speed phase of the WLTC, which reaches 130 km/h, produced much higher NOx emissions than other phases of the test. The results for each phase of these tests are shown in Table 5. Analysis of the PEMS NOx emissions by engine speed and load points [10] indicates that for this vehicle NOx is well controlled at engines speeds up to approximately 2000 rpm in combination with engine loads up to approximately 75%. Each of the PEMS tests included periods of idling of 70 to 90s. During such periods NOx remained well controlled. At higher speeds and loads, however, NOx emissions are substantially higher. This tends to confirm that the future RDE demands will require further attention to specific areas of the engine map.

	CADC			WLTC			
	Urban phase	Extra-urban phase	Highway phase	Low-speed phase	Medium-speed phase	High-speed phase	Extra-high speed phase
Average	50	30	228	72	55	20	195
Minimum	39	25	207	64	23	15	150
maximum	56	40	240	76	72	28	172
CADC at WLTP inertia	67	55	427				

Table 5: NOx results (mg/km) for CADC and WLTC test phases, diesel vehicle 1.

For diesel vehicle 2, the NOx results for the NEDC tests appeared to have been affected by the instability of this vehicle under this test protocol mentioned earlier. The first test met the Type Approval NOx limit, with emissions of 61 mg/km. However the following two tests results both exhibited higher NOx emissions, at 98 and

102 mg/km respectively. The first test showed comparatively high emissions (242 mg/km) over the first two urban cycles, but then reducing to 50 mg/km over the second two urban cycles and 11 mg/km over the EUDC. For the other two tests the maximum NOx emissions occurred in the second two urban cycles (>150 mg/km) with emissions of just over 50 mg/km over the EUDC. An average of 87 mg/km was achieved for the three tests, some 10% above the Type Approval limit. For this vehicle the NOx emissions on the CADC, WLTC and Random Cycles were also higher than those over the NEDC. In this case the WLTC gave the highest results of the chassis dyno tests, with emissions averaging just under 300 mg/km. The WLTC results were thus comparable to those achieved during the PEMS testing, which ranged from 181 mg/km (on Route C) to 330 mg/km (on Route D). Although displaying lower on-road NOx results than diesel vehicle 1, these still substantially exceeded the 80 mg/km Type Approval limit for Euro 6.

Diesel 3 gave average NOx results that just met the 80 mg/km limit on the NEDC. It produced the highest NOx result in any of the on-road testing, with a test on Route C reaching 603 mg/km. The average on-road results were 547 mg/km for Route C and 454 mg/km for Route D. High results were also found on the CADC tests (all > 300 mg/km), and the CADC test at higher inertia gave well in excess of 400 mg/km. As with diesel vehicle 1, the WLTP NOx results were lower than those on the CADC, but still exceeded the Type Approval limit.

The work by the European Commission's Joint Research Centre (DG-JRC) [3], [11] has indicated that real-world NOx emissions of recent diesel vehicles measured using PEMS may be much higher than those reported for the NEDC test. The results from these test programs agree with their conclusions, with full-route emissions of up to 511 mg/km for diesel vehicle 1, 330 mg/km for diesel vehicle 2 and 603 mg/km for diesel vehicle 3.

PEMS Data Analysis

Methods for the analysis of PEMS data that are now being finalised are intended to allow examination of emissions under 'normal' and more extreme driving conditions. It is also intended that they should allow for the possible exclusion or separation of portions of the data due to factors such as cold-start emissions or diesel particulate filter (DPF) regeneration events. The EMROAD data processing method developed by the European Commission's Joint Research Centre was used to examine the effect of these exclusions for diesel vehicles 2 and 3. For cold-start emissions, a coolant temperature of 70°C was used to determine the end of the cold start condition (as in current heavy-duty vehicle PEMS requirements). DPF regeneration events were identified using exhaust temperature logs to indicate temperature rises with post-injection and the subsequent return to normal temperatures. Figure 7 shows the extent of the data points that would be excluded by these processes. The effect of such exclusions on real-world performance will need to be carefully considered for light-duty vehicles.

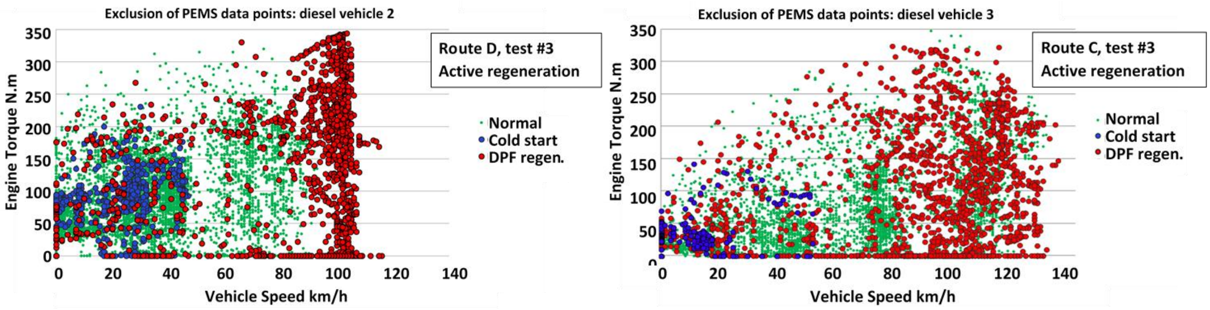

Figure 7: Effect of cold-start and DPF regeneration exclusions on gaseous emissions.

SUMMARY AND CONCLUSIONS

AECC conducted a range of tests on 3 modern vehicles – one Euro 5 gasoline car and three Euro 6 diesels. Tests were conducted using Portable Emissions Measurement Systems (PEMS) over real-world on-road driving as well as conventional chassis dynamometer tests using appropriate legislative measurement equipment. The current Type Approval NEDC test, the Common Artemis Driving Cycles (CADC), the new Worldwide Light-duty Test Cycle (WLTC) and a set of cycles provided by a Random Cycle Generator were used for this. The test results show that, compared to the chassis dyno test cycles, there can be substantial differences for some pollutants measured as 'real driving emissions' (RDE) using PEMS equipment. This does not necessarily mean that the RDE emissions exceed the Type Approval limit values. For all vehicles, average CO, HC and PM results were below the relevant EU limit values. However, in some cases, notably for the NOx emissions of diesel vehicles, the PEMS emissions for complete test routes can exceed Type Approval limits by a substantial margin.

For the gasoline vehicle with a dual injection system strategy, but no particulate filter, PM emissions were well below the limits for Euro 6 on all tests, but particle number emissions on the NEDC and CADC tests were close to the 2017 limit and above that limit on the WLTC and Random Cycles. The diesel vehicles, which all incorporated Diesel Particulate Filters, gave low particulate mass emissions, with average particle number emissions below the Euro 6 limit for all chassis dyno tests. In the case of the two vehicles tested with a new PEMS PN analyser, some results were above $6x10^{11}$ particles/km, but further examination of the instrument will be needed to determine whether the absence of a volatile particle remover is significant in this respect.

For all the diesel vehicles the NOx results on chassis dyno tests other than the NEDC exceeded the current Type Approval limits and the two PEMS routes gave substantially higher NOx emissions. Examination of some of the more detailed data available indicates that the high NOx emissions primarily occurred under conditions of higher speed and load. The results therefore indicate that when the EU introduces their additional requirements for control of Real Driving Emissions, this is one of the areas that will need to be addressed.

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