

# 'Regulated' and 'Non-regulated' Emissions from Modern European Passenger Cars

**Bosteels, D; May, J**

AECC – Association for Emissions Control by Catalyst AECC (AISBL), Belgium

**Karlsson, H; de Serves, C**

AVL-MTC – AVL Motortestcenter AB, Sweden

Copyright © 2006 SAE International

## ABSTRACT

Regulated emissions from four current production European vehicles were measured over the Common Artemis Driving Cycles (CADC). Particulate Mass and Particle Number measurements were made in accordance with the newly-developed draft Particulate Measurement Programme (PMP) developed for the UN-ECE's expert group on pollution and energy (GRPE).

During the test programme measurements were also made of currently non-regulated emissions including PAHs and speciation of the particulate material and key hydrocarbons. CADC results are presented for each of the four vehicles tested (one conventional gasoline vehicle, two different types of diesel without Diesel Particulate Filter (DPF) and one diesel with DPF) with results measured on the regulated New European Driving Cycle (NEDC) test for comparison. The emissions results on the Artemis cycles showed some significant differences from those on the regulated (NEDC) test cycle. These were especially marked on the Artemis Urban cycle, even when compared to the hot urban part of the NEDC. The PMP Particulate Mass and Particle Number results demonstrated the effectiveness of the Diesel Particulate Filter under a variety of driving conditions.

## INTRODUCTION

### OBJECTIVES

A test programme was developed by the Association for Emissions Control by Catalyst (AECC) to examine the emissions performance of a selection of 'state of the art' vehicles meeting Euro 4 emissions requirements. In addition to tests using the New European Drive Cycle (NEDC), routinely used for emissions homologation, measurements were made over the suite of Common Artemis Driving Cycles (CADC) developed as part of an EU-funded framework 5 programme [1] to develop

harmonised models to predict real world emissions. The cycles describe various current driving conditions encountered frequently in Europe and were developed by INRETS (Institut National de Recherche sur les Transports et leur Sécurité, France) from a database of real-world driving conditions for a set of 80 cars from different European countries. The three cycles used are referred as Artemis Urban (AU), Extra-Urban (AEU), and Highway (AH).

Regulated emissions (CO, HC, NO<sub>x</sub>) were measured by conventional analytical techniques, and the draft UN-ECE Particulate Measurement Protocol (PMP) [2] was used for both Particulate Mass and Particle Number measurement. In addition analyses were made of particulate composition and of a number of currently non-regulated emissions including Polycyclic Aromatic Hydrocarbons (PAH)..

This paper examines primarily the results from the CADC tests, using the NEDC results as a baseline comparator. Results for regulated emissions, Particulate Mass and Particle Number and some non-regulated emissions are presented. The test programme was conducted at the AVL-MTC test centre in Haninge, Sweden, a recognised Type Approval laboratory with experience of additional emissions speciation and which had been involved in the development of the Common Artemis Driving Cycles.

### TEST VEHICLES

The test vehicles comprised one gasoline vehicle with multi-point port fuel injection (MPI), two direct injection diesels with different fuelling and emissions control systems, neither of which included a Diesel Particulate Filter (DPF), and one direct injection diesel fitted with a system including a DPF as original equipment. Key engine characteristics are summarised in Table 1.

The vehicles were standard production vehicles from four different manufacturers. The models were selected

to provide a 'mid range' gasoline emissions performance and the Diesels were chosen to provide good spread of diesel PM/NOx performance.

	G	A	B	DPF
	Gasoline vehicle	Diesel 'A' (no DPF)	Diesel 'B' (no DPF)	Diesel with DPF
Engine Type	In-line 4 16 valve	V6 24 valve	In-line 4 16 valve	In-line 6 24 valve
Injection system	Sequential MPI	Distributor pump DI	Common Rail DI	Common Rail DI
Capacity (cm <sup>3</sup> )	1791	2496	2204	2993
Power (kW@rpm)	90@6000	120@4000	103@4000	160@4000
Emission Control System	TWC 2 lambda	EGR 2 x DOC	cooled EGR 3 x DOC	EGR DOC underfloor C-DPF

TWC = Three Way Catalyst  
 EGR = Exhaust Gas Recirculation  
 DOC = Diesel Oxidation Catalyst  
 C-DPF = Catalysed Diesel Particulate Filter

Table 1: Key engine characteristics

Figures 1 and 2 show their emissions performance in comparison to Type Approval data from the UK Vehicle Certification Agency ([www.vca.gov.uk](http://www.vca.gov.uk)).

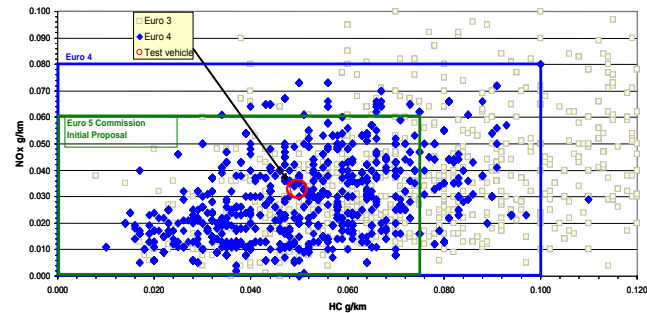


Figure 1: Emissions performance of the gasoline vehicle

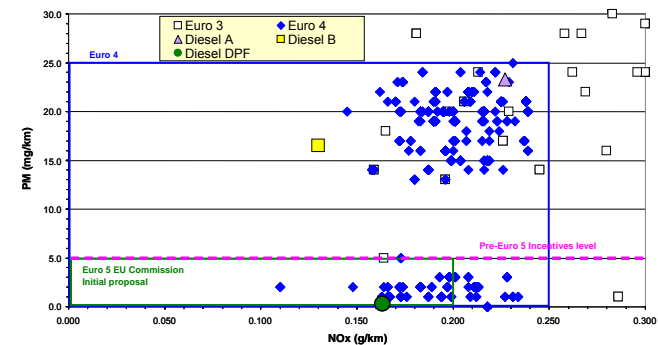


Figure 2: Emissions performance of the diesel vehicles

## TEST PROTOCOL

Prior to the emissions test programme all the vehicles were de-greened by driving a minimum of 4000km using standard Swedish road fuel (<10ppm sulfur). After de-greening the Diesel with DPF was driven on the chassis dynamometer at 120km/h for 20 minutes using the test fuel. Previous experience in the laboratory suggested

that these conditions should stimulate DPF regeneration and hence give a repeatable test condition. However, as the system is expected to encounter both passive and active regenerations it was not possible to precisely define the regeneration state without intrusion into the vehicle system. This driving pattern was used as the DPF regeneration procedure throughout the programme to ensure comparability of results.

The Artemis cycles are all warm start cycles and include a preconditioning part of different lengths for the different cycles. The cycles are shown in Figure 3.

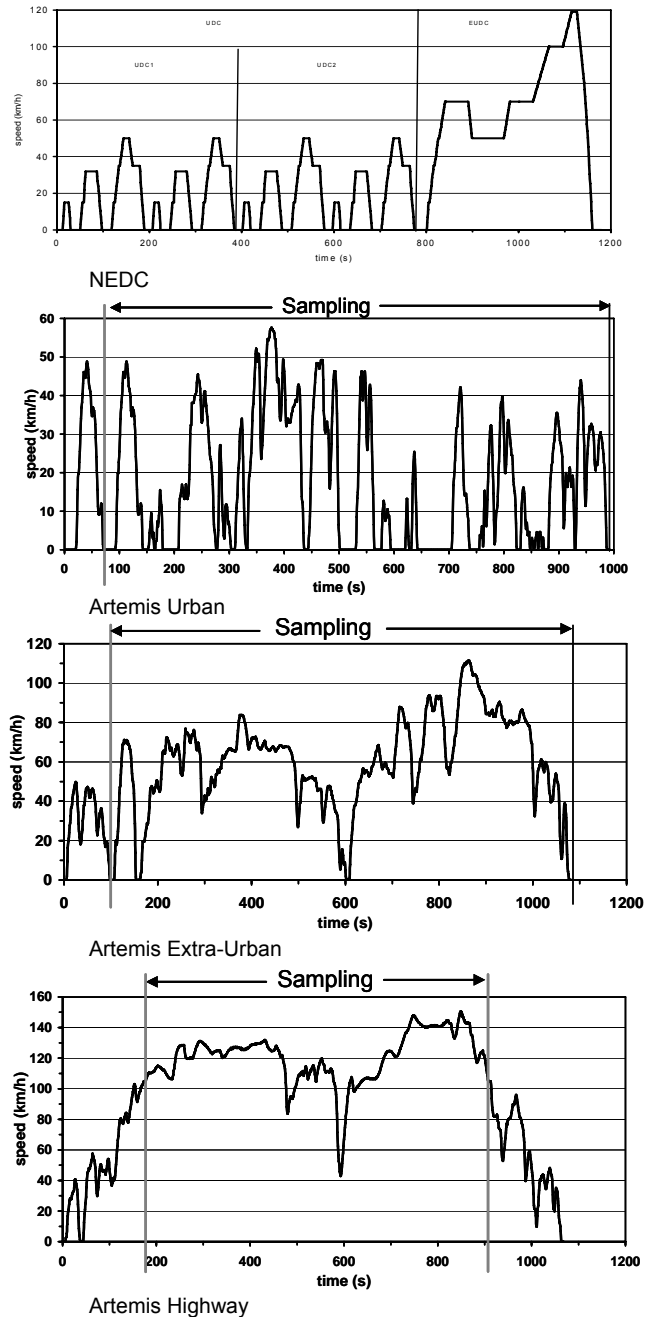


Figure 3: NEDC and CADC test cycles

The preconditioning sections are 73s for the Urban cycle, 102s for Extra-Urban, and 177s for Highway. For the Artemis Highway cycle there is also a post-

conditioning part of the cycle from 912s onwards. During pre- and post-conditioning parts of the cycles, no measurements are performed. All results presented and discussed in the following report only treat the valid part of the cycle. NEDC cycles were performed to the requirements of EU Directives and were all cold start.

Triplicate tests were conducted for regulated emissions and PMP measurements. Non-regulated emissions analysis was carried out only on single tests.

Single batches of each Reference Fuel (Haltermann) were used in the emission tests. The CEC RF-02-03 gasoline fuel fulfilled the EN228 standards. The CEC RF-06-03 diesel fuel fulfilled the EN590 standards.

## PMP METHODOLOGY

The PMP protocol was developed as a collaborative multi-national programme in a working group of the Expert Group on Pollution and Energy (GRPE) of the UN-ECE with the objective of developing measurement systems by which ultrafine particles could in future be controlled in a regulatory framework. The procedures developed cover both an improved gravimetric Particulate Mass measurement, based broadly on the US 2007 methodology, and a standardised procedure for the reliable and repeatable measurement of Particle Number counts. The latter uses a Condensation Particle Counter for measurement with sample pre-conditioning to eliminate the volatile particles which may contribute significantly to variability.

The draft protocol was 'frozen' at the June 2005 meeting of GRPE to enable an inter-laboratory correlation exercise to be undertaken. This exercise, which has been managed by the EU's Joint Research Centre (JRC) is expected to be completed in early 2006. Preliminary results [3] show that the Mass method is sufficiently sensitive to permit repeatable measurements at well below 2.5mg/km and the Number method is approximately 20 times more sensitive than the revised Mass method.

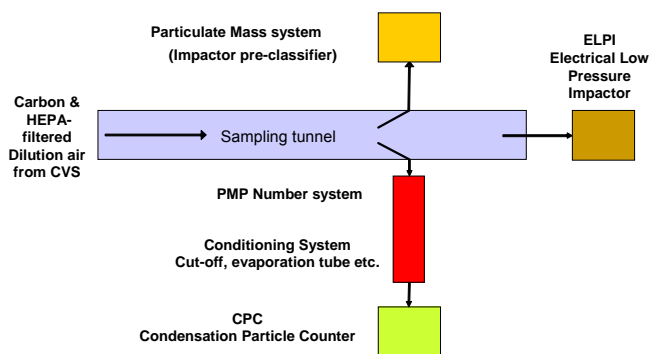


Figure 4: Sampling arrangement for PMP measurements

## ANALYTICAL METHODS

The cars were tested on an electric Clayton DC500 two 500mm roller chassis dynamometer at test cell temperatures of 20-30°C. The dynamometer settings were applied for each vehicle according to the regulations and the vehicle Type Approval data. A critical-flow venturi Constant Volume Sampler (CVS) (Horiba, CVS-9300T) with a 3150mm long sampling tunnel having an inner diameter of 250mm i.d. was used. Cleaned and HEPA filtered test cell air was used for dilution.

The regulated gaseous emissions were measured according to standard EU test procedures using a Horiba Mexa 9000 series instrument for CO and CO<sub>2</sub> (non-dispersive infra-red), HC (heated flame ionisation detector) and NO and NO<sub>x</sub> (heated chemiluminescence) with NO<sub>2</sub> by difference. NEDC samples were collected into 3 bags (first two 'cold' ECE urban cycles; second two 'hot' ECE cycles and Extra-urban cycle) with 3 bags for dilution air; whereas Artemis cycles used single bag sampling. Different bags were used for gasoline and diesel exhausts sampling.

Nitrous oxide (N<sub>2</sub>O) emissions were measured in the bag samples within 0.5h of the tests. An infra-red Horiba N<sub>2</sub>O instrument (detection limit 1ppm) was used initially but as N<sub>2</sub>O was below the limits of detection in the first phase of testing, gas chromatography with a detection limit of 0.45ppm was used for the final test vehicle (Diesel B). Ammonia (NH<sub>3</sub>) was sampled into impingers containing 0.1N HCl solution. Samples were analysed by a standard EN ISO 11732 colorimetric absorption method.

Particulate Mass (PM) measurement was performed in accordance with the PMP-protocol. The filters were 47mm diameter TX40 filters (PTFE bonded glass fibre filters; PALL) mounted in a filter holder meeting the standards for US2007 regulations. In the PMP-protocol the use of a single filter is proposed but in this study two filters in series were used to examine filter break-through for different type of vehicles. Measurements to the current EU test procedure and the full (single filter) PMP procedure were also made for Diesel B and Diesel DPF to allow full comparison. The same flow-rate was used for all measurements. Two reference filters were used as proposed by the PMP protocol; the average weight differences of the reference filters between sample filter weighings were never higher than 5µg.

For the Particle Number measurements a Dekati SAC-65 cyclone was connected to the sample probe. The cyclone particle cut-off diameter changes with the sample flow rates and varies between 2.35µm and 8.97µm for the different set-ups. For the Number measurements, the effect of the changes in cyclone cut-off diameter is insignificant as the Number emissions from combustion engines are largely dominated by particles in the sub-micrometer range. The Evaporation

Tube (ET) consisted of an electrically heated stainless steel tubing of 6.1mm i.d. cooled by pressurised air flowing through an outer jacket. The temperature of the ET was set at 350°C. The ET meets the design criteria in the PMP-protocol and had a volatile particle removal efficiency <99%, complying with the performance criteria in the PMP-protocol.

A TSI3010 CPC with an adjusted lower particle cut-off diameter was used. The cut-off diameter was set at 23nm by adjusting the temperature difference between the vapour chamber and the condenser tube to 9°C in accordance with TSI instructions. The measurement range was 0-10000 particles/cm<sup>3</sup> with a time resolution of 1Hz. Background particle concentrations were measured prior to test. The background measurement includes the CVS-tunnel background and the instrumental background of the respective PMP set-up.

Since the four cars examined in this study showed significant differences in particle emissions, appropriate PMP system dilution set-ups were used for each vehicle to ensure compliance with the PMP protocol requirements and maintain samples within the measurement range of the instrument.

For the gasoline vehicle three ejector dilutors (Dekati, DI-1000) were used. The primary diluter provided a DF of 8.6 and a sample flow rate of 7.0litres/min. The flow-rate resulted in a cyclone cut-off particle diameter of 3.36µm. This dilutor was insulated and electrically heated to keep a stable, continuously measured temperature at 150°C. The secondary diluter provided a DF of 7.0 and a sample flow rate of 3.90litres/min with a resulting residence time of 0.37s at temperatures above 300°C in the ET. A third dilutor with DF of 9.73 and a sample flow rate of 7.8litres/min was used for the CPC.

The particle emission from the Diesel with DPF was observed to be very low and accordingly the lowest possible DF was used, i.e. the set-up was operated without primary and secondary dilution units in accordance with the PMP-protocol. In order to adjust for proper cyclone flow characteristics and ET residence time, an external pump with a critical orifice was mounted that together with the CPC giving a total flow of 2.6litres/min. The resulting cyclone cut-off particle diameter was 8.97µm and the residence time in the ET at temperatures above 300°C was 0.56s.

Due to the high particle emissions from Diesels without DPFs, a rotating disc dilutor (Matter Engineering AG, MD19) was used to achieve a high enough DF in the range of 435 to 695. The rotating disc was operated at 150°C. The sample flow rate of this diluter is 1litre/min and therefore an external pump with a critical orifice was used in order to adjust cyclone operation with a resulting particle cut-off particle diameter of 2.35µm. The secondary ejector dilutor provided a DF of 7.0 and a sample flow rate of 3.90litre/min with a resulting

residence time of 0.37s at temperatures above 300°C in the ET.

For the PM carbon fraction analysis particulate matter was sampled from the CVS tunnel via 37mm diameter quartz-filters. The filters were pre-conditioned by heating. Speciation between organic carbon (OC) and elementary carbon (EC) was performed using a Sunset Laboratories NIOSH instrument, method 5040. The distinction between OC and EC was done automatically by the manufacturer's software.

Sampling of particulate material for chemical analysis with respect to PAH was carried out from the CVS-tunnel using 250mm diameter Teflon coated glass fibre filters (Pallflex T60A20). Downstream of the filter, sampling of semi volatile ('vapour phase') compounds was performed using plugs of polyurethane foam (PUF). The filters and PUFs were supplied, treated and analysed by an external laboratory (Stockholm University). Filters were pre-cleaned using acetone and dried in an oven. The PUFs were pre-cleaned by 24-hour Soxhlet extraction using acetone. After sampling the filters and the PUFs were stored in a freezer at -18°C. The filters were Soxhlet extracted with dichloromethane and the PUFs were Soxhlet extracted using acetone. The dichloromethane extract was evaporated under reduced pressure just to dryness, diluted with acetone and then stored at -18°C until chemical analysis. Blank samples were obtained and treated as described above. Internal standards were added to the aliquot of the raw particulate extracts. The extracts were analyzed for PAH using gas chromatography-mass spectrometry (GC-MS). The gas chromatograph (Hewlett Packard 5890 series II) was equipped with a split/splitless injector (injector temperature 285°C) and a fused-silica capillary column (20m×0.25mm i.d., HP5-MS, Hewlett-Packard, USA). The temperature program was as follows: initial temperature 70°C for 1min followed by a successive increase in temperature at 7°C/min to reach the final temperature of 300°C for 10min. The mass selective detector (Hewlett Packard 5971A) interface temperature was set to 300°C and the ion source temperature to approximately 200°C. The MS was operated in the electron ionization mode at 70 eV and the quantitative analysis was carried out in the Selected Ion Monitoring (SIM) mode. In total, 29 different PAHs were measured.

## TEST RESULTS

### 1 GASEOUS EMISSION RESULTS

#### CO Emissions

CO emissions from all four vehicles were below the relevant limits for Euro 4 on the NEDC test. Results for the three diesel vehicles on the hot-start Artemis cycles were all significantly lower than on the NEDC – in most cases below the limit of detection. For the gasoline

vehicle the results on the Artemis Urban cycle were comparable to the NEDC and those on the Artemis Extra-Urban cycle were some 20% lower. However, CO emissions for the Artemis Highway cycle were some 10 times those on the other cycles.

It could be argued that the results for the Artemis Urban cycle would most directly compare with the hot phases of the NEDC test (elemental urban cycles 3 & 4) and the Artemis Extra-Urban cycle with the extra-urban (EUDC) portion of the legislative test. Figure 5 therefore shows the emissions with the NEDC separated into the cold urban (urban cycles 1 & 2), hot urban (urban cycles 3 & 4) and extra-urban cycles. The results primarily reflect the effect of the cold start in the NEDC tests.

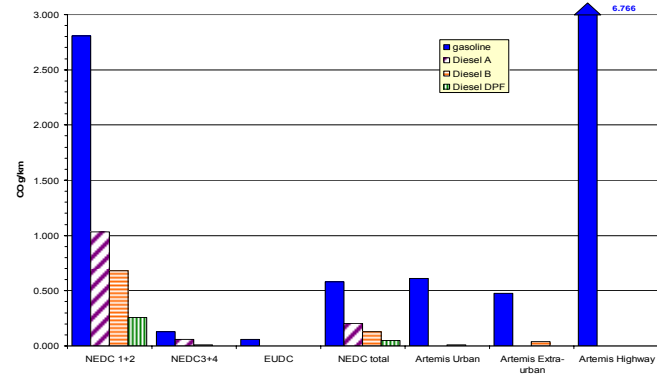


Figure 5: CO emissions with NEDC shown by phases

### HC Emissions

The HC results all show lower emissions on the hot-start Artemis cycles than on the NEDC, for all vehicles. Figure 6 shows the results for complete cycles and with the NEDC data also broken down into the three phases.

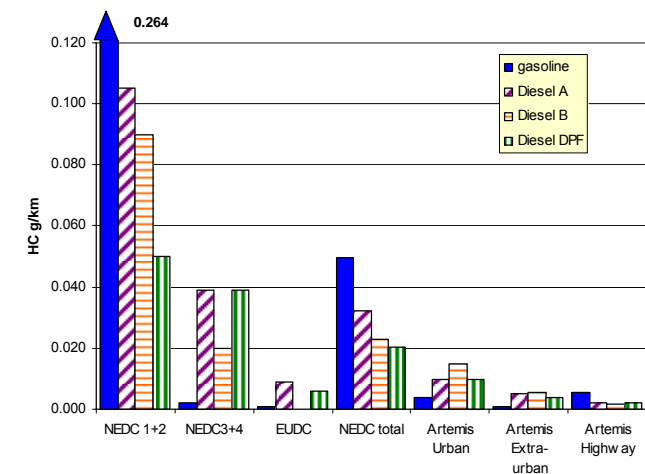


Figure 6: HC emissions with NEDC shown by phases

### NOx Emissions

For NOx (figure 7) the pattern is quite different. The Three-Way Catalyst system of the gasoline vehicle gave good control on all cycles, achieving 33mg/km on the NEDC and 11, 4 and 3mg/km respectively for the Artemis Urban, Extra-Urban and Highway Cycles.

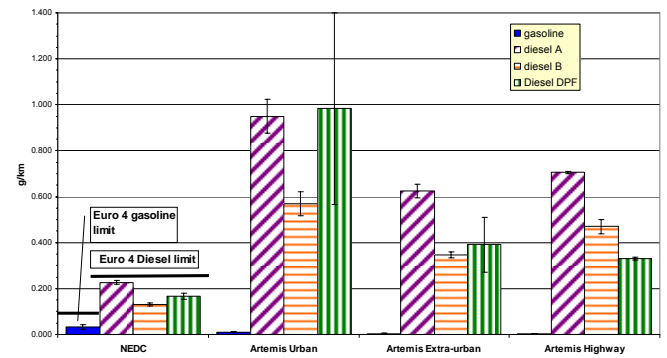


Figure 7: NOx emissions by cycle and vehicle

For all three diesel vehicles, however, where control of NOx is primarily through engine measures, the results on the Artemis cycles were significantly higher than on the NEDC test. As an example, the results for diesel A on the legislative test were relatively close to the legislative limit (227mg/km ± 9mg/km, compared to a limit of 250mg/km). Average NOx emissions on the Artemis Urban cycle were some four times higher at 950mg/km. Artemis Extra-Urban and Highway NOx emissions were 624 and 706mg/km respectively – also well above the NEDC figures.

Comparing the hot ECE urban cycles (NEDC 3+4) with the Artemis Urban cycle indicated that the critical difference does not lie in the cold start of the NEDC figure 8). For all three vehicles the NEDC 3+4 results are lower than the NEDC 1+2 emissions, whereas the Artemis Urban results are significantly higher. Similarly the legislative extra-urban test (EUDC) emissions are lower than the NEDC1+2 results, but those on the Artemis Extra-Urban cycle are significantly higher.

It has been suggested that the official gear-shift points on the Artemis cycles are not optimised for diesel vehicles and hence this may have some influence on the results. Nevertheless, the level of difference from the NEDC cycles suggests that this is not the only factor involved. In addition these shift points are applicable only to vehicles with manual gearboxes. The vehicle with DPF had an automatic gearbox and hence the built-in shift strategy would have been used.

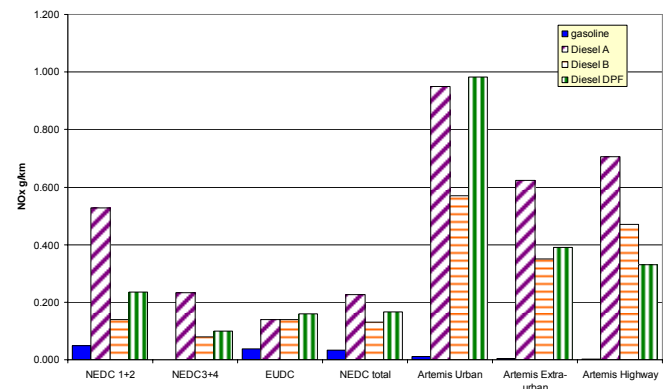


Figure 8: NOx emissions with NEDC shown by phases

## 2 PM AND PMP RESULTS

### PM Emissions

Particulate Mass (PM) emissions results showed that at the low emission values (<1mg/km) of the vehicle fitted with DPF, measurements made using the full single-filter PMP procedure were about half those obtained from the current EU twin-filter sampling system [4]. Results are shown in Figure 9. The limited data available showed the repeatability to be improved by using the PMP procedure.

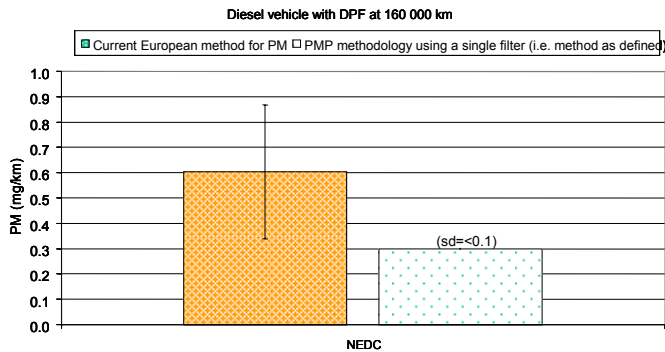


Figure 9: PM by current EU procedure and PMP

For diesel vehicle B (without a DPF) the differences between the two procedures were of the same order of magnitude, but less significantly different in relative terms (16.5mg/km using the current EU procedure, 15.6mg/km using the PMP procedure).

Using the PMP measurement process but with two sampling filters in series (as in the current EU procedure) resulted in a Particulate Mass slightly lower than that from the current EU procedure but greater than the PMP procedure using 1 filter. Taking the weight only of the first of these two filters gave a mass comparable to or marginally higher than the full single-filter PMP procedure. As an example Table 2 shows the results for Diesel DPF measurements on the NEDC.

Test protocol	mg/km	sd
Current EU procedure	0.6	0.3
Full PMP (1 filter) procedure	0.3	<math>< 0.1</math>
2 filter version of PMP procedure	0.5	0.3
1st filter of 2 from 2 filter version of PMP	0.4	0.2

Table 2: PM measured by four procedure variants; Diesel vehicle with DPF, NEDC

Only the 2-filter variant of the PMP procedure was used for all four vehicles. The following PM results use the mass measured on the first of these two filters to allow like-for-like comparison of the four vehicles.

Figure 10 highlights the difference between the two Diesels which did not have DPFs and the other two vehicles. Emissions from the Diesel with a DPF were at least an order of magnitude lower than for the other diesels and were comparable to those of the gasoline vehicle. For all the diesel vehicles the results on the Artemis Urban cycle were higher than on the NEDC test. Whilst the gearshift points (as discussed under NOx emissions) may have had some influence on this it appears that fuel consumption was a critical factor, being substantially higher on the Artemis Urban cycle, as shown in Table 3.

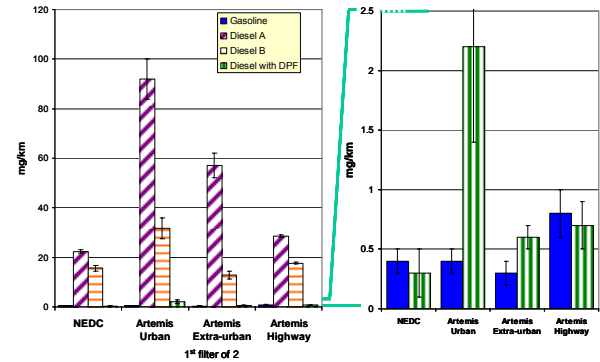


Figure 10 PM emissions for four test vehicles

Fuel consumption l/100km	NEDC	Artemis Urban	Artemis Extra-Urban	Artemis Highway
Gasoline	6.9	10.8	6.2	6.8
Diesel A	7.2	11.0	6.8	6.7
Diesel B	5.2	8.6	4.5	5.2
Diesel DPF	7.8	12.0	5.9	5.7

Table 3: fuel consumption

### Particle Number Emissions

Figure 11 illustrates the average Particle Numbers measured for each vehicle and test cycle.

The Particle Number emissions reinforce the effectiveness of the DPF on all of the test cycles. For all test cycles the uncorrected Particle Numbers for the two diesel vehicles without filters were in the range of  $4.5 \times 10^{13}$  to  $13 \times 10^{13}$  per km. Those for the gasoline vehicle were some 2 orders of magnitude lower; in the range  $1.2 \times 10^{11}$  to  $4.6 \times 10^{11}$  per km and those for the diesel vehicle with DPF at least one order of magnitude lower still at  $1 \times 10^9$  to  $9.9 \times 10^9$  per km.

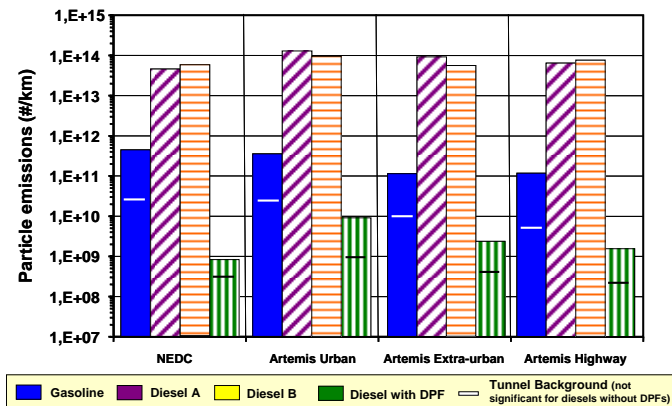


Figure 11: Particle Number emissions

The difference in background levels is due the difference in dilution levels needed to achieve appropriate particle number concentrations for the CPC range.

Continuous monitoring of the Particle Number counts showed low emissions from the Diesel with DPF throughout the test cycles. An example from an Artemis Urban cycle is shown in Figure 12.

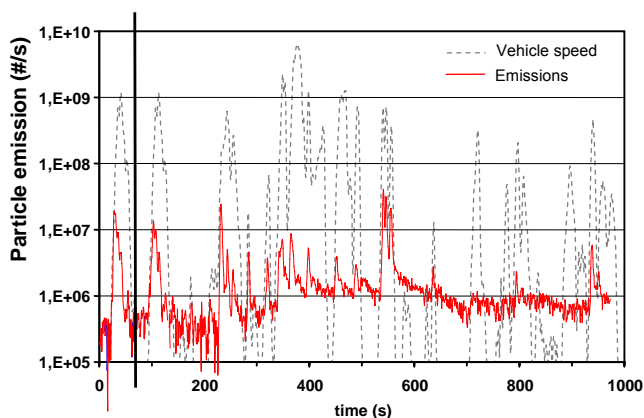


Figure 12: Continuous Particle Number trace from Diesel vehicle with DPF on an Artemis Urban test cycle

### 3 PM SPECIATION

All vehicles were tested on fuels containing less than 10ppm sulfur, so the measured sulfur content of the Particulate Matter was very low. The highest results obtained were 0.11mg/km for Diesel B and 0.08mg/km for the gasoline vehicle, both on the Artemis Urban cycle. All other results were 0.05mg/km or lower. Lubricant-related material varied with vehicle and test cycle, but in all cases was below 2mg/km.

Note: only single tests were conducted for speciation.

The Elemental Carbon (EC) content of the PM is shown in Table 4. For the diesel vehicles without DPF the figure was typically 80% or greater regardless of cycle. As would be expected, this figure is drastically reduced for the Diesel with DPF; for all cycles the elemental carbon content for this vehicle was less than 2%. This is lower even than the gasoline vehicle, where the elemental

carbon content range was up to 32% and appeared very cycle-dependant from these single-test results.

EC (as % of PM)	NEDC	Artemis		
		Urban	Extra-Urban	High-way
Gasoline	32.0	12.0	10.0	4.7
Diesel A	85.0	92.0	92.0	88.0
Diesel B	84.6	86.2	81.6	79.2
Diesel DPF	0.8	0.0	1.9	1.5

Table 4: Elemental carbon as percent of total PM

The Elemental Carbon content should also be considered in the context of total PM emissions, rather than as a simple percentage. The two measurements use different filters, so it is not possible to give absolute figures for elemental carbon as measured g/km. However, combining the two measurements allows a sensible estimate to be made. Figure 13 illustrates a comparison of the four vehicles on the Artemis Highway cycle. Note that the total PM shown in this graph is that for the single cycle on which the EC/OC ratio was measured, rather than the average..

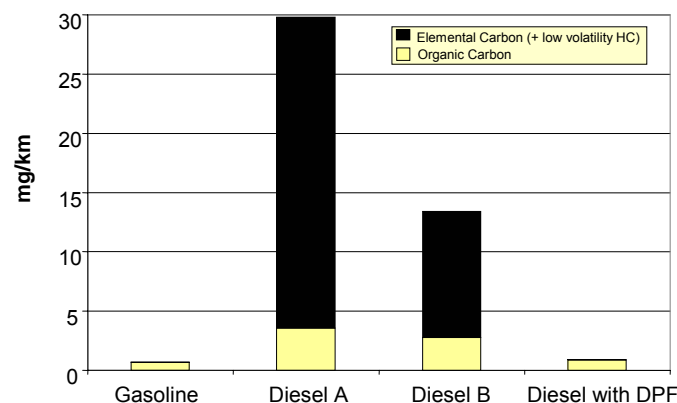


Figure 13: Elemental carbon related to total PM

### 4 NON-REGULATED EMISSIONS

Note that only single tests on each vehicle and cycle were conducted for non-regulated emissions except for NO<sub>2</sub> which was measured with total NO<sub>x</sub>.

#### Nitrous oxide (N<sub>2</sub>O)

N<sub>2</sub>O was not detectable in any test. The limit of detection was 1ppm for the gasoline vehicle, Diesel A and the Diesel with DPF. An improved procedure with a detection limit of 0.45ppm was used for Diesel B.

#### Nitrogen Dioxide (NO<sub>2</sub>)

NO<sub>2</sub> emissions were measured as part of the normal NO<sub>x</sub> bag analysis process. Figure 14 shows the NO<sub>2</sub> and NO (calculated from NO<sub>x</sub> – NO<sub>2</sub>) for each vehicle on the different test cycles. Although there is some influence on NO<sub>2</sub> ratio from the cycle, the main effect of

the driving cycle appears to be on the magnitude of the overall NO<sub>x</sub> emissions rather than the NO<sub>2</sub> ratio.

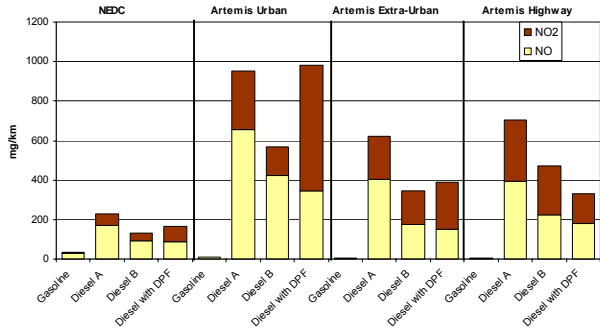


Figure 14: NO and NO<sub>2</sub> emissions

### Ammonia

Ammonia emissions from all four vehicles were low. Figure 15 shows the levels measured for each vehicle. For all three Diesel vehicles ammonia emissions were below 5mg/km on all driving four driving cycles. In most cases emissions on the Artemis cycles were similar to or below the levels measured on the legislative (NEDC) test cycle. The highest emission levels were found for the gasoline vehicle. In this case emissions on all the Artemis cycles were higher than for the NEDC.

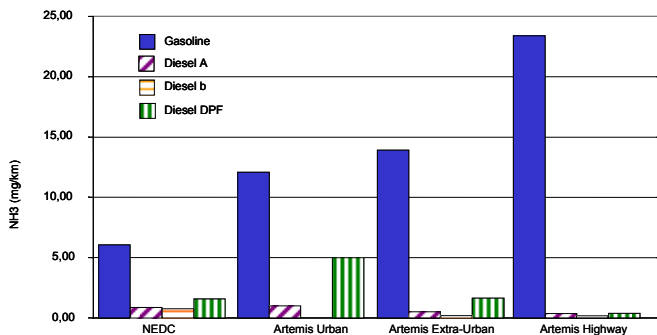


Figure 15: Ammonia emissions

### PAH

PAH emissions were measured both as vapour phase and particulate-phase materials, as described in the analytical methods section. Figure 16 shows these as total nanograms per km for each vehicle and cycle.

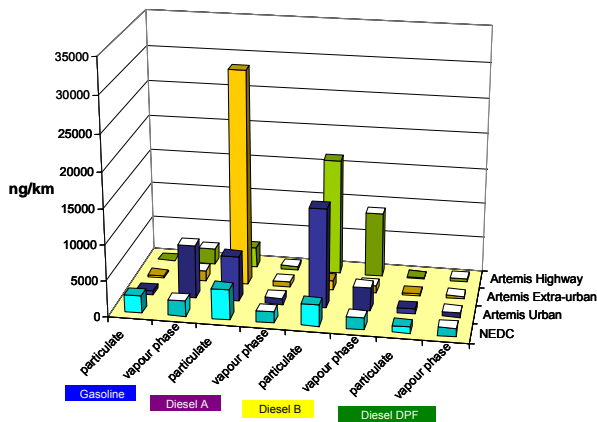


Figure 16: Particulate and vapour PAH emissions

For the Diesel vehicles without DPFs the particulate-phase PAH are significantly higher than the vapour phase PAH. Results on the Artemis cycles were generally higher than for the NEDC for both vehicles, although there was no clear common pattern of any particular cycle exhibiting higher emissions performance than others. For the gasoline vehicle PAH emissions were higher in the vapour phase sample than the particulate phase. For the Diesel with a DPF vapour phase PAH emissions comparable to the levels measured on Diesel A, the lower of the two without DPF. Particulate-phase PAH emissions were substantially reduced compared to the other two diesel vehicles, and were at a similar low level to the vapour phase emissions.

The Diesel vehicles without DPF showed the highest particulate-phase PAH emissions. Diesel A recorded 30µg/km in the particulate phase over the Artemis Extra-Urban cycle and Diesel B reached 16.3µg/km on the Artemis Highway cycle and 13.9µg/km on the Artemis Urban Cycle. The vehicle with DPF produced particulate-phase PAH emissions of less than 1µg/km over all test cycles. For the gasoline vehicle particulate-phase PAH emissions were also below 1µg/km except for the NEDC test, which reached 2.4µg/km.

Vapour phase PAH emissions were below 10µg/km for all vehicles. Those for the Diesel with DPF were the lowest of the four for all cycles, with the highest result being 1.2µg/km over the NEDC test.

### SUMMARY

Regulated emissions, Particulate Mass and Number according to the PMP protocol and non-regulated emissions were measured from a gasoline vehicle, two Diesel vehicles having different fuelling and emissions systems but without a Diesel Particulate Filter (DPF) and a Diesel vehicle with DPF.

Analysis of emissions from these four modern European vehicles over the Artemis suite of Urban, Extra-Urban and Highway driving cycles shows a number of differences from the legislative cycle results.

In general CO and HC emissions from the hot-start Artemis cycles were lower than for the cold-start legislative (NEDC) test. The exemption to this was CO emissions from the gasoline vehicle over the Artemis Highway cycle. For NO<sub>x</sub> emissions the pattern was quite different. The gasoline vehicle with Three-Way Catalyst system gave good control over all cycles. For the Diesel vehicles, where control of NO<sub>x</sub> is achieved primarily through engine measures, emissions were significantly higher on the Artemis cycles than on the NEDC, even if the NEDC is considered as separate cold urban, hot urban and extra-urban phases.

Experience in this test programme with the PMP procedure showed it to be capable of providing a robust

and reliable method for measuring both Particulate Mass and Particle Number emissions for the low PM emissions vehicle. PM measurements at well below 1mg/km were achievable and the Particle Number method was capable of clear differentiation between diesel with and without DPF and between either of these and gasoline vehicles.

Compared to the legislative cycle, Particulate Mass emissions were higher on the Artemis Urban cycle for all three diesel vehicles. This appears to be at least in part due to significantly higher fuel consumption.

The effectiveness of the DPF was reinforced by the Particle Number measurements. Those from the vehicle with DPF were at least three orders of magnitude below the non-DPF vehicles for all test cycles and typically at least one order of magnitude below the gasoline vehicle. Speciation of the particulate matter also showed the elemental carbon content for this vehicle to be less than 2% of the PM, whereas for the diesel vehicles without DPF it was in the range of 79 to 92%.

Nitrous oxide emissions were not detectable for any vehicle or test cycle (limit of detection at or below 1ppm in the sample bags). Ammonia emissions were higher from the gasoline vehicle than for any of the three Diesel vehicles. For the gasoline vehicle ammonia emissions were higher on the Artemis cycles than on the NEDC, whereas there was no such clear trend for the Diesel vehicles, where emissions on all cycles were below 5mg/km. For NO<sub>2</sub> there may be some influence from the cycle on the NO:NO<sub>2</sub> ratio, but the main effect appeared to be on the magnitude of overall NO<sub>x</sub> emissions.

A further benefit of the DPF was seen from the PAH emissions measured. The Diesel vehicles without DPF showed PAH emissions of up to 30µg/km in the

particulate phase over the Artemis Extra-Urban cycle, whereas the vehicle with DPF produced particulate-phase PAH emissions of less than 1µg/km over all test cycles. Gas phase PAH emissions were below 10 µg/km for all vehicles. Those for the diesel with DPF were the lowest of the four for all cycles.

## ACKNOWLEDGMENTS

The authors would like to thank the Members of the Association for Emissions Control by Catalyst (AECC) and the Directors of AVL-MTC for permission to publish this paper.

## REFERENCE

1 de Haan P. & Keller M., Real-world driving cycles for emission measurements: ARTEMIS and Swiss cycles; INFRAS report for BUWAL, Switzerland, 17 March 2001

2 GRPE-48-11-Rev.1, Conclusions on Improving Particulate Mass Measurement Procedures and New Particle Number Measurement Procedures Relative to The Requirements of The 05 Series of Amendments to Regulation No. 83; Geneva, 1 June 2004

3 Andersson J. & Dilara P., UN-ECE Particle Measurement Programme (PMP) – Light-duty Inter-Laboratory Correlation Exercise: Report on first results; SIA Conference Le Post-Traitement Diesel: Perspectives et Développements, Rouen, November 2005

4 GRPE-PMP-15-1; AECC Light-duty Test Programme – PMP measurements; Geneva, 31 May 2005