

160000km Emissions Durability of a Diesel Passenger Car with Particulate Filter

Abgasemissionen eines Dieselfahrzeuges mit Partikelfilter über einen 160000km Dauerlauf

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Abstract / Kurzfassung: Emissions from a current-production diesel passenger car with particulate filter were measured after de-greening at 4000km. The vehicle was then subjected to on-road mixed-operation driving to 160000km and re-tested. At both mileages the vehicle was tested over the standard European driving cycle (NEDC) and over the more transient hot-start Artemis urban, extra-urban and highway cycles which were developed as part of a European programme and which were designed to be representative of typical transient driving patterns. Interim measurements of regulated emissions over the NEDC were made at 40000, 80000 and 120000km.

At 4000 and 160000km, in addition to regulated emissions, the new Particulate Measurement Protocol (PMP) developed under the UN's World Forum for Harmonization of Vehicle Regulations was used for measurement of particulate mass and particle numbers.

The results demonstrate that the new protocols offer repeatable mass measurement and a number methodology capable of measuring the very low particle emissions from vehicles with particulate filters. Particle and regulated emission results remained stable throughout the test period, demonstrating the effectiveness of the system over the increased distance of 160000km which has since been proposed for the Euro 5 European durability requirement.

Key Words / Schlagworte: Diesel Particulate Filter; Emissions; Durability; Particle number; Artemis cycles

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1 Introduction / Einleitung

Public pressure in Germany and other European countries has resulted in the voluntary fitment by many car manufacturers of Diesel Particulate Filters (DPF) as either standard or optional equipment. The European Commission proposed, in January 2005, that a Particulate Matter (PM) emission level of 5mg/km should be used as a basis for any incentive schemes. In December 2005 the same limit was proposed as the level for the Euro 5 light-duty vehicle emissions standard (for the current EU test procedure), together with a reduction in NO_x emission limits to 200mg/km and an increase in the durability requirements to 160000km from the current requirement of 100000km.

Whilst discussions on possible Euro 5 emissions requirements were under way, a test programme was developed by the Association for Emissions Control by Catalyst (AECC) to examine the emissions performance and durability of 'state of the art' European vehicles meeting current (Euro 4) emissions standards. One element of this programme was testing, over 160000km, of a diesel vehicle fitted with a Diesel Particulate Filter as standard. 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. These 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 to as Artemis Urban (AU), Extra-Urban (AEU), and Highway (AH).

Regulated emissions (CO, HC, NO_x, PM) were measured by conventional analytical techniques, and the draft UN-ECE Particulate Measurement Programme (PMP) protocol [2] was used for both Particulate Mass and Particle Number measurement. A comparison of the results obtained by using the current European legislative method and the PMP mass methodology in this test programme has previously been reported [3, 4].

This paper examines the results from the NEDC and CADC tests for a standard series-production Euro 4 diesel vehicle measured after initial de-greening at 4000km and after on-road mileage accumulation at 160000km. The test programme was conducted at the AVL-MTC test centre in Haninge, Sweden, a recognised Type Approval laboratory which had been involved in the development of the Common Artemis Driving Cycles.

2 Test Vehicle and Methodology

2.1 Test Vehicle

The test vehicle was a standard production car with factory-fit Diesel Particulate filter and which met the Euro 4 emissions requirements. The vehicle had an in-line 6 cylinder direct injection diesel engine of 2993 cm³. The engine, which had 4 valves per cylinder, produced 160kW at 4000rpm. The emissions control system used exhaust gas recirculation (EGR) together with a Diesel Oxidation Catalyst (DOC) and an underfloor catalysed Diesel Particulate Filter (DPF).

The homologated emission levels were representative of those achieved by DPF-equipped vehicles. Although at the time of testing Euro 5 limits had not been defined, Type Approval data shows that at 100000km the vehicle would meet the proposed Euro 5 limits of 500mg/km CO, 250mg/km HC+NOx, 200mg/km NOx and 5mg/km PM. Initial measured PM and NOx emissions for the actual test vehicle were both well within the current Euro 5 proposals, as shown in figure 1, and the NOx emissions were intermediate between two non-DPF diesels tested at the same time [3].

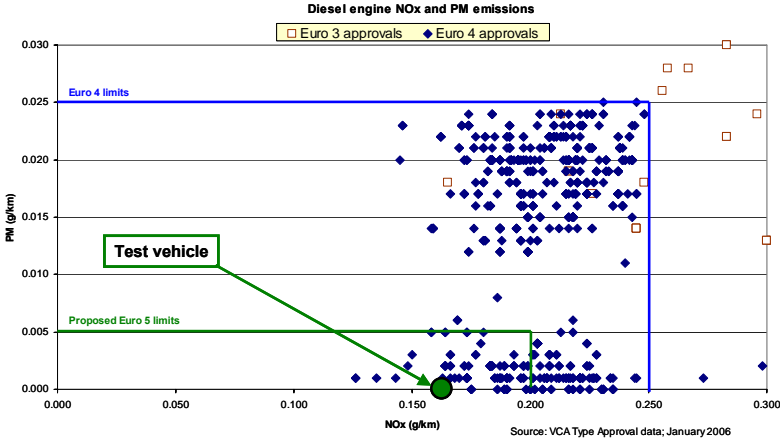


Figure 1: PM and NOx emissions of the test vehicle relative to other Type Approval data

2.2 Test Protocol

Prior to the emissions test programme the vehicle was de-greened by driving 4000km using standard Swedish road fuel (<10ppm sulfur). After de-greening the vehicle 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 was 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 preconditioning cycle was used as the DPF regeneration procedure throughout the programme with the aim of ensuring comparability of test results throughout the testing. Triplicate tests were conducted for regulated emissions and PMP measurements.

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

The cold-start New European Driving Cycle (NEDC) was used in its standards form, as it would be for Type Approval tests. The Artemis cycles, shown in Figure 2, are all warm start cycles and include a preconditioning part of different lengths for the different 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.

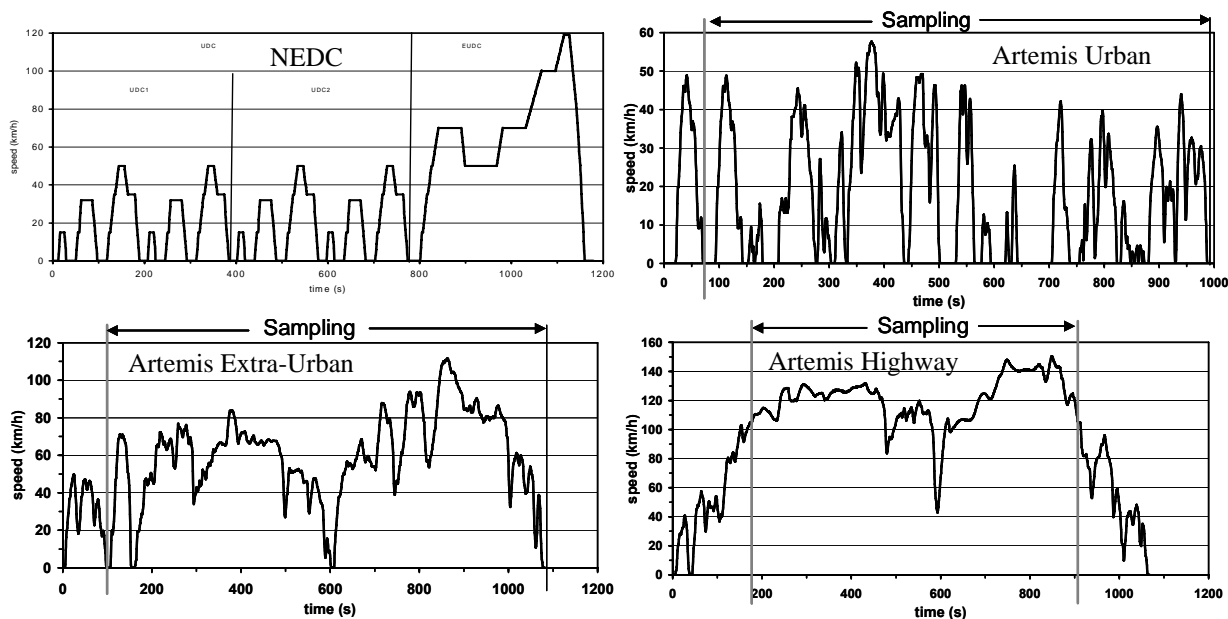


Figure 2: NEDC and Artemis (CADC) Driving Cycles

2.3 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 2004 meeting of GRPE to enable an inter-laboratory correlation exercise to be undertaken. An initial report on this exercise, which has been managed by the EU’s Joint Research Centre (JRC) is expected to be provided for the June 2006 meeting of GRPE. Preliminary results [5] 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.

Testing at 4000km and 160000km used this protocol, with the exception that two filters were used in place of a single filter to explore filter breakthrough. Results quoted are from the first of the two filters, and comparative test work previously reported [3,4] indicates that these results are slightly higher than would be obtained by the use of a single filter.

2.4 Analytical Methods

An electric Clayton chassis dynamometer with two 500mm rollers was used for all tests, with a test cell temperatures of 20-30°C. Dynamometer settings were applied according to the regulations and the vehicle Type Approval data. An Horiba CVS-9300T critical-flow venturi Constant Volume Sampler (CVS) with a 250mm i.d., 3150mm long sampling tunnel 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 CO₂ (non-dispersive infra-red), HC (heated flame ionisation detector) and NO and NO_x (heated chemiluminescence) with NO₂ by difference. NEDC samples were collected into 3 bags (first two 'cold' ECE urban cycles; second two 'hot' ECE cycles and third Extra-urban cycle) with 3 bags for dilution air; whereas Artemis cycles used single bag sampling for each of the Artemis sub-cycles.

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. 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 was found to be approximately 8.97µm for the tests at 4000km and 7.8µm for the tests at 160000km. 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 cooler was used in order to reduce thermophoretic losses of particles. The temperature of the ET was set at 350°C that resulted in a residence time of 0.5 s at temperatures at minimum 300°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/cm³ 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 PMP set-up.

Appropriate PMP system dilution set-up was used to ensure compliance with the PMP protocol requirements and maintain samples within the measurement range of the instrument.

The particle emission levels from the vehicle were observed to be very low and accordingly the lowest possible DF was used at 4000km, i.e. the set-up was operated without primary and secondary dilution units in accordance with the PMP-protocol and an external pump with a critical orifice was mounted together with the CPC in order to adjust for proper cyclone flow characteristics and ET residence time. At 160000km, in the light of experience gained in the

earlier part of the test programme, an ejector diluter operating at 150°C was used as the primary dilution unit since the particle concentrations during the initial tests were observed to be higher than 10000 particles/cm³. Both set-ups meet the criteria of the PMP-protocol. The possible impact of the ejector diluter in the later phase of the study, besides the desired dilution, can however be discussed. Two effects may be taken into account: the effect of hot dilution on condensed material, and loss of particles in the dilution through diffusion and thermophoresis. The hot dilution suppresses particles containing condensed material since the vapour pressure of condensable matter is reduced. However, this effect only generates an important difference if the removal efficiency of condensed material in the ET is not sufficient. The removal efficiency of condensed material in the ET at the temperatures used was high (>99%) and so this effect should be negligible. Concerning the losses of particles in the ejector diluter, measurement data for particle penetration provided by the manufacturer of the diluter (Dekati) performed at ambient temperature shows particle penetrations higher than 90%, at around 95%, over the particle size range 30 nm to 300 nm. Furthermore, losses through thermophoresis are believed to be small since the body of the diluter is heated. Thus, the effect of the two PMP set-ups used for the two phases of the study is likely to be small. For 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.

2.5 Mileage Accumulation

Following full testing at 4000km, the vehicle was aged on-road for 160000km. During this period duplicate intermediate emission tests were performed at 40000, 80000, and 120000km vehicle mileage respectively using the new European Driving Cycle (NEDC). These tests were intended only as an overcheck that the vehicle continued to meet legislative requirements. PM emissions at these points were therefore measured using only the current European procedure with measurements recorded to 1mg/km, whereas the PMP procedure permitted measurements to be recorded to 0.1mg/km. After 160000km aging, the vehicle was tested for emissions on both the NEDC and Artemis driving cycles using the same procedures, including PMP, that had been used at 4000km. Before the 4000km, intermediate emission tests and the 160000km tests, the vehicle was driven on the chassis dynamometer at 120km/h for 20 minutes before NEDC conditioning. Both the intermediate and 160000km tests used the same batch of reference fuel that had been used at 4000km.

The fuel used for mileage accumulation met the standards for commercial Swedish environmental class 1 fuel with sulfur content below 10ppm.

Mileage accumulation was conducted over a period of 6 months on normal Swedish roads with a mixture of urban, extra-urban and highway driving. The routes used were a 900km round trip from Stockholm to Sundsvall, which incorporated approximately 20% Highway driving followed by a 1000km round trip from Stockholm to Gothenburg, involving approximately 80% Highway driving, as shown in Figure 3.



Figure 3: Mileage accumulation route

During mileage accumulation the vehicle was serviced to manufacturers instructions by an authorised dealer at intervals shown by the vehicle’s service indicator. The engine lubricant used for servicing was a manufacturer-recommended 0W/30 grade; oil consumption was measured during all the services.

The only replacement part required during the mileage accumulation was the intake throttle valve which was changed during servicing at 122000km following appearance of an error code for this component. The Malfunction Indicator Light (MIL) was not activated at any time during the mileage accumulation or test programme.

3 Test results

3.1 Overview with Intermediate Measurements

Figure 4 shows a plot of the average results obtained from the full testing at 4000 and 160000km together with the intermediate tests at 40000, 80000 and 120000km. The results are tabulated, together with the non-methane hydrocarbon (NMHC) and CO₂ emissions and calculated fuel economy, in Table 1.

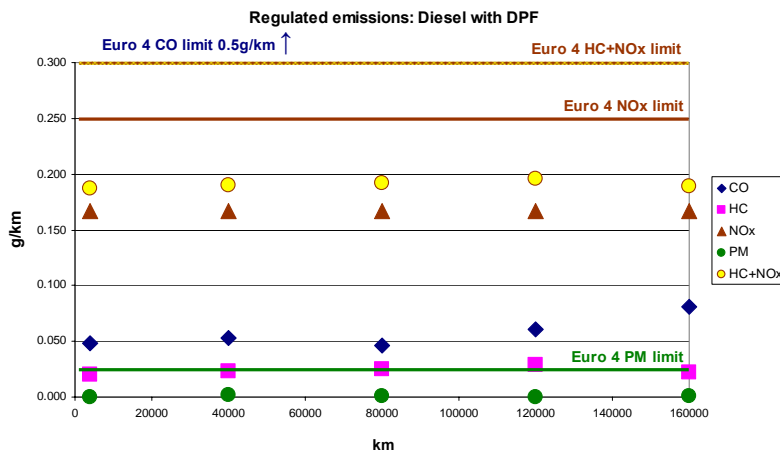


Figure 4: Regulated emissions throughout mileage accumulation

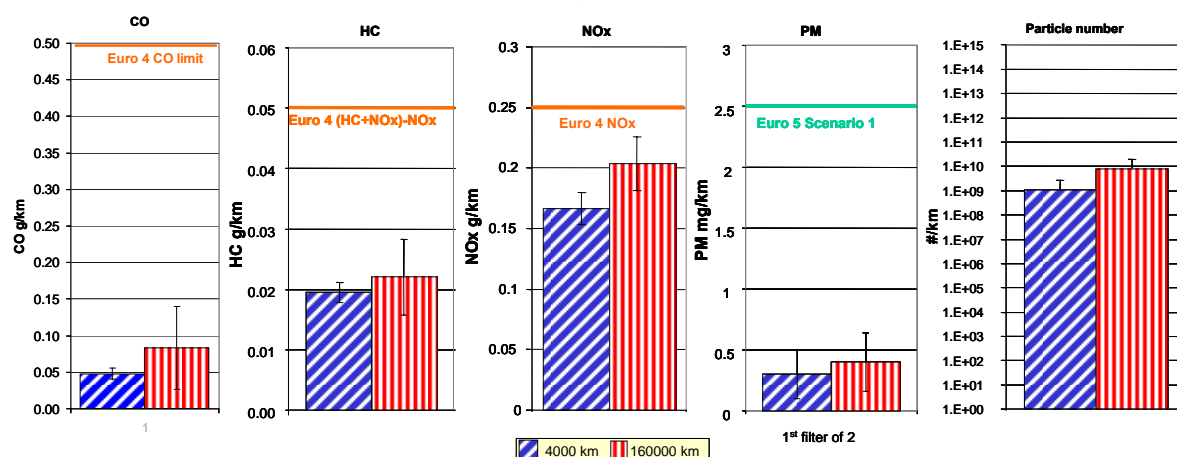
Table 1: Regulated emissions, non-methane hydrocarbons (NMHC), CO₂ and fuel consumption

Distance	CO (g/km)	HC (g/km)	NO _x (g/km)	CO ₂ (g/km)	PM (g/km)	FC (l/100km)
4000km	0.048	0.020	0.167	205.3	0.000	7.8
40000km	0.053	0.023	0.169	205.9	0.002	7.8
80000km	0.046	0.025	0.162	207.4	0.001	7.9
120000km	0.061	0.029	0.182	204.9	0.000	7.8
160000km	0.081	0.022	0.204	207.0	0.001	7.8

Throughout, all regulated emissions were stable and remained at a very low level well below Euro 4 standards. There was, as would be expected, a small increase in CO, HC and NO_x emissions over the 160000km, but this was within normal expectations. PM emissions during the intermediate tests were measured using only the current regulatory procedure rather than the improved PMP procedure with improved sensitivity. PM emissions remained at very low levels during the aging process, indicating that DPF had not deteriorated. Fuel consumption also remained stable during the period.

3.2 Regulated and Particle Emissions, NEDC tests at 4000 and 160000km

The tests from the full test programme at 4000 and 160000km show a small increase in CO and HC emissions levels over this extended durability (160000km) test. CO nevertheless remains at less than 20% of the limit applicable for Euro 4. There is no specific HC limit for diesel vehicles in Euro 4, but taking an appropriate HC level to be the difference between the Euro 4 (HC+NO_x) and NO_x limits, then HC emission remained well below half of this level. NO_x emissions, which are controlled by engine internal measures such as EGR, remained stable to 80000km, but then increased slightly at the 120000km intermediate test and again at the 160000km point. Nevertheless, NO_x emissions over the NEDC were below the Euro 4 emissions standard at both 4000 and 160000km. At 4000km the NO_x emissions would have readily met the proposed Euro 5 requirement of 200mg/km (average of 3 tests = 163mg/km with a standard deviation of 13mg/km), but at 160000km average emissions were marginally over this requirement at an average of 204mg/km.

**Figure 5:** Emissions at 4000 and 160000km

Average particulate mass emissions on the NEDC at 4000km were 0.3mg/km, compared to the Euro 4 PM limit of 25mg/km. The measured emission level would readily meet the proposed Euro 5 requirement of 5mg/km and is also comfortably below even the 2.5mg/km limit used for 'Scenario 1' in the European Commission's questionnaire on technologies and costs which was put forward in 2004. The average PM emissions at 160000km appeared marginally higher (0.4mg/km) but were within the error bar for the results at 4000km and remained well below any proposed limits.

Particle numbers (number/km) at both 4000 and 160000km were more than three orders of magnitude lower than diesel vehicles without particulate filter measured as part of the same overall programme [6].

3.3 Comparison of Emissions on the NEDC and Artemis Cycles

The NEDC test includes a cold start, with emissions measured from key-on, whereas the more transient Artemis cycles are all hot start. The emissions of CO and HC primarily reflect the lack of cold start on the Artemis tests and the effectiveness of the oxidation catalyst, with the result that CO emissions were at the limit of detection for most of the Artemis tests. HC emissions were also close to the limit of detection for the Artemis Highway tests. At both the start and end of the test programme the HC emissions for the Artemis cycles were all below the results for the NEDC with some limited deterioration for all cycles over the durability period. Average HC emissions are shown in figure 6.

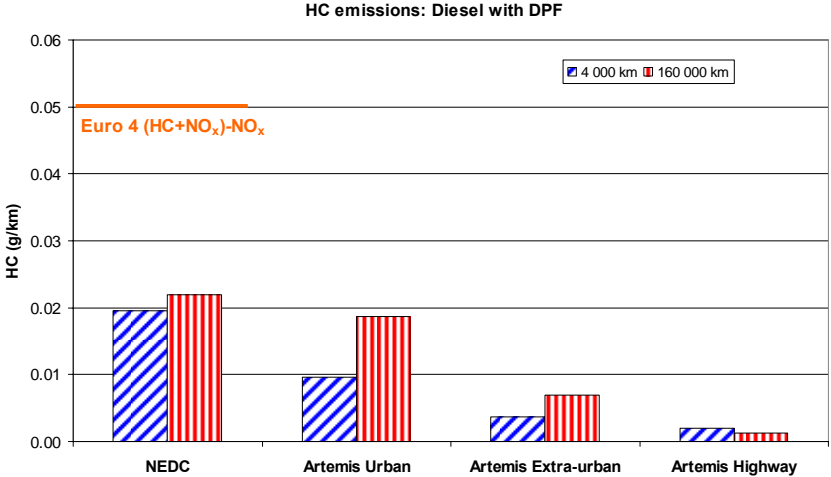


Figure 6: HC emissions at 4000 and 160000km, all cycles

The pattern for NO_x emissions was quite different, as may be seen from figure 7. The results on all the Artemis cycles were substantially higher than those obtained on the NEDC test. The emissions over the Artemis Urban cycle were some four to five times higher than those obtained on the NEDC tests, with a high degree of variability. This applied to results at both 4000 and 160000km. There was no clear trend with regards to deterioration over the durability period, with the NEDC and Artemis Highway tests showing limited deterioration at 160000km but the Artemis Urban and Extra-Urban tests showing limited improvement.

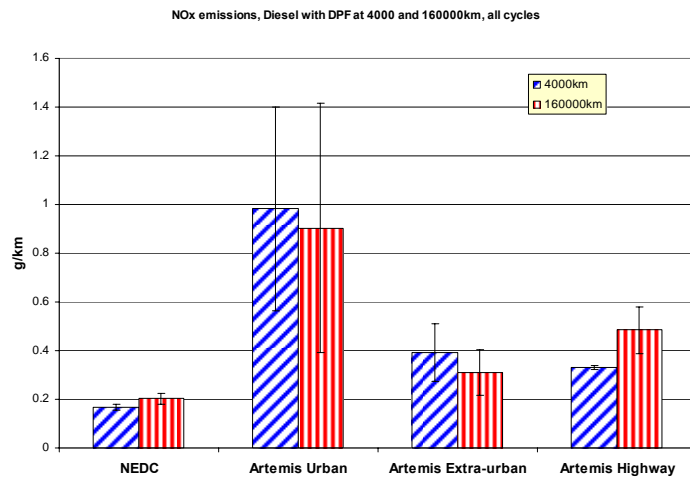


Figure 7: NO_x emissions at 4000 and 160000km, all cycles

PM emissions for all tests cycles at both 4000 and 160000km remained well below the proposed Euro 5 limit of 5mg/km and even below the 'Scenario 1' limit of 2.5mg/km, as shown in Figure 8. Although average PM emissions at 160000km on the NEDC were slightly higher than at 4000km (but still less than one tenth of the proposed Euro 5 limit), average emissions on the Artemis cycles at 160000km were all slightly lower than at 4000km. Although the 120km/h conditioning was routinely used prior to emissions tests with the objective of inducing a consistent regeneration state, it seems likely that there was some variation in DPF fill state between tests which may account for these differences.

For the Artemis Extra-Urban and Artemis Highway cycles all results remained below 1mg/km. Emissions on the Artemis Urban cycle were somewhat higher than for the other cycles, albeit still below 2.5mg/km. A prime factor in this appears to be that fuel consumption on this cycle is substantially higher than on the other cycles leading to a significantly higher throughput of exhaust. Table 2 shows the CO₂ and fuel consumption data for all cycles at both test points, and highlights the significantly higher figures for the Artemis Urban cycle. A similar phenomenon was noted for other (non-DPF) vehicles tested.

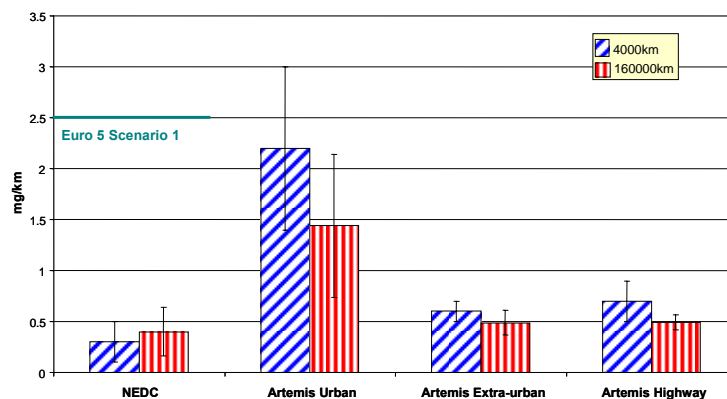


Figure 8: PM emissions at 4000 and 160000km, all cycles

Table 2: CO₂ and fuel consumption data

	NEDC	AU	AEU	AH
CO ₂ (g/km)				
4000km	205.1	316.2	156.0	149.5
160000km	207.0	306.4	153.2	171.5
Fuel consumption (litres/100km)				
4000km	7.8	12.0	5.9	5.7
160000km	7.8	11.6	5.8	6.5

Particle numbers for all test cycles were close to background levels. They were consistently several orders of magnitude below typical levels for non-DPF diesel vehicles and even below those for a gasoline vehicle tested as part of the same programme [3,4], with no major differences between cycles or mileage points.

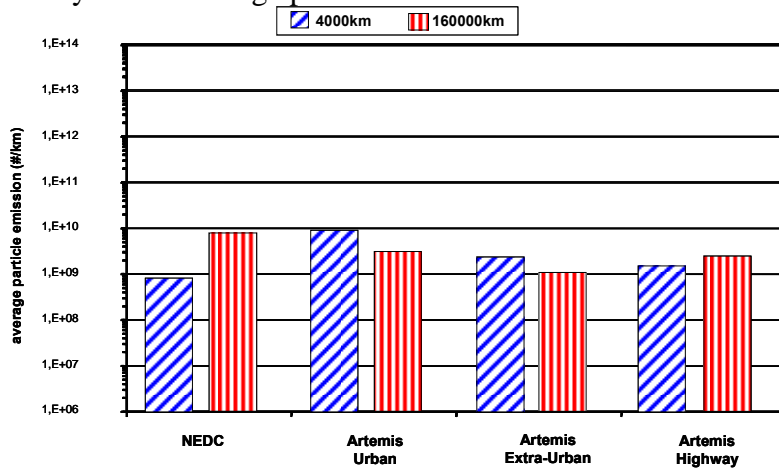


Figure 9: Average Particle Number emissions at 4000 and 160000km, all cycles

It has been proposed [7] that there is a strong correlation between Particulate Mass (PM) and Particle Number. Whilst data from diesel vehicles without DPFs tends to support this, the results from the different test cycles used in this test programme (plotted in figure 10) do not show such a correlation for the low particulate mass and number emissions found for the vehicle with DPF.

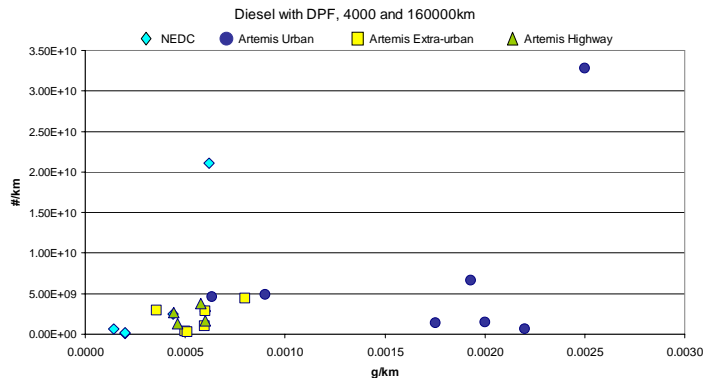


Figure 10: Particulate Mass vs. Particle Number

In addition to the measurement of particulate mass and particle number, the ratio of elemental carbon (EC) to organic carbon (OC) of the particulate matter was analysed for samples from each of the test cycles. For diesel vehicles without particulate filters a substantial proportion of the particulate matter is normally elemental carbon. Work on the health effects of particulate matter suggests that it is desirable that this elemental carbon be removed. Figure 11 shows the EC:OC ratio for the vehicle on the NEDC and Artemis test cycles at both 4000 and 160000km. Results show that the Diesel Particulate Filter virtually eliminates elemental carbon.

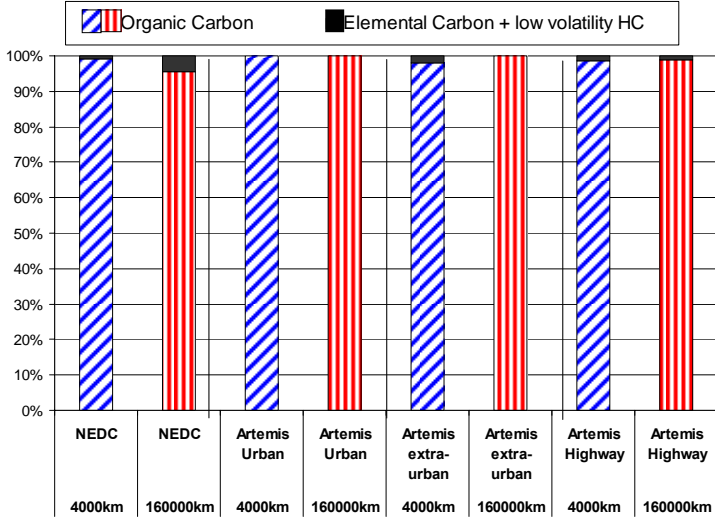


Figure 11: Elemental Carbon to Organic Carbon ratio

3.4 Examination of the Emission Control System (DOC+DPF) at End of Test

On conclusion of the test programme the exhaust system was removed and the Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter were examined by AECC members. The Diesel Oxidation Catalyst and its mat were intact with no evidence of plugging or other problems. Contaminant profiles were examined using XRF analysis for phosphorus, calcium, zinc and iron with sulfur and carbon content analysed using a Leco instrument. The majority of contaminants were iron-based or were materials typical of lubricant residues (figure 12).

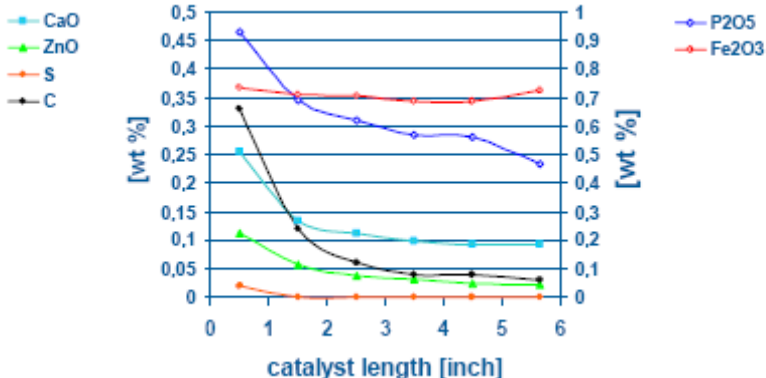


Figure 12: Contaminant profiles of the Diesel Oxidation Catalyst

Visual inspection of the Diesel Particulate Filter showed no evidence of microcracks or flow by-pass. Examination by computer tomography also showed no evidence of microcracks and indicated that ash deposition was essentially homogeneous, with slightly higher volumes at the rim. The ash occupied approximately the rear 10% of the DPF volume.

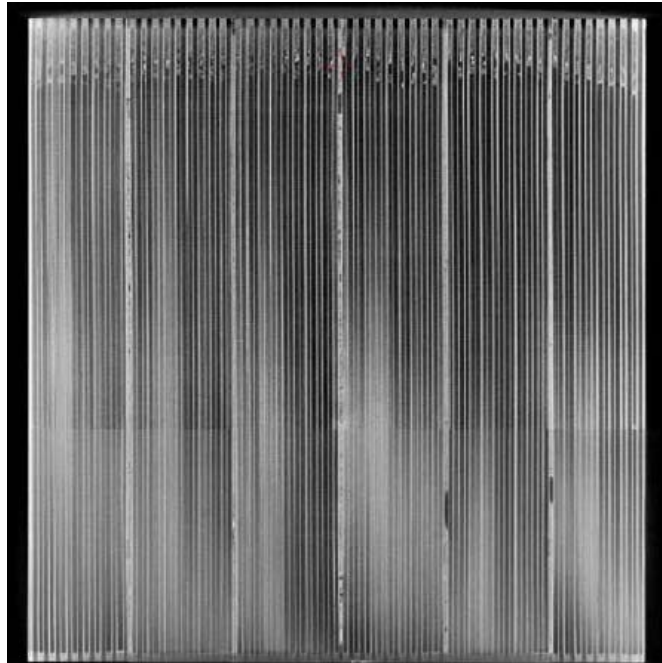


Figure 13: Computer Tomography scan of the DPF showing ash deposition

The examinations concluded that the key components of the emission control system were in good condition and capable of continued operation.

4 Summary and Outlook / Zusammenfassung und Ausblick

A standard production Euro 4 Diesel Passenger Car with Diesel Particulate Filter was tested after de-greening at 4000km and again after on-road mileage accumulation at 160000km.

The results showed good emissions stability for gaseous emissions, particulate mass and particle number emissions, with the vehicle readily meeting Euro 4 emissions limits even after 160000km.

The vehicle met the proposed Euro 5 standards for all emissions at the start of the programme. At 160000km it met the proposed standard in all respects except NO_x emissions, where the average emissions were marginally above the proposed standard (204mg/km against a standard of 200mg/km).

The most significant difference between results on the Type Approval (NEDC) tests and the transient, hot-start Artemis test was the substantially higher NO_x results obtained on the Artemis tests, especially the Urban cycle. The primary NO_x emission control technology used on this vehicle was exhaust gas recirculation (EGR).

Particulate Mass emissions on all tests cycles were significantly below the proposed Euro 5 limit of 5mg/km (NEDC test). Particle Number emissions were consistent and some 3 to 4 orders of magnitude below typical results for vehicle without Diesel Particulate Filters. Examination of the key exhaust emission control components showed them to be in good condition and suitable for continued operation.

Acknowledgements / Danksagungen

The authors wish to thank the Members of AECC and the management of AVL-MTC for their support in the preparation of this paper.

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