Association for Emissions Control by Catalyst AISBL

Particulate Emissions from Typical Light-Duty Vehicles taken from the European Fleet, Equipped with a Variety of Emissions Control Technologies

John May, Dirk Bosteels and Cécile Favre,

Association for Emissions Control by Catalyst (AECC) AISBL
Diamant Building, Boulevard Auguste Reyers 80, Brussels, B-1030 Belgium

Test programmes have been conducted by AECC over the last three years to provide data on the emissions of a range of current and near-future light duty vehicles. The vehicles were selected from those available in the European fleet, but it cannot be claimed that they are necessarily wholly representative of that fleet. In addition to assessment of regulated gaseous emissions, the work has included the measurement of Particulate Mass and Particle Number emissions using the PMP (Particulate Measurement Programme) procedures developed under UNECE – GRPE. This paper provides an overview of these measurements.

Range of vehicles tested and test cycles

The vehicle range tested covers stoichiometric port fuel injection and direct injection petrol vehicles, lean-burn direct injection petrol vehicles, and diesels without and with particulate filters. The latter includes diesel vehicles fitted with systems for the control of both NOx and particulates as well as vehicles from the existing fleet fitted with particulate control systems only. All vehicles were standard production cars and the selection as a whole covered a wide selection of the European market, with engine capacities ranging from 1.2 to 3.5 litres and power outputs of between 60 and 220 kW. The emissions levels of the vehicles covered the technologies used to meet the Euro 3, Euro 4, Euro 5 and Euro 6a- emissions stages. As would be expected, all Euro 5 and 6 diesel vehicles had Diesel Particulate Filters (DPFs).

All vehicles were tested on both the European legislative cycle (NEDC) and the Common Artemis Driving Cycle (CADC) with measurements over the full extent of each of the three CADC elements (urban, extra-urban and motorway). In each case 3 repeat tests were conducted.

Cycle results

For the diesel vehicles, the Particulate Mass (PM) and Particle Number (PN) results clearly showed the effect of vehicles equipped with diesel particulate filters (DPFs). For the Euro 3 and Euro 4 vehicles without DPF, PM emissions were in the range of 20 to 35 mg/km depending on vehicle and cycle – these were within the EU's NEDC limits of 50 mg/km at Euro 3 and 25 mg/km at Euro 4. All vehicles fitted with DPFs gave results below 2 mg/km, comfortably below the Euro 5b/6 limit of 4.5 mg/km. Similarly for PN, emissions for the vehicles without DPFs were in the

range of 5 to 8×10^{13} particles/km, whereas for the range of vehicles fitted with DPF all results, from both NEDC and CADC tests, were below 1×10^{11} particles/km. This compares well with the Euro 5b/6 limit of 6×10^{11} /km. For PM, the results tended to be slightly higher on the combined CADC test than on the NEDC. For PN there was no clear trend, with examples of both higher and lower results on the CADC compared to the legislative test.

The petrol-engined vehicles tested comprised two vehicles with multi-point injections – one a Euro 3 vehicle that had 120 000 km accumulated mileage and the other a Euro 4 vehicle with 60 000 km mileage – and a selection with both lean-burn and stoichiometric direct injection engines, with mileages ranging from 3 000 to 18 000 km. Both of the MPI vehicles were of the same basic engine type, although of course with differences relevant to the change from Euro 3 to Euro 4 emissions levels.

The PM results for these petrol-engined vehicles all gave results below 2 mg/km over the NEDC. Over the CADC, the majority gave emissions below the Euro 5b/6 limit of 4.5 mg/km over the Artemis suite, but two vehicles (the high-mileage Euro 3 MPI car and one of the lean-burn DI vehicles) gave emissions above this level at 5 and 22 mg/km respectively, averaged over 3 tests in each case. For PN, all petrol vehicles tested gave results above 6×10^{11} particles/km, with the majority in the range of 1×10^{12} to 1×10^{13} particles/km. Discussion with the test laboratory suggests that the unusually high PN results from the two MPI vehicles did not result from oil consumption and may relate to the characteristics of the particular engine type.

Additional measurements

In addition to results from the complete test cycles, data on each vehicle is available for the three elements of the CADC and for three parts of the NEDC tests - cold-start 1st + 2nd urban cycles (ECE1+2); 3rd & 4th urban cycles (ECE3+4); and extra-urban cycle, (EUDC). In addition, some of the vehicles were tested from a cold start over the Artemis Urban cycle, which is normally a hot-start cycle. Data was also collected of continuous and cumulative particle number emissions, and for the final set of petrol direct-injection test vehicles, particle number measurements were also made using a TSI EEPS (Engine Exhaust Particle Sizer) in addition to the PMP measurement system. This data allowed a comparison of the PMP particle number data over the PMP size range (d50 of 23 nm to 2.5 µm) with EEPS measurements for ranges of both 5 to 500 nm and 20 to 500 nm. In addition, the EEPS allowed an examination of the size distribution of vehicles during the various test cycles.

PM and PN emissions by test phase

The full set of data shows that in general the highest PM emissions were over the motorway portion of the Artemis suite. However, there were variations between vehicles. For the lean petrol vehicle that gave high PM results on the Artemis suite, for instance, this was almost entirely due to

emissions on the motorway part of the tests (43, 39 and 40 mg/km over the repeat tests) with all other results NEDC and CADC results below 2 mg/km. On the other hand for one of the modern (Euro 6a-) diesel vehicles, all PM emissions were at or below 1.0 mg/km over each test phase, with the highest level (still well below the limit value) over the ECE 3+4 part of the test. PN emissions were not necessarily proportional to PM emissions. The ECE3+4 phase, which resulted in a higher level of PM than the other NEDC and CADC phases for the Euro 6a- diesel (even though still only 1.0 mg/km) gave the lowest PN results of any phase for this vehicle, with emissions of under 7×10^{8} particles/km. On the other had the vehicle which had high PM emissions on the Artemis Motorway phase gave very similar PN emissions on the extra-urban and motorway phases.

Each of the vehicles tested on the cold-start version of the Artemis Urban cycle met the NEDC limit of 4.5 mg/km PM in both the cold-start and hot-start versions of the CADC Urban test. Both the diesel vehicles met the Euro 6 (NEDC) limit for PN in both the cold-start and hot-start versions of the CADC Urban test. For the three DI petrol vehicles, PN emissions were somewhat higher for the cold-start tests than for the hot-start, but within less than 1 order of magnitude.

The continuous and cumulative traces indicate an initial peak of particle emissions at the first acceleration of the NEDC for most of the petrol-engined vehicles. The overall cumulative pattern, though, showed some differences in overall pattern, with some vehicles – notably the older MPI vehicles – showing a marked increase in particles around the highest speed portion of the EUDC.

Particle size distribution

The comparison of the PMP data with that from the EEPS showed good agreement. As might be expected, the lack of a thermal denuder in the EEPS system resulted in higher particle numbers when compared to the condensation particle counter (CPC) figures from the PMP system. The EEPS ranges of 5 to 500 nm and 20 to 500 nm showed comparatively little difference from each other which agrees with the size distribution data indicating that the modal value of particle emissions from all of the cycles is consistent with the majority being accumulation mode particles.

Summary

AECC conducted test programmes measuring PM and PN emissions over the NEDC and CADC (Artemis) test cycles from a range of petrol and diesel vehicles covering the Euro 3 to Euro 6 emissions standards. Data is available on the emissions by test phase, continuous and cumulative particle number emissions and particle size distribution.

Diesel vehicles with DPFs met the Euro 6 PM and PN emissions limits over all cycles. On the NEDC, PN emissions from stoichiometric and lean-burn petrol engines were in the range of 1×10^{12} to 4×10^{12}/km. For the same vehicles on the complete Artemis (CADC) suite, PN emissions ranged from 7×10^{11} to 1.5×10^{13}/km.

Particulate emissions from Euro 3 to Euro 6 light-duty vehicles

John May, Dirk Bosteels, Cécile Favre
AECC, Brussels

15th ETH Conference on Combustion Generated Nanoparticles

Association for Emissions Control by Catalyst AISBL

Association for Emissions Control by Catalyst (AECC) AISBL

AECC members: European emissions control companies

BASF

CORNING

EMITEC

IBIDEN CO., LTD.

JM Johnson Matthey

NGK

NGK Europe GmbH

Rhodia

umicore Automotive Catalysts

Technology for exhaust emissions control on all new cars (OEM and Aftermarket) and an increasing number of commercial vehicles, non-road applications and motorcycles.

Work Programme

- Over the last 3 years AECC has conducted test programmes to provide data on the emissions of current and future light duty vehicles.
- The tests included measurement of particulate mass and particle number emissions using the UNECE-developed PMP procedures.
- All vehicles were tested over the standard EU legislative cycle (NEDC) and over the full Common Artemis Driving Cycles (CADC).

Diesel Vehicles

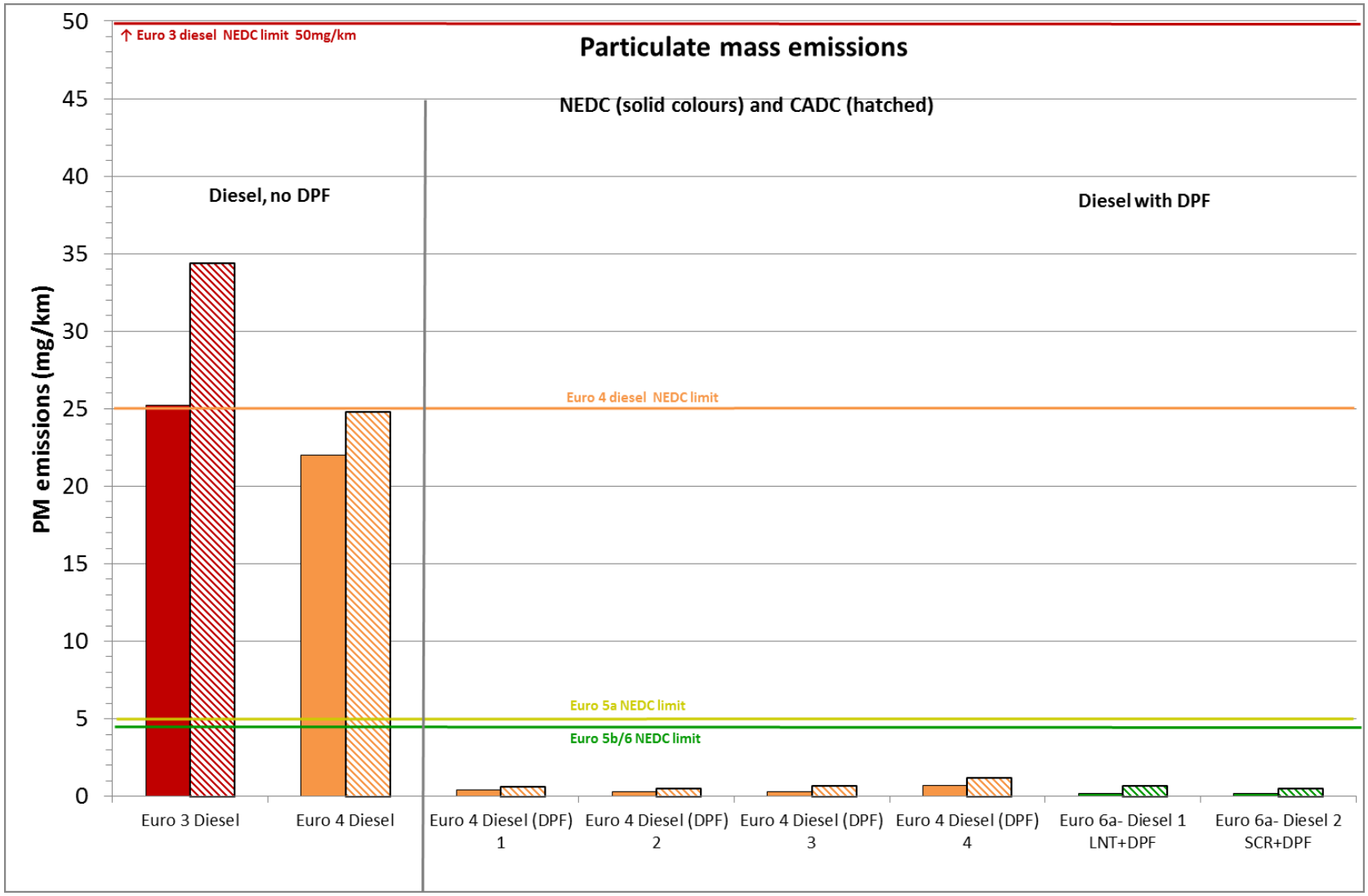
Working Principle	Emission Approval	Engine capacity	Power (kW)	Registration year	Gearbox	Mileage (km)	Date of test
DI diesel, DOC, no DPF	Euro 3	1.9 litre	85	1999	M6	180000	April 2008
DI diesel, DOC, no DPF	Euro 4	1.9 litre	77	2005	M6	45000	June 2008
DI diesel with DOC & DPF, #1	Euro 4	2 litre	100	2005	M6	15500	May 2008
DI diesel with DOC & DPF, #2	Euro 4	2 litre	100	2008	M6	15000	September 2008
Di diesel with c-DPF, #1	Euro 4	1.9 litre	77	2006	M6	61000	August 2008
Di diesel with c-DPF, #2	Euro 4	1.9 litre	77	(2007)	M6	14250	October 2008
DI diesel with LNT+DPF	Euro 6a-	3 litre	180	2009	M6	25000	February 2010
DI diesel with SCR+DPF	Euro 6a-	3 litre	155	2010	AT7	8750	May 2010

DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
c-DPF	catalysed Diesel Particulate Filter
LNT	Lean NOx Trap
SCR	Selective Catalytic reduction

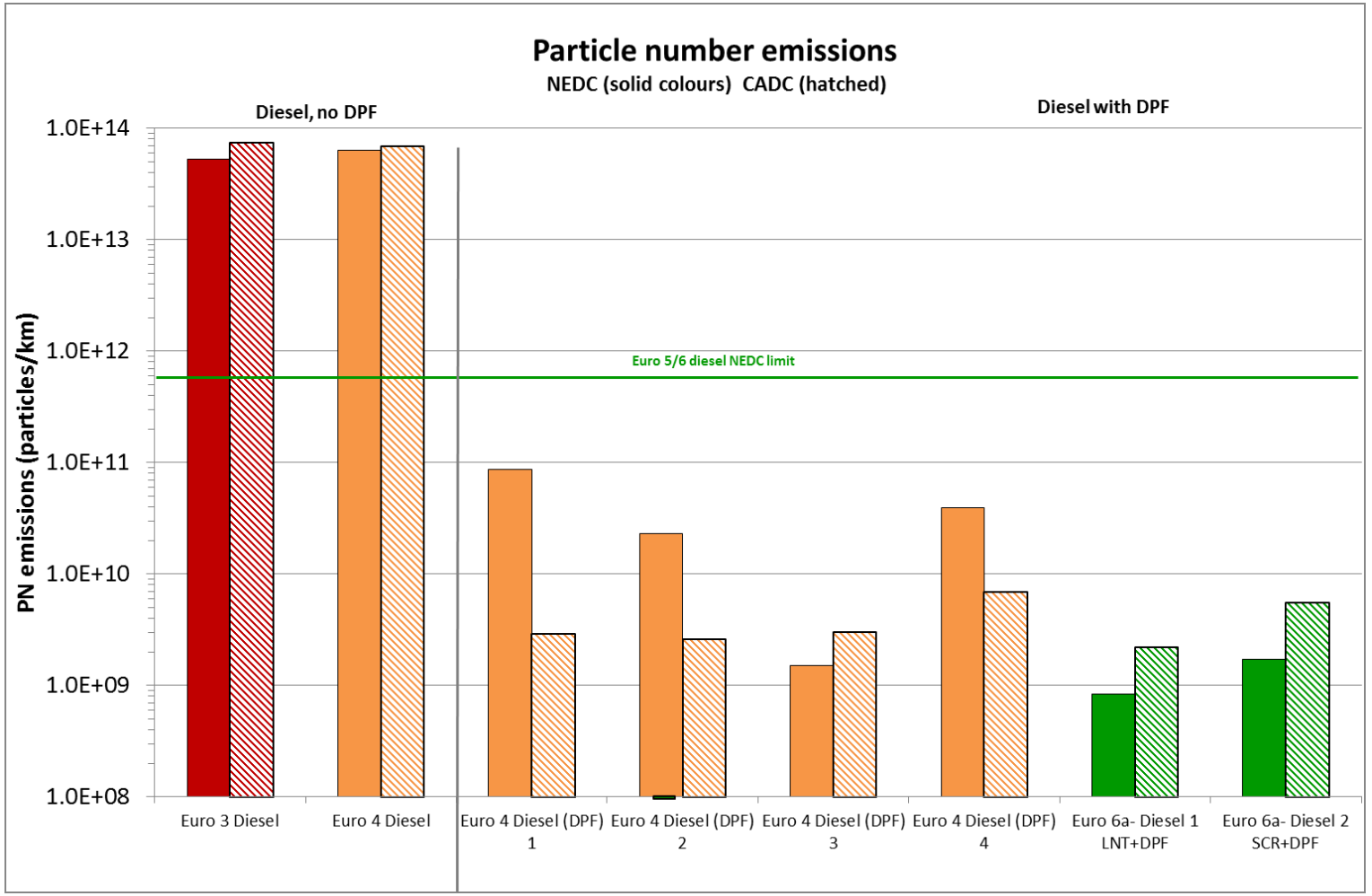
DI	Direct Injection
M	Manual Transmission
AT	Automatic Transmission

following figure is the number of gears

Diesel Vehicles, Particulate Mass



Diesel Vehicles, Particle Number



- All DPF-equipped Diesels show Particle Numbers $<6\times10^{11}$/km.
- No clear trend for PN emissions on CADC compared to NEDC.

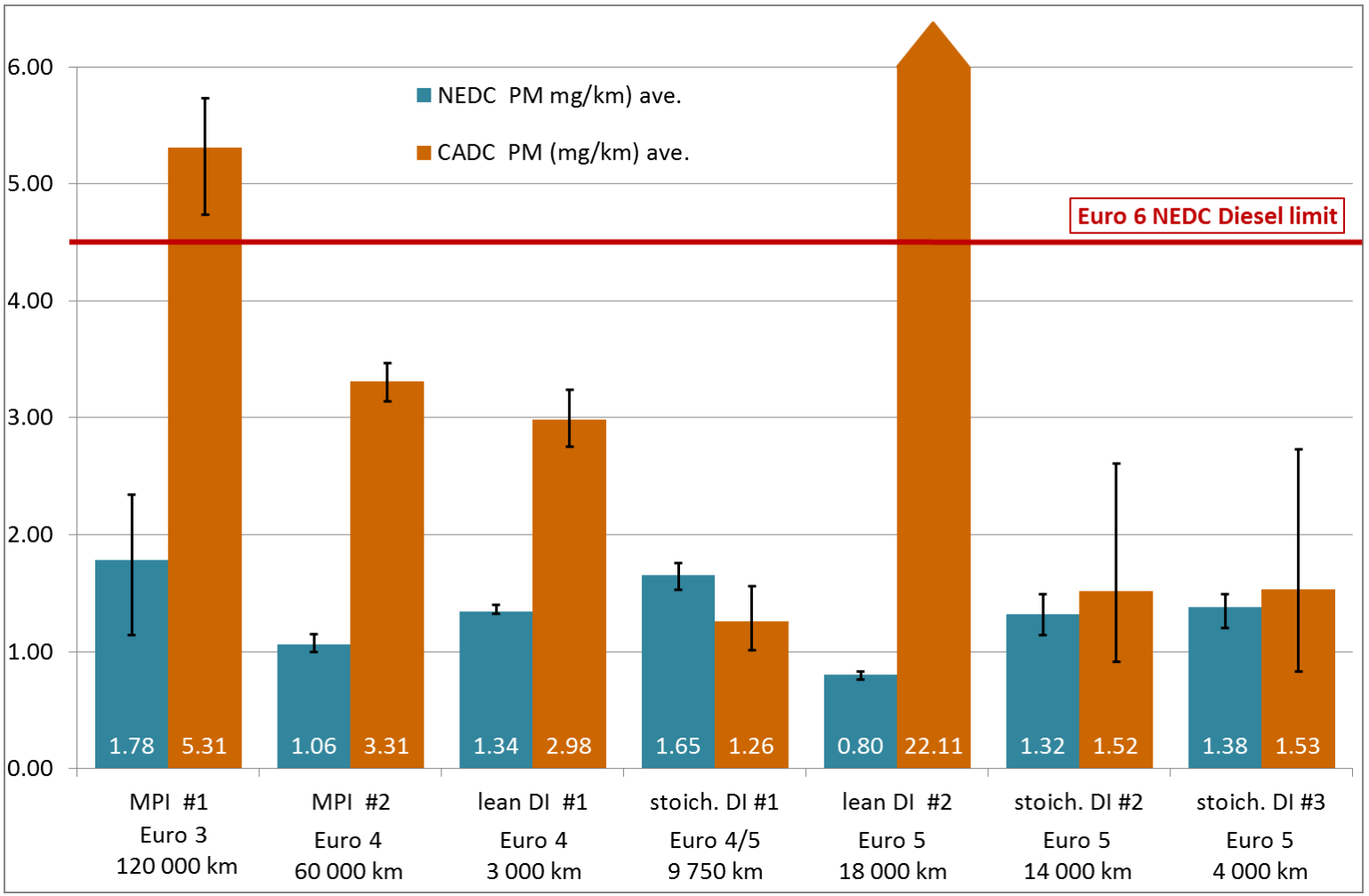
Petrol Vehicles

Working Principle	Engine Capacity	Power (kW)	Emission Approval	Registration year	Gearbox	Mileage (km)	Date of Test
MPI #1	2 litre	85	Euro 3	1999	M5	120000	April 2008
MPI #2	2 litre	85	Euro 4	2001	M5	60000	November 2008
lean DI #1	2 litre	105	Euro 4	2008	M6	3000	Aug. 2008
stoichiometric DI #1	1.4 litre	92	Euro 4 / 5	2008	M6	9750	Nov. 2008
lean DI #2	3.5 litre	215	Euro 5	2009	AT7	18000	Nov. 2010
stoichiometric DI #2	1.6 litre	115	Euro 5	2009	M6	14000	Dec. 2010
stoichiometric DI #3	1.2 litre	63	Euro 5	2010	M5	4000	Jan. 2011

MPI Multi-Point (indirect) Injection
DI Direct Injection

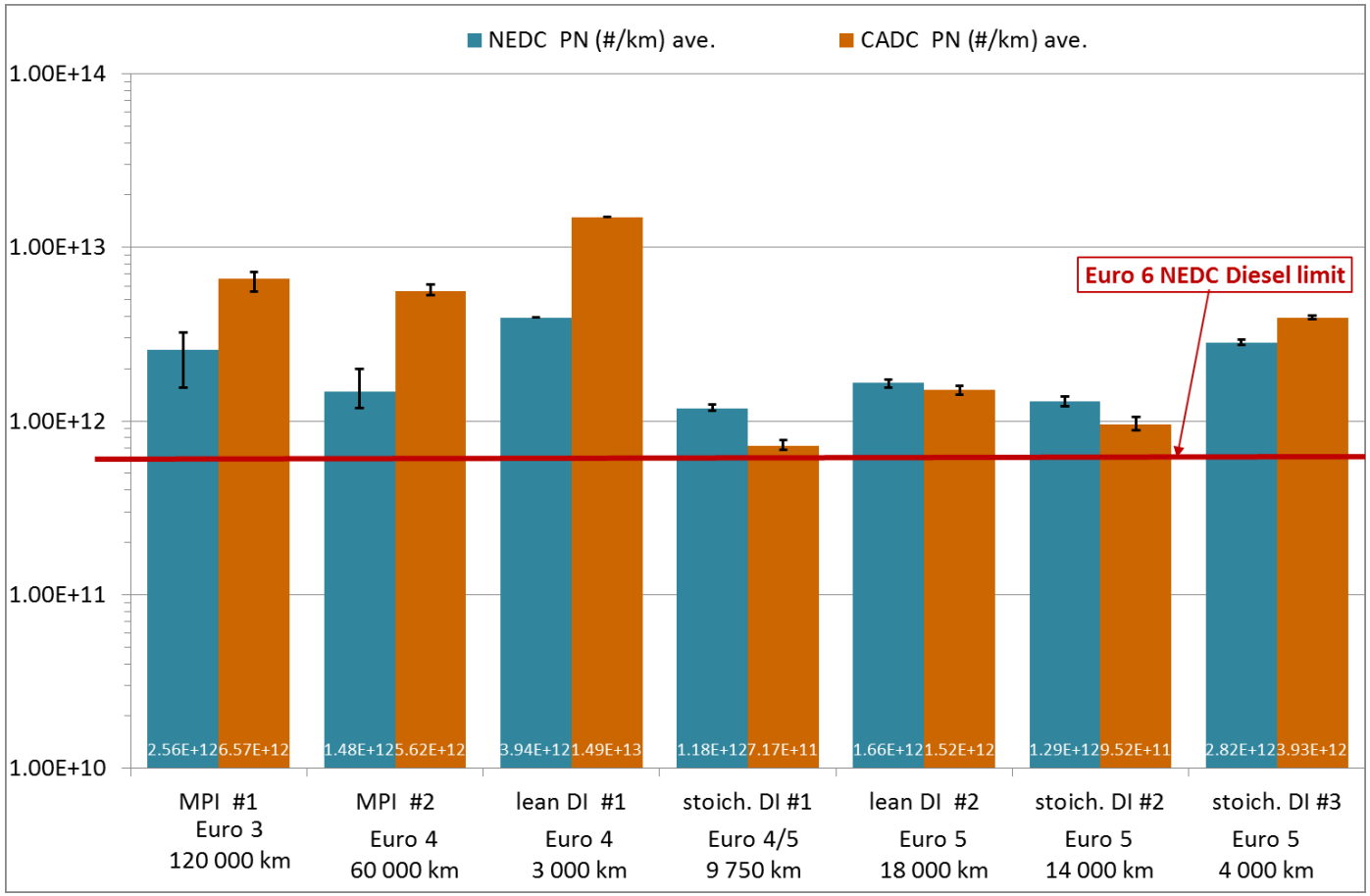
MPI and stoichiometric DI vehicles were equipped with 3-way catalysts (TWC)
Lean DI vehicles were equipped with lean NOx trap (LNT) + TWC

Particulate Mass emissions NEDC & CADC



- For the majority of vehicles, emissions on the Artemis suite are higher than on the NEDC, but the extent of the difference varies.

Particle Number emissions (NEDC & CADC)

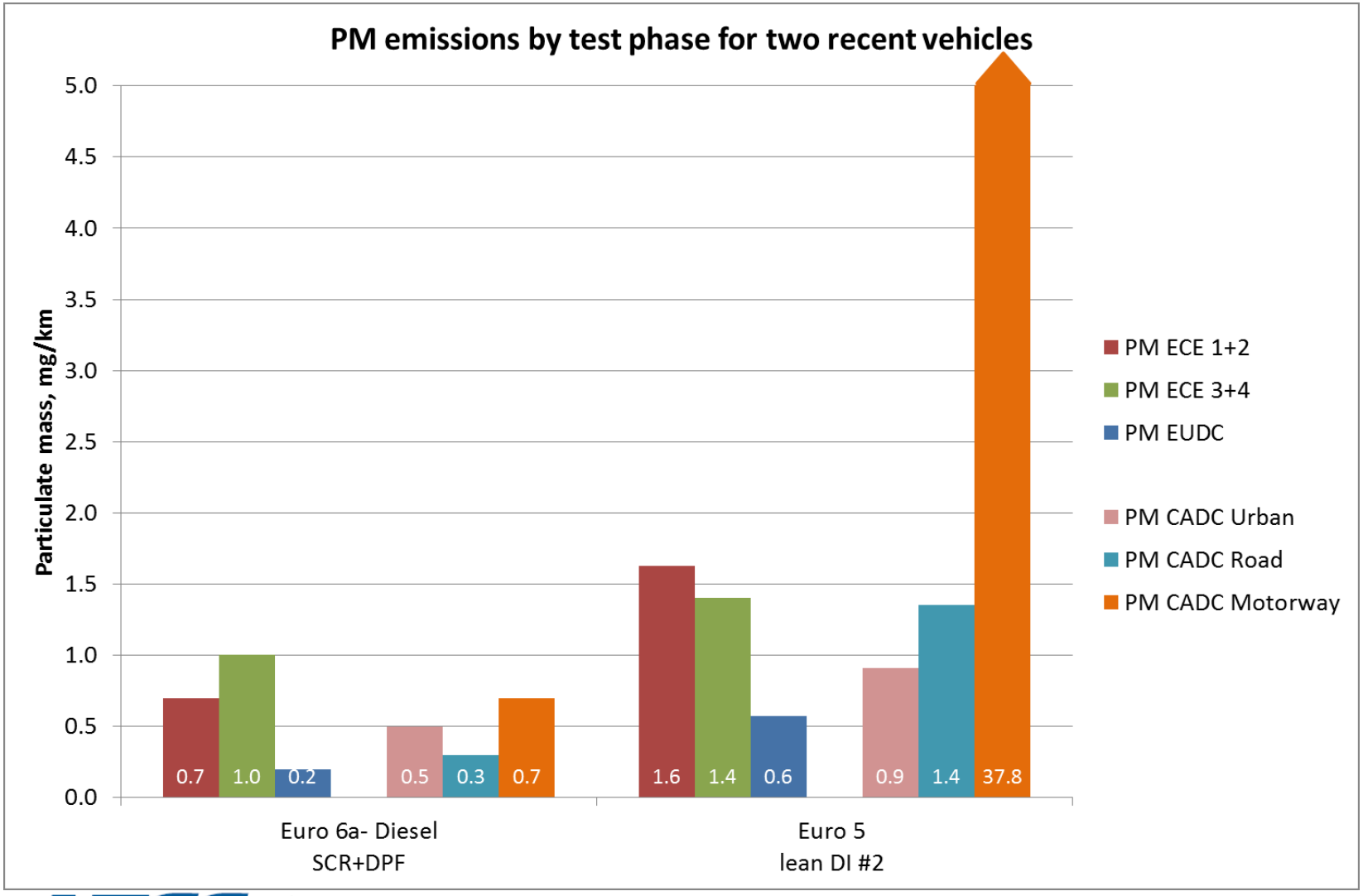


- The high particle numbers for the two MPI vehicles (which had similar engines) are believed to be related to engine characteristics rather than the high mileages.

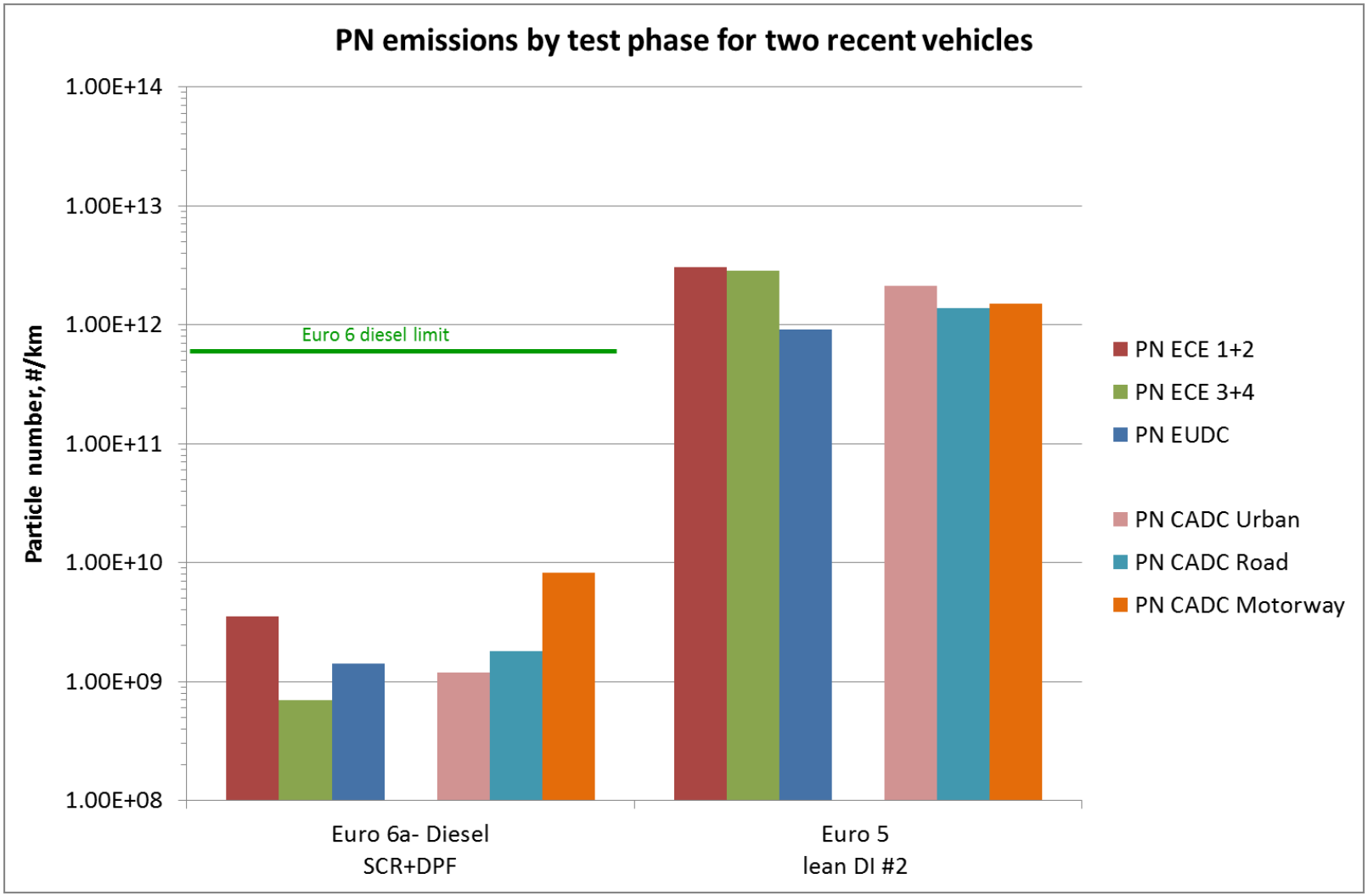
Test regime – additional data

- In addition to full cycle test results, data was collected for ECE 1+2, ECE 3+4, EUDC, and for the full CADC Urban, CADC Rural and CADC Motorway tests.
- CADC tests are hot start, but single cold-start tests (at normal test temperature) are available for vehicles tested towards the end of the programme.
- For the final 3 (DI petrol) vehicles particle size analysis (EEPS) was included.

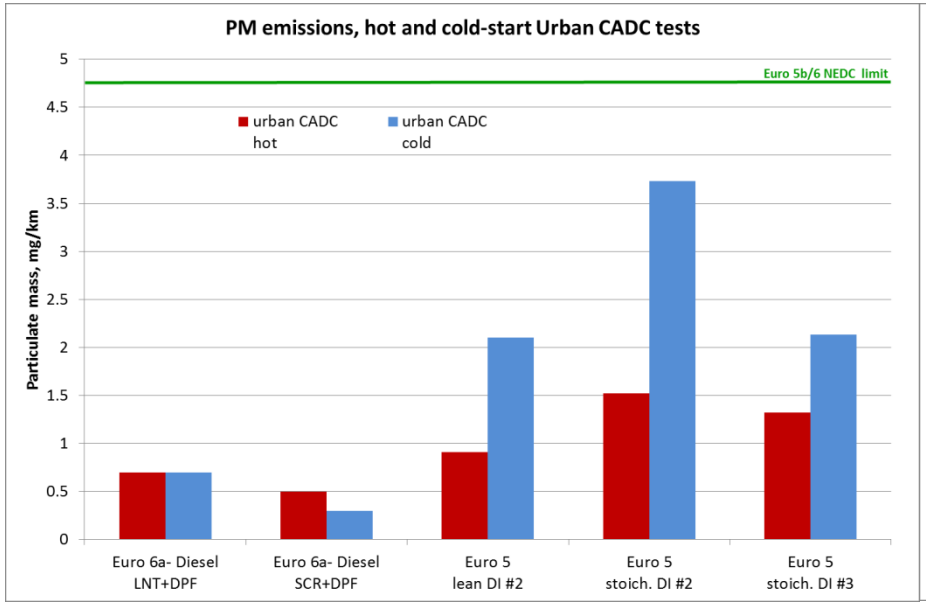
Example of PM emissions by test phase

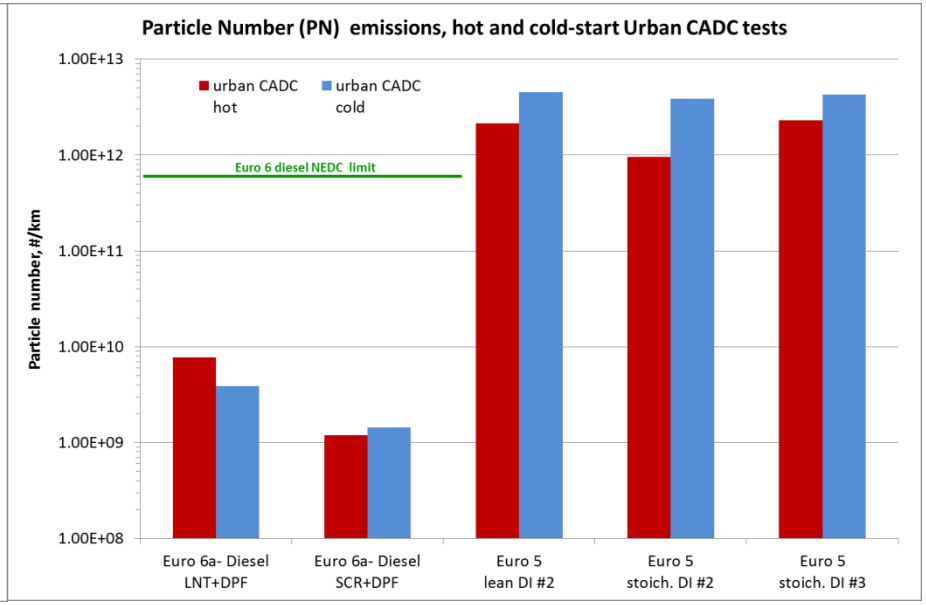


Example of PN emissions by test phase



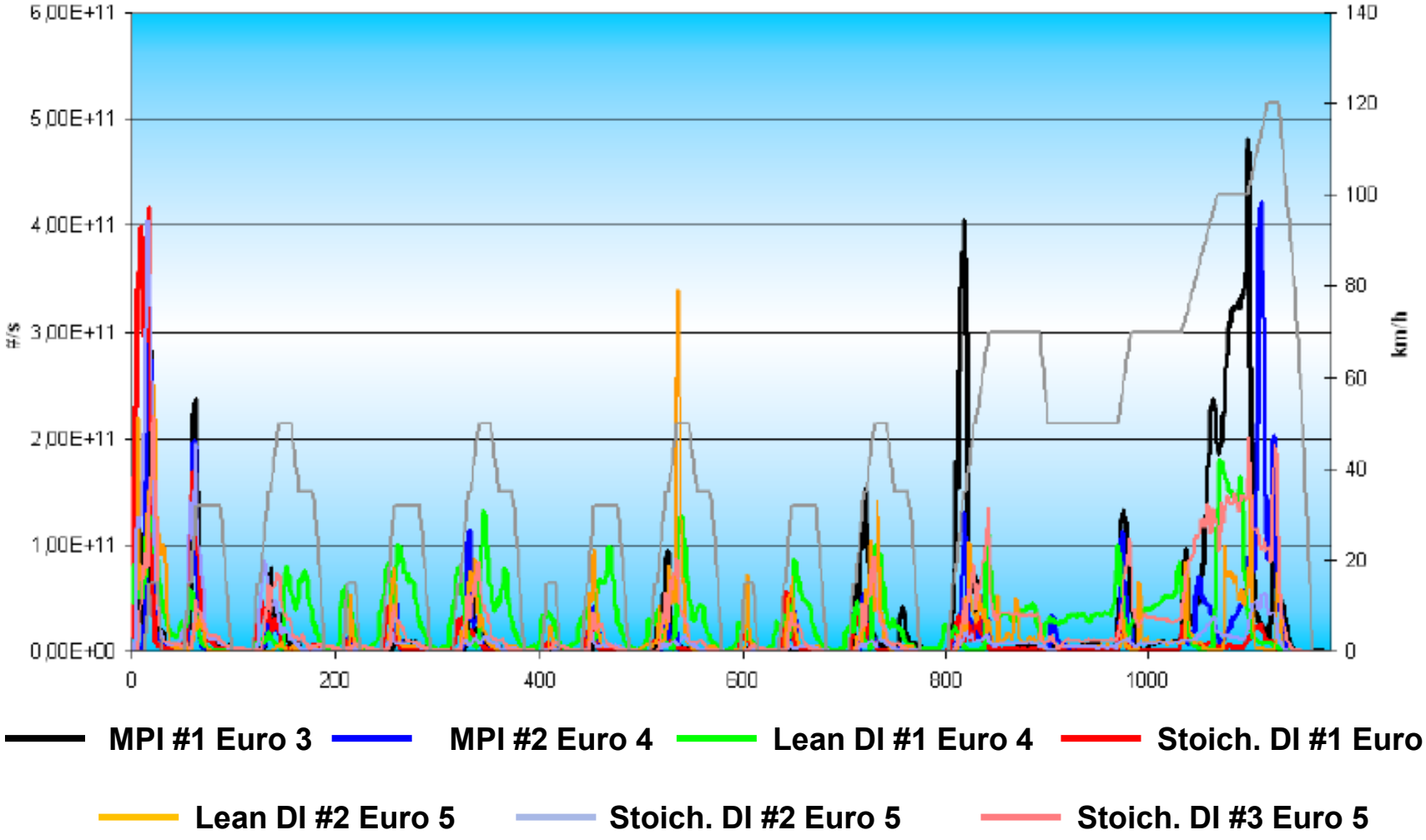
Effect of cold start on the CADC Urban test



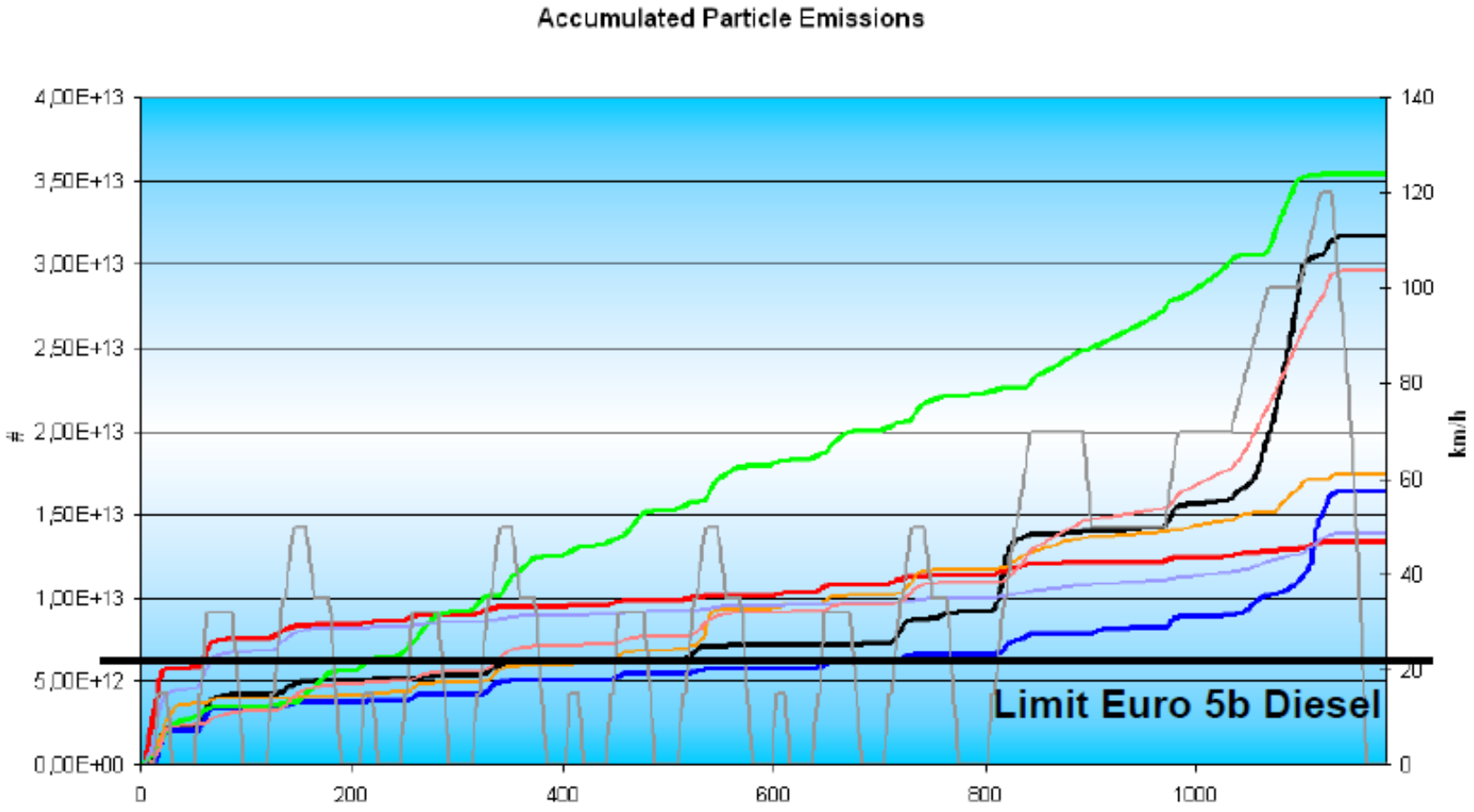


- Each of the vehicles met the NEDC PM limit of 4.5mg/km in both the cold-start and hot-start versions of the CADC Urban test.
- Both the diesel vehicles met the Euro 6 PN limit in both the cold-start and hot-start versions of the CADC Urban test.
- For the three DI petrol vehicles, PN emissions were somewhat higher for the cold-start tests than for the hot-start, but within less than 1 order of magnitude.

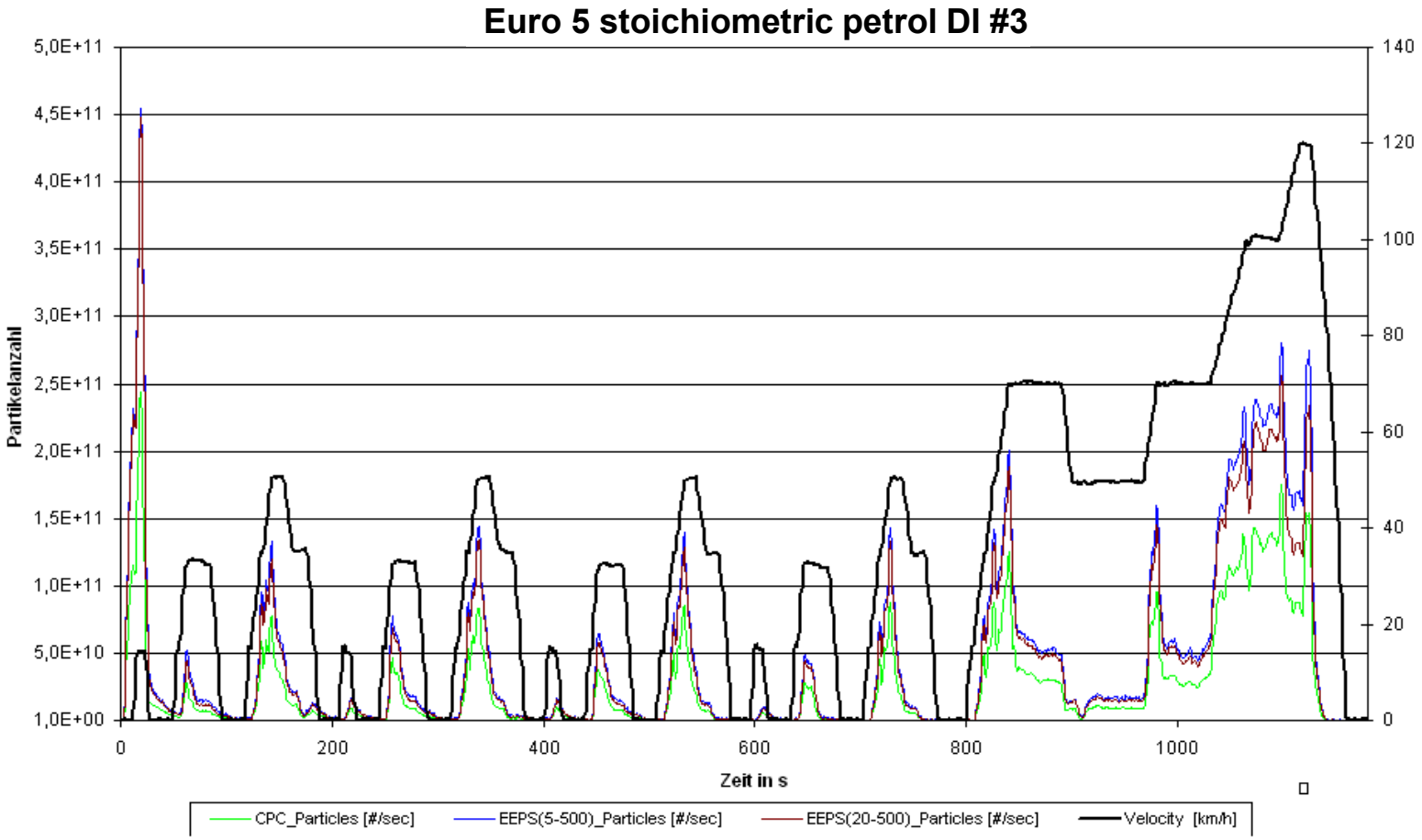
Particle Number emissions for petrol vehicles NEDC continuous data



Cumulative Particle Number emissions for petrol vehicles (NEDC)

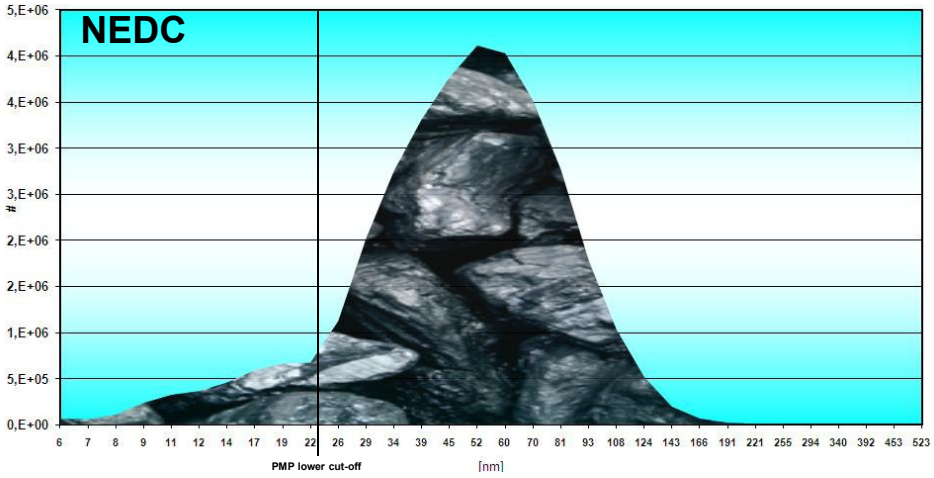


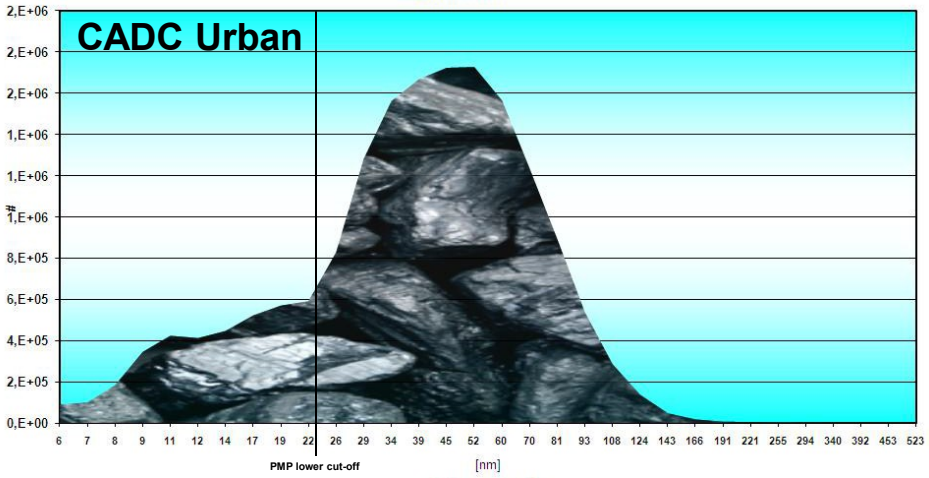
Comparison of PN by CPC and EEPS

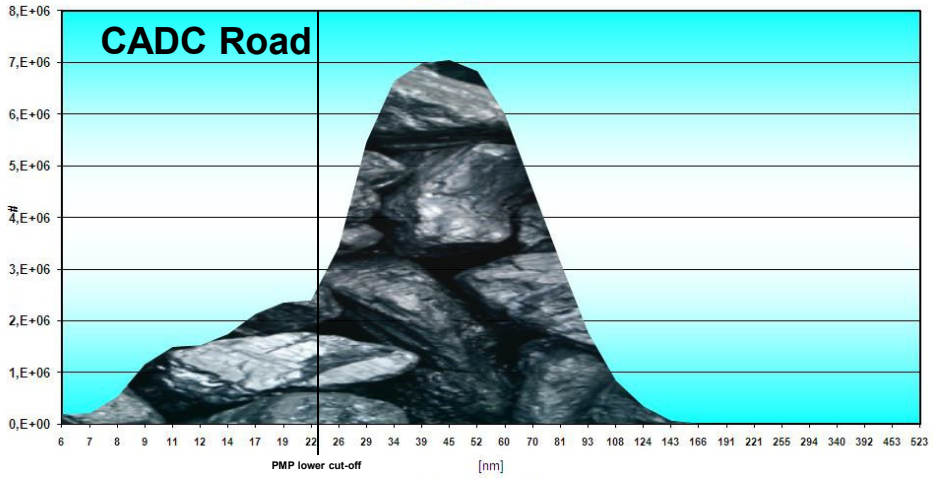


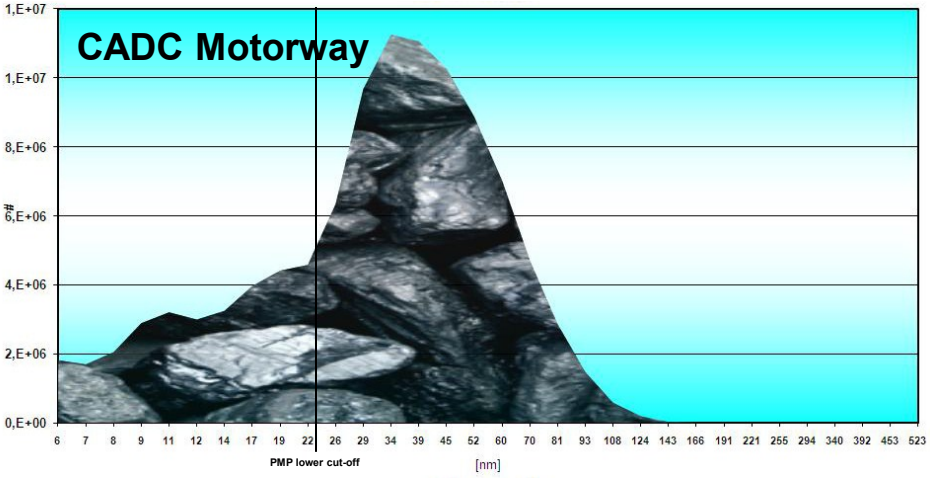
- Note EEPS measures total particles without volatile particle remover

Example of Particle Size Distribution by EEPS





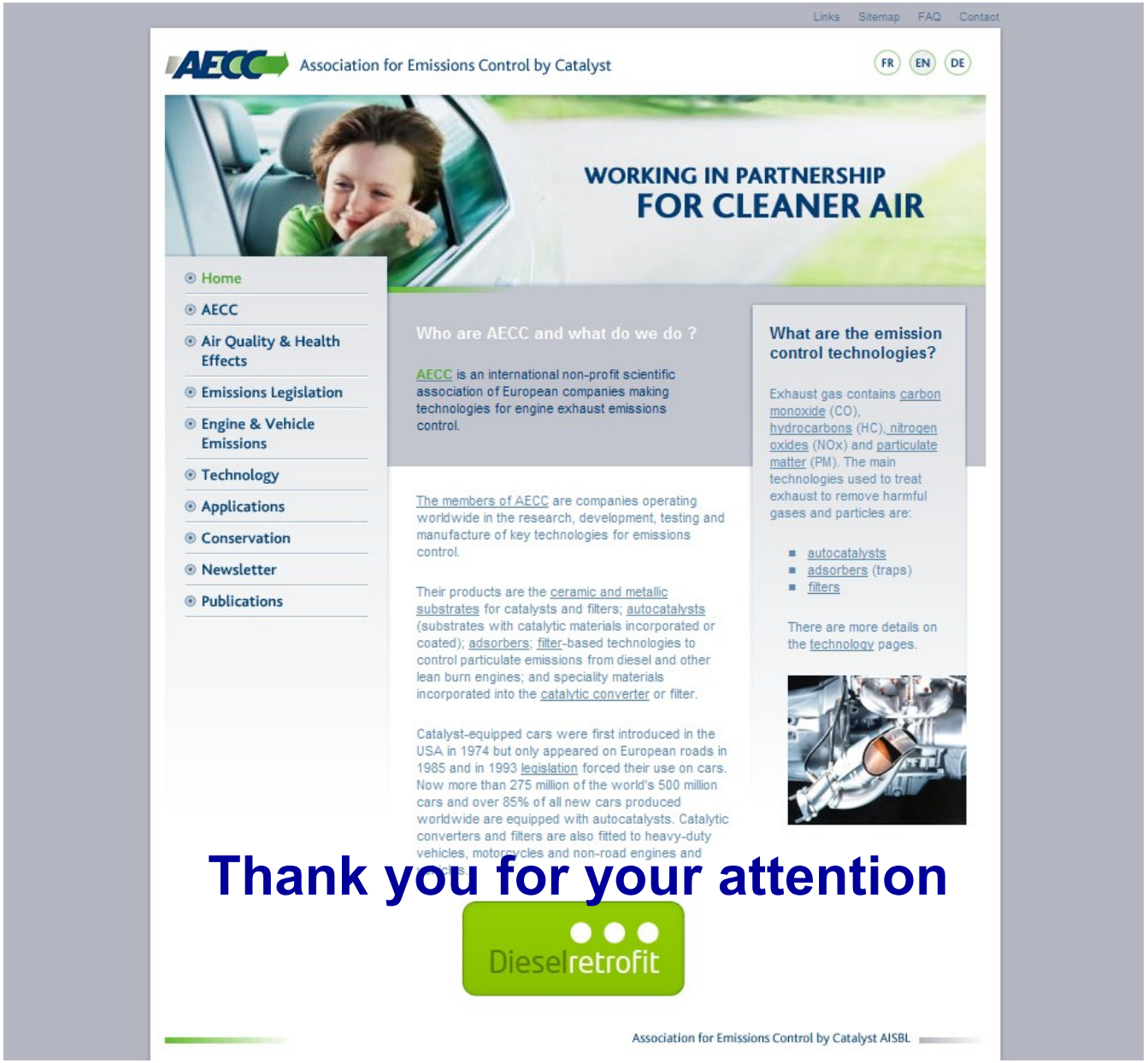




Euro 5 stoichiometric petrol DI #3

Summary

- AECC has conducted test programmes measuring PM and PN emissions over the NEDC and CADC (Artemis) test cycles from a range of petrol and diesel vehicles covering the Euro 3 to Euro 6 emissions standards.
- Diesel vehicles with DPFs met the Euro 6 PM and PN emissions limits over all cycles.
- Data is available on the emissions by test phase, continuous and cumulative particle number emissions and particle size distribution.
- On the NEDC, PN emissions from stoichiometric and lean-burn petrol engines were in the range of 1×10^{12} to 4×10^{12}/km.
- For the same vehicles on the complete Artemis (CADC) suite, PN emissions ranged from 7×10^{11} to 1.5×10^{13}/km.



Thank you for your attention

Dieselretrofit