EMRP ENV02 PartEmission

WP2
Task 2.2
Deliverable 2.2.1

Field measurements with suitable instruments carried out under controlled conditions similar to Type1 type approval testing, using also additional test cycles not foreseen in the legislation

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CONTENT

1 INTRODUCTION

Vehicles are a major source of particulate matter (PM) in urban areas causing adverse health effects. The European legislation regulates the PM emissions from light duty vehicles with the UNECE Regulation No. 83 setting limits for the emitted mass and number of particles per kilometer. With the entry into force of the particle number (PN) limit for compress injection (diesel) light duty vehicles (September 2011), all diesel vehicles are equipped with Diesel Particulate Filters (DPF) which assure the compliance with the new PN limit leading to considerable reduction of particulate emissions from modern diesel vehicles.

The regulated measurement principles for type approval test in Europe are the gravimetric collection of particles of filter (for PM) and the detection of particles typically in a Condensation Particle Counter (CPC). In addition, in order to measure only the non-volatile fraction of the particles, a pre-conditioning unit is coupled with the CPC, which removes the volatile fraction through a hot dilution and an evaporation tube kept at least at 300°C.

Currently the regulation requires that the periodic emission control of the emission of diesel vehicles is performed with an opacimeter [1]. The opacimeter is an instrument based on the measurement principle of light extinction; however modern diesel vehicles (equipped with DPFs) emit a concentration of particles which is often below to the detection limit of instruments based on light extinction.

The aim of the EMRP ENV02 "PartEmission" Work package 2 "*Evaluation of measuring methods for particle emission from modern diesel vehicles in periodic emissions control*" is to develop a metrological background for validation of novel instruments measuring the concentration of combustion particles in exhaust gases from diesel vehicles, which can be used for the regulatory periodic emissions control of vehicles. In Task 2.1, the available prototypes and potential future measurement principles were summarized and aligned with specific requirements concerning periodic emission control [2,3]. Task 2.2 is the trial of the suitable instruments, determined in task 2.1, in field tests and their comparison with the current standards. This report summarizes the actions of the project partners aimed to test the novel instruments for periodic emission control on a vehicle chassis dynamometer under controlled conditions similar to the type-approval testing. The first section of the report will describe the experimental setup at JRC, presenting the test vehicles, the dynamic driving cycles that have been applied and the current standard for particle measurement at the chassis dynamometer. The second part of the report will show the experimental results obtained on the chassis dynamometer, directly comparing the results of the novel instruments with the standard particle measurement system as defined in the type-approval EC regulation. The results of this report fulfill the deliverable 2.2.1 of ENV02 "PartEmission".

2 EXPERIMENTAL SETUP

The comparison of the novel instruments for periodic emission control with the current standard for particle emissions have been performed at the chassis dynamometer of the Vehicle Emission LAboratory (VELA1) at JRC. The following sub-sections will describe the test vehicles, the test cycles and the reference instrument.

2.1 Test vehicles

Two vehicles were tested at JRC: Fiat 500L (Test Vehicle 1) and Peugeot 508 (Test Vehicle 2), both compression engine vehicles equipped with Diesel Particulate Filter (DPF) and compliant to the Euro 5B emission standards. The vehicle registrations are reported in Annex A.

Figure 1: Fiat 500L and Peugeot 508 during tests in Vela1 at JRC.

2.2 Test cycles

The following 4 test cycles have been applied at the chassis dynamometer on both vehicles

1. *New European Driving Cycle (NEDC)*
2. *Worldwide harmonized Light vehicles Test Cycle (WLTC)*
3. *Repeated accelerations*
4. *Steady states*

The NEDC is the current type I approval cycle, while the WLTC is the suggested cycle for the world harmonized light duty procedures. The repeated acceleration consisted of 5 accelerations from 0 to 50 km/h, while the steady states were performed at 120 and 130 km/h for about 200 seconds. In between of the two steady states the speed was reduced to 50 km/h for about 150 seconds. The speed profiles of the test cycles 1, 2, 3 and 4 are shown in Figure 2.

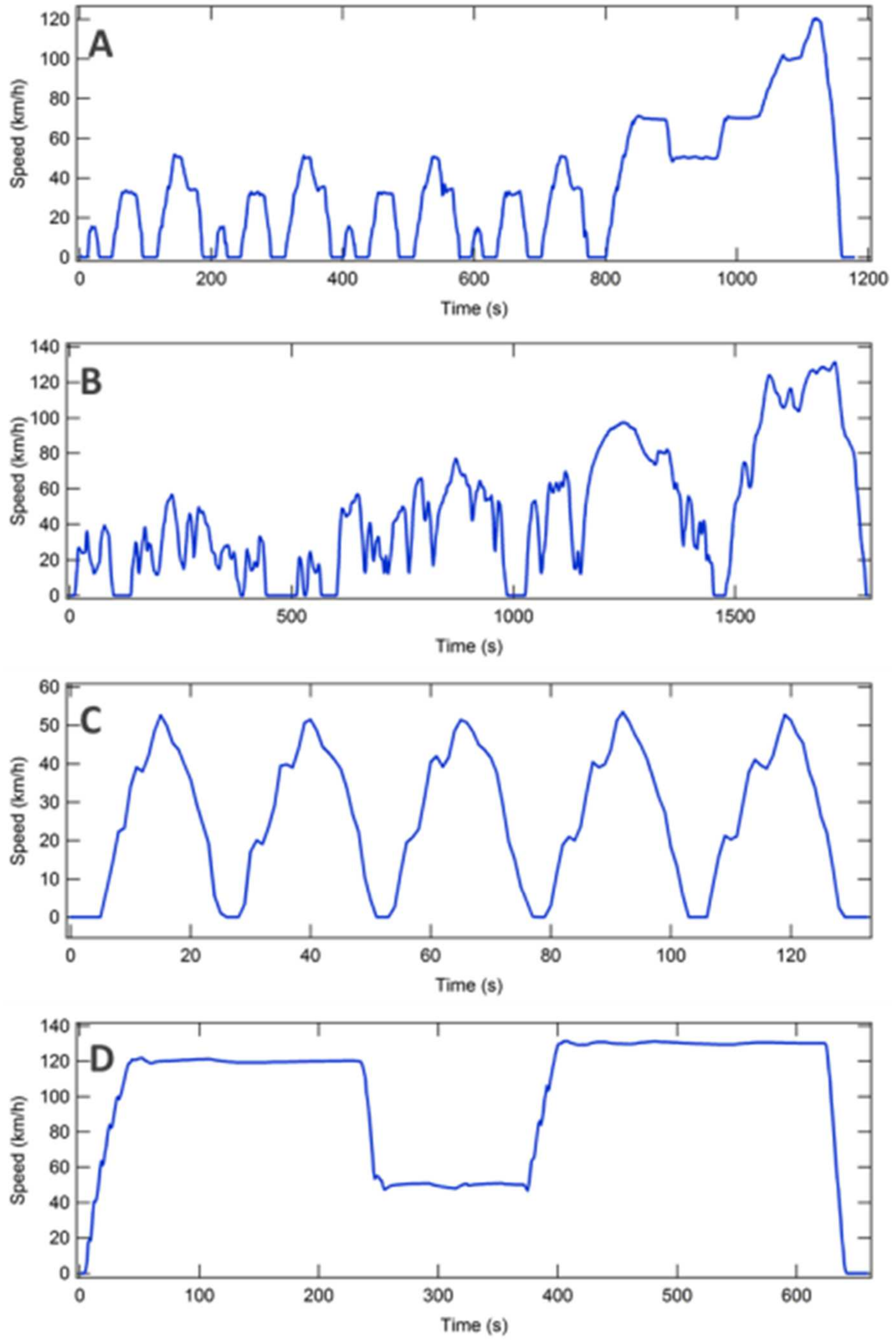


Figure 2: Recorded speed profiles of NEDC (A), WLTC (B), repeated accelerations (C) and steady states (D) cycles.

2.3 Instruments and sampling system

The six instruments identified in the laboratory test phase [2] as suitable for periodic emission control were connected in parallel to the tailpipe by means of a multi-probe connector (see Figure 3). Each sampling probe of the connector consists of a 8 mm multi-hole probe inside the extension of tailpipe.

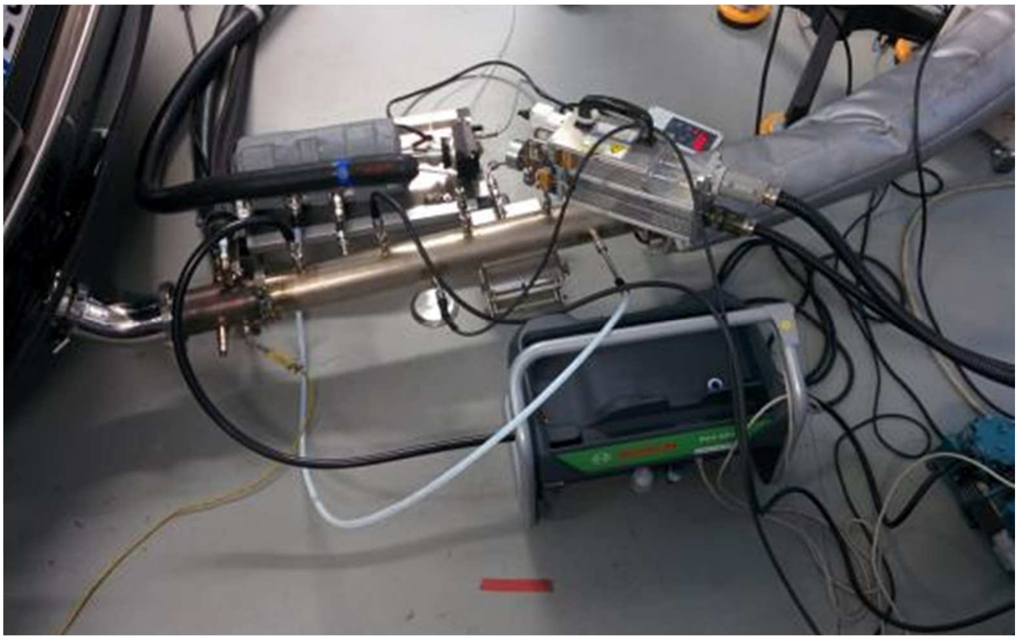


Figure 3: Parallel sampling from the tailpipe and connection hose to CVS.

The operating principles of the candidate instruments and the metrics are reported in Table 1.

Instrument		Operating principle	Reported metric		
			Mass	Number	Opacity
Candidate instruments	L1	Light scattering	x		x
	L2	Light scattering	x		x
	L3	Light scattering	x		x
	DC1	Electrical charging & sensing	x	x	
	DC2	Electrical charging & sensing	x	x	
	IC	Ionization chamber	x	x	

Table 1: Operating principles and metrics of the candidate instruments

The chassis dynamometer test cell at VELA is equipped with instruments for gas and particles measurement compliant with the UNECE Regulation 83 [4]. Since the test vehicles are compliant with the standard Euro 5B, the most suitable metric to assess the very low particulate emissions is the particle number emission rate. The instrument compliant with the regulation according to Particle Measurement Programme (PMP) installed in VELA is the APC (AVL), this instrument was sampling at the Constant Volume Sampler (CVS) dilution tunnel as defined in Regulation 83. The particle number concentration provided by this device will be the reference value for the periodic emission control instruments. Another PMP compliant reference instrument (NanoMet-C from Matter Aerosol) was installed at the tailpipe of the vehicles inside the test cell in parallel to the periodic emission control instruments.

While all instruments were sampling at 1 Hz, the comparison between the novel instrument and the reference PMP particle counter is presented as averaged distance specific emission rates (#/km). The choice of this type of metric is due to the fact that it is not possible to compare the second by second results due to the not constant time delay between the measurement performed at tailpipe and the measurement performed at CVS. Indeed the

time delay changes as a function of the exhaust flow rate. Moreover, the different time responses of the candidate instruments based on different working principles would increase the uncertainty relative to the second by second comparisons.
In order to calculate the distance specific emission rates (#/km) the values (per unit of volume) reported by the different devices have to be multiplied by the exhaust flow rate. In VELA1 the exhaust flow rate is calculated with the difference of total and dilution air flow rates.
Two of the light scattering instruments (L2 and L3) did not show any value different from zero during the tests. The reason is that the light scattering instruments are built to cover the full range on opacity values, from values typical of Euro 3 diesel vehicles to values typical of Euro 5/6 diesel vehicles equipped with DPF, resulting close to their detection limit in the latter case. During real operation of this type of devices it would be beneficial for the user to know in advance if the instrument is performing properly even in case of vehicles compliant with emission standard Euro 5/6 by means of a functionality check performed prior to the beginning of the test. Otherwise the operator is left with the doubt that a zero value is not due to the very low emission rates but due to malfunctioning of the instrument itself.
The measurement performed with light scattering L1 instrument provides the mass concentration based on the scattered light and the calibration factor of the manufacturer. In order to convert the mass concentration to number concentration a constant factor was applied. The factor used for L1 was $2 \cdot 10^{12}$, this factor was applied to the concentration provided in mg/m^3 in order to obtain the results in particles/m^3 [5]. DC1, DC2 and IC directly provide number concentration deriving from manufacturer calibration. We will compare the results expressed in #/km as provided by the manufactures as well as the scaled results applying the conversion factors deriving from the best fit to the reference results; In the latter case we will assess only the variability of the results of devices under tests and not their accuracy that was evaluated during the laboratory tests.

3 RESULTS

Figure 4 reports the distance specific emissions in particles per kilometer during the test cycles for both test vehicles measured by the four devices under tests. These devices are compared to the reference concentration provided by the AVL Particle Counter (PMP compliant system) which was sampling at CVS. In addition Figure 4 reports the particle emissions measured by a PMP compliant system sampling at tailpipe and the emission standard Euro 5b of $6 \cdot 10^{11}$ #/km (black dashed line).

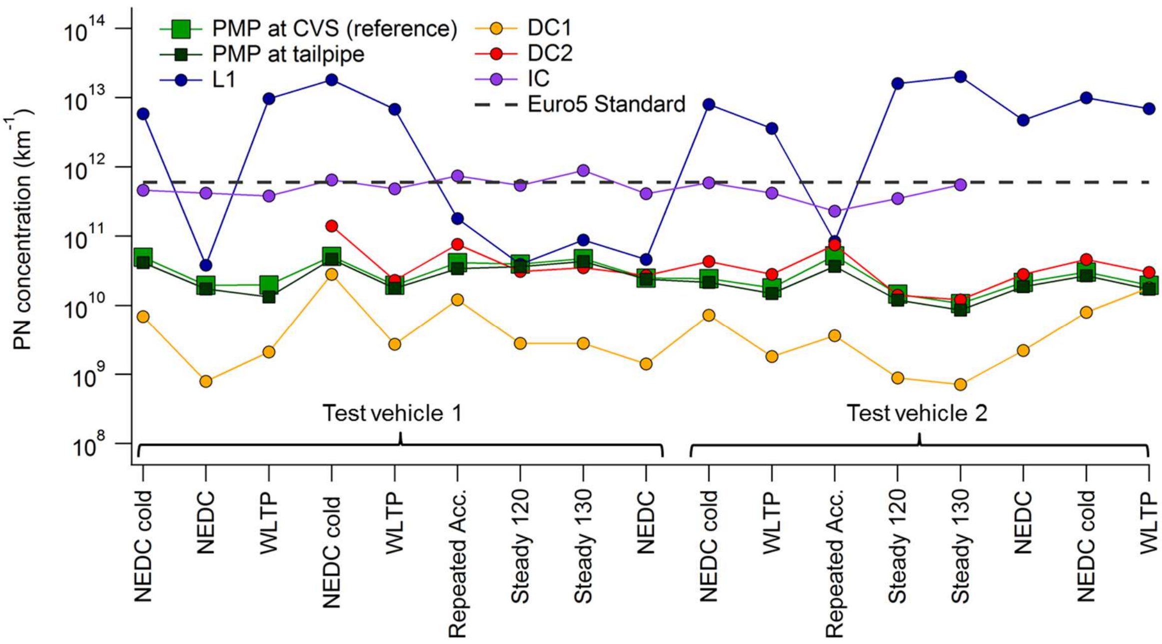


Figure 4: Comparison of the distance specific PN emissions measured by the reference instrument (AVL Partcile Counter PMP compliant at CVS), a PMP compliant particle counter at tailpipe (Nanomet-C, Matter Aerosol) and the devices under test (L1, DC1, DC2 and IC) for both tested vehicles.

The PMP compliant particle counters (sampling at CVS and at tailpipe) are reported in green; These two instruments track each other very well with an average deviation of 20% and maximum deviation of 50%, giving us an indication of the acceptable variability between CVS and tailpipe measurements with PMP compliant particle counters. The DC2 instrument is the one that match better the PMP systems. While DC1 underestimates the PMP systems, IC overestimates the PMP devices. Finally the L1 instrument shows variable results from close to the PMP systems to great overestimation of the PN concentration. The average measured PN concentration and the corresponding standard deviation for vehicle 1 and vehicle 2 are given in Tables 2 and 3 respectively for all measuring instruments.

Table 2: Average and standard deviation of the PN concentrations measured by the PMP system measuring, the PMP system measuring at CVS and the candidate instruments for vehicle 1.

	Average (#/km)	**St. Dev. (#/km)**
PMP CVS	3.71E+10	1.48E+10
PMP TP	3.08E+10	1.19E+10
L1	4.45E+12	6.12E+12
DC1	6.54E+09	8.64E+09
DC2	5.53E+10	4.54E+10
IC	5.52E+11	1.75E+11

Table 3: Average and standard deviation of the PN concentrations measured by the PMP system measuring, the PMP system measuring at CVS and the candidate instruments for vehicle 2.

	Average (#/km)	**St. Dev. (#/km)**
PMP CVS	2.38E+10	1.28E+10
PMP TP	1.75E+10	1.02E+10
L1	8.68E+12	6.65E+12
DC1	5.27E+09	5.77E+09
DC2	3.44E+10	2.02E+10
IC	4.29E+11	1.46E+11

The comparison of the time series concentrations measured with the PMP system sampling at tailpipe and the reference PMP system sampling at CVS during a WLTC test is provided in Figure 5: At low particle concentrations (~$2\cdot10^6$ #/s) the PMP sampling at CVS detects more particles than the PMP system sampling at tailpipe, the reason is due to the background concentration of particles in the CVS. These deviations occur only in the lowest particle emission range, hence do not affect the distance specific emission rates reported in Figure 4 which are averaged over the whole test cycle. On a second to second time scale the instrument sampling at tailpipe shows a larger number of spikes than the instrument sampling at CVS (at both high and low particle concentrations), this is due to the fact the CVS acts as a mixer and smooth off the particle concentration values. This highlights the fact that the comparison of results deriving from instruments measuring at different sampling points is not straightforward and should carefully take into account, smoothing effects and time delay.

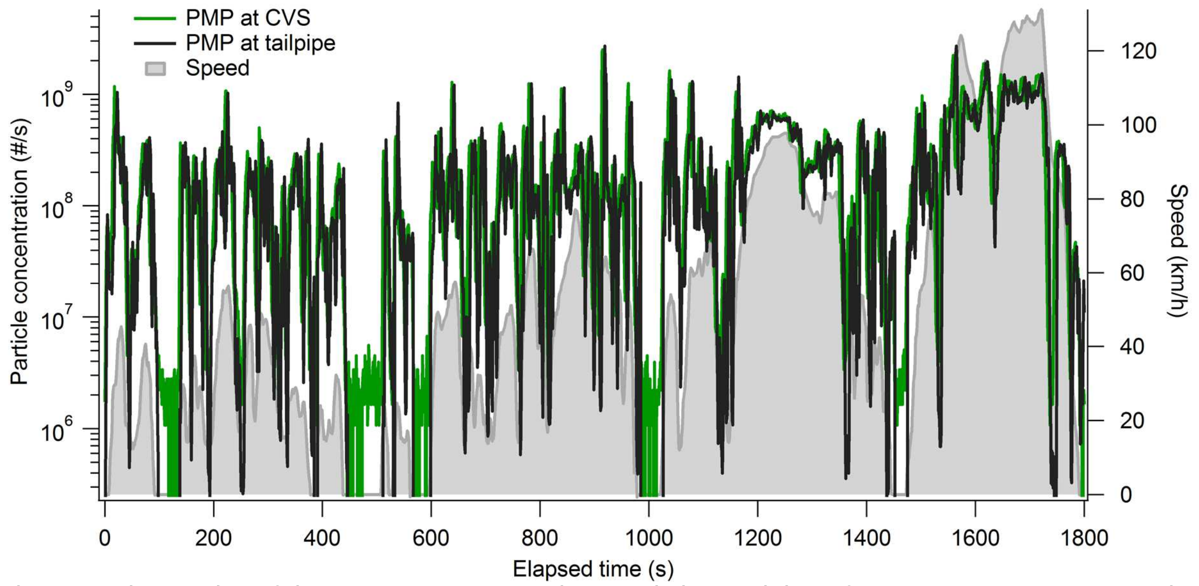


Figure 5: Time series of the PMP system sampling at tailpipe and the reference PMP system sampling at CVS for a WLTC test. The speed is reported in grey on the right-hand scale.

Figures 6 to 9 report the time series measured with the four candidate instruments measuring at tailpipe and the time series of the reference PMP system sampling at CVS for a WLTC. L1 results in accordance with the reference instrument only during the sections of the cycles with emissions ranging between 10^8 and 10^9 #/s, for the other parts either underestimates the emissions measured by the reference or dramatically overestimates them of about 3 orders of magnitude (Figure 6); this is reflected in the very high distance specific emissions of L1 in Figure 4. DC1 underestimates the reference values and it presents a noisier signal compared to the reference PMP system (Figure 7), the reason is the high dilution ratio (DR) used for the tests (DR=100) that reduced the signal-to-noise ratio.

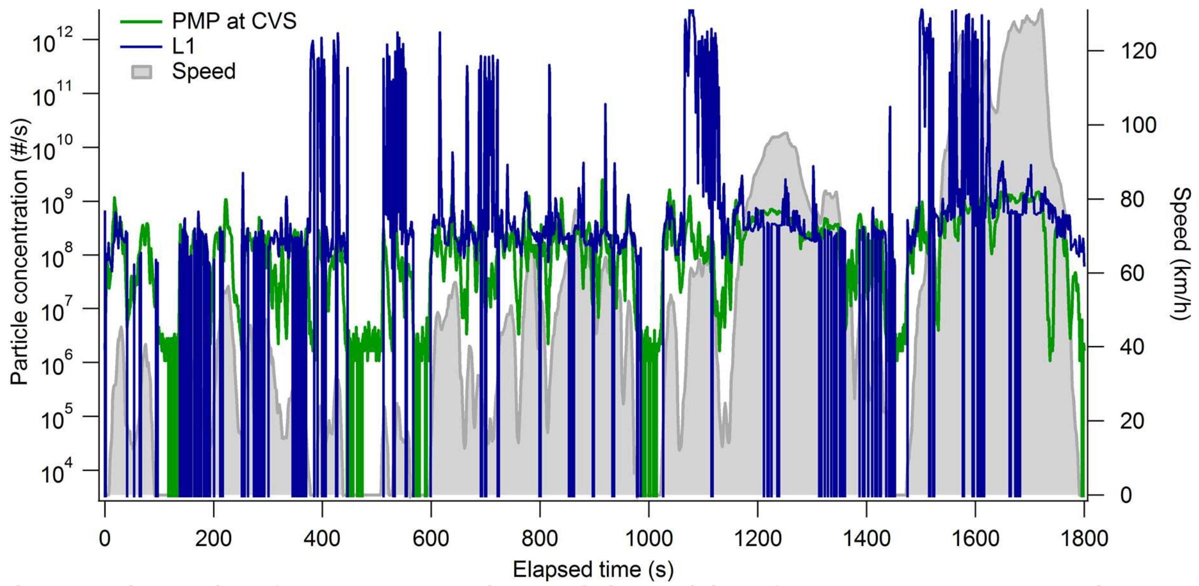


Figure 6: Time series of L1 system sampling at tailpipe and the reference PMP system sampling at CVS for a WLTC test. The speed is reported in grey on the right-hand scale.

The DC2 device is the one that better matches the reference PMP instrument at tailpipe (Figure 8). The accordance with the reference instrument for all the tests cycles is shown in Figure 4, where the DC2 (red line) is the closer to the reference instrument throughout the tests (the first three tests are missing due to a delay in the delivery of the device).

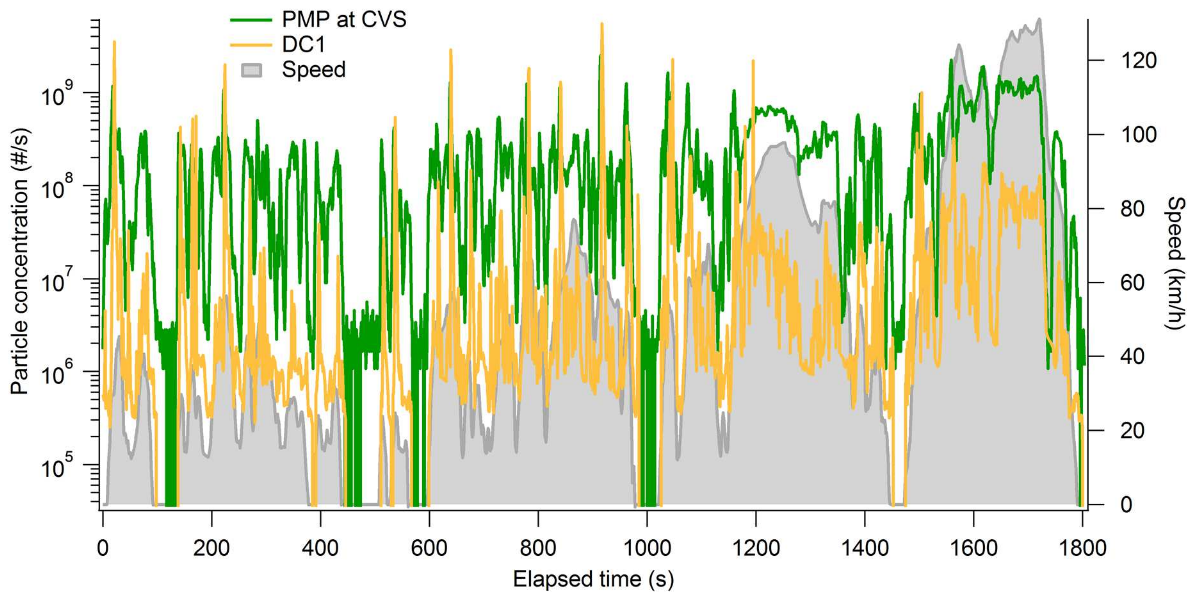


Figure 7: Time series of DC1 system sampling at tailpipe and the reference PMP system sampling at CVS for a WLTC test. The speed is reported in grey on the right-hand scale..

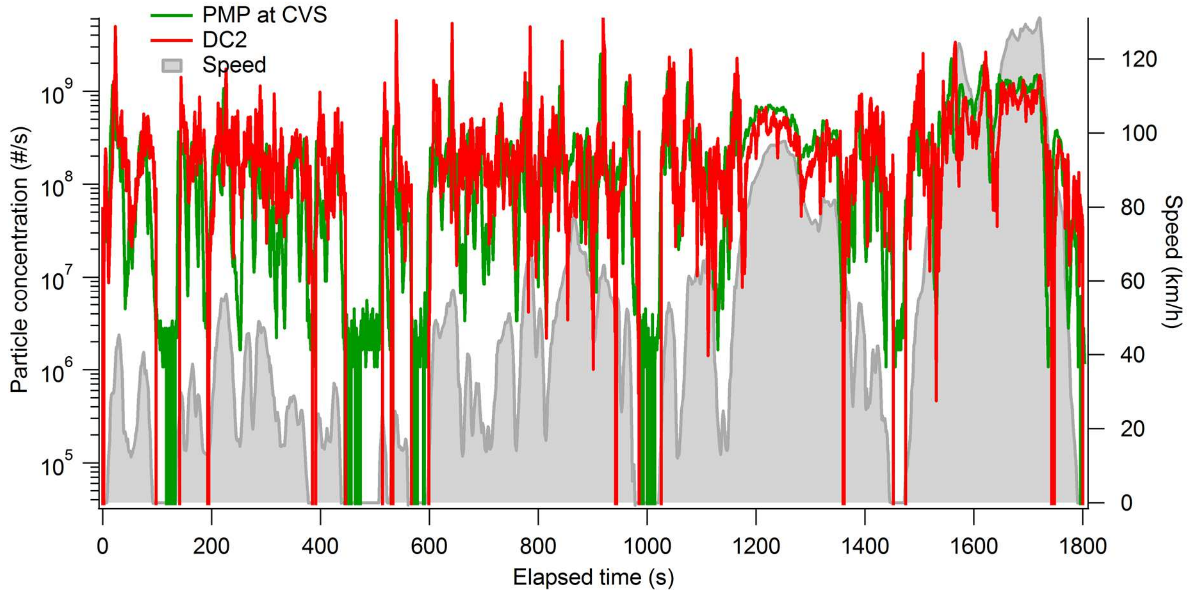


Figure 8: Time series of DC2 system sampling at tailpipe and the reference PMP system sampling at CVS for a WLTC test. The speed is reported in grey on the right-hand scale.

IC measured concentrations of more than one order of magnitude higher than the reference instrument together with a narrowed dynamic range limited between 10^9 and 10^{10} #/s (Figure 9). It should be noted that the deviation from the reference instrument consists of a rather constant offset through the cycle; Recalibration of the device would improve the agreement with the reference PMP system..

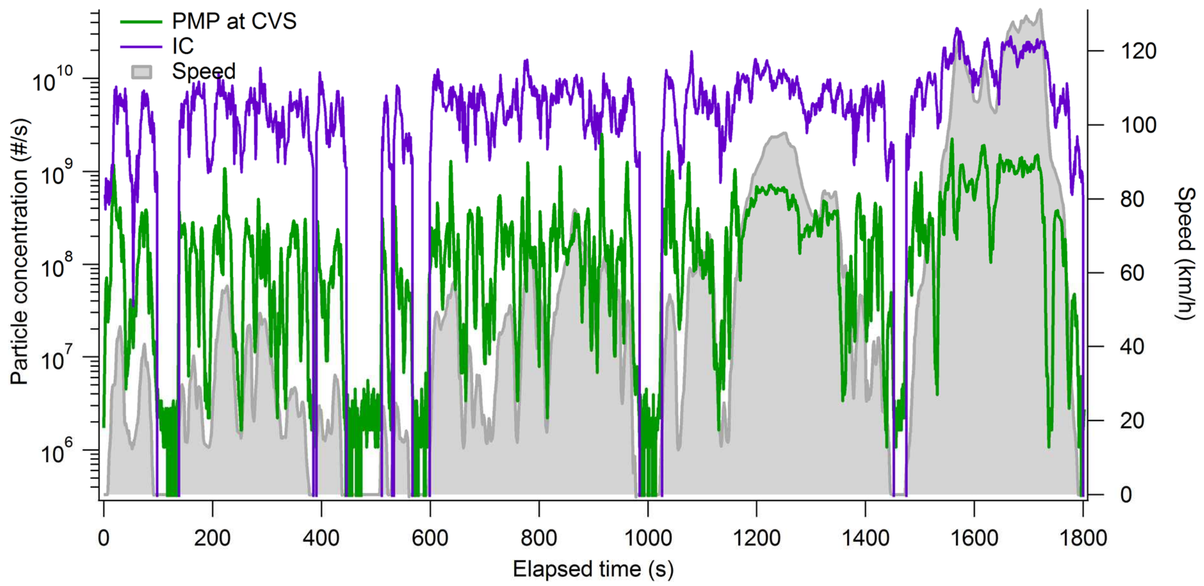


Figure 9: Time series of IC system sampling at tailpipe and the reference PMP system sampling at CVS for a WLTC test. The speed is reported in grey on the right-hand scale.

	Average (-)	St. Dev. (-)	Max (-)
L1	336.86	491.28	1922.93
DC1	-0.81	0.23	-0.09
DC2	0.15	0.72	1.74
IC	19.14	11.01	51.27

Table 4: Average, standard deviation and maximum of the relative difference between the devices under test and the reference particle number PMP system at CVS (relative difference is calculated for single tests and then averaged).

	Average (-)	St. Dev. (-)	Max (-)
L1	409.56	608.14	2364.30
DC1	-0.79	0.25	0.04
DC2	0.34	0.83	2.01
IC	22.93	13.67	63.26

Table 5: Average, standard deviation and maximum of the relative difference between the devices under test and the particle number PMP system at tailpipe (relative difference is calculated for single tests and then averaged).

Tables 4 and 5 report the average, standard deviation and maximum of the relative difference between the devices under test and the particle number PMP system at CVS and at tailpipe. In general, the response of the DC2 instrument based on diffusion charging technique resulted closer to the response of reference instrument compared to the other devices. DC2 is also the instrument that better captured the small variability of the emissions deriving from the different test cycles (Figure 4). The average relative difference between the DC2 instrument and the reference instrument over all the tests is 15% (DC2 overestimated the reference value by 15%). The average relative difference between the DC1 instrument and the reference instrument through all the tests is 81% (DC1 underestimated the reference value by 81%). The IC instrument overestimates the reference concentrations by a factor of 19.14 and results not capable of following the small variability of the results (e.g. steady state test at 130 km/h with the test vehicle 2, Figure 4). The light scattering instrument L1 overestimates the reference concentration by almost 3 orders of magnitude, with a maximum factor of 1922.93 (Table 4). L1 suffered from being too close to the detection limit. Also the distance specific mass emissions (in mg/km) measured by L1 showed a large variability spanning both above and below the Euro 5b particulate mass emission standard (Figure 10). Figure 10 shows also the concentration in mg/km measured by the DC2 instrument (the conversion factor used by the instrument's manufacturer is $4.8 \cdot 10^{12}$ p/mg). Particulate mass emission of DPF equipped diesel vehicles are often typically in the same range of the CVS background PM smaller than 1 microgram/km [6]. DC2 showed a PM mass in the order of 0.01 mg/km which is consistent with typical particulate mass emission of DPF equipped diesel vehicles are in the same range of the CVS background PM (smaller than 1 mg/km) [6]. L1 showed PM mass larger than 1 mg/km for 11 of the 17 tests, and between 0.01 and 0.1 for 6 other tests. This variability is not supported by the rather constant PN emissions measured by the PMP systems (Figure 4), indicating that instruments based on light scattering are not suitable to measure accurately PM emissions of modern DPF equipped diesel vehicles.

As anticipated the other two light scattering devices under test L2 and L3 were not able to detect the emissions of the two diesel vehicles equipped with DPF due to the extremely low concentrations of soot.

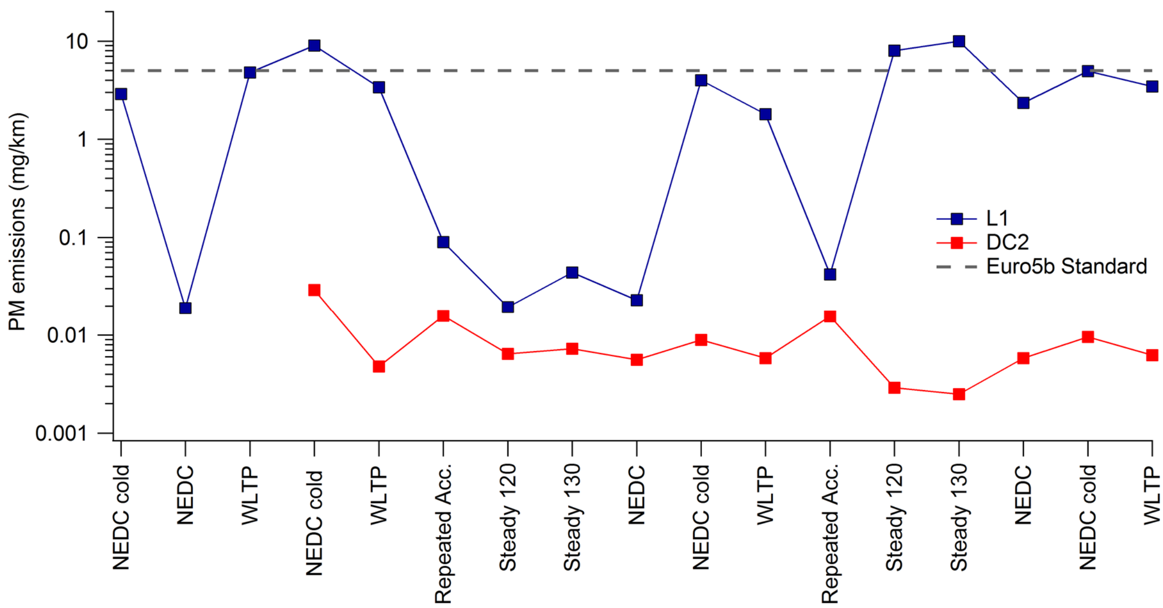


Figure 10: Comparison of the distance specific PM emissions measured by L1 and DC2. Dashed line represents the Euro 5b particulate mass emission standard.

4 CONCLUSIONS

The test were performed comparing the periodic emission control candidate devices with the reference value of particle number as requested by the EC Regulation 83 for type approval tests. The diffusion charging technique, based on the measurement of the whole current carried by the sampled particles, resulted capable of capturing the small emissions differences between the different test cycles for vehicles equipped with a well-functioning DPF. In particular, the diffusion charging instrument DC2 was the instrument that showed the lowest deviation from the reference across the whole measurement campaign. While having an above than average accuracy, the diffusion charging devices suffers from a high limit of detection (LOD, typically a few thousands of particles per cubic centimeter), it then becomes crucial to adjust the dilution such that the range of measurement is always above the LOD (this was not always the case for L1 device). A recommendation for the diffusion charger instrument's manufacturers is to allow the variation of the dilution accordingly to the expected emission level (according to type approved Euro standard). Moreover, the preferable solution would be to provide an instrument with an automatic continuous adjustment of the dilution ration as a function of the emission levels in order to keep the concentration in the range above the LOD of the specific diffusion charging instrument.

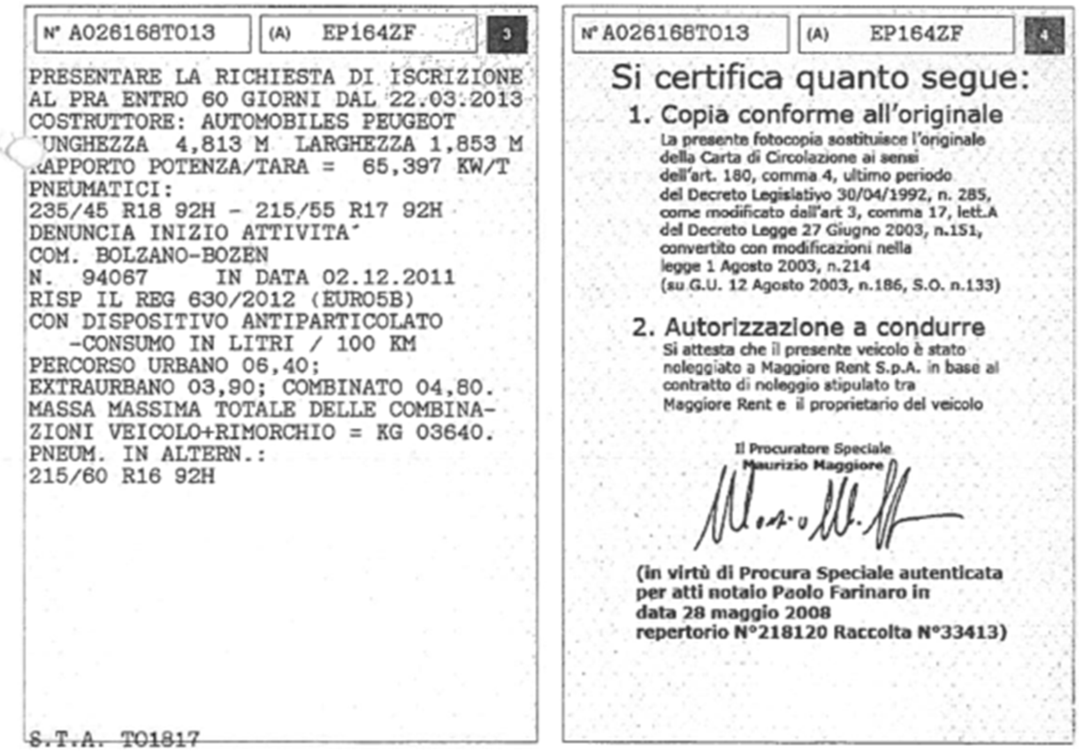
The field tests measurements performed under controlled conditions similar to Type1 type approval test resulted to be too challenging for the light scattering instruments: L1 showed a large variability of the emissions through the tests and largely overestimated some of the emissions, this highlights that the light scattering technique is not suitable to measure accurately the particulate emissions in the concentration range typical of DPF equipped diesel vehicles. L2 and L3 resulted always below their limit of detection. The reason for this is that the light scattering instruments were designed to cover a wide range of emissions in order to capture possible failures of the DPFs, and not specifically designed to measure particle number concentration as the reference instrument.

The low cost IC device showed to have the potential to be used as for periodic emission control measuring system if calibrated accurately, but further development of the prototype is needed.

For future legislation it is recommended to define specific functional checks that should be carried out before any periodic emission control measurement in order to assure that the measurement below the detection limit is due to the well-functioning DPF and not due to failure of the instrument's sensor or sampling. In this context it is suggested that instrument manufacturers already start adding a simple functional check in their user's manual to be performed by the operator in order to assure that the instrument is properly working prior to any measurement.

5 ANNEX A

Vehicles registration papers.



N° A026168T013 (A) EP164ZF 3

PRESENTARE LA RICHIESTA DI ISCRIZIONE
AL PRA ENTRO 60 GIORNI DAL 22.03.2013
COSTRUTTORE: AUTOMOBILES PEUGEOT
LUNGHEZZA 4,813 M LARGHEZZA 1,853 M
RAPPORTO POTENZA/TARA = 65,397 KW/T
PNEUMATICI:
235/45 R18 92H - 215/55 R17 92H
DENUNCIA INIZIO ATTIVITA'
COM. BOLZANO-BOZEN
N. 94067 IN DATA 02.12.2011
RISP IL REG 630/2012 (EURO5B)
CON DISPOSITIVO ANTIPARTICOLATO
-CONSUMO IN LITRI / 100 KM
PERCORSO URBANO 06,40;
EXTRAURBANO 03,90; COMBINATO 04,80.
MASSA MASSIMA TOTALE DELLE COMBINA-
ZIONI VEICOLO+RIMORCHIO = KG 03640.
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La presente fotocopia sostituisce l'originale della Carta di Circolazione ai sensi dell'art. 180, comma 4, ultimo periodo del Decreto Legislativo 30/04/1992, n. 285, come modificato dall'art 3, comma 17, lett.A del Decreto Legge 27 Giugno 2003, n.151, convertito con modificazioni nella legge 1 Agosto 2003, n.214 (su G.U. 12 Agosto 2003, n.186, S.O. n.133)

2. Autorizzazione a condurre
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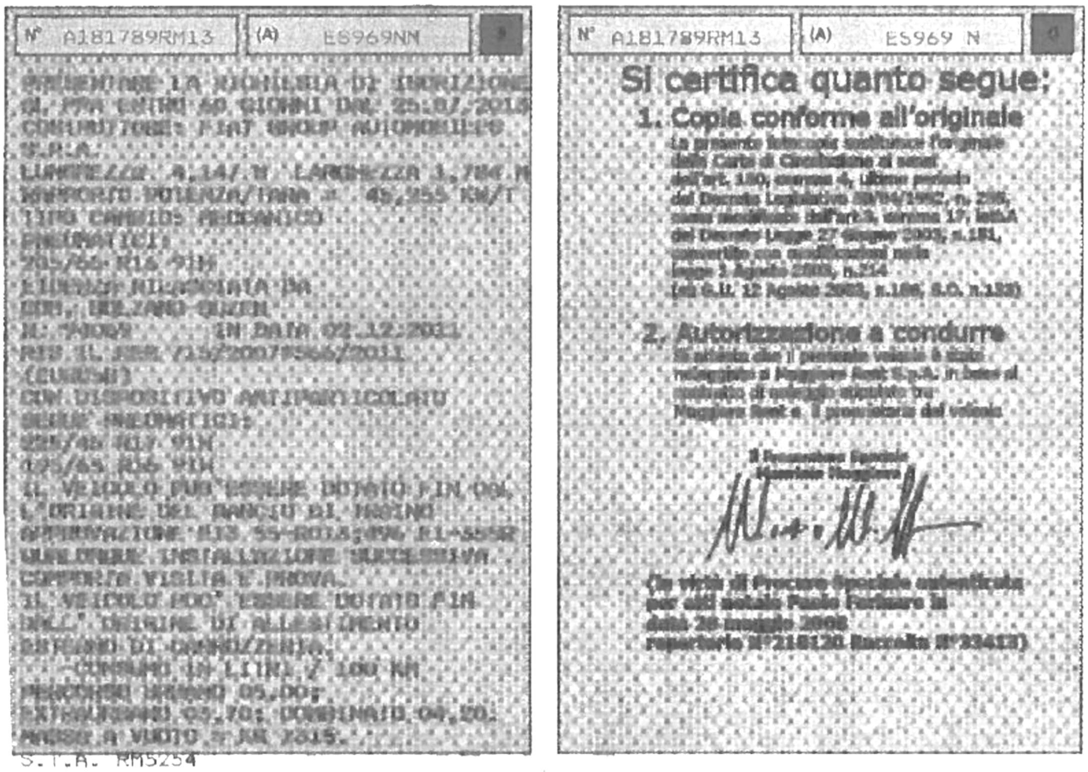
Il Procuratore Speciale
Maurizio Maggiore

(in virtù di Procura Speciale autenticata per atti notaio Paolo Farinaro in data 28 maggio 2008 repertorio N°218120 Raccolta N°33413)

Figure A1: Vehicle regsitartion of Peugeot 508 (Test Vehicle 2).



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S.T.A. RM5254

Figure A2: Vehicle registration of Fial 500L (Test Vehicle 2).

6 REFERENCES

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