European
Commission

JRC TECHNICAL REPORT

EU-PEMS PM Pilot Program: Testing, data analysis and results.

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2015

Report EUR 27326 EN

Joint Research Centre

European Commission
Joint Research Centre
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http://ec.europa.eu/jrc
This publication is a Reference Report by the Joint Research Centre of the European Commission.

JRC95342

EUR 27326 EN

ISBN 978-92-79-49236-5 (pdf)
ISBN 978-92-79-49235-8 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi: 10.2790/46867 (online)

Luxembourg: Publications Office of the European Union, 2015

Abstract :

The present work was conducted in the frame of the EU PEMS PM Evaluation programme. The program was launched in 2008 by the European Commission [1] to assess the potential of portable instruments to measure particulate emissions on-board of vehicles. The EU-PEMS program is a voluntary program, receiving contributions from the European Joint Research Centre (JRC), some portable emissions instrument manufacturers (AVL, Control Sistem, Sensors Inc, Horiba) and the European association of heavy-duty engines manufacturers (ACEA).

After the successful completion of the laboratory evaluation program with the identification and recommendation of the candidate principles [3, 4, 5], the second phase of the process was launched with the on-road measurement of PM with the updated instrumentation recommended in the validation program (PEMS PM Pilot Program). The PEMS PM Pilot program concludes the research phase of the PEMS PM instrumentation into its inclusion in the Euro VI regulation.

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Acknowledge.

The authors would like to thank AVL-MTC and ACEA for the collaboration in providing the necessary data that has allowed undergoing the present PEMS PM Pre-Pilot and Pilot programs.

Special thanks to AVL, Sensors Inc, Horiba and Control Sistems who provided the candidate instruments and the support on testing.

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1. Introduction

1.1. *Background*

The present work was conducted in the frame of the EU PEMS PM Evaluation Program. The program was launched in 2008 by the European Commission [1] to assess the potential of portable instruments to measure particulate[1] emissions on-board of vehicles. The EU-PEMS program is a voluntary program, receiving contributions from the European Joint Research Centre (JRC), some portable emissions instrument manufacturers (AVL, Control Sistem, Sensors Inc, Horiba) and the European association of heavy-duty engines manufacturers (ACEA).

1.2. *EU-PEMS Project*

Since the EURO V stage, the European emissions legislation requires the verification of the conformity of heavy-duty engines with the applicable emissions certification standards: these provisions are identified as “In Service Conformity” (ISC).

At the moment of elaboration of the ISC requirements, it was considered impractical and expensive to adopt a scheme which required the removal of engines from vehicles for testing pollutant emissions against legislative limits. As consequence, it was proposed to develop a protocol for ISC based on the use of Portable Emission Measurement Systems (PEMS).

The European Commission, through DG ENTR in co-operation with DG JRC, launched in January 2004 a co-operative research Program, the EU PEMS project, in order to study the feasibility of PEMS in view of its application in Europe for ISC of heavy-duty engines [2]. The technical and experimental activities started in August 2004, with the goal of assessing different PEMS systems and their potential application to on-road measurements of heavy-duty vehicles.

The main objectives of the above mentioned program were the following:

- To assess and validate the applicability to ISC and the performance of portable instrumentation, relative to each other and in comparison with alternative options for ISC testing;
- To develop a test protocol on the use of portable instrumentation for ISC of heavy-duty vehicles;
- To evaluate the US ‘Not To Exceed’ (NTE) approach and develop a simplified method in order to propose ISC pass/fail criteria;
- To address the learning needs of the European industry, authorities and test houses.

Following the successful outcome of the EU-PEMS project, the Commission announced at the 97th MVEG Meeting on 1 December 2005, the intention to launch a manufacturer-run Pilot Program, with the main purpose of confirming and validating the robustness of the PEMS test protocol that had been developed in the EU-PEMS Project. The program was also designed to contribute to the sharing of ‘best practice’ approach amongst all involved parties, including Member State

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[1] Regulation No. 49 (E/ECE/324/Rev.1/Add.48/Rev.6) Article 2, point 2.42 defines: ***"Particulate matter (PM)"*** means any material collected on a specified filter medium after diluting exhaust with a clean filtered diluent to a temperature between 315 K (42 °C) and 325 K (52 °C); this is primarily carbon, condensed hydrocarbons, and sulphates with associated water.

authorities and technical services. The outcome of the program provided further information on the introduction of ISC provisions based on the PEMS approach in the European type-approval legislation.

1.3. EU-PEMS Heavy-Duty PM Pilot Program

Both above-mentioned projects and the follow-up pilot program did not require the measurement of PM emissions: this was due to the absence of commercially available portable systems able to measure the PM mass emissions following the requirements of the laboratory standards (in terms of dilution, temperature control and filter media conditioning for instance). It was therefore decided to launch a laboratory evaluation program to assess their potential. This decision has been formalized by the European Commission in a Call for Expression of Interest [1].

After the successful completion of the laboratory evaluation program with the identification and recommendation of the candidate principles [3, 4, 5], the second phase of the process was launched with the on-road measurement of PM with the updated instrumentation recommended in the validation program (PEMS PM Pilot Program). This was a manufacturer-run with several members of ACEA and member states supplying test data.

To support the PEMS PM Pilot Program, DG JRC conducted a Pre-Pilot Program with the collaboration of one of the ACEA’s member, IVECO, and PM instrument manufacturers. The aim of this activity was to look into all the logistic necessary to mount both the PEMS PM and PEMS gaseous equipment in a HDV, and to check for the system good functioning. One gaseous PEMS and four candidates PEMS PM instruments were operated together on the same vehicle and the experience was shared with all the participants on the PEMS PM Pilot program.

The Pre-Pilot program was run at the JRC Vela 7 and on the roads around the JRC-Ispra site. The Pilot Program was performed within different locations by the ACEA members with support of test equipment suppliers and JRC.

2. Scope

This document presents the findings of the PEMS PM Pre-Pilot and Pilot programs. It also provides recommendations on the possible procedure to perform PEMS PM measurements and data analysis.

3. Summary of the PEMS PM procedure state of play

The assessment of the PEMS PM instruments began with the production of 3 reports [3,4,5] based on the EU-PEMS PM evaluation program, where several tests were performed with candidate instruments fulfilling the following basic requirements:

- To measure the total Particulate Matter (PM) mass over a long sampling period, either following the standard method or using a method proven to be equivalent to the standard method[2];
- To provide a second-by second (“real-time”) information on the emitted PM mass at any time during the test. This is a necessary pre-requisite for

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[2] Regulation No. 49 (E/ECE/324/Rev.1/Add.48/Rev.6) Annex 4, Appendix 2

evaluating the data according to the Moving Average Window (MAW) method (either work or CO2 based);

- To be ready for on-vehicle tests and in particular to include a solution to transport the raw or the diluted exhaust, to allow for an installation of the system within a few meters from the vehicle tailpipe.

Measurement principles that were not fully in line with the laboratory standard methods to measure PM mass were also accepted for evaluation, either with variations of the dilution method (e.g. constant dilution) or with alternative physical principles (e.g. measurement of the soot instead of total PM).

Upon the completion of the EU-PEMS PM evaluation program, the main conclusions were to recommend the candidate principle(s) and to discuss whether the corresponding technological progress of the instruments was sufficient to foresee its introduction in the legislation in a short term.

The objective of the PEMS PM Pilot Program is to evaluate the technical readiness of the candidate instruments to operate and measure PM on-road tests.

The data obtained by the equipment during the different tests were processed following the PEMS gaseous procedure; i.e. considering the PM data equivalent to a gaseous pollutant. Previously to that and in order to use EMROAD (or any other calculation tool) the integrated PM mass was converted in mass emitted per second using the real time detector signal.

3.1. PEMS PM Calculation principle

The total PM emission in a given test from the gravimetric (filter) method is obtained as:

$$mass_{PM} = \frac{Filter\ mass \cdot Total\ exhaust\ mass}{Sampled\ exhaust\ mass}\ [g] \qquad \text{(Eq. 1)}$$

The equivalent mass estimated by the real time sensor is obtained by:

$$mass_{RT}[\text{a.u.}] = \int_0^t RT(t) \cdot DR(t) \cdot EF(t) \cdot dt$$

Where:

$RT(t)$ is the Real Time sensor measurement [a.u.[3]]

$DR(t)$ is the Dilution Ratio.

$EF(t)$ is the exhaust flow

$$mass_{RT}[\text{g}] = K \cdot \text{mass}_{RT}[a.u.] \qquad \text{(Eq. 2)}$$

K is the mass conversion factor

Since $mass_{PM}$ [g] = $mass_{RT}$ [g] then from Eq.1 and Eq. 2 then the mass conversion factor K can be obtained:

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[3] a.u. = arbitrary units. Each PM real-time sensor provides a signal in units related to the physical measuring principle used by the sensor.

$$K = \frac{mass_{PM}}{mass_{RT}}\left[\frac{g}{a.u.}\right] \quad \text{(Eq. 3)}$$

Therefore, the real-time PM mass emissions at time t can be obtained by:

$$PM(t) = K \cdot RT(t) \cdot DR(t) \cdot EF(t) \quad \text{(Eq. 4)}$$

Where:

$PM(t)$ is the Real Time PM mass [g] at time t

EMROAD requires as input (to be uploaded to TEST DATA): · $RT(t)$, $DR(t)$ and $mass_{PM}$

EMROAD calculates: · K, $mass_{RT}$ and $PM(t)$

In this way the calculation processor (EMROAD or any other available data processing software) normalises the real time sensor signal to the total mass collected in the filter.

4. PEMS PM Pre-Pilot Program

The objectives of the Pre-pilot program were the following:

1. Perform a baseline test in order to analyse the comparability of the results and potential installation issues between the participating instruments.
2. Perform a correlation study on the results obtained using the PEMS PM instruments with that acquired using the testing cell measuring device.
3. Perform a correlation of the results obtained in the road-tests among all participating instruments.
4. Look into the logistics necessary to mount both the PEMS PM and PEMS gaseous instrumentation in a HDV.

4.1. Vehicle

ACEA defined and supplied the vehicle to be tested under the PEMS PM Pre-pilot program. The vehicle provided was an IVECO Eurocargo© with the following specifications (Table 4-1):

Table 4-1 Pre-pilot vehicle characteristics.

IVECO Eurocargo	
Emissions category:	Euro IV
Engine type:	F4AE3682A*P
Max power:	220 kW @ 2500rpm
Fuel:	Diesel
ETC ref work:	32.75 kWh
Cylinders:	6
Aftertreatment	SCR

4.2. PEMS Instrumentation on-board

The vehicle was equipped with 4 different PEMS PM instruments available:

- AVL MOVE PEMS PM (AVL-MOVE/MSS)
- Control Sistem PEMS PM (CS-PSS)
- Horiba TPRM (HOR/OBS)
- Semtech Ecostar (ECO)

And 1 gaseous PEMS:

- Semtech DS

A detailed description of the PEMS PM instruments can be found in [3, 4, 5 and 6].

4.3. PEMS PM Pre-Pilot procedure

The procedure followed on the Pre-pilot program was to test the vehicle at the VELA laboratory; both with the test cell and the PEMS PM instruments, then run a series of on-road test for which a specific route was determined in order to be able to have comparable results.

4.3.1. VELA 7 testing

The laboratory based testing included several WHVC test runs to be able to correlate the different PEMS PM testing instruments with the laboratory based emissions system (Section 10.1 depicts a short description of VELA 7). Figure 4-1 below shows the test schedule followed by the test on laboratory, it is important to point out that neither Horiba nor Ecostar PEMS PM were available for the laboratory testing; hence no results are shown from this instrumentation for this phase. The applied cycle is composed of two WHVC cycles back-to-back; the first is considered a conditioning cycle (initial 1800 s) and the second cycle the one used to measure the emissions.

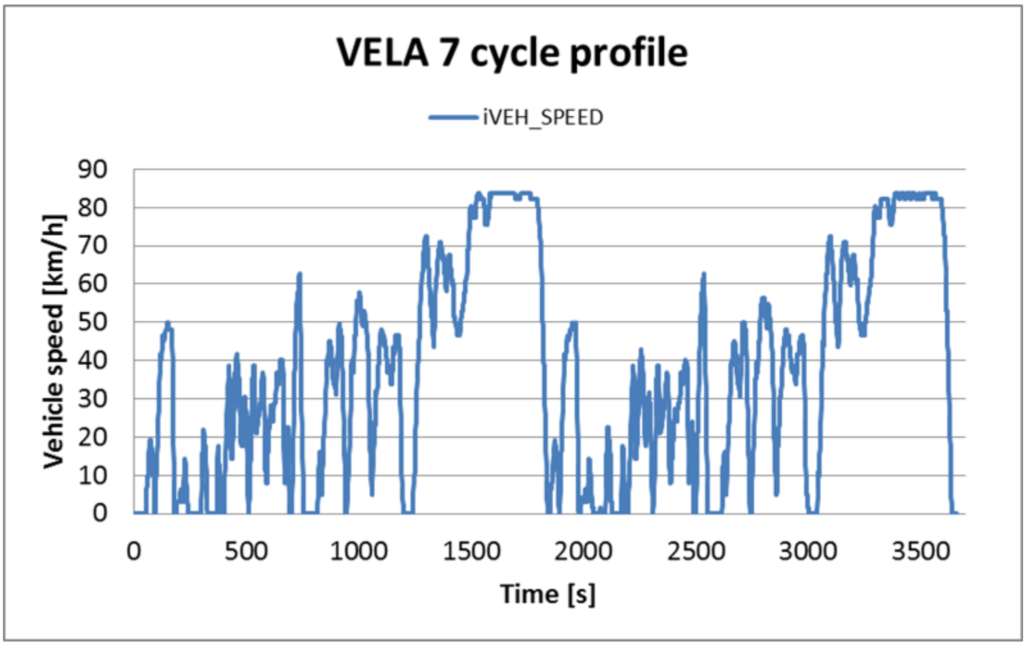


Figure 4-1 WHVC test schedule.

Together with the WHVC transient cycle, steady state cycles were also performed. Each run was made of steady velocity portions for a total time equivalent to a WHVC cycle (total 1800 s). Data from the laboratory equipment and PEMS instrument were collected for comparison. Figure 4-2 shows the profile of the steady speed tests.

The idea behind running steady speed tests was to understand the PEMS PM instruments measurements under those conditions and the difference that could be found against a transient cycle.

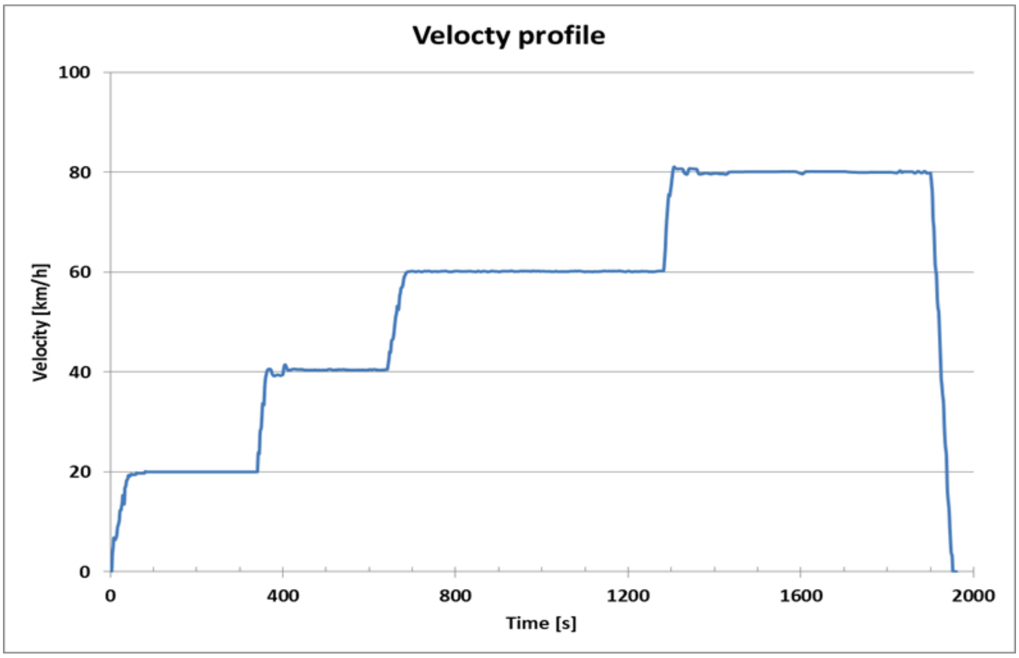
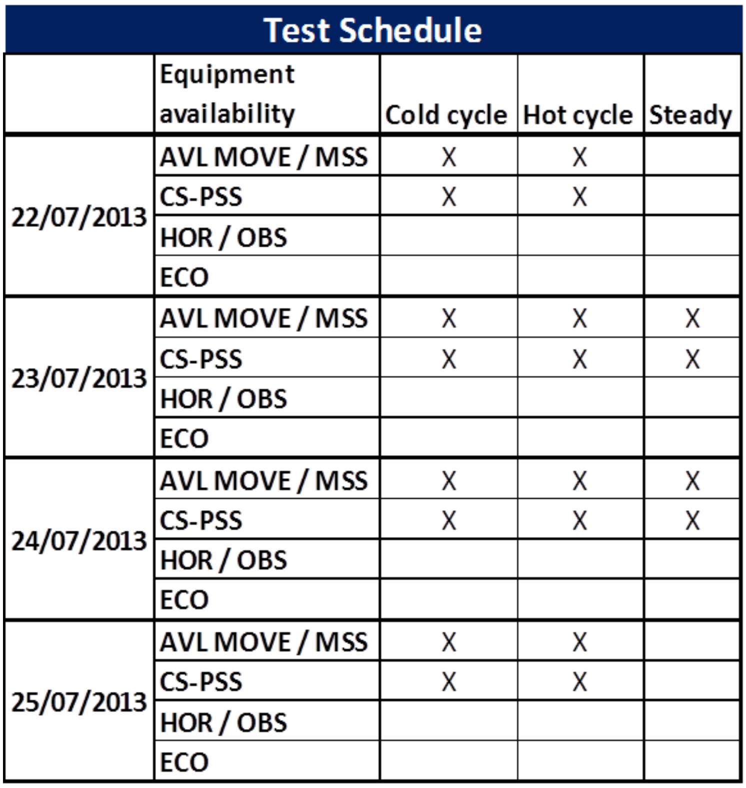


Figure 4-2 Steady state test schedule.

The daily test schedule (Table 4-2) included a cold test, hot test and some days also the steady speed test. As the objective of the pre-pilot program was to understand the readiness for use of the different test instruments, the analysis of the results of the hot part of the cycle was the focus of this activity. Thus, the following sections address this specific operating phase.

Table 4-2 Availablity of different PEMS PM instruments for laboratory based testing.



Test Schedule

	Equipment availability	Cold cycle	Hot cycle	Steady
22/07/2013	AVL MOVE / MSS	X	X	
	CS-PSS	X	X	
	HOR / OBS			
	ECO			
23/07/2013	AVL MOVE / MSS	X	X	X
	CS-PSS	X	X	X
	HOR / OBS			
	ECO			
24/07/2013	AVL MOVE / MSS	X	X	X
	CS-PSS	X	X	X
	HOR / OBS			
	ECO			
25/07/2013	AVL MOVE / MSS	X	X	
	CS-PSS	X	X	
	HOR / OBS			
	ECO			

4.3.2. VELA 7 correlation with PEMS PM candidate instruments

As explained above, special attention was put on the correlation between the data obtained with the PEMS PM instrumentation and those results of the hot phase of the test acquired with the VELA laboratory reference instruments (See Section 10.1). Because most of the real-time instruments were acquiring data at different frequencies and measuring different physical quantities (units), the challenge was to properly align the data and analyse the specific grams per test to be able to properly compare the final figures. Further to this, the work per test was calculated for each part of the cycle in order to be able to compare PM in g/kWh.

Several checks were performed before starting the final data analysis (EMROAD standard procedures: data alignment, data consistency check e.g. all data available …). Figure 4-3 and Figure 4-4 show two examples (cycles 22/07/13 and 24/07/13) of the correlation from the hot WHVC between the real time signal from CS PSS and the AVL MOVE (MSS) as well as the correlation between the real time signal from VELA 7 with the CS PSS and the MSS. It can be seen a good correlation between the two PEMS-PM instruments ($r^2 \approx 0.8$). A good correlation between the VELA 7 and the CS PSS is also found ($r^2 > 0.9$) in these cases, while for the cases of the correlation between VELA 7 and the MSS is not as satisfactory ($r^2 > 0.6$). Besides these two examples, it must be emphasised that the correlation factor (r^2) between the real time signal from CS PSS and the AVL MOVE (MSS) for all the hot WHVC tests are larger than 0.78; while in the case of the correlation (r^2) between the real time signal from VELA 7 and the CS PSS are larger than 0.87. It is important to appreciate that the different instrumentation, working with different physical measurement principles and different units were used to quantify the real-time PM measurement.

Besides consistency checks on parameters as exhaust flow meter, CO2 and speed measurements between the ECU/PEMS PM and in-cell instrumentation, the importance of Figure 4-3 and Figure 4-4 is the correlation between the reference device and 2 of the PEMS PM instruments.

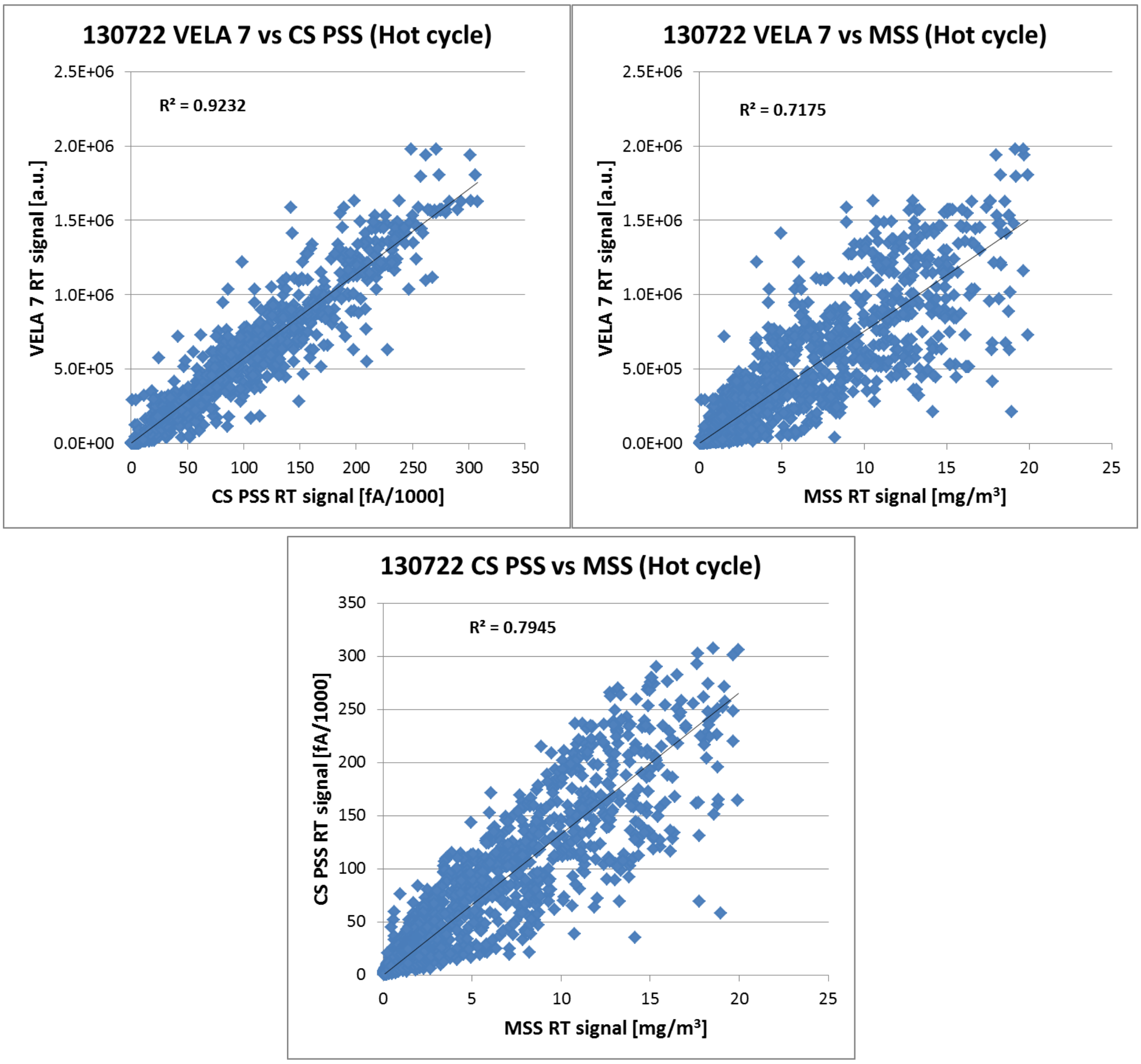


Figure 4-3 VELA 7 vs CS-PSS and MSS, and CS-PSS vs MSS real time PM signal correlation (WHVC-13/07/22).

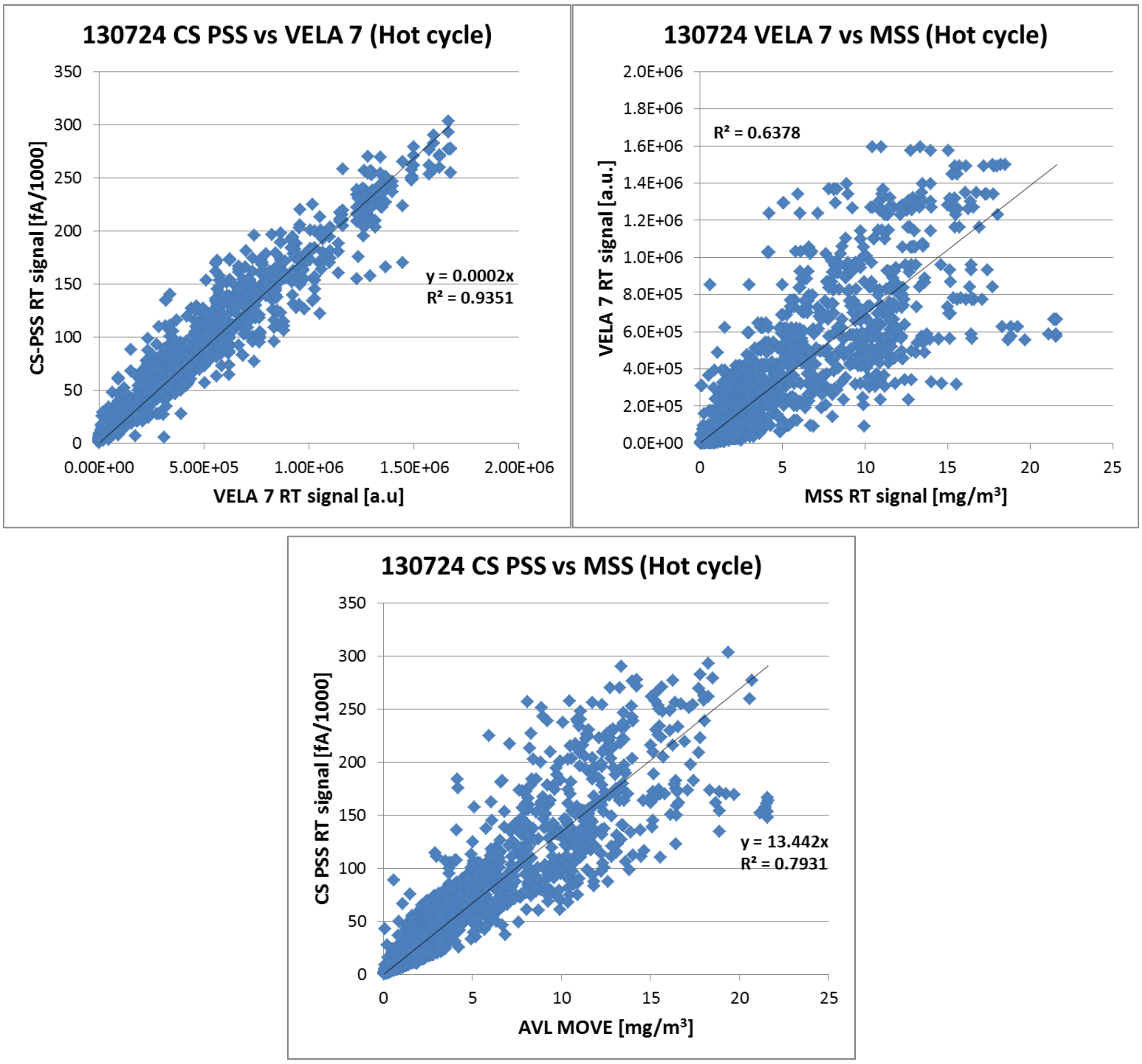


Figure 4-4 VELA 7 vs CS-PSS and MSS (AVL MOVE), and CS-PSS vs MSS (AVL MOVE) real time PM signal correlation (WHVC-13/07/24).

Figure 4-5 shows the comparison between the total PM mass per test (g) of the two operative instruments tested in the laboratory setup with the laboratory reference instrument for both the transient and the steady state cases.

As it can be seen, the agreement between the VELA 7 (reference) and the PEMS PM instruments is reasonably good for the hot cycle tests (WHVC and steady state). The spread of the data (represented by the error bars) are within each other, demonstrating that the instrumentation is capable of achieving consistent results.

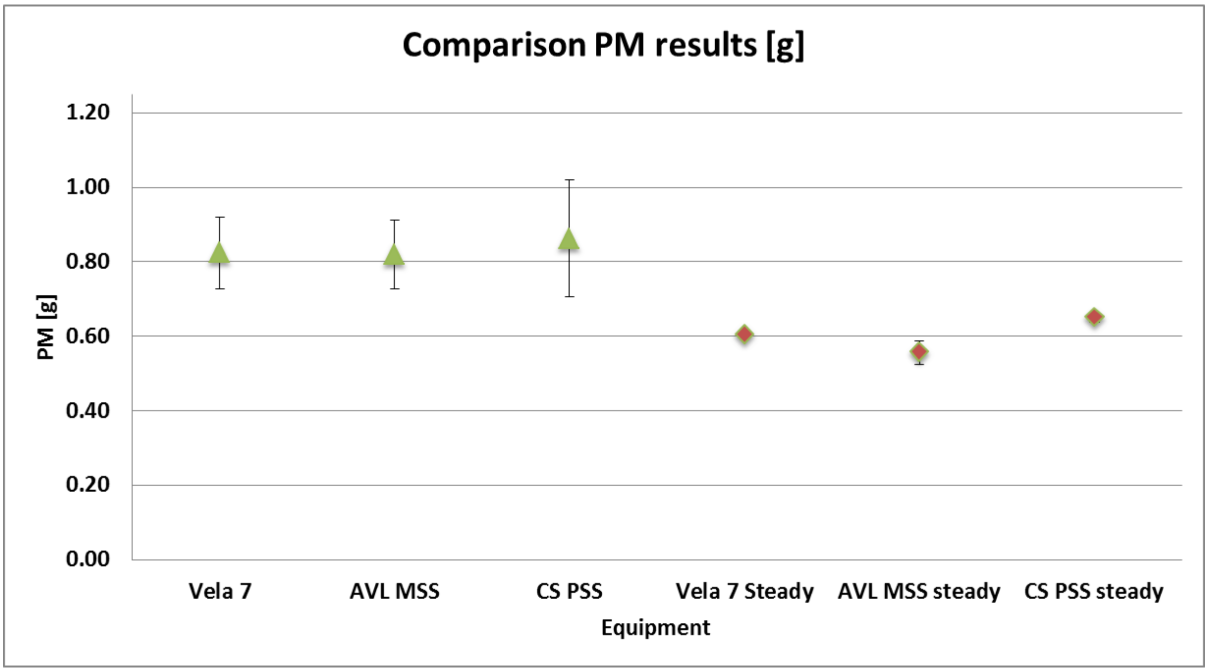


Figure 4-5 PM (g/test) comparison of laboratory based tests.

4.3.3. *On-road measurements*

The on-road measurement phase started by defining a trip which included different percentages of urban, rural and motor way operation; the trips were planned to be as consistent as possible between each other, this was made to be able to compare the results of the different trips.

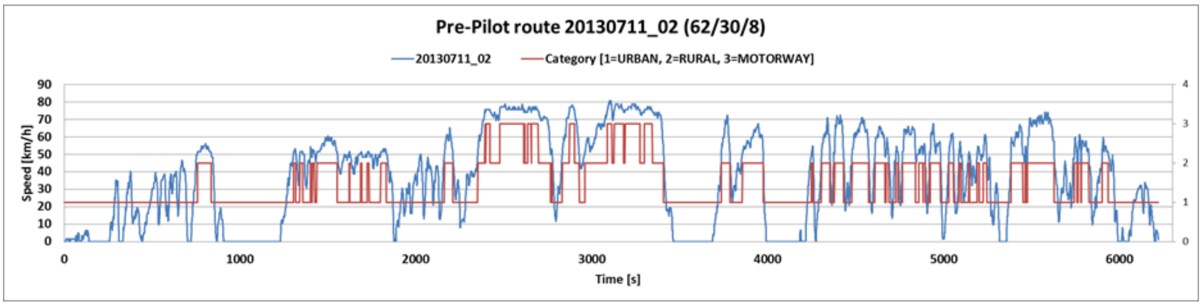
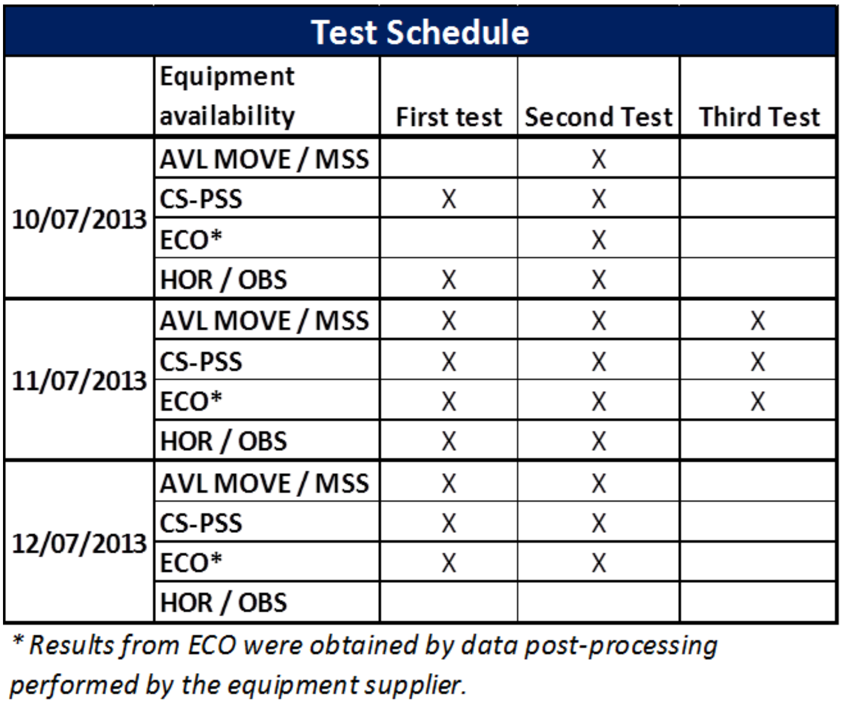


Figure 4-6 On-road trip speed profile.

Figure 4-6 above shows one of the trips speed profiles. The route has a number of stops which allowed certain percentage of idle operation. The same vehicle as in the laboratory correlation was used (a Euro IV, see Section 4.1). This means that the level of PM produced by the vehicle was high, which allowed to see a good amount of PM deposited on the filters. Same plausibility and consistency analysis were performed for these results as explained in Section 4.3.2.

Table 4-3 below shows the availability of the different instruments on the different test runs. The tests performed in the chassis dyno were carried out after these on-road tests with the consequence that some instruments were not available for the chassis dyno test (see Table 4-2)

Table 4-3 Availability of different PEMS PM instrumentation for on-road testing.



Test Schedule				
	Equipment availability	First test	Second Test	Third Test
10/07/2013	AVL MOVE / MSS		X	
	CS-PSS	X	X	
	ECO*		X	
	HOR / OBS	X	X	
11/07/2013	AVL MOVE / MSS	X	X	X
	CS-PSS	X	X	X
	ECO*	X	X	X
	HOR / OBS	X	X	
12/07/2013	AVL MOVE / MSS	X	X	
	CS-PSS	X	X	
	ECO*	X	X	
	HOR / OBS			

** Results from ECO were obtained by data post-processing performed by the equipment supplier.*

As indicated in the footnote on Table 4-3, the results obtained from the Ecostar instrument came from a post processing performed by the manufacturer; this was necessary because the level of the available software at the time was not mature enough to allow the JRC to process these results.

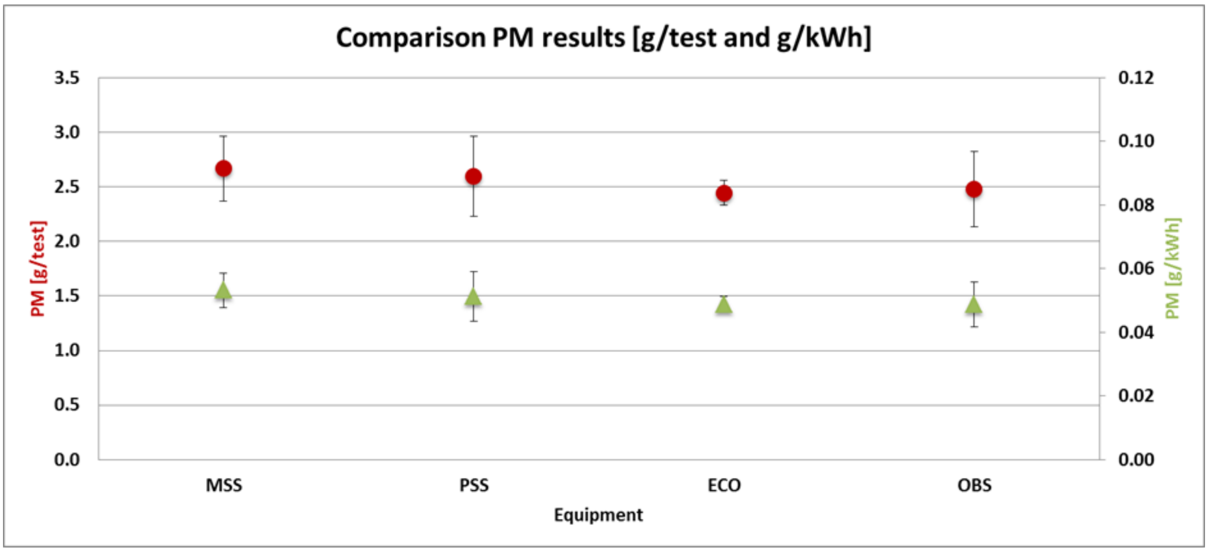


Figure 4-7 Correlation of the averaged PM results between the different instruments. The error bars correspond to one standard deviation (data spread).

The results of the on-road tests underwent consistency checks and an analysis similar to that made with the dynamometer-based results. Following the PEMS PM calculation principle (Section 3.1) the total grams per test of PM (see Figure 4-7) using the mass on the filters and the exhaust flow measurements performed by the different instruments was calculated (the spread of results are represented by the error bars). Further to this, the specific PM values (g/kWh) were determined using the work calculated by the torque signal obtained from the ECU. The resulting comparison is shown, in Figure 4-7. The good agreement between the values in term of PM mass per test and specific PM values is not surprising because all the trips were similar in length, trip shares and consequently in total work performed (48.46 kWh ≤ work ≤ 54.23 kWh).

The averaged results of the different tests performed with the different PEMS PM instruments show consistency. The difference of the values (one standard deviation) of the averaged results of tests per instrument is below 1%. This correlation shows it is possible to achieve a level of consistency using any of these PEMS-PM instruments.

Last comparison made on these on-road PM results was the Moving Average Window (MAW) analysis based on the normal MAW analysis made to gaseous emissions results. The principle of this analysis is explained in Section 10.2.

Figure 4-8 shows the conformity factor of the different tests with the different instruments. The relationship between the conformity factors show a bigger spread in relation to results shown in Figure 4-7, but still in good agreement with each other. This is probably caused by the fact that the instantaneous PM real time signal introduces some additional variance which is reflected in the calculation of the CF (work-based window with a length equal to the ETC reference work). The CFs' standard deviation on averaged values along the on-road tests is 16%.

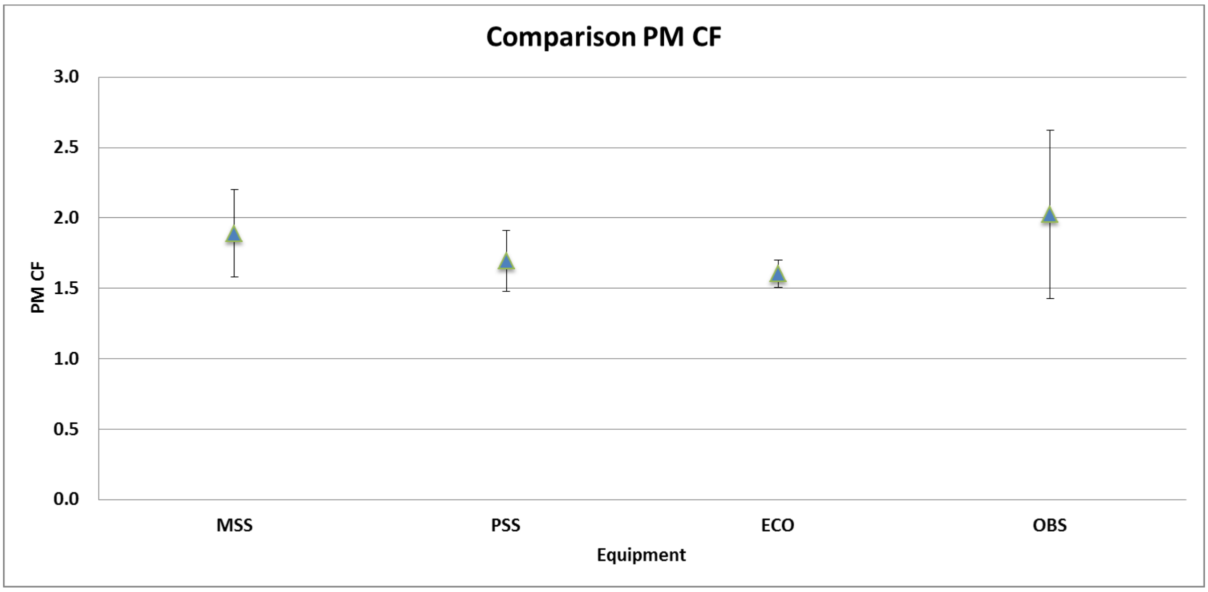


Figure 4-8 Correlation of the PM results between the different instruments using the MAW. The error bars correspond to one standard deviation.

5. PEMS PM Pilot program

5.1. Objectives

The main objective for the PEMS-PM Pilot program is to test if the available PEMS-PM instruments fulfil the requirements to be used as part of the PEMS procedure for HDV within the Euro VI legislation.

The instrument must be capable of:

- Measuring the total Particulate Matter mass over a long sampling period

- Provide second-by-second ("real time") information on the emitted PM mass at any time during the test
- Being ready for on-road tests:
    - Solution to transport the raw or diluted exhaust
    - Allow for an installation of the system within a few meters from the vehicle tailpipe

The general objectives were:

- To run the PEMS PM Pilot program along with ACEA members in different testing conditions, within different locations in Europe aided by the manufacturers of the different participating instruments.
- Add installation "best practices" to HDV PEMS guidance document[4] through the experience on software and hardware debugging of both the Pre and Pilot programs.
- Determine if the PEMS PM measurement procedure can be achieved as defined by the PEMS gaseous current (Regulation EU 582/2011) or future regulation.

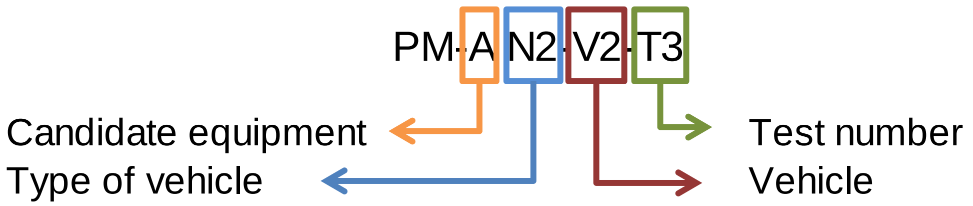
5.2. Vehicles

The vehicle/engine combinations to be tested in the present program shall comply with the requirements of the European Directive in force (Euro VI).

5.3. Selection of vehicle/engine combinations

JRC suggested during the preparation phase of the PEMS-PM pilot program a test matrix (see Section 10.3) with a well-balanced choice of vehicle categories and testing conditions (payload and routes)[5]. The data was kindly shared by ACEA members[6], Table 5-1 below shows the statistics of the vehicle data shared and instruments used. Please note that on the N1/N2 vehicles the number of tests is 9, but some of the tests were performed with more than one PEMS PM instrumentation; hence, the sum of test per instrument is greater than the total tests number.

Furthermore, Table 5-2 shows the characteristics of the vehicles participating on the program together with some basic information regarding the different test conditions. It also lists the different test by code as follows:



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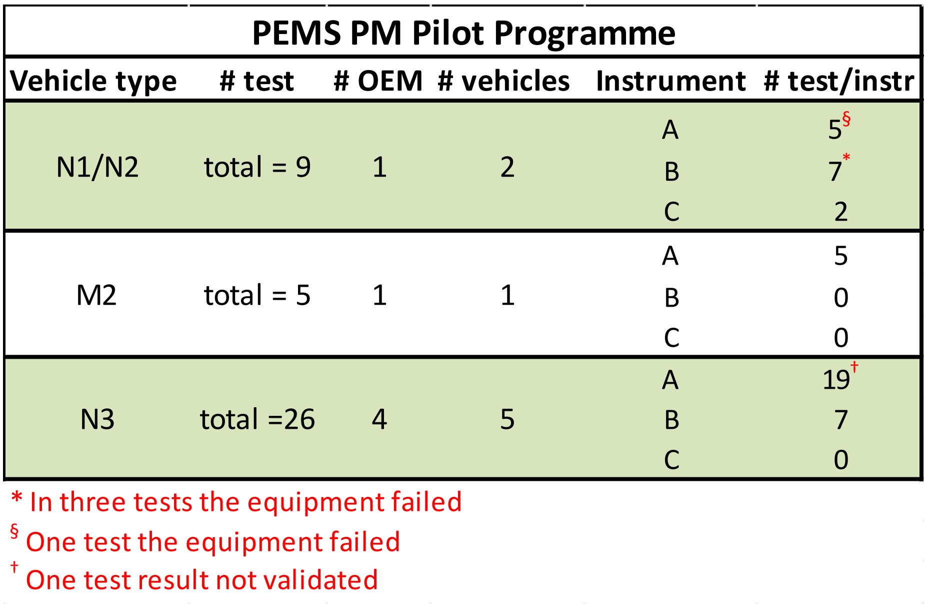
[4] PEMS BASED IN-SERVICE TESTING: PRACTICAL RECOMMENDATIONS FOR HEAVY-DUTY ENGINES/ VEHICLES. JRC Technical Reports (To be published)

[5] https://circabc.europa.eu/sd/a/9b75e426-1563-4aba-a7d1-fdda0f4fdc5b/PEMS_PM_EC_JRC_131105.pdf

[6] Unfortunately, the lack of Euro VI vehicle availability did not permit ACEA to perform fully JRC's suggested test matrix.

Table 5-1 Tests, vehicles and instruments used on the PEMS PM pilot program.



PEMS PM Pilot Programme					
Vehicle type	# test	# OEM	# vehicles	Instrument	# test/instr
N1/N2	total = 9	1	2	A	5§
				B	7*
				C	2
M2	total = 5	1	1	A	5
				B	0
				C	0
N3	total =26	4	5	A	19†
				B	7
				C	0

* In three tests the equipment failed

§ One test the equipment failed

† One test result not validated

Table 5-2 Characteristics of tests perfomed for the PEMS PM pilot program.

Vehicle type	Test no.	WHTC Work ref [kWh]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
N2	PM-A N2-V2-T1	10.32	0	C	49%	27%	24%
	PM-A N2-V2-T2		0	C	48%	27%	25%
	PM-A N2-V2-T3		0	C	49%	27%	24%
	PM-A N2-V2-T4		0	C	49%	28%	23%
	PM-A N2-V2-T5		0	W	42%	33%	25%
	PM-B N2-V2-T1		0	C	49%	27%	24%
	PM-B N2-V2-T2		0	C	48%	27%	25%
	PM-B N2-V2-T3		0	C	49%	27%	24%
	PM-B N2-V2-T4		0	C	49%	28%	23%
	PM-B N2-V2-T5		0	W	42%	33%	25%
	PM-B N2-V1-T3	8.99	0	W	53%	22%	25%
	PM-B N2-V1-T4		0	W	54%	22%	24%
	PM-C N2-V1-T1		0	W	49%	23%	28%
	PM-C N2-V1-T2		0	W	48%	23%	29%

Vehicle type	Test no.	WHTC Work ref [kWh]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
M2	PM-A M2-V2-T1	10	100	W	52%	23%	26%
	PM-A M2-V2-T2		100	C	54%	22%	24%
	PM-A M2-V2-T3		100	W	56%	20%	24%
	PM-A M2-V2-T4		100	C	53%	22%	25%
	PM-A M2-V2-T5		100	W	59%	20%	21%

Vehicle type	Test no.	WHTC Work ref [kWh]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
N3	PM-A N3-V1-T1	34	0	W	26%	23%	51%
	PM-A N3-V1-T2			C	25%	25%	51%
	PM-A N3-V1-T3			W	28%	23%	49%
	PM-A N3-V2-T1	33	10	W	35%	63%	2%
	PM-A N3-V2-T2			C	39%	21%	40%
	PM-A N3-V2-T3			W	36%	22%	41%
	PM-A N3-V2-T4			W	33%	23%	44%
	PM-A N3-V2-T5			W	33%	24%	43%
	PM-A N3-V2-T6			W	35%	63%	2%
	PM-A N3 V2-T7			W	85%	15%	0%
	PM-A N3 V2-T8			W	84%	15%	1%
	PM-A N3 V2-T9			W	61%	16%	23%
	PM-A N3 V2-T10			W	37%	28%	35%
	PM-A N3 V2-T11			W	42%	25%	33%
	PM-A N3 V2-T12			W	42%	29%	30%
	PM-A N3-V3-T1	23.5	25	C	22%	23%	55%
	PM-A N3-V3-T2		25	C	26%	23%	51%
	PM-A N3-V4-T1	35.1	50	C	27%	27%	46%
	PM-A N3-V4-T2		25	C	24%	23%	53%
	PM-B N3-V5-T1	29.5	55	C	48%	13%	38%
	PM-B N3-V5-T2			C	45%	14%	41%
	PM-B N3-V5-T3			C	44%	15%	42%
	PM-B N3-V5-T4			C	39%	16%	44%
	PM-B N3-V5-T5			C	63%	18%	19%
	PM-B N3-V5-T6		10	C	52%	13%	34%
	PM-B N3-V5-T7		55	C	32%	10%	58%

5.4. Screening of test vehicles

There was no specific screening of vehicles because the availability of Euro VI HDV was very limited, having said that, the instrumentation was available to whoever requested it for test, including support from the different suppliers.

5.5. Test conditions

The test conditions were in line with Regulation EU 582/2011, Annex II.

5.6. Measurement of emissions and PM

The base measurement principle shall be a filter mass-based measurement accompanied by a real-time continuous aerosol concentration measurement carried out on the diluted exhaust.

5.6.1. PEMS Gaseous instruments

The gaseous PEMS systems shall comply with the requirements laid down in Regulation 582/2011, Annex II.

5.6.2. PEMS PM instruments

The PEMS systems shall comply with the recommendations laid down in [3, 4, 5, 6]

5.6.3. Test protocol

The tests shall be conducted according to the requirements laid down in Regulation 582/2011, Annex II and the proposed test matrix (Section 10.3).

5.6.4. Data analysis

The data analysis shall be conducted according to the requirements laid down in Regulation 582/2011, Annex II.

5.7. Results and discussion

The PEMS PM analysis obtained from the data that the different manufacturers and JRC provided was divided by vehicle and candidate instrument used. In order to have a fair analysis and result discussion both, vehicles and PEMS test instrumentation have been rendered anonymous.

Tests were performed in different conditions. There was no specific trip defined as some of the tests included in this assessment were also part of the HDV ISC assessment; it is worth to point out that the main objective of the pilot program is to understand the capability of the different instruments to measure the PM mass, and to recommend a practical and useful procedure.

Big focus was given to the processing of the data; as the different candidate instruments produced files with different variables it was very important to understand the information that each was giving. The JRC worked closely with the different suppliers in order to have confidence in the information obtained.

Alignment of the data obtained by the gaseous PEMS and the PM PEMS was a key issue to tackle before performing any analysis in a complete set of data. Mainly, exhaust mass flow measurement which was reported by both instruments was used as a mean to align the gaseous with the PM mass real time signal.

It is also as important to have confidence on the measured PM mass deposited on the filter. The measured mass on the filter is one of the most important factors along with the measured sampled exhaust and total exhaust mass flows. The handling of the filter constitutes the most important task which, if done incorrectly, can lead to calculation errors that end up having a big impact on PM conformity factors.

The following sections include the findings which are believed to be key as part of a PEMS PM data acquisition procedure and analysis.

5.7.1. Mass weighted on filter

Figure 5-1 presents the mass on filter measured by the different instruments on N2 vehicles. As it can be seen, there are significant differences on the amount of mass measured by the different instruments. On the case of tests PM-A N2-V2-T1 to T5 and PM-B N2-V2-T1 to T5, these tests were conducted on the same vehicle but measured with 2 different instruments mounted in parallel; the difference in flow passing through the filter (sampled exhaust flow) accounts for the different amounts of mass deposited in the filter.

Instruments B and C share a common measurement concept, even though they were not mounted in parallel on the vehicle (V1) the tests were similar (i.e. trip duration and composition nearly identical, see Section 10.4) resulting in similar mass weighted on the filter. This condition is due to the similar amount of sample flow passing through the filter.

Further, the following points must be taken into consideration where filter weighted mass present's significant differences:

i. The measured PM on filter depends on many factors, from the length of the test to the dilution that is being used by the different instruments
ii. Mass on filter is a critical value for the calculations, thus filter handling is a key part of the procedure which requires to be carefully executed (Regulation No. 49 - E/ECE/324/Rev.1/Add.48/Rev.6).
iii. Proper conditioning of the filter is required to be able to obtain constant/consistent results as required by the present regulation (Regulation No. 49 - E/ECE/324/Rev.1/Add.48/Rev.6).

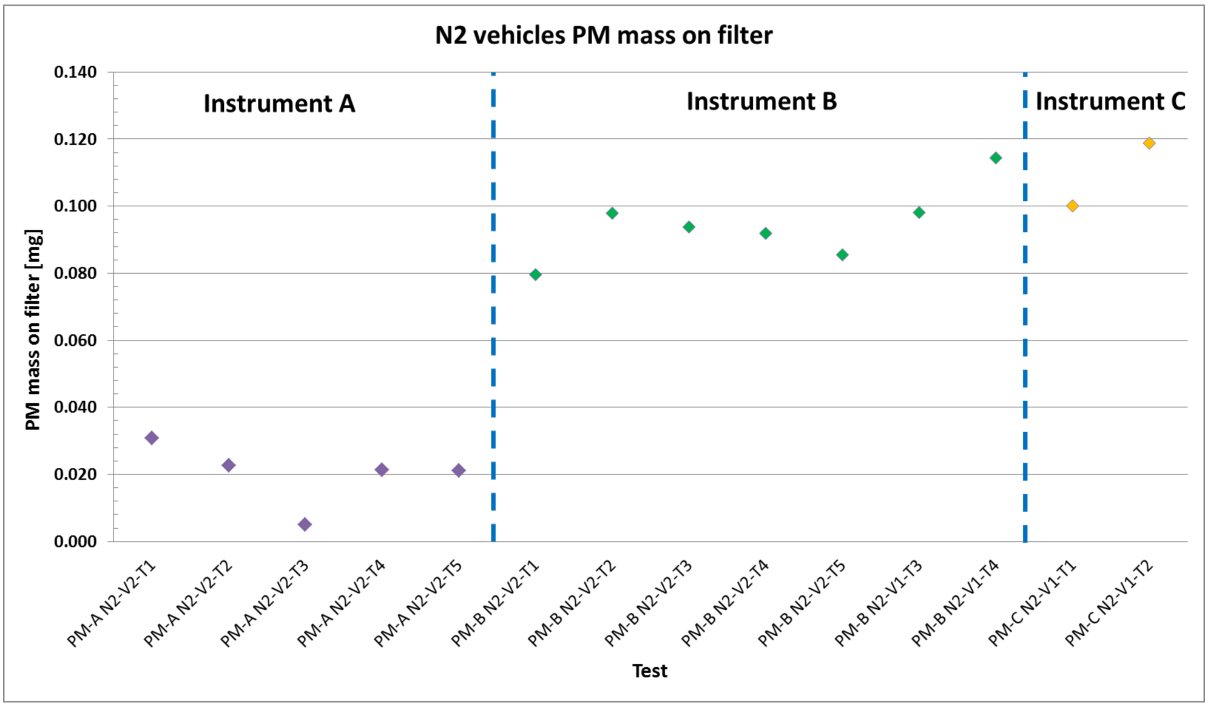


Figure 5-1 PM mass weighted on filter for N2 vehicles tests.

A larger spread of the mass on the filter is found in the case of N3 and M2 vehicles (Figure 5-2 and Figure 5-3 respectively). This supports the fact that the amount of mass deposited on the filter is determined by many factors; in any case, the masses are of the order of those found in N2 vehicles reflecting the efficiency of the Diesel Particle Filter (DPF).

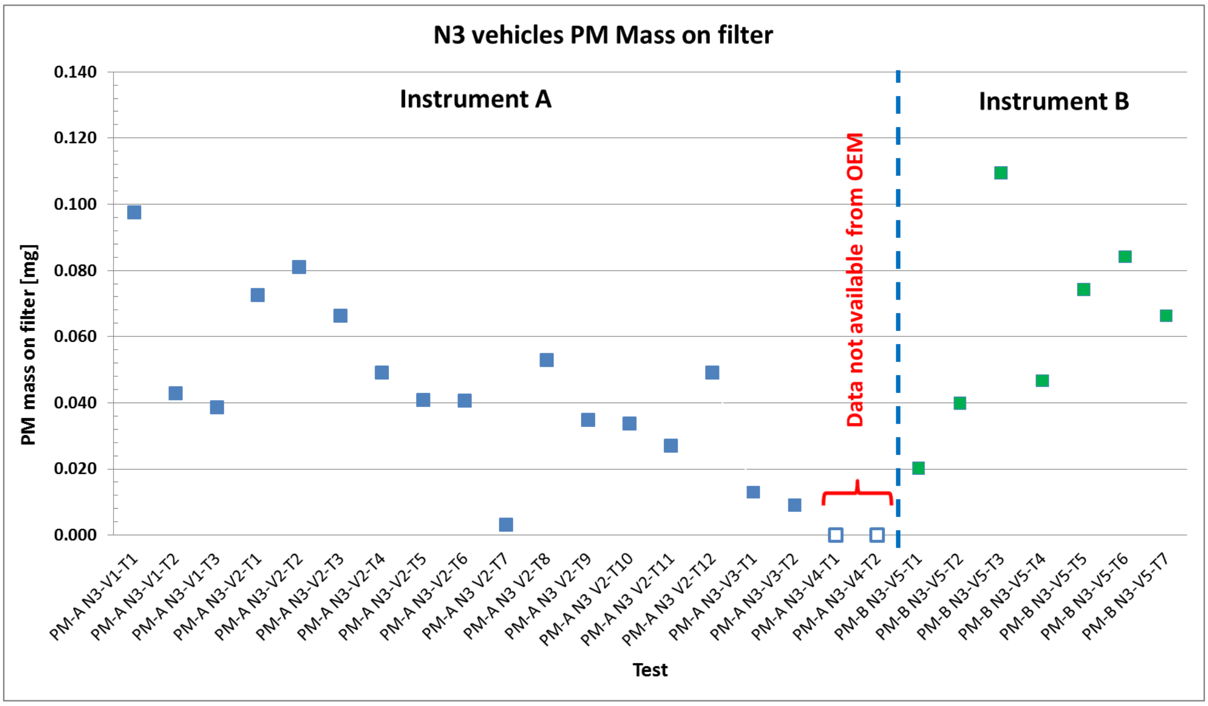


Figure 5-2 PM mass weighted on filter for N3 vehicles tests.

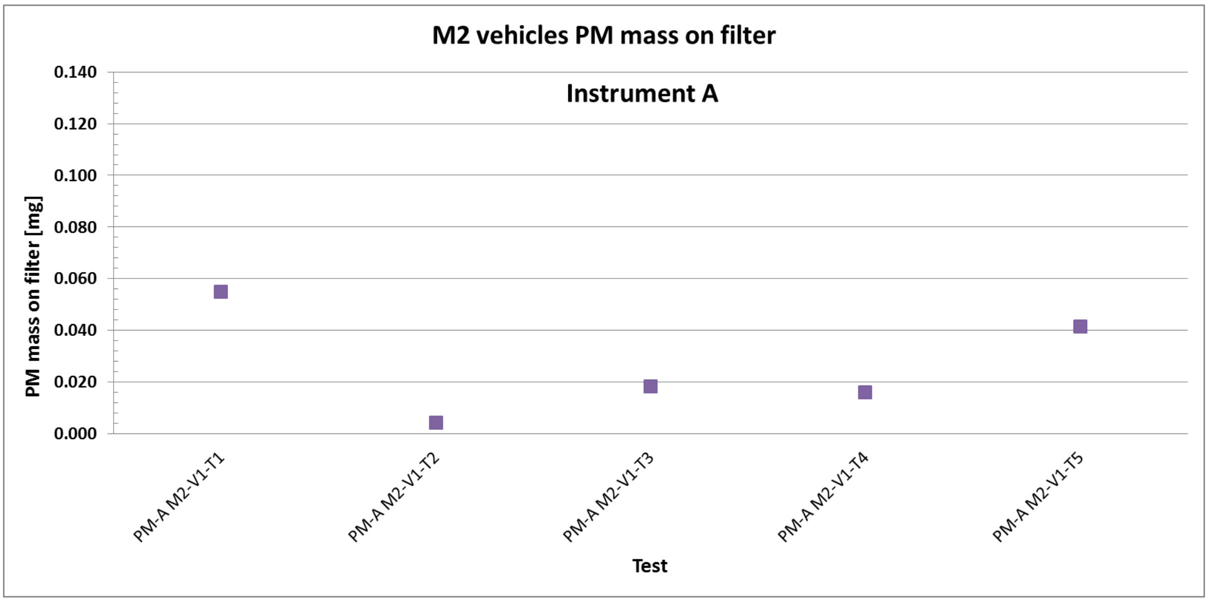


Figure 5-3 PM mass weighted on filter for M2 vehicles tests.

Being a mechanical filter, the DPF efficiency depends on the amount of PM concentrated on the brick (cake) and if it has regenerated before the test; hence the resulting mass will also be dependent on the condition of the DPF on any specific trip.

5.7.2. PM mass and boundary conditions

The PM mass required for the MAW analysis is the grams per test of PM produced by the vehicle; this mass per test is obtained by the procedure detailed in Section 3.1, one important detail to take into account is that the mass contained on the filter comes from sampling over the whole length of the trip.

This detail comes into play when it is required to apply the different boundary conditions written on current gaseous legislation (Annex II EC Regulation 582/2011). Should this legislation apply to the PEMS-PM measurements, same boundaries will be applied to the second by second data and the consequent MAW analysis.

While the EMROAD analysis tool requires the PM in grams per test, the grams per test obtained from a whole trip may need to be revised to subtract the portion of PM produced, for instance, in the cold start period. Leaving the grams per test intact and running the MAW analysis may lead to higher conformity factors as the PM mass of the total trip will be distributed in a shorter operation period than it is supposed to[7].

For instance, let us take Figure 5-4 below, this figure shows the conformity factors obtained by the operation of a specific trip which contained an amount of cold start operation. As it can be seen, the blue trace represents the same MAW analysis without the cold start operation share but the grams per test were not revised hence causing higher CFs (same trend but higher values).

Once the grams per test have been calculated, a good practice is to normalize the mass obtained to the signal using the dilution factor as instructed in Section 3.1

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[7] EMROAD needs to be revised to correct the PM g/test according to the above indication and in order to perform the correct CF analysis.

hence obtaining the mass per second. Once this mass per second is obtained, one can make an adjustment on the grams per test by subtracting the share of the cold start and running the analysis for the warm operation only. While some software tools may be already design to do this extra step, it will not be evident until performing the analysis with and without cold start operation.

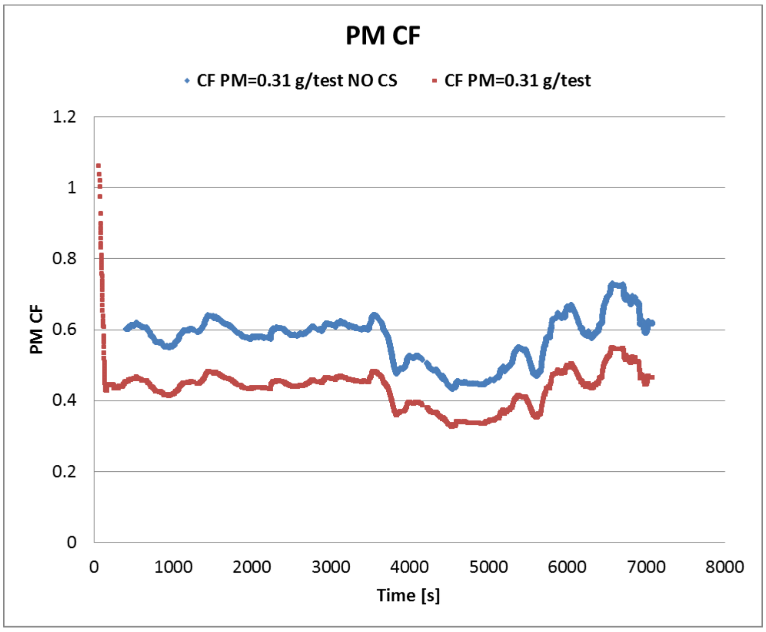

Figure 5-4 Effect on CF by not substracting CS operation mass from PM (g/test) when performing MAW analysis (~500s CS operation) [test PM-B-N2-V2-T4 with start coolant temperature of 306 K]

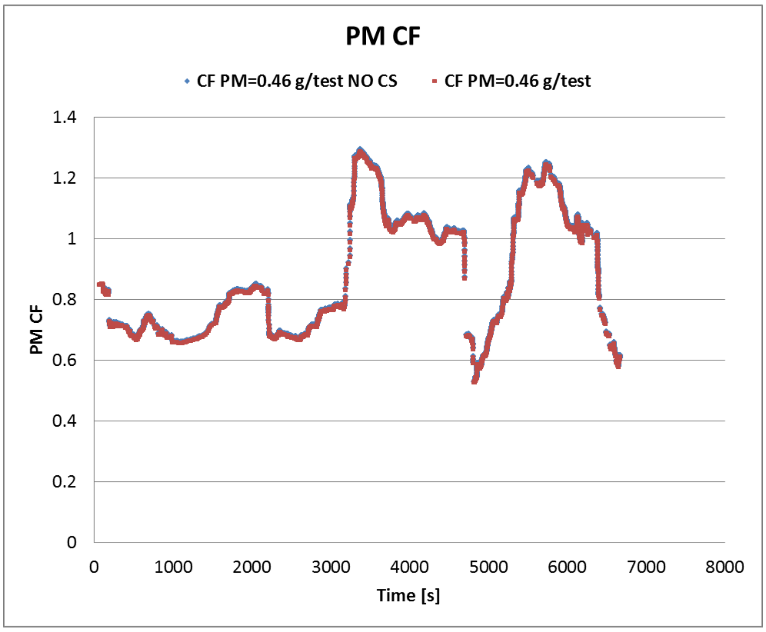

Figure 5-5 Effect on CF by not substracting CS operation mass from PM (g/test) when performing MAW analysis (~130s CS operation)) [test PM-B-N2-V2-T2 with start coolant temperature of 342 K]

Figure 5-5 shows the same effect of PM mass not revised on a shorter cold start operation (~130sec). Furthermore, other boundary conditions (e.g. 20% power threshold or 90th percentile) do not have this specific issue.

5.7.3. *MAW results*

Figure 5-6 shows the result distribution for the CF of N2 vehicles.

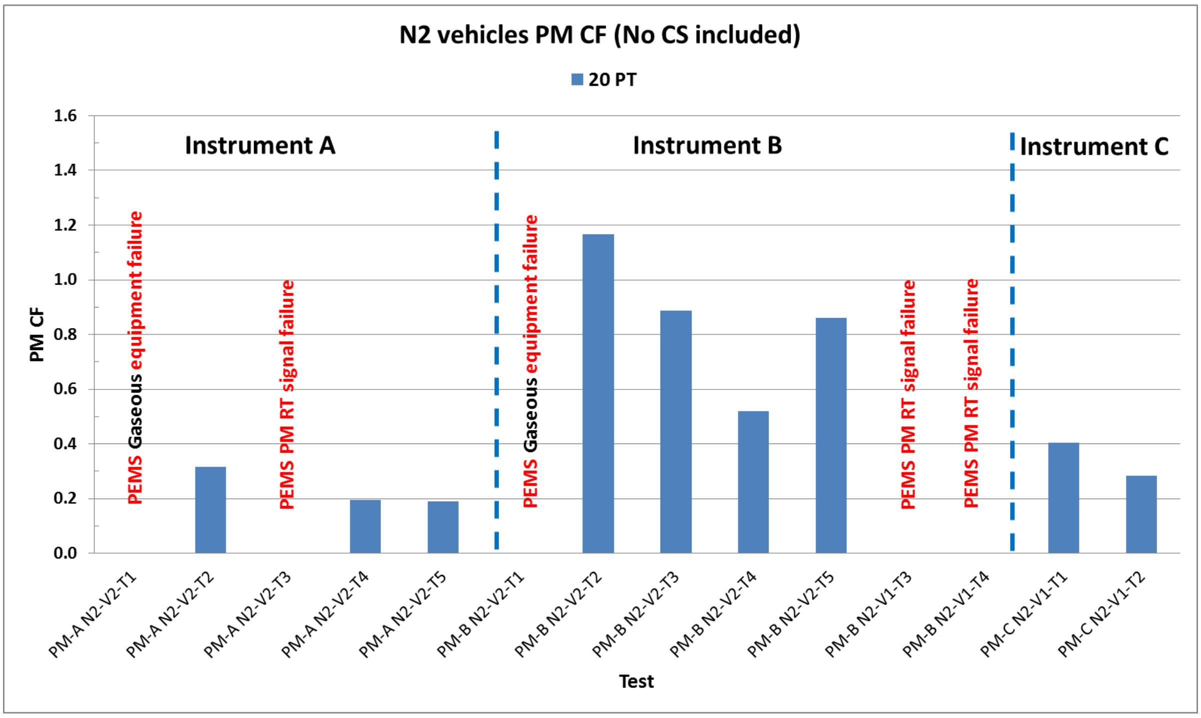

Figure 5-6 PM CF for N2 vehicles tests excluding cold-start operations.

In this figure, it is important to observe the difference in CFs resulting from using two different candidate instruments on the same vehicle and same trips. In this case the difference might be due to issues on data acquisition from one of the candidate instrument (Equipment B). As it can be seen the levels of CF from Equipment A and C relate to each other; the tests performed with Equipment C are different from those from Equipment A, but the CFs are on the same range. This is to be expected because they are similar vehicles performing similar trips in composition and duration (see Section 10.4). This fact indicates a good consistency between different instruments.

Further, Figure 5-7 shows the range of CFs from N3 vehicles. As it can be seen, most of the conformity factors are between a range from 0 to 0.5, this figure represents 5 different vehicles performing different trips in different conditions. PM-A N3-V2-T7 and T8 do not have enough valid windows (i.e. more than 50% valid windows) at 20% (15%) power threshold. It is worthwhile to note that the efficiency of DPFs are influenced by its previous history (i.e. amount of PM concentrated on the brick (cake) and/or whether a regeneration has occurred before the test) which is not available to the JRC. Therefore a variability of the CF from these vehicles, tests and PEMS-PM instruments can be reasonably expected.

The elevated value found on PM-A N3-V1-T1 may be caused due to an elevated mass deposited on the filter. As it can be seen in Figure 5-2, the particle mass deposited in the PM-A N3-V1-T1 filter is more than twice that for the case of PM-A N3-V1-T2 & T3 which are filters of two other trips on the same vehicle running similar trips in shares (as can be drawn from the trip share shown in Table 5-2 and Section 10.5) and length. Although previous history of operation of the vehicle along with details on the procedure followed to perform the test were not shared, these are assumed to be in-line with what is described in regulation EC 582/2011. Having said this, by comparing raw data (real-time signal and exhaust flows reported by the PEMS PM instrument - Section 10.5), it is believed that the elevated weight on the filter might be due to problems related to filter handling.

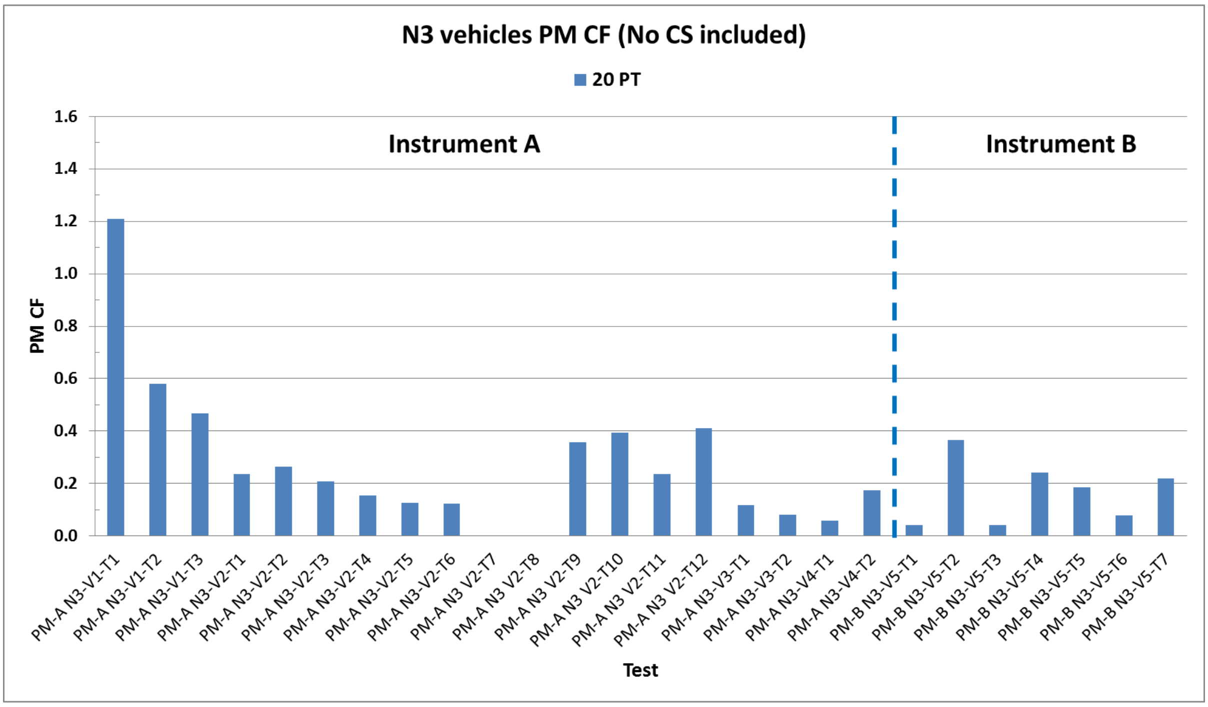

Figure 5-7 PM CF for N3 vehicles tests. PM-A N3-V2-T7 and T8 do not have enough valid windows (i.e. more than 50% valid windows) at 20% (15%) PT

M2 vehicles PM data is presented in the following sections where a detailed analysis is performed varying the power threshold in the analysis; this is because four out of five trips do not have enough valid windows at 20% (15%) power threshold which is the boundary condition addressed in this section.

6. Current PEMS gaseous procedures boundaries evaluation applied to PEMS-PM data.

Once the feasibility of using PEMS-PM instruments has been confirmed in the above sections, in this section the different boundary conditions for the PEMS methodology for gaseous pollutants are applied to analyse the PEMS-PM second-by-second data. Further information and effects of the different boundary conditions on PEMS gaseous emissions measurements can be found in the PEMS assessment report [7]. The goal of this discussion is to provide enough evidence to define a PEMS-PM procedure as indicated in Section 5.1.

6.1. Cold start operation

In the present gaseous legislation cold-start is defined as the operation with a coolant temperature below 343 K (70 °C) [9], data produced during this period is not considered in the data evaluation.

As it was indicated in Section 5.7.2, a comparison was made by analysing the trips containing cold start with and without the cold start operation, Figure 6-1 shows the comparison at 20% power threshold, 90th cumulative percentile of the PM conformity factors with and without cold start operation included for N2 vehicles. As it can be seen, the effect of the cold start operation using current legislative boundaries on conformity factor is negligible.

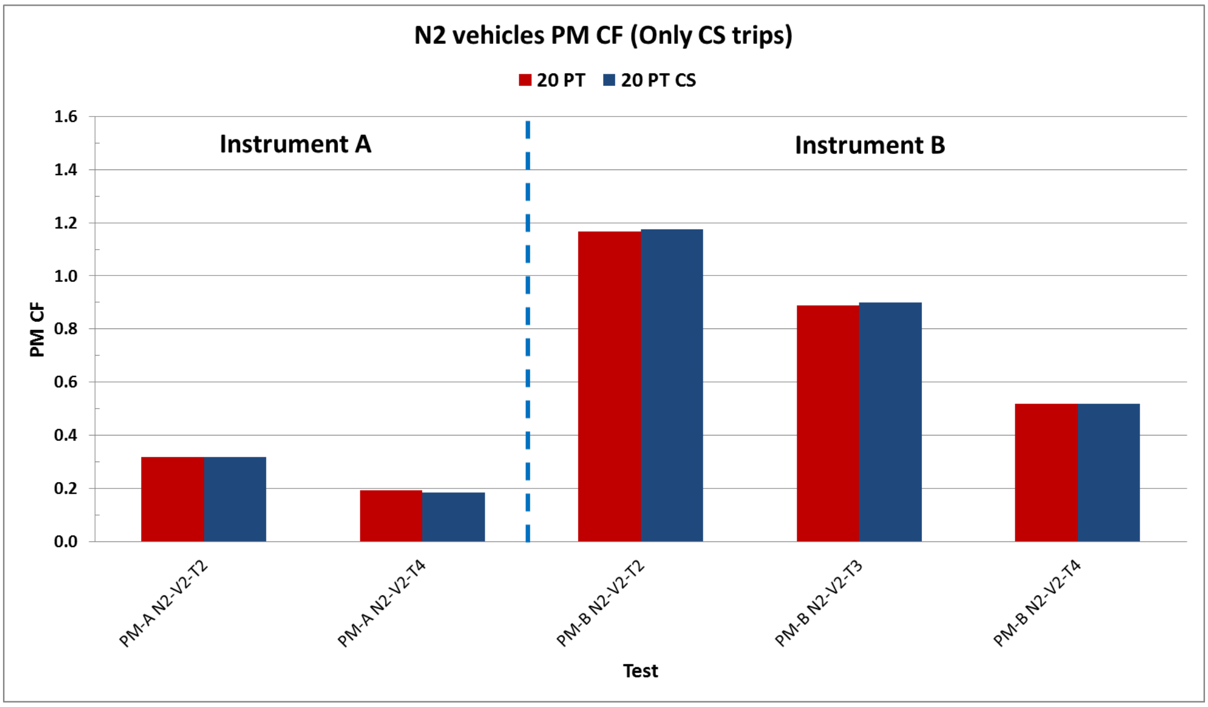

Figure 6-1 N2 vehicles PM CF comparison between MAW analysis with and without CS considered (20% PT and 90th cumulative percentile).

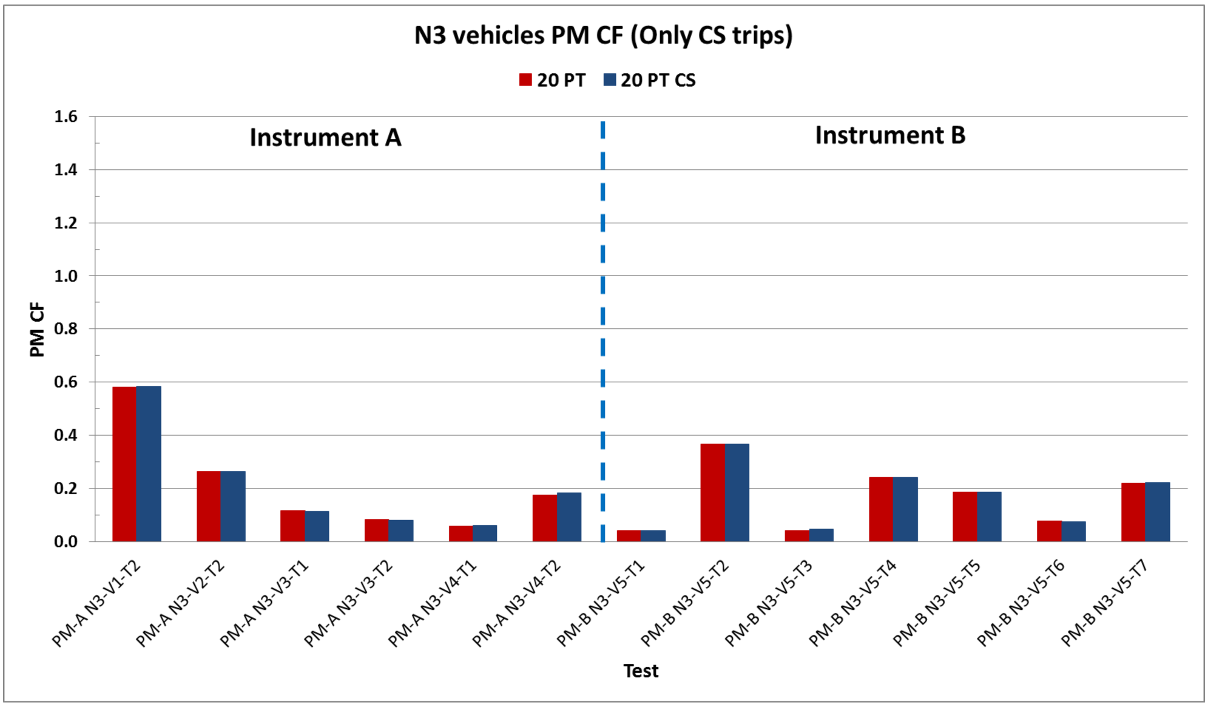

Figure 6-2 N3 vehicles PM CF comparison between MAW analysis with and without CS considered (20% PT and 90th cumulative percentile).

Same is confirmed by Figure 6-2 for N3 vehicles. In general terms, the effect of the cold start operation is not a factor which impacts the PM under the present applicable boundary conditions.

6.2. Low power operations

Low power operations were also analysed on the PM PEMS data, Figure 6-3, Figure 6-4 and Figure 6-5 depict how the different power thresholds affect the conformity factors. It is possible to say that the low power operation has a non-negligible impact on the results. In most of the cases the inclusion of lower power operation results on a slightly higher/lower CF, this is mainly due to the increased amount of windows to analyse and the fact that some of these windows will have a higher/lower CF [7].

Results on these figures represent the 90th cumulative percentile of the conformity factor after analysing the data with the different power thresholds.

As it can be seen in Figure 6-5, most of the M2 trips do not show values for 20 and 15% power thresholds, this is due to lack of valid windows (i.e. 50% valid windows) to be able to perform the MAW analysis.

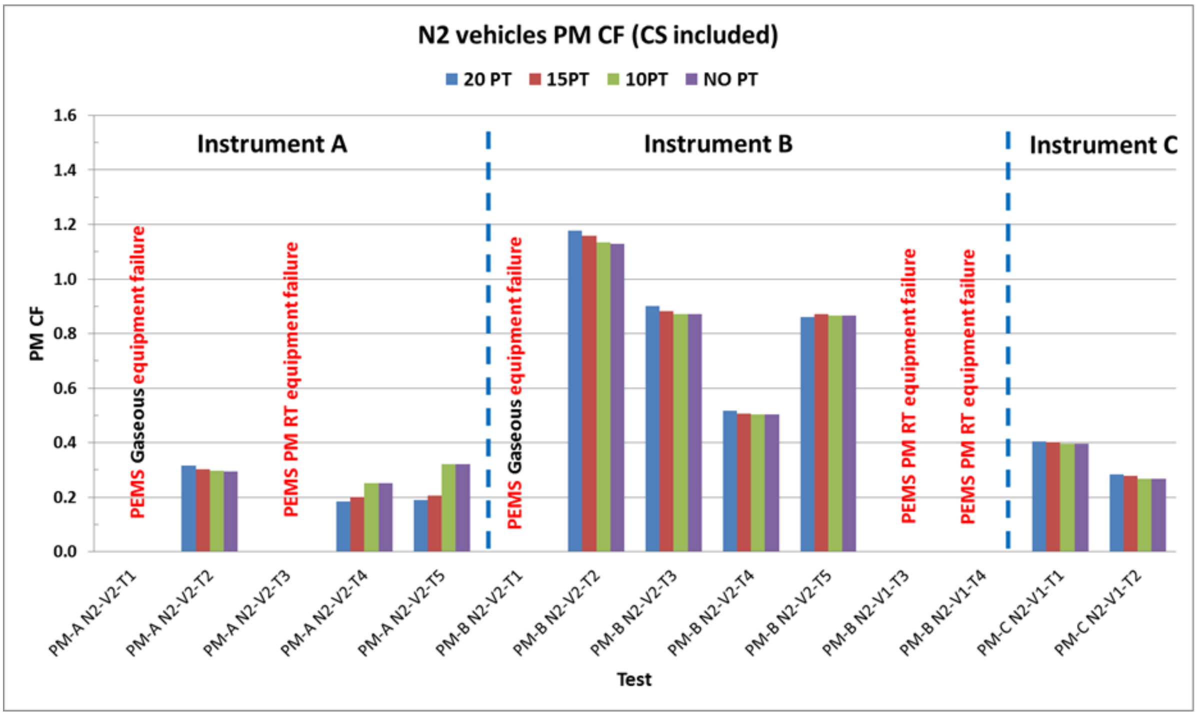

Figure 6-3 N2 vehicles effect on PM CF through different power thresholds (90th cumulative percentile)

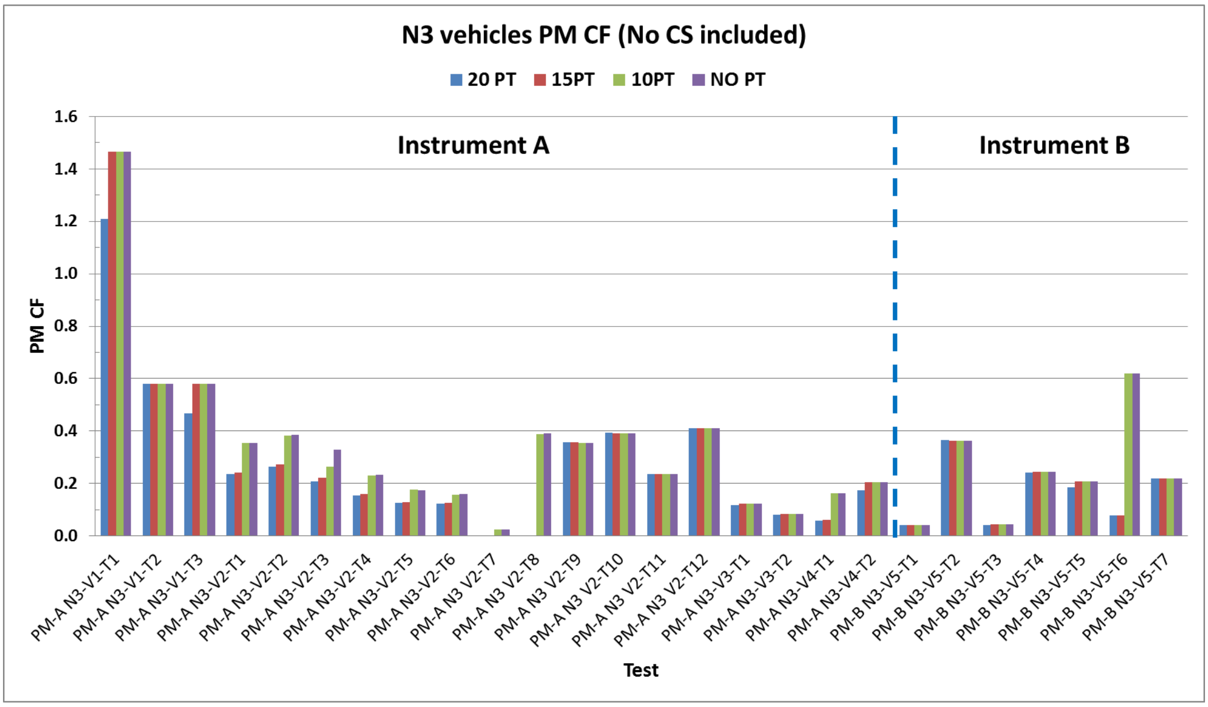

Figure 6-4 N3 vehicles effect on PM CF through different power thresholds (90th cumulative percentile)

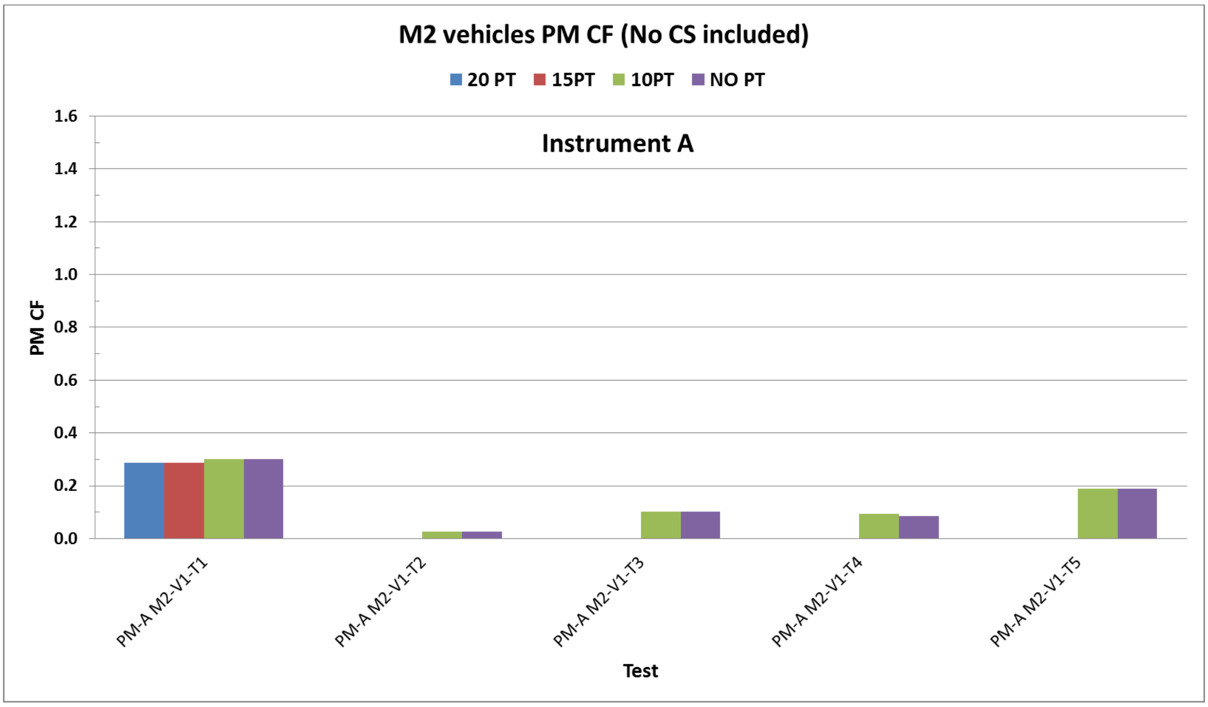

Figure 6-5 M2 vehicles effect on PM CF through different power thresholds (90th cumulative percentile)

6.3. Objectives settings

In order to account for the nature of on-road testing which includes the variability of the testing conditions generated by among others the traffic conditions and the driver for a given test route, a 90% cumulative percentile was deemed to be the better indicator of the engine emission performance. In this case, the 100th percentile (max value) for PM CF was also calculated.

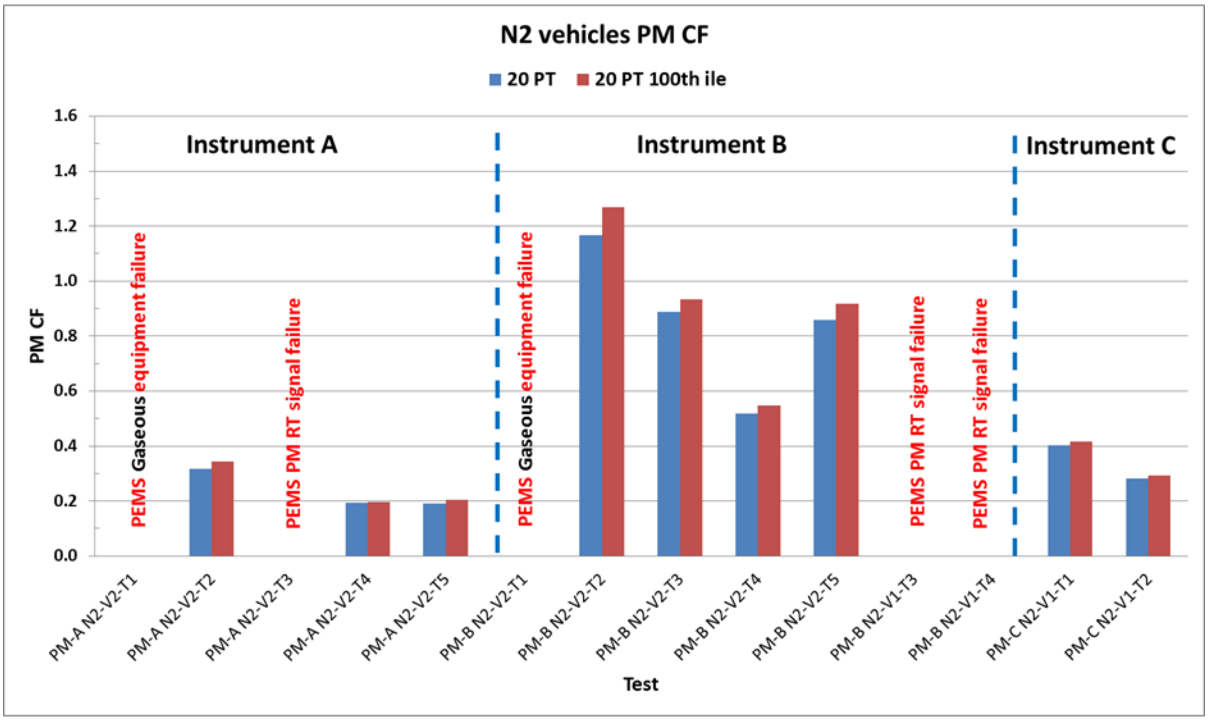

Figure 6-6 N2 vehicles PM CF comparison between 90th and 100th cumulative percentile (at 20% PT).

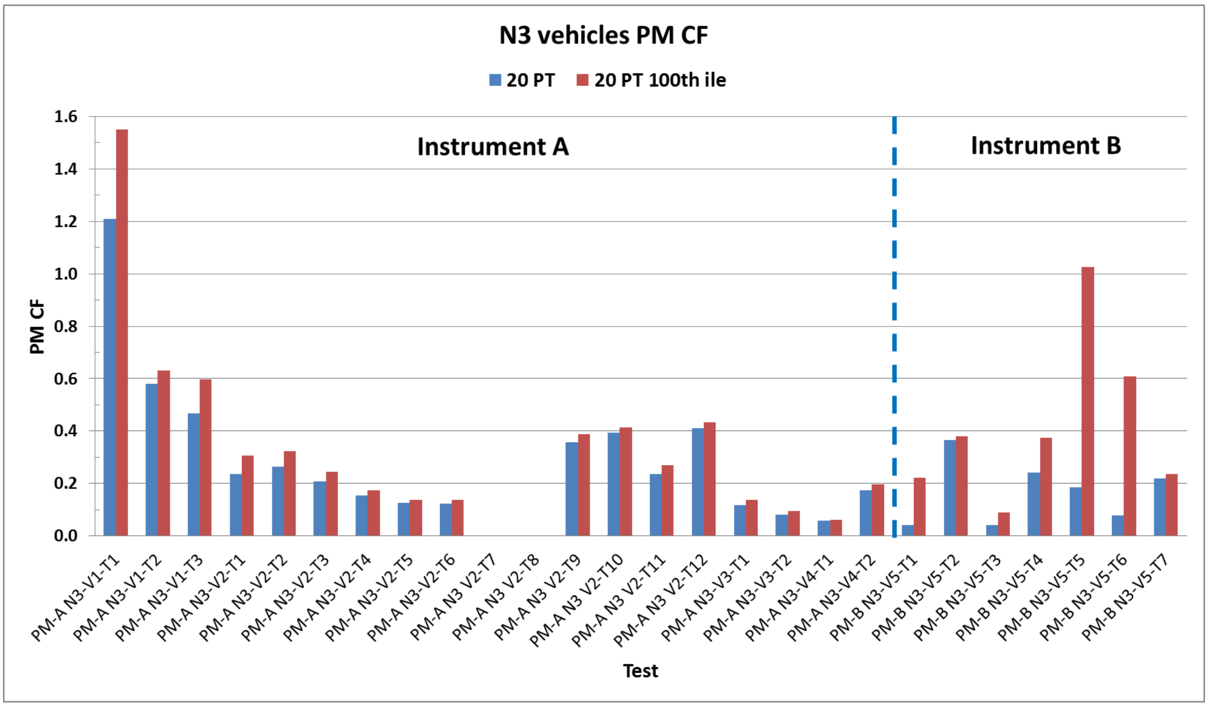

Figure 6-7 N3 vehicles PM CF comparison between 90th and 100th cumulative percentile (at 20% PT).

As it can be seen, Figure 6-6 and Figure 6-7 show the comparison between those 90th and 100th cumulative percentile values for PM CF. Both of the figures show the 20% PT analysis; some of the values have a significant difference between each other, meaning that high CF windows are out of the 90th percentile threshold. The amount of PM left out by this boundary will be looked at in the next sections.

As noted in previous sections, results of M2 are not shown as the majority of the tests didn't have enough windows at 20% (15%) PT used to analyse the rest of the data.

6.4. Trip composition

The analysis of the effect on regulated emissions due to the order of the shares of operation in which the on-road test is conducted has shown an impact on some of them [7]. In the case of PM, result analysis show an effect which may be attributed to the urban operation start. However, this effect may also be due to the cold start condition (further detail on cold start operation please see sections 6.1, 6.5.1 and 6.5.2).

Figure 6-8 shows 2 speed traces, same vehicle, with similar shares of operation but with an important difference, while PM-A N3-V2-T2 is starting with urban operation, PM-A N3-V2-T3 begins operating on the motorway.

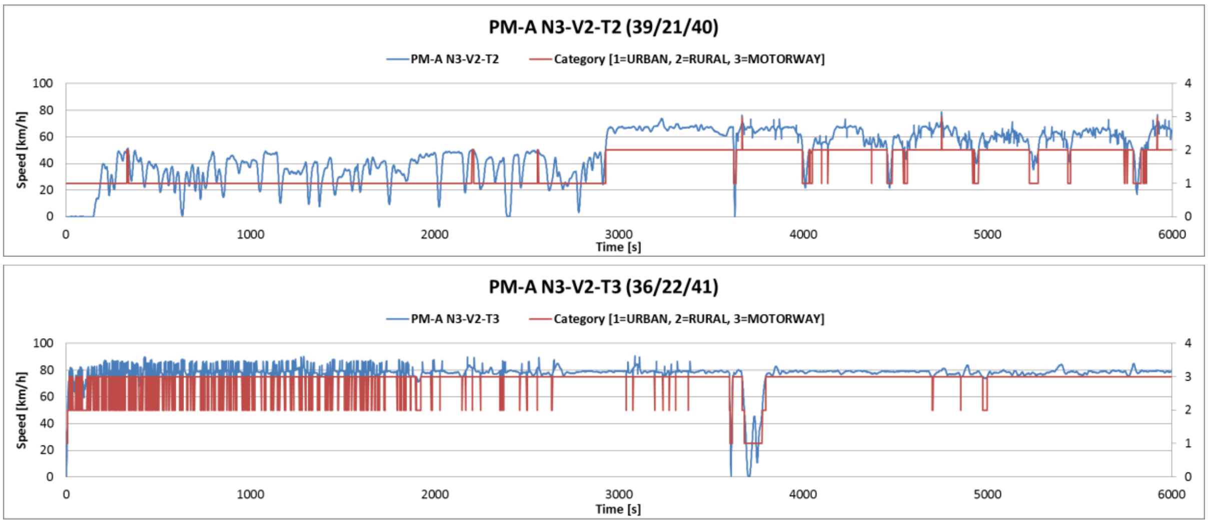

Figure 6-8 Speed traces details of first 6000 sec of tests PM-A N3-V2-T2 & T3.

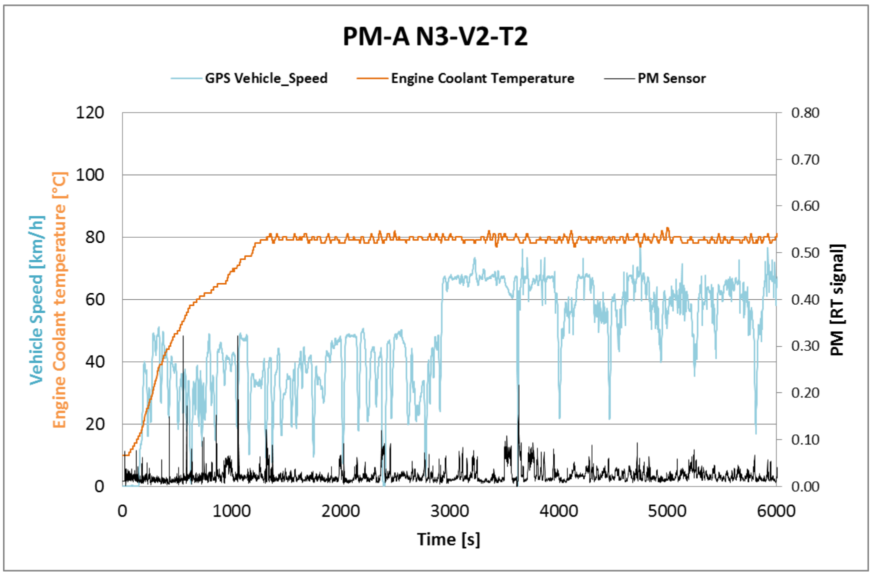

Figure 6-9 PM-A N3-V2-T2 PM real-time signal behaviour.

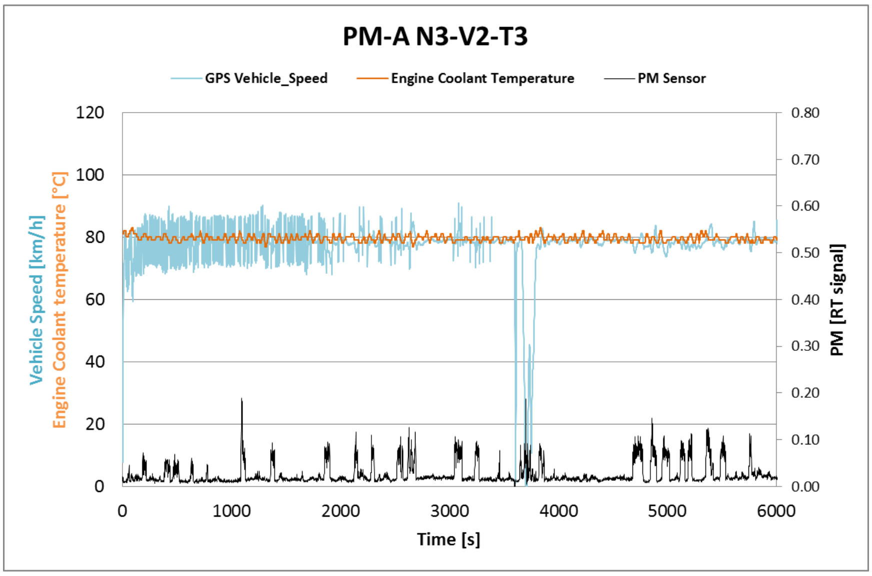

Figure 6-10 PM-A N3-V2-T3 PM real-time signal behaviour.

Figure 6-9 and Figure 6-10 show the behaviour of the PM real-time signal on both starting conditions, urban and motorway respectively. As it can be seen, the effect of the urban start on the real-time PM signal evidence some peaks while the engine coolant temperature is below 70°C, these peaks are about twice the size of the highest shown during the motorway operation. Figure 6-10 shows a steadier behaviour of the PM, where some small peaks appear during the motorway operation which may be related to slight changes on the pedal position (acceleration or deceleration).

6.5. Overview of the amount of PM emitted and not considered in the MAW analysis due to combined boundary conditions.

Previous sections of this report have hinted that sometimes it will be necessary to analyse the impact of boundary conditions/exclusion criteria acting concurrently as it seemed that they may act redundantly when taken separately. This section intends to address this possibility by studying the effects on the PM mass when the data is processed addressing more than one of the boundary conditions/exclusion criteria at once. This will allow understanding to what extent the current prescriptions defined in Annex II to Regulation 582/2011 for Conformity of in-service engines or vehicles provide a fair representation of the emissions behaviour of the vehicles under study.

6.5.1. Engine coolant temperature and power threshold

Section 4.3 of Annex II to regulation 582/2011, which calls Paragraph 2.6.1 from Appendix 1 to Annex II to the same regulation states:

"…the data evaluation shall start after the coolant temperature has reached 343K (70°C) or after the coolant temperature is stabilised within +/-2K over a period of 5 minutes whichever comes first but no later than 20 minutes after engine start."

And Section 4.2.2 to the same Appendix:

"…The valid windows are the windows whose average power exceeds the power threshold of 20 % of the maximum engine power. The percentage of valid windows shall be equal or greater than 50 %".

The boundaries contained in these two paragraphs limit the valid data that could potentially be used in the analysis.

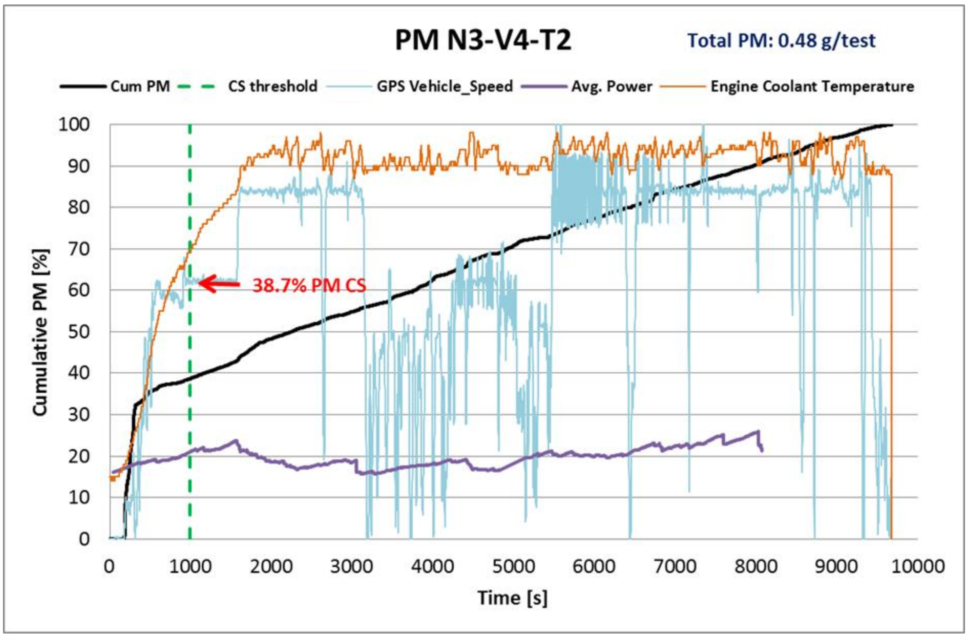

Figure 6-11 N3 vehicle test percentage of PM mass excluded due to cold start condition.

Figure 6-11 pictures the amount of PM not considered due to cold start exclusion on this specific test. Cold start is a boundary that directly affects the amount of PM taken into account for the analysis. Because the DPF is a mechanical filter, it is not expected to be affected by cold start condition; however, there are other factors contributing to this surge on PM concentration at cold start as explained by Giechaskiel et al. [8]. Particles may be formed by nucleation/condensation of volatile material previously stored within the exhaust system, after treatment or particulate layer and released as the system heats up, the surge may also be caused by the state of loading of the DPF. Because of the previous history of the vehicles which took part on the pilot program is unknown, it is not possible to attribute the behaviour to this latter condition.

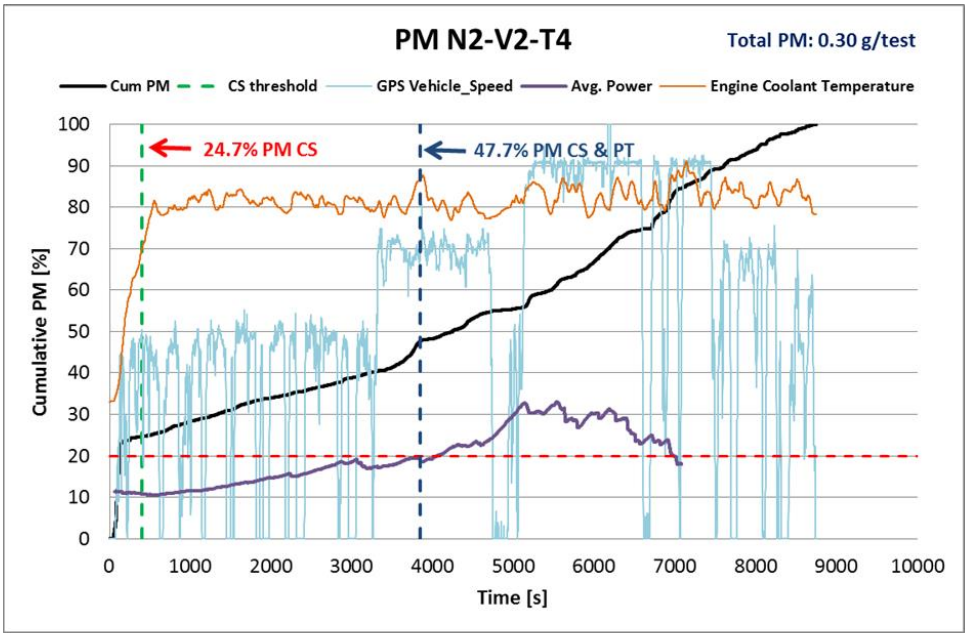

Figure 6-12 N2 vehicle test percentage of PM mass excluded by cold start and power threshold.

The fact that the boundary exists, causes the exclusion of an important part of the PM mass produced in cold starting operations.

Figure 6-12 is another example, in this case, the figure also show the percentage of PM excluded due to the 20% power threshold boundary.

It is important to note, that these two boundary conditions combined are leaving almost 48% of the PM mass produced by this vehicle on this trip out of the MAW analysis.

6.5.2. 90th cumulative percentile and cold start.

The objective setting of the 90th cumulative percentile is a boundary condition imposed by the procedure to analyse the data. It works as a statistic approach to obtain a realistic conformity factor which represents the PM emitted through the trip; the 90th cumulative percentile prevents taking the maximum conformity factor which may be due to a specific event which does not represent the vehicle performance correctly. However, when the 90th cumulative percentile is combined with the inclusion of cold-start operations, some problems arise.

As previously noted, the cold start of the vehicle produces an increased amount of particles; this is invariably shown in the real-time signal and confirmed by the filter weight.

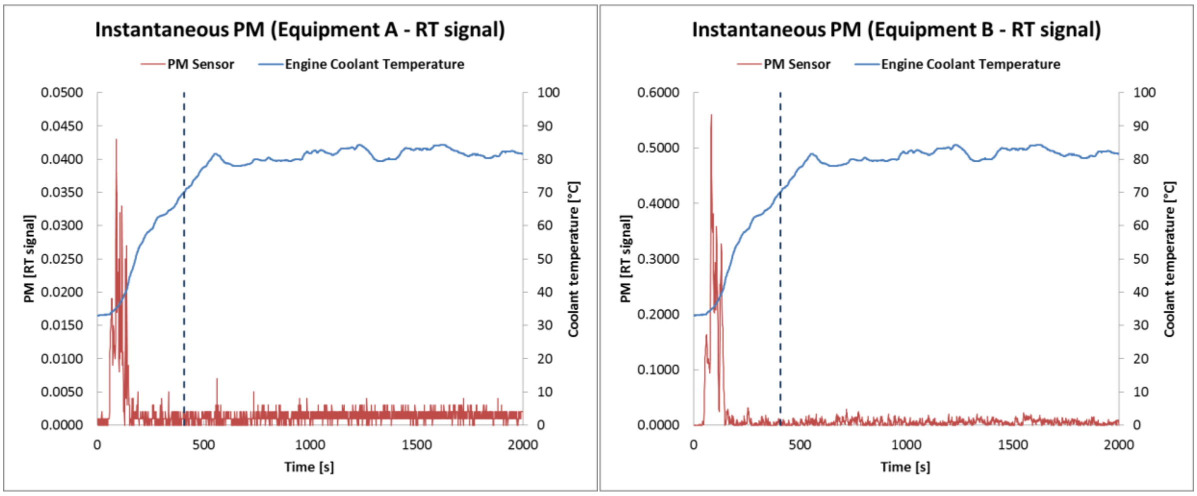

Figure 6-13 N2 vehicle test showing PM RT signal peak at the beginning of the trip with 2 instruments.

Figure 6-13 shows an example of the PM real-time signal of a test performed with two different instruments. In this figure, the red line shows the PM real-time signal at the beginning of the trip, where the coolant temperature is ~33°C. Please note that both instruments are showing the increase of the PM real-time signal for about 150 seconds. In this case, the amount of PM mass left out of the analysis due to the exclusion of cold start operation is 25%. Figure 6-14 shows the same real-time trace and the engine speed, the reason behind showing this operation is to have a clear understanding that this condition is found at the very beginning of a cold start test (engine start).

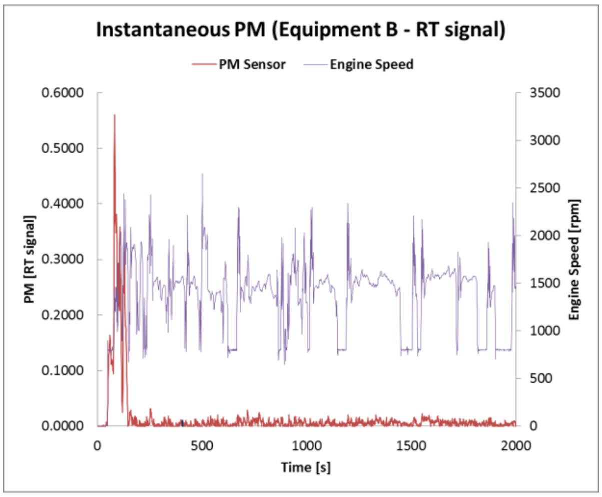

Figure 6-14 N2 vehicle trip PM real-time signal and engine speed.

Another example is shown in Figure 6-15. In this case, the whole operation is portrayed to be able to look at the elevated PM real-time signal in the cold start region of the trip; the right part of the figure shows the first 2000 seconds. In these seconds, the coolant temperature begins at ~33°C and starts rising, the engine speed starts logging and there's a sudden rise of PM signal at ~1200 seconds (coolant temp ~40°C). The red PM signal peak at ~1200 seconds is the highest value found in the trip. The cold start operation (until coolant temperature arrived to 70°C) produced 70% of the total PM on this trip.

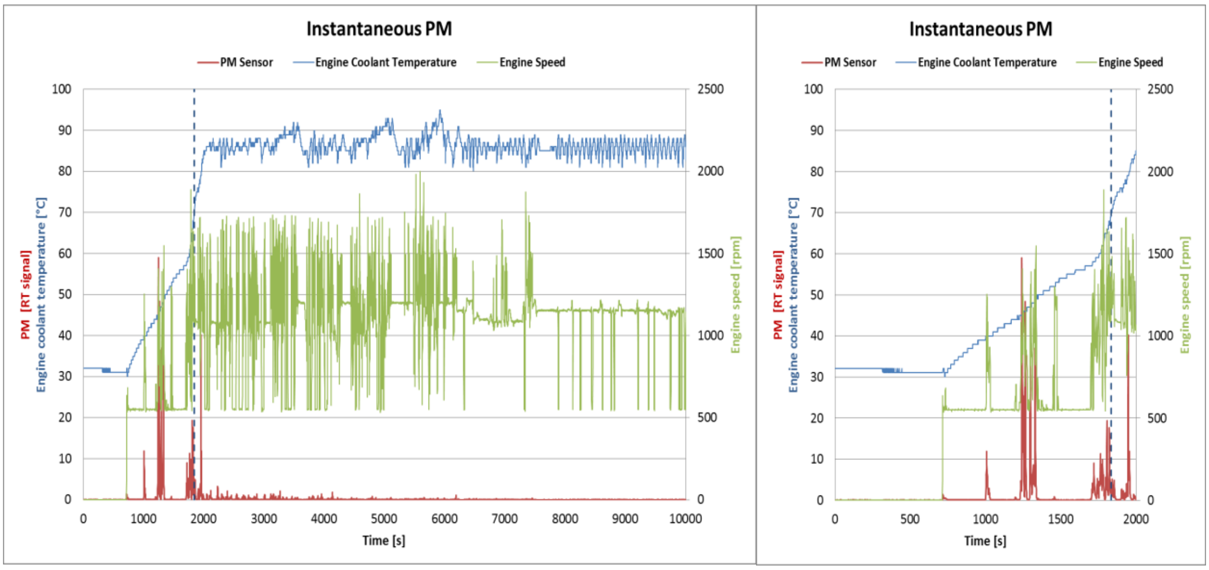

Figure 6-15 N3 vehicle trip PM real time signal, engine coolant temperature and engine speed.

The effect of the 90th cumulative percentile on elevated PM real-time signal is critical as the highest values will be deemed outliers or will fall on the top 10 percentile left out of the windows considered for analysis.

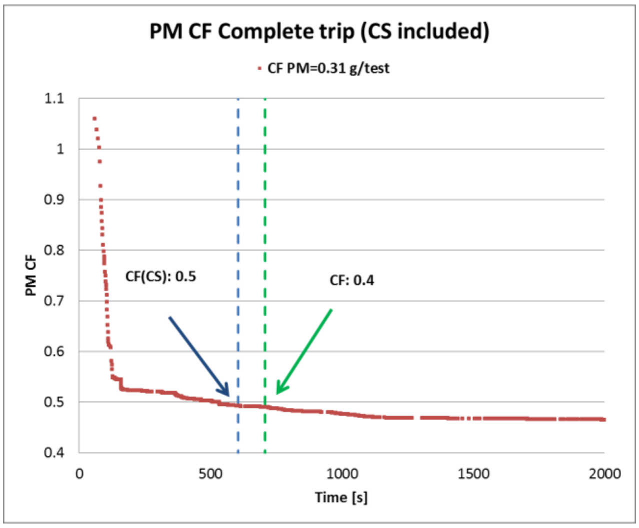

Figure 6-16 Effect of 90th cumulative percentile on PM CF.

Figure 6-16 shows the difference between the CF with and without the cold start operation included. In both cases, the 90th cumulative percentile boundary is applied to the values of conformity factor. As it can be seen, the CF belonging to the concentration surge from the cold start operation is excluded in both cases.

As it can be seen, the statistic approach taken while using the 90th cumulative percentile is robust enough for warm operation, but it has an important limitation when analysing the cold start behaviour.

Based on these appreciations, the discussion on the inclusion of the cold start operation on gaseous emissions [7] would need to address the PM mass effect as well.

7. Regeneration

Regeneration is an important part on the life of the particle after treatment system; it cleans the diesel particle filter and turns the conglomerate of particles into ash and CO2. While this operation is necessary to sustain the working life of the DPF, there has been much debate on whether include it or supress it from any PEMS based test. This debate is directed to the fact that the larger PM mass concentrations found while the regeneration is occurring is not considered as a normal mass emitted by an engine while in regular operation.

JRC analysis of the PM Pilot program results show that, while the regeneration produces a high concentration of PM mass, the analysis of the data and the correct use of the procedure detailed in Section 3.1 must suffice in order to be able to normalize the filter weight to the real-time signal and extract this part from the MAW analysis (this must be done as a manual post-processing of the data). Having said this, JRC concurs on the fact that this operation complicates the data analysis.

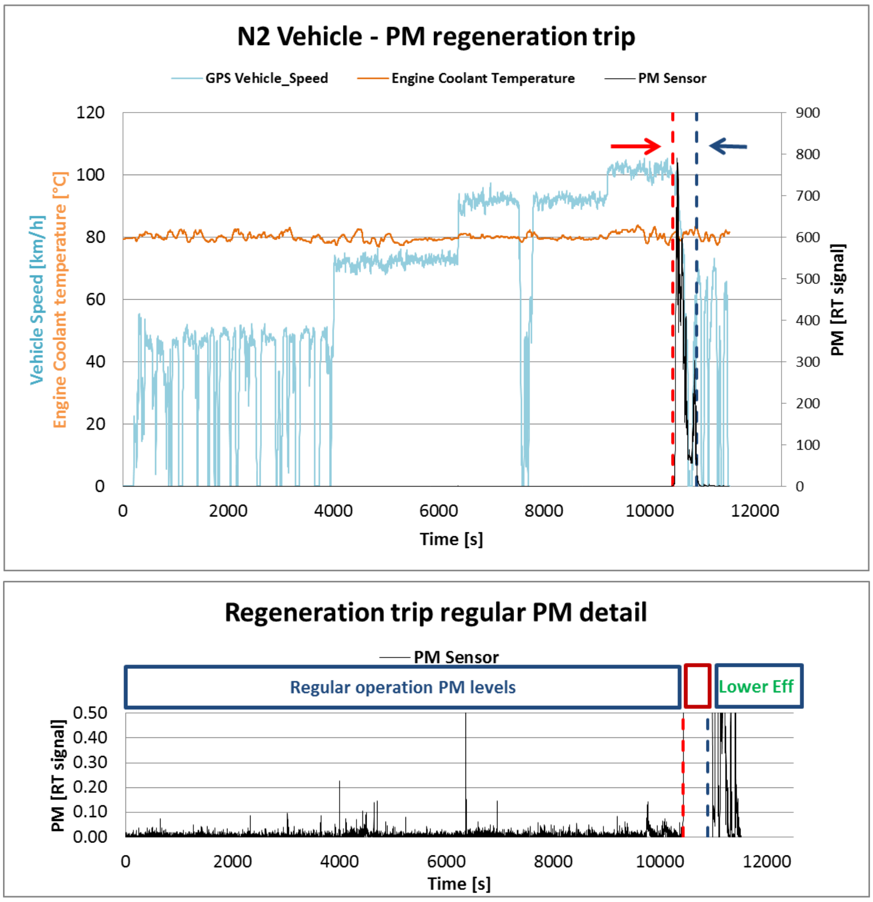

Figure 7-1 N2 vehicle test with regeneration event.

Figure 7-1 represents an N2 vehicle trip which had a regeneration event. On the top of the figure, the regeneration event is delimited by the dotted lines; this regeneration event ran for ~460 seconds. The bottom of the figure shows the PM behaviour detail which is divided in three areas, the regular operation PM levels, the red rectangle which represents the main regeneration event and the lower DPF efficiency levels of PM which is the part of the operation where the level of efficiency of the DPF falls due to the regeneration event.

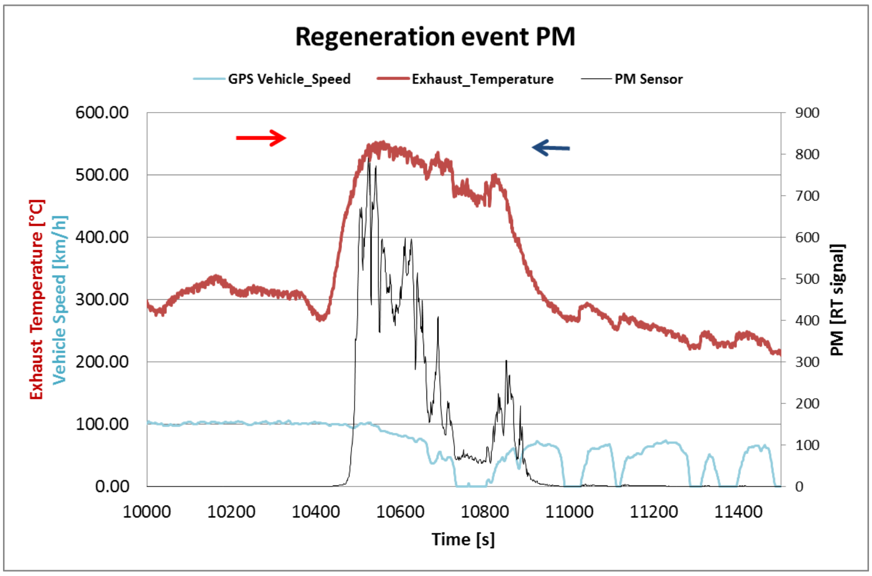

Figure 7-2 Exhaust temperature during the regeneration event

Figure 7-2 shows the exhaust temperature rise where the regeneration takes place.

While the real-time signal clearly shows the regeneration, the quantification of the mass of PM left on a filter due to this event is difficult. The normalization of the real-time signal with the grams per test of PM is possible; however, the levels of flow with a high content of regeneration material may affect the sensor readings on some instruments leading to erroneous analyses.

Figure 7-3 shows another example where a regeneration event takes place on an M2 vehicle trip. In this case the regeneration event duration is approximately 1500 seconds. It was decided to perform the MAW for this case and compare the conformity factors with and without the regeneration event included. The procedure followed to perform this analysis was to obtain the grams per test of PM including the regeneration based on the filter weight obtained.

Next step was to calculate the amount of grams of PM belonging to the regeneration, one important point to be aware of, is to be able to recognize the end of the regeneration; this is of relevance as the efficiency of the DPF falls just after the regeneration has taken place, thus, factors like exhaust temperature or NOx levels must be taken into account to determine the end of the event.

After subtracting the grams of PM produced by the regeneration from the grams per test, the MAW was repeated to obtain the CF with and without regeneration, the conformity factor varied from 0.66 to 0.19 respectively (in this case the evaluation was performed at 10% PT as there were not enough valid windows at 20% (15%)PT, the 90th cumulative percentile was also applied).

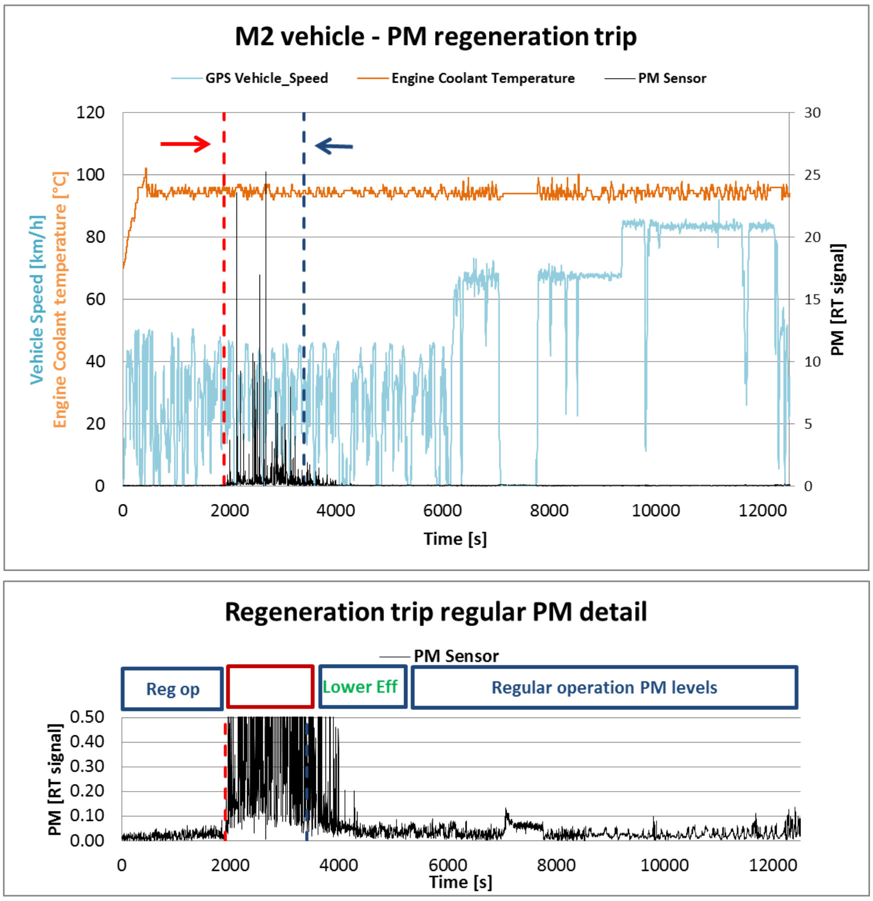

Figure 7-3 M2 vehicle regeneration event.

Figure 7-4 shows further details on the length and exhaust temperature of the regeneration event.

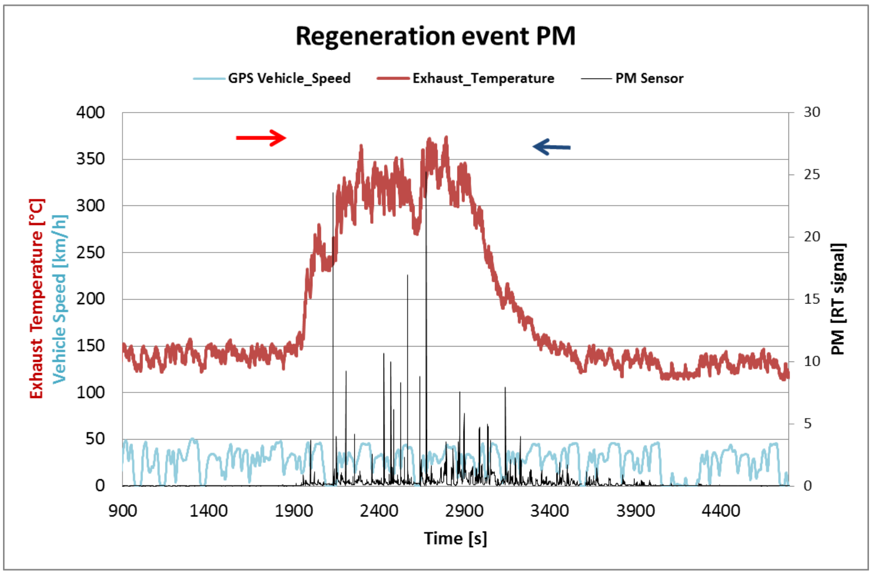

Figure 7-4 Operating details of a regeneration event.

Currently, the industry proposal is to declare void any PEMS based test in which regeneration occurs. While this is a viable option, it may lead to a number of valid tests rendered invalid causing the constructors to spend time and resources repeating these tests. A better path to follow may be to have the option on the PEMS

PM instrumentation to stop measuring while the regeneration is happening, this may be achieved by the use of a flag (signal from the ECU) where the PEMS PM instrumentation detect the start of the regeneration event, hence by-passing the filter and stop logging the real-time signal for the duration of the event.

Having said this, options may need to be explored further in order to save time and resources from the OEMs opening the opportunity for PEMS PM instrumentation suppliers to propose solutions on this topic.

Moreover, UNECE Regulation 49 rev.06 (referred to in COMMISSION REGULATION (EU) No 133/2014) [9, 10] prescribes the test procedures and the performance requirements for the emission of particulate pollutants (Annex 4, §5) and its determination, both for continuous regeneration and periodic regeneration exhaust after-treatment systems (Annex 4, §6), at type approval. It also specifies how to calculate the specific emissions when periodic regeneration in accordance with paragraph 6.6.2 applies. Therefore, it would be advisable to further explore how regeneration of the after-treatment system could be considered within the PEMS procedure (COMMISSION REGULATION (EU) No 582/2011, Annex II [11]).

8. Conclusions

The EU PEMS PM Evaluation Program evaluated the measurement performance of PEMS-PM instruments under controlled laboratory conditions [3, 4, 5, 6]. Its results showed that the standard laboratory principle; i.e. the proportional and partial flow sampling using a filter to collect the PM sampled in the diluted exhaust, was reproducible at a lower scale with the real-time detectors exhibiting a satisfactory sensitivity. The PEMS PM Pilot Program addresses the suitability of using PEMS PM instruments on-board of EUR VI vehicles in on-road conditions.

The following points can summarise the findings in the PEMS PM Pilot Program performed and reported in the above sections:

1. PEMS PM measurement instruments are ready and available to measure PM mass using the mass collected in the filter and a real-time signal method. Therefore, they are suitable to be used as part of the PEMS procedure.
2. The PEMS PM analysis procedure can follow the procedure performed to analyse the gaseous pollutants (detailed in Section 10.2 of this report).
3. As in the gaseous emissions, significant amount of PM mass may be excluded by applying current PEMS testing boundary conditions.
4. Regeneration is able to be detected by the PEMS PM instrumentation, however, solutions need to be discussed further on the possibility to be able to proceed with the analysis of trips with regeneration events.

9. References

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[2] Bonnel, J. Kubelot and A. Provenza. Heavy-Duty Engines Conformity testing Based on PEMS: Lessons Learned from the European Pilot Program. EUR 24921 EN – 2011 (ISBN 978-92-79-21039-6 (online)).

[3] Bonnel, P., Carriero M., Forni F., Alessandrini S., Montigny F.,Demircioglu H., Giechaskiel B. EU-PEMS PM EVALUATION PROGRAM - First Report.

[4] A. Mamakos, M. Carriero, P. Bonnel, H. Demircioglu, K. Douglas, S. Alessandrini, F. Forni, F. Montigny, D. Lesueur. EU-PEMS PM EVALUATION PROGRAM - Second Report - Study on Post DPF PM/PN Emissions

[5] A. Mamakos, M. Carriero, P. Bonnel, H. Demircioglu, K. Douglas, S. Alessandrini, F. Forni, F. Montigny, D. Lesueur EU-PEMS PM EVALUATION PROGRAM - Third Report – Further Study on Post DPF PM/PN Emissions

[6] A. Mamakos, P. Bonnel, A. Perujo, M. Carriero, “Assessment of portable emission measurement systems (PEMS) for heavy-duty diesel engines with respect to particulate matter”. Journal of Aerosol Science 57 (2013) 54-70.

[7] A. Perujo, P Mendoza-Villafuerte, “PEMS EMISSIONS TESTING OF HEAVY DUTY VEHICLES/ENGINES: ASSESSMENT OF PEMS PROCEDURES IN FULFILMENT OF ARTICLE 14(3) TO REGULATION (EU) 582/2011”. JRC Technical Reports, EUR 27251 EN

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[9] Regulation No 49. Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emission of gaseous pollutants from positive-ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles. Revision 6. UNECE - United Nations Economic Commission for Europe. Geneva, Switzerland.

[10] COMMISSION REGULATION (EU) No 133/2014 of 31 January 2014 amending, for the purposes of adapting to technical progress as regards emission limits, Directive 2007/46/EC of the European Parliament and of the Council, Regulation (EC) No 595/2009 of the European Parliament and of the Council and Commission Regulation (EU) No 582/2011

[11] COMMISSION REGULATION (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council

10. Annexes

10.1. VELA 7: Emission test cell for HD vehicles

The climatic test cell has an air circulation system that provides enough number of cell air changes (≥15) in order to allow the testing of vehicles fuelled with diesel, gasoline, CH2, LH2, LPG, LNG and CNG. The cell is equipped with dedicated sensors for gaseous fuels.

Analysers:

On-line measurement of gaseous pollutants on raw exhaust (modal analysis post cat, pre cat, bag gasoline and diesel and ULEV), AVL AMA 4000 Advanced

Bag sampling unit:

Manufacturer: CGM Electronics

Constant volume sampler (CVS) for full exhaust dilution

The dilution air used for the primary dilution of the exhaust in the CVS tunnel is first charcoal scrubbed and then passed through a secondary filter. The secondary filter is capable of reducing particles in the most penetrating particle size of the filter material by at least 99.95%, or through a filter of at least class H13 of international standard EN 1822; this represents the specification of High Efficiency Particulate Air (HEPA) filters.

The dilution air is taken from the climatic chamber.

The CVS system is prepared for the execution of tests for the full temperature range of the climatic chamber (-10 to +40 °C), i.e. include a heating system of the dilution air for ‘cold tests’.

Particulate sampling unit

This system collects diluted diesel engine exhaust gas in a filter at a constant flow rate, after the exhaust gas is thoroughly mixed with clean air from a dilution tunnel.

A PMP compliance equipment is used to measure particle number i.e. Real Time signal (AVL APC-489)

10.2. Moving Averaging Window (MAW) method

The averaging window method is a moving averaging process, based on a reference quantity obtained from the engine characteristics and its performance on the type approval transient cycle. The reference quantity sets the characteristics of the averaging process (i.e. the duration of the windows). Using the MAW method, the emissions are integrated over windows whose common characteristic is the reference engine work or CO_2 mass emissions. The reference quantity is easy to calculate or (better) to measure at type approval:

- In the case of work: from the basic engine characteristics (Maximum power), the duration and the average power of the reference transient certification cycle;
- In the case of the CO2 mass: from the engine CO2 emissions on its certification cycle.

Using the engine work or CO2 mass over a fixed cycle as reference quantity is an essential feature of the method, leading to the same level of averaging and range of results for various engines. Time based averaging (i.e. windows of constant duration) could lead to varying levels of averaging for two different engines.

The first window (i.e. averaged value) is obtained between the first data point and the data point for which the reference quantity (1 x CO_2 or work achieved at the WHTC) is reached. The calculation is then moving, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- The periodic verification of the instruments and/or after the zero drift verifications;
- The data outside the applicable conditions (e.g. altitude or cold engine).

For the sake of completion, in the following section we recall the details of the calculation methods.

10.2.1. Work based method (Figure 10-1)

The duration $(t_{2,i} - t_{1,i})$ of the ith averaging window is determined by:

$$W(t_{2,i}) - W(t_{1,i}) \geq W_{ref}$$

Where:

- $W(t_{j,i})$ is the engine work measured between the start and time $t_{j,i}$, kWh;
- W_{ref} is the engine work for the WHTC, kWh.

$t_{2,i}$ shall be selected such as:

$$W(t_{2,i} - \Delta t) - W(t_{1,i}) < W_{ref} \leq W(t_{2,i}) - W(t_{1,i})$$

Where Δt is the data sampling period, equal to 1 second or less.

The mass emissions (g/window) shall be determined using the emissions calculation formula for raw exhaust gas, as described in the European Directives 2005/55/EC-2005/78/EC in Annex III, Appendix 2, Section 5.

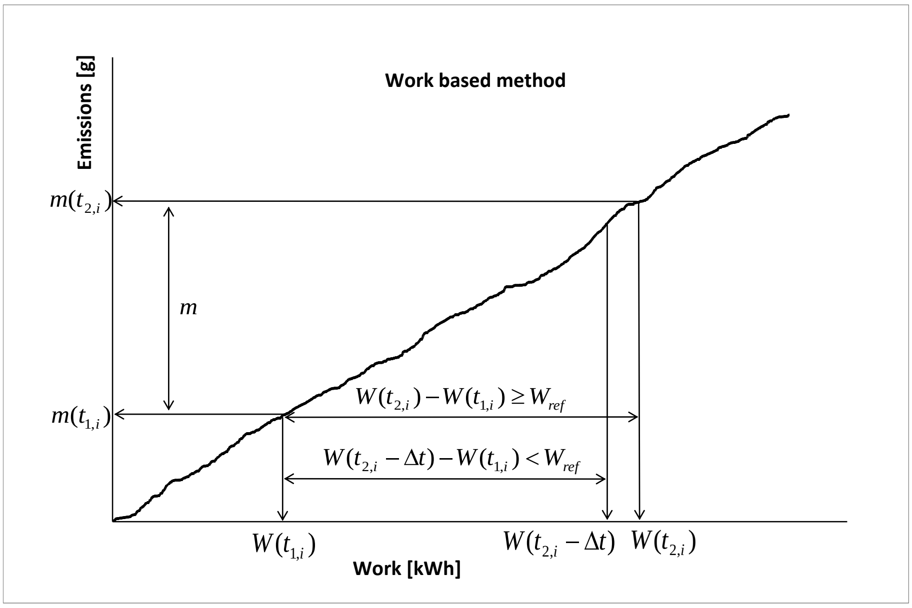


Figure 10-1 MAW Work based method

The specific emissions e_{gas} (g/kWh) are calculated for each window and each pollutant in the following way:

$$e_{gas} = \frac{m}{W_{ref}}$$

Where:

m is the mass emission of the component, g/window

W_{ref} is the engine work for the WHTC, kWh

Calculation of the conformity factors (CF) is as follows:

$$CF = \frac{e}{L}$$

Where:

e is the brake-specific emission of the component, g/kWh

L is the applicable limit, g/kWh

In Regulation 582/2011 only the windows whose average power exceeds the power threshold of 20% of the maximum engine power are considered valid.

10.2.2. *CO2 mass based method (Figure 10-2)*

The duration $(t_{2,i} - t_{1,i})$ of the ith averaging window is determined by:

$$m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i}) \geq m_{CO2,ref}$$

Where:

$m_{CO2}(t_{j,i})$ is the CO_2 mass measured between the test start and time $t_{j,i}$, in g;

$m_{CO2,ref}$ is the CO_2 mass determined for the WHTC, in g;

$t_{2,i}$ shall be selected such as:

$$m_{CO2}(t_{2,i} - \Delta t) - m_{CO2}(t_{1,i}) < m_{CO2,ref} \leq m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$$

Where *Δt* is the data sampling period, equal to 1 second or less.

In each window, the CO2 mass is calculated integrating the instantaneous emissions.

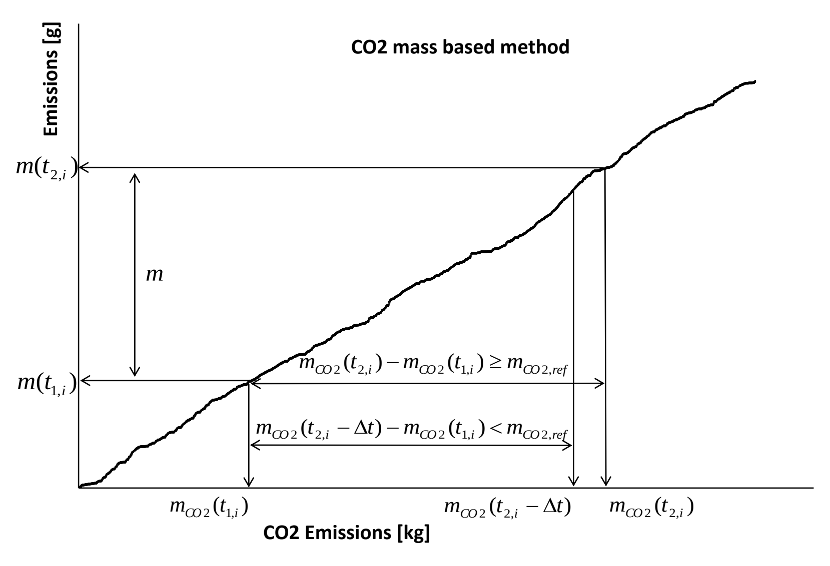


Figure 10-2 MAW CO2 based method

The conformity factors (CF) are calculated for each individual window and each individual pollutant in the following way:

CO2 mass based method:

$$CF = \frac{CF_I}{CF_C}$$

With $CF_I = \frac{m}{m_{CO_2,ref}}$ (in service ratio) and $CF_C = \frac{m_L}{m_{CO_2,ref}}$ (certification ratio)

Where:

m is the mass emission of the component, g/window

$m_{CO_2,ref}$ is the engine CO2 mass measured on the NRTC or calculated from:

$$m_{CO_2,ref} = 3{,}172 \cdot BSFC \cdot W_{ref}$$

m_L is the mass emission of the component corresponding to the applicable limit on the WHTC, expressed in grams.

The valid windows are the windows whose duration does not exceed the threshold duration calculated from:

$$D_{\max} = 3600 \cdot \frac{W_{ref}}{0.2 \cdot P_{\max}}$$

Where:

$D_{\max}$ is the maximum allowed window duration, s

$P_{\max}$ is the maximum engine power, kW

10.2.3. Calculation steps

To calculate the conformity factors, the following steps have to be followed:

Step 1: (If necessary) Additional and empirical time-alignment.

Step 2: Invalid data: Exclusion of data points not meeting the applicable ambient and altitude conditions: these conditions (on engine coolant temperature, altitude and ambient temperature) were defined in the Regulation [3].

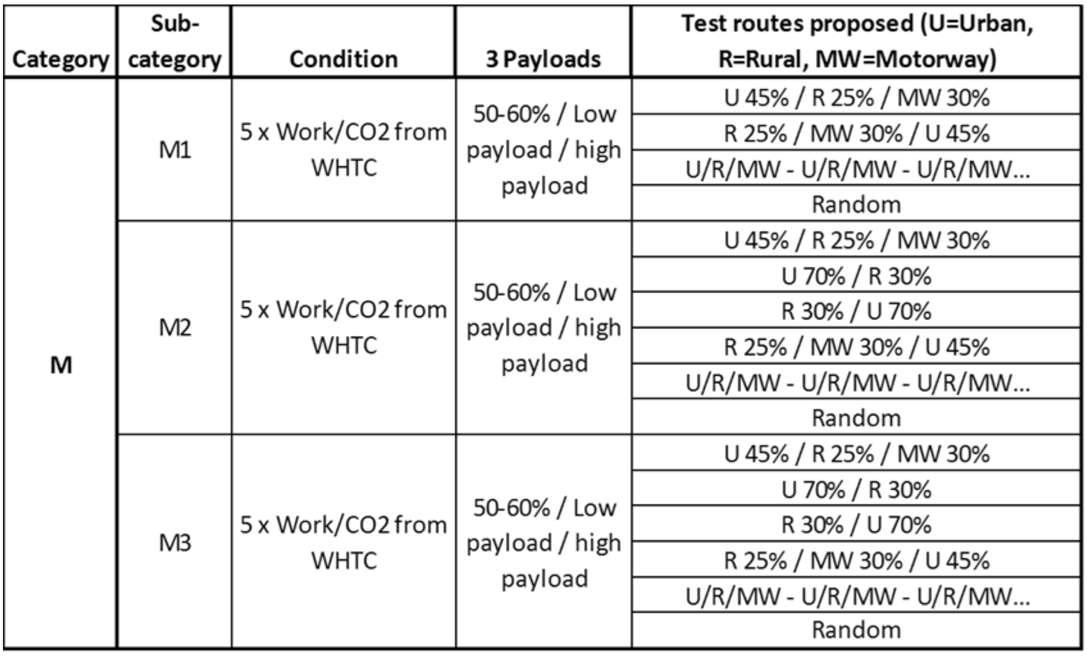
Step 3: Moving and averaging window calculation, excluding the invalid data. If the reference quantity is not reached, the averaging process restarts after a section with invalid data.

Step 4: Invalid windows: Exclusion of windows whose power is below 20% of maximum engine power.

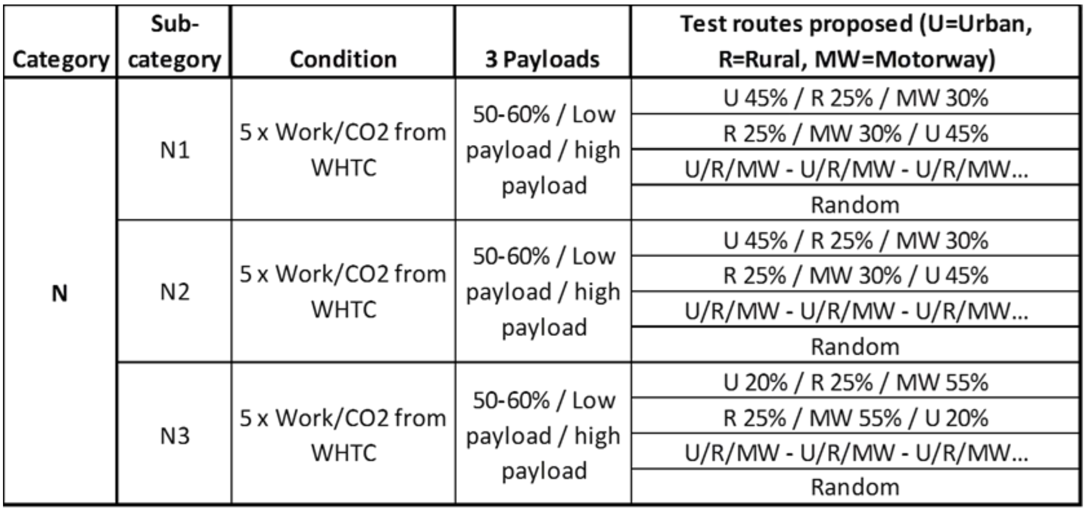
Step 5: Selection of the reference value from the valid windows: 90% cumulative percentile.

Steps 2 to *5* applies to all regulated gaseous pollutants (and most probably will apply to PM in the future).

10.3. JRC’s Proposed testing matrix for the PEMS PM Pilot Program

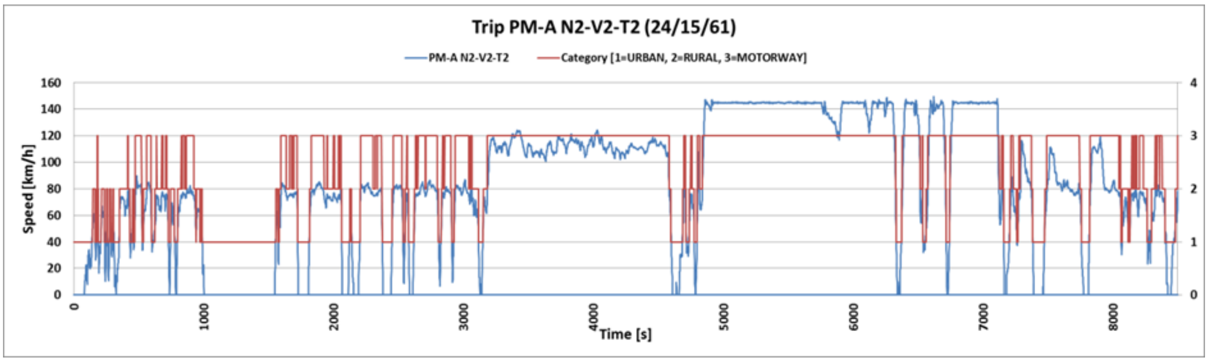


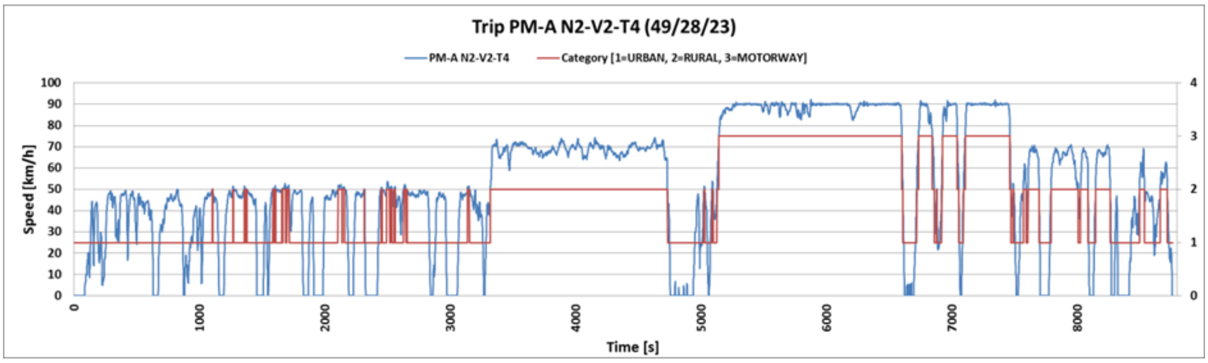
Category	Sub-category	Condition	3 Payloads	Test routes proposed (U=Urban, R=Rural, MW=Motorway)
M	M1	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 45% / R 25% / MW 30%
				R 25% / MW 30% / U 45%
				U/R/MW - U/R/MW - U/R/MW…
				Random
	M2	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 45% / R 25% / MW 30%
				U 70% / R 30%
				R 30% / U 70%
				R 25% / MW 30% / U 45%
				U/R/MW - U/R/MW - U/R/MW…
				Random
	M3	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 45% / R 25% / MW 30%
				U 70% / R 30%
				R 30% / U 70%
				R 25% / MW 30% / U 45%
				U/R/MW - U/R/MW - U/R/MW…
				Random

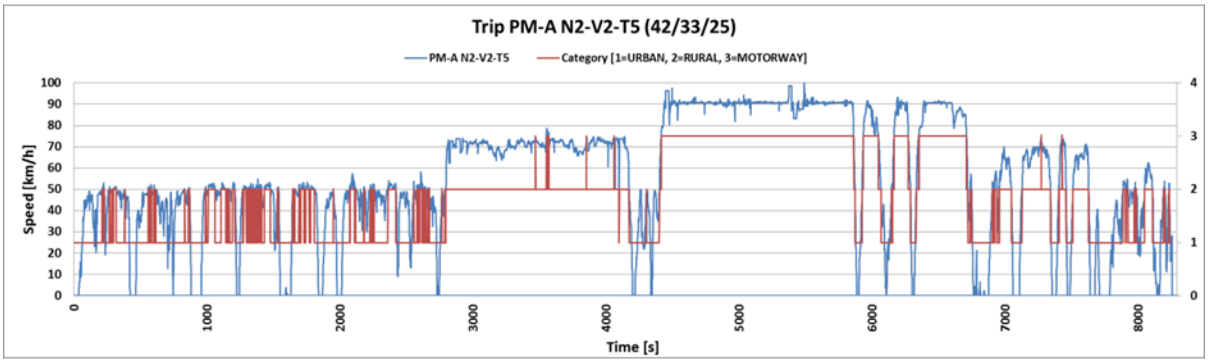


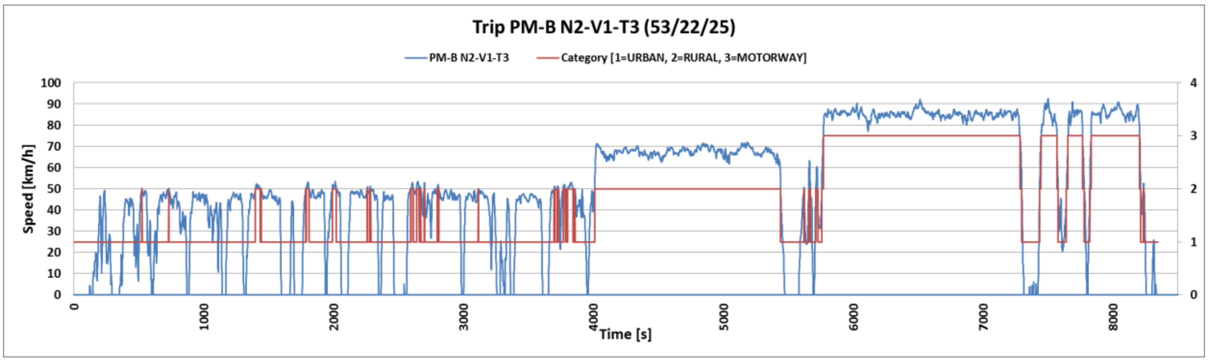
Category	Sub-category	Condition	3 Payloads	Test routes proposed (U=Urban, R=Rural, MW=Motorway)
N	N1	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 45% / R 25% / MW 30%
				R 25% / MW 30% / U 45%
				U/R/MW - U/R/MW - U/R/MW…
				Random
	N2	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 45% / R 25% / MW 30%
				R 25% / MW 30% / U 45%
				U/R/MW - U/R/MW - U/R/MW…
				Random
	N3	5 x Work/CO2 from WHTC	50-60% / Low payload / high payload	U 20% / R 25% / MW 55%
				R 25% / MW 55% / U 20%
				U/R/MW - U/R/MW - U/R/MW…
				Random

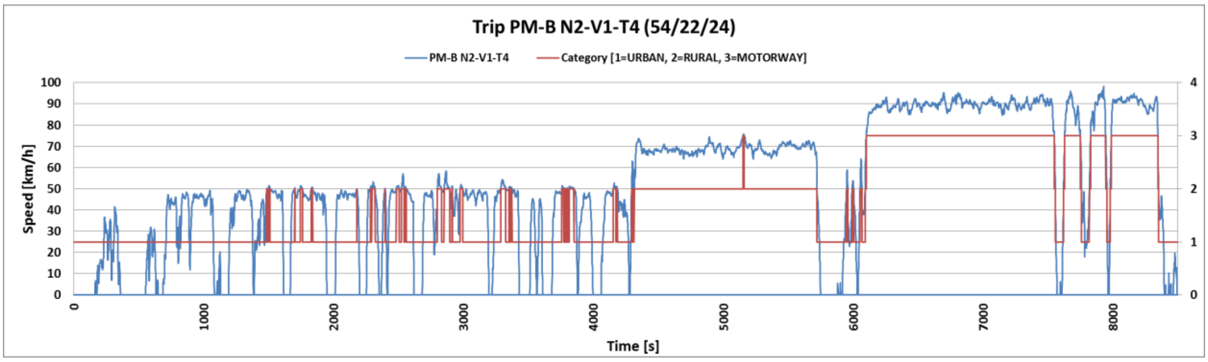
10.4. Comparison of speed profiles from trips measured with instruments A, B and C in N2 vehicles.

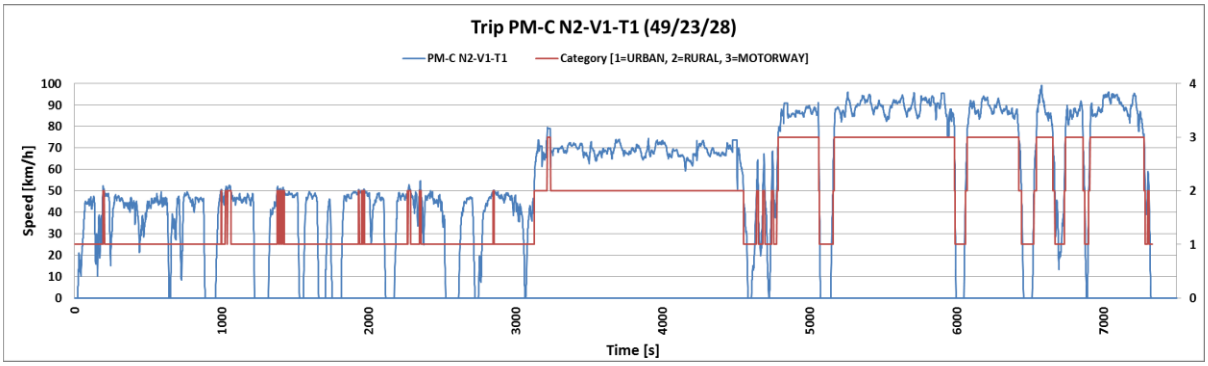


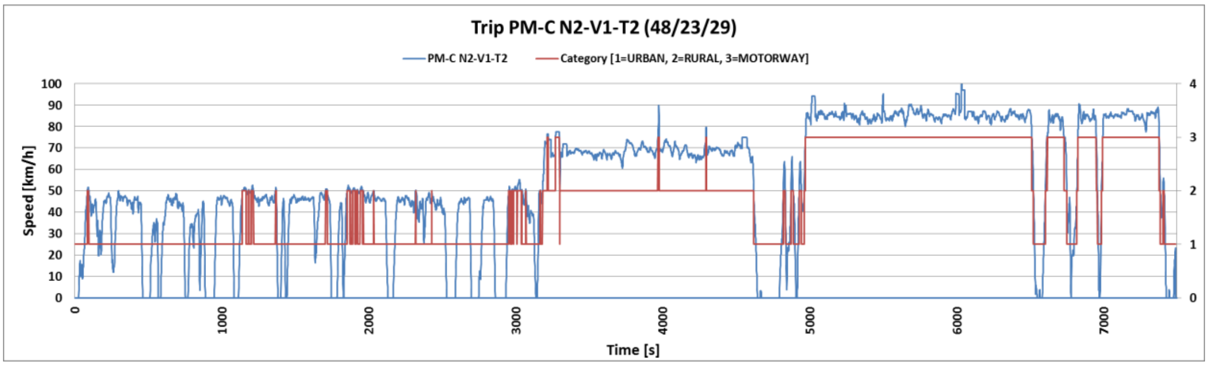




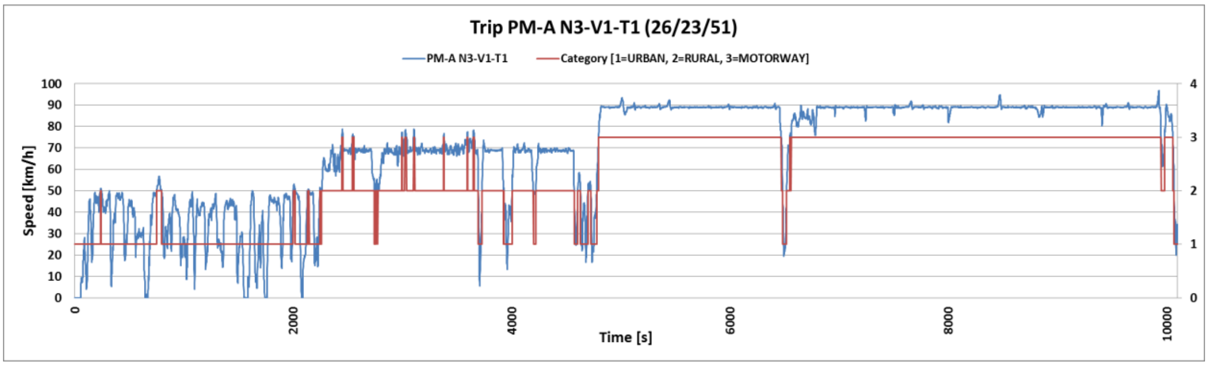


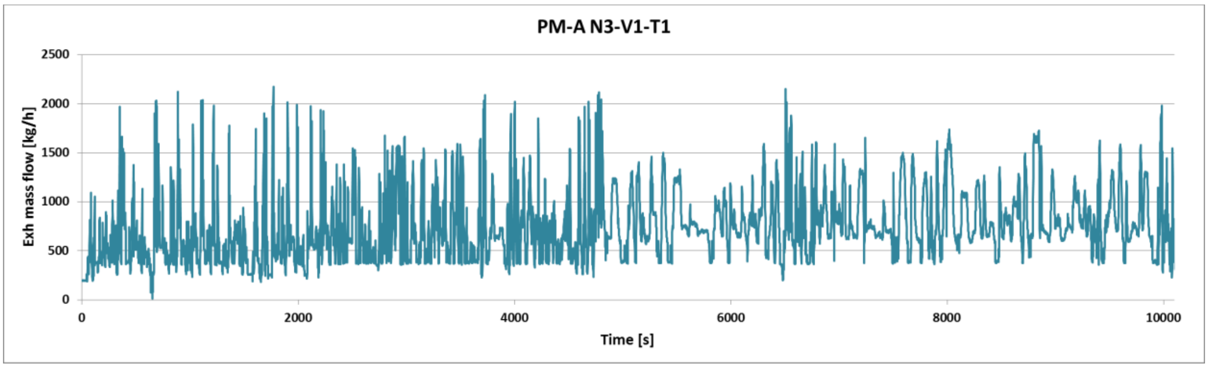

Trip PM-B N2-V1-T4 (54/22/24)
PM-B N2-V1-T4
Category [1=URBAN, 2=RURAL, 3=MOTORWAY]
Speed [km/h]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
0
1000
2000
3000
4000
5000
6000
7000
8000
Time [s]

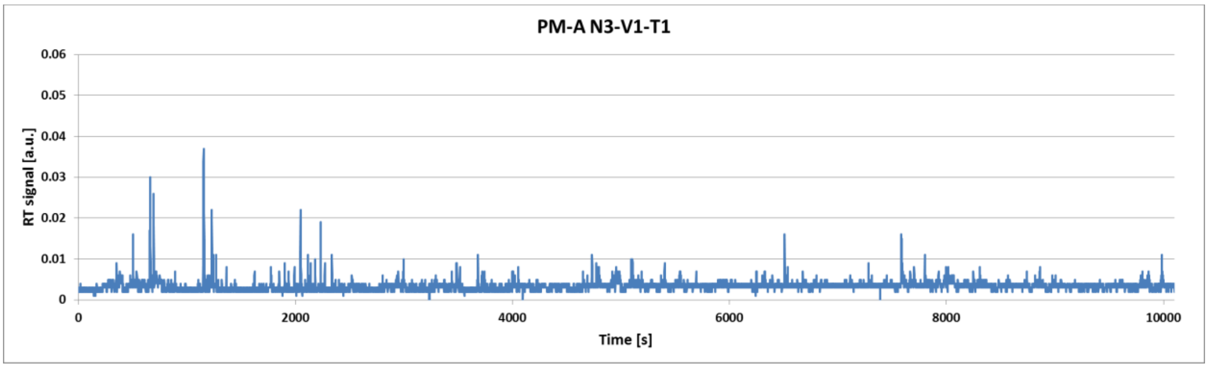

Trip PM-C N2-V1-T1 (49/23/28)
PM-C N2-V1-T1
Category [1=URBAN, 2=RURAL, 3=MOTORWAY]
Speed [km/h]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
0
1000
2000
3000
4000
5000
6000
7000
Time [s]

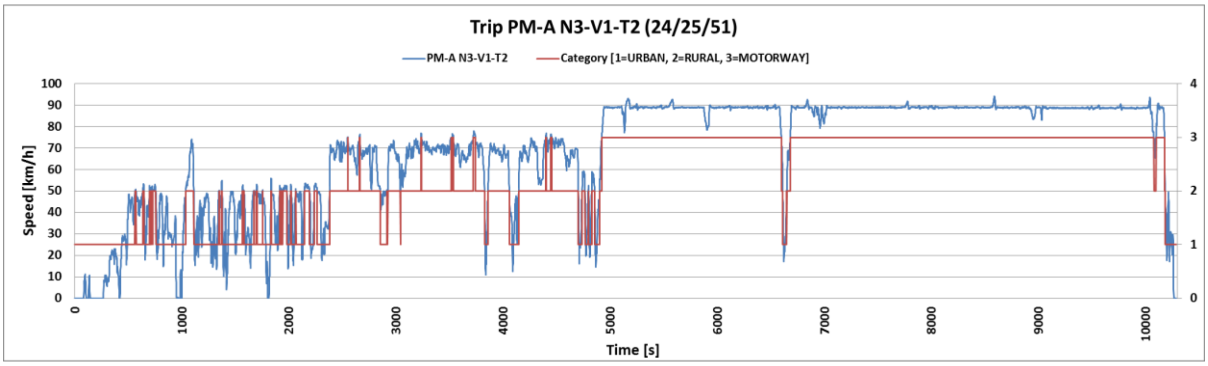

Trip PM-C N2-V1-T2 (48/23/29)
PM-C N2-V1-T2
Category [1=URBAN, 2=RURAL, 3=MOTORWAY]
Speed [km/h]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
0
1000
2000
3000
4000
5000
6000
7000
Time [s]

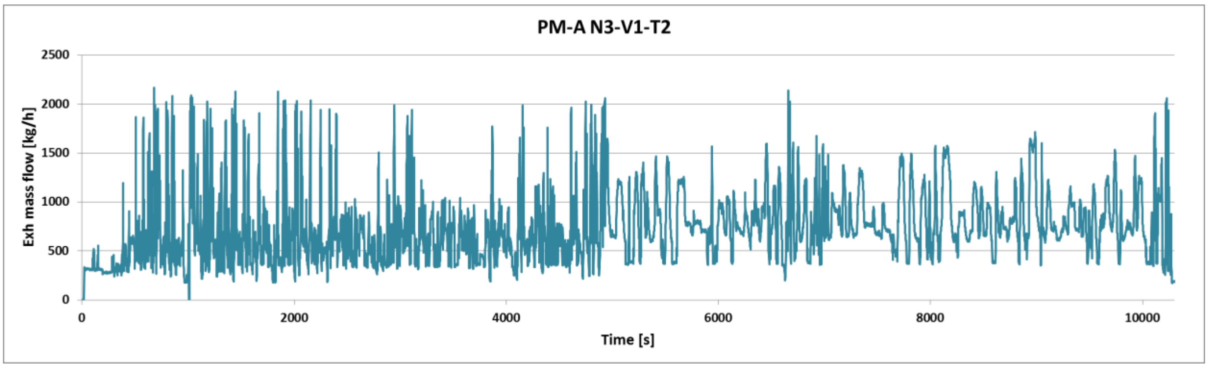
10.5. *Comparison of speed profiles, RT signal and exhaust mass flow from trips measured with instrument A in vehicle N3-V1.*



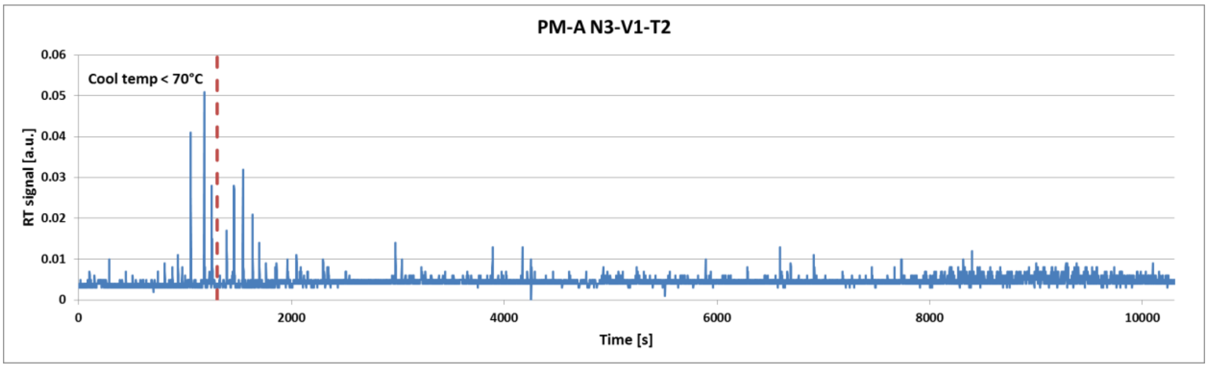








PM-A N3-V1-T2



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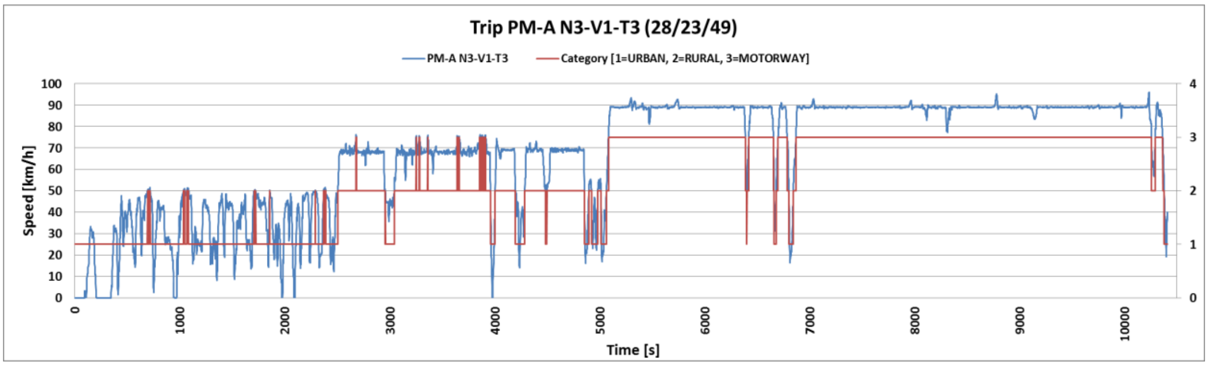
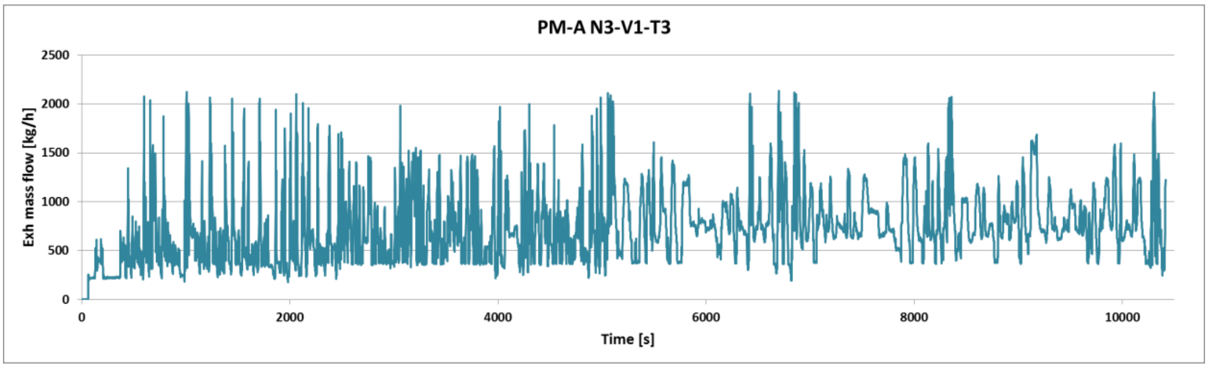


Trip PM-A N3-V1-T3 (28/23/49)



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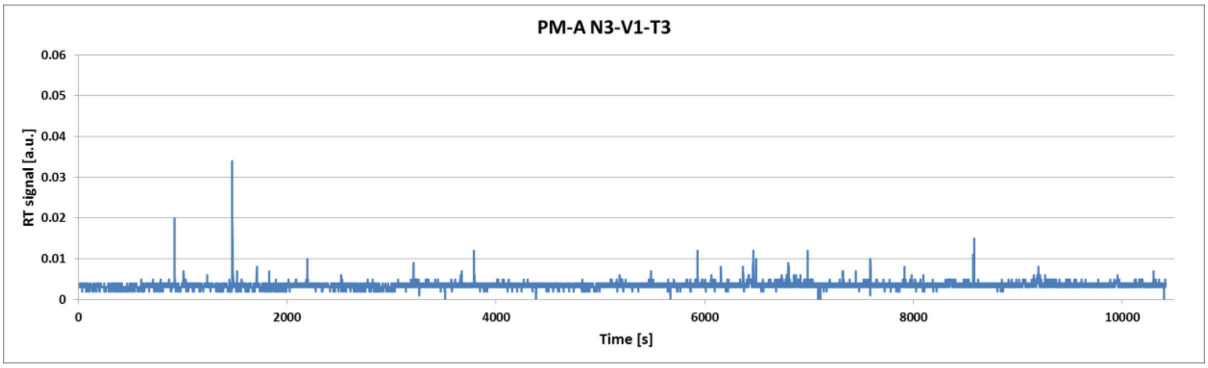

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European Commission
EUR 27326 EN – Joint Research Centre – Institute for Energy and Transport

Title: EU-PEMS PM Pilot Program: Testing, data analysis and results.

Author(s): Pablo Mendoza Villafuerte, Adolfo Perujo Mateos del Parque, Pierre Bonnel, Massimo Carriero, Fausto Forni, Francesco Riccobono

Luxembourg: Publications Office of the European Union

2015 – 56 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-49236-5 (pdf)
ISBN 978-92-79-49235-8 (print)

doi: 10.2790/46867 (online)

LD-NA-27326-EN-N

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ISBN 978-92-79-49236-5