JRC TECHNICAL REPORT

In Service Monitoring based on PEMS of NRE engines under 19kW

Lessons Learned from the European Pilot Program

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KOHLER (Lombardini Srl)

KUBOTA (Kubota Corporation)

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Contents

Abstract

This report summarizes the results of a pilot program dedicated to develop a procedure for the In Service Monitoring of NRMM Small Compressed Ignition engines (categories NRE-v-1, NRE-v-2, NRE-c-1, NRE-c-2) based on Portable Emission Measurement System (PEMS). The tests took place between January 2018 and February 2019.

The work addresses how to mount the measurement equipment on board of such machinery and the accuracy and precision of the exhaust gaseous pollutant emission measurements using PEMS. Compared to a standard test performed in an engine test cell (VELA_6 and at OEM facilities) the concentration measurements accuracy and precision was within 10%.

In service tests showed that the results were stable and reproducible.

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Authors

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Executive summary

Regulation (EU) 2016/1628 (the so-called NRMM Stage V), which repeals Directive 97/68/EC, lays down gaseous and particulate emission limits and type approval requirements for internal combustion engines installed in Non-Road Mobile Machinery. This so-called Stage V emission standard includes a wider range of engine types and sizes and it covers previously unregulated engines, including snowmobiles, All Terrain Vehicles (ATV) and engines below 19 kW or over 560 kW. Furthermore, the Stage V regulation prescribes for the first time the monitoring of actual in-use emissions of in-service engines installed in non-road mobile machinery and operated over their normal operating duty cycles. It also empowers the Commission "to conduct pilot programmes with a view to developing appropriate test procedures for those engines categories and sub-categories in respect of which such test procedures are not in place".

This report presents the outcome of the pilot programme designed to explore the suitability of the already existing procedure to monitor the gaseous pollutant emissions from variable speed engines in the 56 kW to 560 kW power range (engines of categories NRE-v-5 and NRE-v-6) for its application to test in-service (ISM) internal combustion engines installed in NRMM category NRE (i.e. CI engines exclusively for use in Non Road Engines) with power below 19 kW. The report confirms that for ISM tests, the use of Portable Emission Measurement Systems (PEMS) is suitable as it can be reliably mounted on the tested machine and the data can also be processed in a similar fashion as in the case for NRMM engines of category NRE-v-5 and NRE-v-6.

Because of the characteristics of these Small Compression Ignition engines (NRMM categories NRE-v-1, NRE-v-2, NRE-c-1, NRE-c-2); i.e. this category of engines tend to be single-, 2- or 3-cylinders, the measurement of the exhaust mass flow using flow meters (EFM) has turned to be crucial and more complicated than expected due to the exhaust flow pulsation typical of this kind of engines, in particular single and 2-cylinders. Technical solutions have been found to measure the exhaust flow with an acceptable uncertainty.

During the performance of the pilot programme solutions were also found for the definition of the reference quantities; i.e. work and CO_2 for the case that the type approval test is the NRSC (steady state test cycle) rather than the NRTC (transient test cycle). It has also been proposed a methodology to calculate an equivalent power from the measured CO_2 flow in order to make possible the definition of working and non-working event for the case of mechanically controlled engines (no ECU). The validation of this approach suggests that the approach is suitable for the purpose to define valid/invalid events.

Finally, some recommendations are made in term of test duration (i.e. 3 to 5 times the reference quantity rather than 5 to 7 times) and the use of combined data sampling to satisfy the operational characteristic of this category of engines in view to amend the present ISM regulation. This is needed to extend the ISM procedures to all the NRMM engine categories as required by the STAGE V legislation.

1 Introduction

The European Commission is committed to improve the EU air quality by, among other instruments, the implementation of emission regulations. The Commission also works on the improvement of testing procedures for pollutant emissions and fuel consumption. This helps to assess the performance of vehicles under real-life conditions.

The European Union legislation on Non-Road Mobile Machinery (NRMM[1]) Regulation (EU) 2016/1628[2], which repeals Directive 97/68/EC[3], lays down gaseous and particulate emission limits and type approval requirements for internal combustion engines installed in such NRMM. This so-called Stage V emission standard includes a wider range of engine types and sizes and it covers previously unregulated engines, including snowmobiles, All Terrain Vehicles (ATV) and engines below 19 kW or over 560 kW. Furthermore, the new Stage V NRMM regulation prescribes for the first time the monitoring of actual in-use emissions of in-service engines[4] installed in non-road mobile machinery and operated over their normal operating duty cycles. It also empowers the Commission "to conduct pilot programmes with a view to developing appropriate test procedures for those engines categories and sub-categories in respect of which such test procedures are not in place". In-Service Monitoring procedures prescriptions for engines in the categories NRE-v-5 and NRE-v-6 (variable speed engines with power in the 56 to 560 kW range) are given by Regulation (EU) 2017/655[5] and they are based on the use of Portable Emissions Measurement Systems (PEMS).

DG-GROW[6] has commissioned to the European Commission - Joint Research Centre (EC-JRC) In-service Monitoring (ISM) Pilot Programmes, in the framework of the Administrative Agreement No *SI2.784345 - JRC.35074*, to develop such ISM test procedures.

The study reported here investigates whether the ISM provisions already in place for engines in the categories NRE-v-5 and NRE-v-6 are fit to be used in Non Road Engines NRE-v-1 and NRE-v-2 (hereafter Small Compression Ignition engines – SCI). Based on the outcome of this Pilot Program that JRC has launched in close collaboration with EUROMOT, the Commission will propose a methodology to perform the ISM of NRMM for this category of machines.

The main goals of this pilot program phase are:

1. to verify the feasibility in the assembling of such PEMS equipment on these small machineries;
2. to check for the accuracy of the emission measurements using Portable Emission Measurement System (PEMS) together with the possibility to evaluate the exhaust mass flow rate using an Exhaust Flow Meter (EFM);
3. to define an appropriate testing protocol with the participation of the OEMs.

The data evaluation principle used is the so-called Moving Averaging Windows (MAW) method based on either the work performed or the CO_2 mass emission at engine type approval.

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[1] 'Non-Road Mobile Machinery' means any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads.

[2] REGULATION (EU) 2016/1628 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC. Official Journal L 252/53. Available at: http://eur-lex.europa.eu

[3] DIRECTIVE 97/68/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery, Official Journal L 59. Available at: http://eur-lex.europa.eu

[4] 'In-service engine' means an engine that is operated in non-road mobile machinery over its normal operating patterns, conditions and payloads, and is used to perform the emission monitoring tests.

[5] COMMISSION DELEGATED REGULATION (EU) 2017/655 of 19 December 2016 supplementing Regulation (EU) 2016/1628 of the European Parliament and of the Council with regard to monitoring of gaseous pollutant emissions from in-service internal combustion engines installed in non-road mobile machinery. Available at: http://eur-lex.europa.eu

[6] Directorate General Internal Market, Industry, Entrepreneurship and SMEs. http://ec.europa.eu/growth/index_en

2 NRMM PEMS Pilot Program for NRE-v-1, NRE-v-2 engines

2.1 Objectives

The NRMM PEMS Pilot Program and the relative test campaign were launched to facilitate the understanding of the PEMS application as a tool for ISM.

The objectives of the program were defined as follows:

- To give a sort of guideline for the installation of PEMS in vehicle used for gardening, construction and agricultural purpose (included mechanical fittings);
- To validate the use of gaseous PEMS for checking the ISM of NRMM as tillers, mini tractors, excavators, lawn movers, compactor and hydraulic pumps among others;
- To develop a test protocol for the above mentioned vehicles;
- To develop and share ‘best practise’ for the use of gaseous PEMS approach in NRMM ISM testing to all relevant stakeholders.

2.2 Scope

This Pilot Programme is dedicated to NRMM different machines with variable/constant speed, compression-ignition engines in order to ensure that the designed procedure, which is based on a reduced set of data, is appropriate to limit the exhaust pollutant emissions of engines installed in NRMM over their normal operation.

2.3 Technical Elements

The envisaged technical elements were formulated paying particular attention to:

1. The application of the test protocol, e.g. to judge whether the mandatory data and its quality were appropriate for the final evaluation;

2. The method used to analyse the emissions data i.e. to answer the following question: “Once the data has been collected correctly, what is the most appropriate method to the test data measured with PEMS to judge whether the engine is in conformity with the applicable emissions limits?”

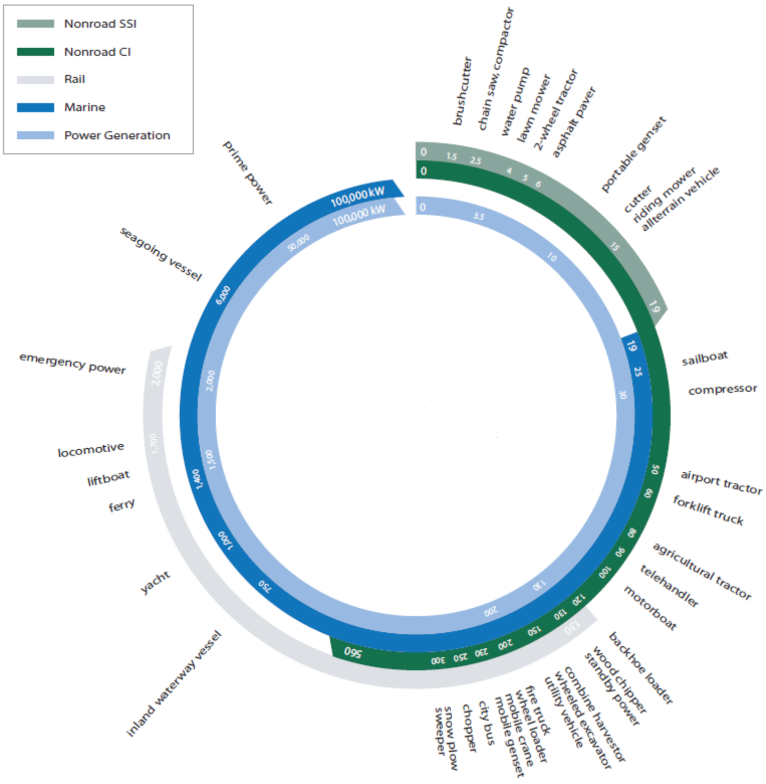
3 Tests description

3.1 Test machines

The definition of a strategy for the selection of vehicles was part of the pilot program. The selection process involved vehicles manufacturers and the industrial association (EUROMOT)[7].

Established in 1991, EUROMOT's primary focus has consistently been on communicating the benefits of internal combustion (IC) engine power to regulators worldwide, providing reliable know-how on advanced engine technologies in general, as well as on environmentally efficient and cost-effective product regulations. EUROMOT partners with other associations and institutions around the world to develop technically and economically feasible regulations for local or global contexts, while also driving mobility and economic growth in modern societies. Its members, which includes all major manufacturers of internal combustion engines in Europe and worldwide, produce engines for liquid and gaseous fuels, and represent 85% of the EU market (see Figure 1). The European market turnover for the business exceeds EUR 25 billion.

Figure 1. EUROMOT business sectors.



Source: EUROMOT

The participating manufacturers tested between one and two machines during the test campaign. Some variations might be observed from one machine to another.

EUROMOT has summarised into two main categories (see Tables 1 and 2), the engines intended for the purpose of ISM. In particular, DOC (Diesel Oxidation Catalyst) converter will become the mainstream emission control technology once NRMM Stage V becomes applicable. However, until then, current engines may not be equipped with any emission control system, as they were not yet falling into the new NRMM regulation scope.

The machine duty cycles had to be representative of the machine type, i.e. the manufacturers had to ensure that the testing was conducted within the normal range of applications for that machine type. Particular attention was paid to the PEMS installation constraints.

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[7] European Association of Internal Combustion Engine Manufacturers

Table 1. EU-PEMS NRE-v-1 and NRE-v-2 Pilot program groups.

	Group 1	**Group 2**
Engine type	4 strokes	4 strokes
Fuel Type	Diesel	Diesel
Fuel system	Mechanical pump	Mechanical pump
Cooling system	Air-cooled	Water-cooled
Emission control system	None	None
Engine displacement range	350-700cc	450-1000cc
Number of cylinder	1	2 or 3

Source: OEM, 2017

Table 2. EU-PEMS NRE-v-1 and NRE-v-2 Pilot program groups (further details).

CODE	GROUP	QTY OF CYLINDERS	AFTERTREATMENT
A	1	1	NONE
B	2	3	NONE
C	2	2	NONE
D	1	1	NONE
E	2	3	NONE
F	1	1	NONE

3.2 Engine and machinery details (fleet)

During this campaign, different machineries for different purpose were tested:

GARDENING: lawn mowers, mini tractors

AGRICOLTURAL: tillers

INDUSTRIAL: motor pump

CONSTRUCTION: excavator, compactor

It is important to highlight, that the same engines are also merchandized for other different application fields. The details of the different machines are summarised in Table 3.

Table 3. EU-PEMS NRE-v-1 and NRE-v-2 Pilot program (detail of machines)

Machinery	OEM	Category	No. of Cylinder	Displacement (Actual Vehicle Engine)	Displacement (Parent Engine)	Stroke	Fuel	Rated Power (MODE_1)	Aftertreatment	Family Emission Limits (*) g/kWh	
				[cc]	[cc]			[kW]		NOx+THC	CO
A	1	NRE-V-1	1	350	350	4	Diesel	4.47	None	7.5	8.0
B	2	NRE-V-2	3	903	854	4	Diesel	15.12	None	7.5	6.6
C	3	NRE-V-2	2	482	782	4	Diesel	8.54	None	7.5	6.6
D	4	NRE-V/C-1	1	667	667	4	Diesel	9.40	None	7.5	8.0
E	2	NRE-V-2	3	993	993	4	Diesel	17.72	None	7.5	6.6
F	4	NRE-V/C-1	1	667	667	4	Diesel	9.40	None	7.5	8.0

Source: OEM, 2017

[*] See Annex 1 for an overview of the Stage V emission limits by engine category.

(*) The PM content has not been measured

3.3 Test circuit

Depending on the application, the most suitable ground to perform the test was identified, trying to replicate the normal in-use activities. In Figures 2 to 7 same examples are depicted of the test pattern used during the ISM campaign. For every machineries typology, a dedicated test sequence has been designed.

Figure 2. Lawn mowing operations.

Figure 3. Compacting operations.

Figure 4. Excavation operations.

Figure 5. Tiller works.

Figure 6. Ground moving.

Figure 7. Pumping operation.

3.4 Test executions

3.4.1 Test Equipment

The PEMS systems used to test the vehicles had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. To work with a low power consumption so that tests of at least 1 hour can be run with a single set of batteries;
3. To measure and record the concentrations of NOx, CO, CO2, THC gases in the engine exhaust;
4. To record the relevant parameters (engine data from the ECU, machine position from the GPS, weather data, etc.) on an included data logger.

The EFM systems used to test the machinery had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. The pipe size and diameter should be choose according to the machinery exhaust flow values (see EFM manufacturer recommendation);
3. To measure and record the Exhaust Mass Emission in appropriate units (e.g. kg/h).

3.4.2 Test protocol and test condition

The tests were conducted in agreement with the OEMs and following their recommendations developed in the preliminary phases. Most of the tests were eye witnessed and supervised by the manufacturer. The test machines had to run over normal duty cycles, conditions and payloads, defined by the manufacturers, in consultation with their type approval authorities. According to the draft test protocol[8], the test duration had to be selected to have a cumulative engine work produced during the test between 5 to 7 times the work on the certification cycle (NRSC – G2 MODE).

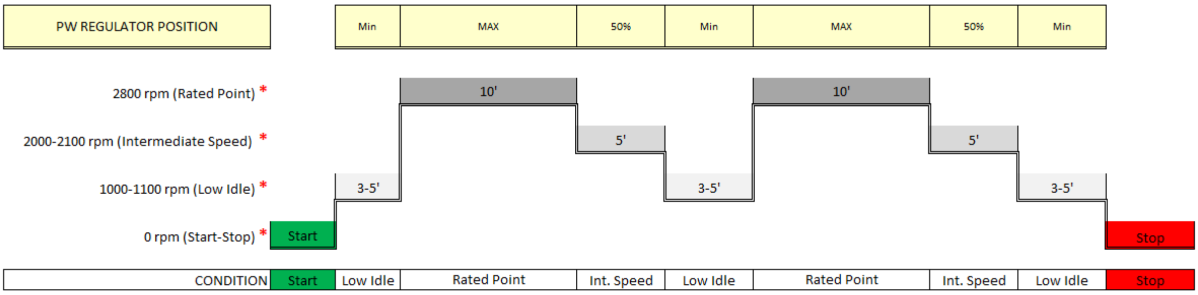
3.4.3 Test trips and cycles

Each machine was tested according to a duty cycle representative of the category (see Figure 8).

Test cycles have been selected according to the indication provided by OEMs, and adapted to the test ground field available internally to JRC.

Figure 8. Test pattern examples.

COMPACTOR:



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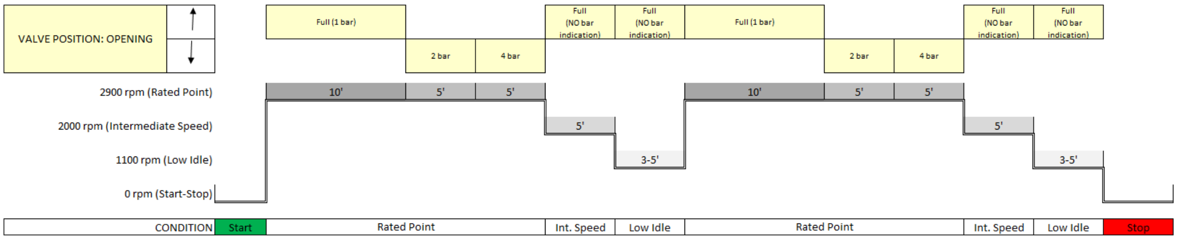
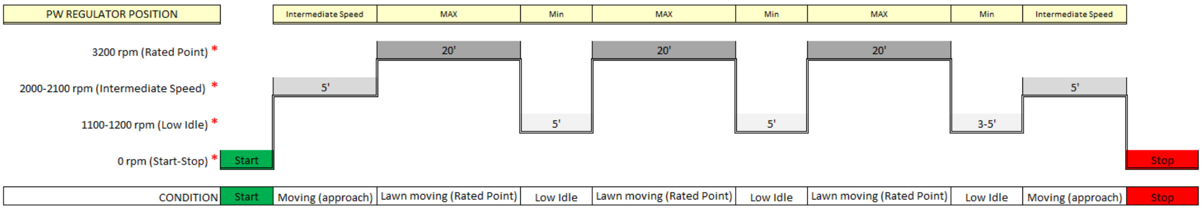
[8] The bases for the test were those defined in Reg. (EU) 2017/655; i.e. ISM procedure for engines NRE-v-5 and NRE-v-6

MOTORPUMP:



LAWNMOWER:



In all the tested machineries different working phases were combined, which included:

- Working at rated point (maximum power)
- Working at intermediate speed and load
- Idling

After each working step, 3 or 5 minutes of idle engine speed was introduced to measure exhaust emission also at idle but also to make general inspection of the machine, for instance status of instrumentation due to high vibrations, fuel level control and battery replacement if necessary.

In average, the complete test had a total duration of 1 hour. All the exhaust emission and additional vehicle parameters were recorded for later post-processing.

Emissions and some engine parameters were always measured and recorded along the entire test performed.

3.5 Data handling procedures and tools

3.5.1 Test data

The parameters that had to be recorded are listed in Table 4. The unit mentioned is the reference unit whereas the source column shows the measuring methods that were used.

3.5.2 Time alignment

The test parameters listed in Table 4 are split in 2 different categories:

a. Category 1: Gas analyser (THC, CO, CO2, NOx concentrations);
b. Category 2: Exhaust flow meter (Exhaust mass flow and exhaust temperature).

According to the procedure developed for heavy-duty engines and transposed to the case of NRMM[5], the time alignment of each category with the other categories has to be verified by finding the highest correlation coefficient between two series. All the parameters in a category are shifted to maximize the correlation factor.

The only possible parameters, which may be used to calculate the correlation coefficients to time-align Category 1 with Category 2 are using the CO2 concentration and the exhaust mass flow or the GPS data and exhaust mass flow (the latter only in some cases).

The method was found suitable for NRMM engines.

Table 4. List of test parameters.

Parameter	Unit	Source
HC concentration (1)	ppm	Analyser
CO concentration (1)	ppm	Analyser
NOx concentration (1)	ppm	Analyser
CO_2 concentration (1)	ppm	Analyser
Exhaust gas flow	kg/h	Exhaust Flow Meter (hereinafter EFM)
Exhaust temperature	°K	EFM
Ambient temperature (2)	°K	Sensor
Engine Speed	rpm	Sensor
Vehicle longitude	degree	GPS
Vehicle latitude	degree	GPS
Vehicle Speed	km/h	GPS

Notes

(1) Measured or corrected to a wet basis

(2) Use the ambient temperature sensor or an intake air temperature sensor

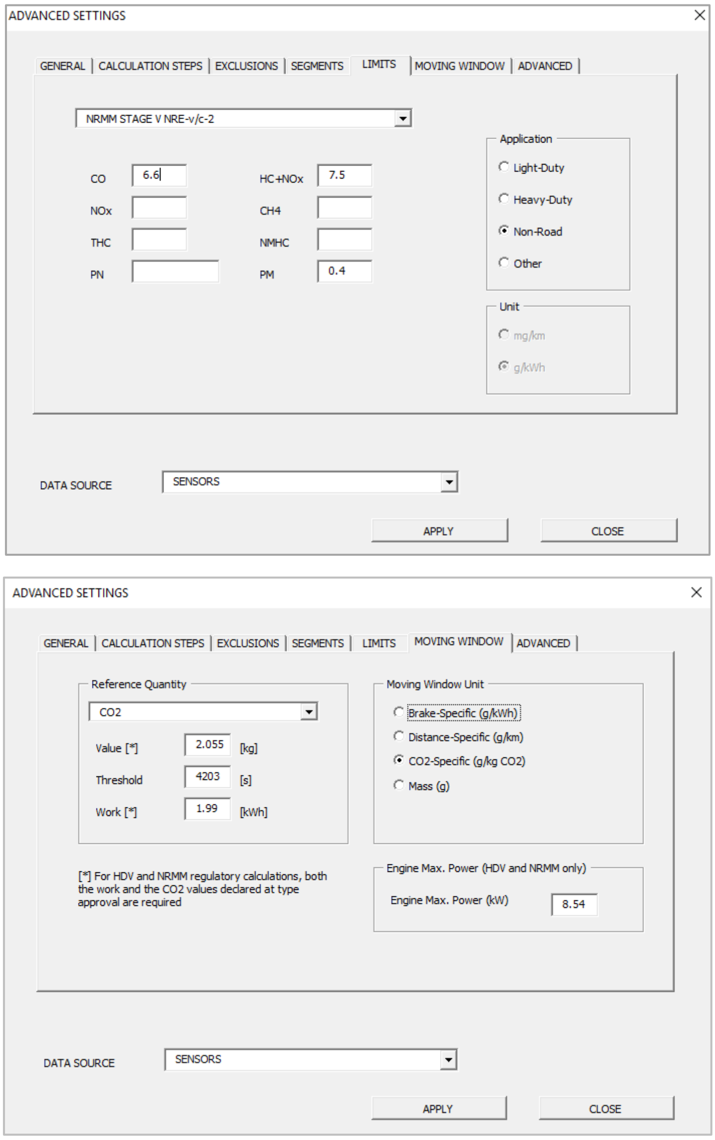
3.5.3 EMROAD©

Reporting templates and an automated data analysis were used to ensure that all the calculations (of mass, distance specific and brake specific emissions) and verifications were done consistently throughout the pilot program. The in-house developed excel add-in EMROAD© has been used for such automated data analysis (see Figure 9 as example of EMROAD's setting interface forms).

The standardized reporting templates included, for every test:

1. Second by second test data for all the mandatory test parameters;
2. Second by second calculated data (mass emissions, distance, fuel and brake specific);
3. Improved time alignment procedures between the different families of measured signals (analysers, EFM, engine);
4. Data verification routines, using the duplication of measurement principle, to check for instance the directly measured exhaust flow against the calculated one;
5. Averages and integrated values (mass emissions, distance, fuel and brake specific).

Figure 9. EMROAD setting interface forms.



ADVANCED SETTINGS

LIMITS

NRMM STAGE V NRE-v/c-2

CO 6.6
HC+NOx 7.5
NOx
CH4
THC
NMHC
PN
PM 0.4

Application
○ Light-Duty
○ Heavy-Duty
● Non-Road
○ Other

Unit
○ mg/km
● g/kWh

DATA SOURCE SENSORS

ADVANCED SETTINGS

MOVING WINDOW

Reference Quantity
CO2
Value [*] 2.055 [kg]
Threshold 4203 [s]
Work [*] 1.99 [kWh]

Moving Window Unit
○ Brake-Specific (g/kWh)
○ Distance-Specific (g/km)
● CO2-Specific (g/kg CO2)
○ Mass (g)

[*] For HDV and NRMM regulatory calculations, both the work and the CO2 values declared at type approval are required

Engine Max. Power (HDV and NRMM only)
Engine Max. Power (kW) 8.54

DATA SOURCE SENSORS

Source: JRC.Vela, 2019

3.5.4 Data screening principles

The calculations and the data screening were carried out using EMROAD©.

4 PEMS equipment

The lessons learned from the European PEMS pilot program for NonRoad Mobile Machinery engines can be summarised as follows.

4.1 Installation of PEMS equipment

Unlike in the case of HDV the installation and operation of the PEMS equipment as well as the definition of a test “trip or cycle” has been more complicated than expected (see later on in this report) due to the characteristics of the machinery being tested in the SCI NRMM PEMS Pilot Program.

The following is a non-exhaustive list of suggestions/recommendations extracted from the experience obtained in the field during the test program.

1. Installation of instruments should be made on a stable plate. The gas analyzer should be mounted using suitable damper to reduce the vibrations and shocks (see Figure 10);
2. Some degrees of freedom needs to be allowed for the EFM connection to the tail pipe, i.e. allow the instrument to move slightly without risking to damage tubes, cables (slack) and connections (military type), to compensate for vibrations and high accelerations;
3. EFM: possibility to use a flexible tube needs to be considered, maybe fixing the EFM onto the mounting frames (see Figure 11);

Figure 10. Mechanical works necessary to safely installing the gas analyzer and the EFM.

Figure 11. Mechanical works necessary to assembly the EFM. Detail of flexible pipe to connect the tail pipe.

Figure 12. Machinery equipped with PEMS – Final Installation.

4. To protect the equipment from dust, water, shocks, etc., it is necessary to use a suitable coverage (e.g. wrapped plastic or undeformable plastic sheet);
5. Instruments can be installed in the rack situated in the rear of the machinery: therefore, a mounting platform is needed and modifications to the machine structure and exhaust tailpipe are difficult to avoid (see Figure 10, Figure 11 and Figure 12); the battery pack can be installed in different positions: in either a front rack, in a rear rack or even in under the driver seat, according with the space at disposal. It is recommendable to create a rear platform to allocate the PEMS equipment;
6. For safety reasons, the mounting platform in which is installed the equipment need to be secured to the machinery: straps are considerated a good solution;
7. Due to the outline and the reduced dimension of the rear rack, installing the equipment onto the platform of the vehicle can prevent access to the gas analyzer components (e.g FID fuel bottle, filter);
8. Permanent machinery modifications must be avoided as those will not be acceptable to the machinery owner;
9. Access to the test equipment is necessary – either for the installation or for the checks between the tests –. Safety aspect needs to be considered;
10. Minimum power required: batteries BUT the batteries have a limited autonomy and need to be replaced or recharged. The replacement is difficult because of their weight (~30 kg), therefore the use of Gel batteries are recommended or more advanced battery chemistry (e.g. Li-ion batteries);
11. FID fuel bottle: 0.5 liter bottle has an autonomy of about 6 hours (which must include warm-up and calibration) – Larger bottles could be used (1 liter) in case of enough space available;
12. Field testing: span gas bottles must be taken to the field to zero-span the gas analyzers, unless the measurements start from and finish in a workshop;
13. Avoid contamination of the air used to zero the gas analyzers (by the engine itself, the power generator or any other source) ;
14. Recommendation: Remote monitoring of the instruments using Wifi;

Figure 13. Use of a trolley or an additional vehicle to support the installation of the equipment (gas analyser, EFM, battery).

15. Recommendation for the laptops: they need to be ruggedized, for high autonomy, dust and water proof, lighting of the monitor, etc;
16. When the weight of the complete installation (PEMS,EFM, battery and other measuring equipment) is comparable with the weight of the machinery under test, or in case there is no enough space or, again, the working operation become too difficult, it is better to use a trolley or an additional/support vehicle in which allocate all the instrumentation (see Figure 13). Otherwise the normal operability of the machinery could be compromised as well as the safety (see Figure 14).

Figure 14. Dangerous configuration.

4.2 Validation of PEMS with dynamometer test cell

The validation of PEMS instruments applied to two and three cylinders engines, was carried out at the Vehicles Emissions laboratory (VELA) of the Suistainable Transport Unit, Directorate for Energy, Transport and Climate, European Commission – Joint Research Centre, located in Ispra, Italy.

Instead the validation of PEMS instruments applied to single-cylinder engines, was carried out at manufacturers facilities. (Hatz laboratories in Ruhstorf an der Rott – Germany and in Kohler laboratories in Reggio Emilia- Italy).

The chosen reference test bench was the VELA_6 (see Figures 15 and 16). The test cell equipped with a dyno test bench, is capable to perform raw exhaust emission test and it suitable for small engines up to 40kW.

The climatized test cell is equipped with the following instruments and equipment (see Table 5):

Figure 15. View of JRC VELA_6 during preliminary comparison test (1).

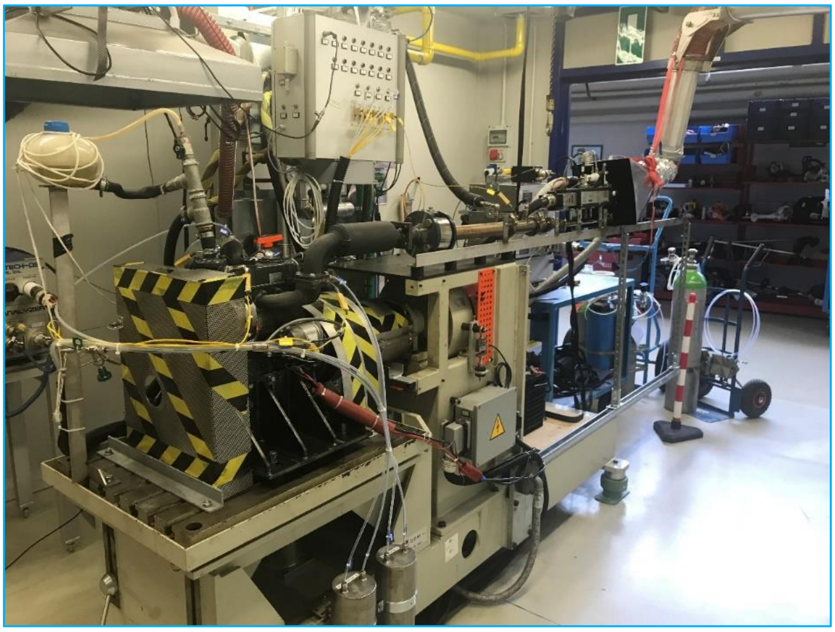


Figure 16. View of JRC VELA_6 during preliminary comparison test (2).

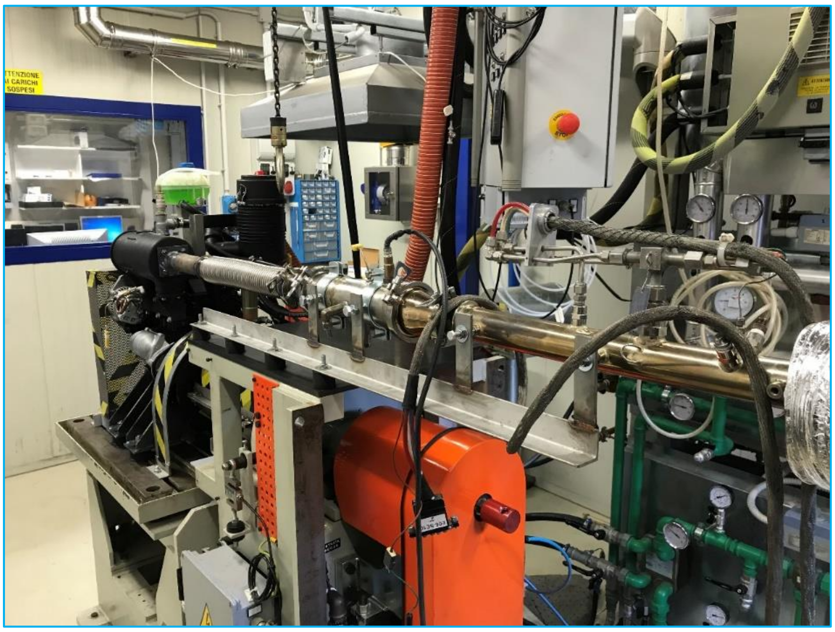


Table 5. Technical specification of the VELA_6 test cell.

EQUIPMENT	MODEL	PARAMETER
Dynamometer	API-COM FR50	FR50 Max Engine Speed 15000rpm Max Torque: 150Nm
Exhaust Gas Analyzer	Rosemount Analytical N200	THC: Flame Ionisation detector CO, CO_2 : Non-Dispersive Infrared NOx: Chemi-Luminescence detector O_2: Electrochemical cell
Fuel Consumption	Emerson Micro Motion CM010	Fuel Mass Flow (Coriolis effect)
Exhaust mass flow	-	Carbon balance method
Oxygen Sensor	ETAS-LA4-E	Lambda sensor
Thermocouples	K-Thermocouples	Engine manifold, fuel, exhaust, intake air
Pressure		Oil, Fuel, Intake air, Backpressure
Environment Stations	Air conditioning equipment - Test Cell	Ambient temperature and humidity, barometric pressure

Source: JRC.Vela, 2017

The reference test cycle applicable to the engines that equipped the tested machinery is a NRSC G2 test cycle, which foreseen 6 modes, that is 6 points of measurement according to Table 6. Every mode has a different weighting factor.

Table 6. NRSC G2 test cycle.

Cycle G2						
Mode Number	1	2	3	4	5	6
Speed	100%					Idle
Torque[9] %	100	75	50	25	10	0
Weighting factor	0.09	0.20	0.29	0.30	0.07	0.05

Source Reg. (EU) 2017/654

In a NRSC test cycle (e.g.: G2 test), gaseous and particulate components emitted by the engine submitted for testing are measured by the methods described in Reg. (EU) 2017/654 (although the actual machines tested were not yet Stage V compliant), while the exhaust mass flow is obtained by an indirect measurement as

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[9] The % torque is relative to the maximum torque at the commanded engine speed

prescribed in Reg. (EU) 2017/654. More in details, the fuel flow is measured using a fuel mass flow meter based on the Coriolis effect and then the carbon balance method is used.

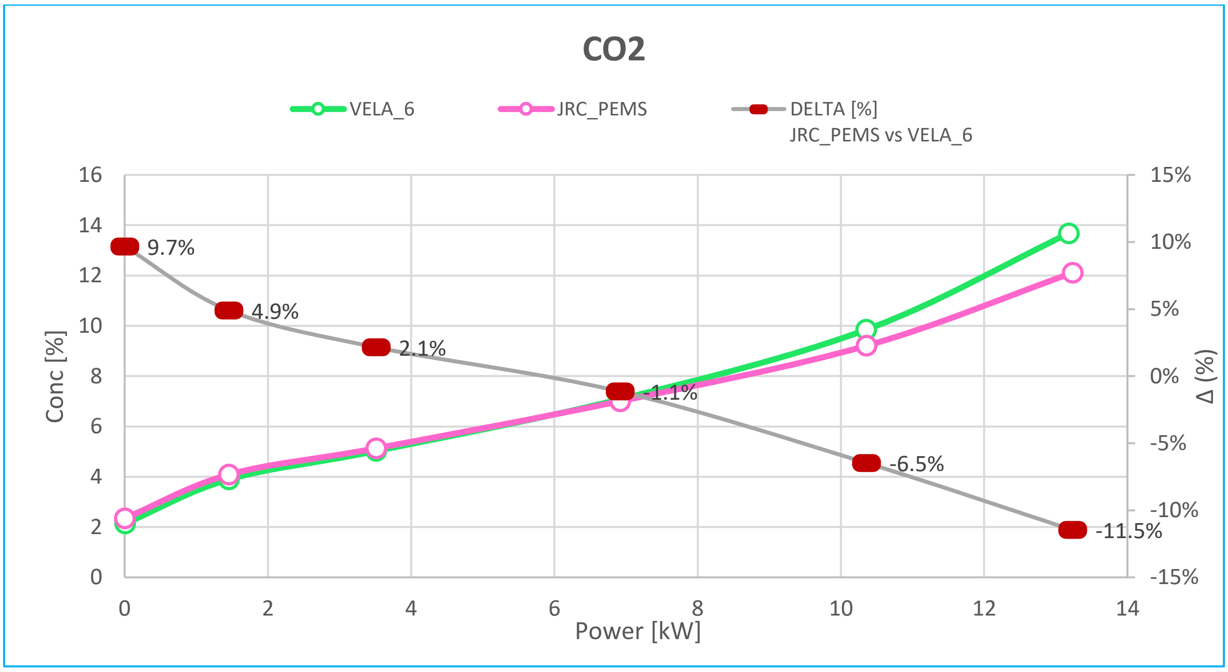
In the next paragraphs, we will introduce the validation of pollutant concentration and the validation of the exhaust mass flow divided by engine groups (see Table 1 and 2): single cylinders (group 1) and 2-, 3-cylinders (group 2) comparing the PEMS results to the reference test bench.

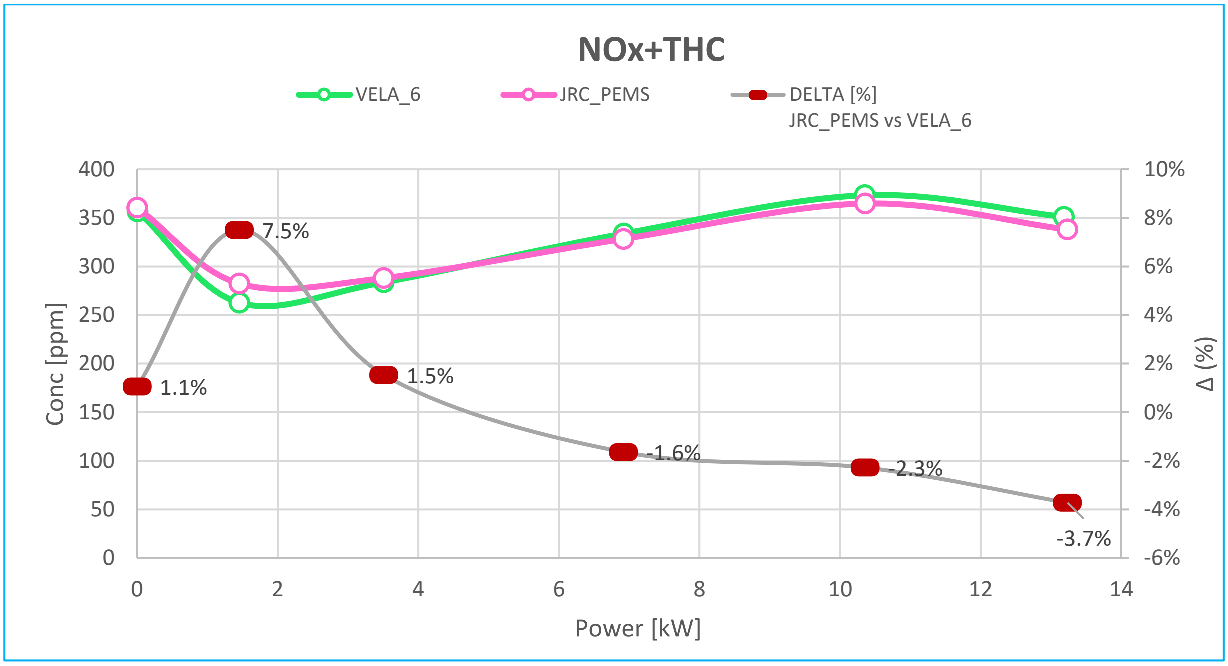
4.2.1 Validation of pollutant concentration for group 2: VELA 6 (reference test bench) vs JRC PEMS – Example 1

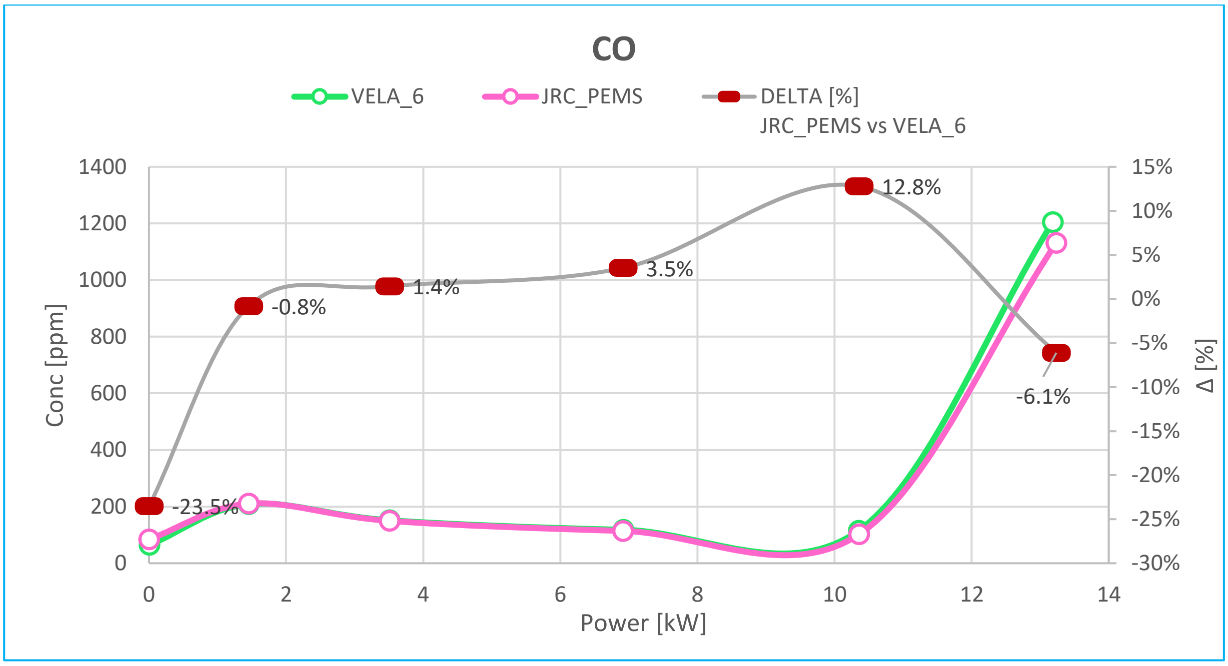
This test was performed to demonstrate the reliability in measuring the concentration of the pollutant in exhaust gas using PEMS instruments instead of a traditional test bench method, which consists in the measurement of air flow and fuel flow or in the measurement of fuel flow and then applying the carbon balance method as in our case. One 3-cylinders engines (parent engine of machinery C) was tested. The test performed is a G2 cycle, starting at hot conditions, after a pre conditioning reaching the minimum threshold of 90°C as oil temperature, that means that the engine was completely saturated. Figure 17 shows the very good correlation between the laboratory-base analytical instruments and PEMS measurements.

Figure 17. Correlation of the concentration values obtained by PEMS and the VELA_6 for the parent engine of the machinery C.

Test Item	VELA_6 vs JRC_PEMS
Engine	Parent engine
Machine Model	Machine C
Test detail	G2 test cycle







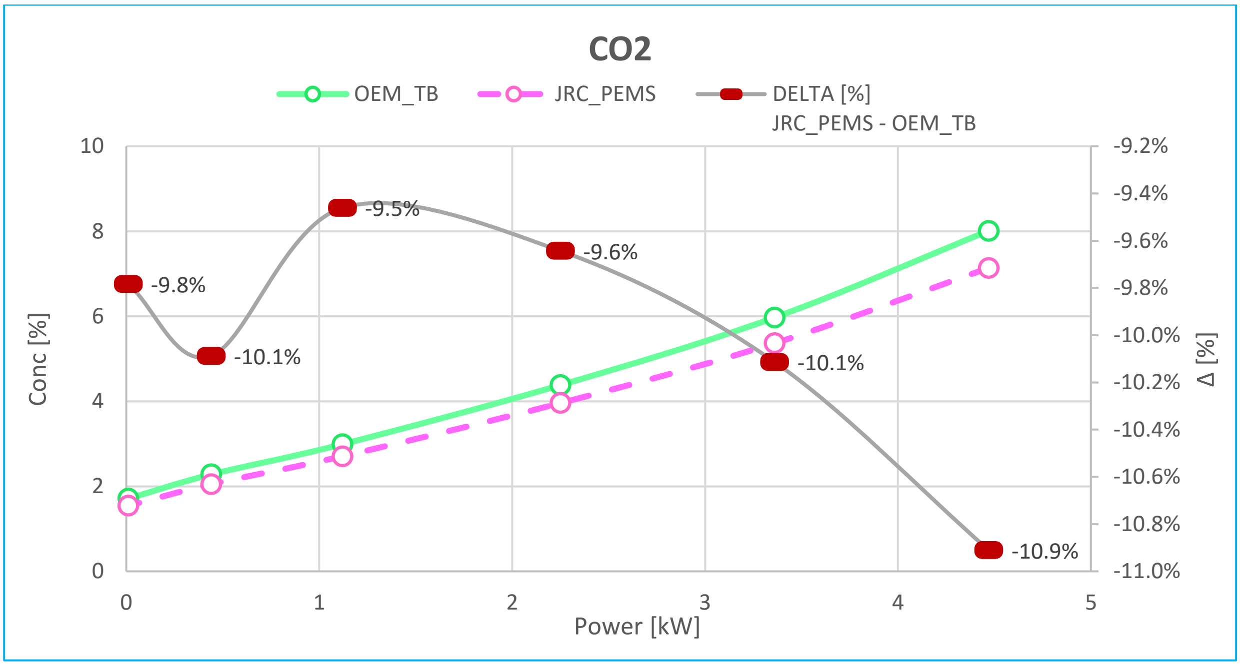
Source: JRC.Vela, 2018

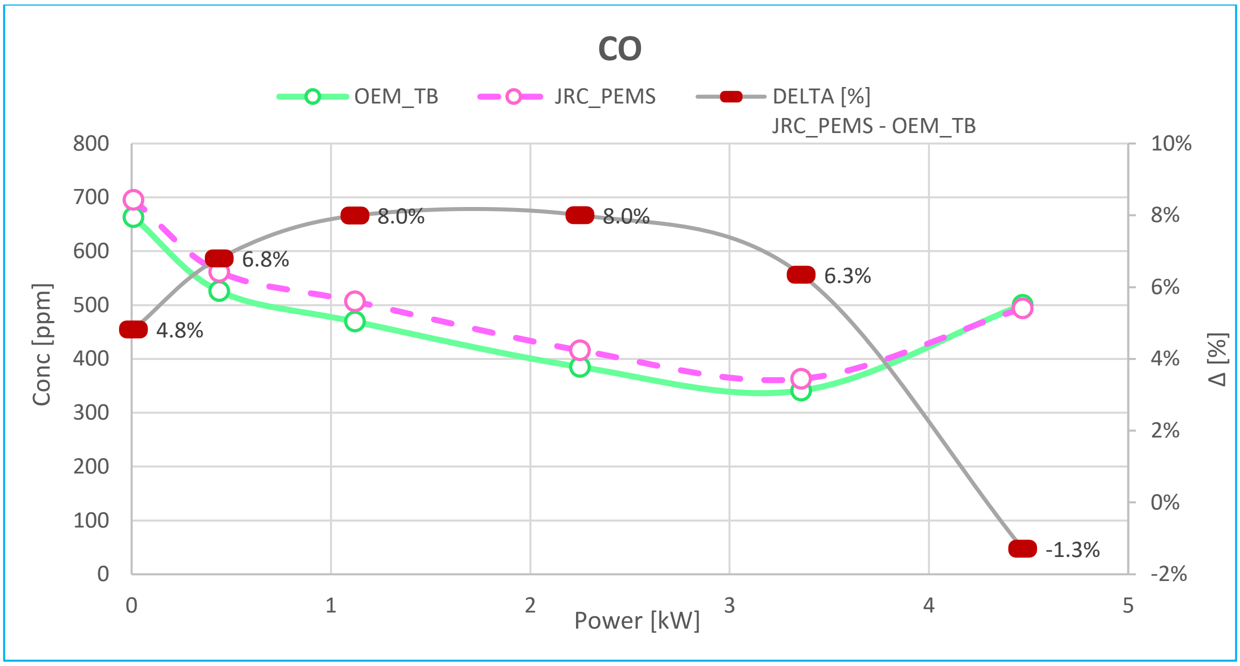
4.2.2 Validation of pollutant concentration for group 1: OEM_TB (reference test bench) vs PEMS – Example 2

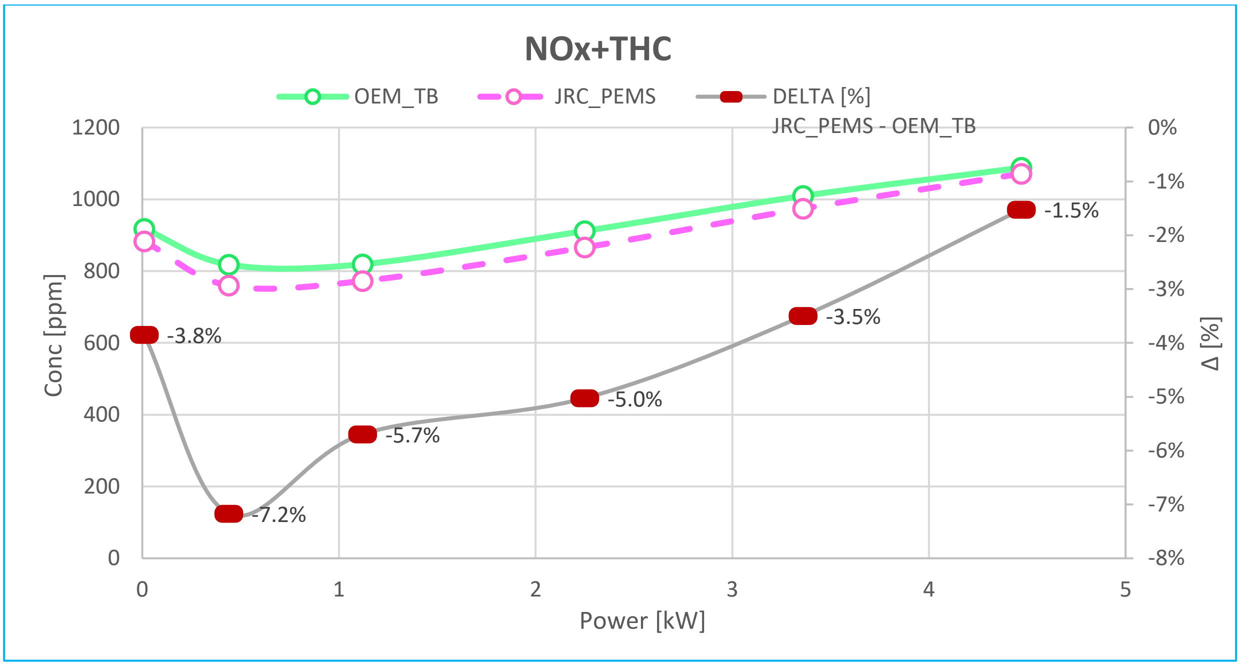
The following table and graphs refer to a single-cylinder engine. In this specific case, the comparison is done between JRC PEMS instruments and the OEM test bench, that is taken as reference. Since JRC is not equipped to test the single-cylinder, due to their high vibrations, these tests were performed directly at the manufacturer facilities. Also in this case, the correlation is very good. The test is still a G2 test, starting at hot conditions (oil temperature over 90°C).

Figure 18. Correlation of the concentration values obtained by PEMS and the OEM_TB for the parent engine of the machinery A.

Test Item	VELA_6 vs JRC_PEMS
Engine	Machine engine (installed)
Machine Model	Machine A
Test detail	G2 test cycle







Source: JRC.Vela, 2018

4.2.3 Validation of exhaust flow rate

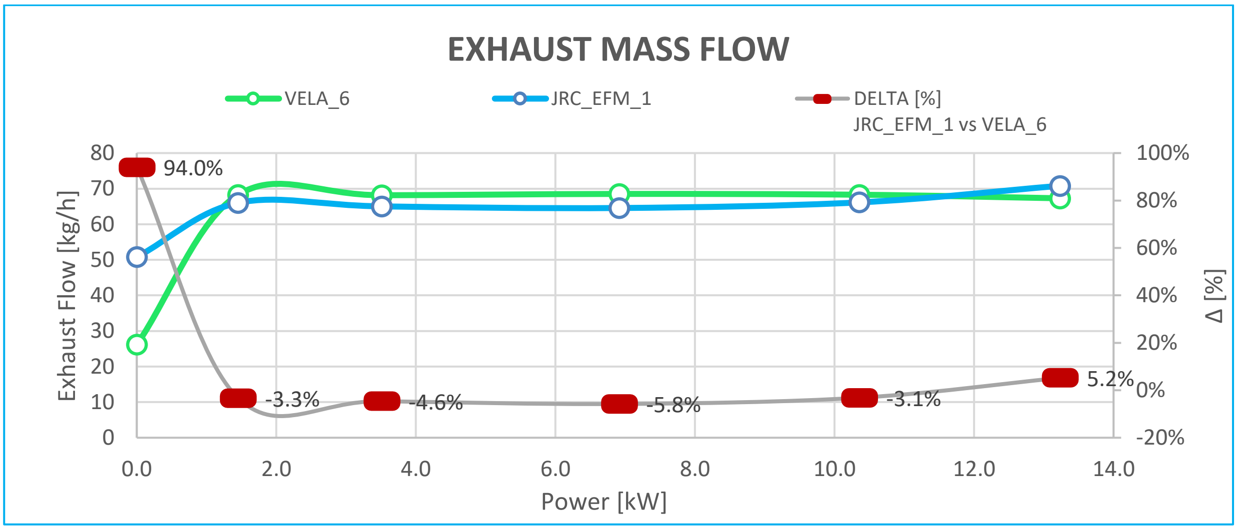
Because of the mass emission is governed by the exhaust flow mass rate. The EFM used with the PEMS instruments has been correlated with the flow calculated using the carbon balance method (in JRC laboratories) or measuring the air mass flow and the fuel mass flow (at manufacturer site). The engines were installed on the dyno test bench to undergo a G2 test and a more complete engine mapping test, with different combination of engine speed and load.

Single cylinder engines operates with pulsations which are responsible for the uncertainty showed in this measurement. Therefore, the use of EFM having higher data acquisition rate is recommended in order to minimised this effect. The initial measurements were made using a first EFM solution (in the following named as JRC_EFM_1), then a second solution (called JRC_EFM_2), more suitable for pulsating engines was used. In particular the measurements were affected by a large error in the idle speed range.

4.2.3.1 VELA 6 (reference test bench) vs JRC EFM – Example 1

One 3-cylinders engine (parent engine of machinery C) was tested. The test performed is a G2 cycle, starting at hot conditions, after a pre conditioning reaching the minimum threshold of 90°C for the oil temperature, that means that the engine was completely saturated. Figure 19 shows that using the JRC_EFM_1, the correlation between the laboratory-base analytical instruments and EFM measurements is very poor at idling speed (MODE 6 of the G2 test).

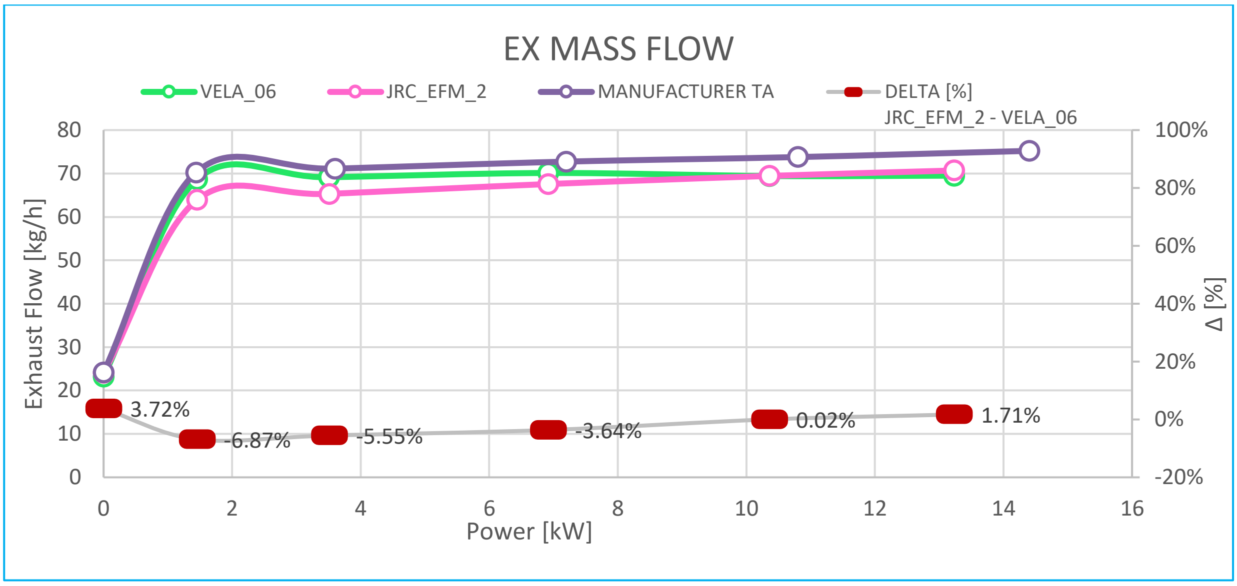
Figure 19. Exhaust mass flow measurement using JRC_EFM_1 and test bench reference (fuel flow and carbon balance method) for engine 1, which is the parent engine of vehicle C.



Source: JRC.Vela, 2018

Using the second solution (JRC_EFM_2), the error is within an acceptable range at the rated point, as well as at the idle speed (see Figure 20).

Figure 20. Exhaust mass flow measurement using JRC_EFM_2 and test bench reference (fuel flow and carbon balance method) for engine 1.

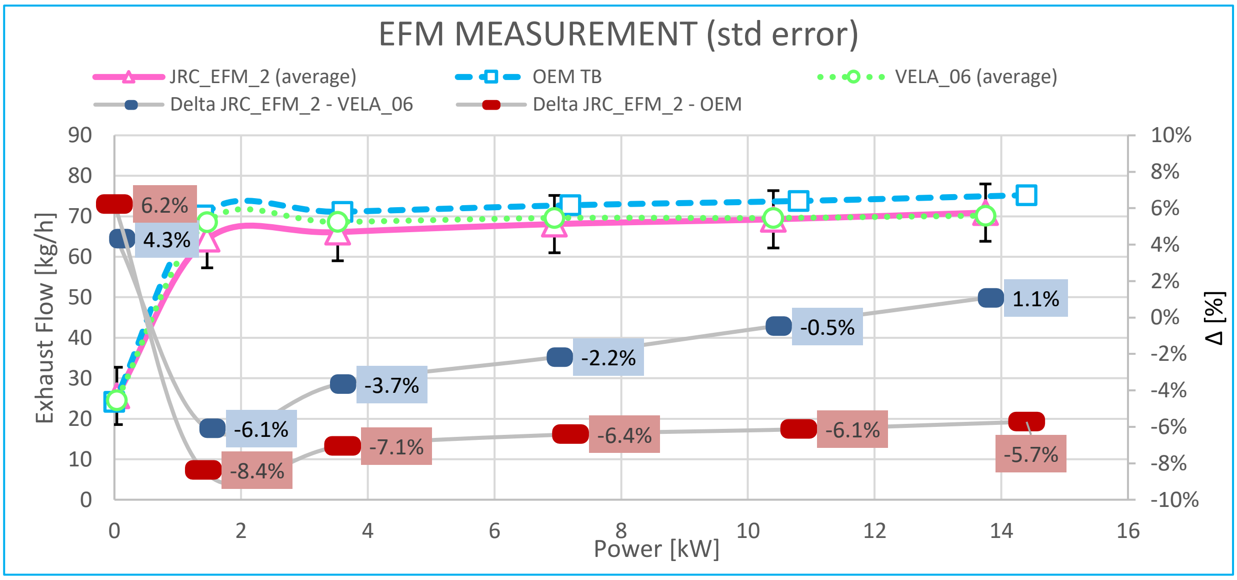


Source: JRC.Vela, 2018

In Figure 20, we also compared (as further reference), the values obtained during a test similar to the Type Approval (TA), performed at OEM laboratories.

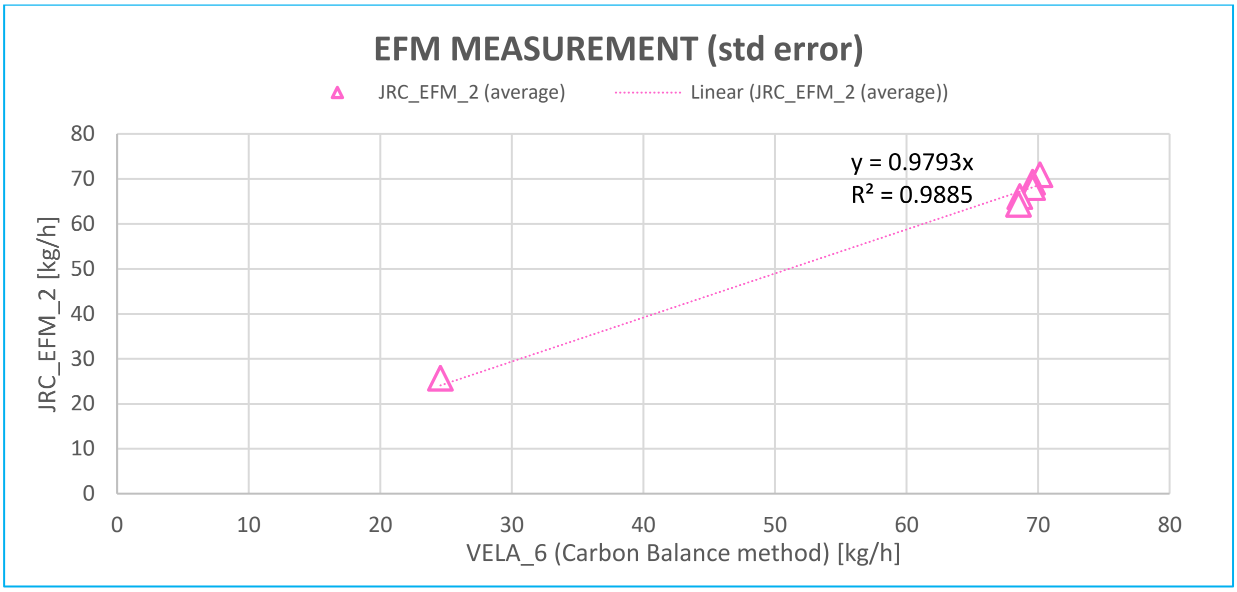
The previous comparison was made using only one test, if the average of 5 tests on the above engine is used a very good agreement is found: the maximum standard error (see Figure 21) is around 6% if compared with the reference test bench (VELA_6) and within 8.5% if compared with the type approval test (done in a different test bench, with different conditions). While Figure 22 shows a very good correlation of both systems (VELA_6 vs. JRC_EFM_2), indicating an average difference of less than 3%. This uncertainty will be the one governing the PEMS measurement uncertainty when an ISM test is performed.

Figure 21. Exhaust mass flow average measurement using JRC_EFM_2 and the test bench reference (fuel flow and carbon balance method) for engine 1/parent engine for machinery C (5 tests average)



Source: JRC.Vela, 2018

Figure 22. Exhaust mass flow correlation between the JRC_EFM_2 and those measured by the reference test bench (VELA_6) by carbon balance method (5 tests average).

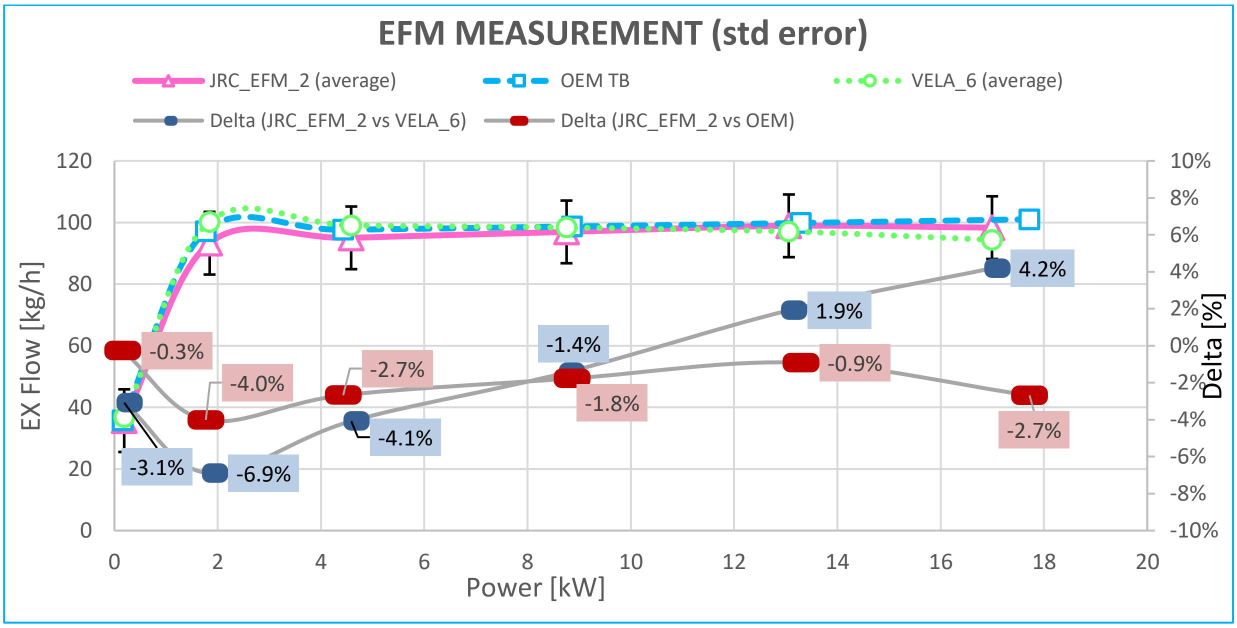


Source: JRC.Vela, 2018

4.2.3.2 VELA 6 (reference test bench) vs JRC EFM – Example 2

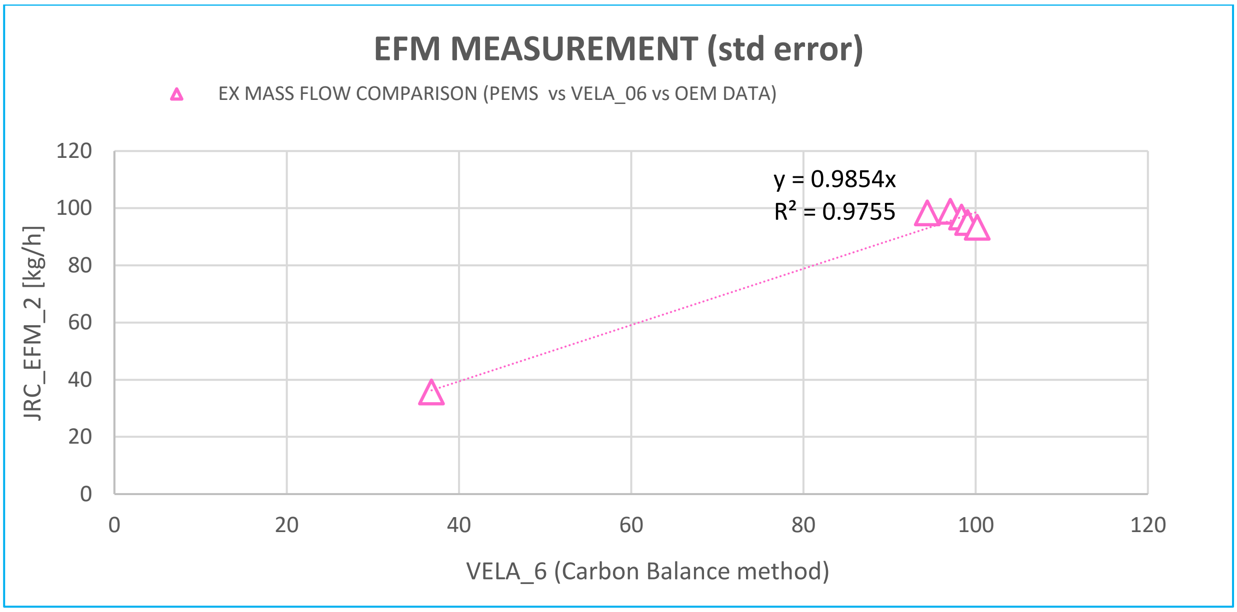
A further 3-cylinders engines (machinery E) was also tested, using also JRC_EFM_2 and the results comfirm the positive trend in using this exhaust mass flow meter. In fact the maximum error detected is around 4% (See Figure 23).

Figure 23. Exhaust mass flow correlation between the JRC_EFM_2 and those measured by test bench reference (fuel flow and carbon balance method) for engine 2, which equipped machinery E (2 tests average).



Source: JRC.Vela, 2018

Figure 24. Exhaust mass flow correlation between the JRC_EFM_2 and those measured by the reference test bench (VELA_6) by carbon balance method (2 tests average) – Engine 2/Machinery E.



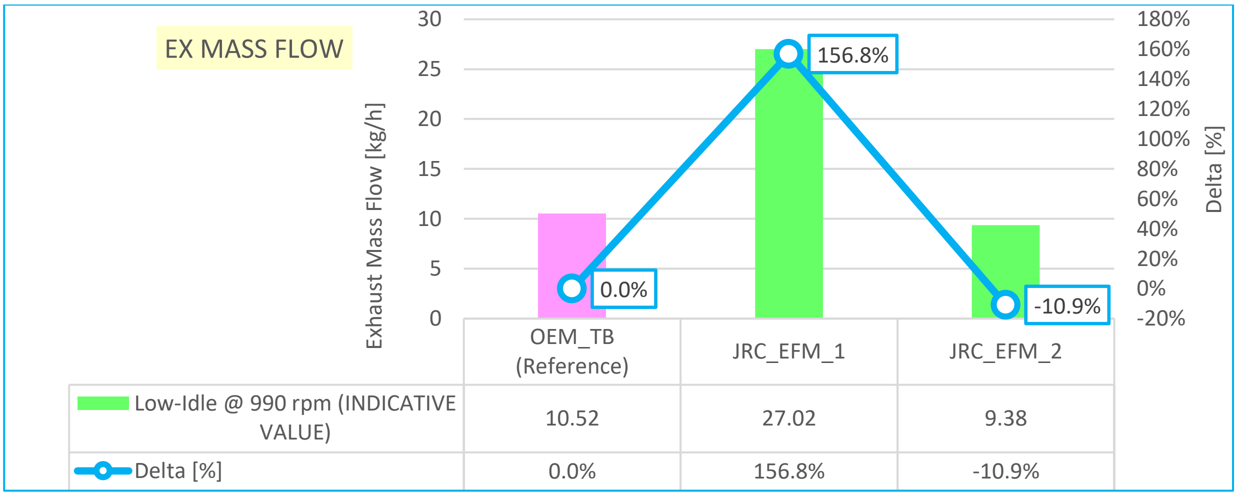
Source: JRC.Vela, 2018

Figure 24 shows a very good correlation of the two measurements systems (VELA_6 vs. JRC_EFM_2), indicating an average difference of around 1,5%.

4.2.3.3 JRC_EFM_1 versus JRC_EFM_2 on a single-cylinder engine

The agreement worsens when a single-cylinder engine is considered. The following test refers to a single-cylinder engine using JRC_EFM_1 and performed with the engine mounted on the machinery at low idle (region of interest for the comparison at around 990 rpm). The result is not satisfactory with about +157% difference (see Figure 25). However if JRC_EFM_2 is used, then the flow measured at idle remains within an acceptable range (-11%) as compared to the values obtained in the OEM's engine test bench. In this comparison it should keep in mind that the test conditions for both tests although similar they are not identical as the conditions on the machine cannot be precisely controlled.

Figure 25. Exhaust mass flow measurements using the JRC_EFM_1 and JRC_EFM_2 on single cylinder at idling (Machinery A).



	OEM_TB (Reference)	JRC_EFM_1	JRC_EFM_2
🟩 Low-Idle @ 990 rpm (INDICATIVE VALUE)	10.52	27.02	9.38
Delta [%]	0.0%	156.8%	-10.9%

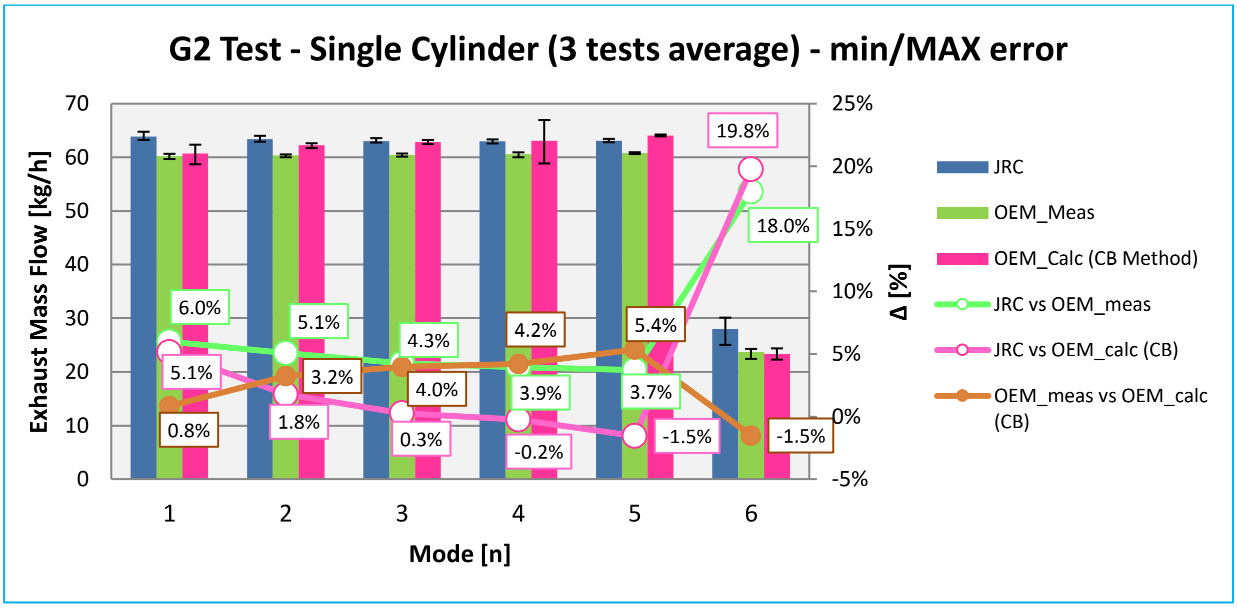
Source: JRC.Vela, 2018

4.2.3.4 VELA 6 (reference test bench) vs JRC EFM – Example 3

In what follows the results of the test at the OEM facility using a second generation EFM (JRC_EFM_2) is presented. The tests have been performed on a single cylinder engine (Machinery F).

During the G2 test the test outcome in terms of percentage different could be considered acceptable (see Figure 26). However, when the exhaust flow is further investigated by mapping the engine in different condition of engine speed and load (mainly 2 steps: high load: 100% load and low load: 25% load), the performance of the JRC_EFM_2 decreased drastically; in particular at low engine speeds and high load conditions. The minimum and maximum error committed among the different tests is very limited.

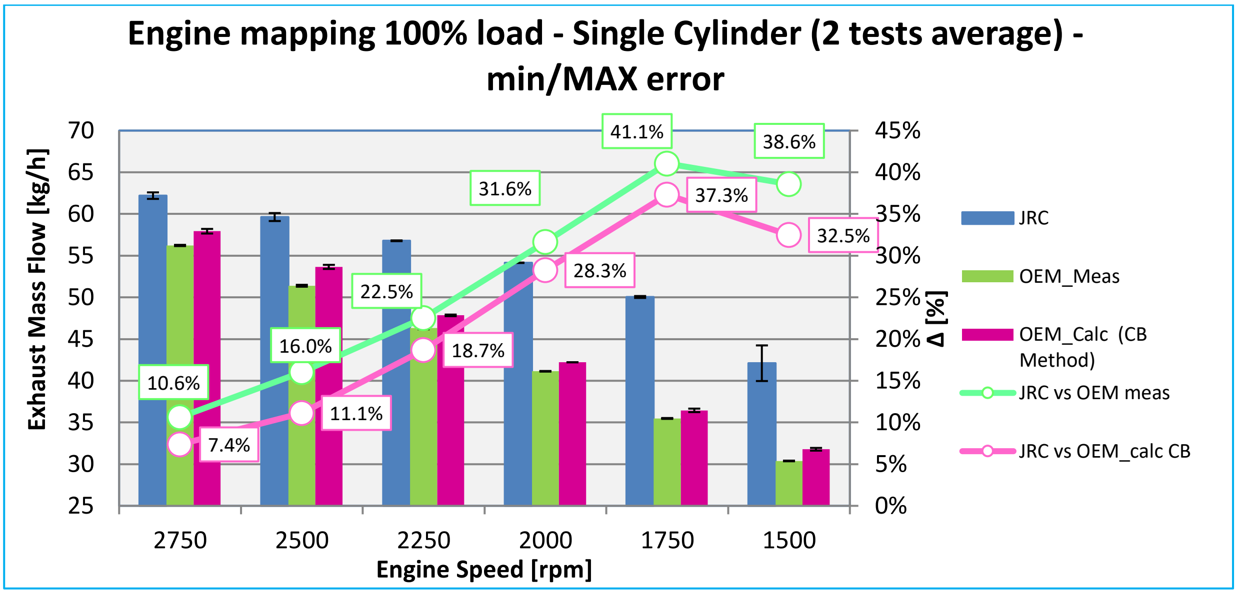
Figure 26. G2 test on single cylinder engine (average on 3 tests).



Source: JRC.Vela, 2019 – OEM data

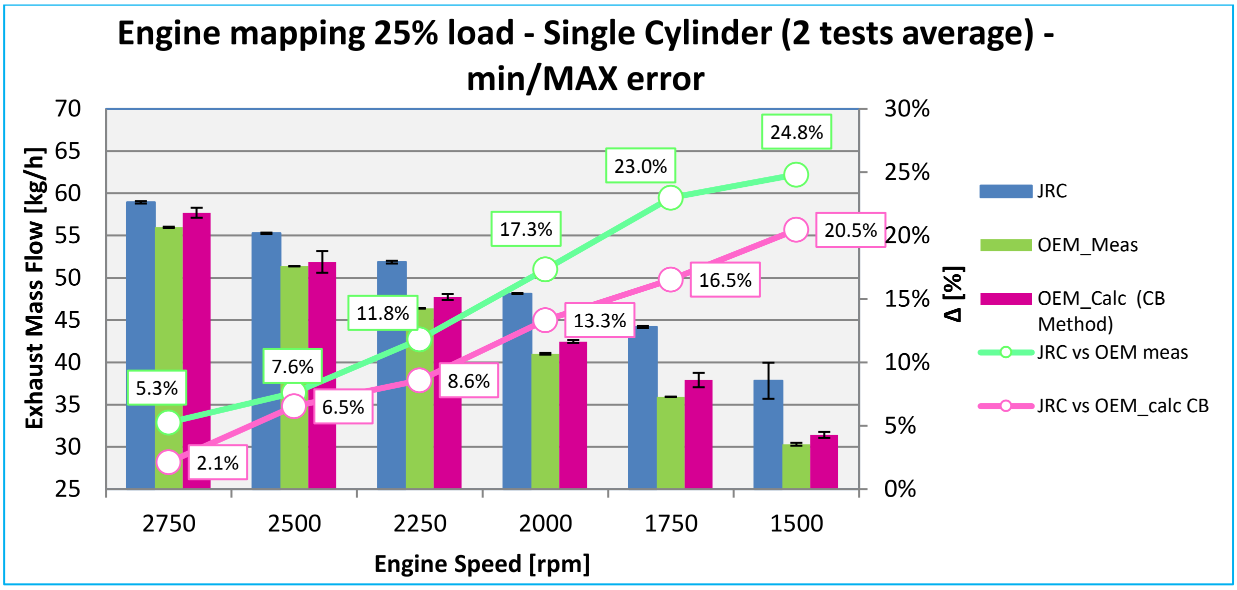
Figures 27 and 28 depict this behaviour respectively at 100% load and 25% load averaging the data of 2 tests.

Figure 27. Engine Mapping at 100% of the load on single cylinder engine (2 tests average).



Source: JRC.Vela, 2019 – OEM data

Figure 28. Engine Mapping at 25% of the load on single cylinder engine (2 tests average).

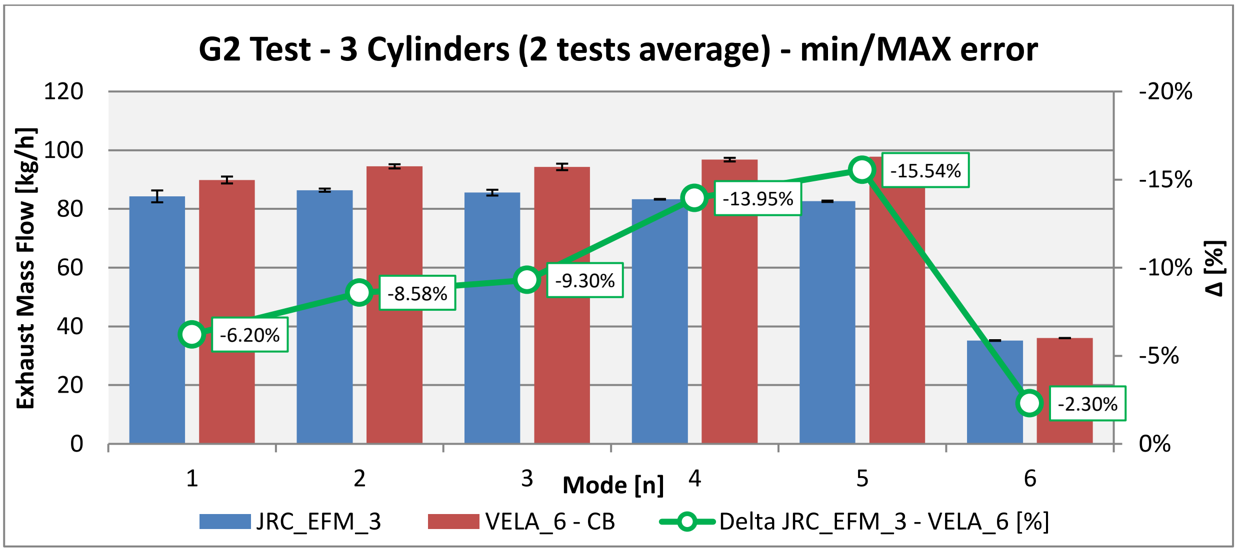


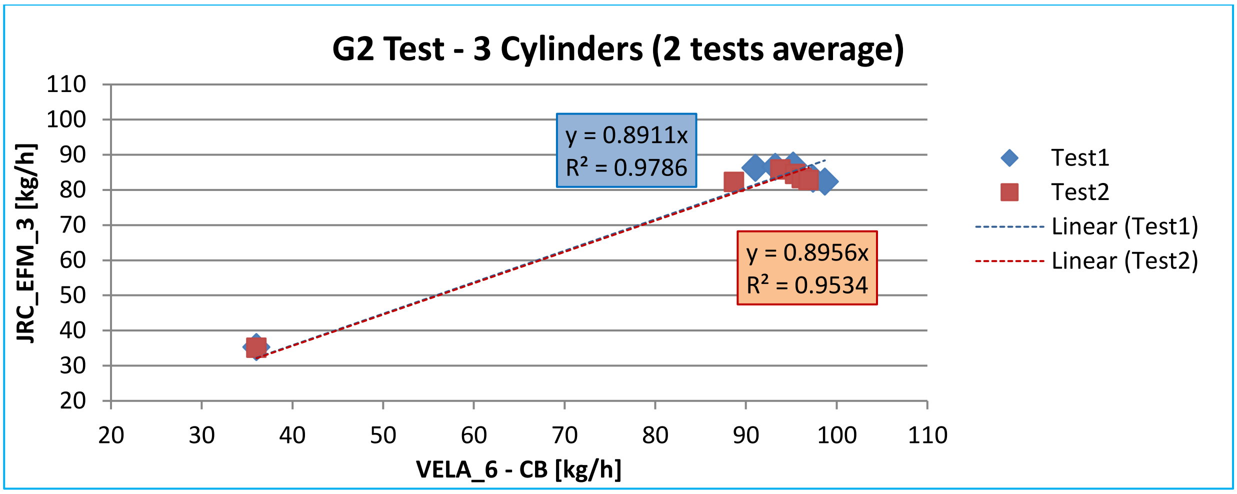
Source: JRC.Vela, 2019 – OEM data

In VELA 6 a third EFM from a different manufacturer was also tested to measure the exhaust mass flow, the so-called JRC_EFM_3.

The tests were performed on a 3-cylinders engine (machinery E). Two G2 tests as well as two mapping tests in the worst conditions, i.e. at maximum load, and the results were encouraging. Figure 29 shows the behaviour during the G2 test (average data on 2 tests), instead Figure 30 shows the trend in a complete engine mapping at 100% of the load (worst condition – average data on 2 tests).

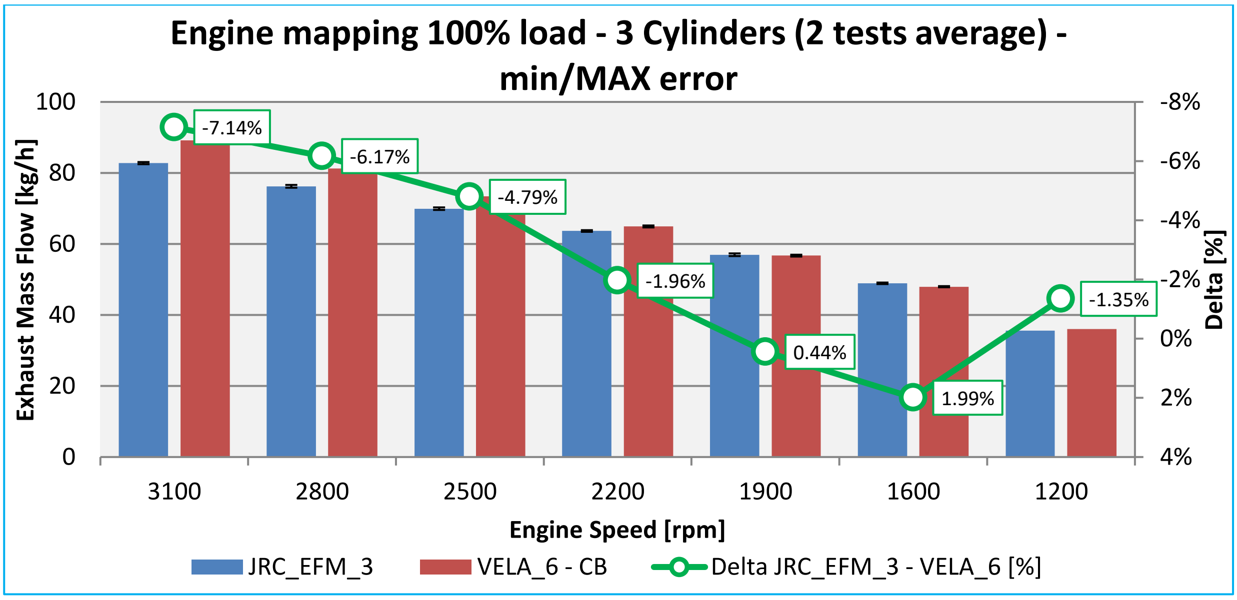
Figure 29. G2 test on single cylinder engine (2 tests average), using EFM_JRC_3

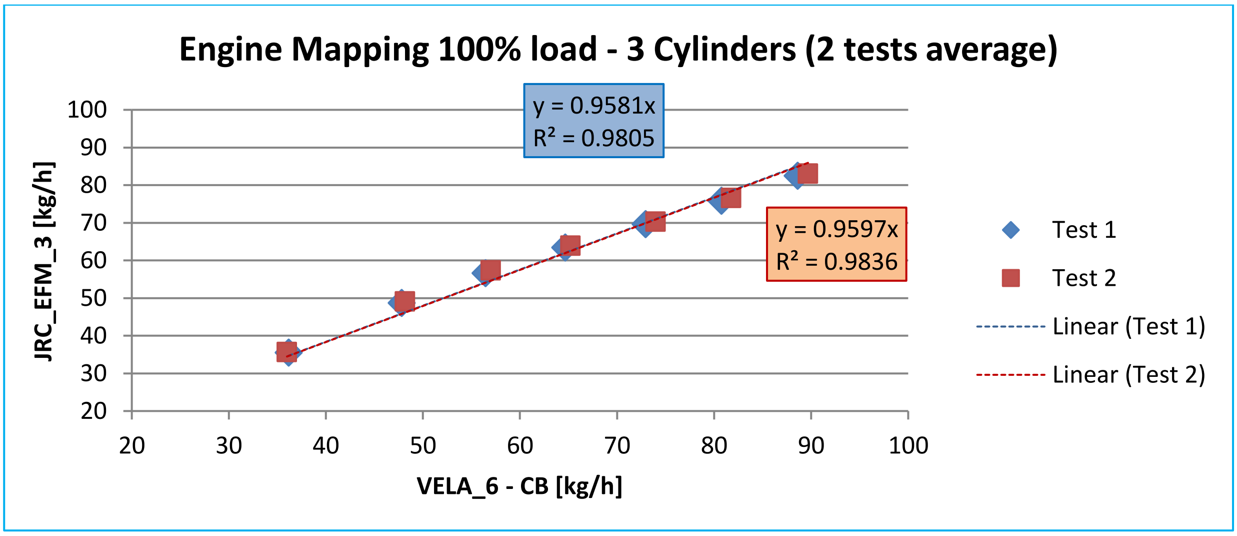




Source: JRC.Vela, 2019

Figure 30. Engine Mapping at 100% of the load on single cylinder engine (average on 2 tests), using EFM_JRC_3.





Source: JRC.Vela, 2019

5 Reference magnitudes (i.e. work and CO_2)

Reference CO2

Reference work and CO_2 are obtained at the applicable test cycles:

a) The hot-start NRTC for engine categories NRE-v-3, NRE-v-4, NRE-v-5, NRE-v-6;

b) The LSI-NRTC for engine categories NRS-v-2b, NRS-v-3;

c) The discrete-mode or RMC NRSC for the corresponding engine category [not a) nor b)]

$$W_{ref} = \sum_{i=1}^{N} P_i \cdot \Delta t_i = \frac{1}{f} \cdot \frac{1}{3600} \cdot \frac{1}{10^3} \cdot \frac{2\pi}{60} \cdot \sum_{i=1}^{N} (n_i \cdot T_i)$$

$$m_{CO2,ref} = m_{CO2} / 1000$$

P_i = instantaneous engine power [kW]

n_i = instantaneous engine speed [rpm]

T_i = instantaneous engine torque [Nm]

W_{ref} = the reference work [kWh]

f = data sampling rate [Hz]

N = number of measurements [-]

m_{CO2} = mass of CO_2 for the test cycle

$m_{CO2,ref}$ = reference mass of CO_2

RMC = ramped modal cycle

W_{ref} and $m_{CO2,ref}$ determined from discrete-mode NRSC

$$W_{ref} = \sum_{i=1}^{N_{mode}} (P_i \cdot WF_i) \cdot \frac{t_{ref}}{3600}$$

$$m_{CO2,\,ref} = \sum_{i=1}^{N_{mode}} \frac{\left(q_{mCO2,i} \cdot WF_i\right)}{1000} \cdot \frac{t_{ref}}{3600}$$

Reference time t_{ref} is the total duration of the equivalent RMC

They are either 1800 s (cycles C1,C2, G1 and G2) or 1200 s (cycles D2, E2, E3, F and H)

W_{ref} = the reference work [kWh]

P_i = engine power for mode i [kW]

WF_i = weighting factor for the mode i [-]

t_{ref} = reference time [s]

$q_{mCO2,i}$ = mass flow of CO_2 for mode i [kg/s]

$m_{CO2,ref}$ = reference mass of CO_2

RMC = ramped modal cycle

The reference work and reference CO_2 mass of an engine type, or for all engine types within the same engine family, shall be those specified in points 11.3.1 and 11.3.2 of the addendum to the EU type approval certificate of the engine type or the engine family, as set out in Annex IV to Commission Implementing Regulation (EU) 2017/656[10]; i.e. reference work and reference CO_2 mass of the parent engine.

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[10] Commission Implementing Regulation (EU) 2017/656

6 Working/non-working event validation

The new STAGE V[11] for Non-Road Mobile Machinery (NRMM) regulation prescribes the In-Service Monitoring (ISM) of NRMM. Based on the outcome of a Pilot Program conducted by the JRC in close collaboration with EUROMOT, the Commission has proposed a methodology to perform the ISM of NRMM for engines in the 56 to 560 KW power range (NRE-v-5 and NRE-v-6). The method includes among others the definition of working and not working events[12] based upon the instantaneous engine power being above or below 10% respectively of the maximum net power of the engine under test. The proposed method also describes the procedure for the determination of emissions using the Work based Averaging Window (WAW) or the CO_2 mass based Averaging Window (CO2AW) methods. While in the first case (i.e. WAW) the selection of working and not working events is straight forward, in the second case (i.e. CO2AW) is not so and indeed the proposed method does not address this point, making the method by the facto not applicable.

Valid events are based on the concept of working and non-working events. Non-working events are categorised as short non-working events (≤ D2) and long non-working events (> D2) (see the Table 8 for the value of D2).

The following marking steps are conducted:

- Non-working events shorter than D0 shall be considered as working events and merged with the surrounding working events (see the Table 7 for the values of D0);
- The take-off phase following long non-working events (> D2) shall also be considered as a non-working event until the exhaust gas temperature reaches 523 K. If the exhaust gas temperature does not reach 523 K within D3 minutes, all events after D3 shall be considered as working events (see the Table 7 for the values of D3);
- For all non-working events, the first D1 minutes of the event shall be considered as working event (see the Table 7 for the values of D1).

Table 7. Values for the parameters used to mark working and non-working events.

Parameter	Value [min]
D0	2
D1	2
D2	10
D3	4

Source: JRC.Vela, 2018

Appendix 4 to the Annex of Reg. (EU) 2017/655 includes the marking algorithm used for the definition of the working/non-working events.

6.1 Calculation of engine instant equivalent power from the instantaneous CO2 mass flow

This section proposes a methodology to calculate the instant equivalent power of the engine under ISM test from the instantaneous measured CO_2 mass flow, hence allowing the determination of working and not working events.

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[11] Reg. (EU) 2016/1628

[12] 'event' means the data measured in an in-service monitoring test for the gaseous pollutant emissions calculations obtained in a time increment Δt equal to the data sampling period,

6.1.1 Equivalent power determination from CO_2 mass flow

<u>"Veline" approach for LDV:</u>

The Veline equation defines the CO_2 mass flow as function of the wheel power

$$CO_{2_i} = k_{WLTC} \times P_{w,i} + D_{WLTC} \qquad \text{(Eq.1)}$$

Where:

- CO_{2_i} = the instantaneous emitted CO_2 in [g/h]
- k_{WLTC} = slope of the Veline from WLTC, [g/kWh]
- $P_{w,i}$ = instant power at the wheel
- D_{WLTC} = intercept of the Veline from WLTC, [g/h].

"D" in the equation gives the CO_2 emissions at zero power output or in other words it represents the CO_2 emission value for idling at increased rpm (parasitic losses at engine speed that would result from a regression line with engine speed instead of CO_2).

<u>"Veline" approach for NRMM</u>

A simplified approach is proposed. In this case the "Veline" equation can be simplified by not considering the parasitic losses between the engine and the power to the wheel (i.e. the parameter D in eq. 1) <u>because the interest here is the power delivered by the engine rather that the power to the wheel.</u>

$$CO_{2_i} = k_i \times P_i \quad \text{(Eq.2)}$$

where P_i = instantaneous engine power

If we integrate for the whole duration of the test, then

$$\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i = \sum_{i=0}^{N} k_i \times P_i \times \Delta t_i \qquad \text{(Eq. 3)}$$

We can consider that k_i is the same constant for each point and equal to K, then the eq. 3 becomes:

$$\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i = K \times \sum_{i=0}^{N} P_i \times \Delta t_i \text{ (Eq. 4)}$$

Where:

$\Delta t_i = \Delta t = 1/f$

f is the data sampling rate [Hz]

$\sum_{i=0}^{N} CO_{2_i} \times \Delta t_i$ is the total CO_2 emitted in the trip (cycle) and $\sum_{i=0}^{N} P_i \times \Delta t_i$ is the total work performed in the trip (cycle).

Eq.4 becomes:

$$CO_{2_t} = K \times W_t \quad \text{(Eq. 5)}$$

As eq. 5 should be true for any cycle, then is should also hold true for the regulatory cycle and hence we can find the value of K from the values obtained at Type Approval.

$$K_{NRC} = \frac{CO_{2_{NRC}}}{W_{NRC}} \text{ (Eq. 6)}$$

Where

$CO_{2_{NRC}}$ is the total CO_2 emitted by the engine in the regulatory cycle [g]

W_{NRC} is the total work performed in the regulatory cycle [kWh]

And K_{NRC} is the "veline" constant in [g/kWh]

The equivalent actual engine power shall be calculated from the measured CO_2 mass flow (Eq. 2) according to:

$$P_i = \frac{CO_{2_i}}{K_{NRTC}} \text{ (Eq. 7)}$$

Equivalent power:

The equivalent values of instantaneous power can then be calculated from the emitted CO2 flow using Eq.7 and therefore the selection of working and not working event can be made on the basis of this calculated equivalent power.

6.2 Validation for the proposed method

As in the tested machineries, no one was equipped with an ECU, in what follow the validity of the approach proposed above is tested in an ATV for which the power was available (power broadcasted by the ECU) and the values of the Work and CO_2 at type approval are known. The validation is made on two aproaches: a) comparison of valid events using only the power threshold and, b) applying the working/non-working event algorithm.

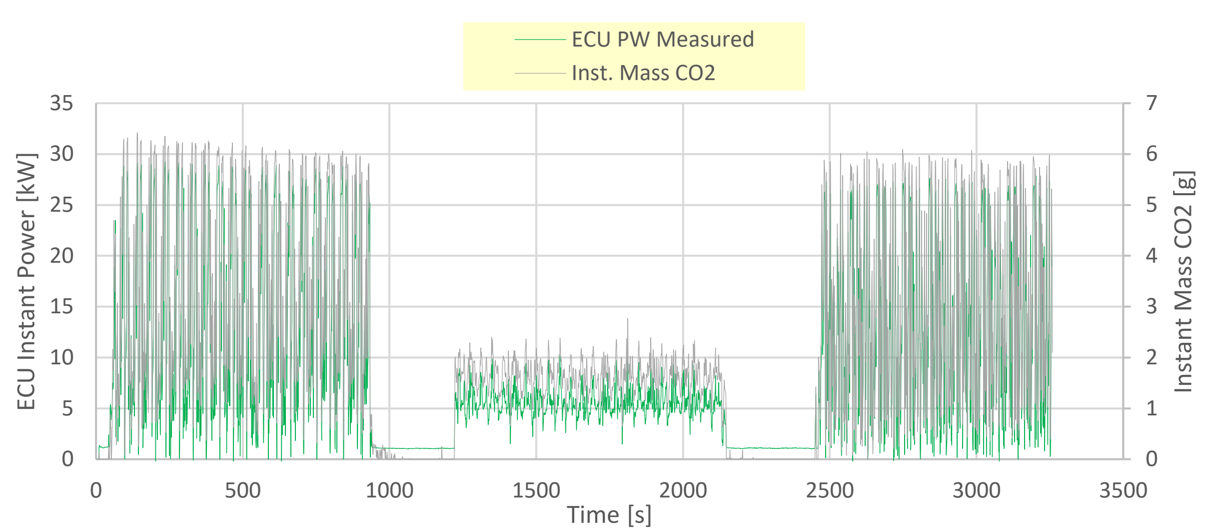
6.2.1 Comparison of events with P> 10% P_{max}

This example refers to a ATV vehicle with an engine whose maximun power is 39.6 kW at Type Approval. The NRSC reference work is 9.263 kWh and the reference CO_2 is 8139 g.

CO_2 values presented are obtained from on-board PEMS measurements. Whereas the power is calculated using the engine speed at actual torque provided by the ECU.

Figure 31 depicts the trace of Power and CO_2 for this machine/vehicle. It seems obvious that there is a linear relationship between both values.

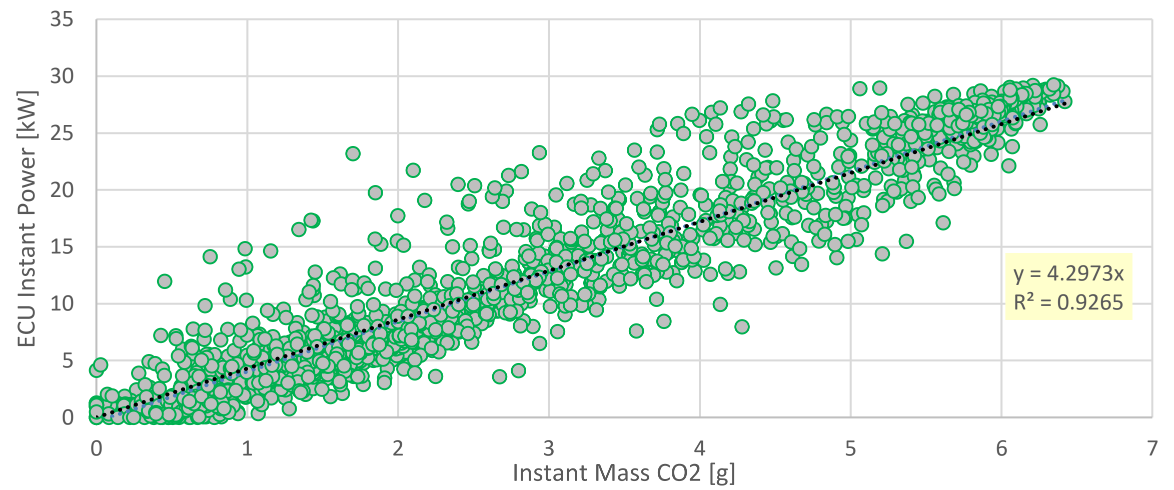
Figure 31. Power (from ECU) and CO2 trace for the tested vehicle.



Source: JRC.Vela, 2018

A better way of seeing the relationship is by plotting the instant power versus the instant CO_2 flow and check for linearity. Figure 32 depicts such plot and the least squares analysis shows a coefficient of determination r^2 of 0,93 which indicates a strong correlation.

Figure 32. Linear correlation between ECU Power and CO2.



Source: JRC.Vela, 2018

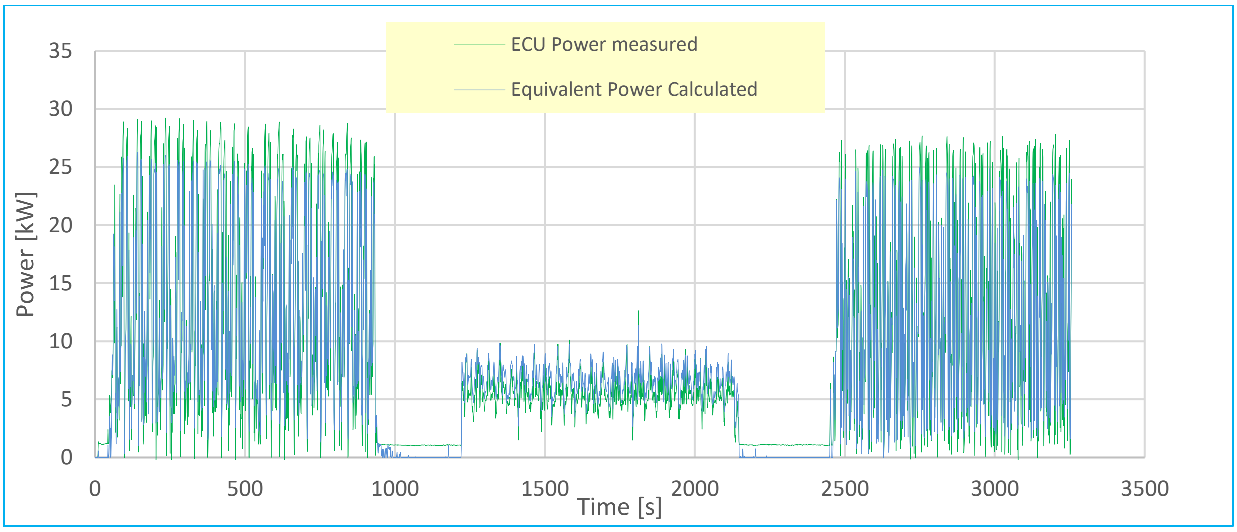
K can be calculated from the type approval values for this engine using Eq. 6: K= 878.66 g/kWh.

$$P_i = \frac{CO_{2_i}}{K_{NRTC}}$$ and considering the CO_2 flow is measured in g/s, then:

$$P_i = \frac{CO_{2_i}}{878.66} \cdot 3600\ [kW]$$

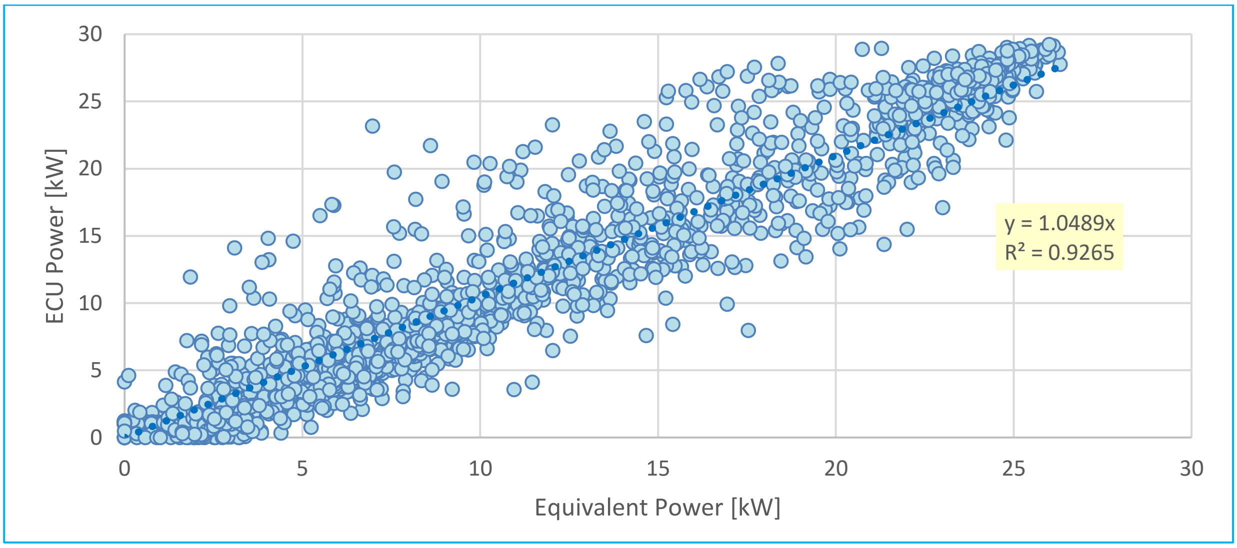
Figures 33 and 34 show the comparison between the power obtained directly from on-board measurements and the calculated values following the proposed methodology (equivalent power).

Figure 33. Power measured by ECU vs Power calculated using the “Veline” approach (equivalent power).



Source: JRC.Vela, 2018

Figure 34. Linear correlation between ECU Power and the Power calculated using the “Veline” approach (equivalent power).

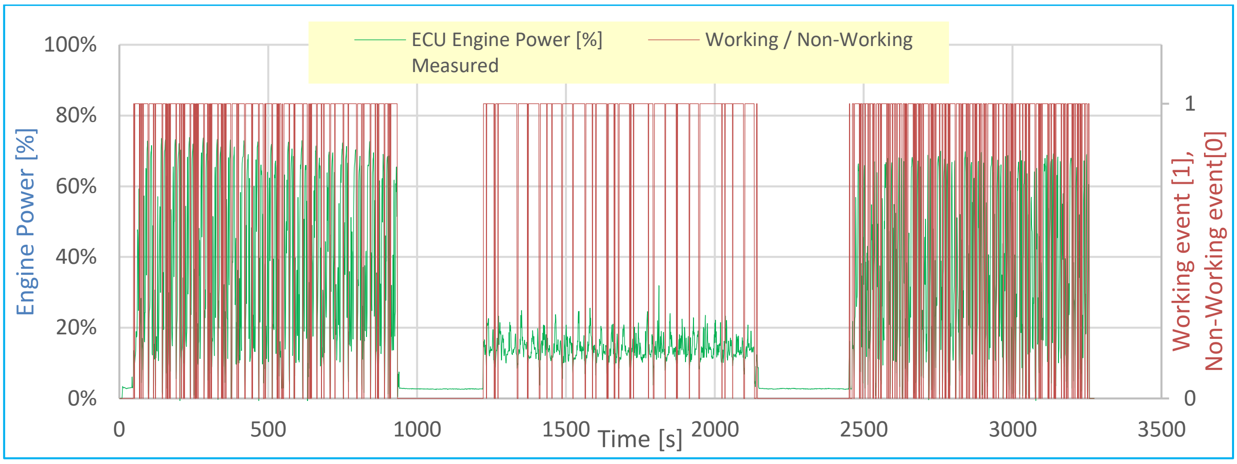


Source: JRC.Vela, 2018

The main purpose of this methodology is the selection of working and not working events for the case where the CO2BW method (see section 7) is used as emission determination procedure. Therefore, it is important to compare the number of events below 10% of the maximun net power of this engine for the case of power being measured (torque x rpm obtained from ECU) and for that of the calculated equivalent power using the proposed methodology.

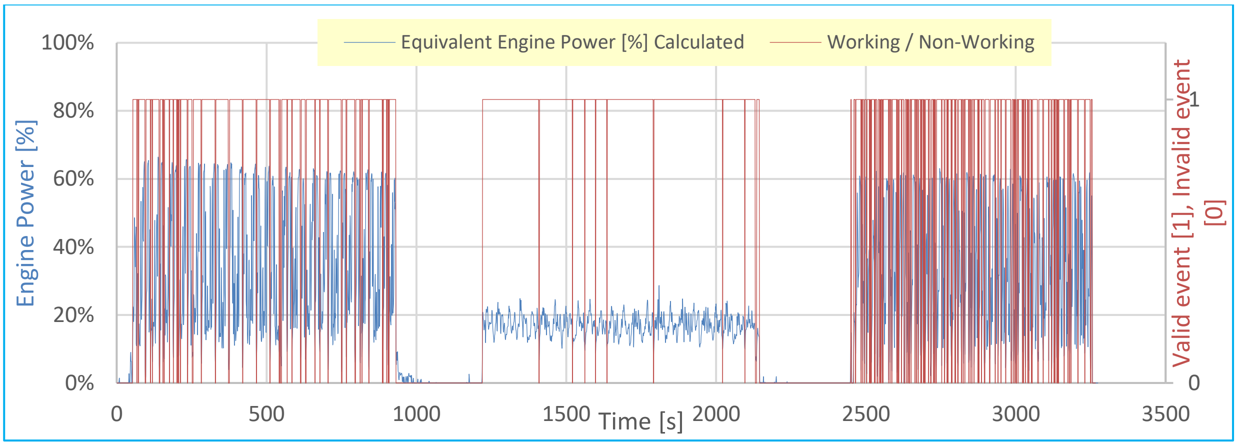
It is also important to find out wether the calculated equivalent power from the CO_2 will provide the same data distribution as in the case of the measured power once the procedure to determine working/non-working events is applied. (i.e. the application of the “machine work” marking algorithm in the EU Delegated legislation regarding monitoring of gaseus pollutant emission from in-service internal combustion engines installed in non-road mobile machinery). See Figures 35 and 36 for reference.

Figure 35. Baseline calculation setting (ECU power measured).



Source: JRC.Vela, 2018

Figure 36. Baseline calculation setting (Equivalent engine power - calculated).



Source: JRC.Vela, 2018

Table 8 shows the number of events below 10% of the maximum power in terms of both absolute and percentage of total number of events for both cases.

Table 8. Difference between the power "measured" by the ECU and the equivalent power calculated using the "Veline" approach (Baseline data – P< 10%P_{max} excluded).

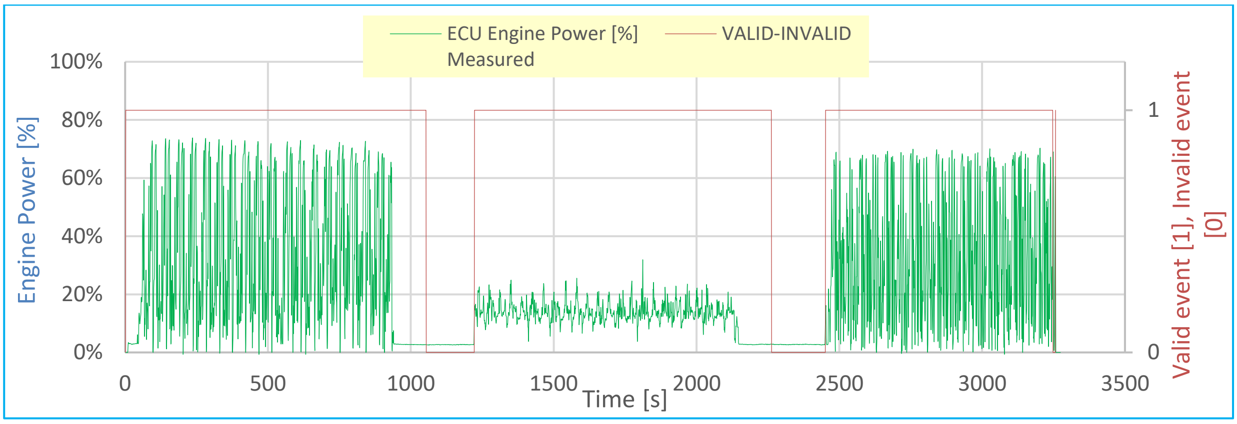
ESCLUSION: BASELINE (P <10% P_{max})	**ECU MEASURED**	**CALCULATED**
Total Number of events	3257	3257
Number of events with P<10% P_{max}	995	860
% of non-working events	**30.55%**	**26.40%**

Source: JRC.Vela, 2018

6.2.2 Calculation using the working/non-working event algorithm

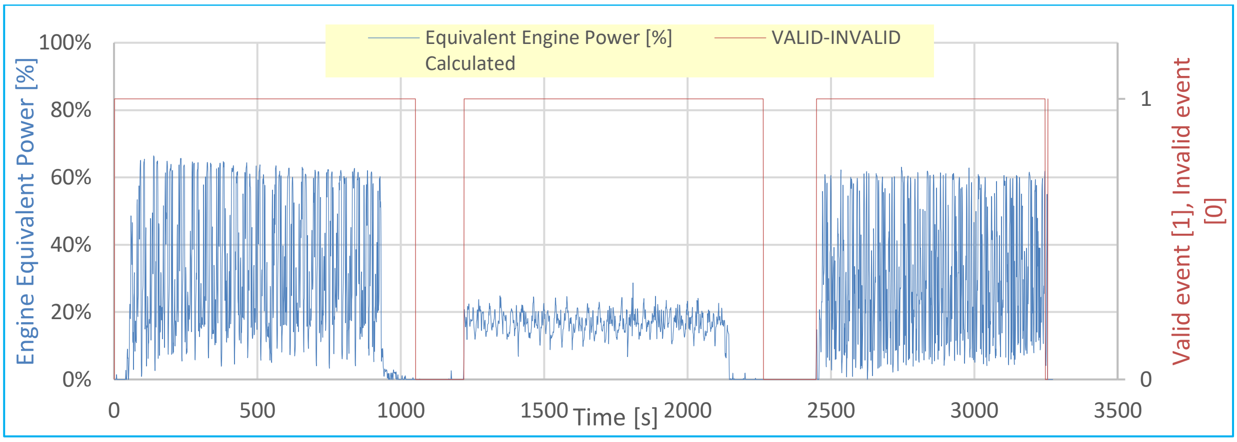
If we introduce the working/non-working events as defined above, taking into account the D0, D1, D2 and D3 parameters, the two power areas defined by the valid/invalid events line, become equivalent. See Figure 37 and 38.

Figure 37. Valid/invalid events using the measured power (ECU).



Source: JRC.Vela, 2018

Figure 38. Valid/invalid events using the calculated equivalent power.



Source: JRC.Vela, 2018

Table 9. Comparison of the number and percentage of invalid events by using the power “measured” by the ECU and the equivalent power calculated by using the “Veline” approach.

EXCLUSION: BASELINE (P<10% P_{max}) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED**
Total Number of events	3257	3257
Number of invalid events	368	364
% of invalid events	**11.30%**	**11.18%**

Source: JRC.Vela, 2018

As it is reported in Table 9, the differences in percentage between the number of invalid events after applying marking algorithm is below 0.2%.

The marking algorithm applied to the test using the power (torque x rpm) broadcast by the ECU and the equivalent power calculated using the proposed methodology provides the same valid and invalid events with the same distribution.

Hence, it can be claimed that the methodology can be used for the case where the instant power of the machine during and in-service test is not known but only the CO_2 emission flow as it is the case for mechanically controlled engines (no ECU).

The methodology has been validated preliminary also with other examples with different operating modes and engine power.

EXAMPLE 1:

The engine has power of 256 kW and it has been tested in is normal operating conditions, which has foreseen short engine idle periods and consequently very few invalid events.

Figure 39 and Figure 40 show, respectively the measured power broacasted by the ECU and the equivalent calculated power. Table 10 gives all the details from the numerical point of view.

Figure 39. Measured power by ECU in example 1.

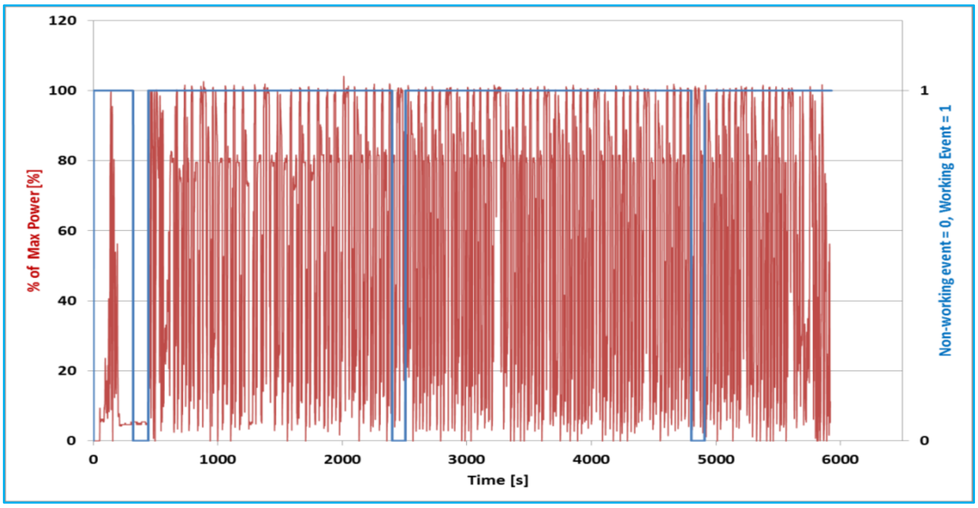
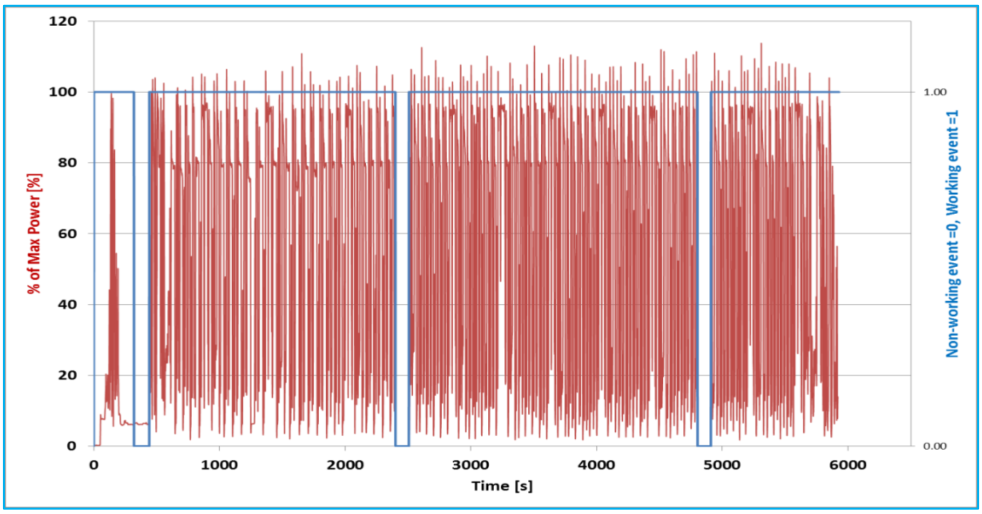


Figure 40. Calculated equivalent power in example 1.



Source: JRC.Vela, 2017

Table 10. Comparison of the number and percentage of invalid events by using the power "measured" by the ECU and the equivalent power calculated by using the "Veline" approach (EXAMPLE1).

EXCLUSION: BASELINE (P<10% P_{max}) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED**
Total Number of events	6143	6143
Number of invalid events	1369	1333
% of invalid events	**22.29%**	**21.70%**

EXAMPLE 2:

The engine has power of 153 kW and it has been tested in is normal operating conditions, which has foreseen long engine idle periods and consequentlya large number of invalid events.

Figure 41 and Figure 42 show, respectively the measured power broacasted by the ECU and the equivalent calculated power. Table 11 gives all the details from the numerical point of view.

Figure 41. Measured power by ECU in example 2.

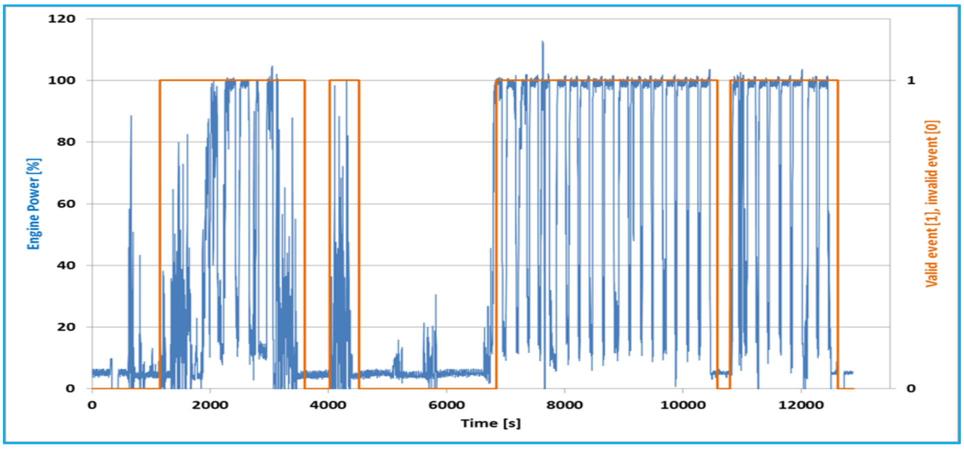
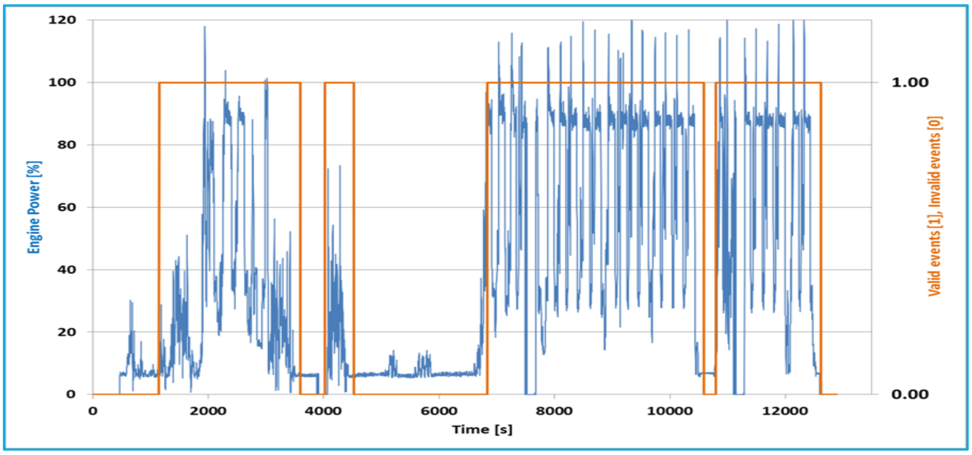


Figure 42. Calculated equivalent power in example 2.



Source: JRC.Vela, 2017

Table 11. Comparison of the number and percentage of invalid events by using the power "measured" by the ECU and the equivalent power calculated by using the "Veline" approach (EXAMPLE2).

EXCLUSION: BASELINE (P<10% Pmax) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED**
Total Number of events	12956	12956
Number of invalid events	5487	5393
% of invalid events	**42.35%**	**41.63%**

7 Emission Evaluation Methods for ISM

7.1 Introduction

In this European NRMM Pilot Program, some principles were adopted to assess the ‘candidate’ data evaluation methods.

The data analysis method in Reg. (EU) 2017/655 developed from the ISC of heavy duty engines, the so-called "averaging window methods" was considered as a baseline method which could require modifications or adaptations for the NRMM case.

7.2 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 while the power is averaged in the 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: the reference work is the one obtained in the certification test cycle.
- In the case of the CO_2 mass: from the engine CO_2 emissions on its certification cycle.

Using the engine work or CO_2 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 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 regulatory cycle) is reached. The calculating window is then moved, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

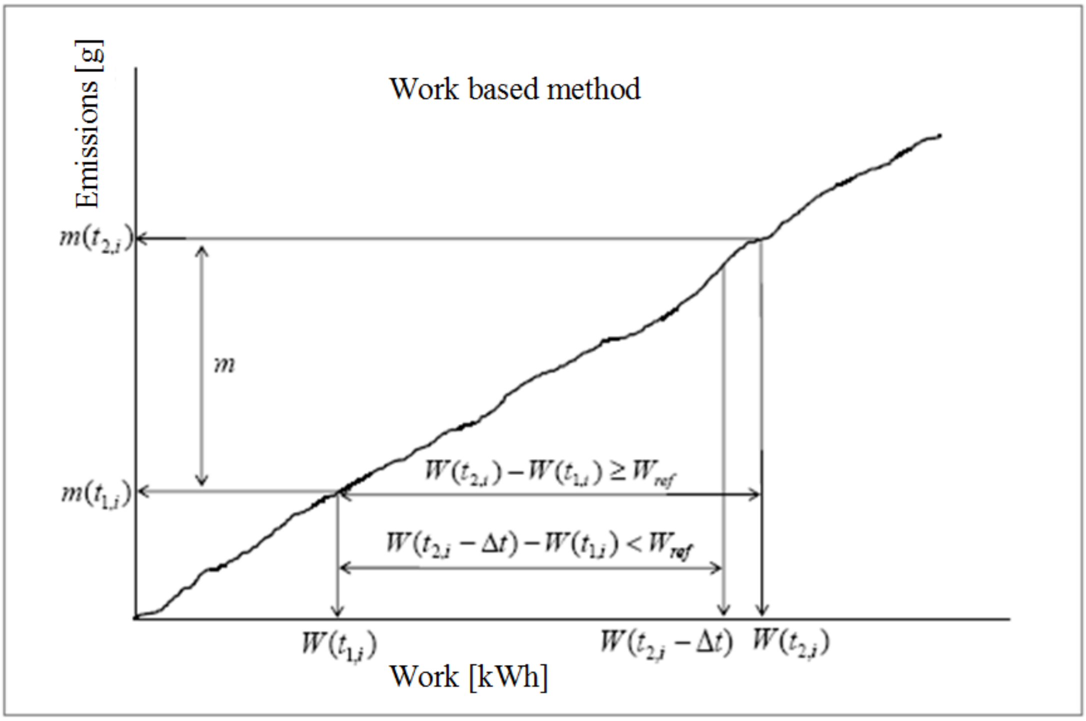
The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- 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.

7.2.1 Work based method

Figure 43. Work based method.



Source: JRC.Vela, 2018

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 homologation cycle, [kWh].
- $t_{2,i}$ shall be selected such that:

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

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

7.2.1.1 Calculations of the brake specific gaseous pollutant emissions

The brake specific gaseous pollutant emissions e_{gas} [g/kWh] shall be calculated for each averaging window and each gaseous pollutant in the following way:

$$e_{gas}=\frac{m}{W(t_{2,i})-W(t_{1,i})}$$

Where:

- *m* is the mass emission of the gaseous pollutant, mg/averaging window
- $W(t_{2,i})-W(t_{1,i})$ is the engine work during the ith averaging window, [kWh]

7.2.1.2 Selection of valid averaging windows

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

The test shall be considered void if the percentage of valid averaging windows is less than 50 %.

7.2.1.3 Calculations of the conformity factors

The conformity factors shall be calculated for each individual valid averaging window and each individual gaseous pollutant in the following way:

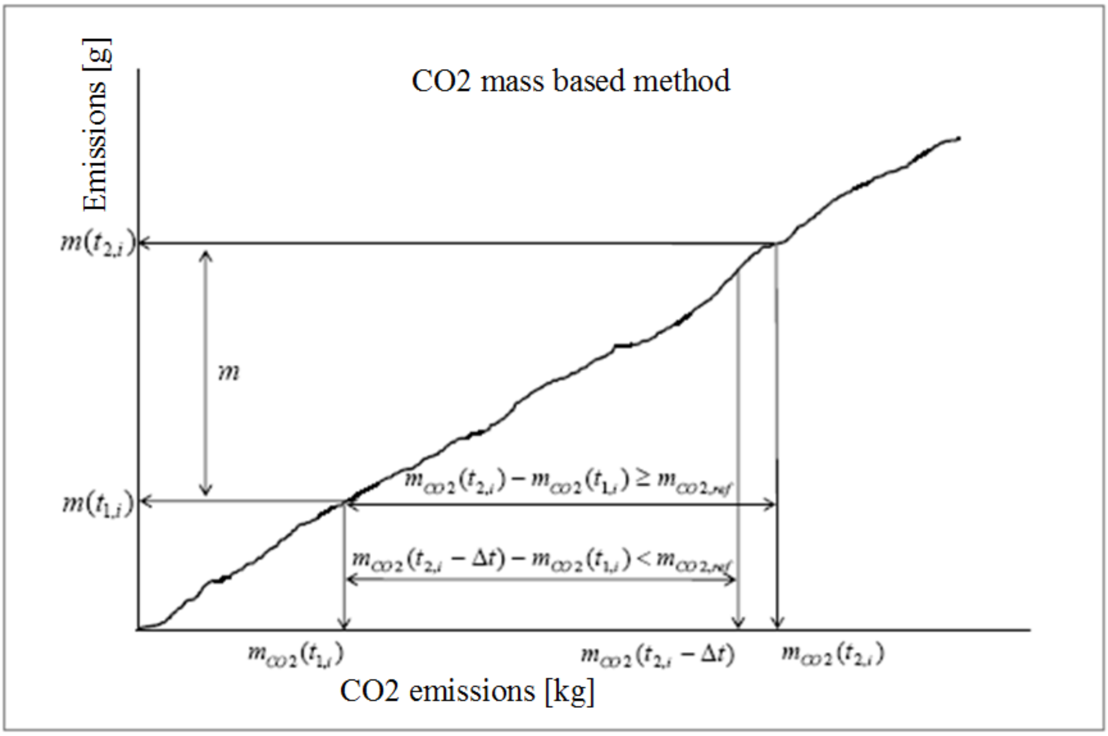
$$CF = \frac{e}{L}$$

Where:

- e is the brake-specific emission of the gaseous pollutant, [g/kWh];
- L is the applicable limit, [g/kWh].

7.2.2 CO2 mass based method

Figure 44. CO2 mass based method.



Source: JRC.Vela, 2018

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 $t_{j,i}$, [kg];
- $m_{CO2,ref}$ is the CO_2 mass determined for the homologation cycle, [kg];
- $t_{2,i}$ 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.

The CO_2 masses are calculated in the averaging windows by integrating the instantaneous gaseous pollutant emissions calculated according to the requirements introduced in point 1 of Appendix 5 to the Annex of Reg. (EU) 2017/655.

7.2.2.1 Selection of valid averaging windows

The valid averaging windows shall be those whose duration does not exceed the maximum duration calculated from:

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

Where:

$D_{\max}$ is the maximum averaging window duration, [s];

$P_{\max}$ is the maximum net engine power, [kW].

The percentage of valid averaging windows shall be equal or greater than 50 per cent.

7.2.2.2 Calculations of the conformity factors

The conformity factors shall be calculated for each individual averaging window and each individual pollutant in the following way:

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

with

$$CF_I = \frac{m}{m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})}$$ (in service ratio) and

$$CF_C = \frac{m_L}{m_{CO2,ref}}$$ (certification ratio)

Where:

- m is the mass emission of the gaseous pollutant, mg/averaging window;
- $m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})$ is the CO_2 mass during the i^{th} averaging window, [kg];
- $m_{CO2,ref}$ is the engine CO_2 mass determined for the homologation cycle, [kg];
- m_L is the mass emission of gaseous pollutant corresponding to the applicable limit on the homologation cycle, [mg].

7.3 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: for the pilot program, these conditions (on engine coolant temperature, altitude and ambient temperature) were defined in the Regulation [R1]. Definition of valid and invalid event as explained above.
- 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: Calculation of the CF for each of the valid windows.
- Step 6: Selection of the reference CF value from all the valid windows: i.e. 90th cumulative percentile.

Steps 2 to 6 apply to all regulated gaseous pollutants.

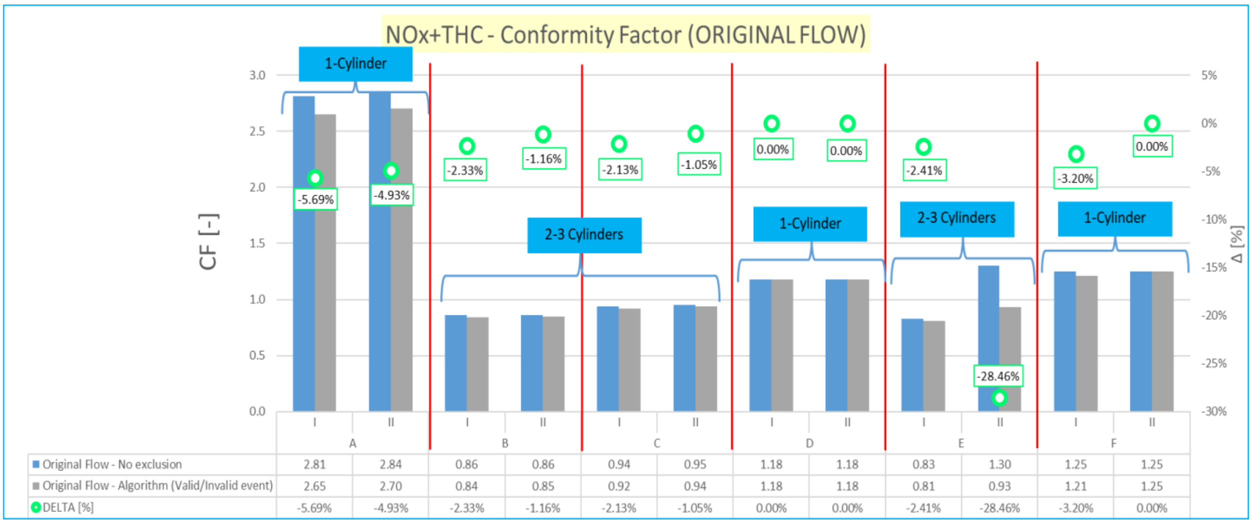
8 Results

Figure 45 depicts the CF for the different NRE machines participating in this pilot programme. The CF assigned to the different tests is the 90th cumulative percentile of all the valid window's CF.

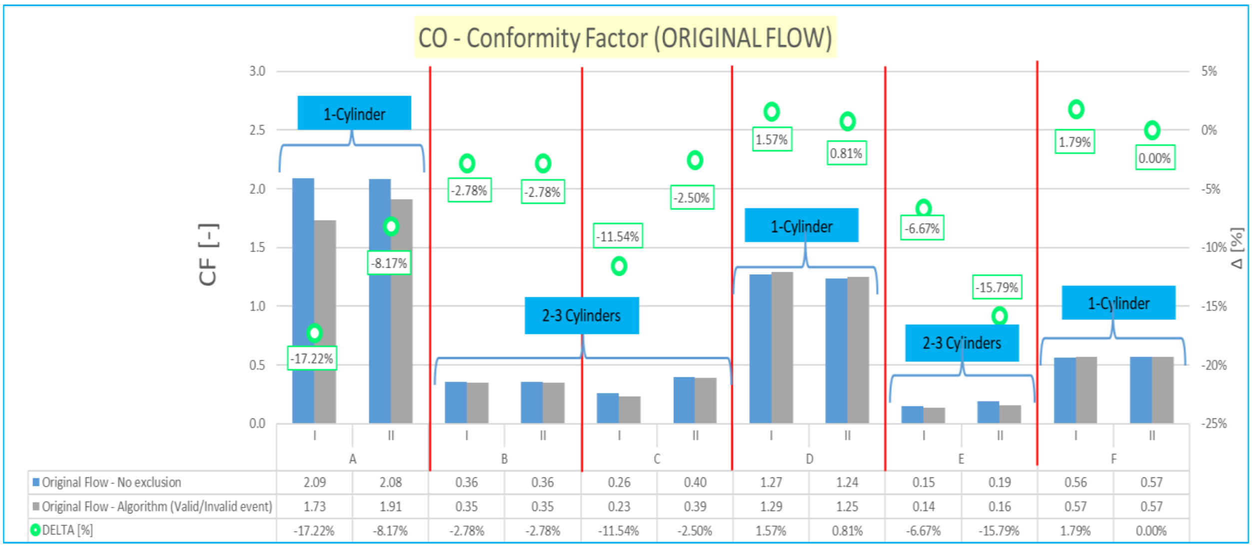
In order to obtain a suitable amount of data with different test characteristics, the tests has been combined either using a single work pattern, according to paragraph 3.4.3 or repeating that combination at least three times. The CF values obtained for these combinations are those referred in Figure 45 as I and II respectively. In this figure, the delta percentage between the original flow without any exclusion and the original flow using the Valid/Invalid algorithm is marked in green.

The difference in the lengths of the test defined as the number of accumulated reference parameter (i.e. the total CO_2 in the homologation cycle) indicates that a reasonable test length will be one with an equivalent duration between 3 to 5 time the reference value. See Figure 46 for details, in which the ratio CO2 total/CO2 reference has been added to show that the range between 3-5 times the reference value is easily obtainable with stitching no more than three different tests and there is not a large impact on the final CFs values.

Figure 45. Conformity Factor for pollutant emission for the different NRE NRMM engines. In the graphs are compared the original flow with all data (NO exclusion) and the original flow applying the VALID/INVALID algorithm. (DELTA percentage detail).



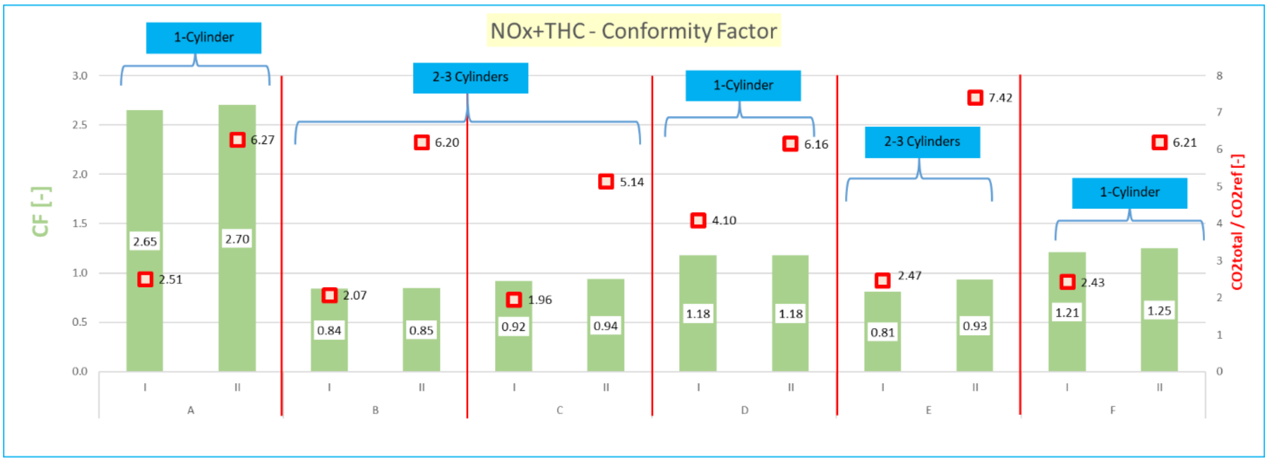
	A I	A II	B I	B II	C I	C II	D I	D II	E I	E II	F I	F II
■ Original Flow - No exclusion	2.81	2.84	0.86	0.86	0.94	0.95	1.18	1.18	0.83	1.30	1.25	1.25
■ Original Flow - Algorithm (Valid/Invalid event)	2.65	2.70	0.84	0.85	0.92	0.94	1.18	1.18	0.81	0.93	1.21	1.25
○ DELTA [%]	-5.69%	-4.93%	-2.33%	-1.16%	-2.13%	-1.05%	0.00%	0.00%	-2.41%	-28.46%	-3.20%	0.00%



	A I	A II	B I	B II	C I	C II	D I	D II	E I	E II	F I	F II
■ Original Flow - No exclusion	2.09	2.08	0.36	0.36	0.26	0.40	1.27	1.24	0.15	0.19	0.56	0.57
■ Original Flow - Algorithm (Valid/Invalid event)	1.73	1.91	0.35	0.35	0.23	0.39	1.29	1.25	0.14	0.16	0.57	0.57
○ DELTA [%]	-17.22%	-8.17%	-2.78%	-2.78%	-11.54%	-2.50%	1.57%	0.81%	-6.67%	-15.79%	1.79%	0.00%

Source: JRC.Vela, 2019

Figure 46. Conformity Factor for pollutant emission for the different NRE NRMM engines. In the graphs are compared the CFs applying the VALID/INVALID algorithm with different amount of reference value.



Source: JRC.Vela, 2019

Note that in the above evaluation of the CFs values, we have always used the installed engine, which in some case is very different from the parent engine. A first investigation in the final CFs values obtained by the using of the installed engine versus the parent engine has given results in good correlation, even if the parent engine has a higher maximum power (Power at MODE_1). In such a case, the use of the parent engine instead of the installed engine on the machine could limit the total number of the valid windows used for the calculation of the CF itself. In fact, since the threshold of the maximum length (D_{max}) is inversely proportional to the above mentioned power, which intervene in the denominator of the formula that calculate the D_{max}, it is possible that the number of valid windows could be drastically reduced, as many of them could be larger than the maximum duration allowed. If the number of valid windows is below the 50% of the total number of the windows created, the test is invalid. This behaviour will be deeply addressed and clarified in a second phase (In-service monitoring stage).

9 EFM measurements and relative corrections

9.1 Original measurements

The original measurement has been performed using a first EFM solution (EFM_JRC_1 from now on).

After a deeper investigation, it seemed that the reading capability of the used instruments was not adapt to the tested engines and machines/vehicles.

This is caused by the high amount of exhaust gas pulsation typical of single-cylinder and 2-cylinders engines and that can affect also 3-cylinders engines, even if to a lesser extent.

An error in the measuring of the exhaust flow will obviously generate an error in the final definition of the Conformity Factor (CF) values.

In the present section, we will try to understand what the impact on CF is by using the original measured exhaust mass flow data and then correct them by a fix amount indicative of the possible uncertainty found in the comparison between mass flow measured using EFM_JRC_2 and that measured in the engine test bench.

In Annex 2, the possible issues of using an EFM based on a Pitot tube are addressed when it is used to measure a pulsating flow.

The Pitot tube flow-metering technique has been used to measure pulsating flow from a machine/vehicle engine exhaust. In general, flow-metering techniques that utilize differential pressure measurements based on Bernoulli's theory are likely to show erroneous readings when measuring an average flowrate of pulsating flow. The primary reason for this is the non-linear relationship between the differential pressure and the flowrate; i.e. the flowrate is proportional to the square root of the differential pressure. Therefore, an average of the differential pressure does not give an average of pulsating flow, unless fast response pressure transducers are used to measure the pulsating pressure. Then the pulsating differential pressure is converted to the flowrate while the pulsation is not averaged. An average flowrate is then calculated in the flowrate domain in order to maintain linearity before and after averaging. The results normally show a large amount of back and forth gas movement in the exhaust tube. This magnitude of pulsation can cause as much as five times higher erroneous results with the pressure domain averaging when compared to a flowrate domain averaging.

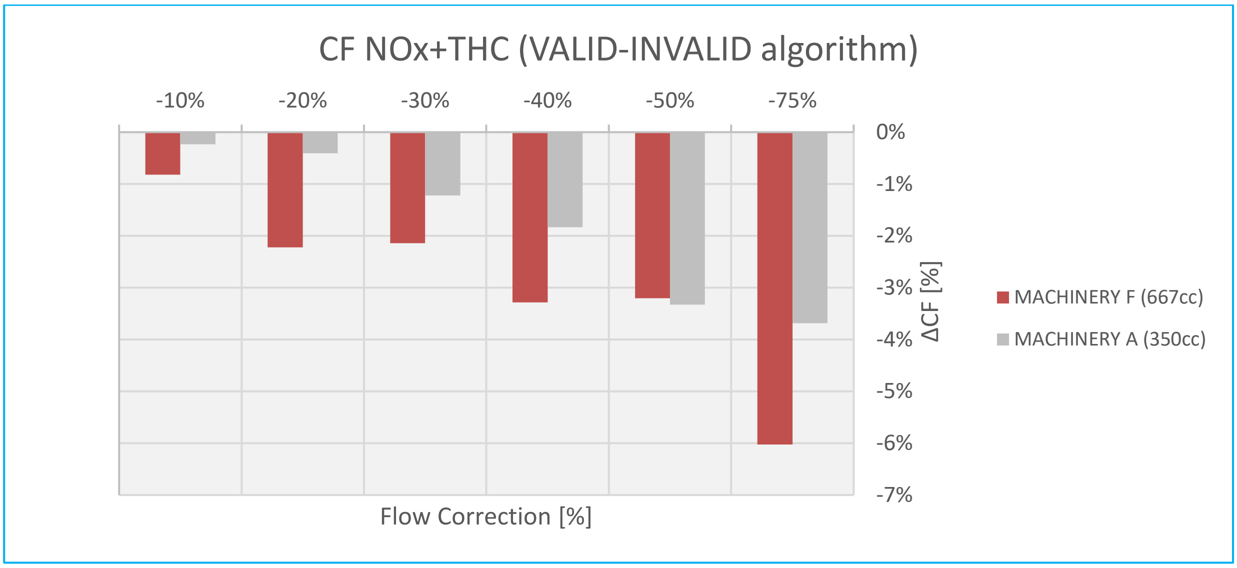
Base on a literature case (see Annex 2), in which a high speed logging instruments was not used, we can said that there is the concrete risk to overestimate the flow, as it is an average measure.

Since it was not possible to perform a direct comparison using a reference test bench, there is no direct differential measurement between the EFM_JRC_1 and the EFM_JRC_2 to understand the possible error range in the exhaust flow measurements. Nevertheless, we proceed by simulating numerically the error.

In the following sensitivity study, the original flow measurement is corrected (the one obtained measuring with a second generation EFM with a fast response pressure transducers; the so-called EFM_JRC_2) with different steps of error: -10%; -20%; -30%; -40%; -50%; -75% of the original measured flow. So acting, a more precise idea of the impact of the measurement uncertainty directly on the final CFs values can be obtained. The evaluation is carried out only for the CO_2 based method. All the CFs refer to the 90th cumulative percentile of all the created valid windows. In the evaluation study the valid/invalid algorithm is applied.

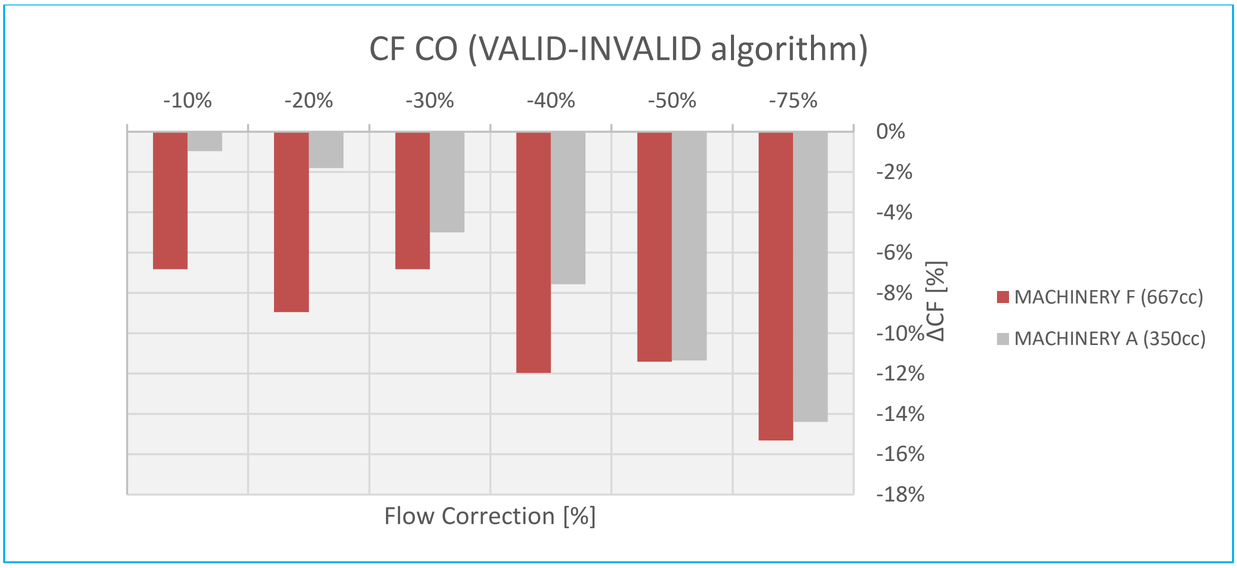
9.1.1 Sensitivity study – Impact on CFs final values

Figure 47. Sensitivity studies on final NOx+THC CF values, using machinery A and F (CO_2 based method).



Source: JRC.Vela, 2019

Figure 48. Sensitivity studies on final CO CF values, using machinery A and F (CO_2 based method).

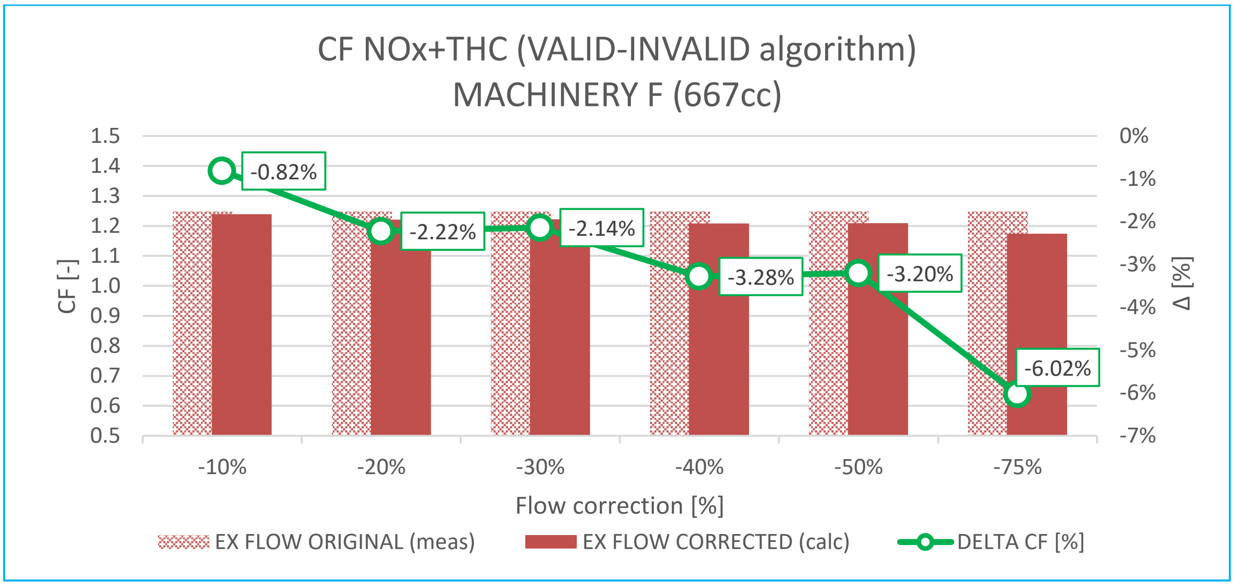


Source: JRC.Vela, 2019

As clearly showed by the Figure 47 and by Figure 48, even though the possible percentage of exhaust flow correction is very high, the impact on the final CFs values is very mitigated. In fact, e.g. considering an exhaust mass flow correction of 40%, the impact on CFs is limited. In the worst case (Machinery F), we have a deviation in the CFs on average of -3.3% for NOx+THC and -12% for CO. The sensitivity study indicates how the CFs final values are in function of a different correction of the original exhaust mass flow measurements. In this sensitivity study only the single cylinders engines have been considered, as they are the engines with the most uncertainty in exhaust flow readings, among the ones in which the portable emission instrument (EFM) has been compared together with a reference test bench.

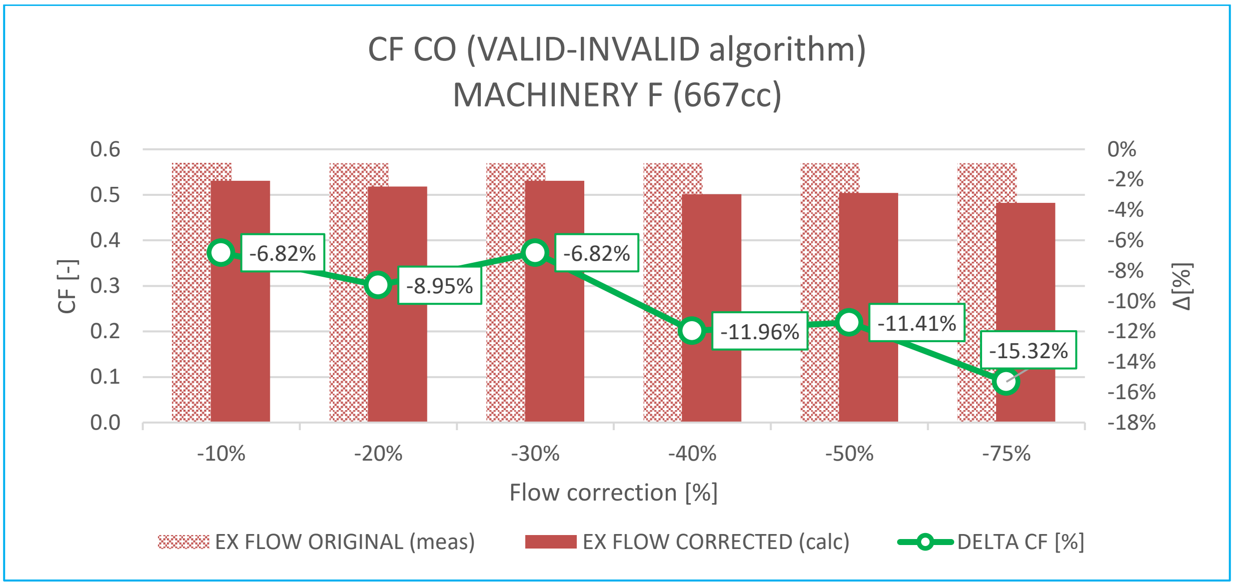
In Figures 49 and 50 are reported the details of the CF evaluation for the Machine F (667cc), distinguishing by original flow and corrected (calculated) one. The green line highlight the delta difference in percentage.

Figure 49. Detail of machinery F. CF NOx+THC variation due to flow correction applying the VALID/INVALID algorithm.



Source: JRC.Vela, 2019

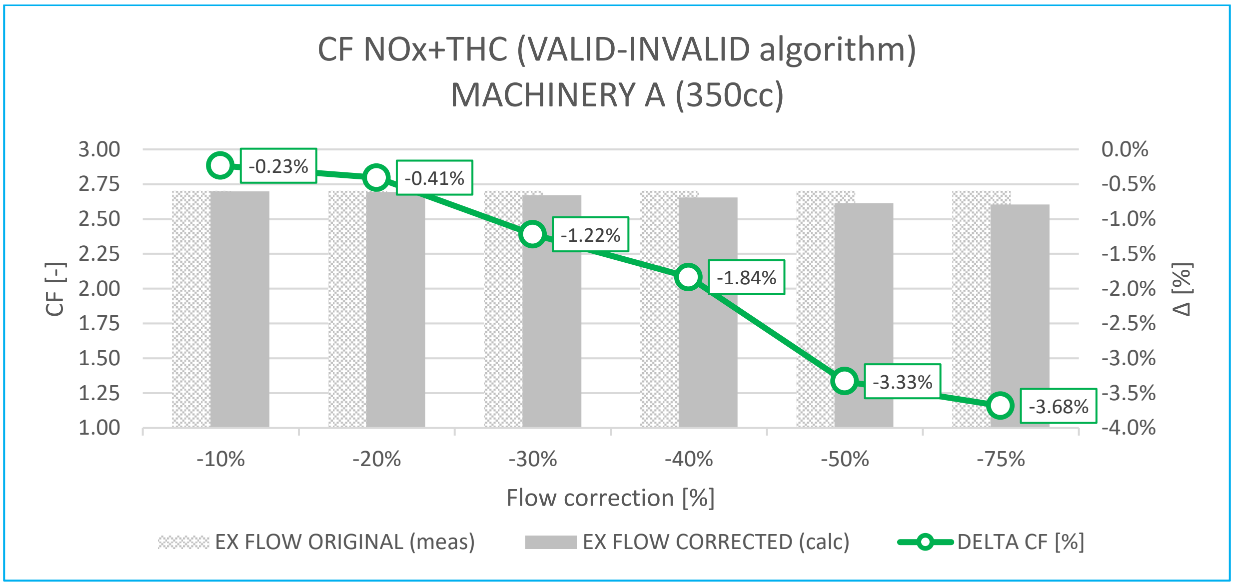
Figure 50. Detail of machinery F. CF CO variation due to flow correction applying the VALID/INVALID algorithm.



Source: JRC.Vela, 2019

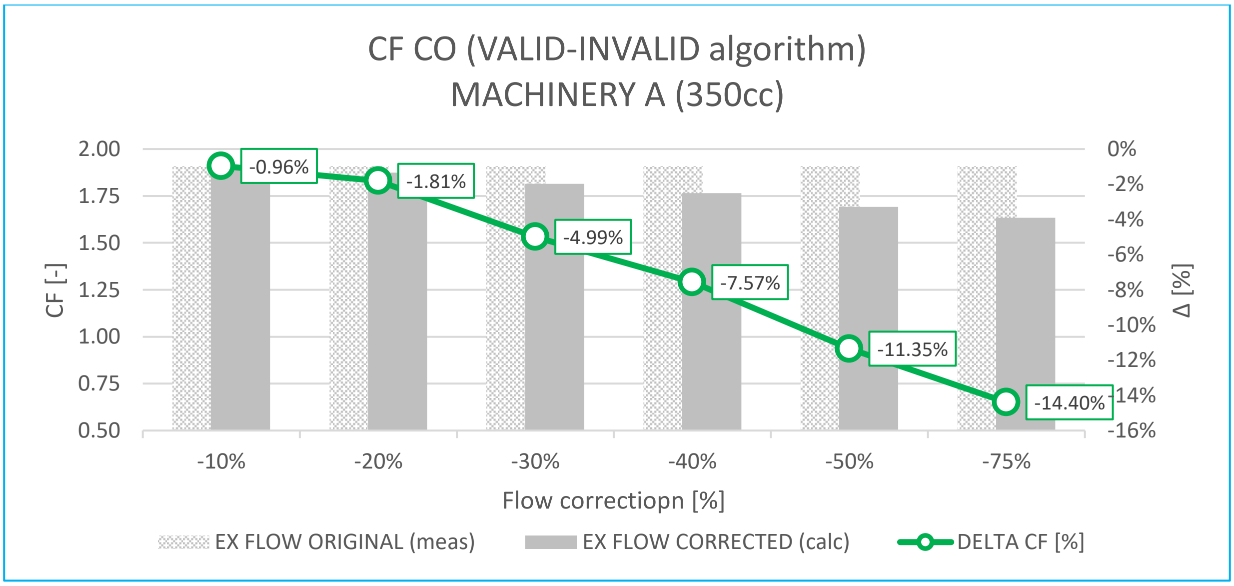
In Figures 51 and 52 are reported the details of the CF evaluation for the Machine A (350cc), distinguishing by original flow and corrected (calculated) one. Also in this case, the green line highlight the delta difference in percentage. The linear dependence of the percentage change of the CF with the emission mass flow percentage change is depicted in Figures 53 and 54, for NO_x + THC and CO respectively, indicating the relatively small impact on the final values of errors in the measurement of exhaust mass flow when the CO2 base MAW approach is used.

Figure 51. Detail of machinery A. CF NOx+THC variation due to flow correction applying the VALID/INVALID algorithm.



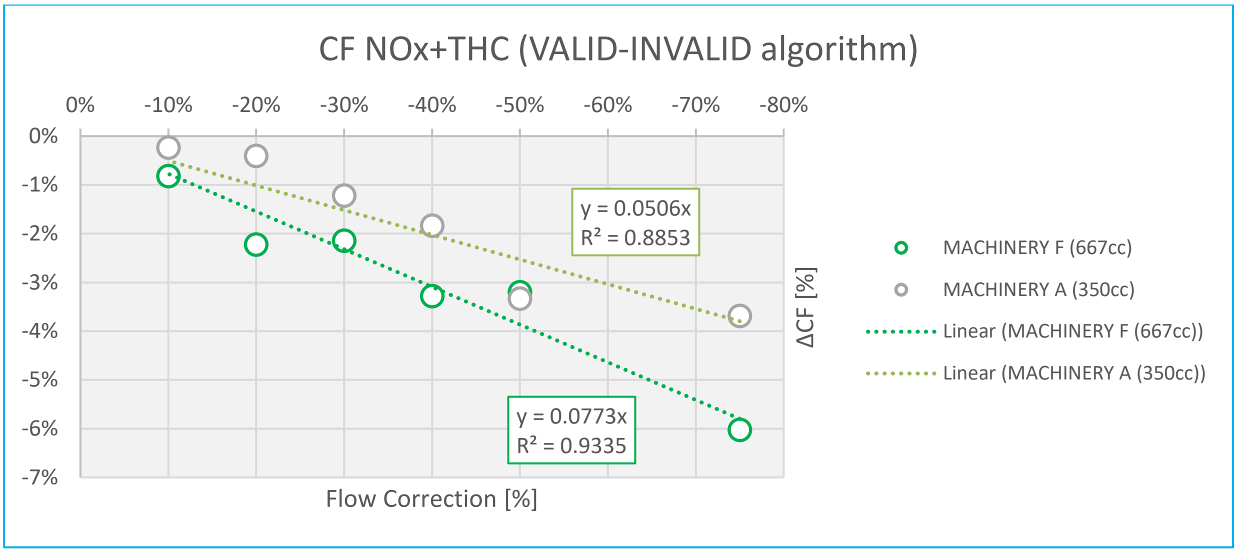
Source: JRC.Vela, 2019

Figure 52. Detail of machinery A. CF CO variation due to flow correction applying the VALID/INVALID algorithm.



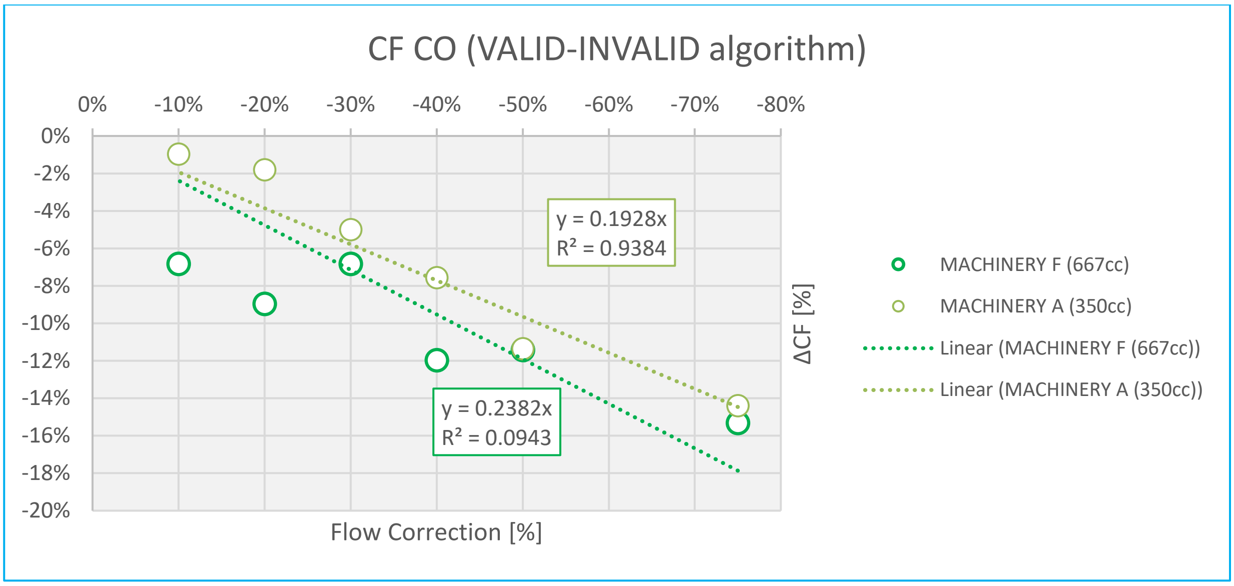
Source: JRC.Vela, 2019

Figure 53. CF NOx+THC linear correlation between exhaust flow correction and CF delta in percentage if compared with the original flow.



Source: JRC.Vela, 2019

Figure 54. CF CO linear correlation between exhaust flow correction and CF delta in percentage if compared with the original flow.



Source: JRC.Vela, 2019

The following tables (Table 12 and 13) indicates the detail of the final CFs value for every hypothetical correction of the exhaust mass flow.

Table 12. Final CFs variation applying a numerical correction of the flow (Machinery A).

MACHINERY A (350cc)						
FLOW CORRECTION	EX FLOW ORIGINAL (meas)		EX FLOW CORRECTED (calc)		**DELTA CF [%]**	
	90ile		90ile			
	NOx+THC	CO	NOx+THC	CO	NOx+THC	CO
-10%	2.704	1.909	2.698	1.891	-0.23%	-0.96%
-20%	2.704	1.909	2.693	1.874	-0.41%	-1.81%
-30%	2.704	1.909	2.671	1.814	-1.22%	-4.99%
-40%	2.704	1.909	2.655	1.765	-1.84%	-7.57%
-50%	2.704	1.909	2.614	1.692	-3.33%	-11.35%
-75%	2.704	1.909	2.605	1.634	-3.68%	-14.40%

Source: JRC.Vela, 2019

Table 13. Final CFs variation applying a numerical correction of the flow (Machinery F).

MACHINERY F (667cc)						
FLOW CORRECTION	EX FLOW ORIGINAL (meas)		EX FLOW CORRECTED (calc)		**DELTA CF [%]**	
	90ile		90ile			
	NOx+THC	CO	NOx+THC	CO	NOx+THC	CO
-10%	1.249	0.569	1.239	0.531	-0.82%	-6.82%
-20%	1.249	0.569	1.221	0.518	-2.22%	-8.95%
-30%	1.249	0.569	1.222	0.531	-2.14%	-6.82%
-40%	1.249	0.569	1.208	0.501	-3.28%	-11.96%
-50%	1.249	0.569	1.209	0.504	-3.20%	-11.41%
-75%	1.249	0.569	1.174	0.482	-6.02%	-15.32%

Source: JRC.Vela, 2019

10 Conclusions and recommendations

This report has presented the outcome of the pilot programme designed to explore the suitability of the already existing procedure to monitor the gaseous pollutant emissions[13] for its application to test in-service (ISM) internal combustion engines installed in NRMM category NRE-v-1 and NRE-v-2. The report confirms that for ISM tests, the use of Portable Emission Measurement Systems (PEMS) is suitable as it can be reliably mounted on the tested machine and the data can also be processed in a similar fashion as in the case for NRMM engines of category NRE-v-5 and NRE-v-6[13].

Because of the characteristics of NRE-v-1 and NRE-v-2 NRMM (i.e. this category of engines tend to be single, 2 or 3-cylinders) the measurement of the exhaust mass flow using flow meters (EFM) has turned to be more complicated than expected due to the exhaust flow pulsation typical of this kind of engines. This was an important point because although the precision and accuracy of the concentration of gaseous pollutants using PEMS has been proven once again, the instant mass of those pollutants are governed by the uncertainty of the EFM.

Technical solutions have been found for both the installation of PEMS on board of NRMM NRE-v-1 and NRE-v-2 machinery and the measurement of the exhaust flow with an acceptable uncertainty. To that extend the following recommendations are made:

1. To measure and record the Exhaust Mass Emission in kg/h at high measurement rate. The use of high-speed sampling by the EFM allows for the correct measurement of the reverse flow for pulsating engines. Some commercially EFM are available from PEMS manufacturers.
2. Commercially available PEMS are suitable for using in the ISM test on the field, although appropriate mounting and protecting solutions need to be found. This report provides some hints to that extend.
3. The ISM test can be carried out by following the normal/usual operations that the NRMM NRE-v-1 and NRE-v-2 undergoes in the field.

During the performance of the pilot programme solutions were also found for the definition of the reference quantities; i.e. work and CO_2 for the case that the type approval test is the NRSC rather than the NRTC. It has also been proposed a methodology to calculate an equivalent power from the measured CO_2 flow in order to make possible the definition of working and non-working event for the case of mechanically controlled engines (no ECU). The validation of this approach suggests that the approach is suitable for the purpose to define valid/invalid events.

Due to the power range of these NRMM engines and the long time necessary to complete 5 to 7 times the reference values (i.e. work or CO_2 at type approval) the reduction of the length of the test to complete 3 to 5 times the reference values is recommended.

Furthermore, regarding the data sampling method and without prejudice of the reduction of the length of the test indicated in the above paragraph the use of combined data sampling following paragraph 4 of the Annex to Reg. (EU) 2017/655 with appropriate adjustments should be allowed. This will reduce the possible burden to the testing team and OEM during the ISM tests.

A suitable plan for monitoring NRE-v-1 and NRE-v-2 in-service engines needs to be developed together with the industrial association (EUROMOT) which needs to include appropriate schemes to provide data at different points in the life of the in-service NRE-v-1 and NRE-v-2 engine similar to that developed for category NRE-v-5 and NRE-v-6[13].

A deeply investigation on the use of the parent engine instead of the installed engine will be addressed and clarified during the in-service monitoring stage. It is recommended to use ISM engines which characteristics (e.g. power) are not far from the parent engine which defines the reference magnitudes (i.e. $CO_{2,ref}$ and W_{ref}).

---

[13] Reg. (EU) 2017/655

List of abbreviations and definitions

CF	Conformity Factor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2AW	CO_2 based Average Window
DG GROW	Directorate General Internal Market, Industry, Entrepreneurship and SMEs
DOC	Diesel Oxidation Catalyst
EC	European Commission
EFM	Exhaust Flow Meter
EU	European Union
EUROMOT	European Association of Internal Combustion Engine Manufacturers
ISM	In-Service Monitoring (Programme)
JRC	Joint Research Centre
MAW	Moving Average Window
NOx	Oxides of Nitrogen
NRE	Non Road Engine
NRMM	Non Road Mobile Machinery
OEMs	Original Equipment Manufacturer
PEMS	Portable Emission Measurement System
SCI	Small Compression Ignition (Engine)
SMEs	Small and Medium Enterprises
THC	Total HydroCarbons, also referred to as HC
VELA	Vehicle Emission LAboratory
WAW	Work based Average Window

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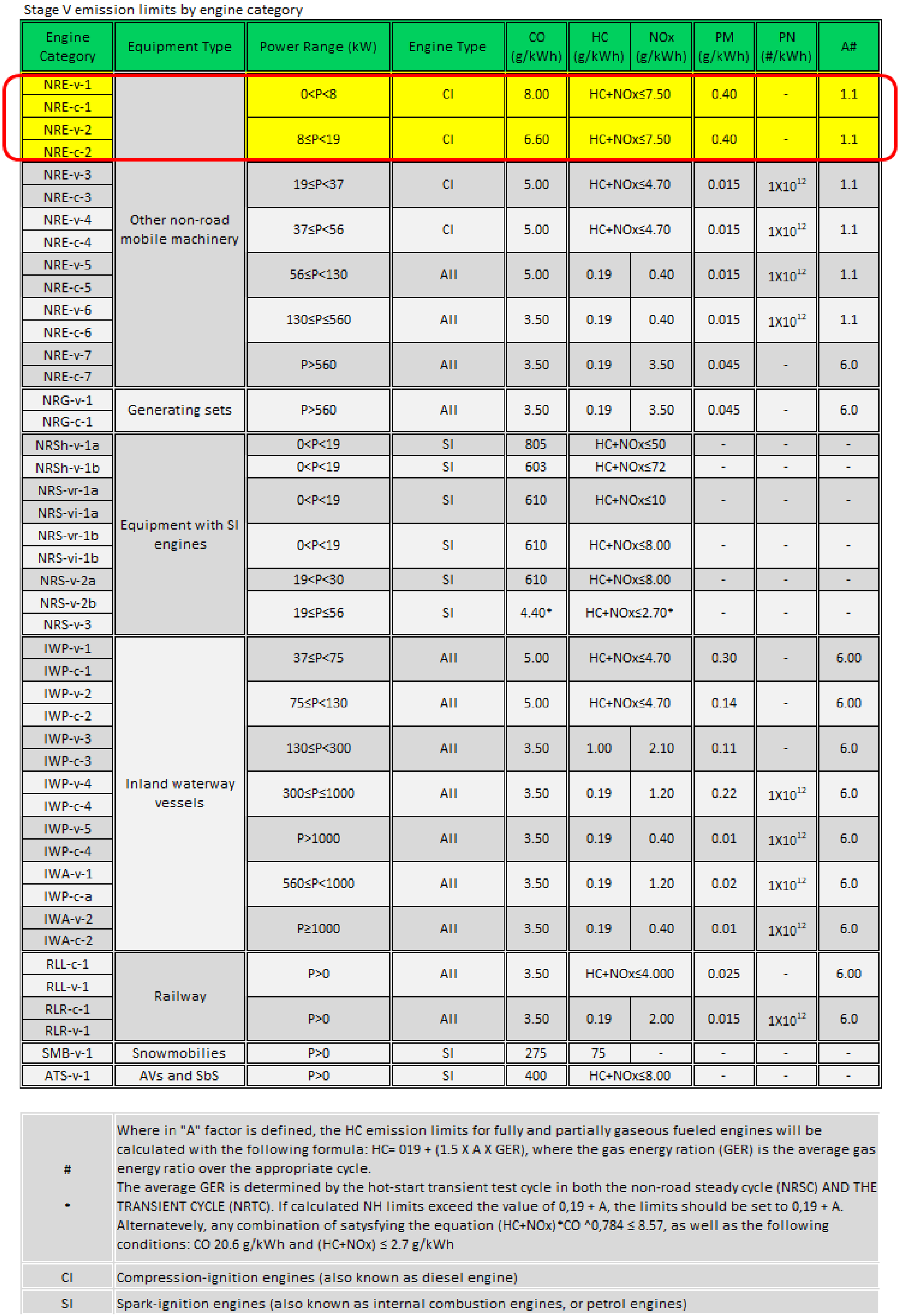
Annexes

Annex 1. Stage V emission limits by engine category

Table 14. Stage V emission limits.



Stage V emission limits by engine category

Engine Category	Equipment Type	Power Range (kW)	Engine Type	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)	PN (#/kWh)	A#
NRE-v-1 NRE-c-1	Other non-road mobile machinery	0<P<8	CI	8.00	HC+NOx≤7.50		0.40	-	1.1
NRE-v-2 NRE-c-2		8≤P<19	CI	6.60	HC+NOx≤7.50		0.40	-	1.1
NRE-v-3 NRE-c-3		19≤P<37	CI	5.00	HC+NOx≤4.70		0.015	$1X10^{12}$	1.1
NRE-v-4 NRE-c-4		37≤P<56	CI	5.00	HC+NOx≤4.70		0.015	$1X10^{12}$	1.1
NRE-v-5 NRE-c-5		56≤P<130	All	5.00	0.19	0.40	0.015	$1X10^{12}$	1.1
NRE-v-6 NRE-c-6		130≤P≤560	All	3.50	0.19	0.40	0.015	$1X10^{12}$	1.1
NRE-v-7 NRE-c-7		P>560	All	3.50	0.19	3.50	0.045	-	6.0
NRG-v-1 NRG-c-1	Generating sets	P>560	All	3.50	0.19	3.50	0.045	-	6.0
NRSh-v-1a	Equipment with SI engines	0<P<19	SI	805	HC+NOx≤50		-	-	-
NRSh-v-1b		0<P<19	SI	603	HC+NOx≤72		-	-	-
NRS-vr-1a NRS-vi-1a		0<P<19	SI	610	HC+NOx≤10		-	-	-
NRS-vr-1b NRS-vi-1b		0<P<19	SI	610	HC+NOx≤8.00		-	-	-
NRS-v-2a		19<P<30	SI	610	HC+NOx≤8.00		-	-	-
NRS-v-2b NRS-v-3		19≤P≤56	SI	4.40*	HC+NOx≤2.70*		-	-	-
IWP-v-1 IWP-c-1	Inland waterway vessels	37≤P<75	All	5.00	HC+NOx≤4.70		0.30	-	6.00
IWP-v-2 IWP-c-2		75≤P<130	All	5.00	HC+NOx≤4.70		0.14	-	6.00
IWP-v-3 IWP-c-3		130≤P<300	All	3.50	1.00	2.10	0.11	-	6.0
IWP-v-4 IWP-c-4		300≤P≤1000	All	3.50	0.19	1.20	0.22	$1X10^{12}$	6.0
IWP-v-5 IWP-c-4		P>1000	All	3.50	0.19	0.40	0.01	$1X10^{12}$	6.0
IWA-v-1 IWP-c-a		560≤P<1000	All	3.50	0.19	1.20	0.02	$1X10^{12}$	6.0
IWA-v-2 IWA-c-2		P≥1000	All	3.50	0.19	0.40	0.01	$1X10^{12}$	6.0
RLL-c-1 RLL-v-1	Railway	P>0	All	3.50	HC+NOx≤4.000		0.025	-	6.00
RLR-c-1 RLR-v-1		P>0	All	3.50	0.19	2.00	0.015	$1X10^{12}$	6.0
SMB-v-1	Snowmobilies	P>0	SI	275	75	-	-	-	-
ATS-v-1	AVs and SbS	P>0	SI	400	HC+NOx≤8.00		-	-	-

# *	Where in "A" factor is defined, the HC emission limits for fully and partially gaseous fueled engines will be calculated with the following formula: HC= 019 + (1.5 X A X GER), where the gas energy ration (GER) is the average gas energy ratio over the appropriate cycle. The average GER is determined by the hot-start transient test cycle in both the non-road steady cycle (NRSC) AND THE TRANSIENT CYCLE (NRTC). If calculated NH limits exceed the value of 0,19 + A, the limits should be set to 0,19 + A. Alternatevely, any combination of satysfying the equation (HC+NOx)*CO ^0,784 ≤ 8.57, as well as the following conditions: CO 20.6 g/kWh and (HC+NOx) ≤ 2.7 g/kWh
CI	Compression-ignition engines (also known as diesel engine)
SI	Spark-ignition engines (also known as internal combustion engines, or petrol engines)

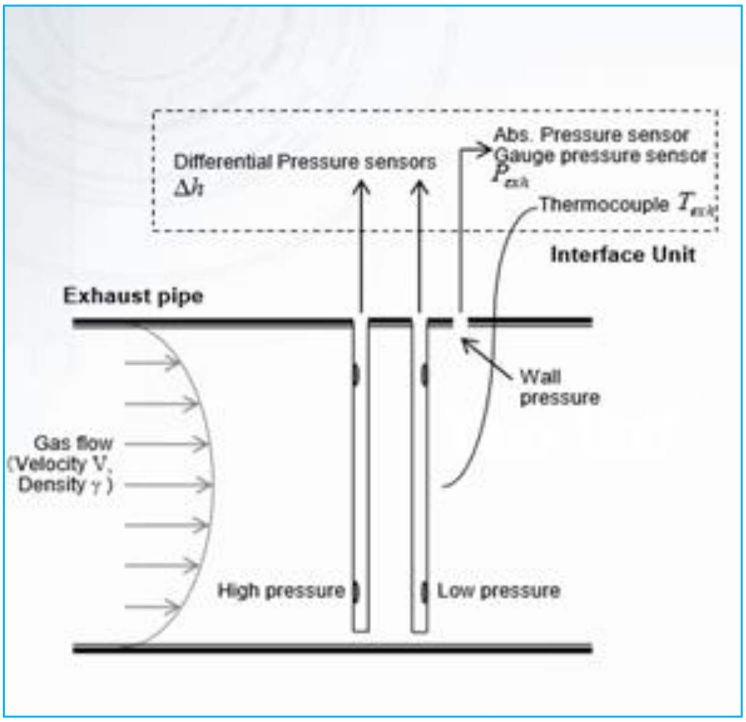
Source: JRC.Vela, 2017

Annex 2. Pitot tube flowmetering technique – Error with high pulsation (Literature case)

The Pitot tube flowmetering technique (see Figure 55) has been used to measure pulsating flow from a machine/vehicle engine exhaust. In general, flowmetering techniques that utilize differential pressure measurements based on Bernoulli's theory are likely to show erroneous readings when measuring an average flowrate of pulsating flow. The primary reason for this is the non-linear relationship between the differential pressure and the flowrate; i.e. the flowrate is proportional to the square root of the differential pressure. Therefore, an average of the differential pressure does not give an average of pulsating flow, unless fast response pressure transducers are used to measure the pulsating pressure. Then the pulsating differential pressure is converted to the flowrate while the pulsation is not averaged. An average flowrate is then calculated in the flowrate domain in order to maintain linearity before and after averaging. The results normally show a large amount of back and forth gas movement in the exhaust tube. This magnitude of pulsation can cause as much as five times higher erroneous results with the pressure domain averaging when compared to a flowrate domain averaging.

Here below is presented a literature case supplied by Horiba[14], in which a high speed logging instruments was not used. As it shown below, the risk to overestimate the flow is concrete, as it is an average measure.

Figure 55. Pitot working principle.



Source: Horiba, 2013

The case study, show a 1.4 liter petrol engine, with a pulsation frequency around 28 Hz (see Figure 56).

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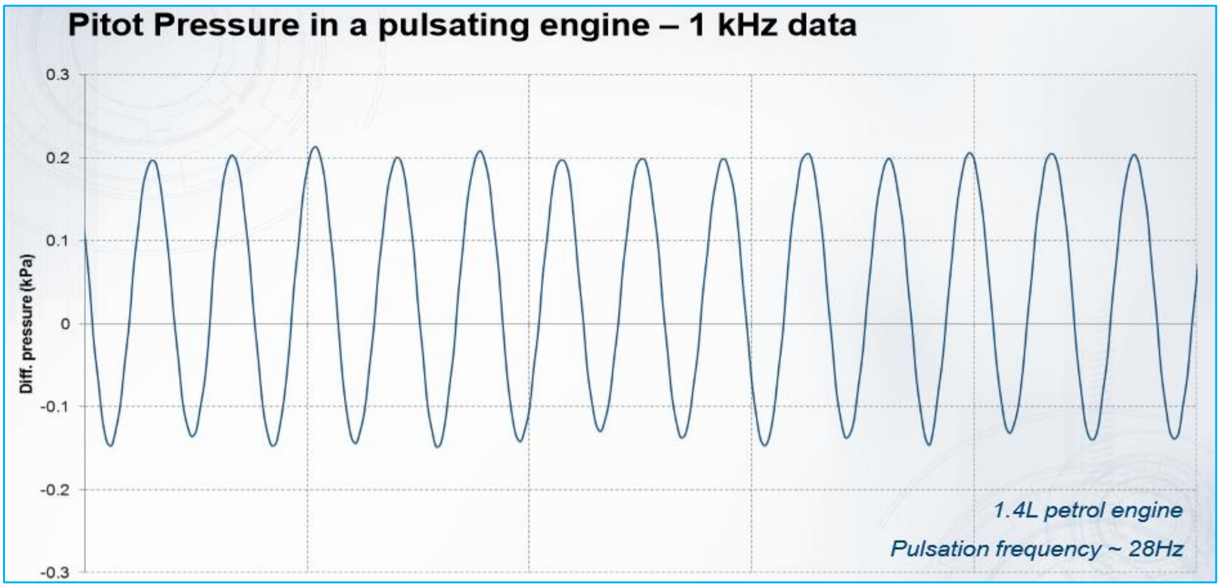
[14] Exhaust Flow Metering Nov 2013 HORIBA

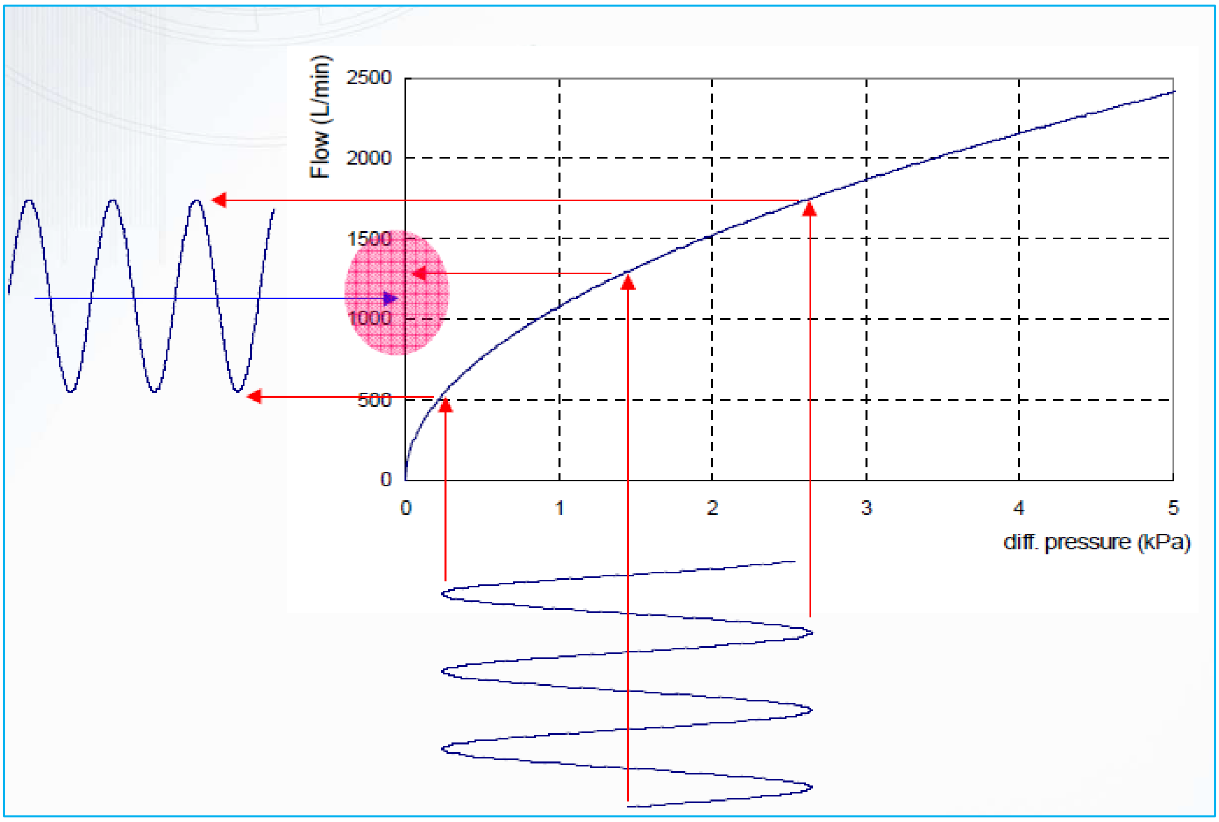
Figure 56. Differential pressure signal in the Pitot in our study case.



Source: Horiba, 2013

This is due to an error in the Root Mean Squared error. According to Horiba and others, an average of pulsation in the differential pressure dimension is different from the average in the flow dimension, owing to the non linear signal, as shown in the figures below (Figure 57-58-59).

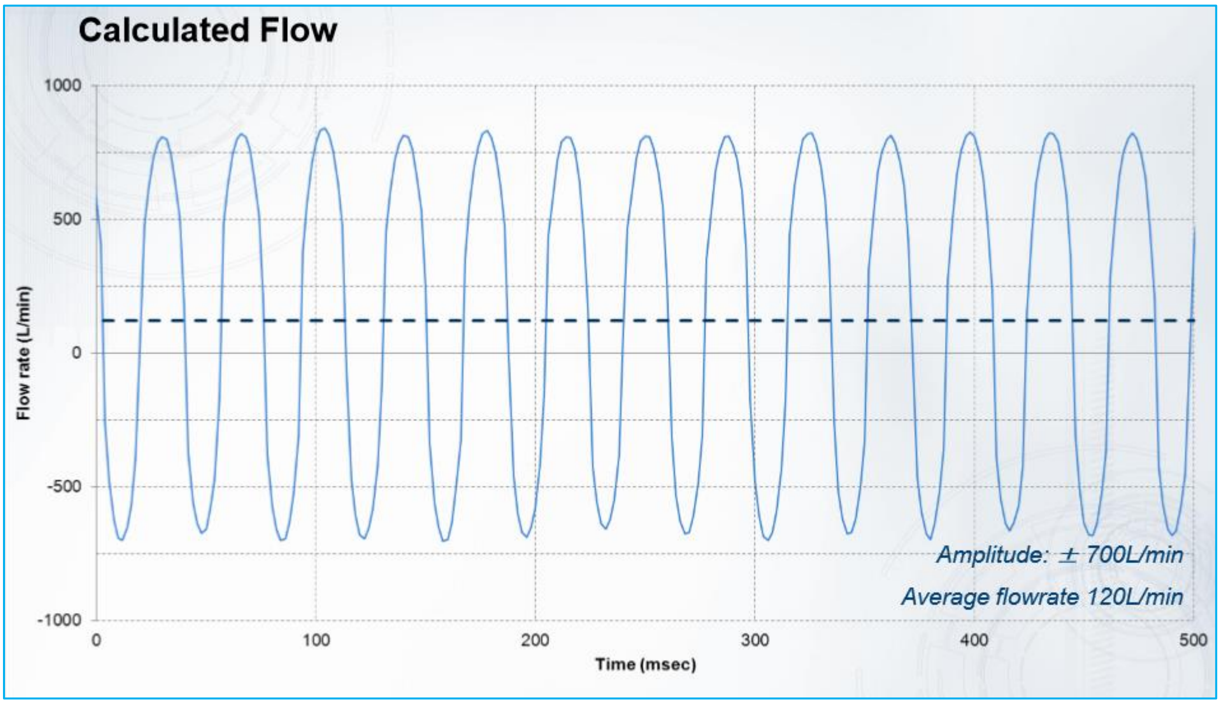
Figure 57. Average flow reading error (1).



Source: Horiba, 2013

In this specific case, we detect a signal with an amplitude of +/- 700 litre/min and an average flow rate of 120 litre/min.

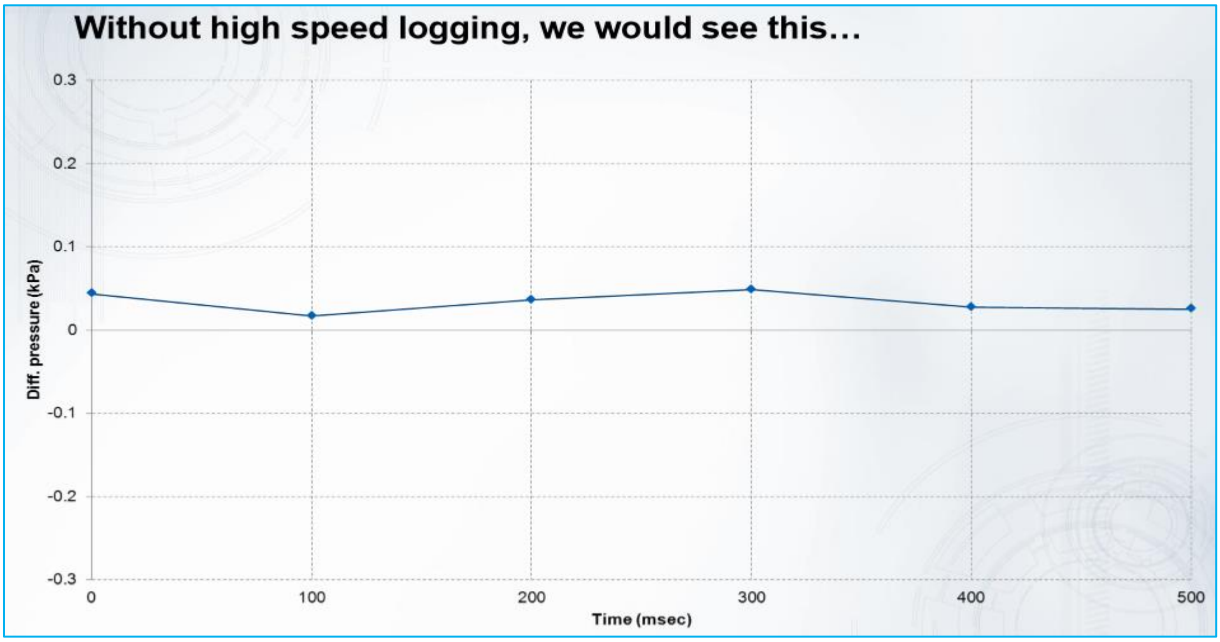
Figure 58. Average flow reading error (2).



Source: Horiba, 2013

Without a high speed logging, the result signal is far from the reality.

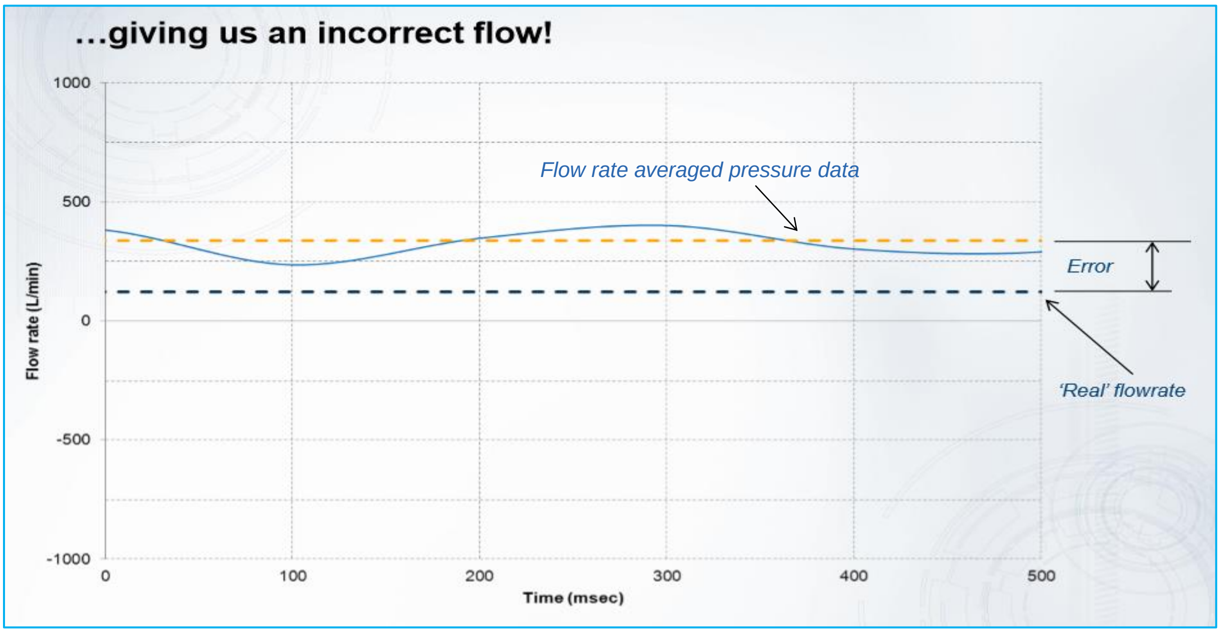
Figure 59. Average flow reading error (3).



Source: Horiba, 2013

that means an incorrect flow reading, as shown in the Figure 60.

Figure 60. Average flow reading error (4).



Source: Horiba, 2013

The error proposed in this study case, is a coarse error.

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