European Commission

SNOWMOBILE VEHICLES: IN SERVICE MONITORING BASED ON PEMS

Lessons learned from the European Pilot Program

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ISMA (International Snowmobile Manufacturers Association)

MTU (Michigan Technological University)

ARCTIC CAT (Arctic Cat Inc.)

SKI-DOO by BRP (Bombardier Recreational Products Inc.)

POLARIS (Polaris Industries Inc.)

YAMAHA (Yamaha Motor Corporation, USA)

Contents

Abstract

This report summarizes the results of a pilot program dedicated to develop a procedure for the In Service Monitoring of NRMM Snowmobile equipped with Spark-Ignition engines, based on Portable Emission Measurement System (PEMS). The tests took place between February 2018 and April 2018.

The work addresses how to mount the measurement equipment on board of such machinery/vehicle and the accuracy and precision of the exhaust gaseous pollutant emission measurements using PEMS. The 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 SMB[1] (this NRMM engine category tends to be 2 or 3-cylinders and two or four strokes). 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.

The measurement of the exhaust mass flow using flow meters (EFM) is particularly complicated due to exhaust exit location (mostly under the vehicle body and in close contact with the snow). An alternative method to calculate the exhaust flows with an acceptable uncertainty has been explored.

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), the possibility to reduce the threshold power in steps of 1% from the 20% until the 15% of maximum engine power if 50% valid window is not reached and the use of combined data sampling. This would satisfy the operational characteristic of this category of engines in view to amend the present ISM regulation, allowing the extension of the ISM procedures to all the NRMM engine categories as required by the STAGE V legislation.

[1] 'category SMB': SI engines exclusively for use in snowmobiles; engines for snowmobiles other than SI engines are included in the category NRE;

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[2]) Regulation (EU) 2016/1628[3], which repeals Directive 97/68/EC[4], 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[5] 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[6] and they are based on the use of Portable Emissions Measurement Systems (PEMS).

DG-GROW[7] 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 SMB-v-1. Based on the outcome of this Pilot Program, which the JRC has launched in close collaboration with ISMA and Michigan Technological University (MTU), 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) or alternative solutions.
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.

2 '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.

3 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

4 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

5 '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.

6 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

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

2 NRMM PEMS Pilot Program for Snowmobiles engines and vehicles

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 snowmobile vehicles (included mechanical fittings)
- To validate the use of gaseous PEMS for checking the ISM of NRMM snowmobiles
- 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 SMB machines with variable speed, positive-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.

- To develop appropriate test procedures to accomplish the in-service monitoring, and
- To adapt Reg. (EU) 2017/655 prescriptions to the SMB category

2.3 Technical Elements

The envisaged technical elements were formulated paying particular attention to:

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

b. 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 Definition

Generally speaking, a snowmobile is a vehicle designed for winter travel and recreational activities on snow. It does not require a road or trail but mostly is driven on open terrain or trails. There is a track that drives the machine and two skis that provide stability and steering. Typically, the exhaust exits the right side of the snowmobile, close to the snow surface. Additional area for cargo is limited on most models, so normally the use of a sledge for extra load is foreseen. According to the Reg. (EU) 2016/1628, *'snowmobile' means a self-propelled machine that is intended for off-road travel primarily on snow, is driven by tracks in contact with snow and steered by a ski or skis in contact with the snow, and has a maximum unladen mass, in running order, of 454 kg (including standard equipment, coolant, lubricants, fuel and tools but excluding optional accessories and the driver);*

3.2 Test machines/vehicles

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 (ISMA[8]).

The International Snowmobile Manufacturers Association (ISMA) is an organization representing the four major snowmobile manufacturers. They coordinate committees within the industry to handle concerns such as snowmobile safety, the promotion of the lifestyle activity of snowmobiling, keeping accurate statistics, reporting the growth of the industry and the positive economic impact of snowmobiling throughout the world. The four major manufacturers that build snowmobiles are:

Textron/Arctic Cat – Headquartered in Thief River Falls, MN;
BRP – Headquartered in Valcourt, Quebec;
Polaris Industries – Headquartered in Medina, MN;
Yamaha Motor Corporation – Headquartered in Ontario, Canada.

In 2018[9] there were 124,786 snowmobiles sold worldwide; 53,179 were sold in the U.S. and 47,024 were sold in Canada.
There are over 1.2 million registered snowmobiles in the US and 600,000 registered snowmobiles in Canada.
The Economic Impact of Snowmobiling:

United States—$26 billion annually

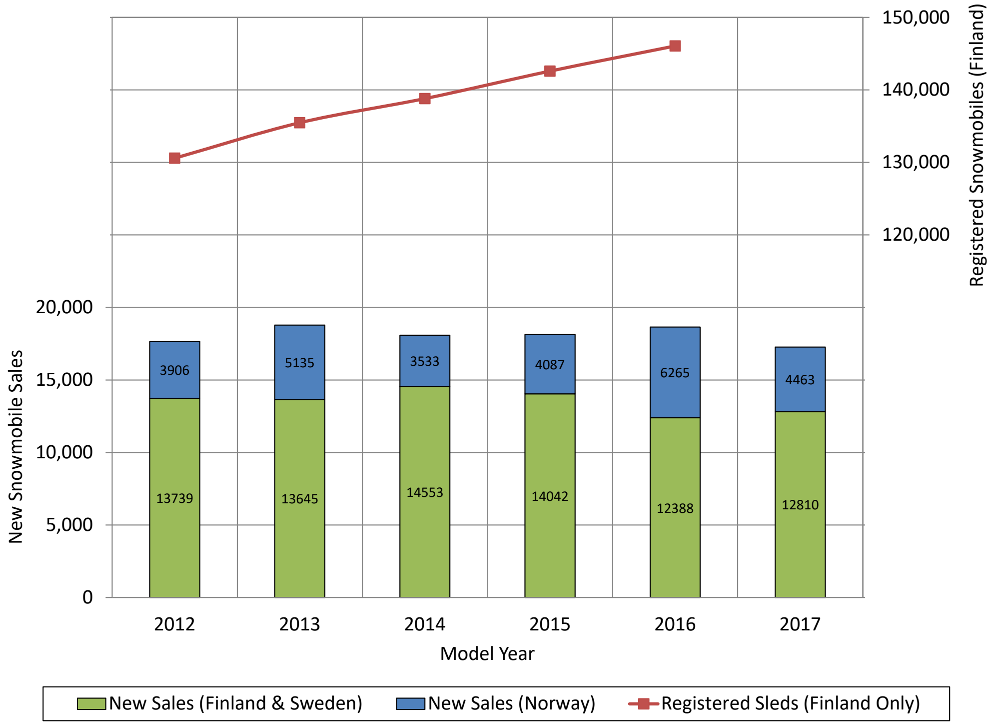
Canada—$8 billion annually

Europe & Russia—$5 billion annually

Over 100,000 full-time jobs are generated by the snowmobile industry in North America. Those jobs are involved in manufacturing, dealerships and tourism related businesses. The Snowmobile Safety and Certification Committee (SSCC) was formed in May 1974 to provide safety regulations for a growing snowmobile industry in order to protect riders. The SSCC has continued to protect riders by ensuring the snowmobiles produced by manufacturers adhere to higher safety standards. The goal of the SSCC is to provide standards and regulations for snowmobile machines and products in order to prevent harm to riders. Through rigorous testing and regulation standards, the SSCC offers manufacturers and riders safety in the international market of snowmobiles.

[8] International Snowmobile Manufacturers Association
[9] Sale volumes and economic impact data has been provided by ISMA

Figure 1. New snowmobile sales and registered vehicles



Source: ISMA, 2017

3.2.1 Market segmentation.

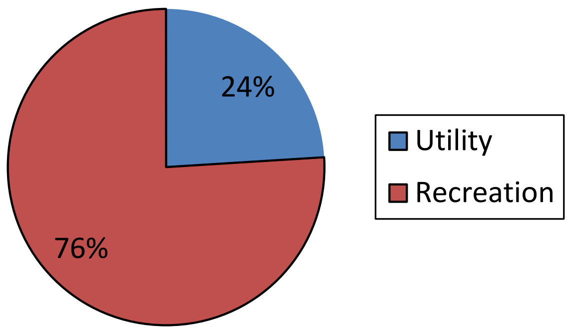
There are two major segments in the snowmobile market:

a. Recreational

b. Utility

The two different segments present same engine, but different configuration (i.e. seats, skis, tracks and chassis).

Figure 2. Snowmobile business sectors



Source: ISMA, 2017

The manufacturers participating in the pilot program provided one machines each to the test campaign.

ISMA has summarised into two main categories (see tables 1 and 2), the engines intended for the purpose of ISM. In particular, TWC (Three Way 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 regulatory scope.

Particular attention was paid to the PEMS instruments installation constraints.

Table 1. EU-PEMS SMB Pilot program groups

	Group 1	Group 2
Engine type	Two-strokes	Four-strokes
Fuel Type	Gasoline	Gasoline
Fuel injection	Direct/semi-direct	Port fuel injection
Cooling system	Liquid-cooled / Fan-cooled	Liquid-cooled / Fan-cooled
Engine displacement range	600-800cc	900-1000cc
Number of cylinder	2	2 or 3

Source: OEM, 2018

Only a small percentage of snowmobiles engines can broadcast engine torque from the ECU.

3.2.2 ECU data broadcast issue

Snowmobile manufacturer's use different communication protocols to broadcast ECU data, in fact, unlike the automotive industry, there is no industry-standard ECU data transmission (OBD-II). OBD-II in the automotive industry is driven by the much larger sales volumes and industry-standardized defect fault detection. Snowmobiles do not use the equipment that necessitates development of OBD standards. Furthermore, calibration strategies for snowmobiles typically do not require knowledge of engine torque, unlike the automotive sector. Therefore, most snowmobile ECU's do not broadcast engine torque or have closed-loop control.

Table 2. EU-PEMS SMB Pilot program groups (further details)

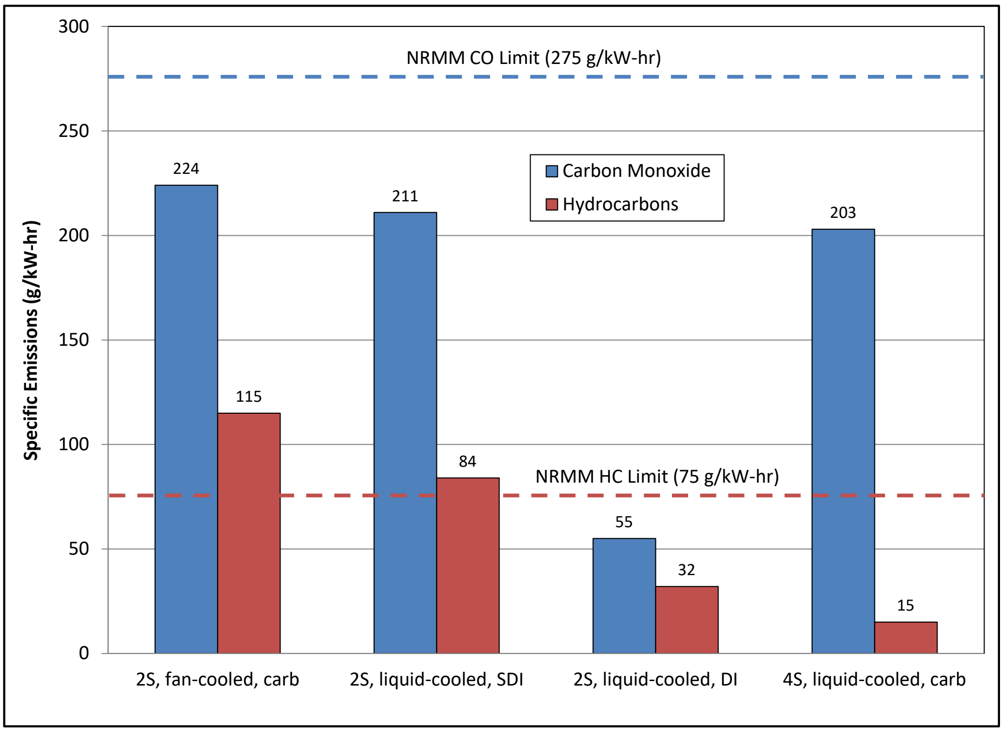
CODE	GROUP	QTY OF CYLINDERS	AFTERTREATMENT
A	1	2	NONE
B	2	3	NONE
C	2	3	NONE
D	1	2	NONE

Source: OEM, 2018

3.2.3 Present emission overview

In Figure 3 depicts the carbon monoxide (CO) and the hydrocarbons (HC) specific emission in g/kWh, in comparison to the NRMM actual limit.

Figure 3. CO and HC in-use data comparison to NRMM



Source: ISMA, 2017

This data comes from the vehicles production for the model year 2009 and 2010. Obviously the models that exceed HC regulation are not available for sale in Europe.

3.3 Engine and machinery details (fleet)

During this campaign, different machineries were tested:

Vehicle A:

- 800cc, 2-cylinder, two-stroke, naturally-aspirated, 144" track
- Engineering Development ECU (2019 cal). Aftermarket (RacePack) CAN logger

Vehicle B:

- 998cc, 3-cylinder, four-stroke, turbocharged, 137" track
- Production ECU (2018 cal). No CAN logging

Vehicle C:

- 900cc, 3-cylinder, four-stroke, naturally-aspirated, 129" track
- Production ECU (2018 cal). Aftermarket (Kvaser) CAN logger

Vehicle D:

- 600cc, 2-cylinder, two-stroke, naturally-aspirated, 153" track
- Engineering Development ECU (2019 cal). OEM CAN logger

The details of the different vehicles/machines are summarised in Table 3

Table 3. EU-PEMS SMB Pilot program (detail of machines/vehicles)

Machinery/vehicles	OEM	Category	No. of Cylinder	Displacement (Actual Vehicle Engine) [cc]	Stroke	Fuel	Maximum Net Power (MODE_1) [kW]	Aftertreatment	Family Emission Limits* g/kWh	
									C	CO
A	1	SMB	2	800	2	Gasoline	100.34	None	75	275
B	2	SMB	3	998	4	Gasoline	132.71	None	75	275
C	3	SMB	3	900	4	Gasoline	68.9	None	75	275
D	4	SMB	2	600	2	Gasoline	79.8	None	75	275

Source: OEM, 2018

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

3.4 Test circuit

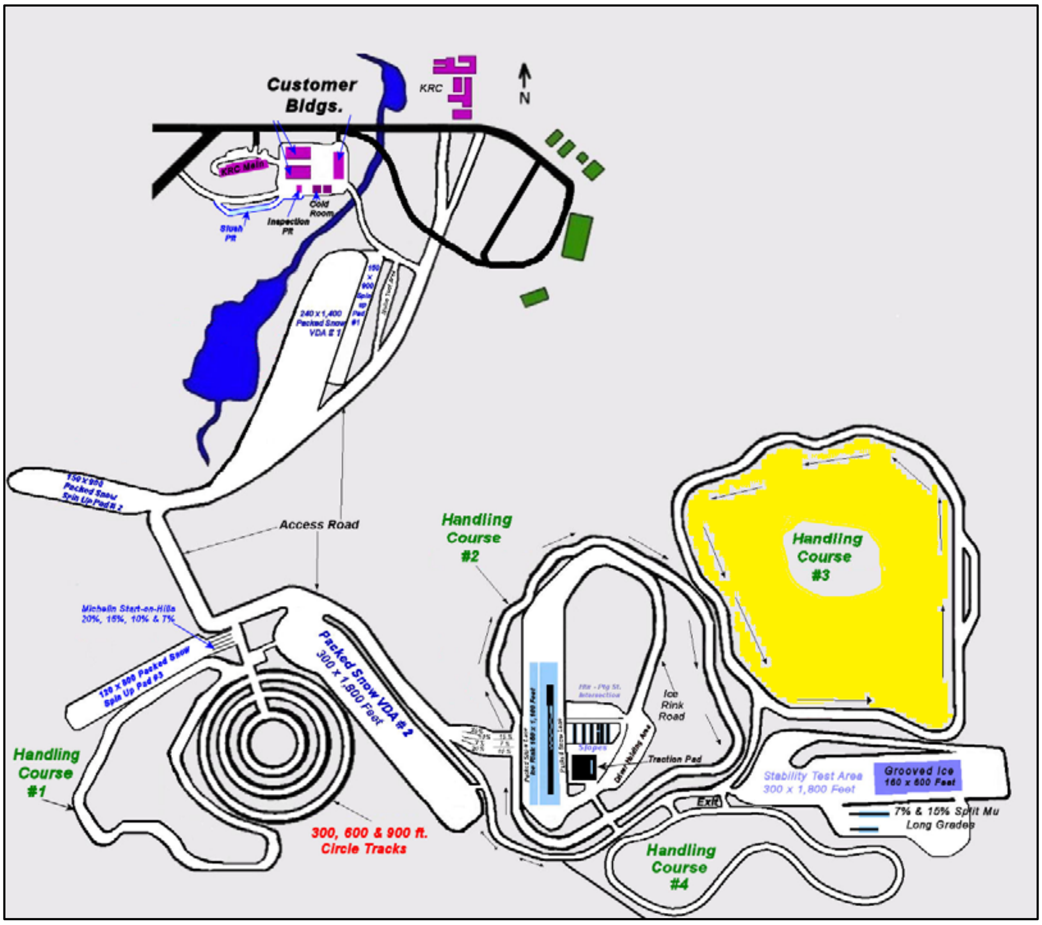
The tests were developed by Michigan Technology University (MTU), at Keweenaw Research Center located in Calumet near Houghton, Michigan (USA) (see Figure 4 and 5).

The Keweenaw Research Center (KRC) is a multidisciplinary research centre of Michigan Technological University (MTU) that is active across a broad spectrum of vehicle development. Originally established by the US Army for deep snow mobility testing, KRC has been involved in military, industrial, and commercial vehicle applications for over 60 years.

KRC maintains more than 900 acres of proving grounds, specifically developed for the evaluation of ground vehicle systems. In addition, the KRC possesses the infrastructure and personnel to properly care for and evaluate vehicles and vehicular components.

As part of the University, the KRC is a not-for-profit academic entity with an educational mission. Staffed by full-time personnel, the KRC draws upon the expertise and resources within the University community to provide diverse research and educational opportunities.

Figure 4. Keweenaw Research Center map overview



Source: MTU, 2018

All the SMB testing campaign was carried on the handling course #3.

Figure 5. Keweenaw Research Center overview

Source: MTU, 2018

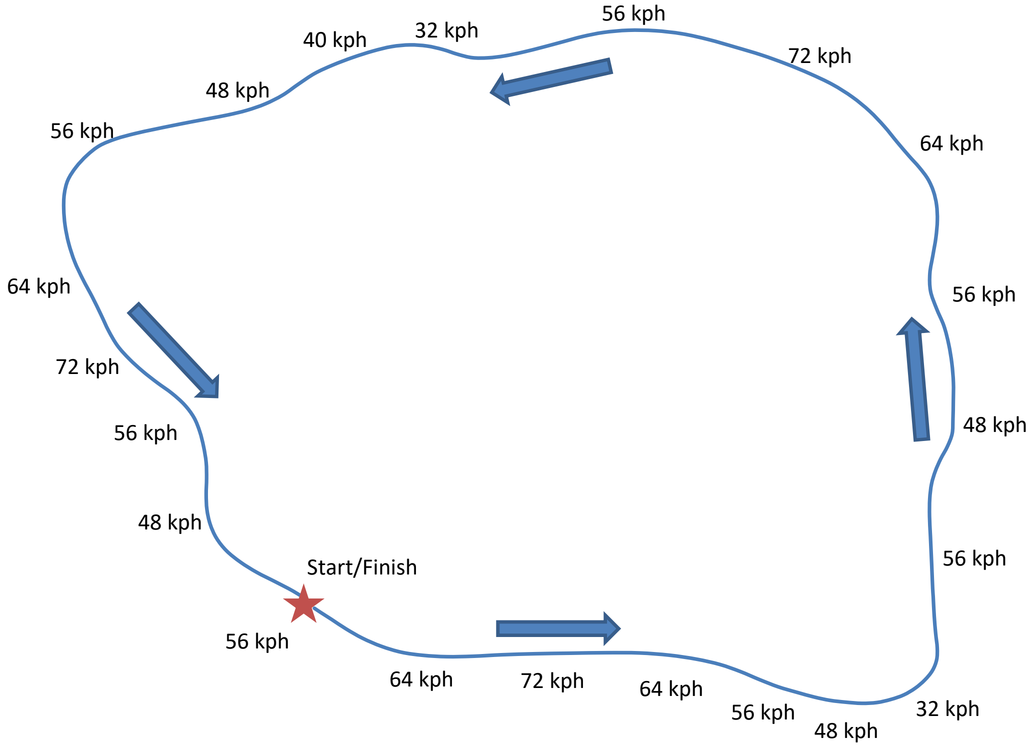
The characteristic of the snow surface changed a lot during the winter season. MTU tried to have different snow conditions from hard pack to the snow melting – situation that normally is possible to meet during springtime.

3.4.1 Circuit features

The circuit (handling course #3) main characteristics are the following (see Figure 6 for details):

- Test performed on the circuit called "Loop 3" of 2.1 km/lap
- Vehicle speed varied from 32 - 72 km/h
- Emissions data sampled at 1Hz
- 7 laps of data collected (Standard)

Figure 6. Keweenaw Research Center "Loop 3" circuit details



Source: MTU, 2018

MTU experience and equipment are suitable to the ISM campaign purpose, since they have a solid background starting from 2003, when they took over the leadership of SAE Clean Snowmobile Challenge event and a strong experience about in-use emissions testing of snowmobiles starting from 2009. The circuit has been developed and used for the SAE International Clean Snowmobile Challenge (CSC). This is an engineering design competition for undergraduate and graduate students. The program provides participants with the opportunity to enhance their engineering design and project management skills by applying learned classroom theories in a challenging competition that tests their designs to reengineer an existing snowmobile to reduce emissions and noise. Participants' modified snowmobiles will compete in a variety of events including emissions, noise, fuel economy/endurance, acceleration, handling, static display, cold start and design. There are two categories in the Internal Combustion in which teams can compete: gasoline or diesel. The intent of the competition is to develop a snowmobile that is acceptable for use in environmentally sensitive areas such as USA National Parks or other pristine areas. The modified snowmobiles are expected to be quiet and emit significantly less unburned hydrocarbons and carbon monoxide than current production snowmobiles, without significantly increasing oxides of nitrogen emissions. Definitely, the intent of the competition is to design a touring snowmobile that will primarily be ridden on groomed snowmobile trails. To achieve the purpose of the competition, the circuit required to the drivers a very smooth driving behaviour, which does not include rapid acceleration, high speed and transient. For more details see the competition website (http://saecleansnowmobile.com/).

3.4.2 Test operations

Three different is-use modality were foreseen during the campaign using the test fleet (Figure 7), to investigate variable driver behaviour and the impact of the different driving mode on the test results.

- Standard Laps (Figure 8) – driver followed posted speed signs (see Figure 6) and attempted to drive in a consistent, repeatable manner to reduce rapid acceleration and deceleration events.
- High Speed Laps (Figure 9) – driver did not follow posted speed signs and focused on completing the lap as fast as possible.
- Highly Transient Laps – driver did not follow posted speed signs and focused on aggressive and frequent throttle inputs.

Figure 7. Snowmobile ISM testing fleet

Source: MTU, 2018

Figure 8. Field test operation – Standards speed laps

Source: JRC, 2018

Figure 9. Field test operation – High speed laps

Source: JRC, 2018

3.5 Test executions

3.5.1 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.

3.5.2 Testing sleigh

All the measuring instruments and equipment was installed on a sleigh in order not to excessively increase the overall weight of the vehicle/machinery under test. See Figures 10, 11, 12, 13, 14, 15 and 16 for details.

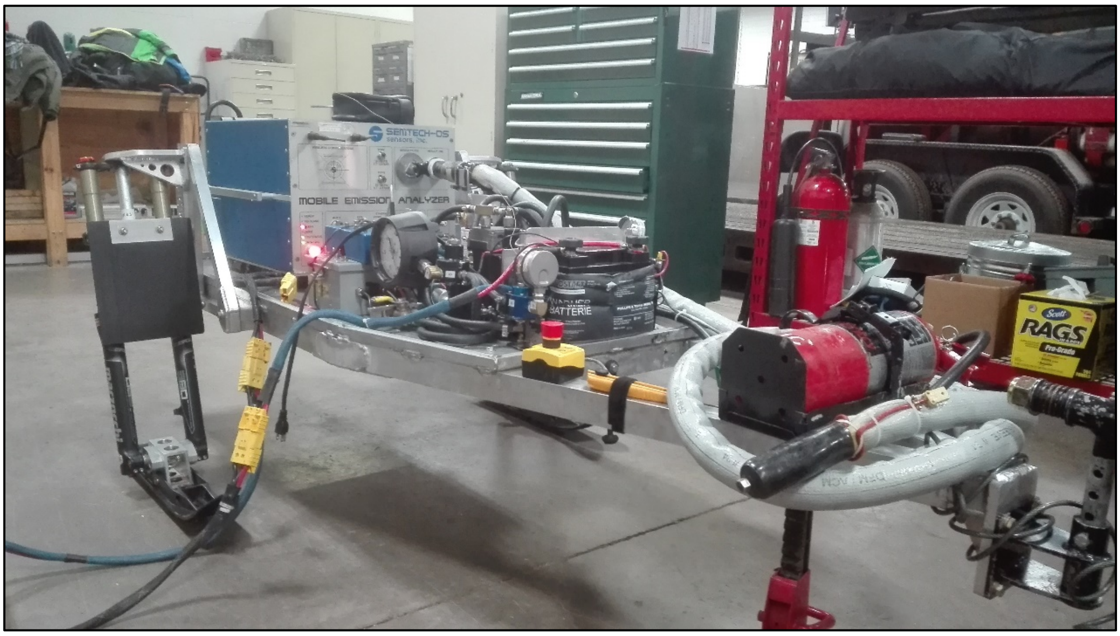
SLEIGH DETAILS:

- Aluminium frame, plastic skis, lexan (plastic) cover, lithium-ion battery
- EURO VI and EPA compliant (CFR 1065) emissions analyser (5-gas)
- Total weight: 113 kg
- On-board custom fuel conditioning and measurement system (positive displacement volumetric (Pierburg PLU126 fuel flow meter).

Figure 10. Vehicle preparation before the test

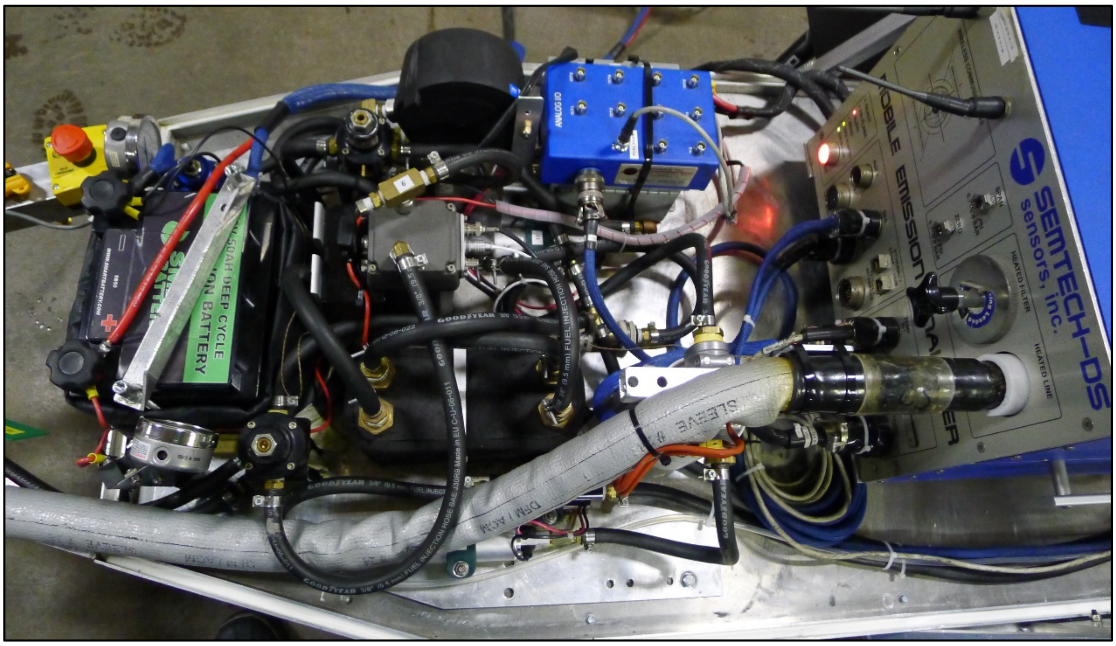
Source: JRC, 2018

Figure 11. Equipment installed on the sleigh



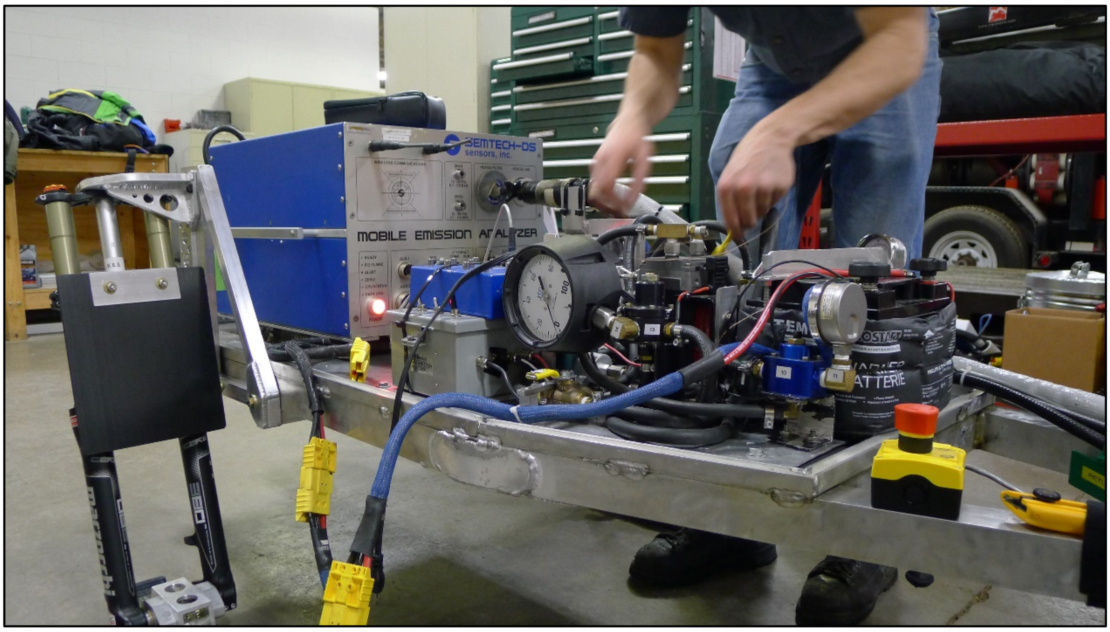
Source: JRC, 2018

Figure 12. Equipment installed on the sleigh (connections details)



Source: JRC, 2018

Figure 13. Sleigh lateral view during pre-test setting phase



Source: JRC, 2018

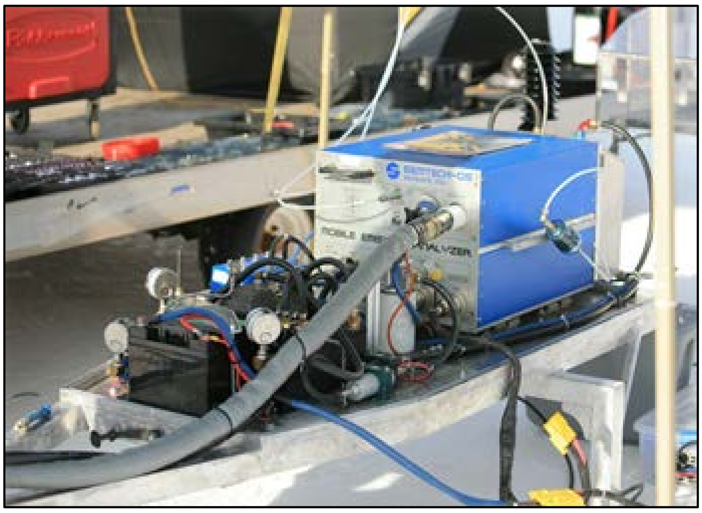
Figure 14. Sleigh final configuration on field (lateral view)

Source: JRC, 2018

Snowmobiles when used as an utility machine/vehicle can normally accommodate up to two persons: the driver and a passenger. Considering the additional weight introduced by the presence of the sleigh (113 kg), this can be considered as a normal in service configuration. In addition, in normal working conditions, it is very common to have the snowmobile directly connected to a service sleigh for the transportation of materials, goods or even luggage when used in some winter ski station/areas.

In Annex 3, we will address more closely the impact of the sleigh on the field tests, in terms of increasing of the specific emissions due to the raise of the overall weight (snowmobile + equipped sleigh).

Figure 15. Equipment check before test on the field



Source: JRC, 2018

Figure 16. Testing on the field (operation detail)

Source: MTU, 2018

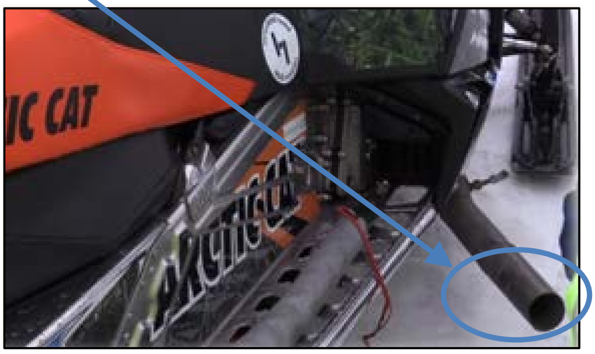
3.5.3 Exhaust flow measurement issue

Most portable emissions measuring systems (PEMS) rely on measuring the exhaust flow directly. This is challenging for snowmobiles, due to exhaust exit location. Furthermore, the packaging is difficult, in fact unlike the ATV's and in other NRMM, in which the exhaust is out the back of the vehicle, facilitating the installation of the exhaust flow meter, in the snowmobiles the exhaust exits downward, close to snow surface (Figures 17 and 18). However, with further changes in the exhaust line, it might be possible to mount an exhaust flow meter. Another difference is that while ATV's exclusively utilize four-stroke engines, the snowmobiles are commonly equipped also with two-stroke engines, that are especially sensitive to changes in exhaust backpressure, affecting emissions and performance. For these reasons during the pilot program alternative methods to calculate the exhaust emissions from other sources has been explored and used.

Figure 17. Typical exhaust exit location in a snowmobile

Source: MTU, 2018

Figure 18. Exhaust exit location (detail)



Source: MTU, 2018

3.5.4 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 directly at MTU Keweenaw Research Center. 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[10], 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 – H Mode cycle).

[10] 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

3.5.5 Test trips and cycles

In average, every single test had a total duration of 20 minutes. 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.

Here below the detail of the test performed on the testing grounds, divided, where applicable, in standard, high speed and high transient laps:

<u>Vehicle A</u>

- Test Date: 02/21-22/2018
- Test Conditions: ~ -1°C, partly cloudy, hard-packed snow on course
- Fuel: 91 E0 (pump fuel)
- Test 23: 7 standard laps, MTU driver
- Test 24: 7 standard laps, MTU driver
- Test 25: 7 standard laps, MTU driver
- Test 29: 3 standard laps, 4 highly transient laps, OEM driver

<u>Vehicle B</u>

- Test Date: 04/05/2018
- Test Conditions: ~ -2°C, Overcast with light snow, light snow cover
- Fuel: 91 E0 (pump fuel)
- Test 4: 7 standard laps, MTU driver
- Test 5: 7 standard laps, MTU driver
- Test 6: 7 standard laps, MTU driver
- Test 7: 4 high speed laps, 2 highly transient laps, MTU driver

<u>Vehicle C</u>

- Test Date: 02/15/2018
- Test Conditions: ~ -1°C, partly cloudy, hard-packed snow on course
- Fuel: 87 E10 (pump fuel), all but last test
- Test 12: 7 standard laps, MTU driver
- Test 13: 7 standard laps, MTU driver
- Test 14: 7 standard laps, MTU driver
- Test 15: 7 standard laps, MTU driver
- Test 16: 7 standard laps, MTU driver
- Test 18: 7 standard laps, MTU driver
- Test 19: 7 high speed laps, 1 highly transient lap, MTU driver

Vehicle D

- Test Date: 02/01/2018
- Test Conditions: ~ -17°C, Overcast, Icy Track, Light Snow Cover
- Fuel: 91 E0 (pump fuel)
- Test 3: 7 standard laps, MTU driver, muffler sample
- Test 4: 7 standard laps, MTU driver, muffler sample
- Test 5: 7 standard laps, MTU driver, mid-pipe sample
- Test 6: 4 standard laps, 3 highly transient laps, A/C driver, mid-pipe sample, MTU driver

3.5.6 Test Fuels

Two different test fuels (a and b) with the following characteristics were used during the testing campaign:

a. 91 E0 (from local fuel station)

   - Anti-knock index (R+M)/2: 91
   - H/C: 1.87
   - Density @ 25°C: 710 kg/m^3

b. 87 E10 (from local fuel station)

   - Anti-knock index (R+M)/2: 87
   - H/C: 1.93
   - O/C: 0.027
   - Density @ 25°C: 740 kg/m^3

3.6 Data handling procedures and tools

3.6.1 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.

3.6.2 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: Fuel flow meter (Fuel flow and fuel temperature);

According to the procedure developed for heavy-duty engines and transposed to the case of NRMM[6], 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 parameter which may be used to calculate the correlation coefficients to time-align Category 1 with Category 2 is the CO2 concentration and the fuel mass flow or the GPS data and fuel 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
Fuel mass flow	kg/h	Fuel Flow Meter: Pierburg PLU126 system using positive displacement volumetric (hereinafter FFM)
Exhaust temperature	°K	Sensor
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

Source: MTU, 2018

3.6.3 Data collection and post-processing

The data has been collected and post processed using the following steps

- Step 1: Collect 7 laps of emissions concentrations, fuel consumption, and CAN data (if applicable)
- Step 2: Compute per-second g/s for HC and CO emissions using raw emissions concentrations, fuel properties (density, H/C, and O/C ratios), and fuel consumption (kg/hr)
- Step 3: Introduce CO2MAW method based on the so called "Veline" approach to estimate the power (later on refer to as equivalent/proxy power). See chapter 7.

In the following chapter a validation of the JRC method will be provided using a comparison with MTU approach of generating a 2^{nd} order fit between fuel consumption and power using 5-mode stationary (type-approval) emissions data. It is important to remember that each snowmobile has a unique own equation.

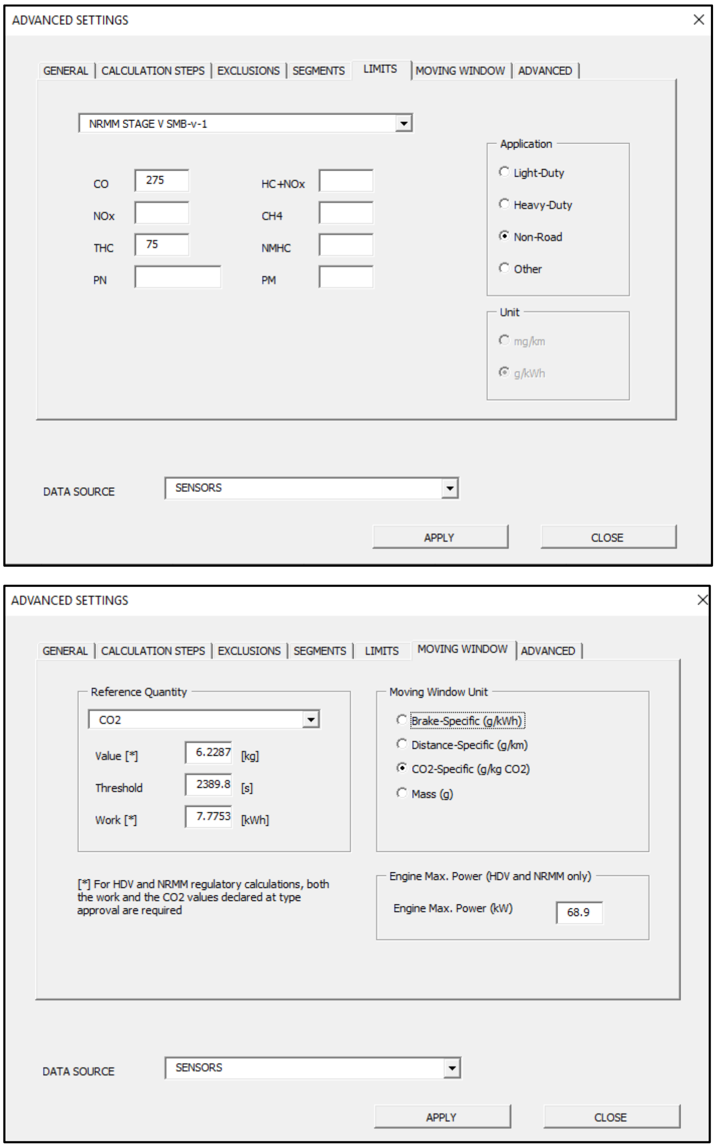
3.6.4 EMROAD©

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 19 as example of EMROAD's setting interface forms)

The standardized reporting templates includes, 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, FFM, engine);
4. Data verification routines, using the duplication of measurement principle, to check for instance the directly measured fuel flow against the calculated one;
5. Averages and integrated values (mass emissions, distance, fuel and brake specific).

Figure 19. EMROAD setting interface forms



Source: JRC Vela, 2019

3.6.5 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.

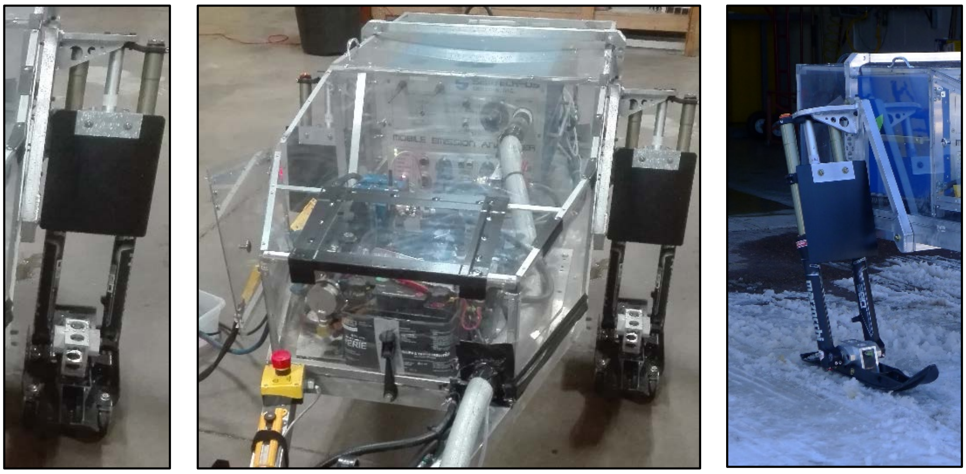
4.1 Installation of PEMS equipment

Unlike in the case of NRE-v-5 and NRE-v-6 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 snowmobiles being tested in the SMB NRMM PEMS Pilot Program.

The following is a non-exhaustive list of suggestions/recommendations extracted from the experience obtained in the field during this and others NRMM test programs.

1. Installation of instruments should be made on a sleigh able to adsorb the shocks thanks to the presence of specific cushioned forks/dampers (see Figure 20)
2. Some degrees of freedom needs to be allowed for the heated probe connected to the tail pipe, i.e. allow the probe to move slightly to compensate vibrations and high accelerations without risking to damage the connections due to some lateral movement of the sleigh itself.

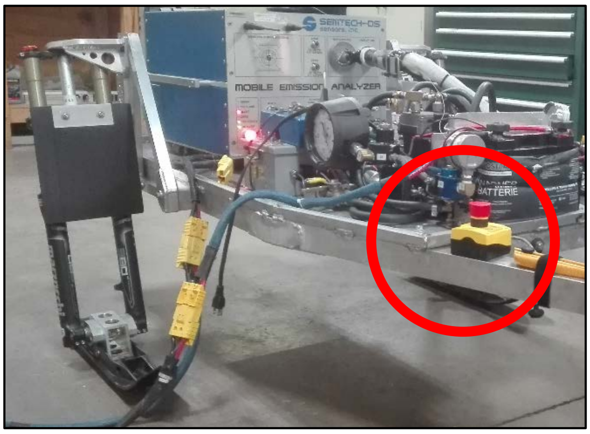
Figure 20. Cushioned forks of MTB derivation



Source: JRC, 2018

3. To protect the equipment from dust, water, shocks, etc., it is necessary to adopt a suitable coverage for the sleigh (e.g. undeformable plastic sheet/glass).
4. For safety reasons, the mounting platform in which is installed the equipment need to be secured to the sleigh: straps are considerated a good solution.
5. Due to the outline and the reduced dimension, installing the equipment onto the sleigh can prevent access to the gas analyzer components (e.g FID fuel bottle, filter). It is reccomandable to foreseen some inspection port.
6. Access to the test equipment is necessary – either for the installation or for the checks between the tests. An inspection port/window should be present on the sleigh superior frame – safety aspect needs to be considered. It is reccomandable to supply the sleigh with an emergency button to switch off the PEMS equipment in case of necessity. See detail of Figure 21.

Figure 21. Emergency button on the sleigh

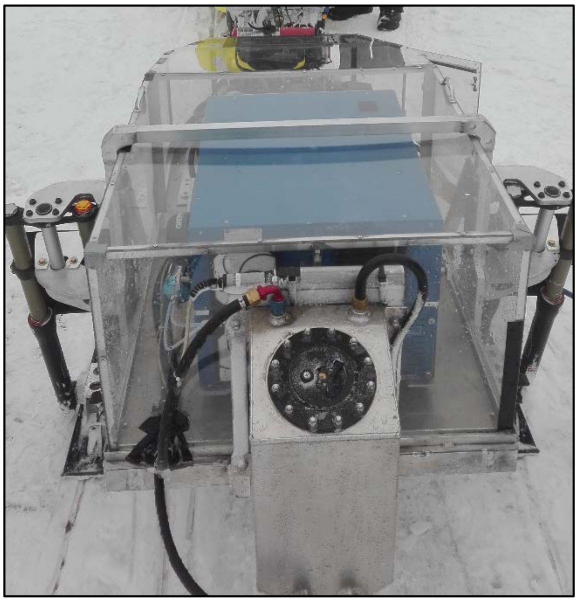


Source: JRC, 2018

7. Permanent machinery modifications must be avoided as those will not be acceptable to the machinery owner.

8. Due to the cold temperature the fuel must be conditioned to avoid condensation and freezing problem in the fue flow measurement system (Figure 22).

Figure 22. Fuel conditioning system



Source: JRC, 2018

9. 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).

10. FID fuel bottle: 0.5 internal liter bottle has an autonomy of about 6 hours (which must include warm-up and calibration) – External larger bottles could be used (1 liters) in case that enough space is available.

11. 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.

12. Avoid contamination of the air used to zero the gas analyzers (by the engine itself, the power generator or any other source)
13. Recommendation: Remote monitoring of the instruments using Wifi
14. Recommendation for the laptops: they need to be ruggedized, for high autonomy, water proof, lighting of the monitor, etc

4.2 PEMS analyzer technical specification

The testing sleigh is equipped with PEMS equipment with the following characteristics (see Table 5). The used equipment is a Semtech-DS, however any other instrument manufacturer can be used if provide similar features. See table 5 for an exhaustive overview.

Table 5. Technical specification of PEMS analyser

Component	Measurement Range	Accuracy	Resolution
CO_2	0 - 20%	+/- 3% of reading	0.01%
CO	0 - 8%	+/- 3% of reading	10 ppm
THC, range 1	0 - 10,000 ppm C1	+/- 2% of reading	1 ppmC
THC, range 2	0 - 40,000 ppm C1	+/- 2% of reading	10 ppmC
NO	0 - 3,000 ppm	+/- 2% of reading	0.1 ppm
O2	0 – 25%	+/- 1% of reading	0.1 %

Source: MTU, 2018

4.3 Reference test cycle

The reference test cycle applicable to the engines that equipped the tested machinery is a NRSC test cycle type H, which foreseen 5 modes, that is 5 points of measurement according to Table 6. Every mode has a different weighting factor.

Table 6. NRSC Test cycle type H

Test cycle type H					
Mode Number	1	2	3	4	5
Speed (a) (%)	100	85	75	65	Idle
Torque (b) (%)	100	51	33	19	0
Weighting factor	0.12	0.27	0.25	0.31	0.05

Source Reg. (EU) 2017/654

(a) See sections 5.2.5, 7.6 and 7.7 of Annex VI for determination of required test speeds.
(b) % torque is relative to the maximum torque at the commanded engine speed.

In a NRSC test cycle (e.g.: Test cycle type H), gaseous and particulate pollutants emitted by the engine submitted for testing are measured following the methodology prescribed 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 prescribed in Reg. (EU) 2017/654, using the fuel flow (measured by means of a fuel mass flow meter based on positive displacement volumetric system) and the carbon balance.

4.4 Validation of PEMS with dynamometer test cell (ATS vehicle comparison)

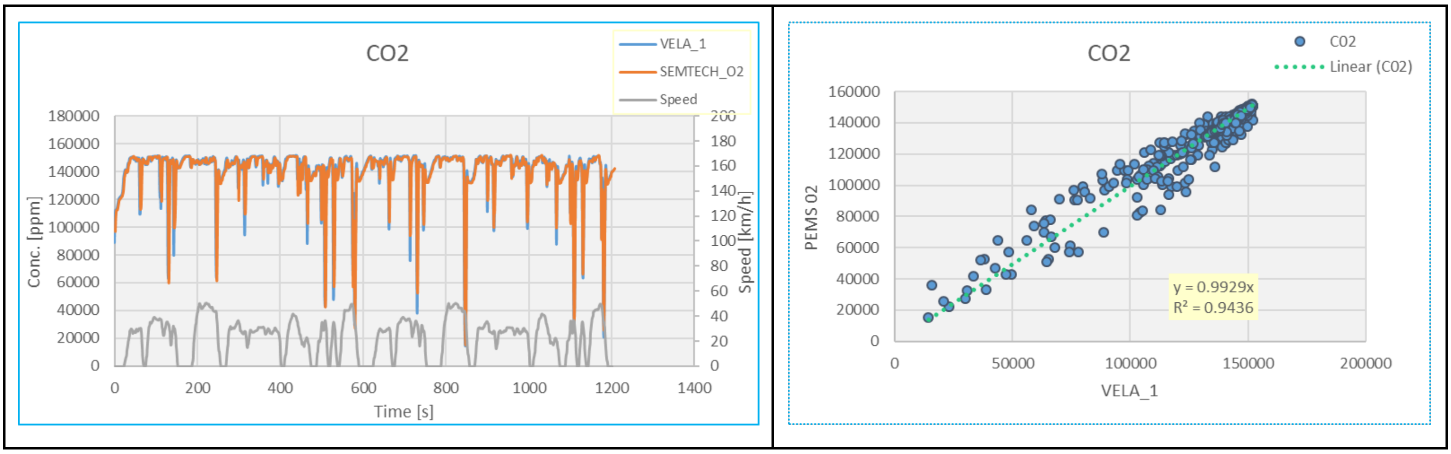
This test was performed to demonstrate the reliability in measuring the concentration of the pollutant in exhaust gas using PEMS instruments instead of a traditional CVS roller test bench. Since we cannot perform this test in our laboratory, in the next session a comparison between ATS engine, which in many cases are similar or even identical to those used on snowmobiles, will be presented[11].

4.4.1 Validation of pollutant concentration: VELA 1 (reference test bench) vs PEMS 02 – Example 1 (SbS engine)

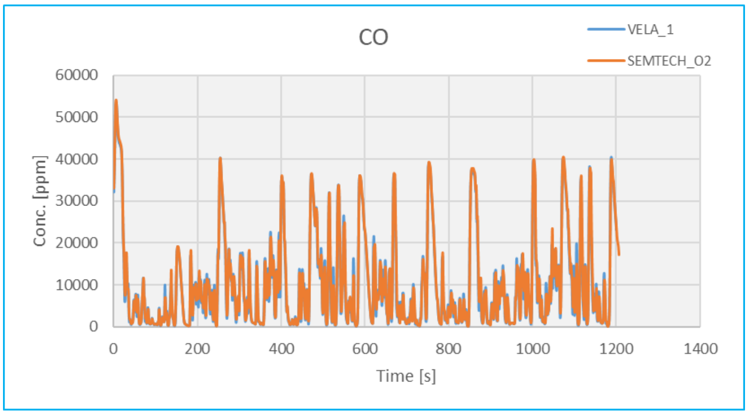
In this case, two SbS vehicles (Vehicle 1 and Vehicle 2) are reported. The test performed is a WMTC cycle starting at cold conditions. Figure 23 shows the very good correlation between the laboratory-base analytical instruments and PEMS measurements

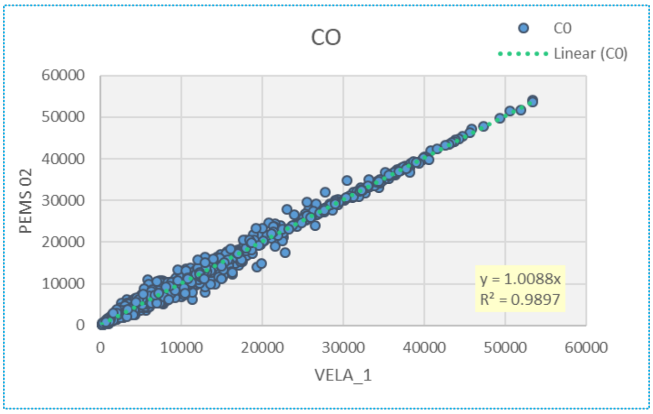
Figure 23. Correlation of the concentration values obtained by PEMS and the CVS of VELA_1 for Vehicle_1

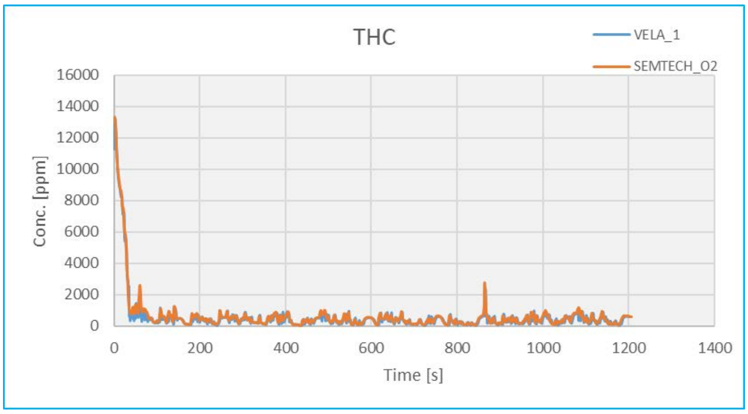
Test Item	COMPARISON VELA_1 vs PEMS_02
Vehicle	SbS
Model	Vehicle_1
Test Date	20171031
Test detail	WMTC Cold

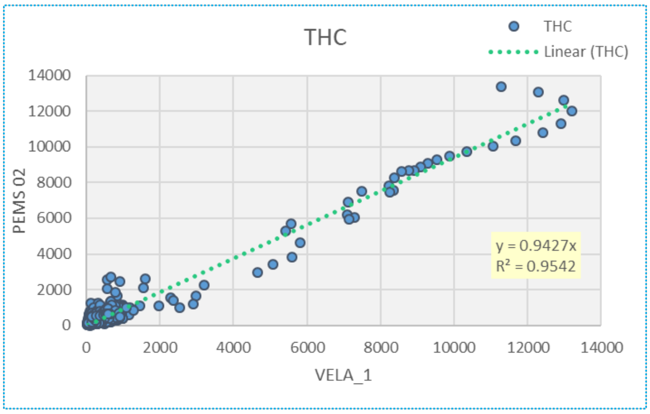


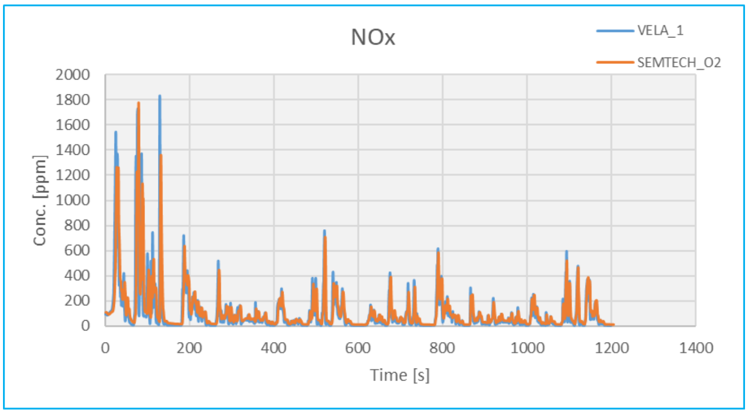
[11] EUR 29920 EN – DOI:10.2760/542636

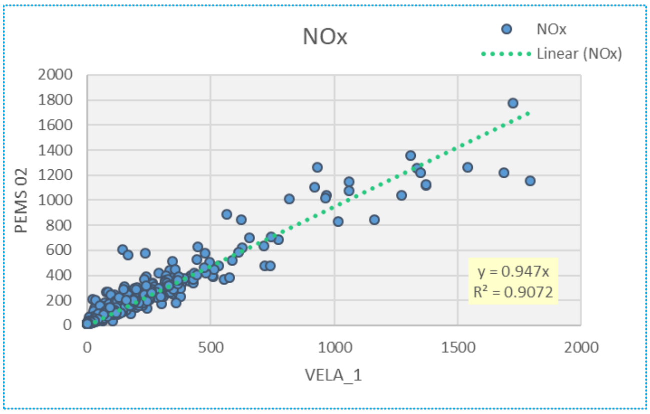

CO
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]

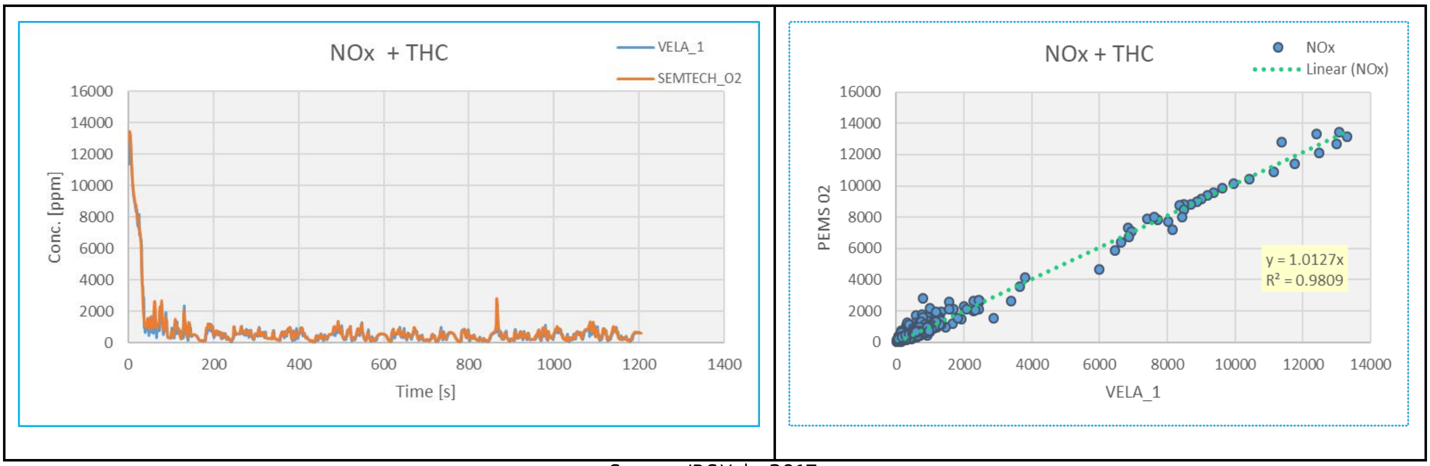

CO
CO
Linear (CO)
PEMS 02
VELA_1
y = 1.0088x
R² = 0.9897


THC
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]


THC
THC
Linear (THC)
PEMS 02
VELA_1
y = 0.9427x
R² = 0.9542


NOx
VELA_1
SEMTECH_O2
Conc. [ppm]
Time [s]


NOx
NOx
Linear (NOx)
PEMS 02
VELA_1
y = 0.947x
R² = 0.9072



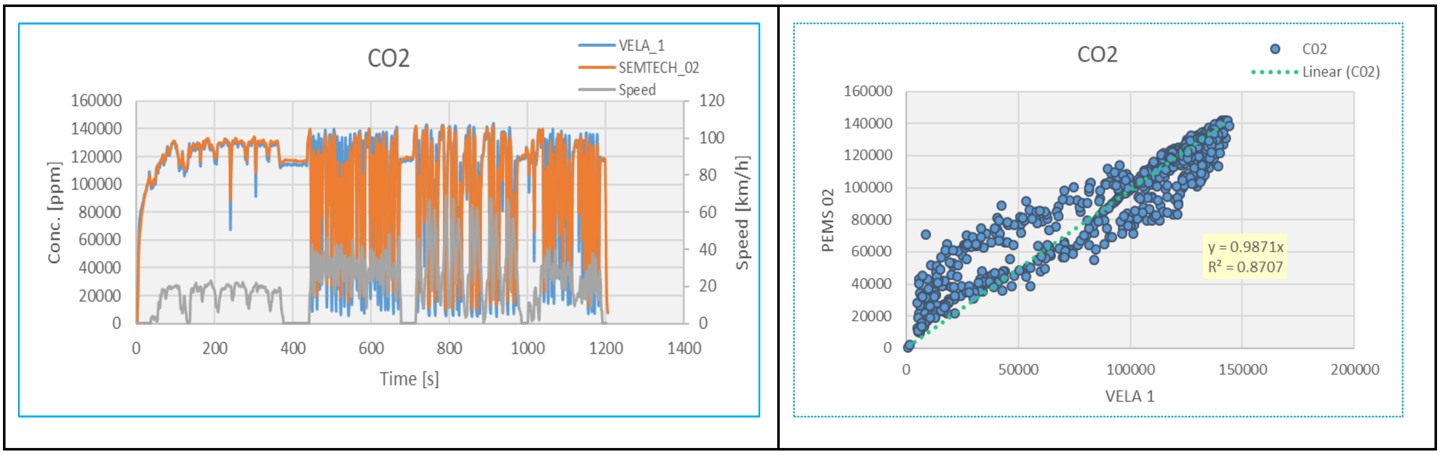
Source: JRC Vela, 2017

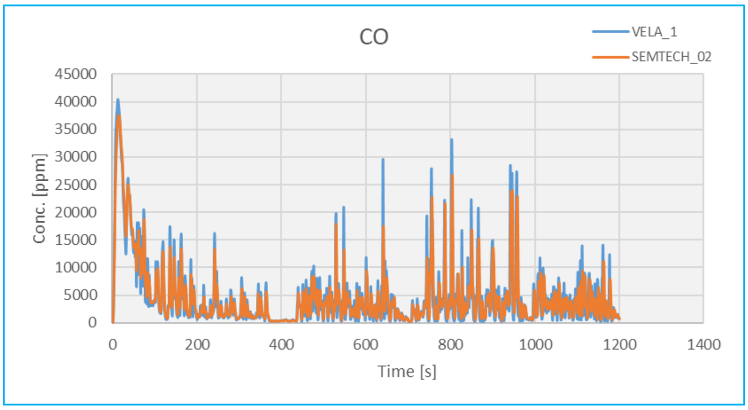
4.4.2 Validation of pollutant concentration: VELA 1 (reference test bench) vs PEMS 02 – Example 2 (SbS engine)

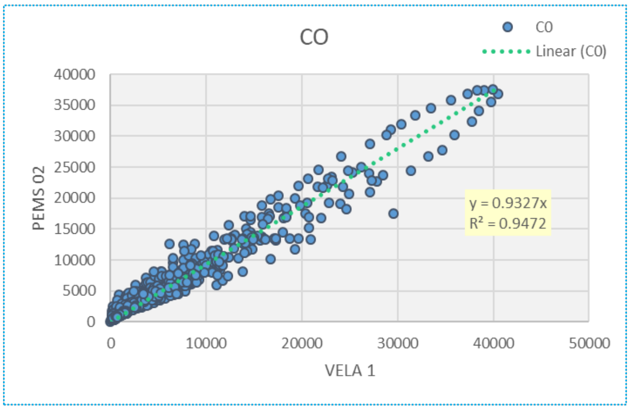
The following table and graph refers to a simulation on roller test bench of a field test, indicating that even in more dynamic condition the correlation is vey good (Figure 24). Also in this example the comparison is made between the reference test bench (VELA_1) and the PEMS equipment (PEMS_02).

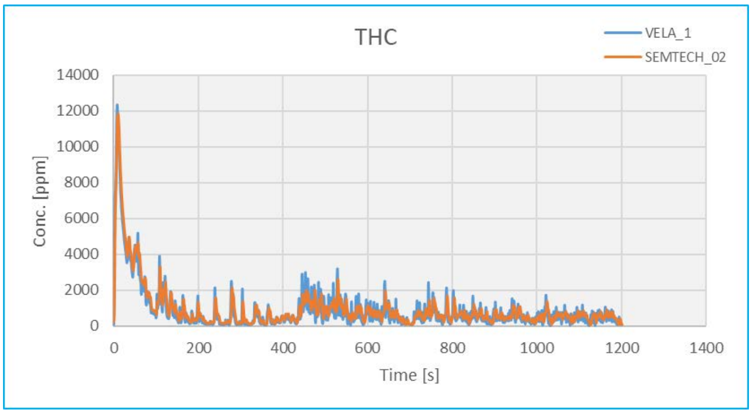
Figure 24. Correlation of the concentration values obtained by PEMS and the CVS of VELA_1 for Vehicle_2

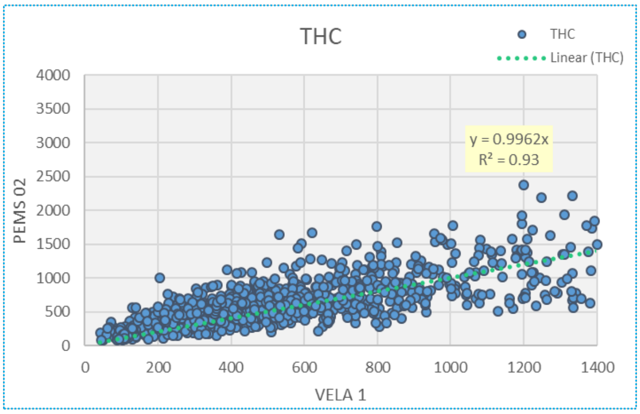
Test Item	COMPARISON VELA_1 vs PEMS_02
Vehicle	SbS
Model	Vehicle_2
Test Date	20171204
Test detail	Field Test

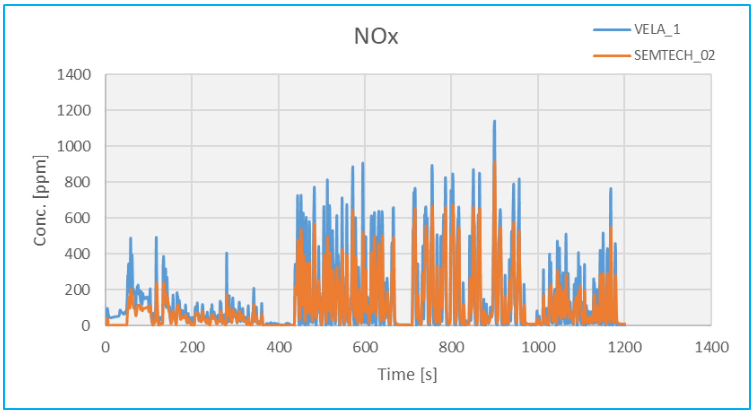


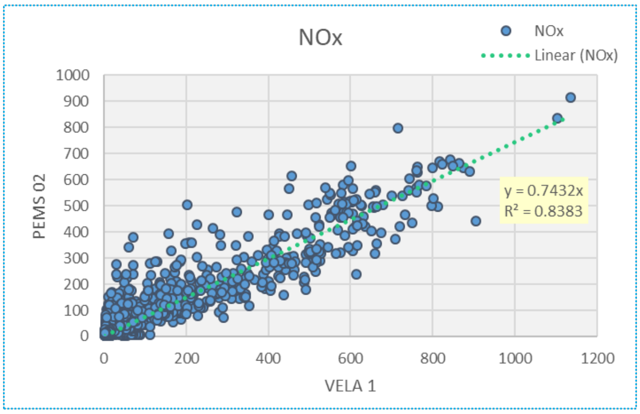

CO
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]

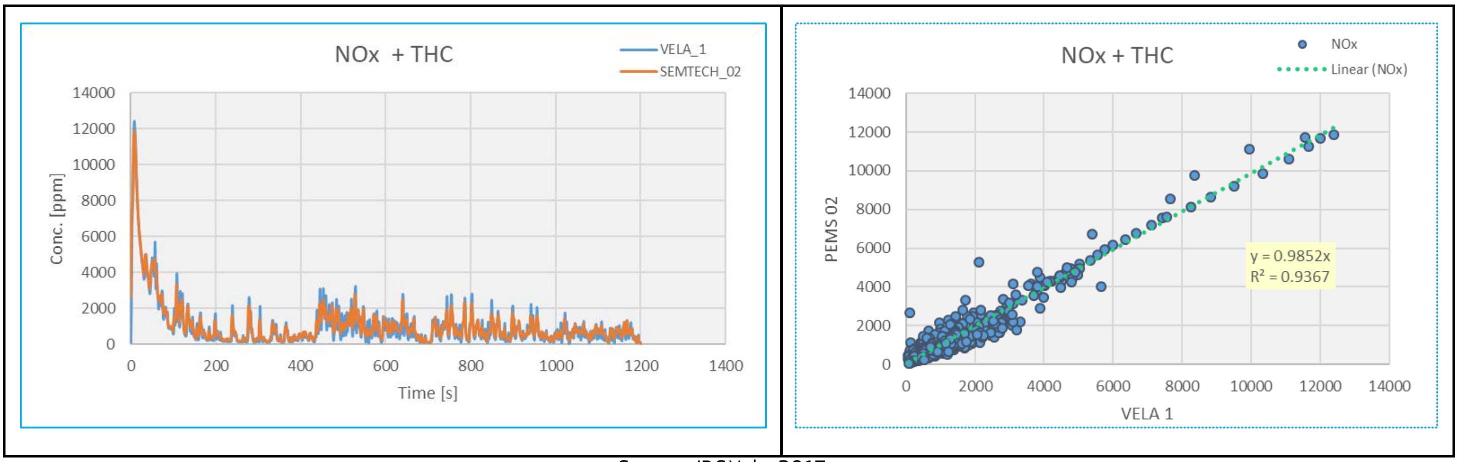

CO
CO
Linear (CO)
PEMS 02
VELA 1
y = 0.9327x
R² = 0.9472


THC
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]


THC
THC
Linear (THC)
PEMS 02
VELA 1
y = 0.9962x
R² = 0.93


NOx
VELA_1
SEMTECH_02
Conc. [ppm]
Time [s]


NOx
NOx
Linear (NOx)
PEMS 02
VELA 1
y = 0.7432x
R² = 0.8383



Source: JRC Vela, 2017

4.5 Validation of fuel flow rate (FFM)

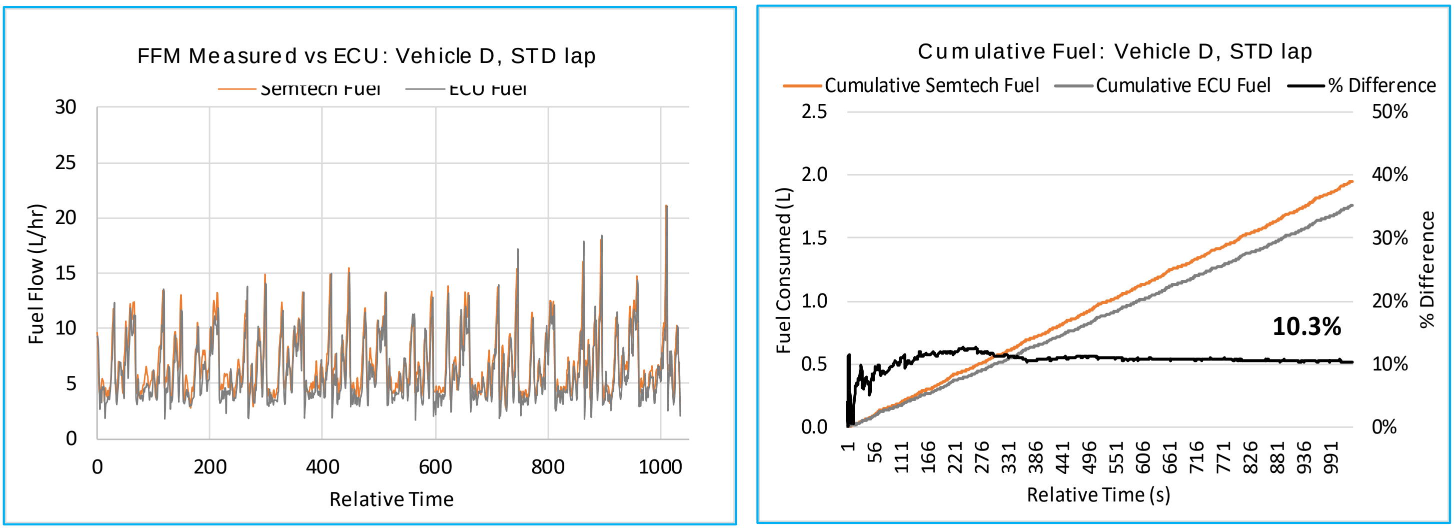
The mass emission is governed by the exhaust flow mass rate. As already stated in session 3.5.3, in a snowmobile it is very complicate to measure the exhaust flow directly, due to exhaust exit location (downward and close to snow surface). However, with further changes in the exhaust line, it might be possible to mount an exhaust flow meter and hence the direct measurement of the exhaust flow.

A practical way is to have an indirect measurement of the exhaust mass flow, that uses the fuel flow rate and the carbon balance method.

In what follows, it will be presented the method of Fuel Flow Meter (FFM) validation used by MTU.

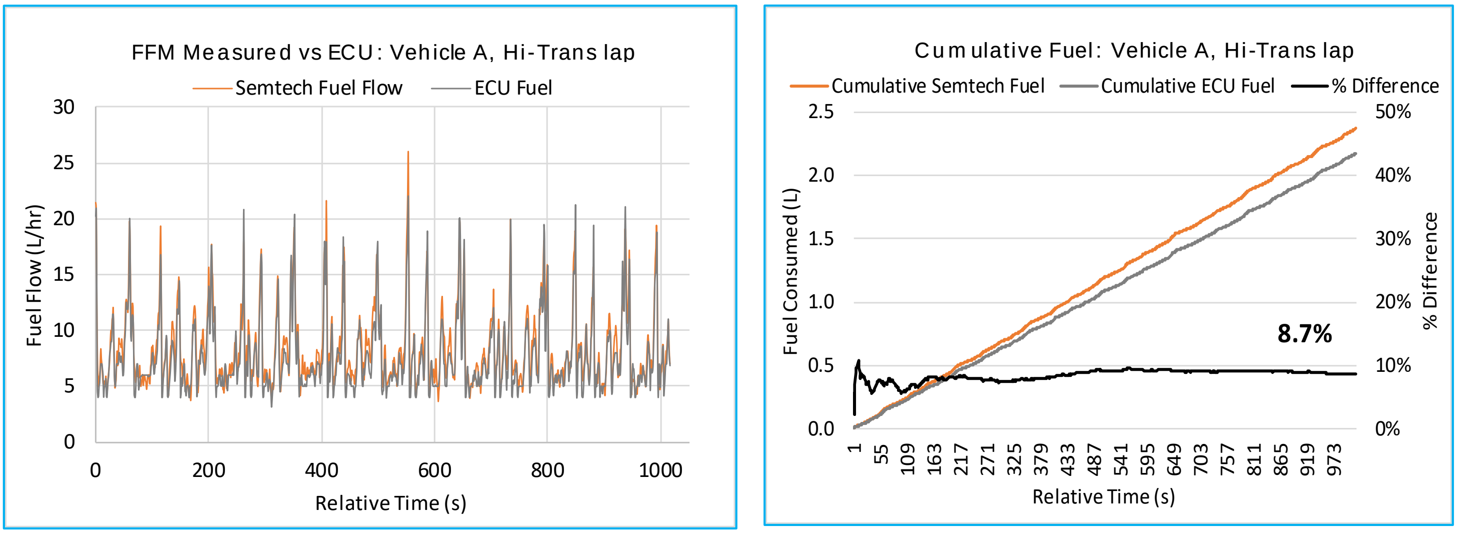
The validation method used by MTU consists in comparing the fuel flow measured by the FFM to the one broadcast by the ECU. Figures 25 to 27 depict the comparison between both fuel flows measurements (i.e. FFM and ECU).

Figure 25. FFM measured vs ECU (Vehicle D, STD lap)



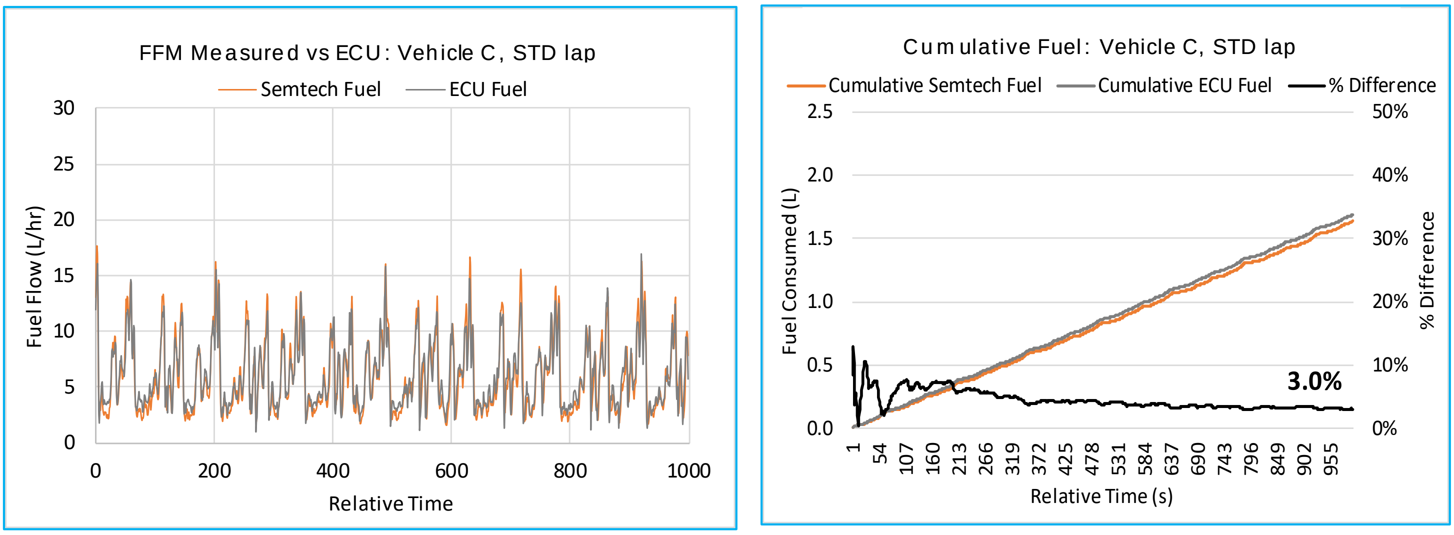
Source: MTU, 2018

Figure 26. FFM measured vs ECU (Vehicle A, High transient lap)



Source: MTU, 2018

Figure 27. FFM measured vs ECU (Vehicle C, STD lap)



Source: MTU, 2018

The above comparison indicates a good correlation between both fuel flow measurements. See Table 7 for a more accurate outlook of the results.

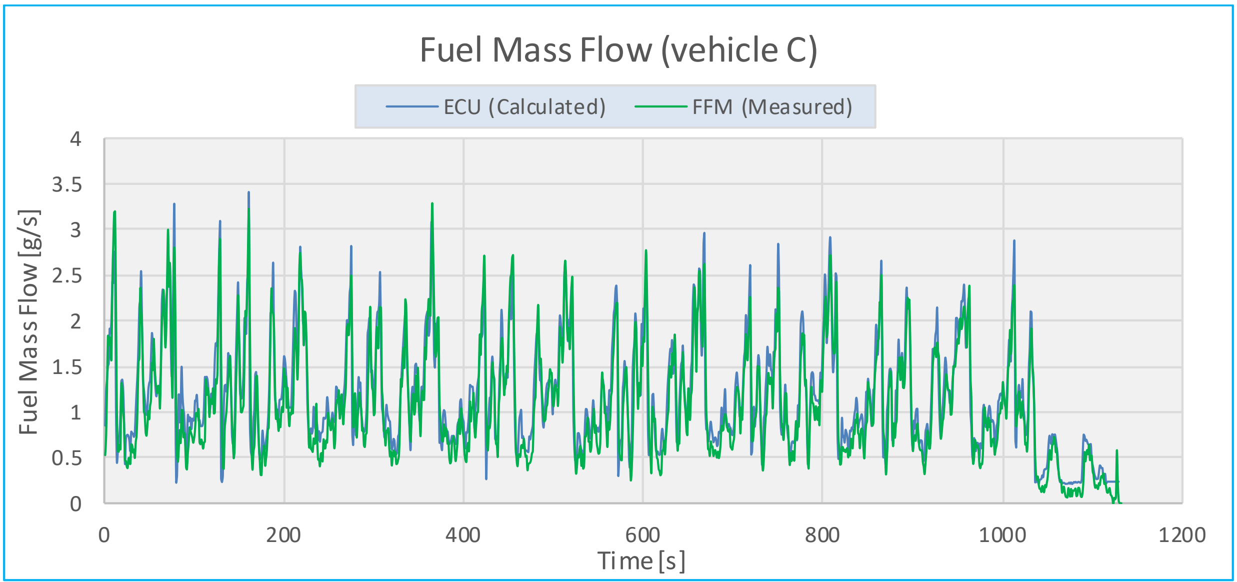
Table 7. FFM measured vs ECU - Results

Vehicle	Test configuration	Cumulative fuel difference [%]
D	STD lap	10.30%
A	High Transient lap	8.70%
B	STD lap	3%

Source: MTU, 2018

JRC confirms the good correlation between the Fuel Mass Flow calculated by the ECU and the Fuel Mass Flow measured by the FFM. Figure 28 compares both measurements for vehicle C.

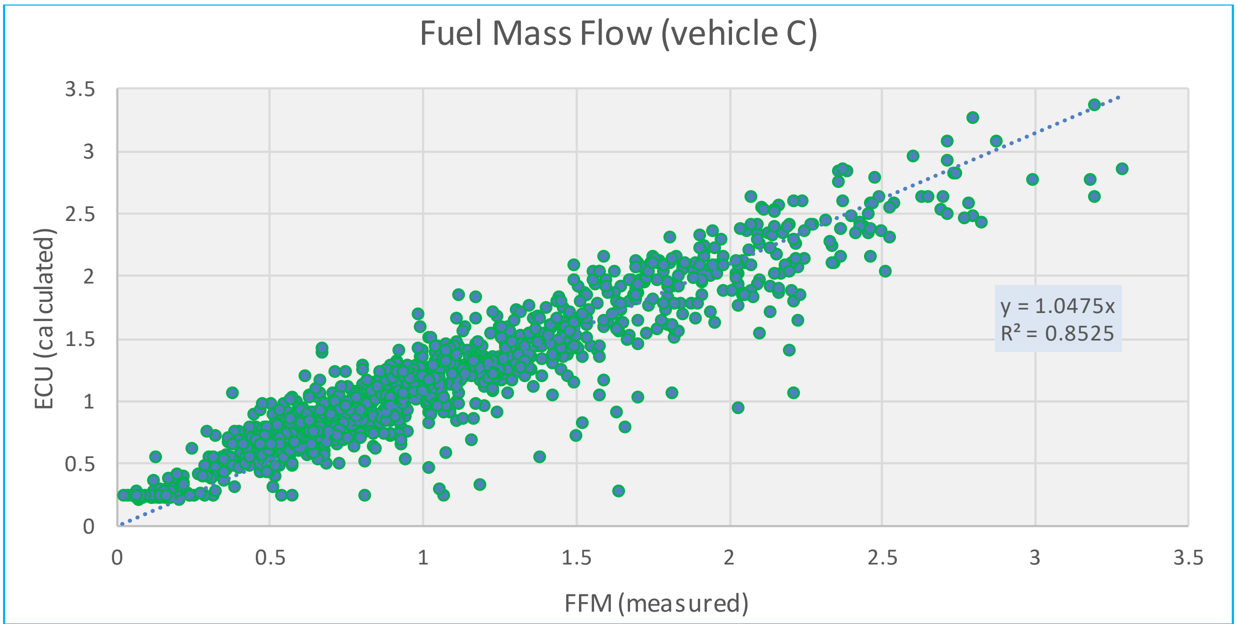
Figure 28. Fuel Mass Flow trace calculated by ECU vs Fuel Mass Flow measured by FFM for the vehicle C (STD lap)



Source: JRC Vela, 2019

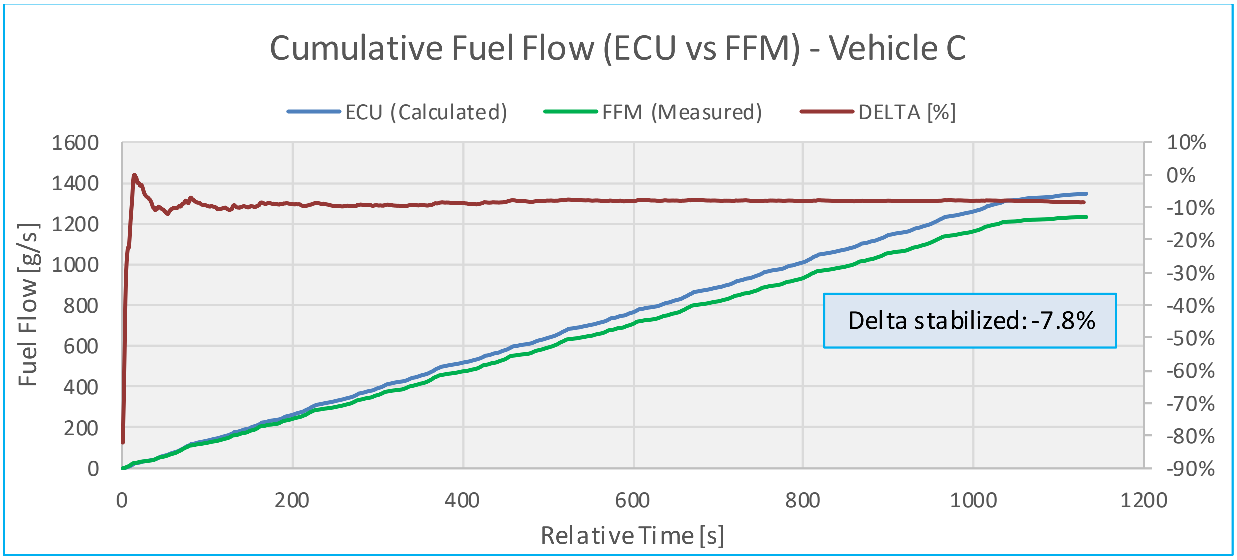
Figure 29 depicts the relationship by plotting the calculated Fuel Mass Flow by the ECU versus the Fuel Mass Flow measured by FMM. The linearity check confirms an acceptable difference of less than 5%, while the least squares analysis shows a coefficient of determination r^2 of 0,85 which indicates a very good correlation. The same results is obtained in the analysis of the cumulative fuel flow: the delta stabilized is also less than 8% (see Figure 30).

Figure 29. Linear correlation between ECU and FFM



Source: JRC Vela, 2019

Figure 30. Cumulative Fuel Mass Flow trace calculated by ECU vs Fuel Mass Flow measured by FFM for the vehicle C (STD lap)



Source: JRC Vela, 2019

In Figure 30, it is also reported the percentage difference between the cumulative fuel flow measured by the FMM and the cumulative fuel flow calculated by the ECU. This last one is assumed as the reference value. The difference is less than 8%.

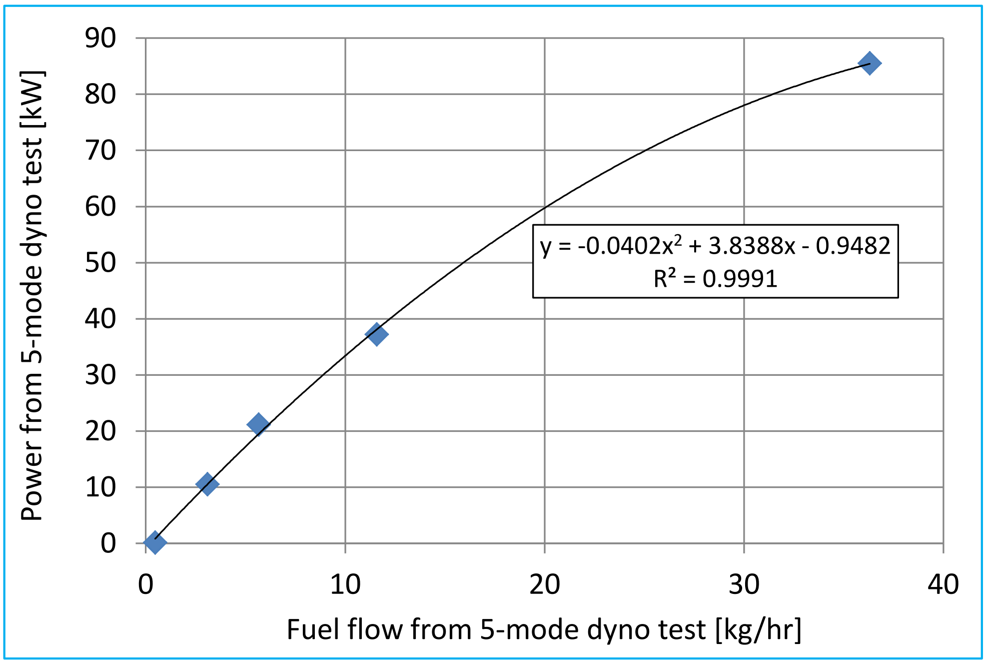
4.6 Power vs. Fuel Correlations (Computing power from Fuel Consumption)

Since the instantaneous power is not available from most machineries/vehicles during the testing campaign in the field, an alternative method based on fuel consumption, which can be measured directly in the field and/or be broadcast from the ECU, needs to be explored. According to MTU, it is possible to correlate fuel consumption and power starting from the steady state 5-mode emission test (NRSC H cycle), which provides both parameters of interest. A regression line can be fitted through these points (5-mode), generating an equation that can be used to back-calculate the power based on the measured fuel consumption rate in the field. The above mentioned curve-fit is an engine specific algorithm.

During the ISM test, the fuel flow rate is measured and recorded every second. A regression equation obtained from the NRSC allows computing the ISM power knowing the instantaneous ISM fuel flow rate.

As shown in Figure 31 for machinery/vehicle C, there is a good correlation between Power and Fuel Flow Rate.

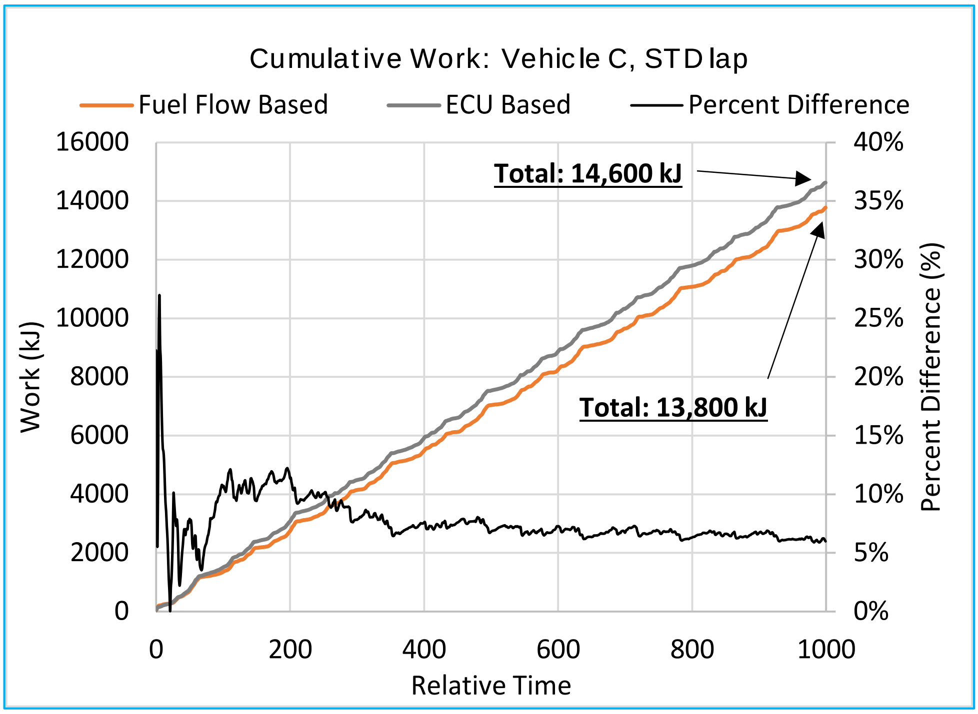
Figure 31. Power vs Fuel Flow rate from 5-mode test data for machinery/vehicle C



Source: MTU, 2018

Using the above correlation equation, it is now possible to calculate the cumulative work using the fuel flow either measured by the FFM or broadcast by the ECU. A validation of this approach can be done for the machinery/vehicle C because both torque and engine speed are available from the ECU. Figure 32 depicts the validation by comparing the cumulative Work obtained using the measured fuel flow (FFM) and ECU. The difference between both approaches are about ~5%.

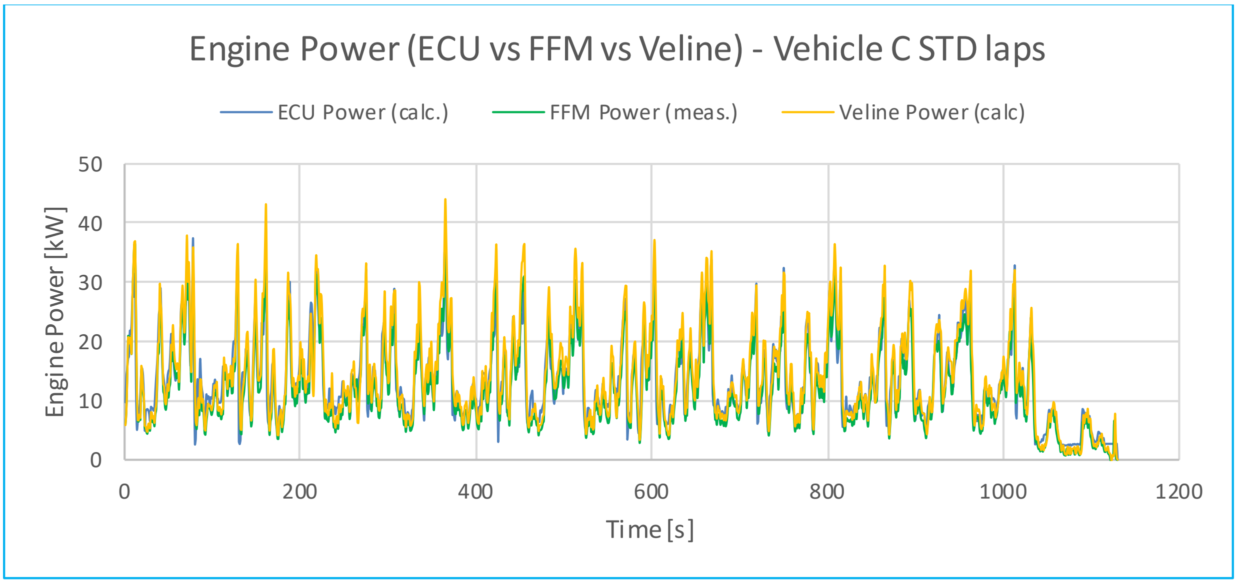
Figure 32. Cumulative Work comparison: Fuel Flow vs ECU (Vehicle C, STD lap)



Source: MTU, 2018

In order to allow for the definition of working and non-working event for mechanically controlled engines, the JRC has developed the “Veline” approach (see section 6.1). In Figure 33 the ECU engine power (torque x rpm) is compared to the one calculated using the measured fuel flow by the FFM and to the one calculated using the “Veline” approach.

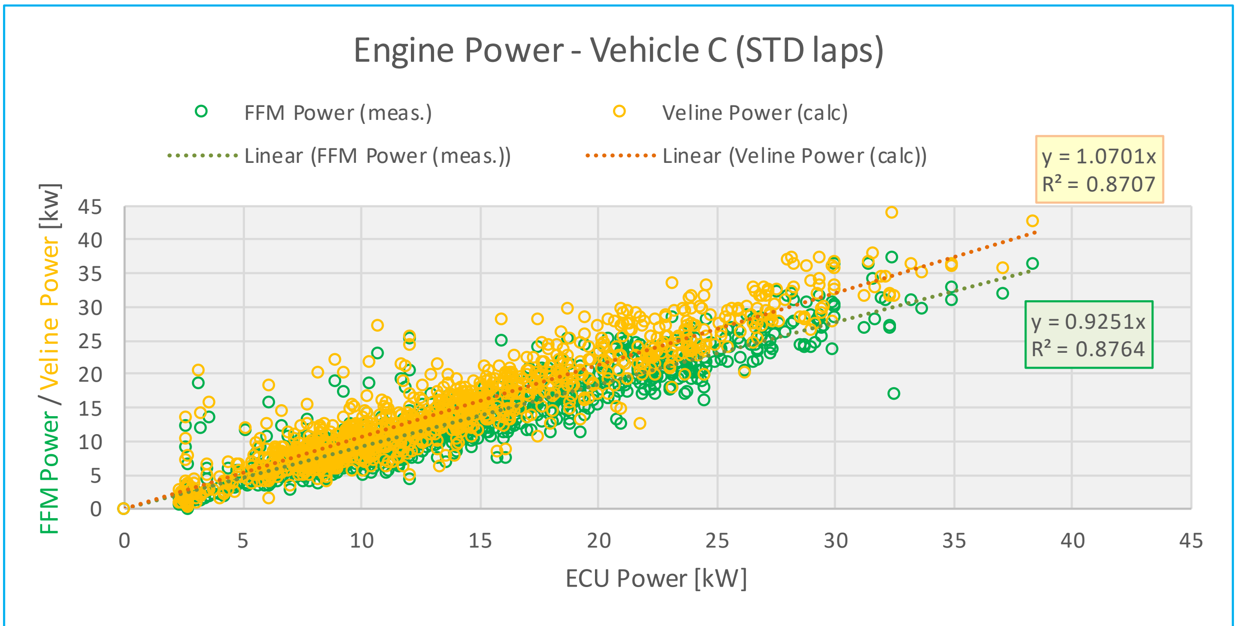
Figure 33. Engine Power: ECU (calculated) vs FFM (measured)



Source: JRC Vela, 2019

Figure 34 depicts the linear correlation between the above mentioned engine power showing a very good correlation.

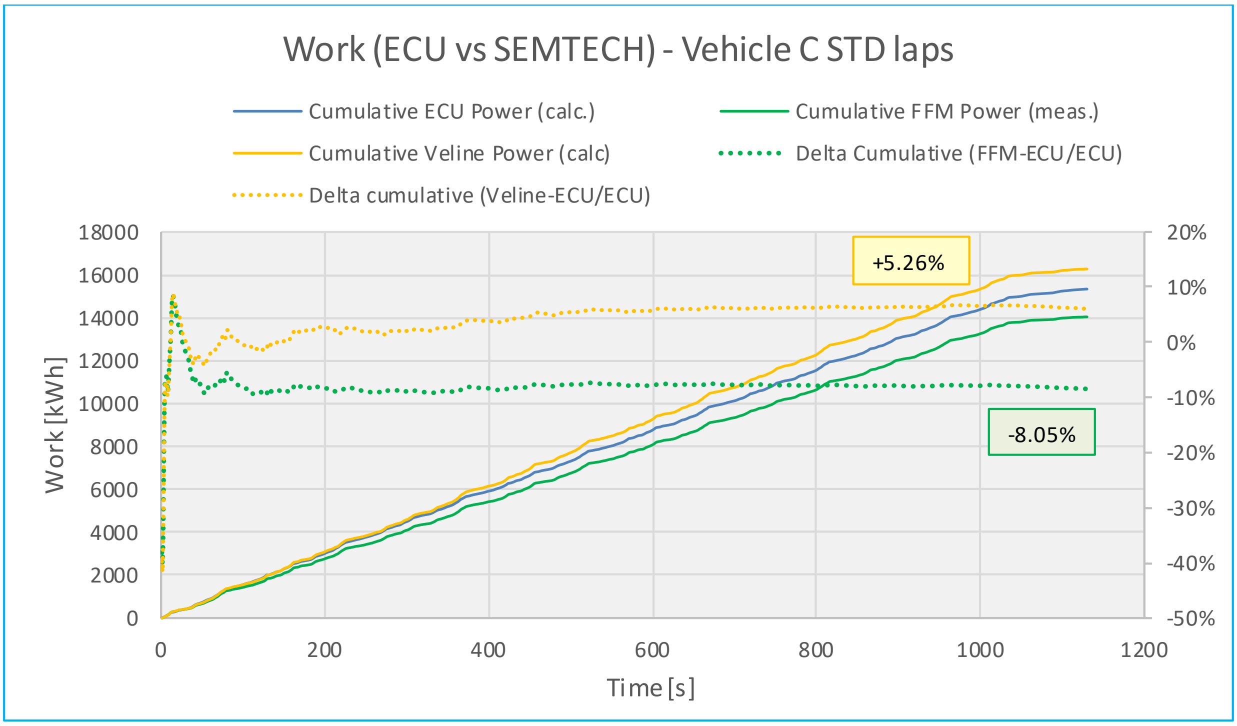
Figure 34. Engine Power linear correlation: ECU (calculated) vs FFM (measured) and “Veline” approach (calculated)



Source: JRC Vela, 2019

Figure 35 shows a comparison of the cumulative work obtained using the MTU and the “Veline” approach. The cumulative work calculated using both approaches are in good agreement with the work calculated using the ECU values. The “Veline” approach seems to provide a slightly better agreement with the ECU. (~ 5%).

Figure 35. Cumulative Work comparison: ECU vs FFM vs Veline approach



Source: JRC Vela, 2019

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

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[12]; i.e. reference work and reference CO_2 mass of the parent engine

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

6 Working/non-working event validation

The new STAGE V[13] 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 manufacturers, the Commission has proposed a methodology to perform the ISM of NRMM for engines in the 56 to 560 KW power range. The method includes among others the definition of working and not working events[14] 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 8 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 8 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 8 for the values of D1).

Table 8. 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 proxy power from the instantaneous CO2 mass flow

This section proposes a methodology to calculate the instant equivalent (proxy) 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.

[13] Reg. (EU) 2016/1628

[14] '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

"Veline" approach for LDV

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).

"Veline" approach for NRMM

A simplified approach is proposed for NRMM. 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 according to (Eq. 7):

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

Equivalent (proxy) power:

The equivalent (proxy) values of instantaneous power can then be calculated from the emitted CO_2 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/vehicles, very few were equipped with an ECU, in what follow the validity of the approach proposed above is tested in an SMB 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.

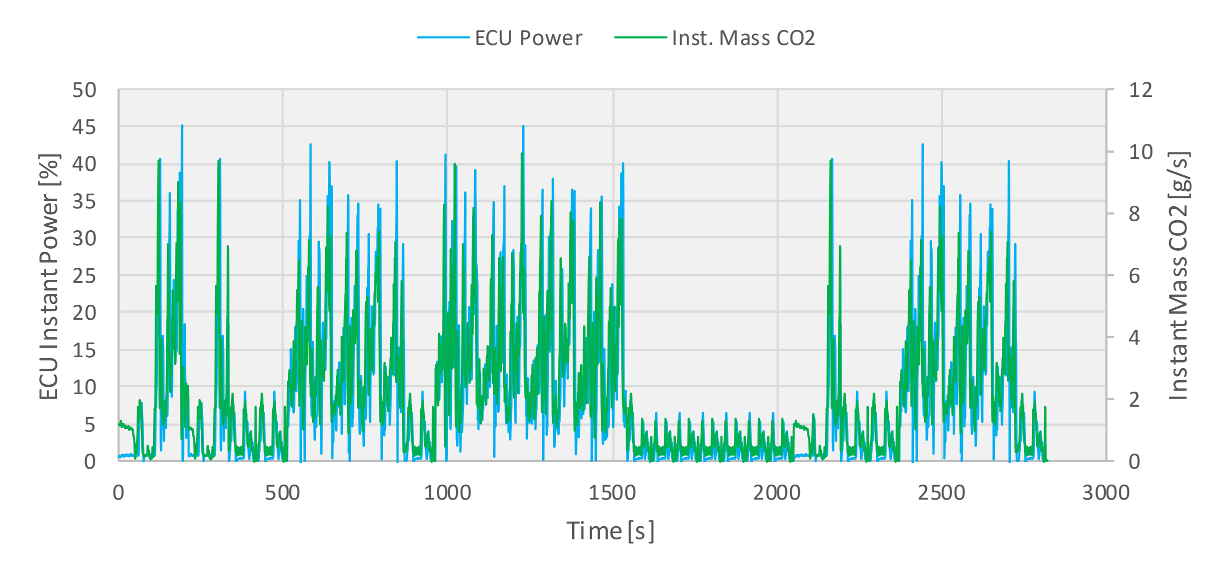
6.2.1 Comparison of events with P> 10% P_{max}

This example refers to a SMB vehicle with an engine whose maximun power is 68.9 kW at Type Approval. The NRSC reference work is 7.7753 kWh and the reference CO_2 is 6228.7 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 36 depicts the trace of Power and CO_2 for this machine/vehicle. It seems obvious that there is a linear relationship between both values.

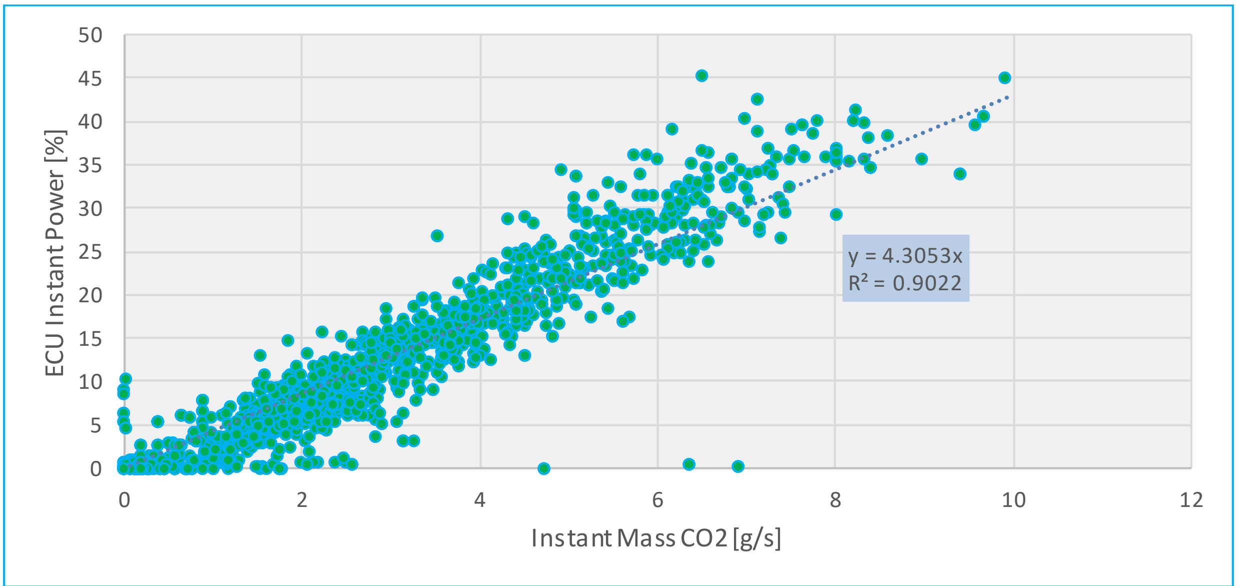
Figure 36. Power (from ECU) and CO2 trace for the tested vehicle



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 37 depicts such plot and the least squares analysis shows a coefficient of determination r^2 of 0,90 which indicates a strong correlation.

Figure 37. Linear correlation between ECU Power and CO2



Source: JRC Vela, 2018

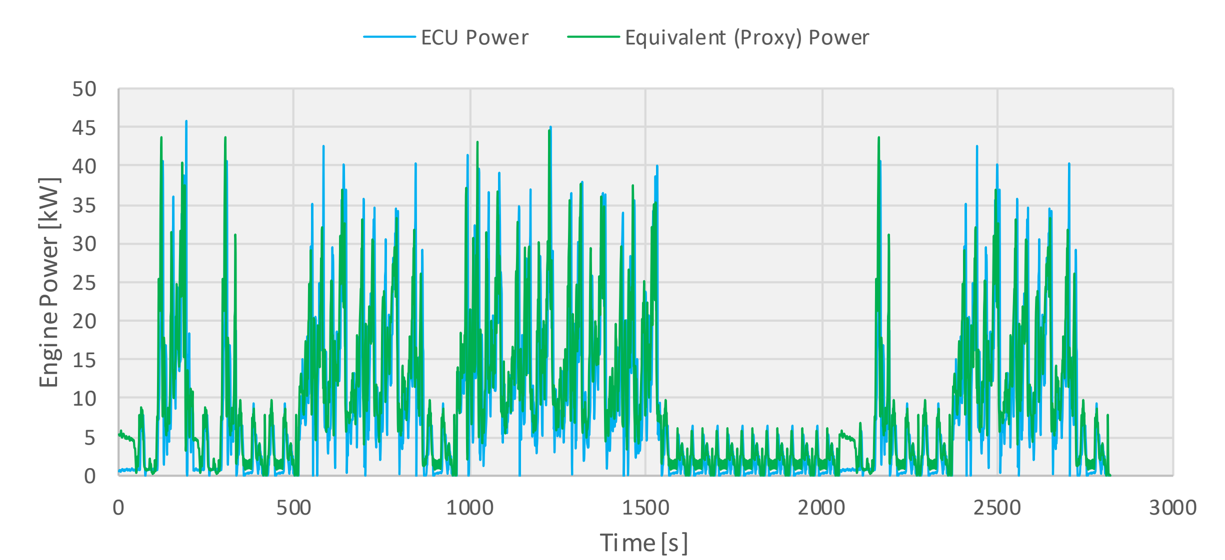
K can be calculated from the type approval values for this engine using Eq. 6: K= 801.09 g/kWh.

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

$$P_i = \frac{CO_{2_i}}{801.09} \cdot 3600 \ [kW]$$

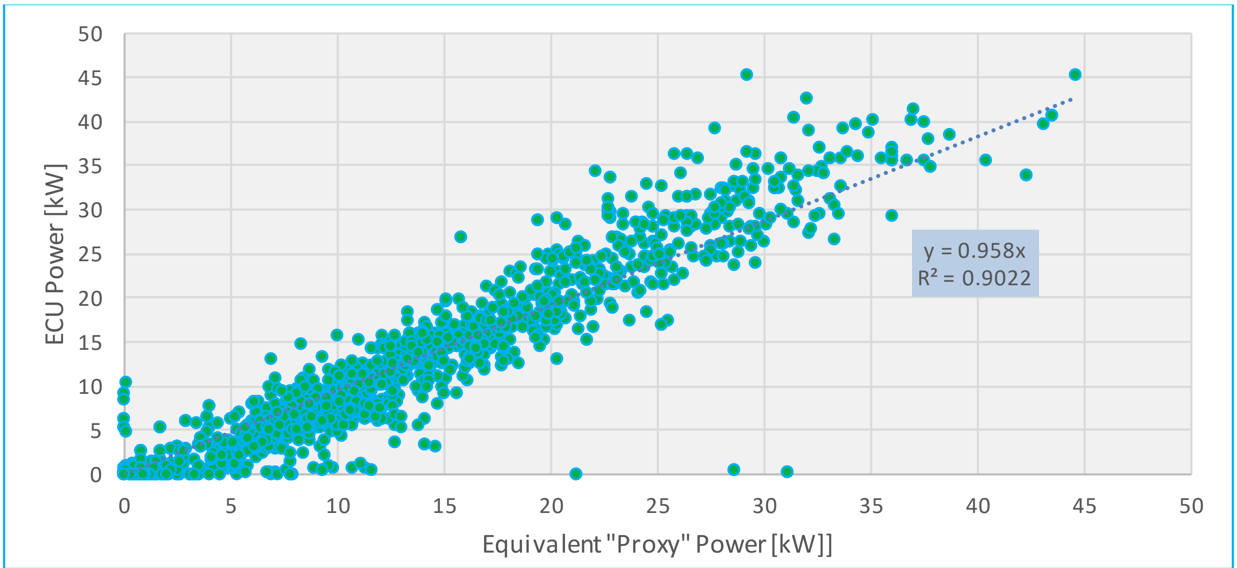
Figures 38 and 39 show the comparison between the power obtained directly from on-board measurements and the calculated values following the proposed methodology (proxy power).

Figure 38. Power measured by ECU vs Power calculated using the "Veline" approach (equivalent "proxy" power)



Source: JRC Vela, 2018

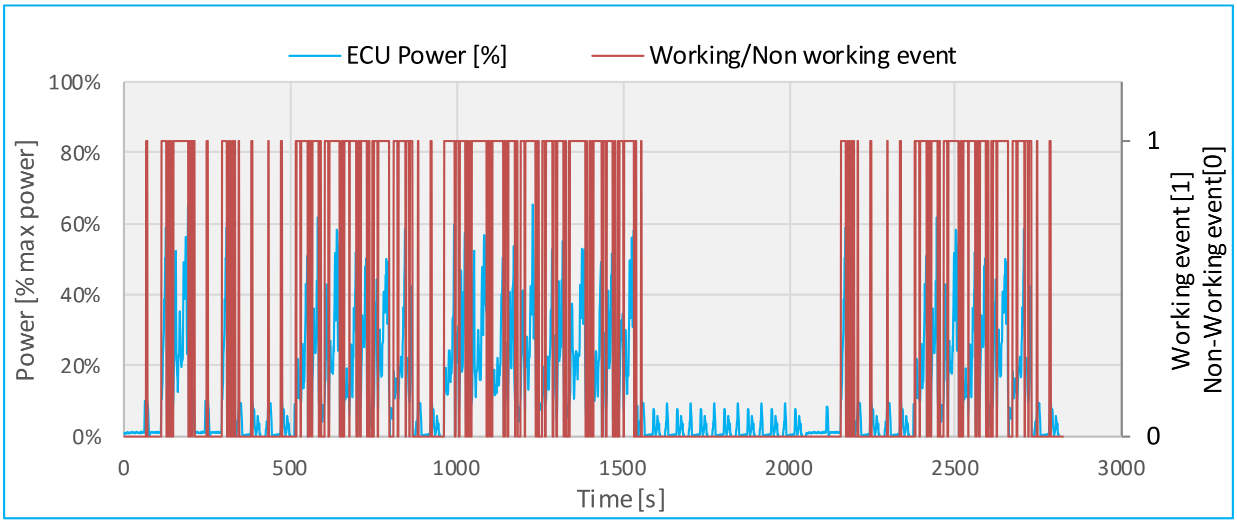
Figure 39. Linear correlation between ECU Power and the Power calculated using the "Veline" approach (equivalent "proxy" power)



Source: JRC Vela, 2018

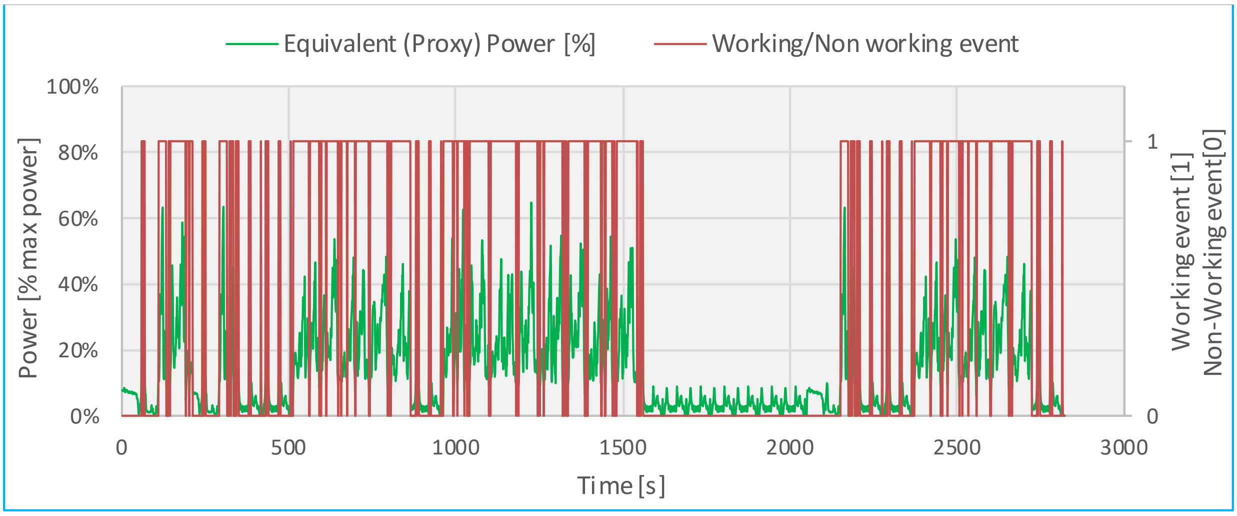
The main purpose of this methodology is the selection of working and not working events for the case where the CO2BW method (see section 7) is used as emission determination procedure. Therefore, it is important to compare the number of events below 10% of the maximun net power of this engine for the 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 40 and 41 for reference.

Figure 40. Baseline calculation setting (ECU power measured)



Source: JRC Vela, 2018

Figure 41. Baseline calculation setting (Equivalent engine power - calculated)



Source: JRC Vela, 2018

Table 9 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 9. Difference between the power "measured" by the ECU and the equivalent power calculated using the "Veline" approach (Baseline data – P < 10% P_{max} excluded)

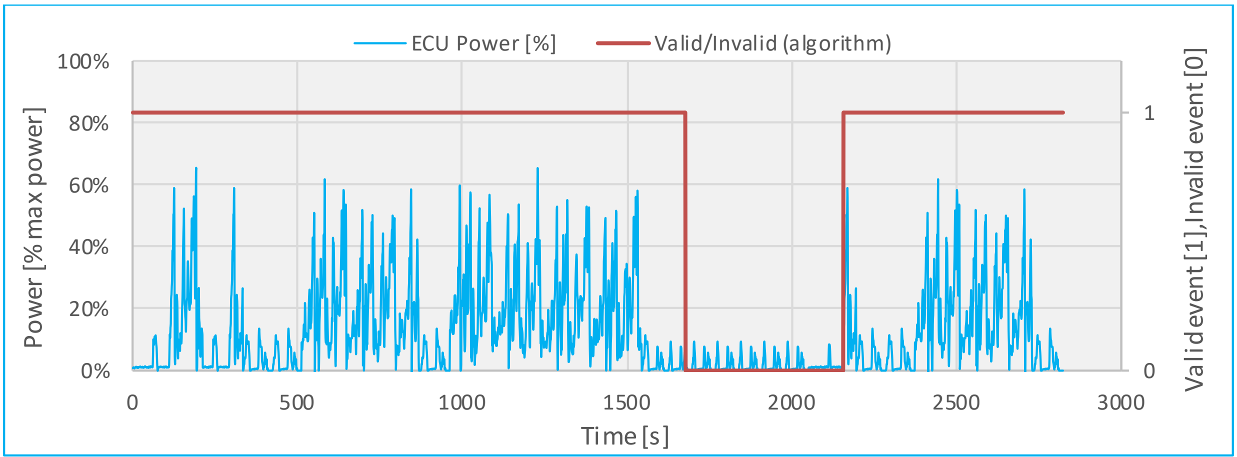
ESCLUSION: BASELINE (P <10% P_{max})	**ECU MEASURED**	**CALCULATED**
Total Number of events	2821	2821
Number of events with P<10% Pmax	1657	1375
% of non-working events	**58.74%**	**48.74%**

Source: JRC Vela, 2018

6.2.2 Calculation using the working/non-working event algorithm

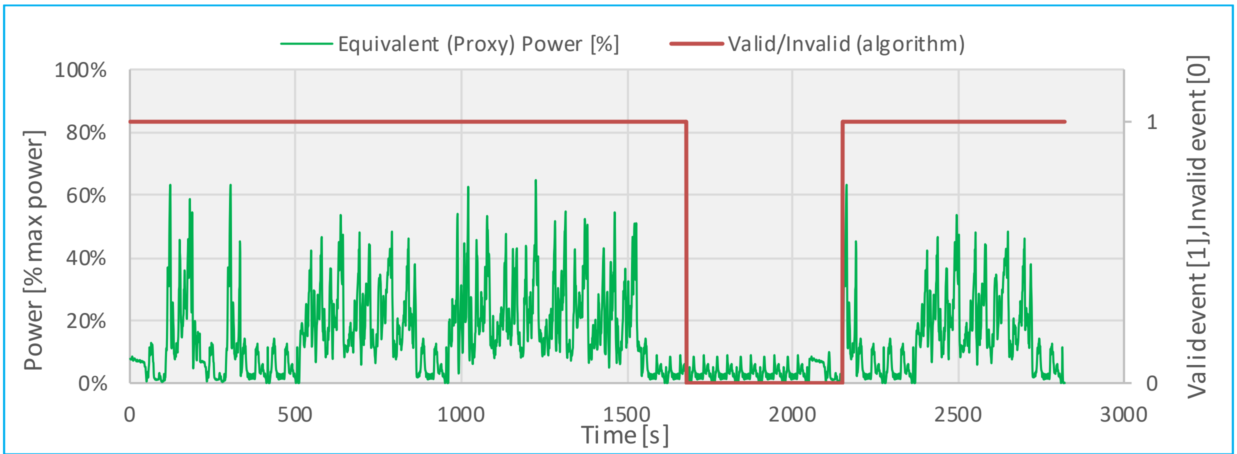
If we introduce the working/non-working events as defined above, taking into account the D0, D1, D2 and D3 parameters, the two power areas defined by the valid/invalid events line, become nearly equivalent. See Figure 42 and 43.

Figure 42. Valid/invalid events using the measured power (ECU)



Source: JRC Vela, 2018

Figure 43. Valid/invalid events using the calculated equivalent power



Source: JRC Vela, 2018

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.

EXCLUSION: BASELINE (P<10% Pmax) + WORKING/NOT WORKING EVENTS (D0/D1/D2/D3)	**ECU MEASURED**	**CALCULATED**
Total Number of events	2821	2821
Number of invalid events	477	471
% of invalid events	**16.91%**	**16.70%**

Source: JRC Vela, 2018

As it is reported in Table 10, the difference in percentage between the number of invalid events after applying marking algorithm is less than 0.25%.

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 44 and Figure 45 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 44. Measured power by ECU in example 1

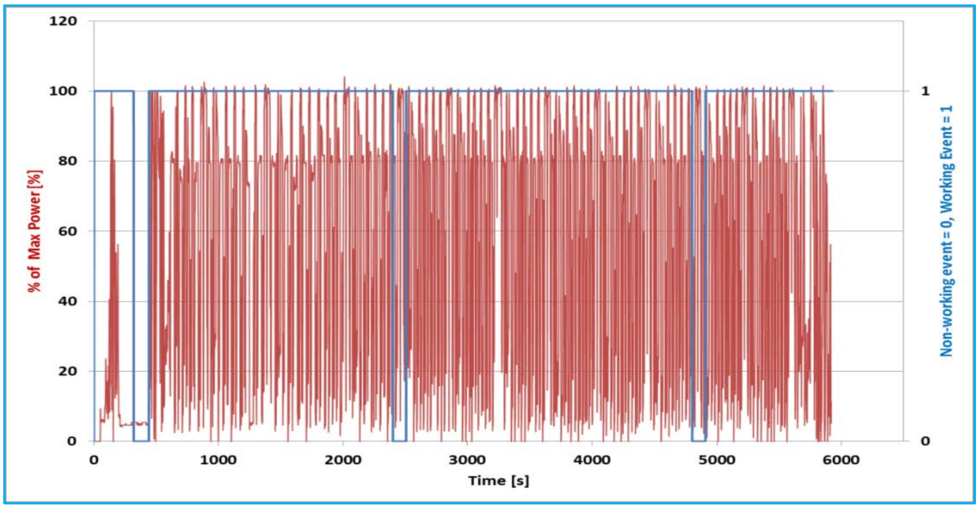
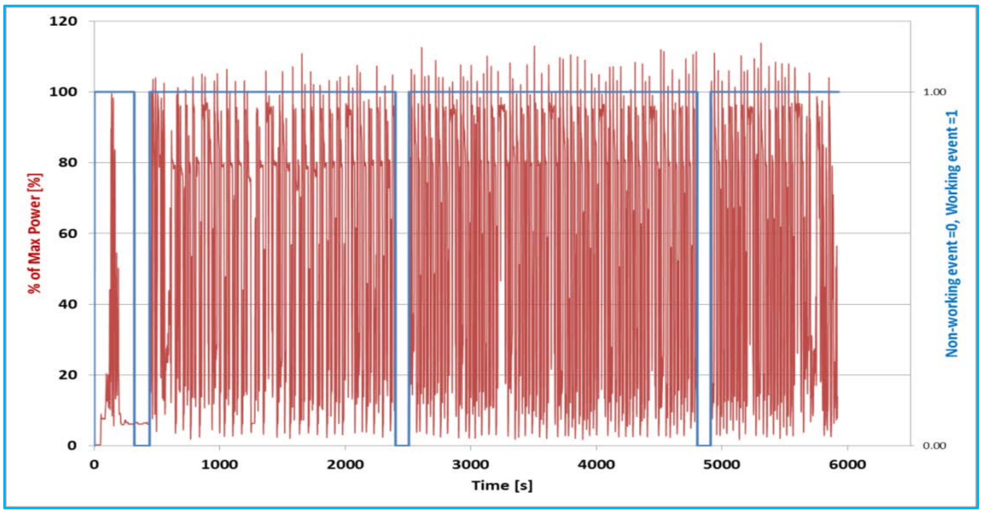


Figure 45. Calculated equivalent power in example 1



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 (EXAMPLE1)

EXCLUSION: BASELINE (P<10% Pmax) + 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%**

Source: JRC Vela, 2018

<u>EXAMPLE 2:</u>

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 46 and Figure 47 show, respectively the measured power broacasted by the ECU and the equivalent calculated power. Table 12 gives all the details from the numerical point of view.

Figure 46. Measured power by ECU in example 2

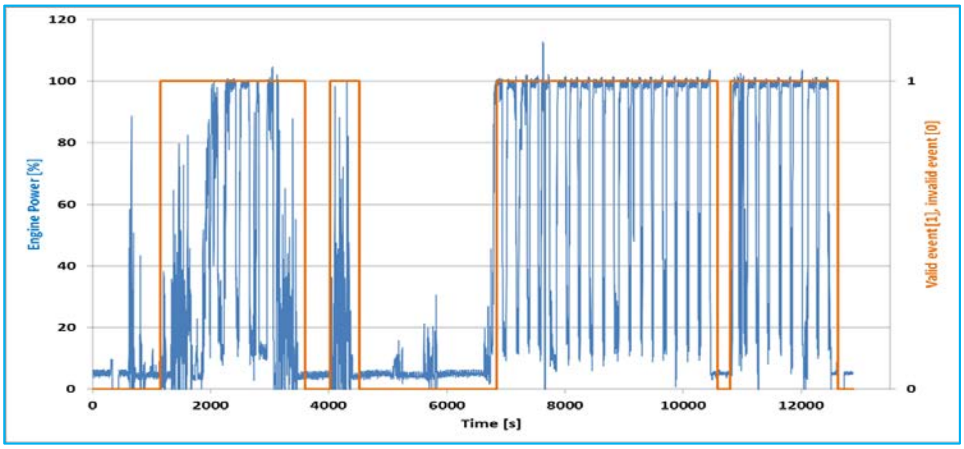
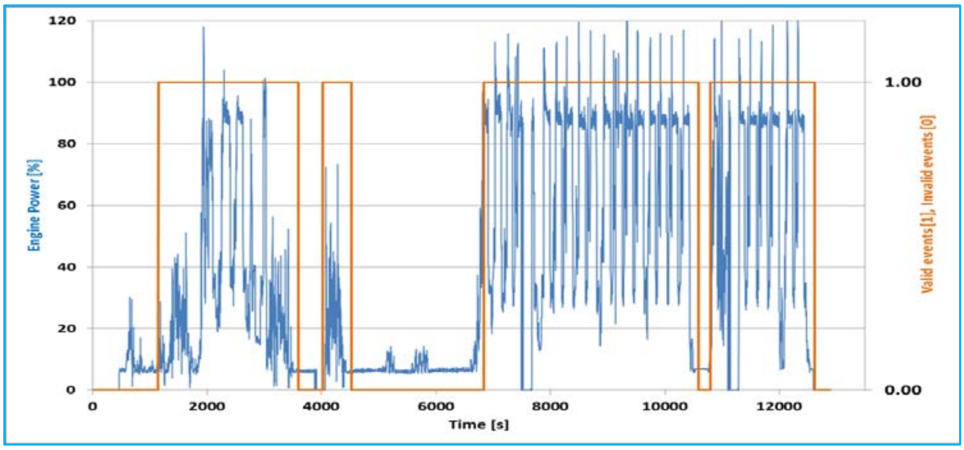


Figure 47. Calculated equivalent power in example 2



Source: JRC Vela, 2017

Table 12. 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%**

Source: JRC Vela, 2018

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).

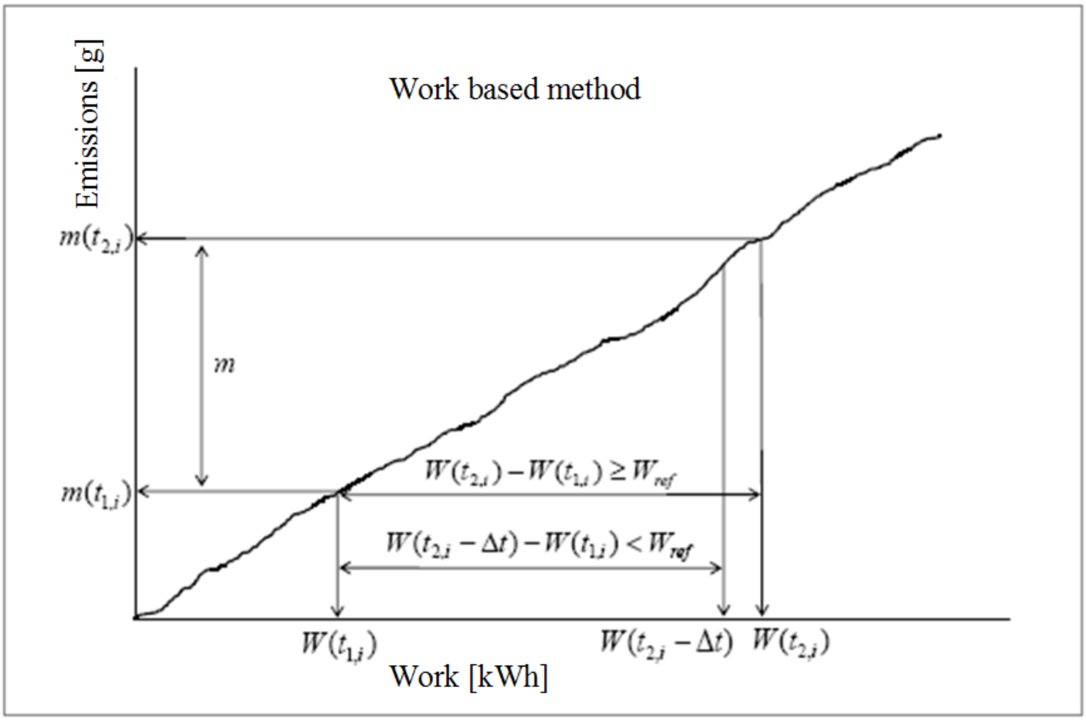
The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- 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 48. Work based method



Source: JRC Vela, 2018

The duration $(t_{2,i}-t_{1,i})$ of the i[th] 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 i[th] 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:

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

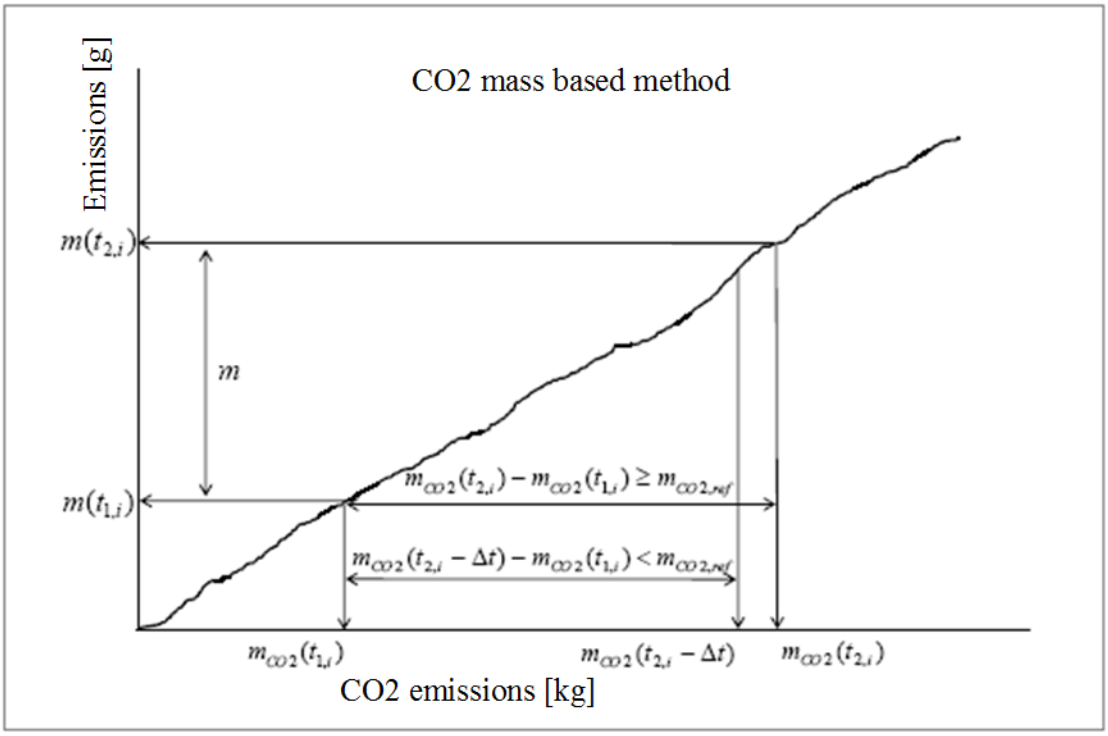
Where:

– 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 49. CO2 mass based method



Source: JRC Vela, 2018

The duration $(t_{2,i} - t_{1,i})$ of the i[th] 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 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. 90^{th} cumulative percentile.

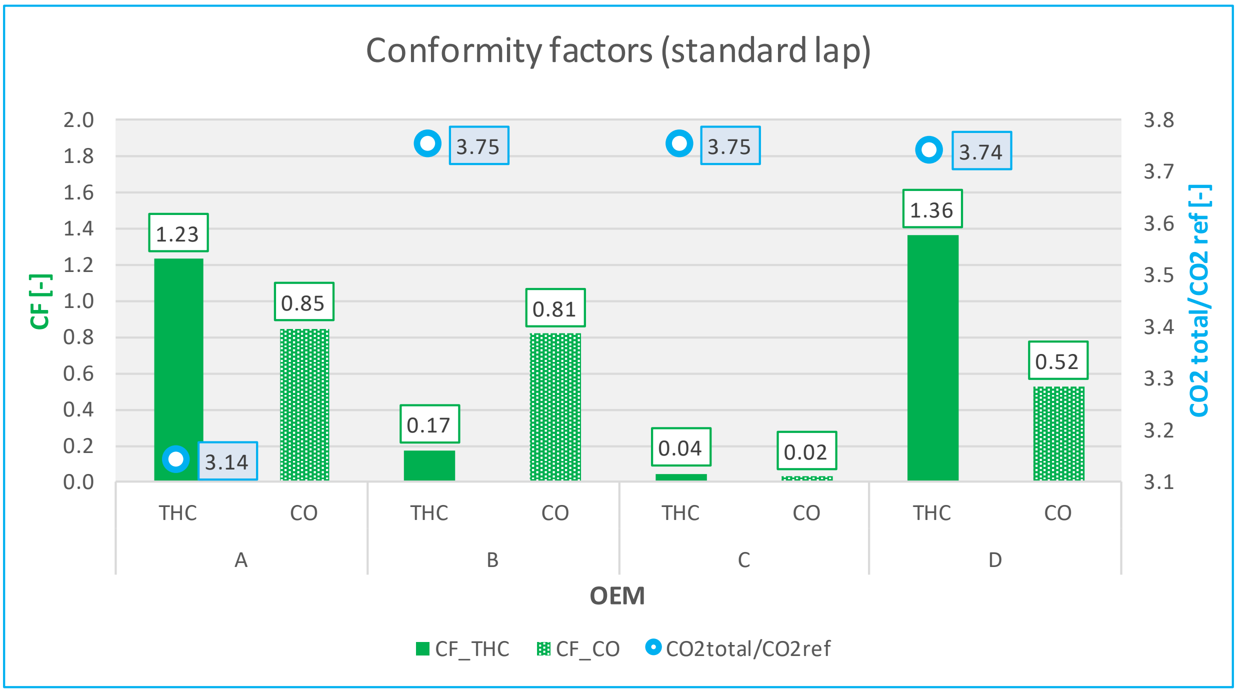
Steps 2 to 6 apply to all regulated gaseous pollutants.

8 Results

Figure 50 depicts the CF for the different SMB 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. The graph refers to a smooth driving behaviour, according to paragraph 3.5.5 compatible to the one used in the so called STD laps.

In order to obtain a suitable amount of data with different test characteristics, the tests have been combined either using a single work pattern (package of 7 laps), according to paragraph 3.5.5 or repeating that combination multiple times. All the tests in Figures 50 to 53 have a test length which vary within 3 to 4 time the total CO_2 in the homologation cycle. In this way, a direct comparison is possible.

Figure 50. THC and CO CFs value using a smooth driving behaviour



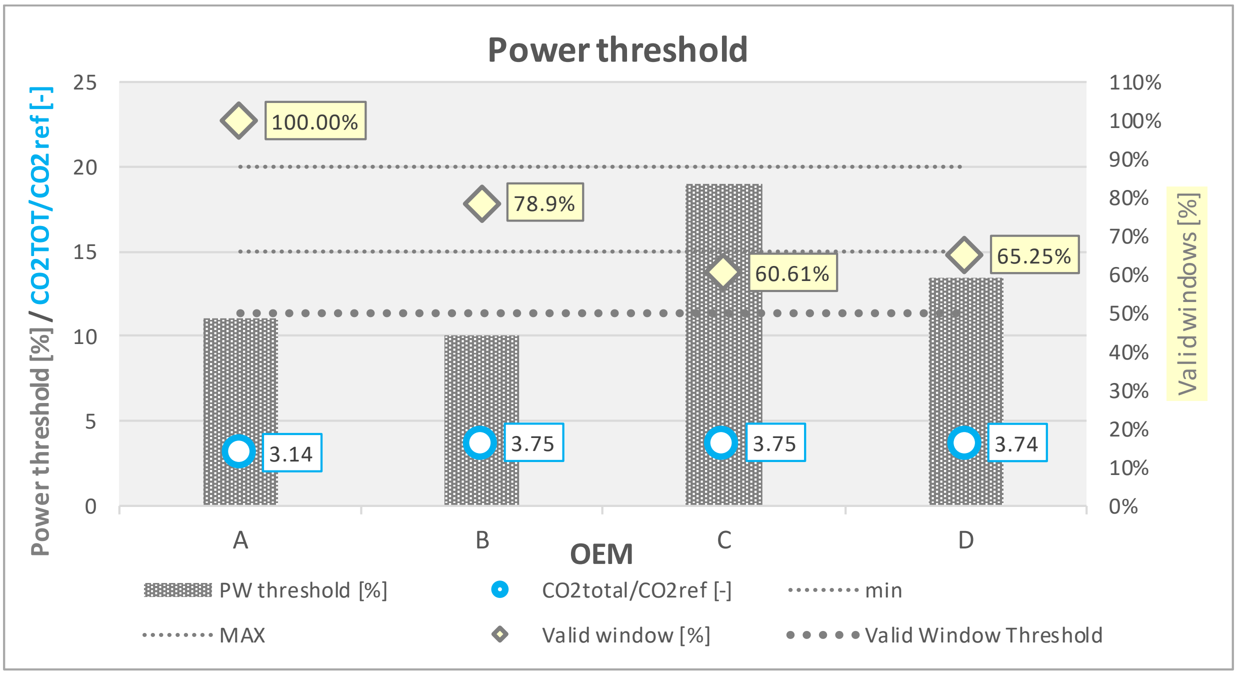
Source: JRC Vela, 2019

For all the tested vehicles, generally speaking, the standard lap(s) does not provide enough engine load and consequently it produces low CO_2 emissions which translates in very long windows to complete the reference CO_2 (window length > D_{max}). Therefore, in these circumstances many windows are invalid and the test could be declared void as it does not reach the 50% of valid windows (see section 7.2.2), which represents the threshold to judge the test as valid. Or in other words, the instant power during in-service is far from the maximum power. In fact, some engines seem to be overpowered for their normal in-service operation.

As shown in Figure 51, to have enough number of valid windows (>50%), it is necessary to strongly decrease the percentage threshold of P_{max}. To obviate the problem and approach similar to the In-Service Conformity procedure for heavy duty vehicle could be adopted[15]; i.e. the possibility of decreasing in steps of 1% the Power Threshold (PT) from 20% till 15% of the maximum power.

[15] Reg. (EU) 582/2011

Figure 51. Power threshold to obtain more than 50% valid windows for a smooth driving behaviour

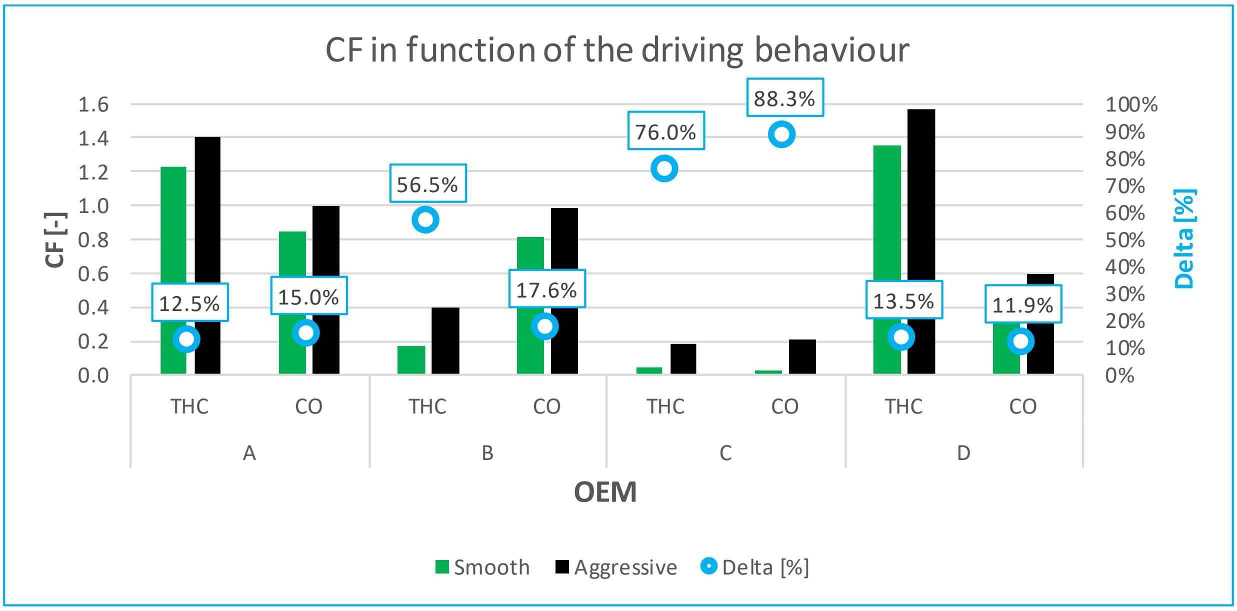


Source: JRC Vela, 2019

In the following, we turn our attention to the influence of different driving behaviour.

Figure 52 depicts the CFs with two different driving behaviour: smooth (equivalent to a standard lap sequences) and aggressive (combination of high and transient laps).

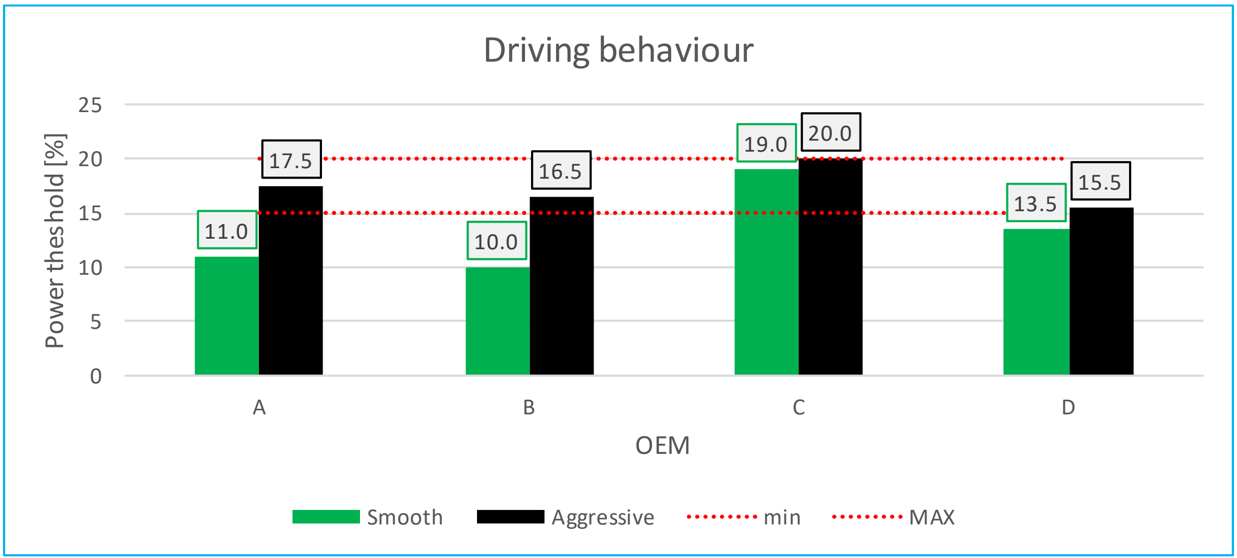
Figure 52. Conformity Factor for pollutant emission for the different SMB NRMM engines.



Source: JRC Vela, 2019

In the graphs are compared the data in which the VALID/INVALID algorithm has been applied (considering also the cold start) for two different driving modalities: smooth or aggressive. The percentage difference is also depicted.

Figure 53. Power threshold percentage for different driving behaviour (smooth and aggressive)



Source: JRC Vela, 2019

Using a smooth driving behaviour (see green histogram in Figure 53), in 3 vehicles out of 4 it is not possible to reach the number of valid windows (above 50%) using a power threshold within 15-20% of the maximum power. To exceed the 50% limit, it is necessary to decrease the power threshold less than 15% (between 10 to 13.5%). Applying a driving style more aggressive we have no problem in all the tested vehicles in remaining between a suitable range of Power Threshold (PT).

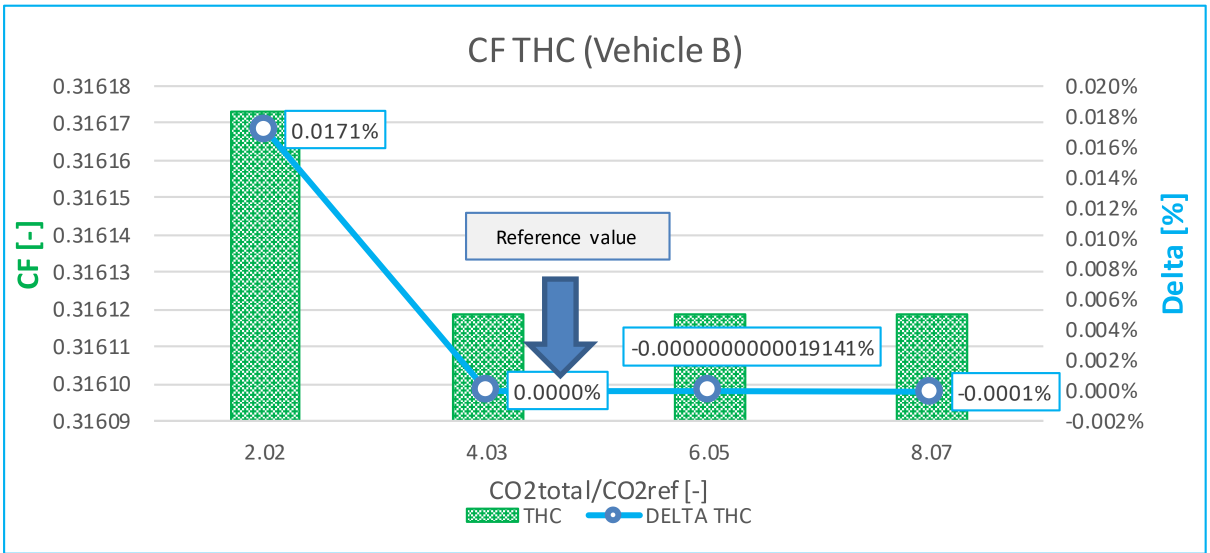
A deeper and exhaustive analysis of the impact of different driving behaviour will be addressed in Chapter 9.

8.1 Test length as a function of accumulated reference parameter

In this section, 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) is discussed.

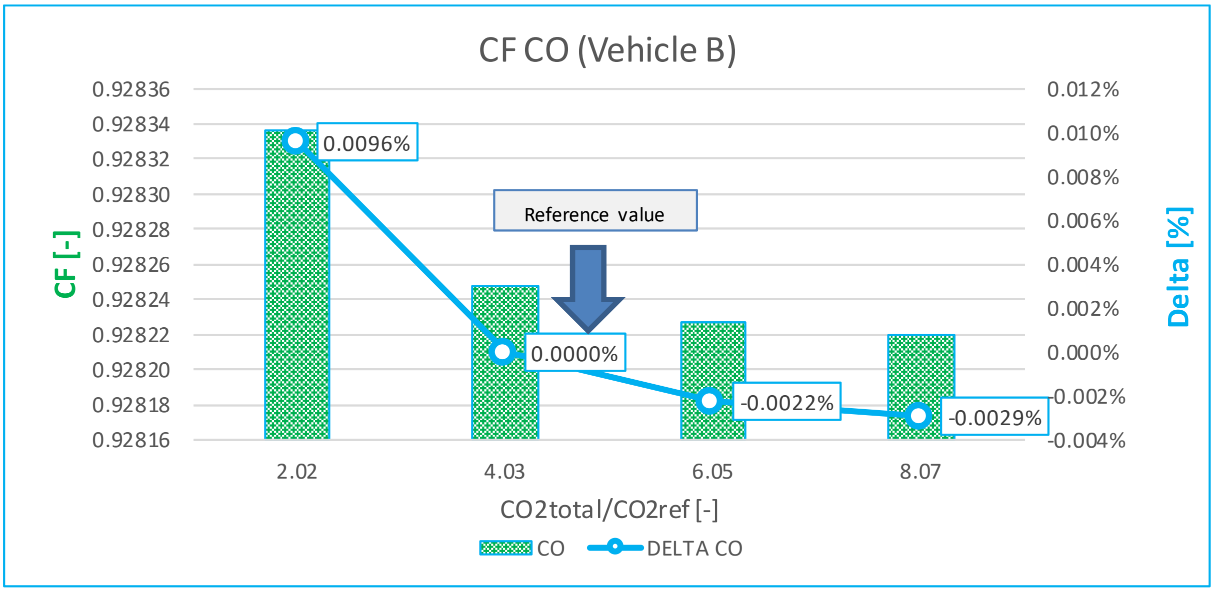
The evaluation has been performed using only vehicle B.

Figure 54. CF THC trend in function of CO_2/CO_2 reference ratio (Vehicle B).



Source: JRC Vela, 2019

Figure 55. CF CO trend in function of CO_2/CO_2 reference ratio (Vehicle B)



Source: JRC Vela, 2019

This study (Figures 54 and 55) indicates that a reasonable test length will be one with an equivalent duration between 3 to 5 time the reference value, as the CF value does have only an imperceptible variation when compared with an equivalent test length between 5 and 7 times the reference value. The blue line represents the percentage variation assuming as reference the test with the CO_2total/CO_2reference ratio in the range 3-5.

In table 13 the characteristic of the test shown in Figure 54 and 55 are summarized

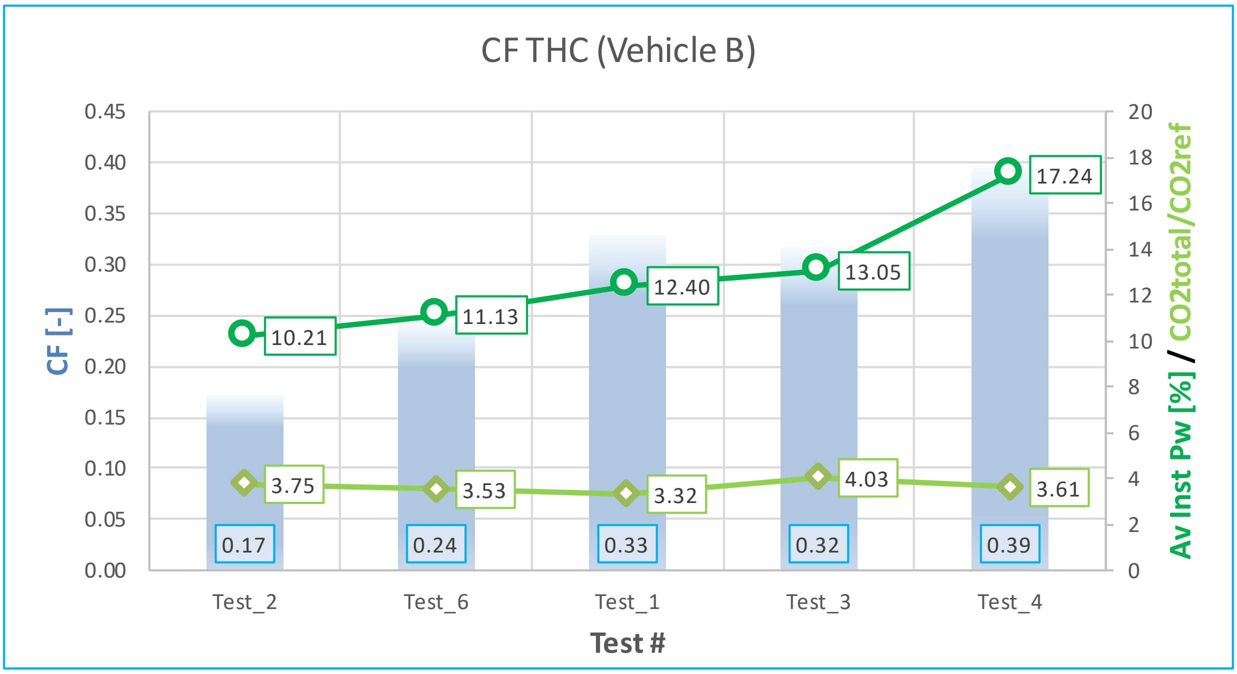
Table 13. Reference data of figures 54 and 55

Vehicle	Test	Test sequence	Cold Start [Y/N]	Test Duration		PT	CO2total/CO2ref	Valid Windows	CF	
				[km]	[min]	[%]	[ratio]	[%]	THC	CO
B	Test_1	4+7+5+7+6+7	N	83.77	104.53	13	**2.02**	52.00%	0.3161731	0.9283364
	Test_2	4+7+5+7+6+7(*2)	N	167.54	209.08	13	**4.03**	50.86%	0.3161189	0.9282474
	Test_3	4+7+5+7+6+7(*3)	N	251.32	313.63	13	**6.05**	50.61%	0.3161189	0.9282266
	Test_4	4+7+5+7+6+7(*4)	N	335.09	418.18	13	**8.07**	50.51%	0.3161187	0.9282203

Source: JRC Vela, 2019

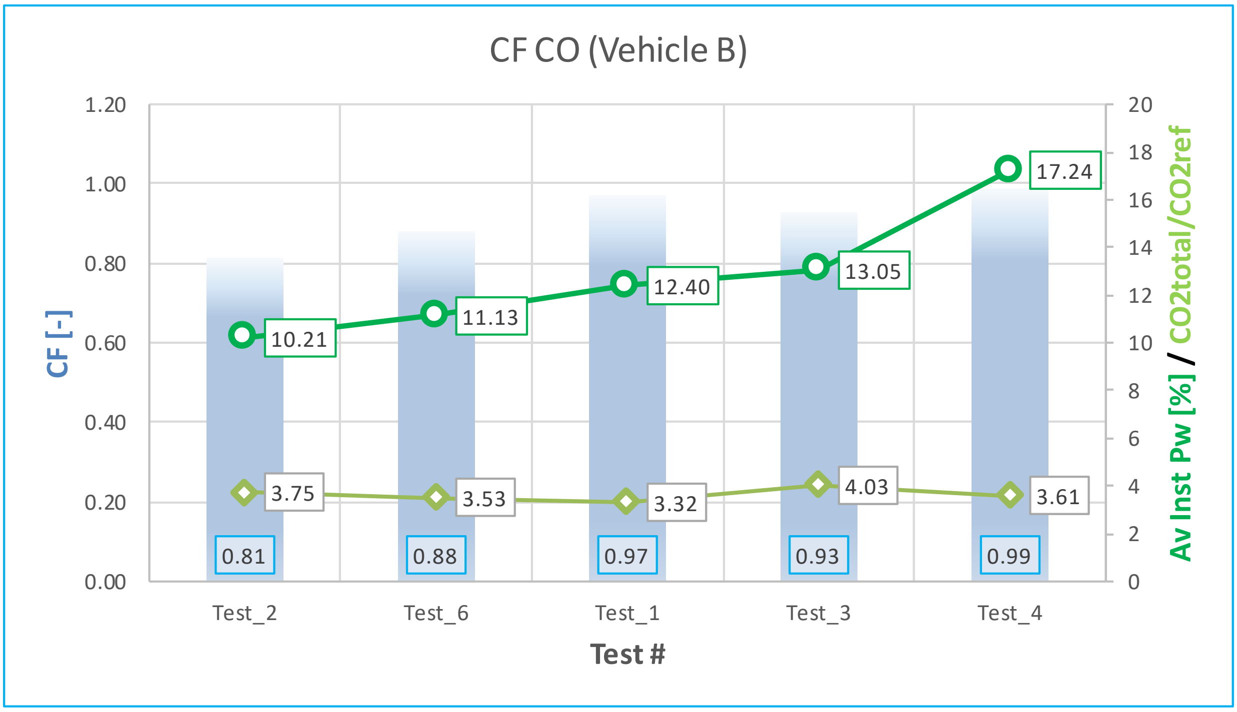
On the other hand, the CFs values (see Figures 56 and 57) grow proportionally with the increasing of the average instantaneous power (emerald green line), more than with the length of the test.

Figure 56. CF THC trend in function of the average instantaneous power. CO_2/CO_2 reference ratio is presented in increasing order. It remains constant for test 1-6-4-2-3.



Source: JRC Vela, 2019

Figure 57. CF CO trend in function of the average instantaneous power. CO_2/CO_2 reference ratio is presented in increasing order. It remains constant for test 1-6-4-2-3.



Source: JRC Vela, 2019

In table 14 the characteristic of the test shown in Figure 56 and 57 are summarized. The test combination (*) legend is the following:

S = test with a smooth driving behaviour

I = test with an intermediate driving behaviour

A = test with an aggressive driving behaviour

Table 14. Reference data of figures 56 and 57

Vehicle	Test	Test sequence combination(*)	Cold Start [Y/N]	Test Duration		PT	AVERAGE PW	CO2total/CO2ref	Valid Windows	CF	
				[km]	[min]	[%]	[%]	[ratio]	[%]	THC	CO
B	Test_2	S+A	N	179.73	248.18	10	10.21	3.75	78.85	0.1715	0.8135
	Test_6	I	N	160.69	214.47	10.5	11.13	3.53	56.75%	0.2421	0.8805
	Test_1	S+A	Y	141.65	180.75	11.5	12.40	3.32	70.98%	0.3285	0.9700
	Test_3	I	N	167.54	209.08	13	13.05	4.03	50.86%	0.3161	0.9282
	Test_4	A	N	129.47	141.65	16.5	17.24	3.61	100.00%	0.3946	0.9872

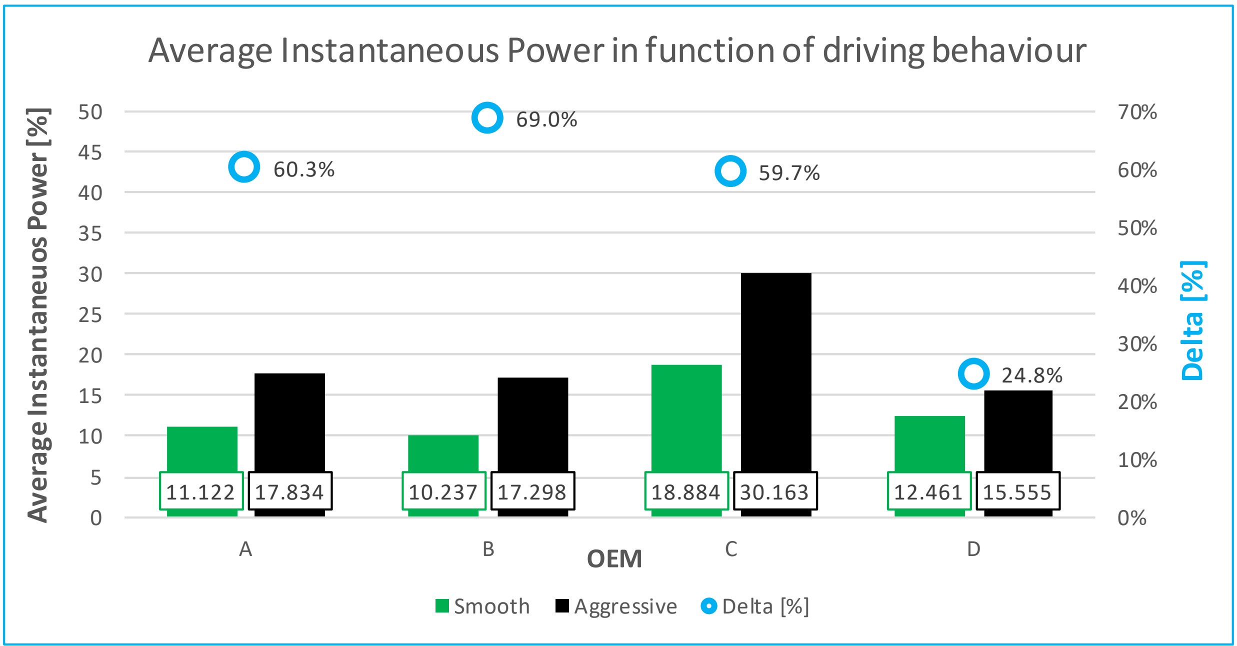
Source: JRC Vela, 2019

9 Driving behaviour impact

During the results analysis in chapter 8, we highlighted the importance to use the vehicle/machinery in a power range that is in line with the maximum power that the engine can deliver. In fact, if the in service power is too low, the risks to have an invalid set of data is quite high.

As mentioned in Figure 51, using a smooth driving behaviour in 3 vehicles out of 4 it is not possible to reach the number of valid windows using a power threshold within 15-20% of the maximum power. To exceed the 50% limit, it is necessary to decrease the power threshold at least at 13.5% for vehicle D. The decreasing is even more pronounced for vehicle A and vehicle B with 11% and 10% respectively. Instead, for vehicle C the minimum threshold valid window (50%) is reached also with a slight decrease in the power threshold, equal to 19%. This because, even with a smooth driving behaviour, vehicle C used higher percentage of engine power in the entire test. Nevertheless, applying a driving style more aggressive we have no problem in all the tested vehicles in remaining between a suitable range of Power Threshold (PT). In particular, this issue is more evident for vehicles equipped with an overpowered engine. See Figure 58.

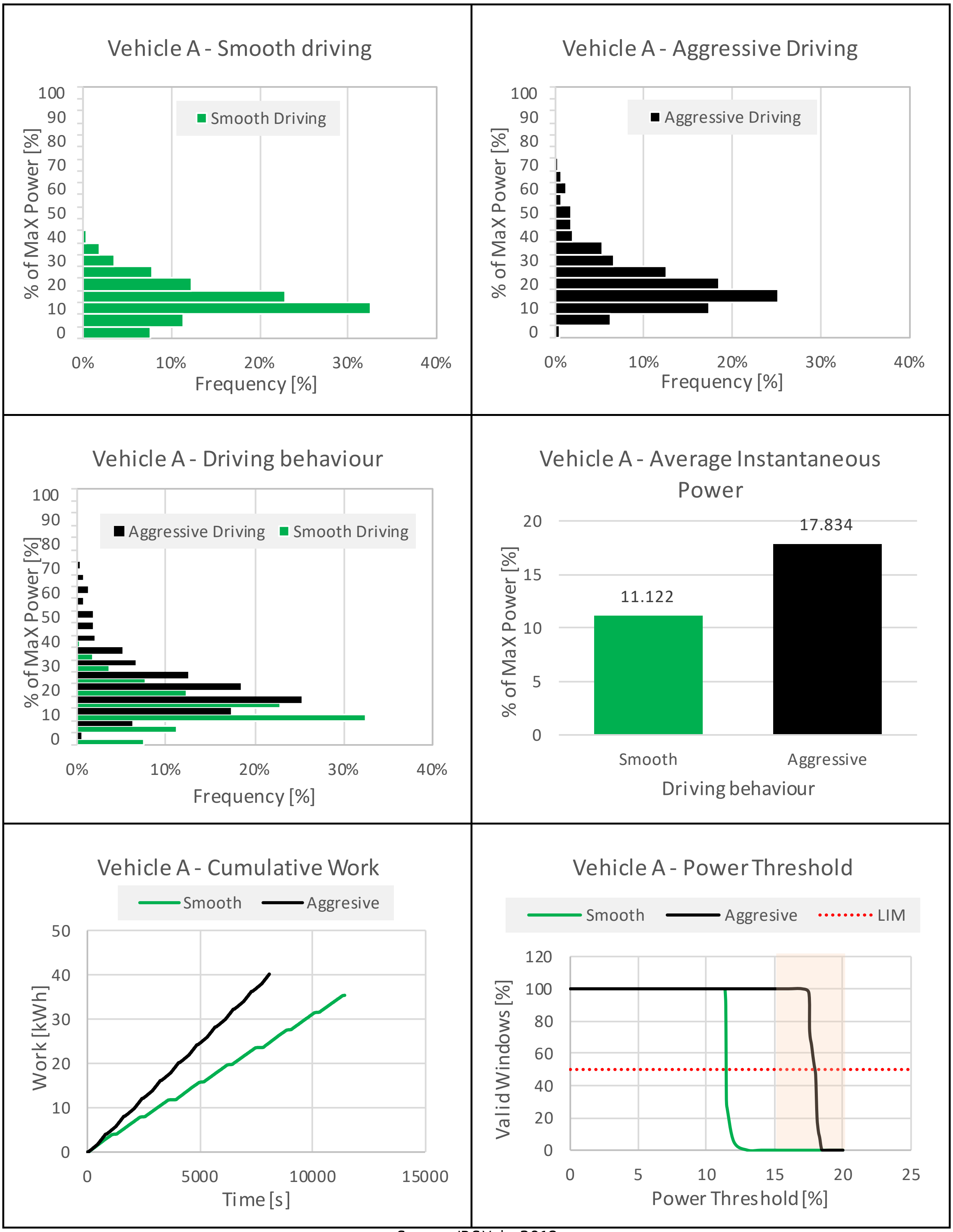
Figure 58. Average instantaneous power as percentage of the maximum engine power. Comparison using different driving behaviour



Source: JRC Vela, 2019

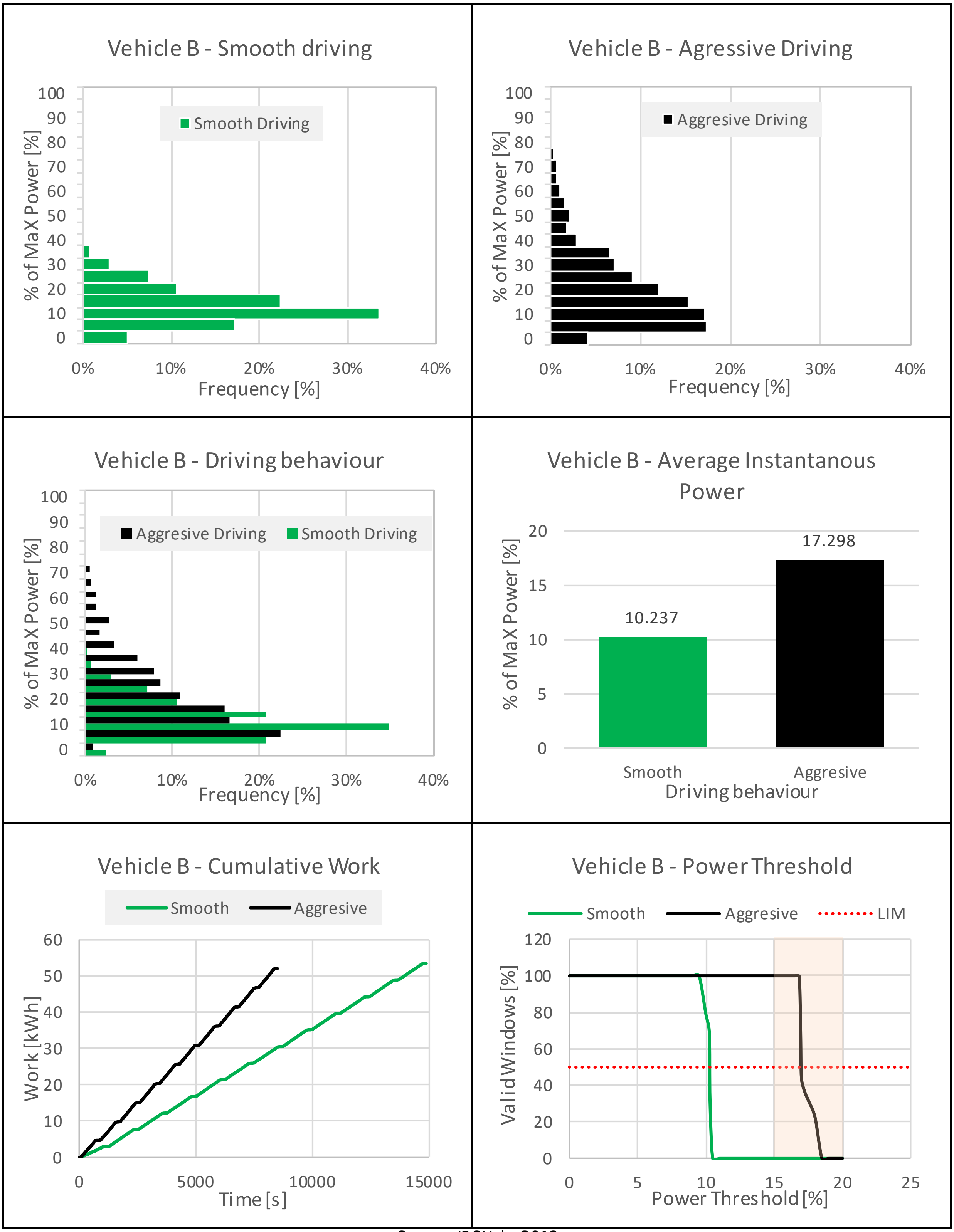
Figures 59 to 62 depict a direct comparison between the two driving styles for each vehicle. In all the figures the smooth driving style is shown in green, while the aggressive one is depicted in black. Vehicle D does not have a real aggressive cycle; we can consider the test as an intermediate situation (no high speed laps has been performed for this vehicle). In all cases an increase on the average instant power (to about 17%) of the test translate to having sufficient valid windows (> 50%) in the bracket of a PT between 15 to 20% and hence making the test valid.

Figure 59. Impact of different driving behaviour (smooth/aggressive) on vehicle A



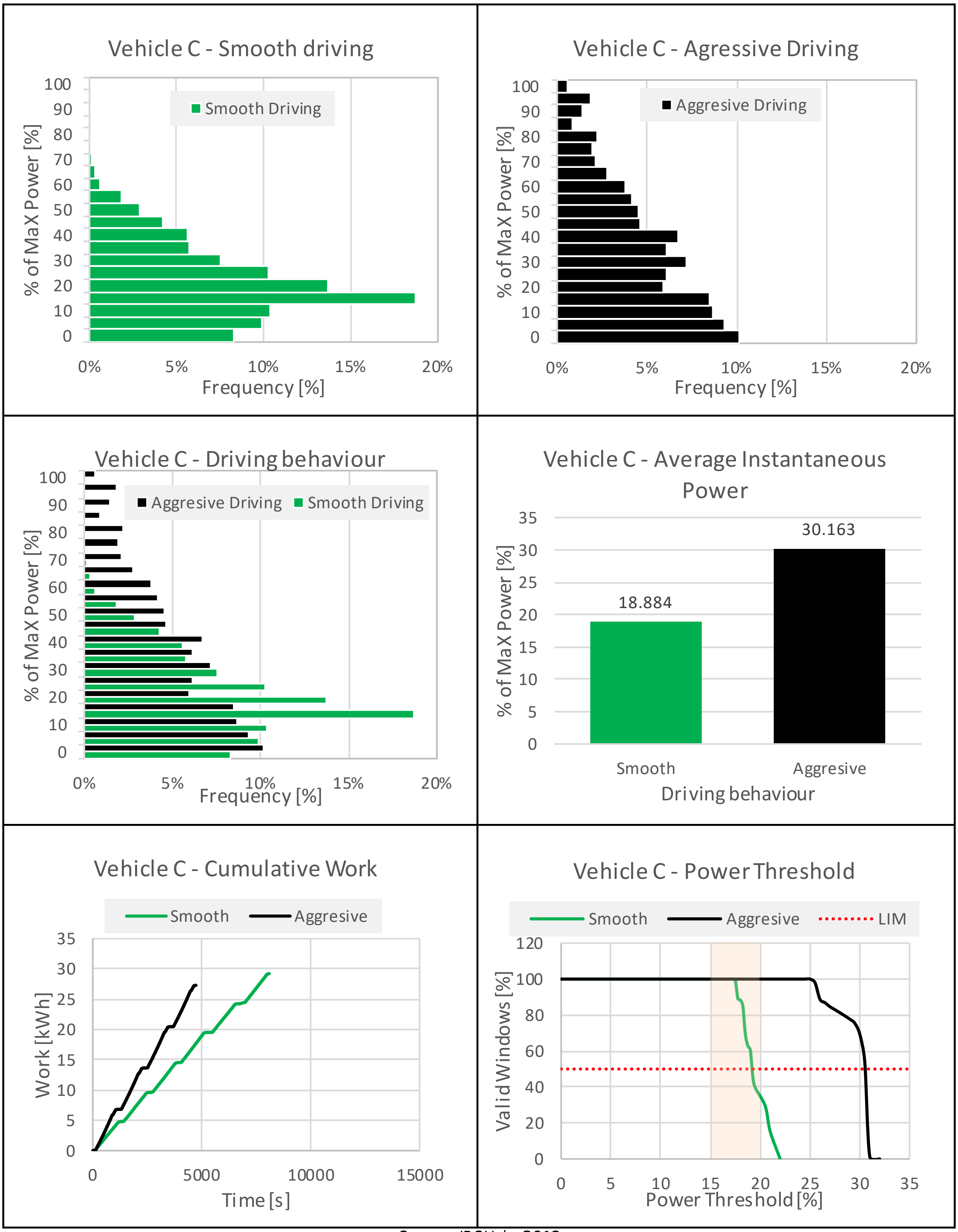
Source: JRC Vela, 2019

Figure 60. Impact of different driving behaviour (smooth/aggressive) on vehicle B



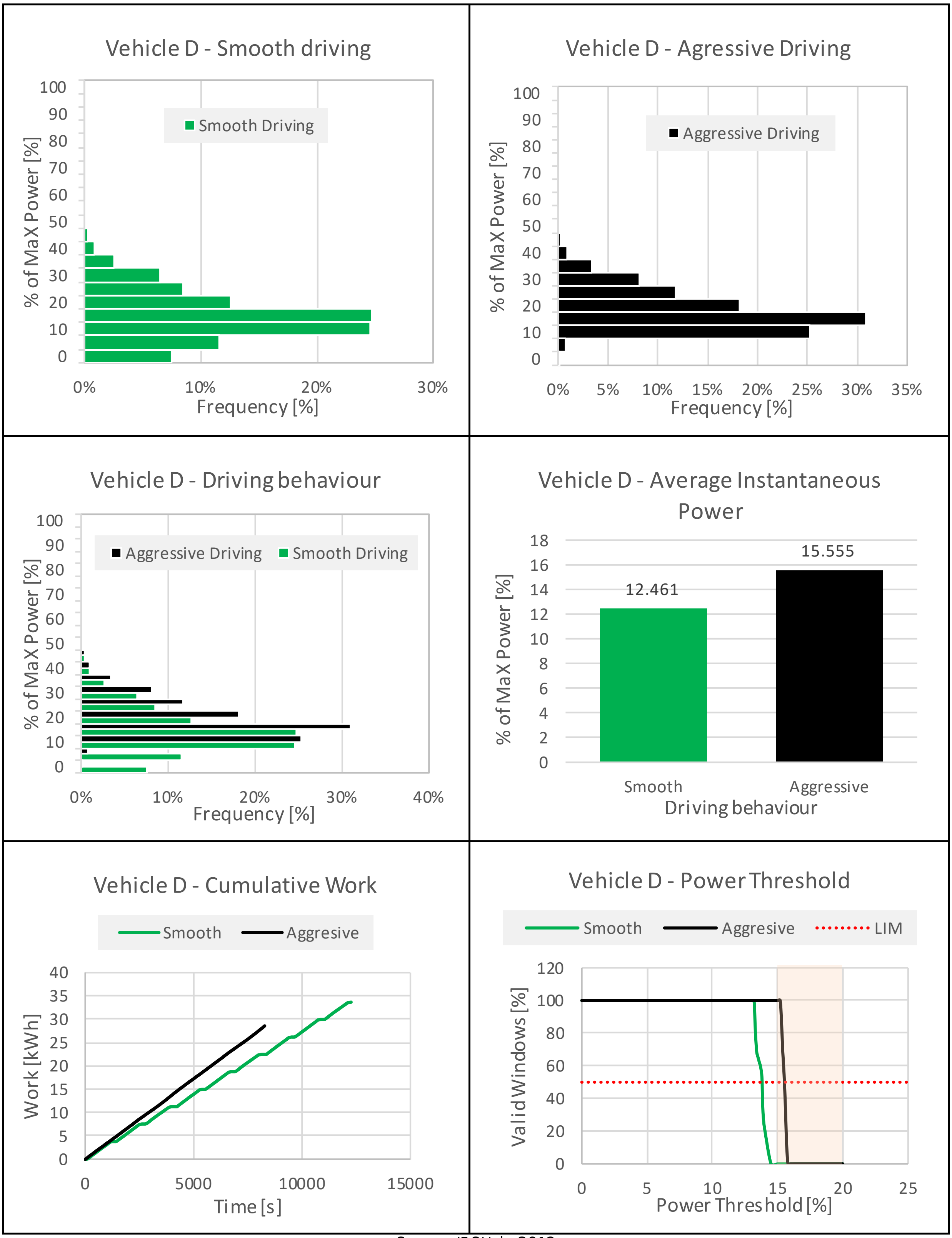
Source: JRC Vela, 2019

Figure 61. Impact of different driving behaviour (smooth/aggressive) on vehicle C



Source: JRC Vela, 2019

Figure 62. Impact of different driving behaviour (smooth/aggressive) on vehicle D



Source: JRC Vela, 2019

9.1 Minimum Power requirement

As clearly showed by the Figure 58, as well in the analysis of the difference of driving behaviour done vehicle by vehicle (reported in Figures 59 to 62), it is necessary to use more power during the In-Service tests, not to have the risks to invalidate the test because it is not possible to create a sufficient number of valid windows.

In particular, this fact affects the vehicles with an overpowered engine. If the difference between the maximum power declared by the manufactures at mode1 of the Type Approval test (NRSC Test cycle type H for SMB- see Table 6) and the maximum of the average instantaneous power during the in-service test is quite large, then the probability to fail increase proportionally.

In our testing campaign, an increasing of around 60% (corresponding to have about 17% of the P_{max}) in the average instantaneous power during the tests is recommendable. In the above mentioned case, the STD laps (which foreseen a smooth driving attitude) has been considered as the reference test pattern.

To reduce this distance, we have only two practicable ways:

1. Downsizing the engine
2. Increased the average instantaneous power during In-service tests

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[16] for its application to test in-service (ISM) internal combustion engines installed in NRMM category SMB-v-1. 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 by the use of a trailing sleigh 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 SMB-v-1 the measurement of the exhaust mass flow using flow meters (EFM) is particularly complicated due to exhaust exit location (downward, close to snow surface). To overcome this issue, it is necessary to measure the exhaust mass flow using an indirect way. In the snowmobile case, the best solution is represented by measuring the fuel flow using a Fuel Flow Meter (FFM) based on positive displacement volumetric principle. Adopting this solution, a pre conditioning of the entire fuel line is mandatory to avoid the condensation of the fuel due to the low operating temperature. Another viable road is to use the fuel flow signal calculated by the ECU, providing a validation of its accuracy during the Type Approval (TA) test. This oblige the OEM to equip all the vehicles with a suitable, precise and accurate ECU.

Technical solutions have been found for both the installation of PEMS on board of NRMM SMB-v-1 vehicles/machineries and the calculation of the exhaust flow with an acceptable uncertainty. To that extend the following recommendations are made:

1. To measure and record the Fuel Mass Flow either by an external fuel flow meter or by the broadcast of the fuel flow by the on-board ECU. The use of Fuel Mass Flow meters based on positive displacement volumetric and fuel conditioning is essential for mechanically controlled engines.
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 (the use of a dedicated sleigh). 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 SMB-v-1 undergoes in the field, although care needs to be exercise to operate in a range of power that will ensure validity of the test, i.e. the difference between the power engaged in the test and the maximum power installed in the snowmobile cannot be very large. It is recommended to engage during the ISM test an average of about 20% of the maximum power of the installed engine.

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 (proxy) 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.

In order to largely reduce the possibility of having many of the tests invalid because not reaching the 50% valid window threshold (valid averaging windows are the averaging windows whose average power exceeds the power threshold of 20 % of the reference power), it is recommended that, as it is the case for heavy duty vehicles (Reg. (EU) 582/2011[17]), if the percentage of valid windows is less than 50 %, the data evaluation shall be repeated using lower power thresholds. The power threshold would be reduced from 20% in steps of 1 % until the percentage of valid windows is equal to or greater than 50 %. The test would be considered void if the percentage of valid averaging windows is less than 50 % at a power threshold of 15%.

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.

[16] Reg. (EU) 2017/655

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

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

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
EC	European Commission
EFM	Exhaust Flow Meter
EU	European Union
FFM	Fuel Flow Meter
IMSA	International Snowmobile Manufacturers Association
ISM	In-Service Monitoring (Programme)
JRC	Joint Research Centre
MAW	Moving Average Window
MTU	Michigan Technological University
NOx	Oxides of Nitrogen
NRMM	Non Road Mobile Machinery
OEMs	Original Equipment Manufacturer
PEMS	Portable Emission Measurement System
PT	Power Threshold
SMB	Snowmobile
SMEs	Small and Medium Enterprises
TA	Type Approval
THC	Total HydroCarbons, also referred to as HC
TWC	Three-way Catalyst
VELA	Vehicle Emission LAboratory
WAW	Work based Average Window

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Annexes

Annex 1. Stage V emission limits by engine category

Table 15. 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. Sleigh characteristics

The sleigh used during the testing campaign may slightly differ from the characteristic of the one reported in the below light-weight sleigh project.

Figure 63. In-Service Light-Weight Sleigh Project

In-Service Emissions Light-Weight Sleigh Project

The In-Service Emissions event was developed by Michigan Tech to gather actual field emissions data, complementing the laboratory emissions test. Sensors Inc., in Ann Arbor, Michigan, donated a portable emissions measurement system (PEMS) for this event. The five-gas analyzer measures total hydro-carbon (THC), carbon monoxide (CO), and oxides of nitrogen (NOx) while the snowmobile is on the trail. The PEMS sits on a sleigh with battery power and a snorkel to reach to the exhaust sampling port on the sled.

Since the PEMS measures constituent concentrations, it is also necessary to measure the flow rate of either the exhaust or the fuel. Through a generous donation from Re-Sol, of Auburn Hills, Michigan, a fuel flow system allows us to make this measurement. The Re-Sol system uses coriolis flow meters to measure mass flow. Knowing the density of the fluid, the flow rate can be calculated.

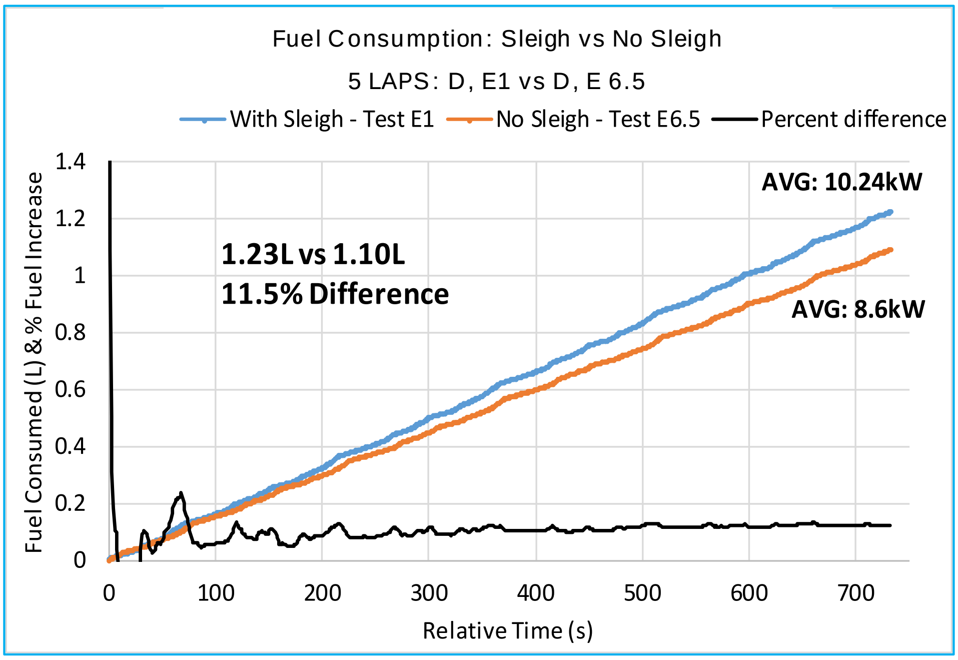
This year another generous donation from Re-Sol has allowed us to reduce the weight of the sleigh by 200 pounds. Previously, the weight of the sleigh was equivalent to two heavy riders. This lighter-weight sleigh should give us results more consistent with lab emissions tests.

Source: MTU, 2018

Annex 3. Impact of Sleigh on Fuel Consumption

MTU performed some tests to study the impact of the trailing sleigh on fuel consumptions. The fuel consumption reported is that broadcast by the on-board ECU. They found that the impact could be important, reporting an increase of 11,5% and f 28,6% in fuel consumption for vehicles powered with a 2-stroke and 4-stroke engine respectively. The different test conditions might also have had an influence on the fuel consumption percentage difference between the two vehicles/machineries. Figures 63 and 64 depict the data analyzed for two machines, with and without trailing sleigh. Figure 63 shows the fuel consumption variation for vehicle D (equipped with Two-stroke engine) measured on 5 STD laps.

Figure 64. Fuel consumption in vehicle D (ECU data). Test Course Conditions: -17° C, Icy with Light Snow Cover.

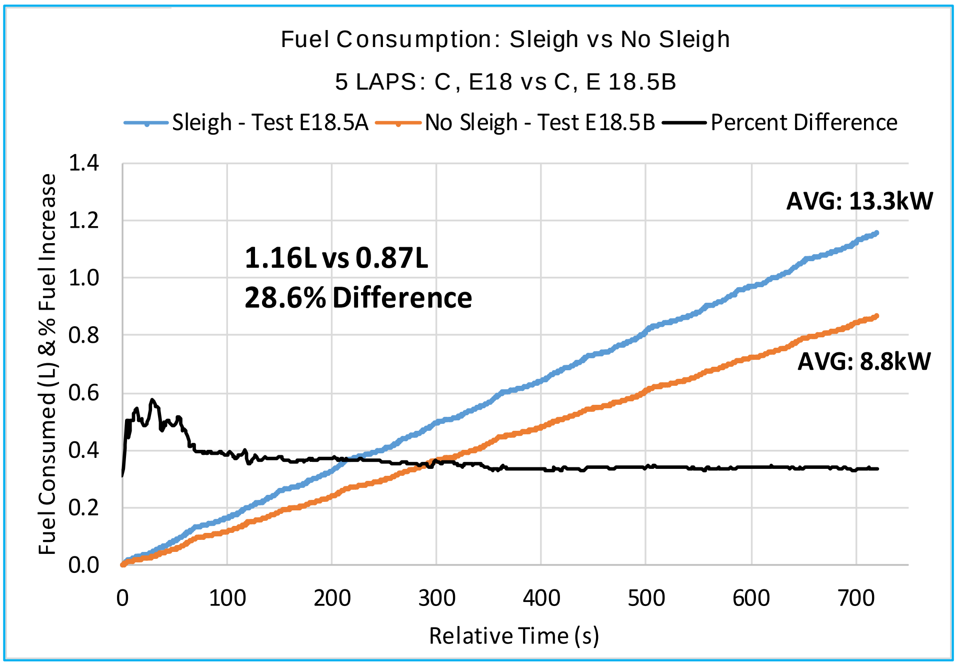


Source: MTU, 2018

In Figure 64, the influence on the fuel consumption variation is plotted for vehicle C (equipped with Four-stroke engine) measured in a trip consisting of 5 STD laps.

For both vehicles, the fuel consumption data comes from the ECU calculation for all tests (with and without sleigh).

Figure 65. Fuel consumption in vehicle C (ECU data). *Test Course Conditions: -1° C, Hard-Packed Snow*



Source: MTU, 2018

Although it is evident there exists an impact on the fuel consumption, it is difficult to generalize from the above data the effect attributable to the trailing sleigh for each class of vehicles (i.e. Two- versus Four-stroke engines) as the test conditions were also different. Vehicle D was operated at -17°C, while vehicle C was operated at -1°C with different snow conditions. Further tests need to be performed to study this influence.

As it was already mentioned in paragraph 3.5.2, some snowmobiles (in particular utility ones) can accommodate up to two riders: the driver and a passenger. Considering the amount of the additional weight intoduced by the presence of the sleigh (113 kg), this can be assumed as a normal in service configuration. In addition, it is quite common to have the snowmobile directly connected to a service sleigh for the transportation of materials, goods or even in some winter ski station/areas luggage. In summary, the configuration of snowmobile plus equipped sleigh is not far from a real normal operating condition.

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