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NON ROAD ENGINES CONFORMITY TESTING BASED ON PEMS

Lessons Learned from the European Pilot Program

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Contents

List of acronyms

A/F:	Air-Fuel ratio
BSFC:	Brake Specific Fuel Consumption
CH4:	Methane gas
CO:	Carbon monoxide gas
CO2:	Carbon dioxide gas
ECU:	Engine Control Unit
EFM:	Exhaust Flow Meter
ESC:	European Steady state Cycle
ETC:	European Transient Cycle
FID:	Flame Ionisation Detector analyser
FS:	Full Scale
GPS:	Global Positioning System
I/O:	Input / Output
ISC:	In Service Conformity
IUC:	In Use Compliance
NRMM	Non Road Mobile Machinery
NDIR:	Non-Dispersive Infrared analyser
NDUV:	Non-Dispersive Ultraviolet analyser
NO:	Nitric oxide gas
NO2:	Nitric dioxide gas
NOx:	Nitric oxides gases
NRTC:	Non Road Transient Cycle
NTE:	Not To Exceed
O2:	Oxygen gas
PEMS:	Portable Emission Measurement System
PM:	Particulate Matter
PFS	Partial Flow Sampling
PID:	Vehicle data Parameter IDentifier
QCM	Quartz Cristal Microbalance
SAE:	Society of Automotive Engineers
STP	Custom Step Cycle
TEOM	Tapered Element Oscillating Microbalance
THC:	Total Hydrocarbons

1 Background

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

It was considered impractical and expensive to adopt an ISC scheme for heavy-duty vehicles requiring the removal of engines from vehicles to test pollutant emissions against legislative limits. Therefore, it was proposed to develop a protocol for in-service conformity checking of heavy-duty vehicles based on the use of Portable Emission Measurement Systems (PEMS). As a result, ISC testing based on PEMS was introduced in the EURO V and the EURO VI standards. The corresponding administrative and technical provisions were formulated in the European Regulations 582/2011 and 64/2012 .

The technical provisions included the applicable test conditions, the test protocol (i.e. the PEMS instrumentation performance requirements and the execution of on-vehicle emissions tests) and the data evaluation method. The data evaluation principle, i.e. a moving averaging window based on the engine work or CO2 mass emissions at type approval - differs from the US (Not To Exceed), found to be impractical for the European heavy-duty vehicle operating conditions.

The above route was followed for non-road engines as well: preliminary research activities studied and confirmed the possibility to apply the methods developed for heavy-duty engines with minor modifications. The basis for the introduction of ISC provisions based on the PEMS approach into the European NRMM type-approval legislation has been established in several texts. Amongst these texts, the Directive 2004/26/EC [R1] includes the following recitals under article 2:

The Commission shall (...):

(g) consider the engine operating conditions under which the maximum permissible percentages by which the emission limit values laid down in Section 4.1.2.5 and 4.1.2.6 of Annex I may be exceeded and present proposals as appropriate to technically adapt the Directive in accordance with the procedure referred to in Article 15 of Directive 97/68/EC;

(h) assess the need for a system for 'in-use compliance' and examine possible options for its implementation;

(i) consider detailed rules to prevent 'cycle beating' and cycle 'bypass'.

2 NRMM PEMS Pilot Program

2.1 Objectives

The NRMM PEMS Pilot Programme was launched to facilitate the introduction into the European NRMM emissions legislation of use of PEMS as a tool for ISC. This had to be achieved by improving the technical procedures (e.g. available from the heavy-duty scheme) and increasing the awareness of the different stakeholders about PEMS as a new regulatory tool.

The objectives of the programme were defined as follows:

- To validate the use of gaseous PEMS for checking the ISC of engines installed in NRMM;
- To evaluate the gaseous PEMS test protocol for NRMM and agricultural & forestry tractor engines and its implementation;
- To provide data to be subsequently used to set the PEMS test parameters at a level appropriate to the non-road technologies actually being used at that time to satisfy the type approval requirements of 97/68/EC;
- To provide further information on incorporating the gaseous PEMS approach in the European type-approval legislation;
- To develop and share 'best practice' approach for the use of gaseous PEMS in NRMM and agricultural & forestry tractor engine ISC testing to all relevant stakeholders;
- To benchmark the dialogue between manufacturers and type-approval bodies;
- Whilst performing the gaseous measurements required for this programme, to conduct, to the extent feasible, measurements of particulate emissions.

2.2 Scope

The Pilot Programme applied primarily to NRMM or Agricultural & Forestry Tractors equipped with stage IIIB variable speed compression-ignition engines of maximum net power between 56 kW and 560 kW. Stage IIIA or stage IV engines were also acceptable, provided that the data would be useful to the development of the technical procedures.

2.3 Technical elements

The envisaged technical elements were formulated in the project plan [R2]. A particular attention was paid 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 and to judge whether the engine is in conformity with the applicable emissions limits?”

3 EU-NRMM PEMS Program dataset

3.1 Test machines

The definition of a strategy for the selection of engines was part of the pilot program. The selection process involved the engine manufacturers and their type approval authorities and was conducted under the supervision of the national technical services. The program mainly focused on engines with high sales volumes.

The participating engines manufacturers tested between 2 and 3 machines during the programme.

The machine duty cycles had to be representative of the machine type, i.e. the machine or engine manufacturers had to screen machines to ensure testing was conducted within the normal range of applications for that machine type. Once the machines were selected, the machine screening was conducted. Particular attention was paid to the PEMS installation constraints. Once the machines had passed the screening process, their engine (both hardware and software) and body could not be modified.

Table 1 EU-PEMS NRMM Pilot Program - Test Machines

Code	Machine Type	Power [kW]	Engine [Litres]	Emission standard	EGR	SCR
A	Tractor	133	6.70	Stage IIIA		
B	Forklift	97	4.39	Stage IIIA		
C	Single drum roller	120	4.39	Stage IIIA		
D	Excavator	137	4.0	Stage IIIA		
E	Forklift	256	12.78	Stage IIIB		X
F	Forklift	185	7.15	Stage IIIB		X
G	Tractor	309	12.0	Stage IIIB	X	
M	Tractor	149		Stage IIIB		
N	Tractor	198		Stage IIIB		
O	Wheel loader	172		Stage IIIB		
P	Excavator	171.5		Stage IIIB		
Q	Tractor	153		Stage IIIB		X
H	Front end loader #1	309	12.0	Stage IV		X
I	Excavator	320	11.95	Stage IV		X
J	Motor Grader	242		Stage IV		X
K	Front end loader #2	248		Stage IV		X

3.2 Test equipment

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

- To be small, lightweight and easy to install;
- To work with a low power consumption so that tests of at least three hours can be run either with a small generator or a set of batteries;
- To measure and record the concentrations of NOx, CO, CO2, THC gases in the vehicle exhaust;
- To record the relevant parameters (engine data from the ECU, vehicle position from the GPS, weather data, etc.) on an included data logger.

It was recommended to use the commercially available PEMS (Sensors Semtech-D/DS and Horiba OBS). Other PEMS than the ones previously mentioned could be used, provided that they offered at least equal characteristics in terms of dimensions, weight and measurement performance.

3.3 Test protocol and test conditions

The tests had to be conducted according to the recommendations developed in the preliminary phases (e.g. the tests conducted with EUROMOT members CNH, JCB and John Deere). These recommendations were formalised in the "Guide for the Preparation and the Execution of In –service Emissions Tests on non-road machines, drafted by JRC before the start of the programme.

The test machines had to run over normal duty cycles, conditions and payloads, defined by the engine manufacturers, in consultation with their type approval authorities. According to the draft test protocol, the test duration had to be selected to have a cumulative engine work produced during the test at least equal from 3 to 5 times the work on the certification cycle (NRTC). Under certain circumstances, it was difficult to achieve the abovementioned objective: in these cases (Discussed in section 4), the tests were segmented and 'stitched' for the analysis of the data.

3.4 Test cycles

Each machine was tested according to a duty cycle representative of the machine type. However, two different situations occurred:

- Machines operated by the engine manufacturer, using work cycles agreed with their type approval authority;
- Machines operated by the owner and run on their normal work cycles.

The second situation corresponds to a limited number of tests conducted in the United States. In this case, the data included significant portions of idling. The implications for the data evaluation principles are discussed in detail in Section 0.

According to the draft protocol, the test duration had to be selected to have a cumulative engine work produced during the test at least equal from 3 to 5 times the work on the transient certification cycle (NRTC). Figure 1 shows that this target was reached for most of the tests, under the conditions which were imposed in the protocol to ensure a sufficient data quality (e.g. zero-span checks before and after the test, auto-zero of the gas analyzers every 2 hours).

These figures only include valid tests, invalid data due to equipment failure or data recording problems has been discarded.

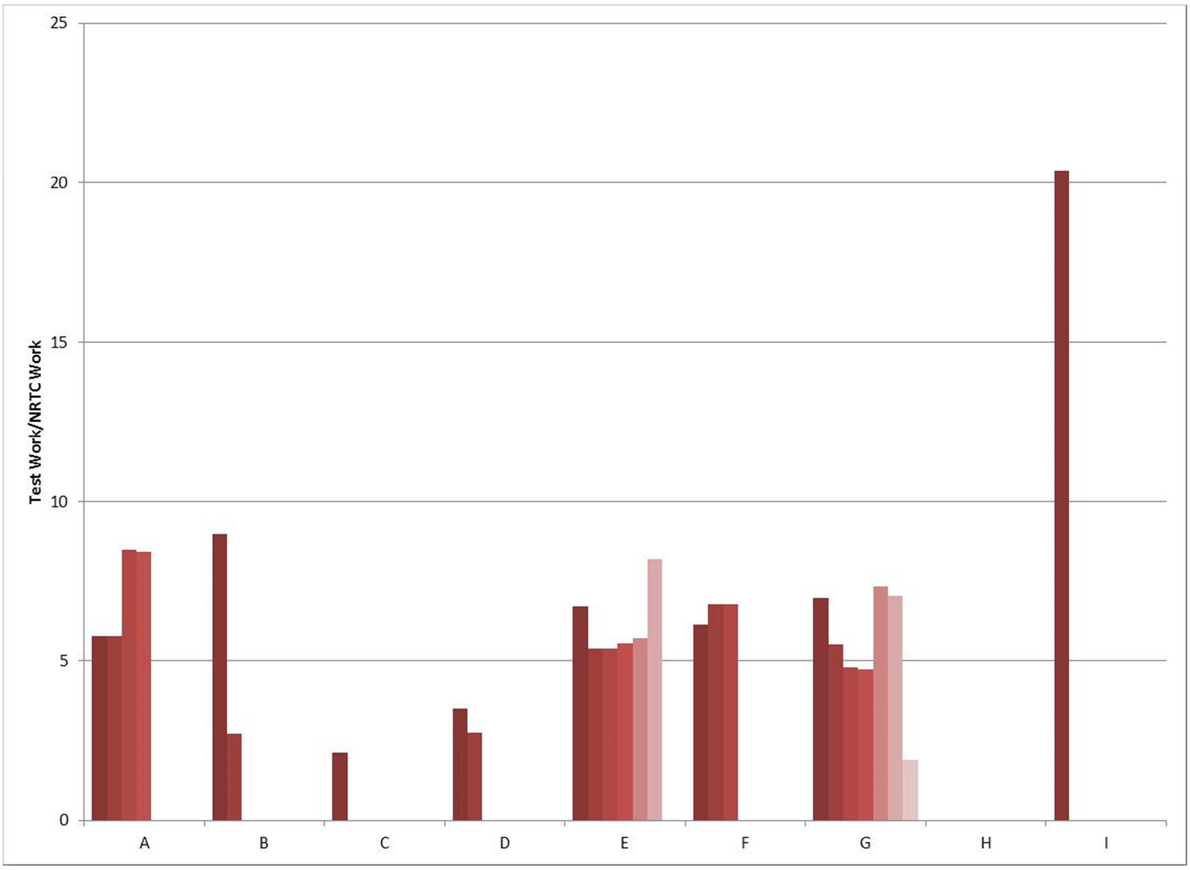

Figure 1 Ratio between the engine work during the PEMS and its estimated work over the NRTC

Another important characteristic under investigation was the average engine power over the PEMS test. It could potentially be used to develop recommendations for the machine work cycle to be selected by a type approval authority and/or to understand whether some cycle could be a posteriori (i.e. after a test) voided.

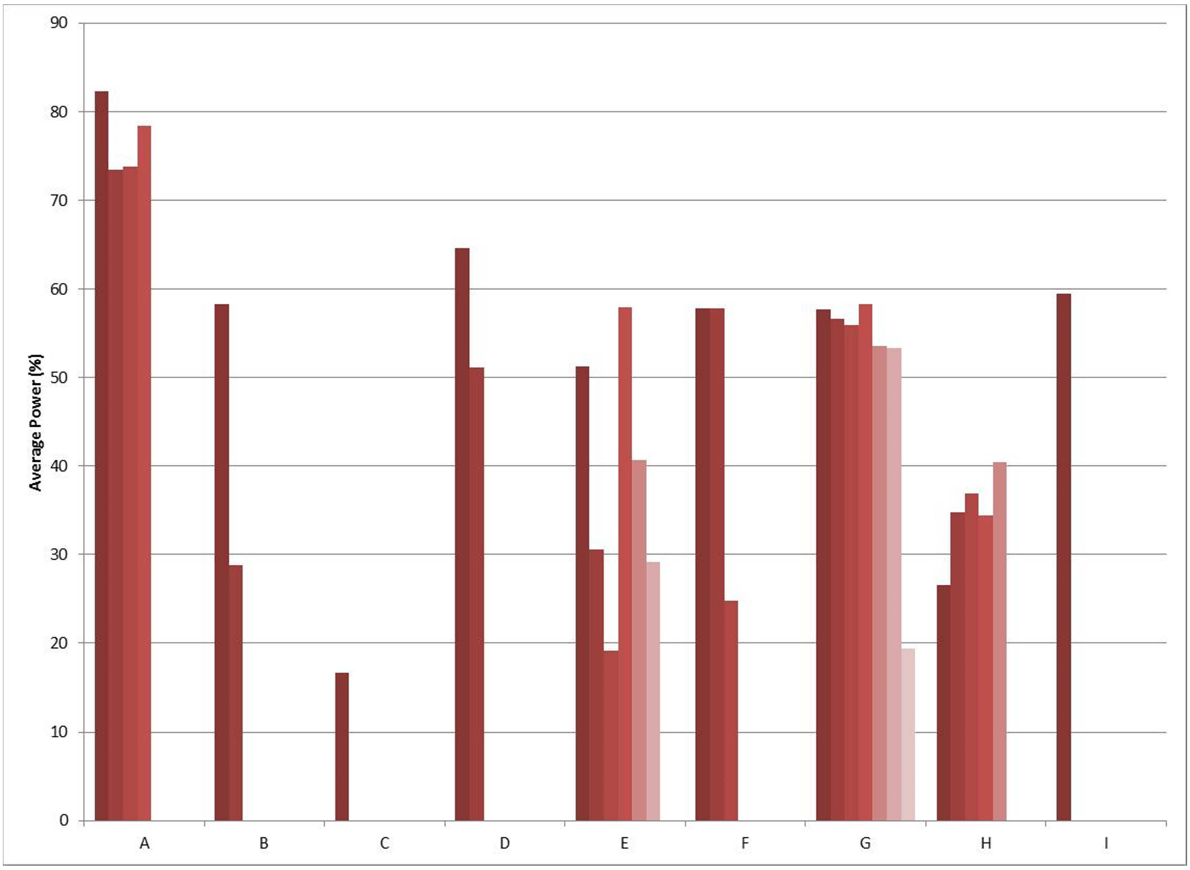

Figure 2 Average engine power during the PEMS tests

3.5 Data handling procedures and tools

3.5.1 Test data

The parameters that had to be recorded are listed in Table 2. The unit mentioned is the reference unit whereas the source column shows the types of methods that were used.

3.5.2 Time alignment

The test parameters listed in Table 2 are split in 3 different categories:

- Category 1: Gas analyzers (THC, CO, CO2, NOx concentrations);
- Category 2: Exhaust flow meter (Exhaust mass flow and exhaust temperature);
- Category 3: Engine (Torque, speed, temperatures, fuel rate, vehicle speed from ECU).

According to the procedure developed for heavy-duty engines, 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 following parameters may be used to calculate the correlation coefficients: To time-align:

- Categories 1 and 2 (Analyzers and EFM data) with category 3 (Engine data): the (vehicle or machine) speed from the GPS and from the ECU.
- Category 1 with category 2: the CO_2 concentration and the exhaust mass flow;
- Category 2 with category 3: the CO_2 concentration and the engine fuel flow.

The method was found suitable for NRMM engines. However, to align Categories 1 and 2 (Analyzers and EFM data) with category 3 (Engine data):

- either the machine group speed is not available;
- or the machine does not move.

Alternative solutions were found on a case by case basis. However, they did not allow proposing a solution which could be systematically applied, regardless of the type of machine. The corresponding provisions could therefore be kept as 'recommended practices'.

Table 2 List of test parameters

Parameter	**Unit**	**Source**
HC concentration [(1)]	ppm	Analyser
CO concentration [(1)]	ppm	Analyser
NO_x concentration [(1)]	ppm	Analyser
CO_2 concentration [(1)]	ppm	Analyser
Exhaust gas flow	kg/h	Exhaust Flow Meter (hereinafter EFM)
Exhaust temperature	°K	EFM
Ambient temperature[(2)]	°K	ECU or Sensor
Ambient pressure	kPa	Sensor
Engine torque[(3)]	Nm	ECU or Sensor
Engine speed	rpm	ECU or Sensor
Engine fuel flow	g/s	ECU or Sensor
Engine coolant temperature	°K	ECU or Sensor
Engine intake air temperature[(2)]	°K	ECU or Sensor
Machine latitude	degree	GPS
Machine longitude	degree	GPS

Notes:
(1) Measured or corrected to a wet basis
(2) Use the ambient temperature sensor or an intake air temperature sensor
(3) The recorded value shall be either (a) the net torque or (b) the net torque calculated from the actual engine percent torque, the friction torque and the reference torque, according to the SAE J1939-71 standard [R1].

3.5.3 EMROAD©

Reporting templates and an automated data analysis were used to ensure that all the calculations (of mass, distance specific and brake specific emissions) and verifications were done consistently throughout the program.

The standardized reporting templates included, for every test:

- Second by second test data for all the mandatory test parameters;
- Second by second calculated data (mass emissions, distance, fuel and brake specific);
- Improved time alignment procedures between the different families of measured signals (analyzers, EFM, engine);

- Data verification routines, using the duplication of measurement principle, to check for instance the directly measured exhaust flow against the calculated one;
- Averages and integrated values (mass emissions, distance, fuel and brake specific).

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

4 Lessons learned from the testing campaigns

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

4.1 Installation of equipment

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

The following figure (Figure 3) tries to capture the main differences between the HDV and NRMM PEMS testing.

	Engine Operation	**Trip/cycle composition**	**PEMS Installation**
	**Reasonable amount of non-idling**	☺	
	**Large amount of engine idling during normal operation**	☹	

Figure 3 Indication of the main differences between PEMS testing of HDV and NRMM

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

1. Installation of instruments should be made in ventilated boxes to protect them from dust, water, shocks, etc. (see Figure 4)
2. Some degrees of freedom needs to be allowed for the instrument in the box, i.e. allow the instrument to move slightly without risking to damage tubes, cables (slack) and connections (military type), to compensate for vibrations and high accelerations
3. EFM: possibility to use a flexible tube needs to be considered, maybe fixing the EFM onto the mounting frames

Figure 4 Protection Boxes for the Instruments

4. Instruments cannot be installed in the cabins: therefore, a mounting platform is needed and modifications to the machine structure and exhaust tailpipe are difficult to avoid (see Figure 5);
5. For safety reasons, the mounting platform and the boxes containing the equipment need to be secured to the vehicle: straps should be avoided, as they can be torn on sharp angles.
6. In the case of excavators, installing the equipment onto the platform of the excavator can prevent access to the engine compartment (Difficulty to find strong points for the platform).
7. Permanent machine modifications must be avoided as those will not be acceptable to the machine owner.
8. Access to the test equipment is necessary – either for the installation or for the checks between the tests – Safety aspect needs to be thought especially if the instruments are installed on the roof.

Figure 5 Some examples of PEMS installation.

9. Power supply: Measuring PM and gaseous emissions simultaneously double the required power. (Future PM measurement)
10. Minimum power required: 2.5 kW generator (designed for mobile platforms) – or 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, Gel batteries only!)
11. FID fuel bottle: 1 liter bottle has an autonomy of about 6 hours (which must include warm-up and calibration) – Larger bottles could be used
12. Field testing: span gas bottles must be taken to the field to zero-span the gas analyzers, unless the measurements start from and finish in a workshop.

13. Gas supply for the test campaigns: transportation of gas cylinders over long distances is difficult (safety issues in tunnels, boats). Therefore it must be supplied locally
14. Avoid contamination of the air used to zero the gas analyzers (by the engine itself, the power generator or any other source)
15. Recommendation: Remote monitoring of the instruments using Wifi
16. Road safety issues for the machines going on the road: local regulations (regarding gas cylinders and projecting loads) shall apply (e.g. tractors)
17. Recommendation for the laptops: they need to be ruggedized, for high autonomy, dust and water proof, lighting of the monitor, etc…

4.2 Data consistency checks

Three types of (post-test) data consistency checks were part of the procedures. Some of them were carried over from the heavy-duty protocols and became part of the 'draft' NRMM procedures used during the Pilot program. These checks are complementary to the 'normal' verifications made during a test, e.g. the zero-span of the gas analysers.

<u>Type 1 check</u>
The first screening a very simple and automated routine checking:

- The presence of all the mandatory parameters;
- The existence of values outside the instrument ranges or outside normally expected ranges;

<u>Type 2 check</u>
The second on is a verification of the exhaust mass flow and the emissions data. It makes use of a correlation between the fuel rate - calculated from the emissions and the exhaust mass flow, using the carbon balance equations in the ISO standard [R1]. A linear regression was performed for the measured and calculated fuel rate values. The method of least squares was used, with the best fit equation having the form:

$$y = mx + b$$

where:
y = Calculated fuel flow [g/s]
m = slope of the regression line
x = Measured fuel flow [g/s]

b = y intercept of the regression line

The slope (m) and the coefficient of determination (r^2) were calculated for each regression line. This analysis was performed in the range [15% of the maximum value - maximum value] and at a

The results of the linear regressions (slope (m) and the coefficient of determination (r^2)) should have been calculated for all tests and all machines. Unfortunately, the fuel rate from the ECU (which was part of the mandatory parameters to be recorded) was only available for a small number of machines (2). Therefore no lessons could be learnt about the relevance and the quality of the Type 2 screening.

Type 3 check

The last verification that was developed looks at the consistency of the ECU torque values with respect to the declared full-load curve. All the submitted data passed with the 'Type 1' verification. Depending on the type of work carried out during the test and the engine settings, two issues (leading to no or few data points hitting the maximum power curve) were observed during the test (see Figure 6):

- Engines tested at relatively low power;
- Engines tested at constant engine speed;

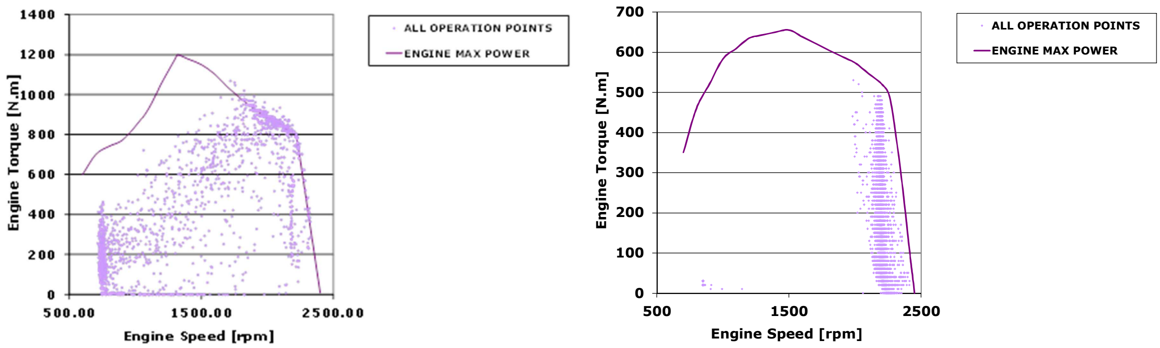

Figure 6 Declared full load curve and ECU obtained torque values.

4.3 Plausibility of BSFC values

The following figure represents the average brake-specific fuel consumption (BSFC) of the machines tested in the Pilot Program. The BSFC results are calculated from the PEMS data: the fuel consumption is obtained from the emissions and exhaust mass flow data whereas the work is calculated from the ECU torque and speed signals.

The results show that only a few BSFC values were found to be anomalous (Figure 7):

- above 500 g/Kwh for one Stage IIIA machine;
- above 300 g/Kwh for one Stage IIIB machine;

The results from the Type 1 and Type 2 checks were used to understand which test parameter is likely to cause such anomalous values: ECU torque, exhaust flow measurement, emissions or all.

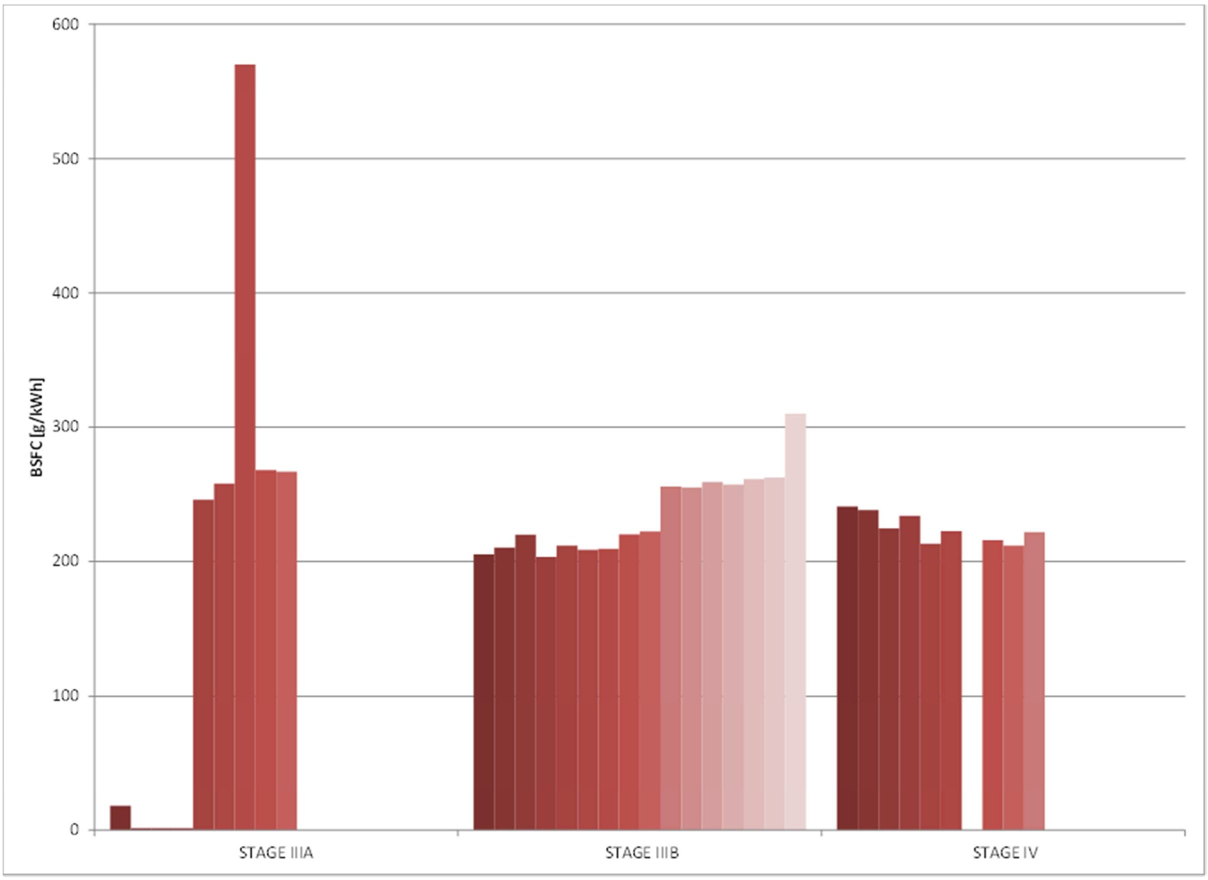

Figure 7 Brake-Specific Fuel Consumption of all machines

From the data screening presented in the present section, a few data sets were found not meeting the required quality. Engine manufacturers received data screening reports summarising these findings for their own machine

5 Emissions Evaluation Methods for ISC

5.1 Introduction

In this European NRMM Pilot Program, some principles were adopted to assess the 'candidate' data evaluation methods:

- The data analysis method in EU 582/2011 developed for 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*.
- Calculations making use of the US-Not to Exceed (NTE) method were also carried out to compare (a) the coverage of operating conditions with respect to the European MAW (b) whenever possible, the level of stringency.

5.2 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 averaged over windows whose common characteristic is the reference engine work or CO_2 mass emissions. The reference quantity is easy to calculate or (better) to measure at type approval:

- In the case of work: from the basic engine characteristics (Maximum power), the duration and the average power of the reference transient certification cycle;
- In the case of the 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 (i.e. averaged value) is obtained between the first data point and the data point for which the reference quantity (1 x CO2 or work achieved at the NRTC) is reached. The calculation is then moving, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

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

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

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

Work based method:

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 NRTC, kWh.

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

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

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

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

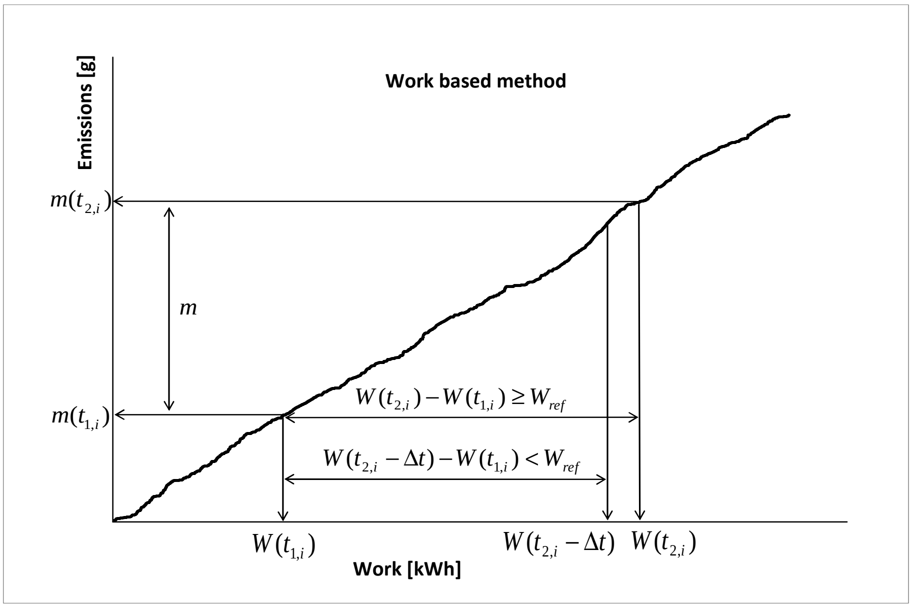

Figure 8 MAW Work based method

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

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

Where:

m is the mass emission of the component, g/window
W_{ref} is the engine work for the NRTC, kWh

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

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

Where:

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

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

CO2 mass based method

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

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

Where:

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

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

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

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

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

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

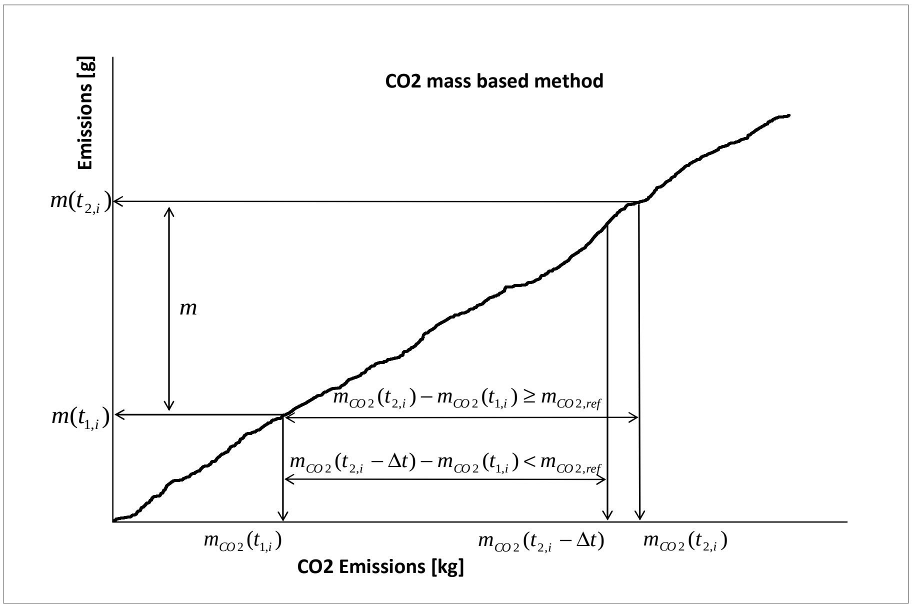

Figure 9 MAW CO2 based method

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

CO2 mass based method:

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

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

Where:

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

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

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

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

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

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

Where:

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

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

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 Directive [R1].

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

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

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

Steps 2 to 5 apply to all regulated gaseous pollutants (and should apply to PM in the future).

5.3 First Results and Issues with the moving averaging window method

Figure 10 shows the MAW results obtained from a work based MAW calculation and for various machines in the program: it shows the MAW emissions versus the MAW average power. For some machines and tests cycles, the disproportionate amount of idling in some windows creates a "tail" effect on the top left of the chart, due to the fact that the mass emissions continue to increase whereas the work remains constant thus leading to higher brake-specific emissions. This effect was also observed for on-road heavy-duty engines during the European Pilot Program [R4][R5][R6] and was one of the reasons which led to the introduction of a 'power threshold'[1].

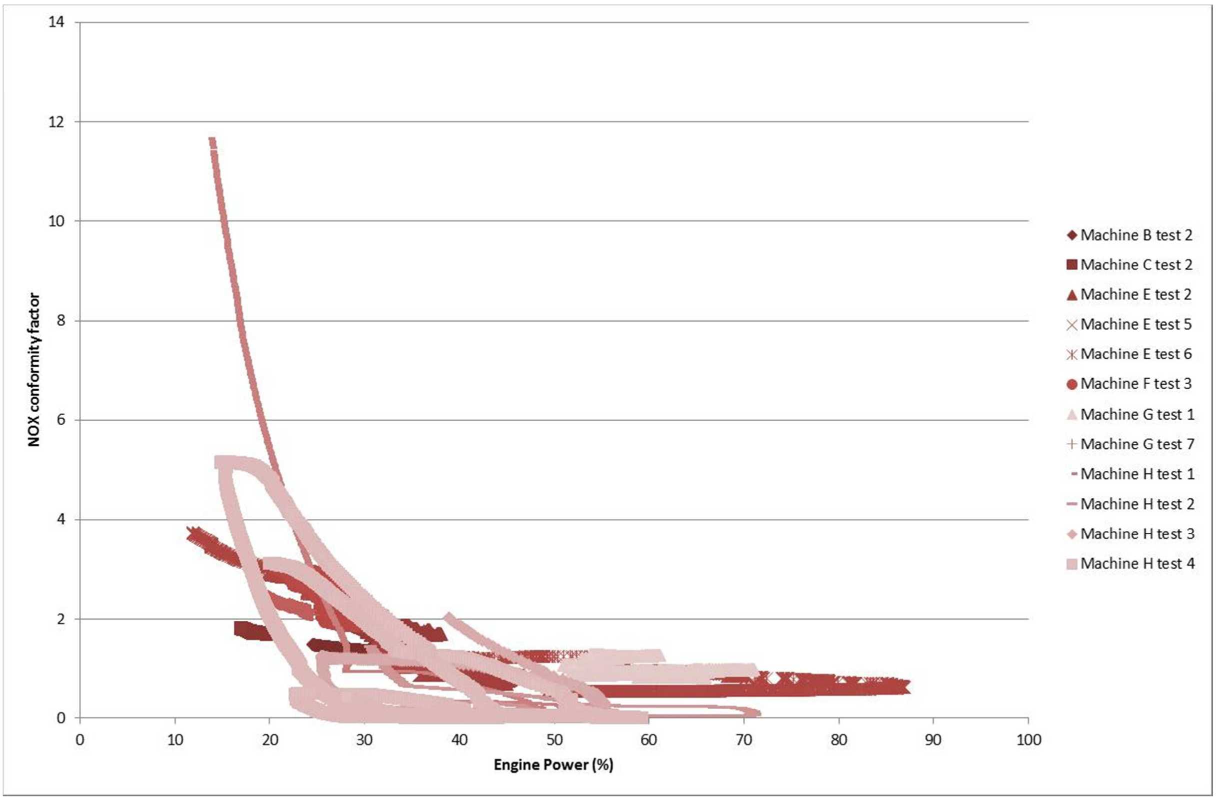

Figure 10 MAW NOx versus Engine average power - All machines, all windows

[1] Windows whose average power does not exceed the 'power threshold' (20% for heavy-duty engines) are excluded from the ISC calculations.

5.4 Issues with the moving averaging window method: First tentative solution

Following the issues identified and discussed under section 5.3, it was proposed to modify the procedure as described below.

Settings of the Existing procedure (baseline)

- MAW Power Threshold :20%
- Minimum percentage of valid MAWs: 50%
- Cold start exclusion: Yes
- Requirements for test cycle duration: 5 times the engine work on NRTC
- Other operational/cycle requirements: none

Settings of the Modified procedure

- MAW Power Threshold : None
- Minimum percentage of valid MAWs: None
- Cold start exclusion: Yes
- Requirements for test cycle duration: 5 times the engine work on NRTC
- Other operational/cycle requirements: Exclusion of idling sequences longer than 5 minutes

The effect upon the behavior discussed in section 5.3 and shown in Figure 10 is illustrated in Figure 11: the 'tail' effect tends to disappear. The proposal had the overall effect to reinforce the control of the test executor over its own test by:

- selecting appropriate working cycles (sufficient average power) to demonstrate the engine conformity;
- forcing the executor of the test to limit the number of idling sequences within a test.

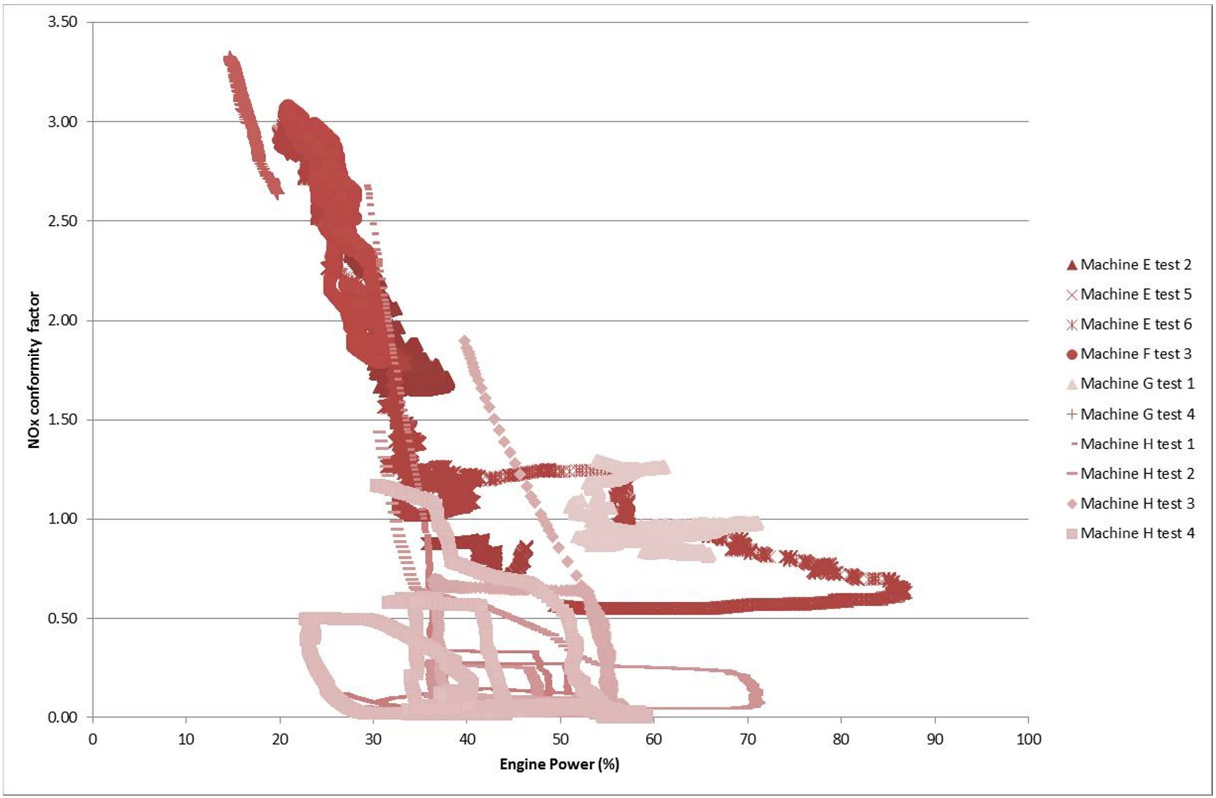

Figure 11 MAW NOx versus Engine average power - All machines, - Cycle power >20% - Exclusion of idling sequences longer than 5 minutes

The 'modified procedure' was further evaluated on 2 stage IV machines and cycles [R3]. On the first example, illustrated in Figure 12, the MAW actual average power stayed above the 20% power threshold for entire test, even during idle. During the extended idling, and due to the lower exhaust temperatures, the (SCR) emissions control system is no longer active, resulting in higher NOx emissions.

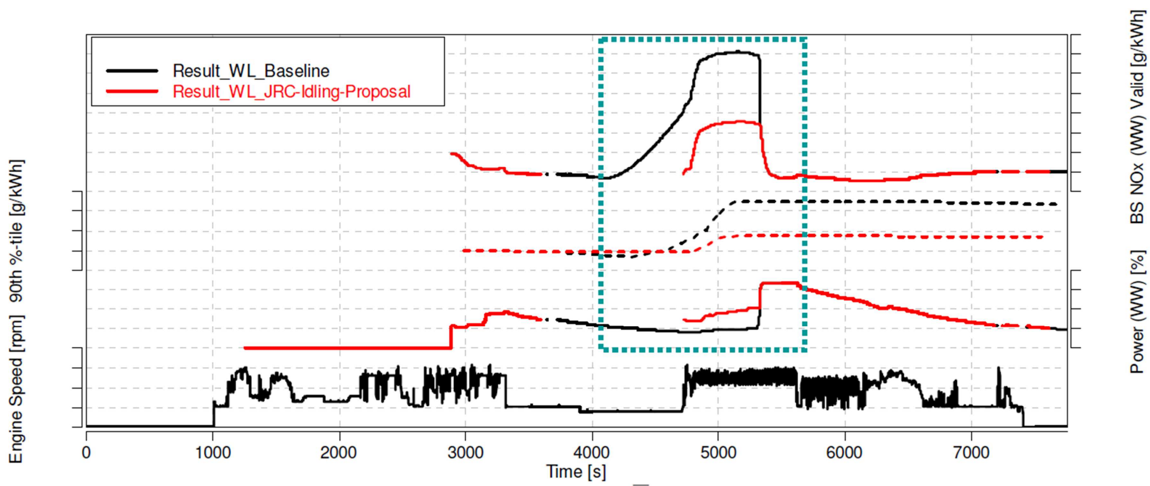

Figure 12 Results for the modified procedure (case 1) - From bottom to top: Engine speed [rpm], MAW Engine average power [%], 90% cumulative percentile and brake-specific NOx emissions [R3]

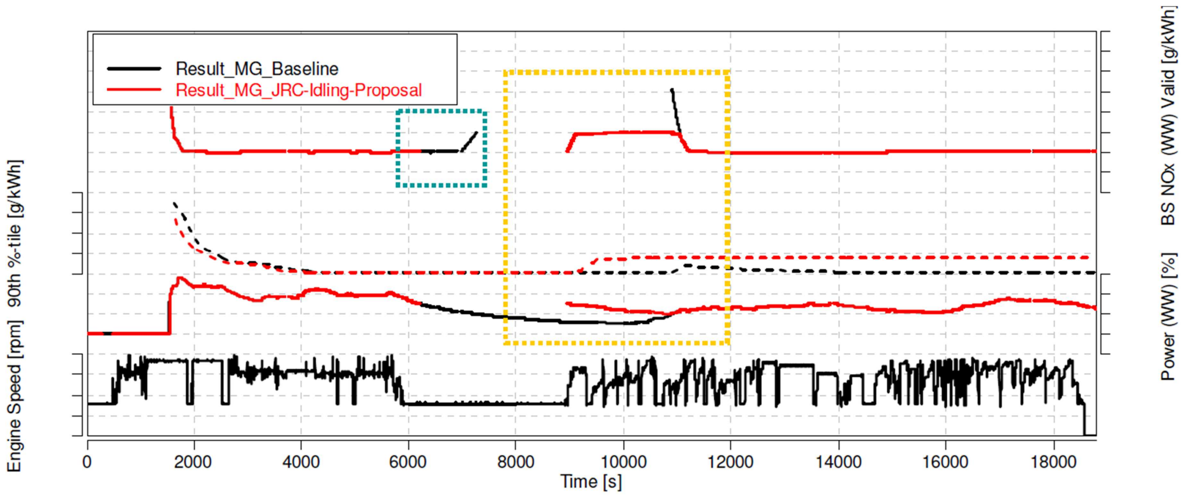

Figure 13 Results for the modified procedure (case 2) - From bottom to top: Engine speed [rpm], MAW Engine average power [%], 90% cumulative percentile and brake-specific NOx emissions [R3]

On the second example, illustrated in Figure 13, the exclusion of idle data strongly influences the MAW average power calculation up, in turn generating MAWs earlier where the emissions control system is cold, resulting as in the previous case in higher NOx emissions.

The idling exclusion (as proposed in the present section) helped to mitigate this issue although not to a satisfactory level for making a decision on the 90% cumulative percentile of the emissions. The latter value, significantly influenced by high emissions events occurring during a test, may be used provided that these high emissions events fall within the boundary conditions of the ISC test, which is typically not the case for extended idling or the re-start phase after a long idling. As a result, it was concluded that the modified procedure did mitigate the issues of extended idling during the tests, but not to a sufficient level. The final and adopted solution is presented and discussed in the next section.

5.5 Final solution with the MAW method

The effects discussed in the previous section were exclusively observed for machines whose engines were idling (or running at very low power) for durations exceeding 5 to 10 minutes. Such situations, though not desirable in a test designed to check the conformity of the engines with respect to a cycle, could occur if the control of the machines during the tests is left to the owner/operator of the machine.

Moreover, the objective of the ISC tests is not to check the level of idling emissions but rather to ensure that the emissions measured in appropriate conditions give sufficient confidence that the test engine would comply on the type approval cycle if extracted from the machine.

To overcome the problem with the effect of idling upon brake-specific emissions, it was decided to introduce the concept of *'working' and 'non-working'* engines. D0, D1, D2, D3 are the durations used to define the working and non-working events as follows:

- D0 defines the minimum duration of working events.
- For all non-working events, the first D1 minutes of the event are valid;
- D2 defines short (<D2 min) and long "non-working" (>D2 min) events;
- For long non-working events, the take-off phase following the idling event may also be excluded until the exhaust gas temperature reaches 250C. If the exhaust gas temperature does not reach 250 ^{o}C within D3 minutes, the data analysis shall restart.

The "Machine Work" marking algorithm is comprised of 4 steps, respectively illustrated in Figure 14 to Figure 17.

Step 1: Detection, data splitting into working and non-working events:
Detection of working and non-working data points, using a power criterion: if the engine power is lower than <10% the machine enters in non-working situation. The duration of the *non-working events* is calculated and the *non-working events* shorter than D0 minutes is considered as *working events*. Finally, the duration of all the events is calculated.

Step 2: Merging of short working events into non-working
Working events shorter than D0 are merged with surrounding *non-working events* longer than D1. This steps deals with the situation of long event interrupted for a very short duration (accidentally or to move the machine).

Step 3: Exclusion of post non-working (take off) data
To account for the thermal effects of the extended idling, D3 minutes can be excluded after long *non-working events* ("Take off emissions").

Step 4: Inclusion of post-working data
To keep some 'hot idling' within the MAWs calculations, D1 minutes of non-working data is added at the end of *working events.*

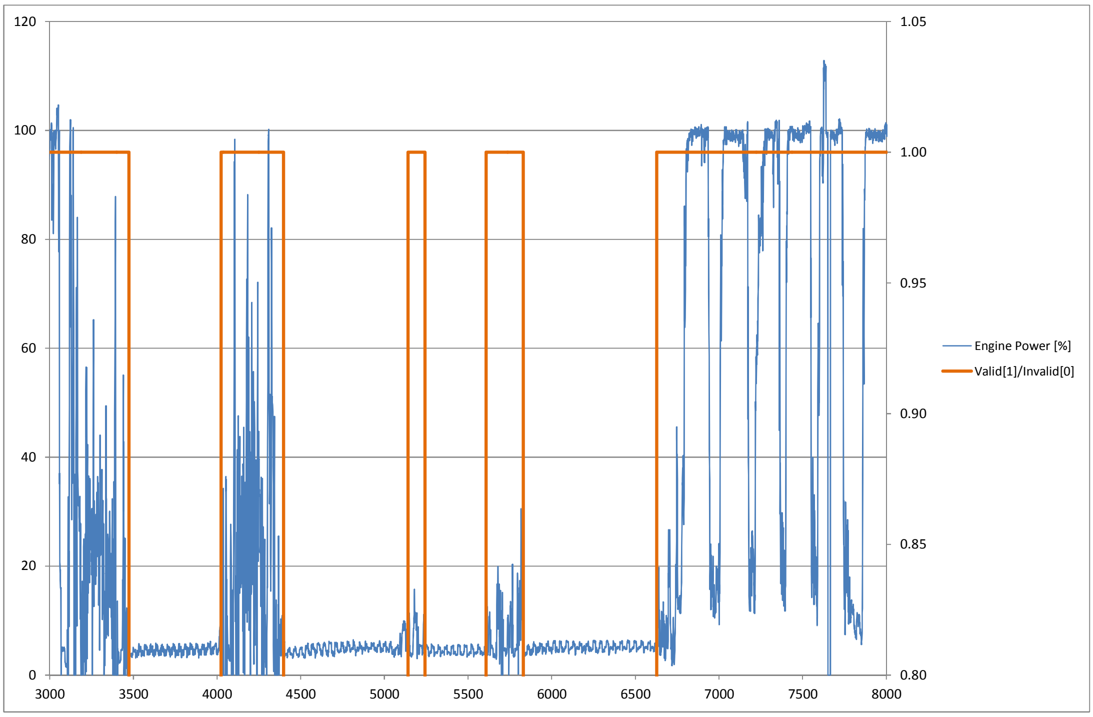

Figure 14 Exclusions non-working data at the end of Step 1

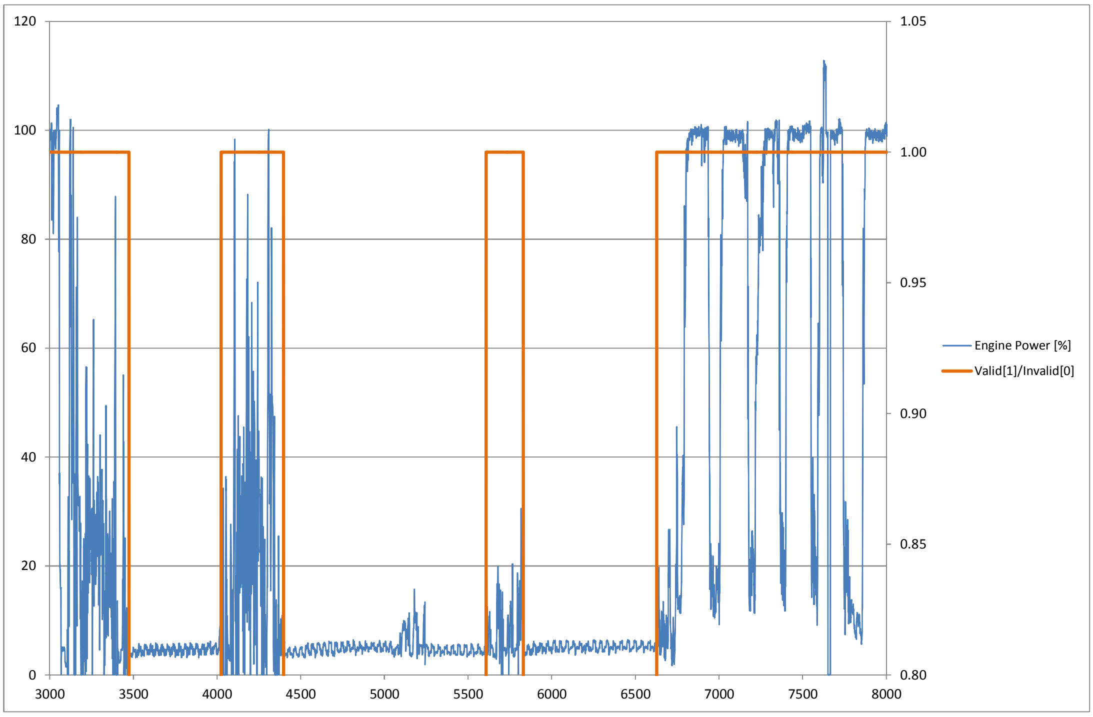

Figure 15 Exclusions non-working data at the end of Step 2

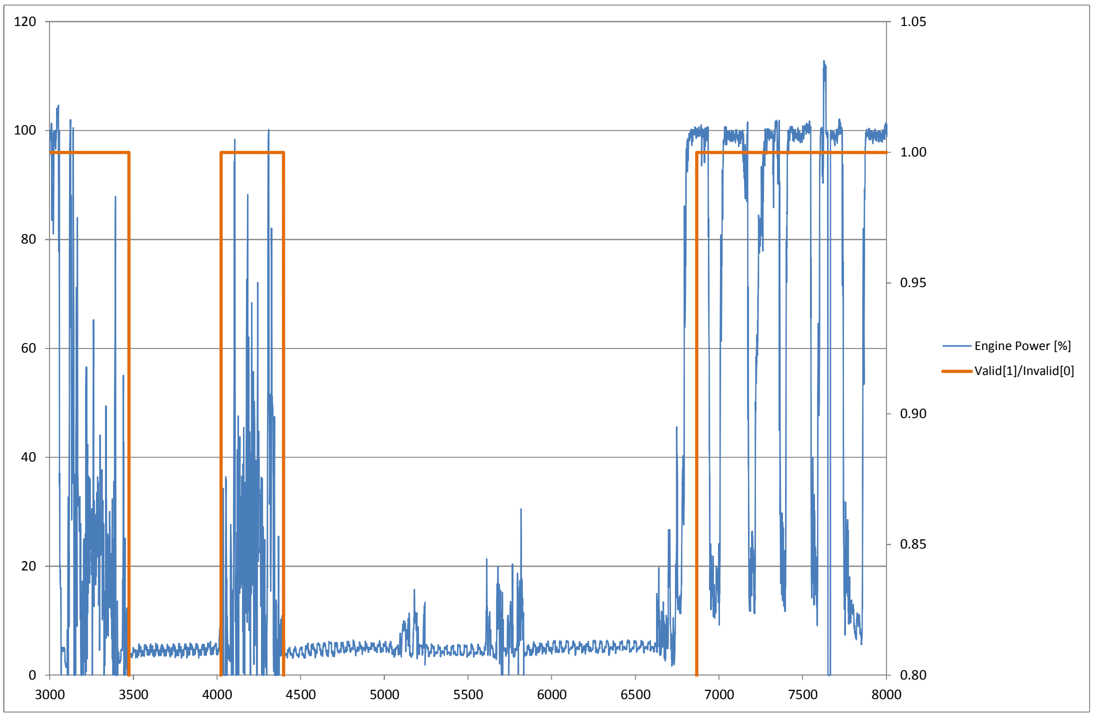

Figure 16 Exclusions of non-working data at the end of Step 3

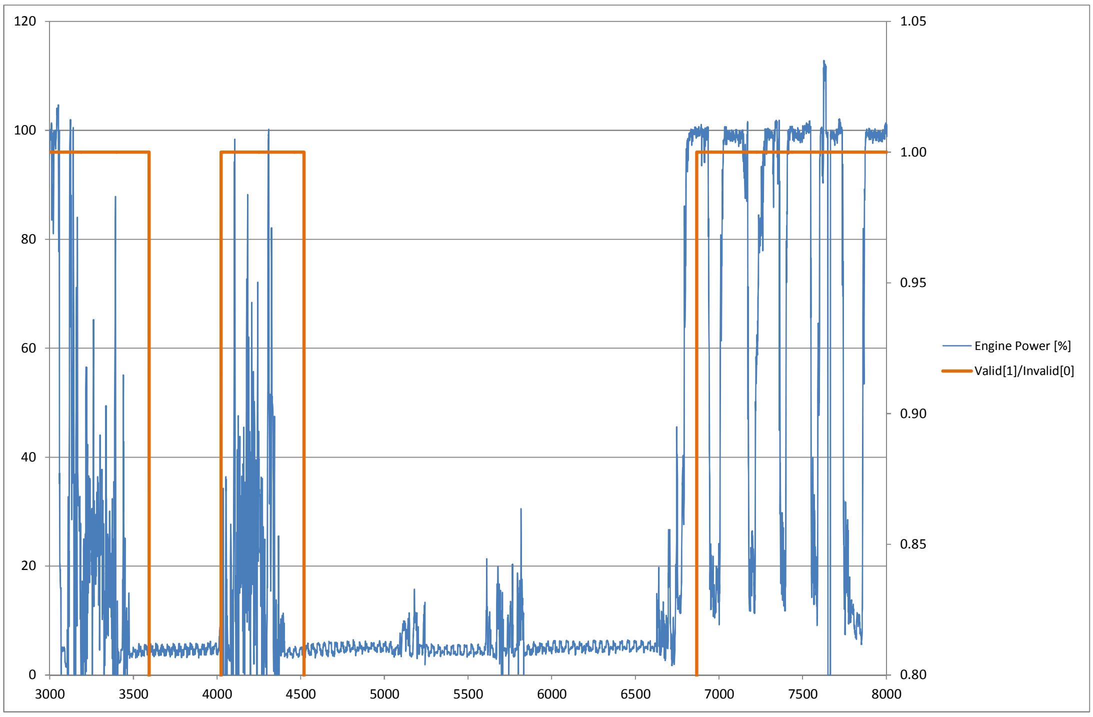

Figure 17 Resulting valid data at the end of Step 4

5.6 Effect of the final solution: 2 Case studies

For the calculations presented in this section, the values agreed upon and used for D0, D1, D2, D3 are the following 2, 2, 10 and 4 minutes respectively. The decision for these durations is based on a 'reasonable' compromise between the total test durations and the non-working durations usually encountered during the real operations of the machines.

The first case study is illustrated in Figure 18 and Figure 19, respectively to show the effect of the baseline calculation settings and the modified method upon the results. The baseline settings lead to an exclusion of some MAWs based on the 20% power threshold rule during and after the long 'central' idling sequence. When entering the long idling event, the amount of idling data kept by both settings is rather similar. Very interestingly, the modified method discards much less (take-off emissions) data after the long idling event (between 6000 and 7000s).

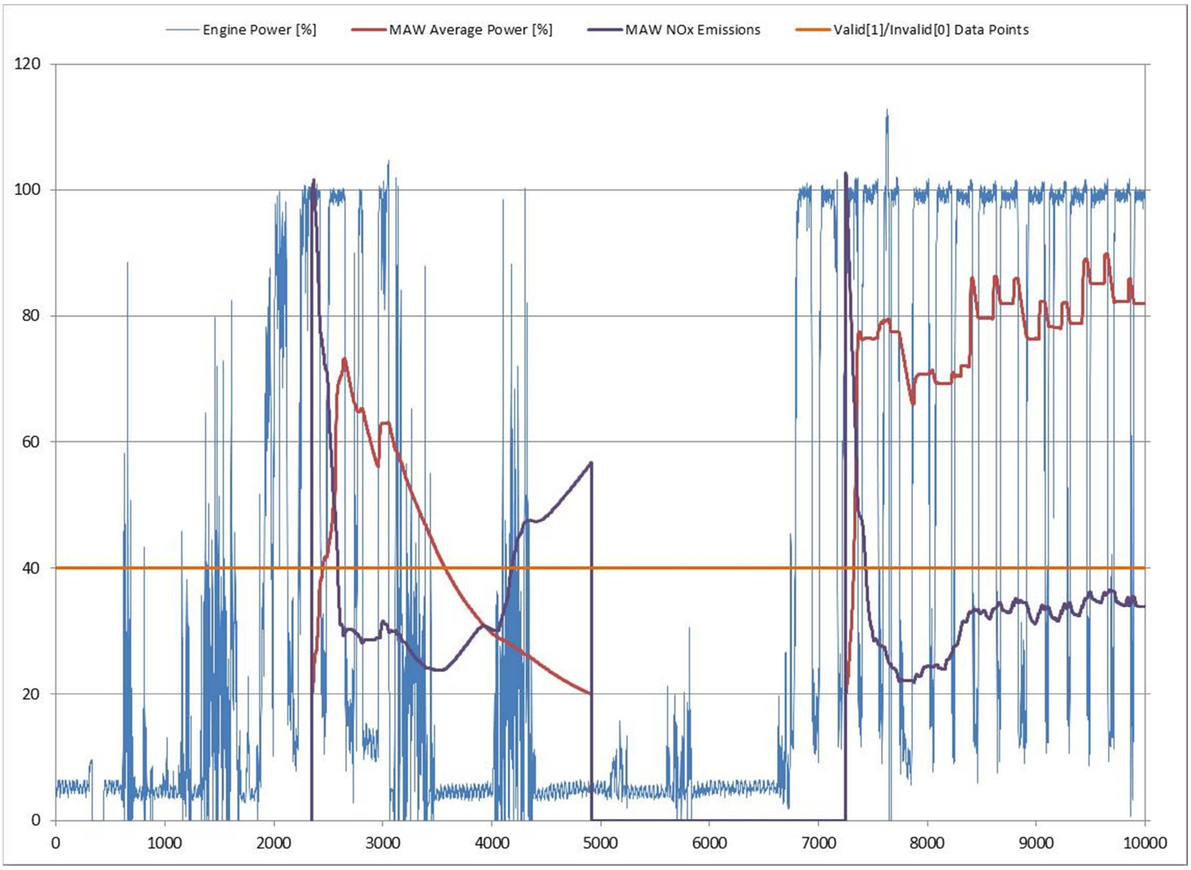

Figure 18 Case study 1 - Analysis with the baseline solution (MAW, 20% power threshold)

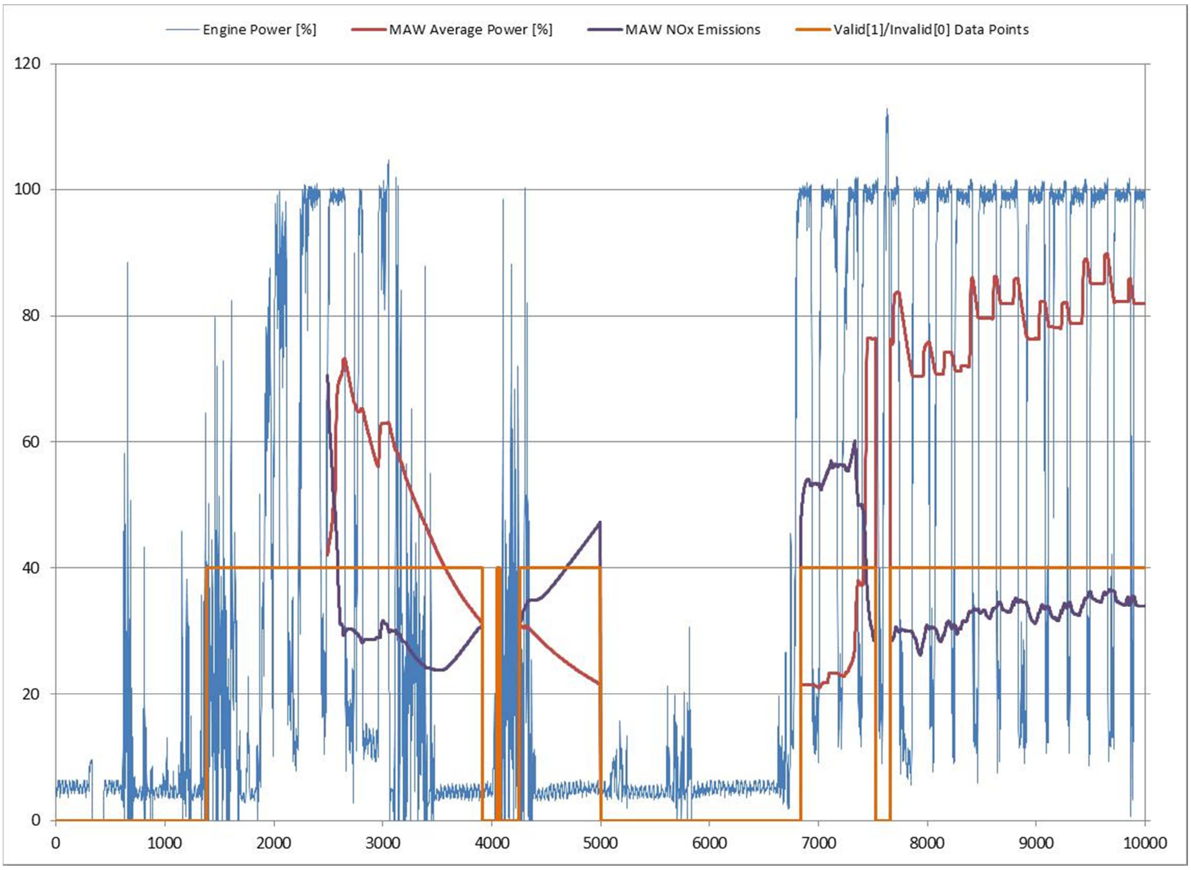

Figure 19 Case study 1 - Analysis with the final solution (MAW, working and non-working algorithm, 20% power threshold)

The second case study is illustrated in Figure 20 and Figure 21, respectively showing the effect of the baseline calculation settings and the modified method upon the results. For both calculations, the cold start emissions were excluded, as shown with the valid/invalid data points curve. For the baseline settings, the MAWs are excluded due to the 20% power threshold rule and appear in the first section of the test. The resulting brake-specific emissions remain high. With the modified method, the first working event following the cold start is considered as non-working under the algorithm Step 2 rules. Similar to case 1, the duration of the 'take-off' emissions phase following the second non-working section is much shorter than with the baseline method.

The final effect of the two methods upon the distribution of brake-specific emissions is shown in Figure 22. Please note that the indicated targets (maximum conformity factors of 1.5 or 2) are shown for information only.

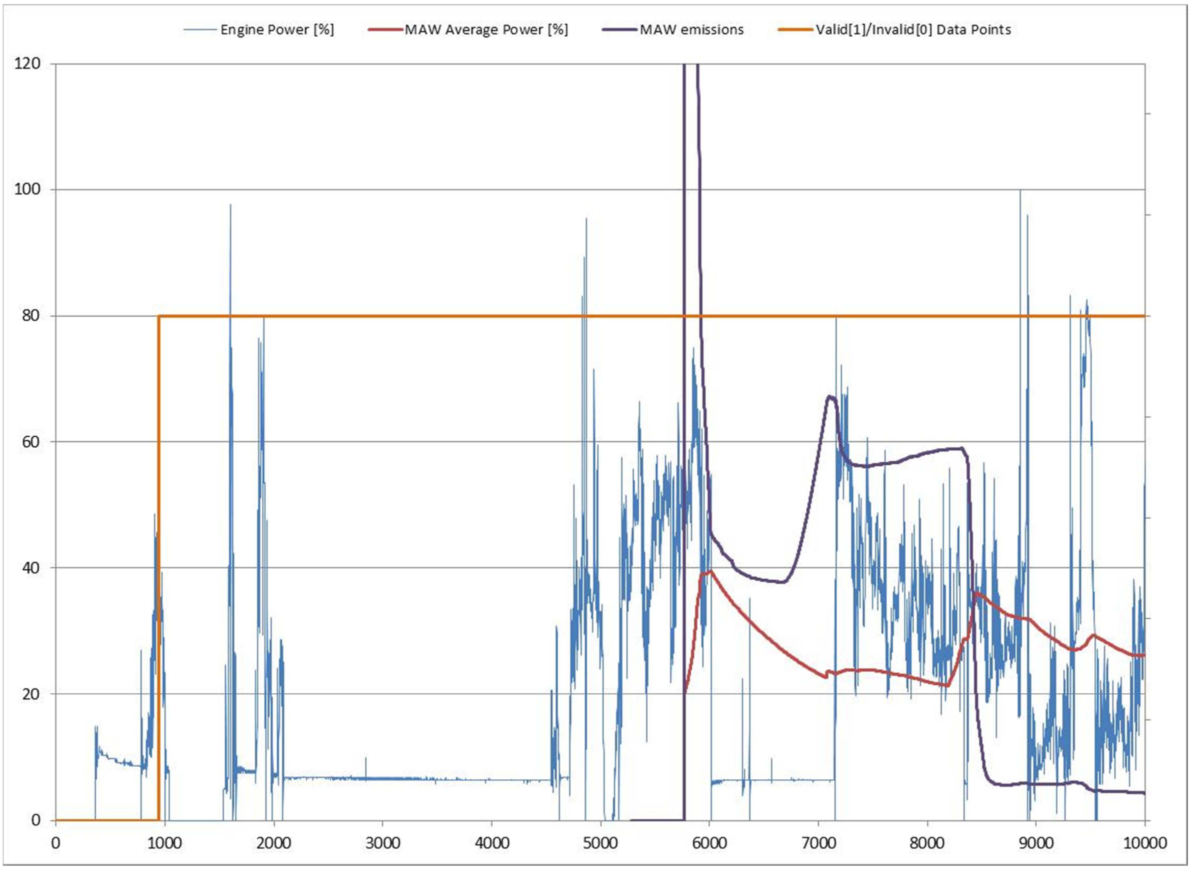

Figure 20 Case study 2 - Analysis with the baseline solution (MAW, 20% power threshold)

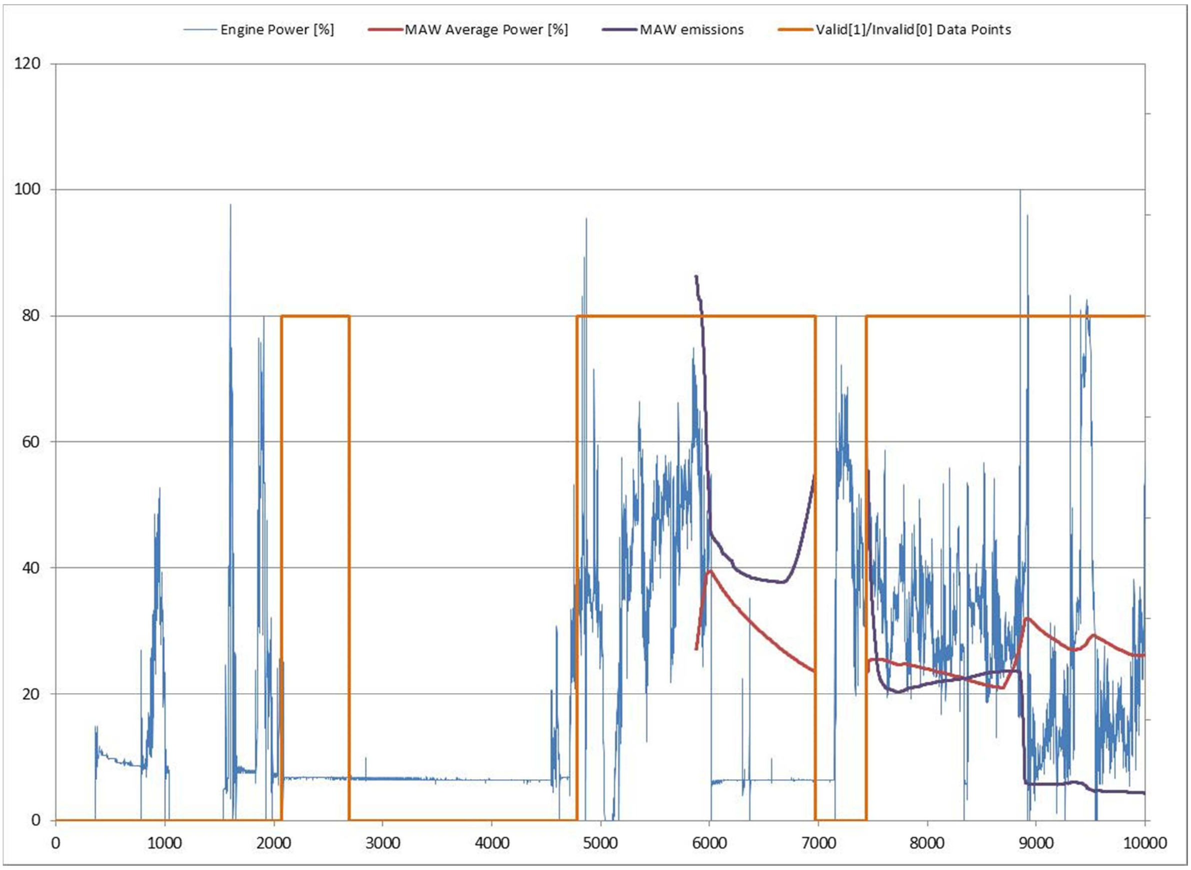

Figure 21 Case study 2 - Analysis with the final solution (MAW, working and non-working algorithm, 20% power threshold)

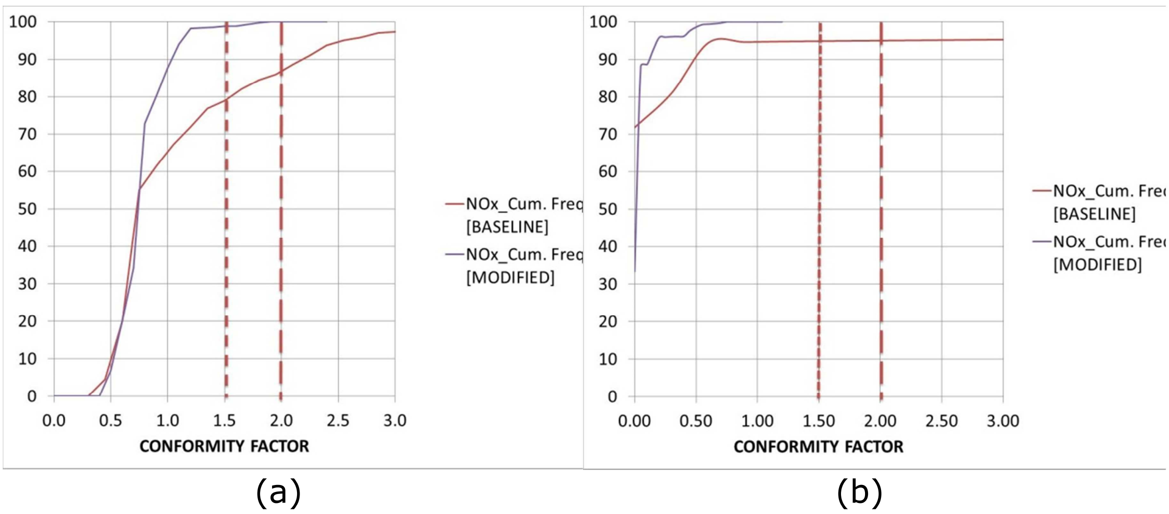

Figure 22 Distribution of MAW NOx emissions for (a) Case study 1 - (b) Case study 2

5.7 Coverage of conditions with respect to the US-NTE method

5.7.1 Reminder – Principles of the US-NTE calculations

The engine *"operating points"* are defined as pairs of engine speed and torque values, typically read from the vehicle ECU when testing with PEMS. The in-service brake-specific emissions are calculated when the engine operating points belong to the control area for a minimum duration, also known as the *"minimum sampling rule"*. An *"event"* can be defined as a sequence of data whose operating points belong to the control area for at least the duration of the minimum sampling rule (at least 30 consecutive seconds in the US-NTE). For each event, a brake-specific emissions value is calculated, dividing the mass emissions by the event work.

The calculations presented in this section were carried out with the US-NTE area and the default minimum sampling rule set to a 30 seconds duration. The speed boundaries of the control area (filled in with a yellow color in Figure 23), are obtained from the engine speeds n_{low} and n_{high} , whereas the power boundary is set to 30% of maximum engine power and the torque boundary to 30% of maximum torque, where:

- n_{high} is determined by calculating 70 % of the declared maximum net power. The highest engine speed where this power value occurs on the power curve is defined as n_{high}.
- n_{low} is determined by calculating 50 % of the declared maximum net power. The lowest engine speed where this power value occurs on the power curve is defined as n_{low}.

The control area low speed boundary is obtained from:

$$NTE_{low} = n_{low} + 0.15(n_{high} - n_{low})$$

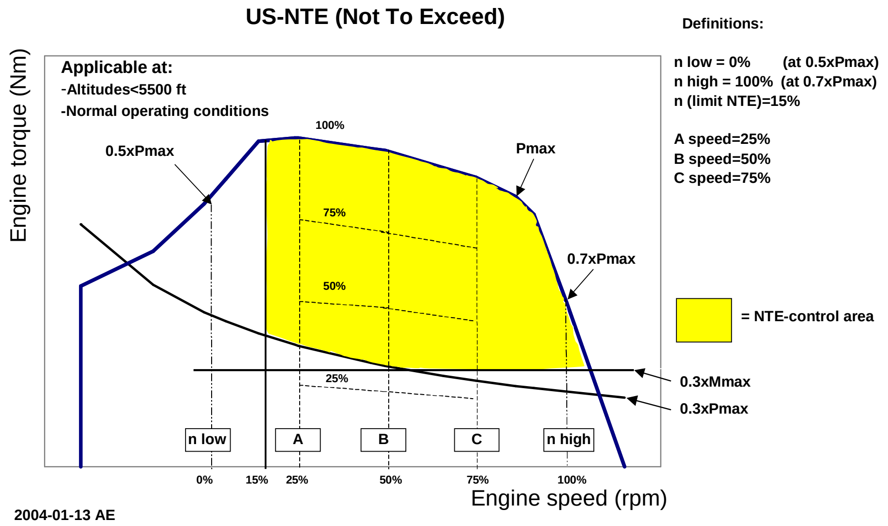

Figure 23 Definition of the US-NTE area

An engine operating point is retained for the calculation when it fulfils the following criteria:

- Rule1: Engine speed ≥ NTE_{low}
- Rule 2: Engine power ≥ 30% of Engine maximum power
- Rule 3: Engine torque ≥ 30% of Engine maximum torque
- Rule 4: Exclude the test point if the engine was equipped with an after treatment device that reduces NOx or NMHC and the exhaust gas temperature < 250 degrees Celsius. The exhaust temperature shall be measured 25 inches downstream the catalytic converter.
- Rule 5: The operating point is part of a set of at least 30 seconds of data which lay always in the control area (minimum sampling rule).

In the United States official rules (Code of Federal Regulations Paragraph 86.007-11 and Paragraph 86.1370-2007). Other criteria (not used for the evaluation in section 5.7.2) are applied on the engine condition.

5.7.2 Case study: coverage of engine operation

In this section, a case study is presented to illustrate the effect of the control area methods upon the validation or invalidation of the test data.
The same machine was tested on two relatively different duty cycles. The characteristics of the **first** cycle (qualified as "agricultural duty cycle") for the first case are as follows:

- 1 Trailer towing (10,000 kg) 30 min.

- 2 Idle 5 min.
- 3 Loading – front bucket 30 min.
- 4 Idle 10 min.
- 5 Site stripping/silage clamp 30 min.
- Total duration = 105 min

The resulting coverage is illustrated in Figure 24 and Figure 25: the 'captured' control area operation occurs <u>only</u> at the maximum engine power and only during the first 'working' phase of the duty cycle. During the second and the third phases (loading and site stripping), no control area events are found, despite the relatively high average power during these phases (40 to 60% of the maximum engine power). This problem is caused by the very transient character of theses phases: the engine operation enters and exits frequently the control area thus resulting in a violation of the 30 seconds minimum sampling rule. For this first cycle, the total time in the control (NTE) area represented 21% of the total test duration, for an average power of 51% over the entire cycle.

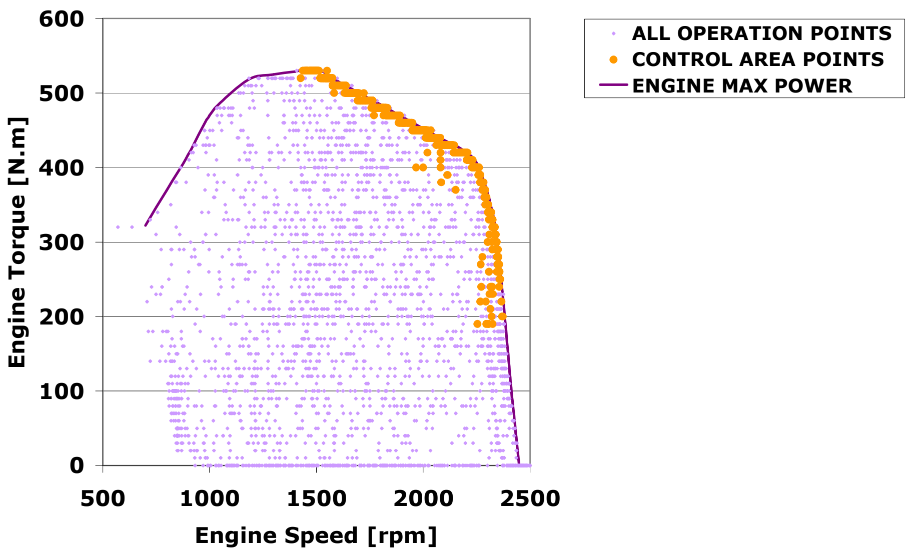

Figure 24 Control Area (US-NTE type) - Case study 1 - Events versus full load curve

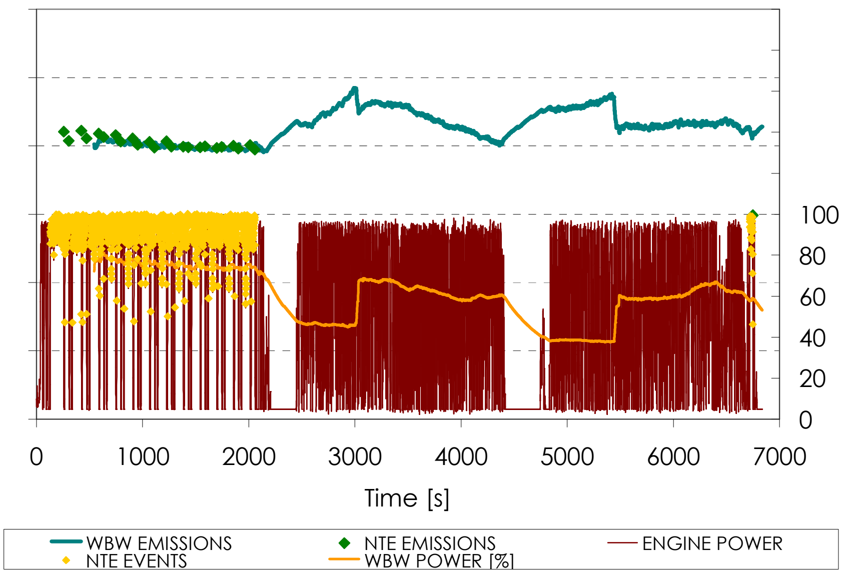

Figure 25 Control Area (US-NTE type) - Case study 1 - Events versus time and the phases of the duty cycle

The characteristics of the **second** cycle (qualified as "construction duty cycle") for the <u>second</u> case are as follows:

- 1 Unload boxes + Roading 25 min.
- 2 Idle 8 min.
- 3 Load boxes + Roading 30 min.
- 4 Idle 8 min.
- 5 Unload 10 boxes + Extend boom 11 min.
- 6 Idle 8 min.
- Total duration = 90 min.

The resulting coverage is illustrated in Figure 26 and Figure 27: the 'captured' control area operation occurs <u>mainly</u> at the maximum engine power and only during the first two 'working' phases of the duty cycle. Similar to the previous duty cycle, the very transient character of the engine operation causes a violation of the 30 seconds minimum sampling rule. For this second cycle, the total time in the control (NTE) area represented less than 5% (!) of the total test duration, for an average power of 29% over the entire cycle.

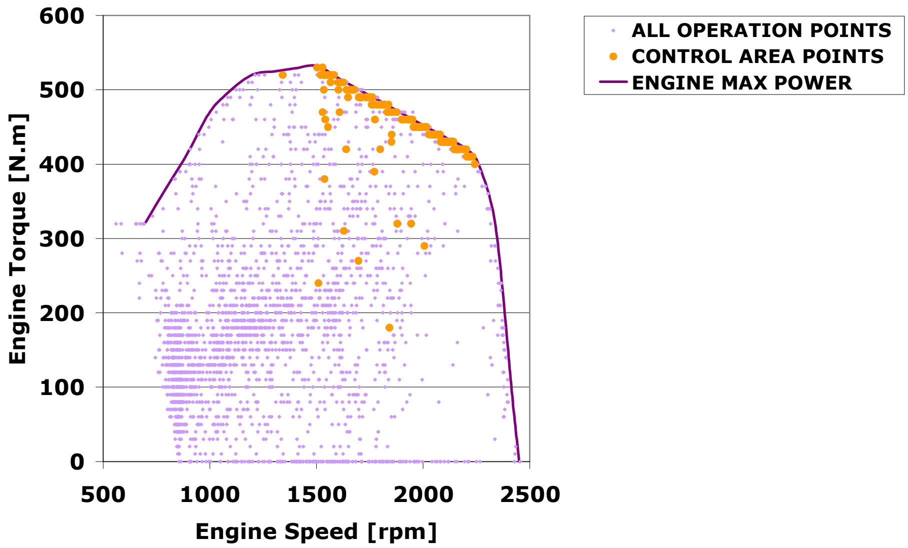

Figure 26 Control Area (US-NTE type) - Case study 2 - Events versus full load curve

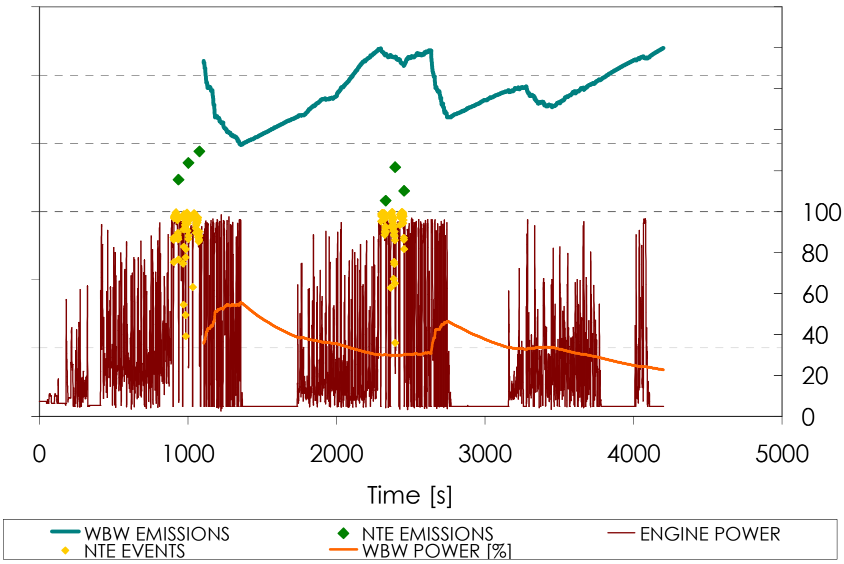

Figure 27 Control Area (US-NTE type) - Case study 2 - Events versus time and the phases of the duty cycle

When comparing the case study in section 5.7.2 to the other machines tested in the program, similar findings were obtained. In most cases, a limited amount of the total test data can be used for the transient test cycles (5 to 20%) and only the engines running at a nearly constant engine load can offer a reliable basis for the evaluation.

6 Conclusions

The lessons learned from the European PEMS pilot program for NRMM engine can be summarized as follows.

6.1 Experiments and data quality

The plausibility verifications have identified a small number of cases for which the uncertainty on some parameters can be qualified as 'high'. The main concern as it was the case for the HDV PEMS program, regarded the torque from the ECU, as it could not be verified nor calibrated with the measures foreseen in the initial test protocol. To overcome this issue, it is advisable to introduce additional rules similar to those in place for the ISC of HDV to check the correctness and the plausibility of the test data, in particular the torque from the ECU and the exhaust flow.

6.2 Data evaluation methods

Since the 'control area' method (such as the US NTE) was not fully applicable for the European situation (see section 5.7), the work focused on the adaptation of the moving averaging window (MAW). The main advantage of the control area methods, which was to eliminate the effect of idling upon the brake-specific emissions, was overcome with the introduction of the concept for working/non-working events for the MAW calculations. In addition, the introduction of a rule for the exhaust temperature during the take-off emissions after a long non-working event offers a similar level of stringency when compared to the US NTE requirements. However and contrary to the US rules, the MAW exhaust temperature requirement does not apply systematically and provides a good incentive for the engine manufacturer to optimise the thermal management of the emissions control systems.

The PEMS based ISC test and the associated data evaluation method are designed to maximize the probability that the engine emissions comply with the applicable standards, i.e. to give a sufficient confidence that the engine would comply if extracted from the vehicle and tested on an engine dynamometer.

7 References

[R1] Directive 2004/26/EC of the European Parliament and of the Council of 21 April 2004 amending Directive 97/68/EC 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

[R2] PEMS based In-service Testing on Non-Road - European Pilot Program - Project Plan - 2010-2012

[R3] EU Pilot – Review and Proposals - Eric R. Walker & Paul Williams, Caterpillar - 12th September, 2012

[R4] European Project On Portable Emissions Measurement Systems: "EU-PEMS" Project: Status and Activity Report 2004-2005, January 2006, EUR Report EUR 22143 EN.

[R5] European Project On Portable Emissions Measurement Systems: "EU-PEMS" Project – Guide for the preparation and the execution on heavy-duty vehicles, version 2, June 2006, EUR Report EUR 22280 EN.

[R6] European Project On Portable Emissions Measurement Systems: "EU-PEMS" - Task 2 Technical Report - Road Tests On Heavy-Duty Vehicles, September 2006

[R7] SAE Standard J1939 - Recommended Practice for a Serial Control and Communication Vehicle Network

[R8] ISO Standard 16183 - Heavy duty engines – Measurement of gaseous emissions from raw exhaust gas and of particulate emissions using partial flow dilution systems under transient test conditions

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Abstract

Since the EURO V standards for heavy-duty engines, the European emissions legislation requires to verify the conformity of heavy-duty engines with the applicable emissions certification standards: these provisions are identified as "In Service Conformity" (ISC).
It was considered impractical and expensive to adopt an ISC scheme for heavy-duty vehicles requiring the removal of engines from vehicles to test pollutant emissions against legislative limits. Therefore, it was proposed to develop a protocol for in-service conformity checking of heavy-duty vehicles based on the use of Portable Emission Measurement Systems (PEMS). As a result, ISC testing based on PEMS was introduced in the EURO V and the EURO VI standards. The corresponding administrative and technical provisions were formulated in the European Regulations 582/2011 and 64/2012.
The above route was followed for non-road engines as well: preliminary research activities studied and confirmed the possibility to apply the methods developed for heavy-duty engines with minor modifications. The basis for the introduction of ISC provisions based on the PEMS approach into the European NRMM type-approval legislation has been established in several texts.
The NRMM PEMS Pilot Program was launched to facilitate the introduction into the European NRMM emissions legislation of use of PEMS as a tool for ISC. This had to be achieved by improving the technical procedures (e.g. available from the heavy-duty scheme) and increasing the awareness of the different stakeholders about PEMS as a new regulatory tool.

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