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JRC TECHNICAL REPORT

PEMS EMISSIONS TESTING OF HEAVY DUTY VEHICLES/ENGINES:

ASSESSMENT OF PEMS PROCEDURES IN FULFILMENT OF ARTICLE 14(3) TO REGULATION (EU) 582/2011

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Abstract :

The Euro VI Regulation (EC) No 595/2009 and the implementing Regulation [2] (EC) 582/2011 introduces a procedure for PEMS testing as a mandatory part of the type approval legislation in order to check the conformity of heavy-duty engines with the applicable emissions certification standards during the normal life of those engines: this is the so-called "In Service Conformity" (ISC) requirements. In addition, Euro VI engines also have to verify their actual in-use emissions already at type approval (PEMS demonstration test). Even if the PEMS procedure has already been introduced into legislation there is still a need for further evaluation and development.

Article 14(3) of the implementing regulation for Euro VI (EC) No 582/2011 states the following: "Any additional requirements with respect to off-cycle in-use vehicle testing referred to in point (d) of paragraph 1 shall be introduced after the assessment of the PEMS procedures set out in Annex II. The assessment shall be finalised by 31 December 2014." An assessment of the currently introduced PEMS procedure should therefore be carried out, and based on the outcome of this assessment; proposals for amending the PEMS procedure should be made.

The European Commission through DG ENTR in co-operation with DG JRC launched in January 2012 a programme to address the legislative mandate to assess the present PEMS procedure. This report describes the activities during the programme, its findings and recommendations for amending the PEMS procedure.

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1.1. Background

The Euro VI Regulation (EC) No 595/2009 and the implementing Regulation [2] (EC) 582/2011 introduces a procedure for PEMS testing as a mandatory part of the type approval legislation in order to check the conformity of heavy-duty engines with the applicable emissions certification standards during the normal life of those engines: this is the so-called “In Service Conformity” (ISC) requirements. In addition, Euro VI engines also have to verify the off-cycle in-use emissions already at type approval (PEMS demonstration test). Even if the PEMS procedure has already been introduced into legislation there is still a need for further evaluation and development.

Article 14(3) of the implementing regulation for Euro VI (EC) No 582/2011 states the following: “**Any additional requirements with respect to off-cycle in-use vehicle testing referred to in point (d) of paragraph 1 shall be introduced after the assessment of the PEMS procedures set out in Annex II. The assessment shall be finalised by 31 December 2014.**” An assessment of the currently introduced PEMS procedure should therefore be carried out, and based on the outcome of this assessment; proposals for amending the PEMS procedure should be made.

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1.2. Expert working group and its Term of Reference

To advice the Commissions services on technical matters related to the assessment procedure, the Commission has been supported by an expert group (Heavy Duty (HD) PEMS expert group) consisting of experts from member states and industry.

Before any new procedures become mandatory, the Heavy Duty (HD) PEMS expert group has served as a platform to stimulate the exchange of information and experience among the involved stakeholders such as vehicle manufacturers, instrument manufacturers, laboratories, type approval authorities etc. A result of this exchange has been a guidance document of “best practices” on various technical subjects related to PEMS testing and data evaluation.

Measurement of particulates (PM) is not yet covered by the PEMS procedure for Euro VI. In order to prepare a proposal for introducing measurement of particulates into the legislation the PEMS expert group has provided advice on the procedure. The European PEMS PM evaluation program run by DG JRC in co-operation with stakeholders has established candidate PEMS PM instruments and principles. This program has provided the basis to proceed with the development of on-vehicle protocols and the dissemination of the technical know-how.

1.2.1. Mandate of the HD PEMS GROUP

The Heavy Duty (HD) PEMS expert group was open to stakeholder experts and should accompany the assessment and development of the HD PEMS procedure under the lead of DG ENTR and DG JRC. In particular, the group provided technical advice and a platform for the exchange of information and contributions of stakeholders that was discussed and agreed during the process.

The group focused on technical issues of the PEMS procedure. Political elements, e.g. the question of legal implementation for Euro VI, will have to be decided elsewhere.

1.2.2. *Organisational matters*

The HD-PEMS working group met regularly, according to demand, either face-to-face or via audio/web or video conferences.

Stakeholders provided their own travel costs unless otherwise indicated by the Commission.

2. Scope

This document presents the findings of the PEMS assessment exercise and provides recommendations on how to improve the existing procedure to perform the Conformity of In-Service Engines or Vehicles. The recommendations are based upon strong scientific/technical findings.

3. Summary of the PEMS procedure state of play

The current PEMS test procedure is described in Annex II of the implementing Regulation (EC) 582/2011 to the Euro VI Regulation (EC) No 595/2009. Annex II sets out requirements for checking and demonstrating the conformity of in-service engines and vehicles. In particular it sets the procedures of ISC, the engine or vehicle selection procedure, and the PEMS test specific conditions, such as: vehicle payload, ambient conditions, engine coolant temperature, and the specifications for the lubricating oil, fuel and reagent. It also prescribes the trip and operational requirements, as well as the availability and conformity of the ECU data stream information which is required for ISC testing.

The emission evaluation is performed in accordance to the Moving Averaging Window (MAW) principle based on the reference CO_2 mass or the reference work. The mass emissions are calculated for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the engine CO_2 mass or work measured over the reference laboratory transient cycle (WHTC).

3.1. *Moving Averaging Window (MAW) method*

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

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

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

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

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

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

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

3.1.1. Work based method (fig.1)

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 WHTC, kWh.

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

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

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

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

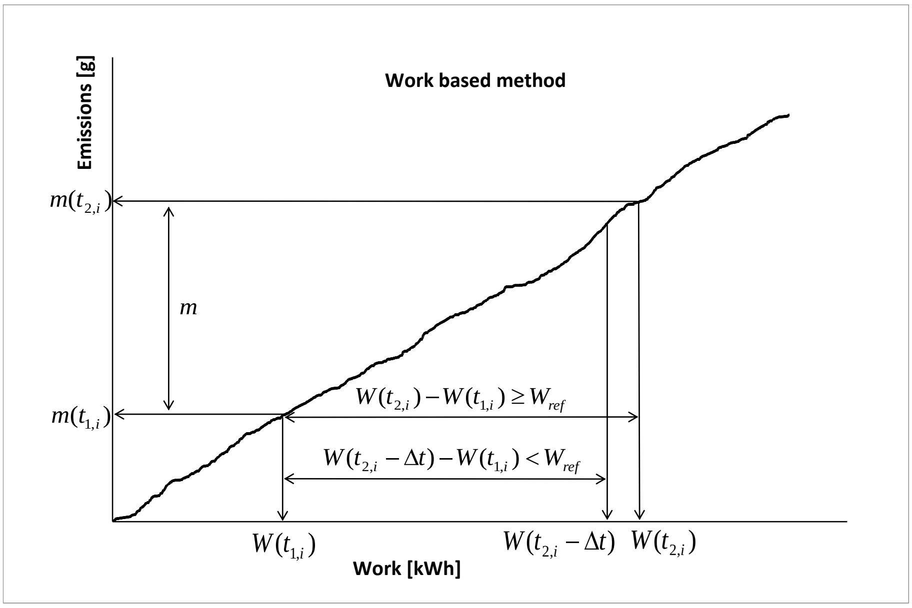


Figure 1 MAW Work based method

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

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

Where:

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

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

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

Where:

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

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

3.1.2. CO2 mass based method (fig.2)

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

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

Where:

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

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

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

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

Where Δt is the data sampling period, equal to 1 second or less.
In each window, the CO2 mass is calculated integrating the instantaneous emissions.

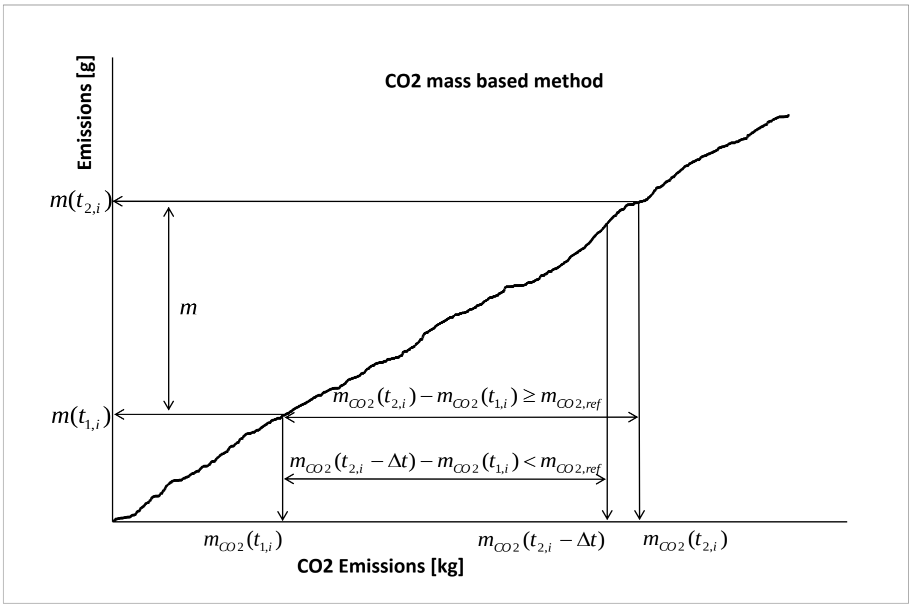


Figure 2 MAW CO2 based method

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

CO2 mass based method:

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

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

Where:

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

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

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

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

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

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

Where:

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

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

3.2. Calculation steps

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

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

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

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

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

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

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

4. PEMS assessment objectives

This chapter describes the topics which need to be considered in the PEMS assessment mentioned in article 14.3 of Regulation 582/2011, implementing Euro VI and therefore addressed within this report. The main objective is the verification of whether the PEMS procedure is able to properly check the conformity of heavy-duty engines with the applicable emissions certification standards during the normal life of those engines and at type approval: this is the so-called “In Service Conformity” (ISC) and PEMS demonstration test requirements.

Currently, the procedure on off-cycle emissions included in Euro VI consists of three main building blocks:

- Block 1: The boundary conditions, i.e. the environmental and vehicle/engine operating conditions under which the real-world emissions requirements have to be fulfilled.
- Block 2: The test and data evaluation procedures.

– Block 3: The objective-setting (as for example a Not-to-Exceed principle, i.e. all the valid data and averaged results cannot exceed a given value).

The Euro VI PEMS procedures already include those blocks and therefore address to a certain extent the real emissions of the vehicles. The main target for the assessment would be to determine if there are aspects that are not covered by the current procedures. The general concern with real NOx emissions in urban areas would be taken in principle as main priority, without detriment to other pollutant emissions. The latter may have a link with specific driving situations such as urban operation, which shall be assessed in depth.

4.1. Current Situation:

4.1.1. Block 1

The boundary conditions include the applicable:

– Ambient temperature and altitude (barometric pressure) ranges.
– Engine condition (Cold start is excluded until the engine coolant temperature reaches 70 ºC or for a maximum of 20 minutes from the beginning of the test).
– Engine operating power ranges (greater than 20% of Maximum Engine Power. If the number of valid windows is lower than 50%, the 20% power threshold can be decreased by steps of 1% until it reaches the 50% valid windows down to the minimum of 15% power threshold).

4.1.2. Block 2

The test and data evaluation procedures:

– Requirements for the composition of the test routes.
– Requirements for the vehicle payload (default of 50-60%).
– Data evaluation method based on a moving averaging principle using reference quantities from the type approval transient cycle (Engine work or CO2).

4.1.3. Block 3

The objective setting:

– Applies to all emitted gaseous pollutants and particle mass, with a maximum conformity factor of 1.5 for 90% of the valid windows.

4.2. List of procedure elements assessed and proposed approach

Based on the blocks set out above, specific issues regarding to its content were assessed.

The JRC has identified the following items as not covered by the current procedures, being therefore subjected to such an assessment:

1. Cold start emissions: Information is needed about the engine warm-up and the resulting cold-start emissions. For the assessment, there is a need to understand:
    a. Magnitude of ‘cold emissions’ with respect to ‘hot emissions’.
    b. Variability of ‘cold emissions’ measured from different PEMS experiments on the same vehicle.
    c. Influence of the test conditions (payload, test route and weather conditions…) upon the warm-up durations and the resulting emissions.

2. Low power operation: Information is needed about the vehicle operating conditions leading to low engine power operation and the resulting emissions.
    a. Influence of the test route composition and vehicle payload upon the engine power, (as instantaneous power or power ranges for the averaging window method).
    b. Influence of the test route composition, vehicle payload upon the composition of individual windows (in terms of urban, rural, motorway), to possibly understand whether the window evaluation method is appropriate to capture specific operating situations (e.g. urban).
3. Test route composition, vehicle payloads: The influence of the route composition (urban, rural, highway) and the vehicle payload are important factors affecting the emissions. It will therefore be the key parameter to understand if additional testing requirements need to be introduced for off-cycle emissions testing.
4. Review of the impact of the objective setting of assigning as the final CF of the test the 90th cumulative percentile for all boundary conditions.

The findings from the analysis could potentially lead to a modification of one or more elements of the procedure:

1. The boundary conditions (e.g. inclusion of cold start with specific objectives or weighing factors/modification of the power threshold).
2. The requirements for the test conditions (to test other vehicle payloads or trip compositions).
3. Specific aspects of data evaluation (e.g. 20% power threshold) and the data evaluation methodology (MAW method or other e.g. binning method).
4. The objective setting (e.g. if it is decided to set objectives for specific situations such as the cold start or the low power operation).

4.2.1. Data-experiments required

A number of experiments could be conducted to provide the required data. The minimum requirements for such tests would be:

- To take as reference the protocol included in 582/2011 Annex II;
- To test, at least, 3 vehicle types: a city bus (M3 Class I), a delivery truck (N1/N2) and a medium/heavy duty size truck (N3);
- Engine technology: Euro VI (DOC+ (EGR) SCR + DPF+ NH_3 slip catalyst).
- Each vehicle shall be tested with the ‘default’ payload (50%) and lower payloads (20 to 25%) and possibly higher payloads (70 to 80%).
- Each vehicle shall be tested on a variety of test routes (at least 3 of very different characteristics, to be carefully selected)

As far as it is possible, the testing program and the results obtained may be combined with other programs carried out at national or institutional levels.

5. Data sets

The engines/vehicles tested in the PEMS Assessment Program complied with the requirements of the European legislation in force (COMMISSION REGULATION (EU) No 582/2011 [2], for the Euro VI emissions standards). The selected vehicles covered the different heavy duty vehicles classes as defined in COMMISSION REGULATION (EU) No 678/2011 [4]. The program involved a total of 20 vehicles performing a total of 108 tests with roughly half of the tests including cold start conditions. Table 1 depicts the different vehicle types, the number of test per vehicles and the distribution of cold and warm start tests, together with the number of vehicles and OEMs involved. It is important to indicate that all the M3 vehicles participating in the program are city buses (***M3 Class I***).

Table 1 Overview of the number of tests and vehicles involved in the present asessment program (WS=Warm start tests and CS = Cold start tests)

PEMS Assessment				
Vehicle type	# test		# OEM	# vehicles
N1/N2	total = 29	WS = 15 CS = 14	5	8
N3	total =56	WS = 37 CS = 19	6	9
M2	total = 5	WS = 3 CS = 2	1	1
M3	total =22	WS = 12 CS = 10	3	4

5.1. Test equipment

The PEMS systems used to test the vehicles had to comply with the following 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 commercially available PEMS.

5.2. Vehicles

The list of vehicles tested in the program and their test characteristics in terms of starting conditions (W=warm and C=cold), reference work or CO_2 (work of CO_2 of their reference cycle; i.e. WHTC) and payload, together with a description of the trip they have performed in terms of its share of urban, rural and highway driving is shown in the Table 2. The calculation methodology to assign the trip shares is not defined in the present legislation. The shares indicated in Table 2 are calculated by analysing the second-by-second instant speed of the trip.

Table 2 Characteristics of the vehicles tested during the PEMS assessment program

Vehicle type	Test no.	WHTC Work ref [kWh]	CO2 ref [kg]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
N2*	N2-V1-T1	8.99	6.513	100	W	44%	24%	31%
	N2-V1-T2				W	38%	27%	35%
	N2-V1-T3				W	37%	26%	37%
	N2-V1-T4				W	49%	23%	28%
	N2-V1-T5				W	48%	23%	29%
	N2-V1-T6				W	53%	22%	25%
	N2-V1-T7				W	53%	23%	25%
N2	N2-V2-T1	13.79	10	50	C	51%	23%	26%
	N2-V2-T2				C	51%	20%	29%
N2	N2-V3-T1	10.32		0	C	48%	27%	25%
	N2-V3-T2				C	49%	27%	24%
	N2-V3-T3				C	49%	28%	23%
	N2-V3-T4				W	42%	33%	25%
N2	N2-V4-T1	15.8	10.4	0	C	46%	24%	31%
N2	N2-V5-T1	16.8	11.8	0	C	44%	25%	32%
N2*	N2-V6-T1	10	7.1	60	C	40%	28%	32%
N2	N2-V7-T1	12	8.38	53	C	45%	25%	30%
	N2-V7-T2				C	39%	27%	34%
	N2-V7-T3				C	74%	26%	0%
	N2-V7-T4				W	75%	25%	0%
N2	N2-V8-T1	15.96	11.5	100	C	54%	24%	22%
	N2-V8-T2			100	C	56%	25%	19%
	N2-V8-T3			40	W	50%	23%	27%
	N2-V8-T4			40	C	58%	20%	22%
	N2-V8-T5			40	W	52%	24%	25%
	N2-V8-T6			40	W	56%	20%	24%
	N2-V8-T7			40	W	54%	20%	26%
	N2-V8-T8			40	W	43%	49%	9%
	N2-V8-T9			40	W	42%	51%	6%

*Depending on the GVW, this vehicle can be defined as N1 or N2.

Vehicle type	Test no.	WHTC Work ref [kWh]	CO2 ref	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
N3	N3-V1-T1	26		10	W	64%	15%	21%
	N3-V1-T2			55	W	59%	19%	22%
	N3-V1-T3*			55	W	62%	11%	27%
	N3-V1-T4			55	C	35%	8%	57%
	N3-V1-T5			55	C	51%	7%	42%
	N3-V1-T6			100	W	41%	11%	48%
N3	N3-V2-T1	27.5		10	W	57%	21%	22%
	N3-V2-T2			55	W	57%	19%	23%
	N3-V2-T3			55	W	58%	21%	22%
	N3-V2-T4			55	C	33%	9%	58%
	N3-V2-T5*			55	W	62%	7%	31%
N3	N3-V3-T1	21.4		55	W	63%	19%	18%
	N3-V3-T2*			55	W	67%	10%	23%
	N3-V3-T3			100	W	65%	19%	16%
	N3-V3-T4			55	C	50%	13%	37%
	N3-V3-T5			10	W	66%	17%	17%
N3	N3-V4-T1	28		55	W	64%	16%	20%
	N3-V4-T2			55	C	54%	8%	38%
	N3-V4-T3			55	W	59%	9%	32%
	N3-V4-T4*			55	W	69%	8%	23%
	N3-V4-T5			10	W	66%	14%	20%
N3	N3-V5-T1	26.5		10	W	61%	19%	20%
	N3-V5-T2			55	W	62%	16%	22%
	N3-V5-T3			55	C	52%	8%	40%
	N3-V5-T4			55	W	68%	11%	21%
	N3-V5-T5			55	C	47%	10%	43%
	N3-V5-T6			100	W	63%	17%	20%
N3	N3-V6-T1	33	22.6	10	W	45%	48%	7%
	N3-V6-T2			10	W	45%	52%	3%
	N3-V6-T3			10	W	39%	25%	36%
	N3-V6-T4			10	W	40%	24%	36%
	N3-V6-T5			50	W	39%	23%	38%
	N3-V6-T6			50	W	39%	24%	37%
	N3-V6-T7			100	W	38%	27%	34%
	N3-V6-T8			100	W	39%	28%	33%
	N3-V6-T9			10	W	37%	28%	35%
	N3-V6-T10			10	W	42%	25%	33%
	N3-V6-T11			10	W	42%	29%	30%
	N3-V6-T12			10	C	36%	21%	43%
	N3-V6-T13			10	W	35%	63%	2%
	N3-V6-T14			10	C	39%	21%	40%
	N3-V6-T15			10	W	36%	22%	41%
	N3-V6-T16			10	W	33%	23%	44%
	N3-V6-T17			10	W	33%	24%	43%
	N3-V6-T18			10	W	35%	63%	2%

Vehicle type	Test no.	WHTC Work ref [kWh]	CO2 ref	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
N3	N3-V7-T1	29.5		55	C	48%	13%	38%
	N3-V7-T2			55	C	45%	14%	41%
	N3-V7-T3			55	C	44%	15%	42%
	N3-V7-T4			55	C	39%	16%	44%
	N3-V7-T5			55	C	63%	18%	19%
	N3-V7-T6			10	C	52%	13%	34%
	N3-V7-T7			55	C	32%	10%	58%
N3	N3-V8-T1	23.5	15.7	25	C	22%	23%	55%
	N3-V8-T2			25	C	26%	23%	51%
N3	N3-V9-T1	35.1	22.4	50	C	27%	27%	46%
	N3-V9-T2			25	C	24%	23%	53%

Vehicle type	Test no.	WHTC Work ref [kWh]	CO2 ref [kg]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
M2	M2-V1-T1	10	7.1	100	W	52%	23%	26%
	M2-V1-T2			100	C	54%	22%	24%
	M2-V1-T3			100	W	56%	20%	24%
	M2-V1-T4			100	C	53%	22%	25%
	M2-V1-T5			100	W	59%	20%	21%

Vehicle type	Test no.	WHTC Work ref [kWh]	CO2 ref [kg]	Payload	Start condition	Urban [%]	Rural [%]	MW [%]
M3 (class I)	M3-V1-T1	18.7	13.88	48	W	70%	18%	12%
	M3-V1-T2			10	W	91%	9%	0%
	M3-V1-T3			10	W	69%	16%	16%
	M3-V1-T4			48	C	70%	20%	9%
	M3-V1-T5			48	C	70%	18%	11%
M3 (class I)	M3-V2-T1	18.6	12.26	90	C	75%	25%	0%
	M3-V2-T2			90	C	75%	25%	0%
	M3-V2-T3			55	C	80%	20%	0%
	M3-V2-T4			55	C	75%	25%	0%
	M3-V2-T5			10	C	75%	25%	0%
	M3-V2-T6			10	C	74%	26%	0%
M3 (class I)	M3-V3-T1	21	16	55	W	72%	28%	0%
	M3-V3-T2			55	W	66%	34%	0%
	M3-V3-T3			55	C	65%	35%	0%
	M3-V3-T4			10	C	70%	30%	0%
	M3-V3-T5			10	W	64%	36%	0%
	M3-V3-T6			10	W	64%	35%	0%
	M3-V3-T7			10	W	40%	24%	37%
	M3-V3-T8			10	W	36%	27%	37%
	M3-V3-T9			10	W	54%	23%	23%
M3 (class I)	M3-V4-T1	26	17.8	50	W	65%	35%	0%
	M3-V4-T2			10	W	67%	33%	0%

5.3. Test routes

The tested vehicles have not been always operated following the present ISC legislation that prescribes for each type of vehicles the share of urban, rural and highway operation. The Euro VI legislation [2] prescribes the trips requirements as follows (this is an extract of the legislation for the sake of completion):

1. The shares of operation shall be expressed as a percentage of the total trip duration.
2. The trip shall consist of urban driving followed by rural and motorway driving according to the shares specified below. In the case another testing order is justified for practical reasons and after the agreement of the approval authority another order of urban, rural and motorway operation may be used.
3. For the purpose of this Section, 'approximately' shall mean the target value ± 5 %.
4. Urban operation is characterised by vehicle speeds between 0 and 50 km/h,
5. Rural operation is characterised by vehicle speeds between 50 and 75 km/h,
6. Motorway operation is characterised by vehicle speeds above 75 km/h.
7. For M 1 and N 1 vehicles the trip shall consist of approximately 45 % urban, 25 % rural and 30 % motorway operation.
8. For M 2 and M 3 vehicles the trip shall consist of approximately 45 % urban, 25 % rural and 30 % motorway operation. M 2 and M 3 vehicles of Class I, II or Class A as defined in Annex I to Directive 2001/85/EC of the European Parliament and of the Council [5] shall be tested in approximately 70 % urban and 30 % rural operation.
9. For N 2 vehicles the trip shall consist of approximately 45 % urban, 25 % rural and followed by 30 % motorway operation.
10. For N 3 vehicles the trip shall consist of approximately 20 % urban, 25 % rural and followed by 55 % motorway operation.

It also provides a distribution of the characteristic trip values from the WHDC database as additional guidance for the evaluation of the trip:

a. accelerating: 26,9 % of the time;
b. decelerating: 22,6 % of the time;
c. cruising: 38,1 % of the time;
d. stop (vehicle speed = 0): 12,4 % of the time.

5.4. Assessment procedure

Each trip was processed following the present applicable methodology as described in the legislation in order to have the baseline to compare with (see section 3.3). Then each of the procedure elements to be assessed in section 4.2 was taken into consideration by applying to each trip the appropriate alternative data-evaluation conditions. For example when addressing the power threshold the trips were processed by reducing the values from 20% (present legislative value) of the maximum engine power to no-power threshold in steps of 5% to investigate the effect in terms of final conformity-factor values and data coverage at each of these power threshold. On the other hand, when addressing cold-start operation, the part of the trip with coolant temperature below 70 ℃ was kept as valid data rather than excluding then as required by the present applicable legislation (see section 3.3, step 2).

Further, a combination of elements were also studied in order to understand the impact on the data evaluation and final results of applying at the same time various exclusion conditions (section 3.3) as are prescribed in the present ISC legislation.

The above procedure was followed for each of the tests (trips) that were obtained from the stakeholders participating in the PEMS assessment program.

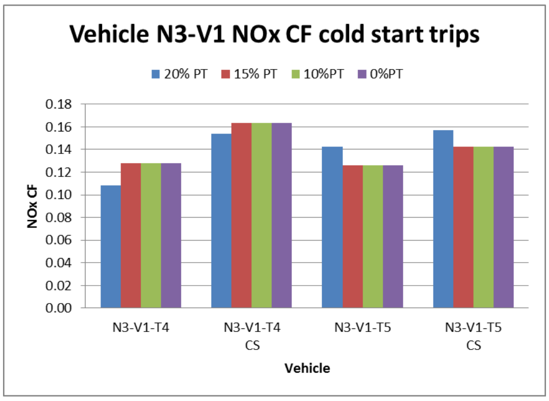
6. Assessment evaluation

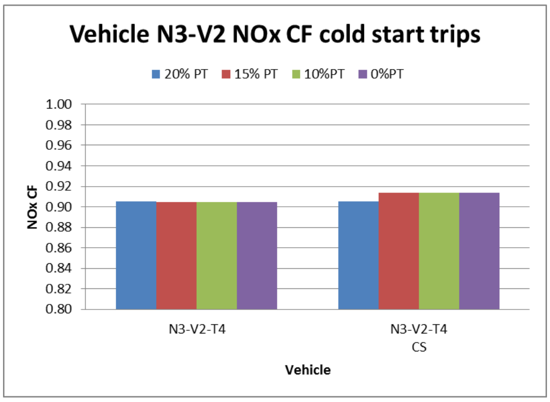
In this section the different procedures elements that were identified in section 4.2 are addressed following the procedure described in section 5.4 for all the vehicle-classes subject of the assessment evaluation.

6.1. Cold start operation

In the present legislation cold-start operation defined as the part of the operation with a coolant temperature below 343 K (70 °C) [6] is not considered in the data evaluation.

The first approach to study the impact of the inclusion of cold-start operation in the data evaluation of the trips was to follow the description of section 5.4; i.e. the inclusion of cold-start operations while keeping all the other parameters fixed to the present legislation (power threshold and 90th cumulative percentile). Figure 6-1, Figure 6-2, Figure 6-3 and Figure 6-4 depicts the results under these conditions obtained for N3, N2 and M3 vehicles respectively. All the considered N3 trips depicted in Figure 6-1 had a trip-length ranging from 8 to 10 times the work at WHTC and starting ambient/coolant temperatures ranging from 10 to 20°C. In the same Figure 6-1 the impact of changing the power threshold is also addressed. However this last point will be treated in more detail in a later section dedicated to the impact of the power threshold in the data processing.





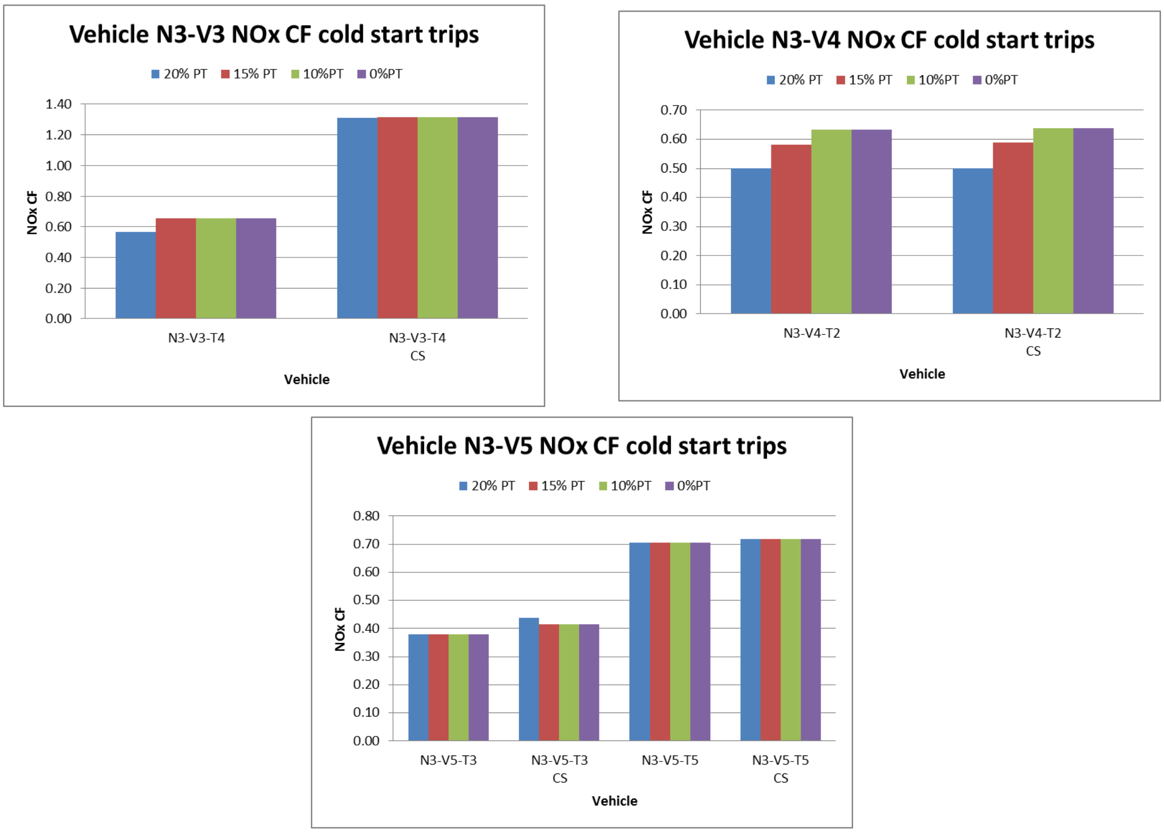


Figure 6-1 Comparison of the NOx CF for N3 vehicles with (#_CS) and without considering the cold-start operation. Please note that the figures have different maximum values on the "Y" axis to be able to see the differences between the different conditions, which in some cases, are too small to notice using the same scale for all cases.

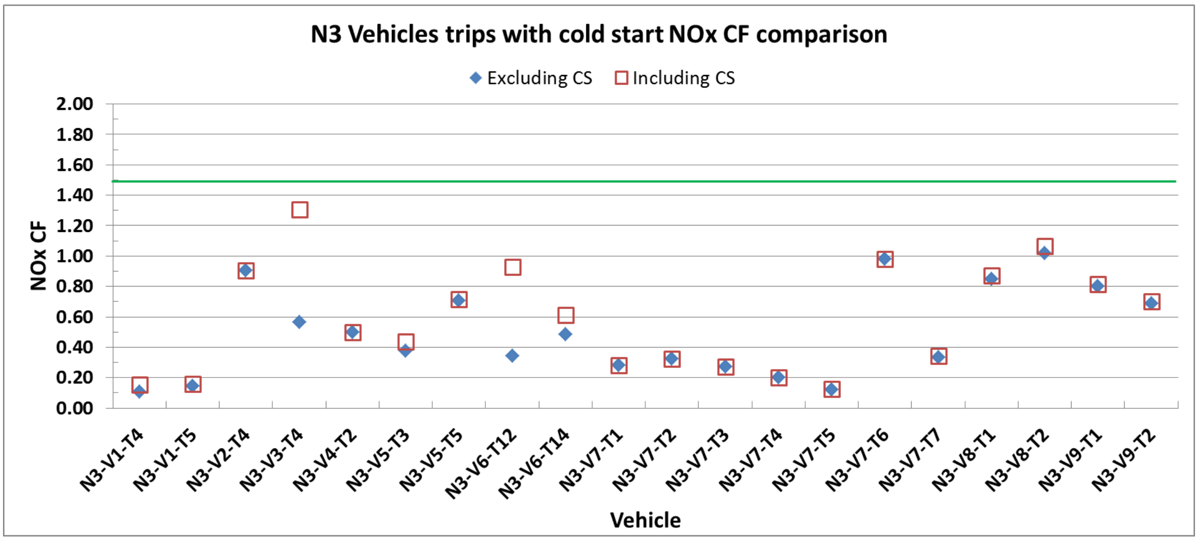


Figure 6-2 Direct comparison of NOx CF between trips including or excluding cold-start operations (N3).

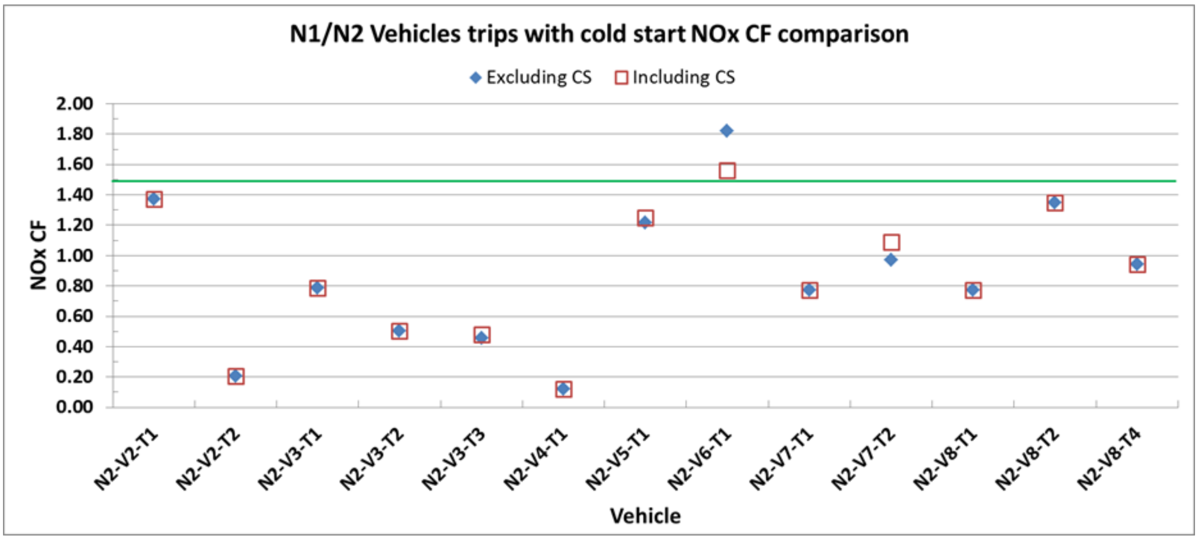


Figure 6-3 Direct comparison of NOx CF between trips including or excluding cold-start operations (N1/N2).

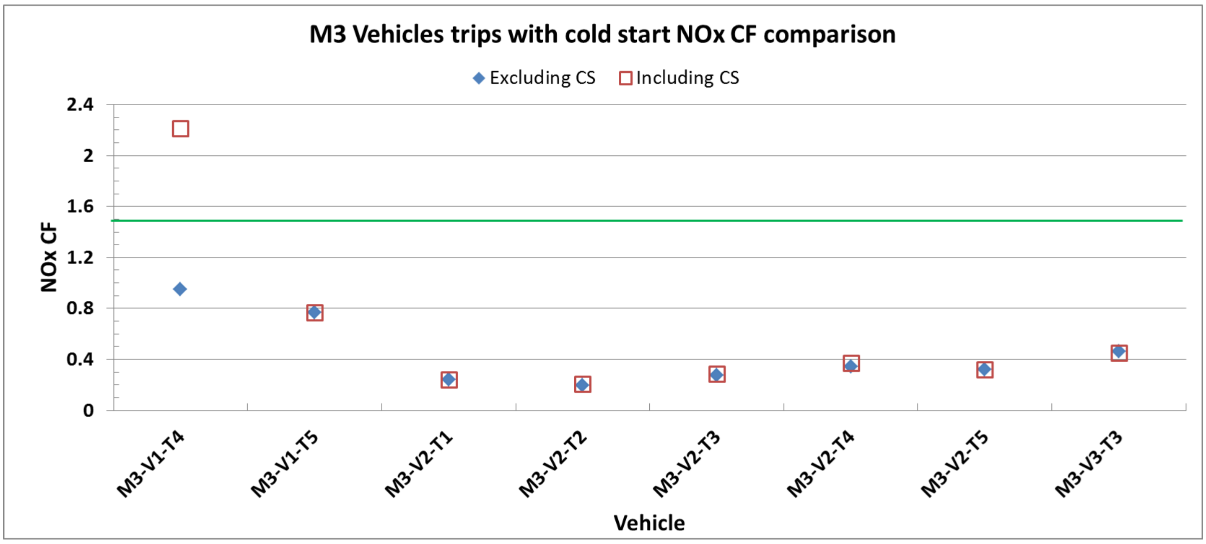


Figure 6-4 Direct comparison of NOx CF between trips including or excluding cold-start operations (M3).

In a first approach it seems that these results support the idea that the present methodology could be used to provide an assessment of cold-start operations as it can distinguish those vehicles with some difficulties in controlling their emissions during the cold-start operation as compared with those with a better cold-start emission control (see Figure 6-5 and Figure 6-6). These figures also show the valid windows both with and without cold-operation.

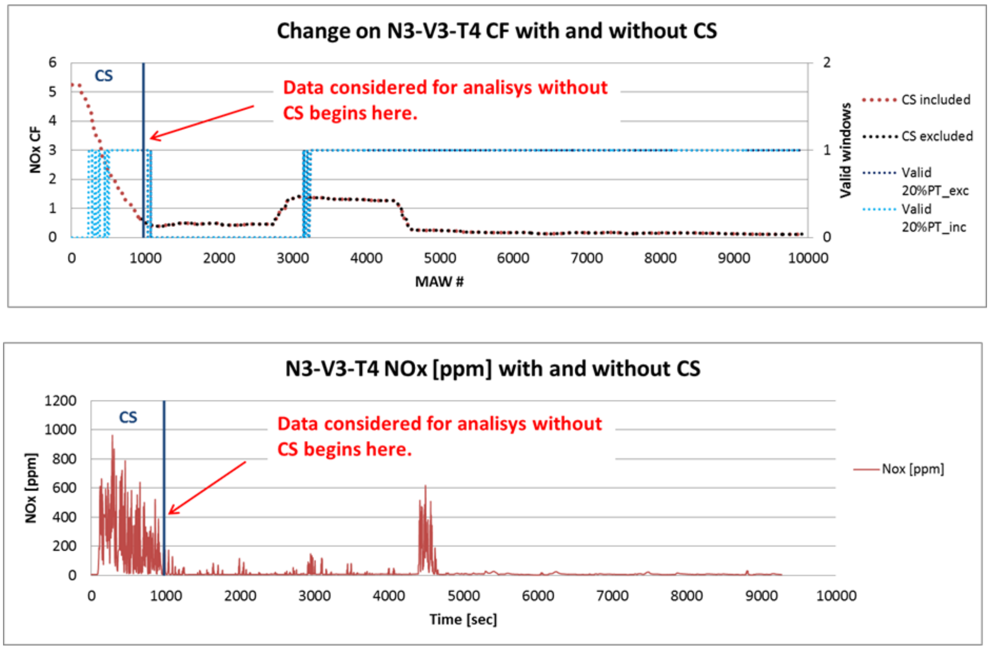


Figure 6-5 Vehicle with difficulties in controlling emissions during cold-start operation (longer CS and higher NOx emissions)

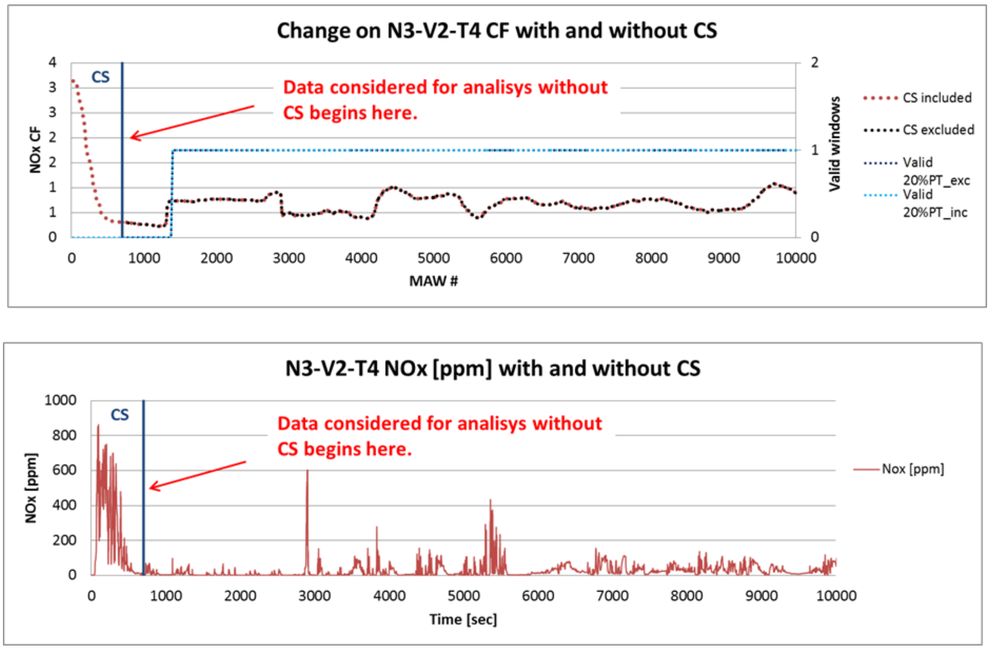


Figure 6-6 Vehicle with better NOx emissions during cold-start operation (shorter CS and lower NOx emissions)

However, it was very early recognised (Figure 6-7) that the inclusion of cold-start operation in the PEMS methodology and its insertion in ISC procedure could not be decoupled from other conditions (for example: boundary conditions – 20% power threshold – and objective settings – 90th cumulative percentile–).

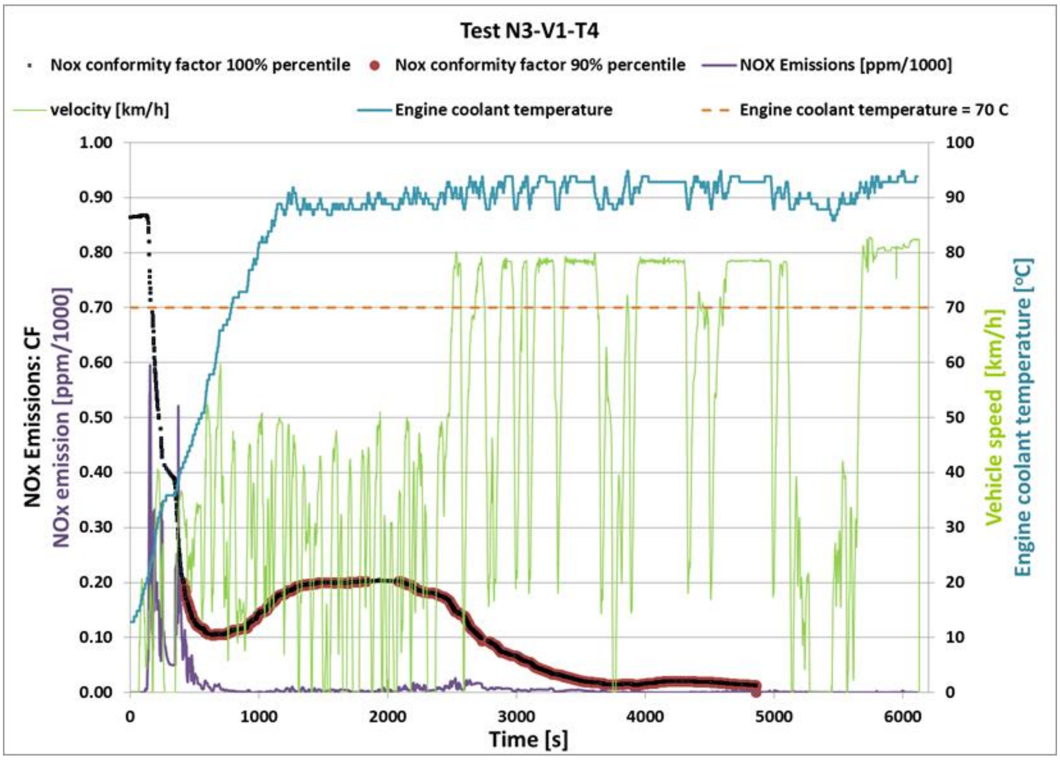


Figure 6-7 Operational and emission parameter of a trip with cold-start operation indicating the part that will be considered if the objective setting of 90th percentile is considered. Obviously most of the NOx emitted during the cold-operation will not be part of the final result.

The objective setting of 90th cumulative percentile (Figure 6-7) will result in not having considered most of the emissions during the cold-start operation period. In other cases, the inclusion of the 20% power threshold will further reduce the amount of NOx emissions considered during cold-start operation. Figure 6-8 and Figure 6-9 clearly shows the impact on the NOx CF values when taking 10% power threshold rather than the presently prescribed 20%. The differences are more marked for N1/N2 vehicles as compared with N3 vehicles (Figure 6-8 compared with Figure 6-3).

Further insight on the cold start operation and the impact of other parameters will be addressed later in the report.

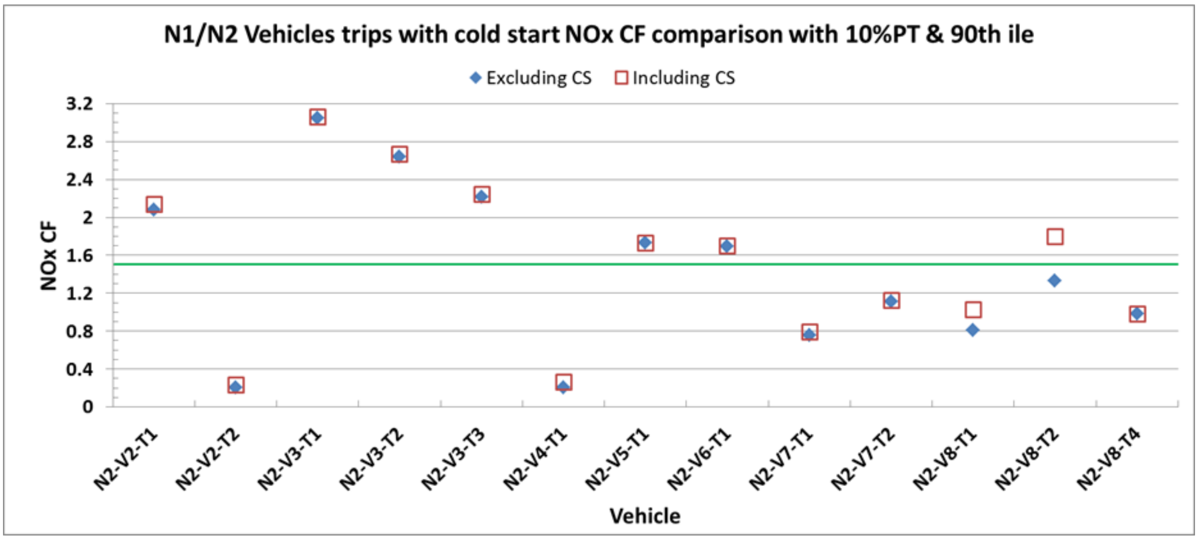


Figure 6-8 Direct comparison of NOx CF between trips including or excluding cold-start operations (N1/N2) but using 10% power threshold as boundary condition.

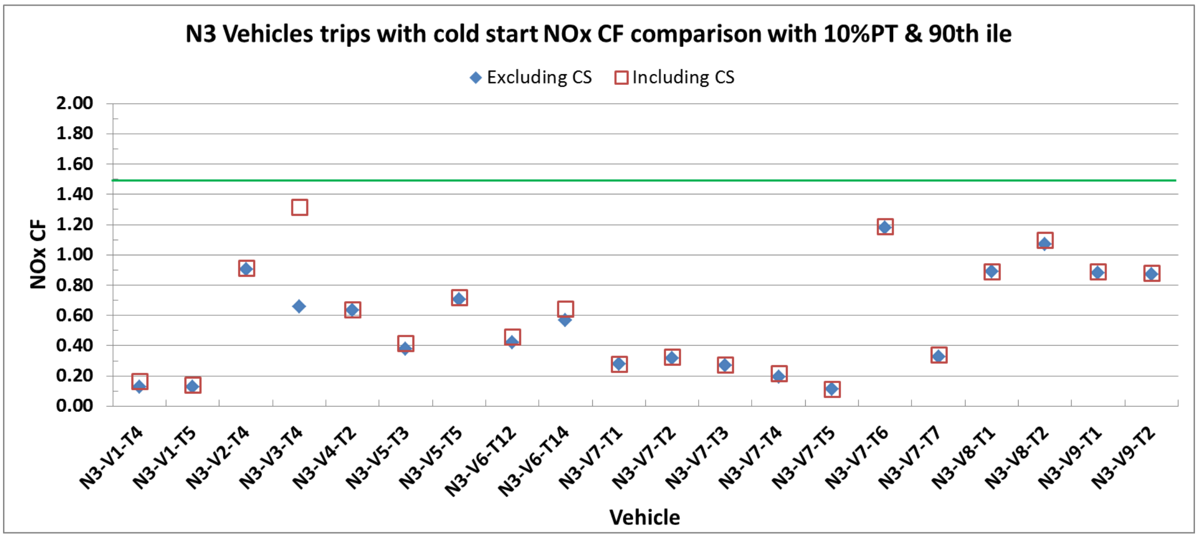


Figure 6-9 Direct comparison of NOx CF between trips including or excluding cold-start operations (N3) but using 10% power threshold as boundary condition.

6.2. Low power operations

Figure 6-10, Figure 6-11, Figure 6-12 and Figure 6-13 depicts the NOx CF for the different heavy duty vehicle classes at different imposed power threshold (it ranges from 20% of maximum engine power to no-power threshold) in the data processing methodology. An inspection of the graphs shows that in the majority of cases (some exceptions) there is an increase of the NOx CF when the power threshold is reduced from the present values of 20% of the maximum engine power. The increase is more striking for N1/N2 vehicle class. It is also noteworthy to highlighted that for M2 vehicles there are not enough valid windows (>50%) at 20% (or even at 15%) power threshold in many occasions This indicates that in these vehicle classes the power threshold is critical and that in many occasion a large amount of the NOx emitted is not considered in the data processing.

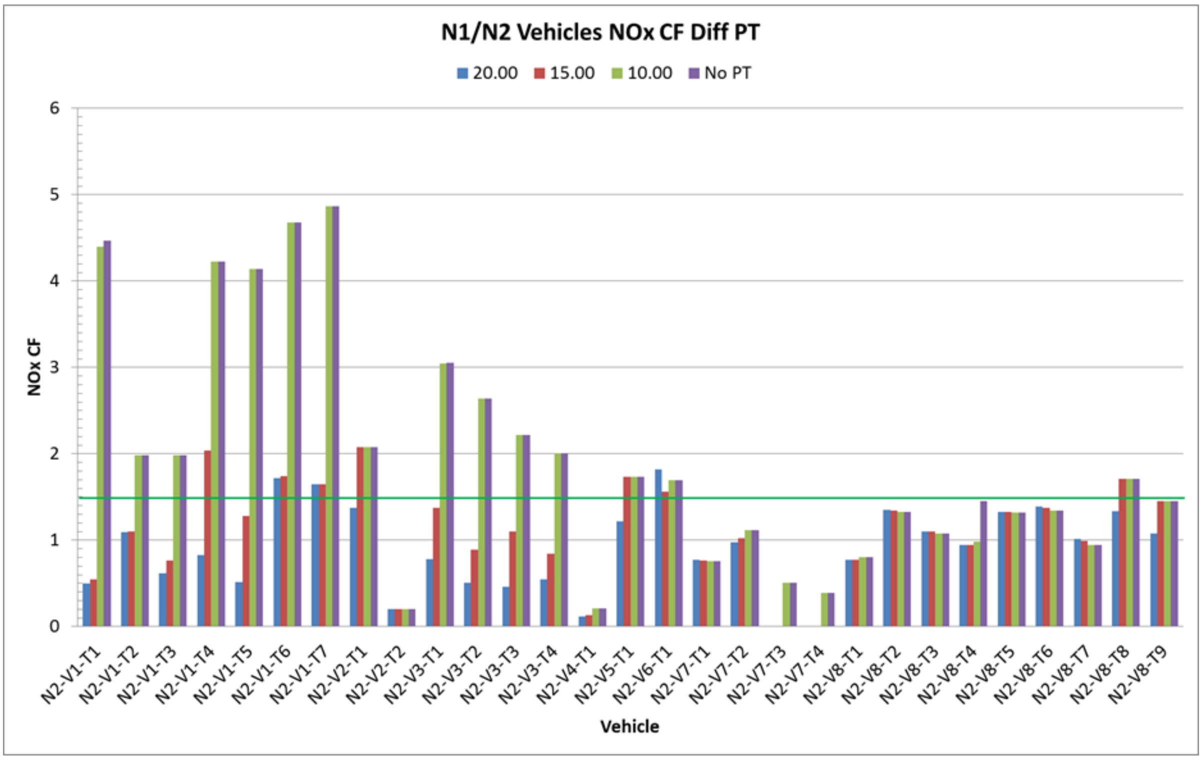


Figure 6-10 NOx CF for N1/N2 vehicles excluding data above different power threshold (20%, 15%, 10% and no power threshold)

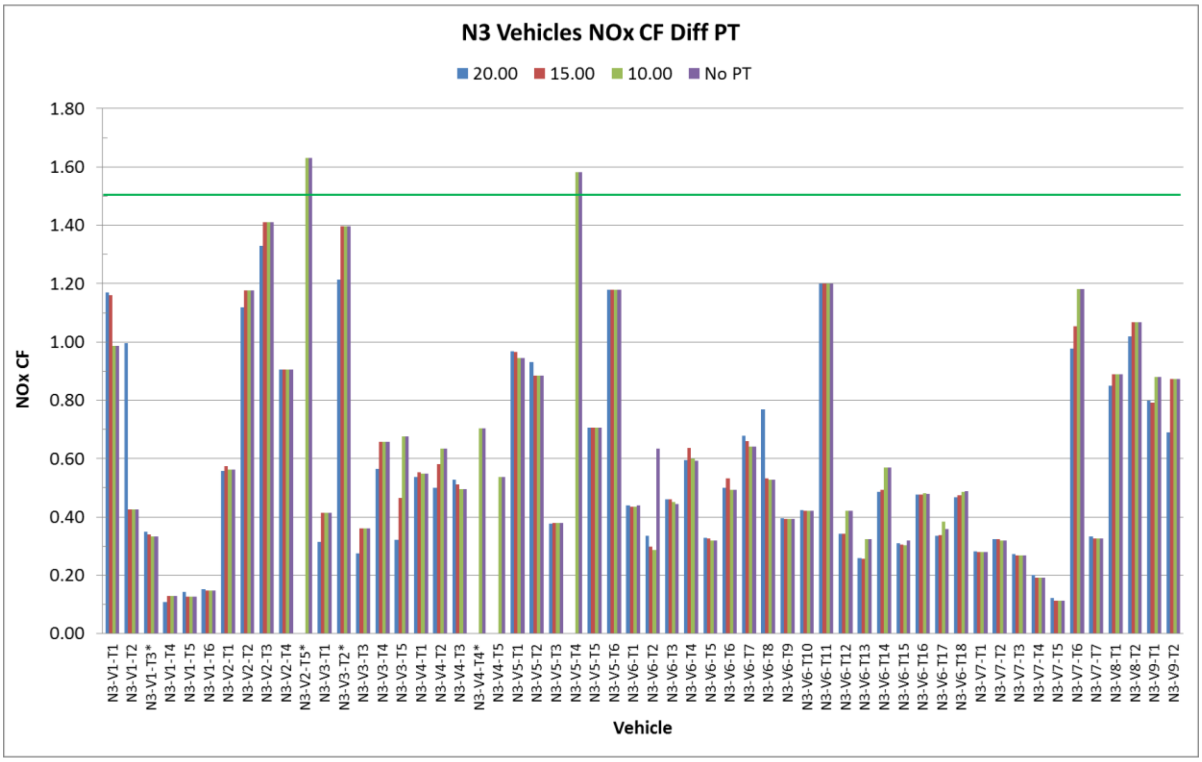


Figure 6-11 NOx CF for N3 vehicles excluding data above different power threshold (20%, 15%, 10% and no power threshold). Trips with an * indicate trips with a large percentage of idle (idle trips)

A closer look at the NOx emissions throughout the test (trip) shows that the operational area which the 20% power threshold excludes from the data processing mostly corresponds to the low power operation (urban operation) part of the prescribed trip applicable to these vehicles categories. Figure 6-14 shows an example of this situation: due to the 20% power threshold imposed in the data processing of the trip, nearly all the urban operation of the vehicle is not taken into consideration.

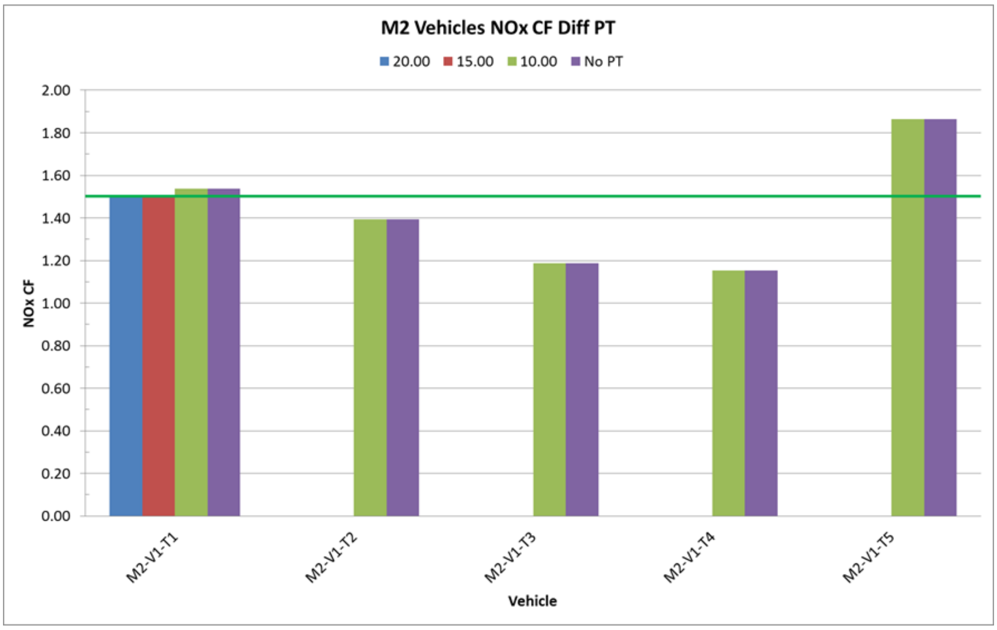


Figure 6-12 NOx CF for M2 vehicle excluding data above different power threshold (20%, 15%, 10% and no power threshold).

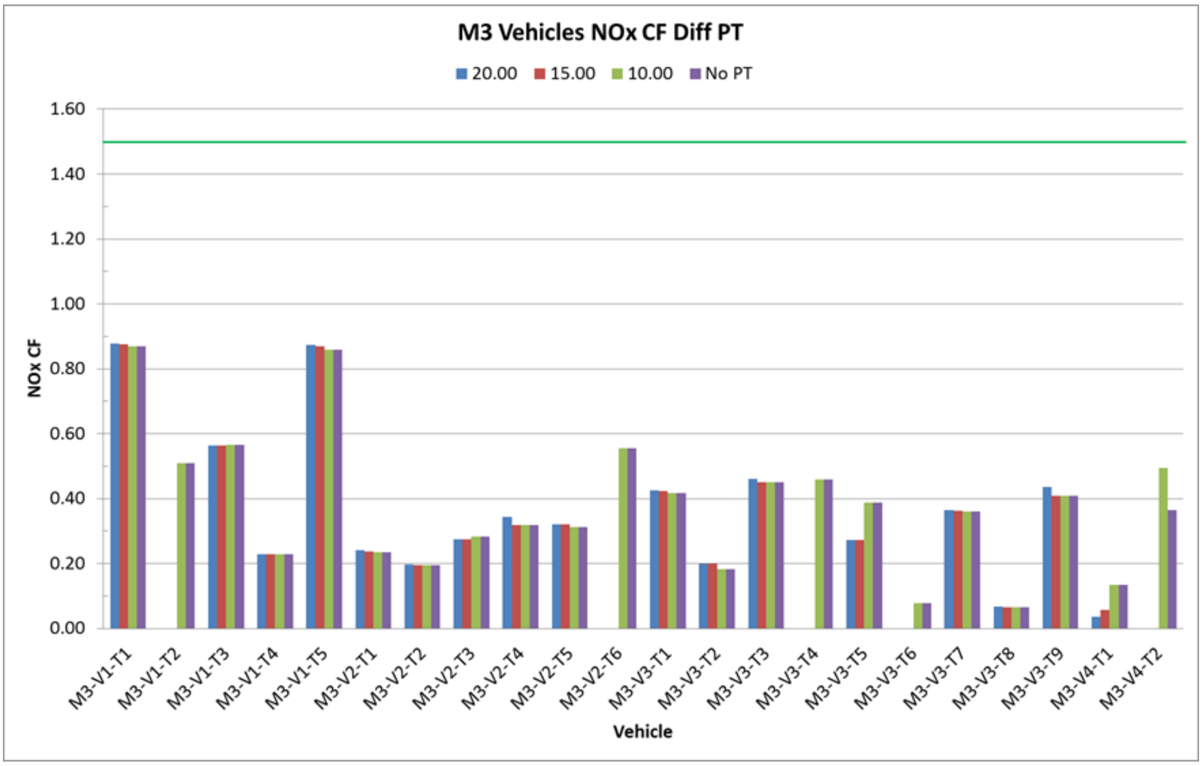


Figure 6-13 NOx CF for M3 (Class I) vehicles excluding data above different power threshold (20%, 15%, 10% and no power threshold).

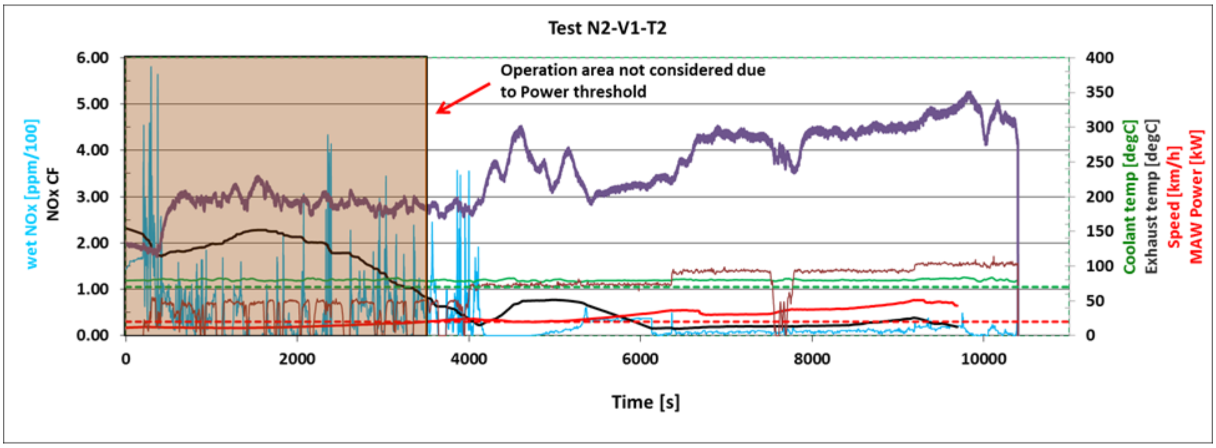


Figure 6-14 Example of a trip (N2 vehicle category) where the part of data not considered because it is below the 20% power threshold is highlated. Most of the low power operation (urban operation) part is disregarded.

The above finding is quite worrisome because these vehicle categories (N1/N2) are largely found operating in an urban environment where the impact of emissions on the public at large is more acute.

The lack of urban operation coverage with the presently applicable boundary conditions will be further supported by data analysis later in this report (section 6.3) when the vehicle emission behaviour in urban, rural and highway operation will be presented.

6.3. Trip composition

In this section the contribution to the overall emission in terms of NOx CF of the different components of the trip is studied and reported: i.e. the contribution of the urban, rural and highway operations for the different vehicle categories.

One needs to keep in mind that when calculating the different contribution of the different parts of the trip, the objective setting of 90th cumulative percentile and the exclusion of cold-start operation are applied, while the 20% maximum engine power threshold is ignored. In other words all the windows within an operation area are considered.

The assignation to urban, rural or highway operation is done based on the average vehicle speed of the window (MAW); e.g. if the average speed of a given window is lower than 50 km/h then it is considered to be an urban operation window.

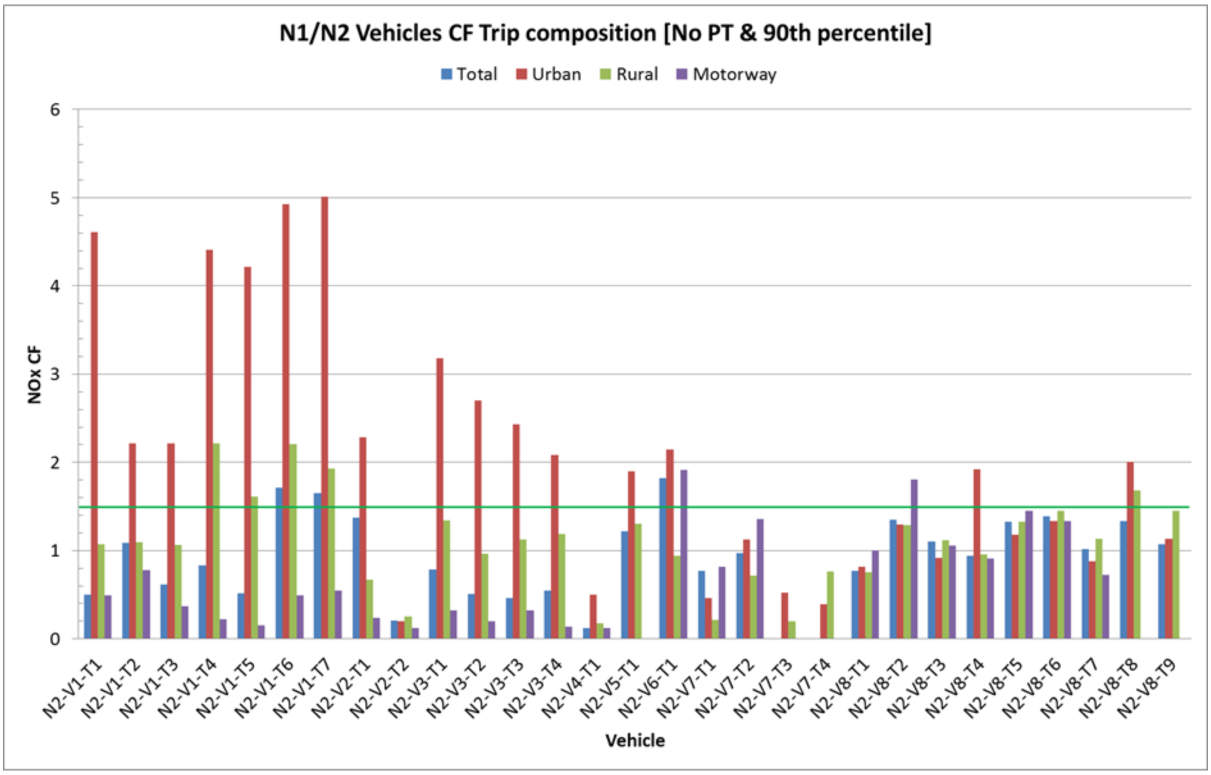


Figure 6-15 NOx emissions (CF) of the different components of the trip (U-R-M) for N1/N2 vehicle category

The large difference found between the overall NOx CF value and those taken into consideration only the urban operation (no power threshold is imposed in this case) supports the findings in the previous section (see Figure 6-15, Figure 6-16, Figure 6-17 and Figure 6-18); i.e. that the power threshold set at 20% translates largely in a disregard of large part of the emissions produced during the low-power (urban) operation. This is more critical in the N1/N2 vehicle category and in a lesser extent in the rest of vehicle categories. However, it is necessary to point out, as it was the case in the previous section, that in most of the tests, M2 vehicles did not comply with the minimum number of valid windows (50%) when imposing the 20% power threshold; or indeed the 15% power threshold as this is the lower limit in power allowance if the 20% power threshold does not meet the requirements (see Section 4.1.1)

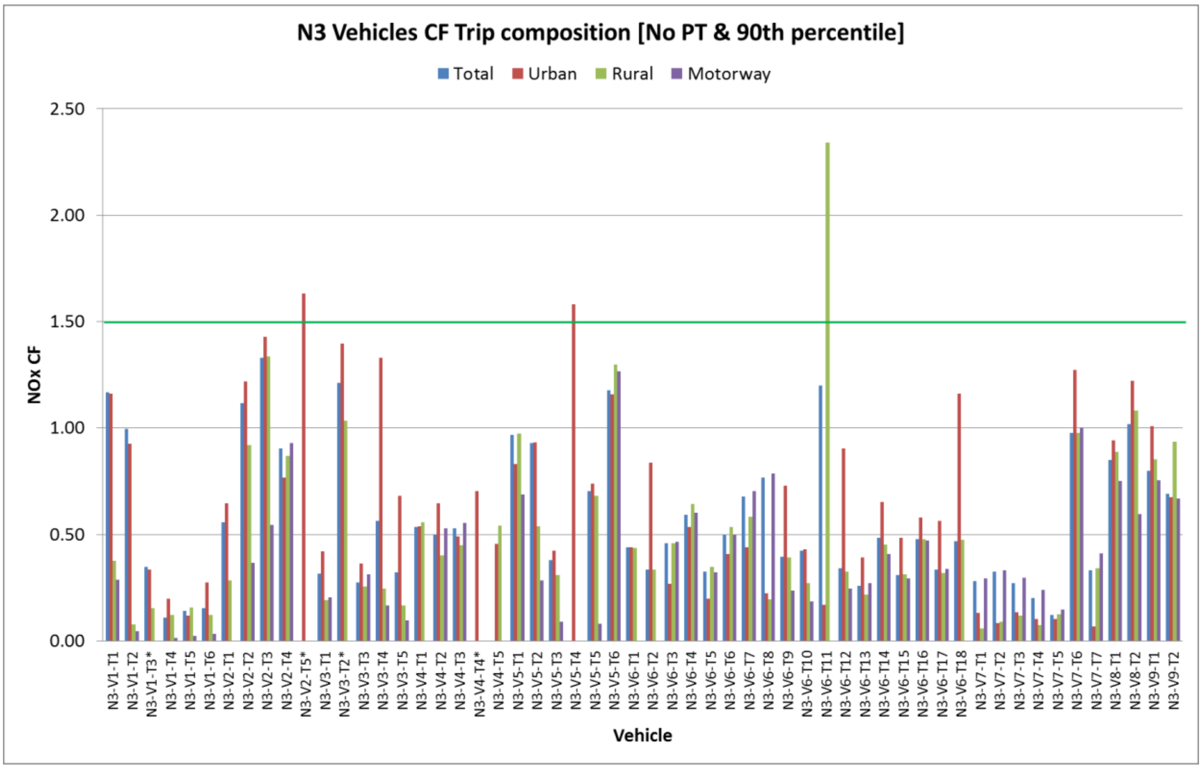


Figure 6-16 NOx emissions (CF) of the different components of the trip (U-R-M) for N3 vehicle category. Trips with an * indicate trips with a large percentage of idle (idle trips)

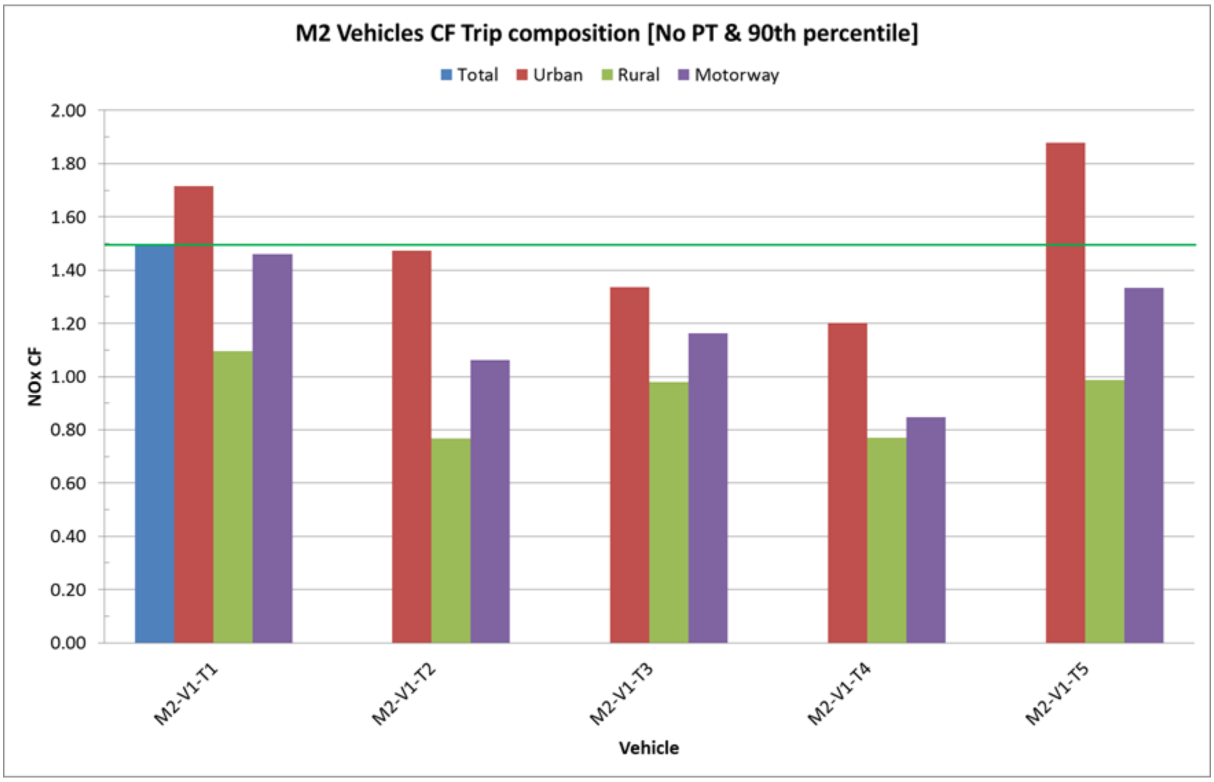


Figure 6-17 NOx emissions (CF) of the different components of the trip (U-R-M) for M2 vehicle category

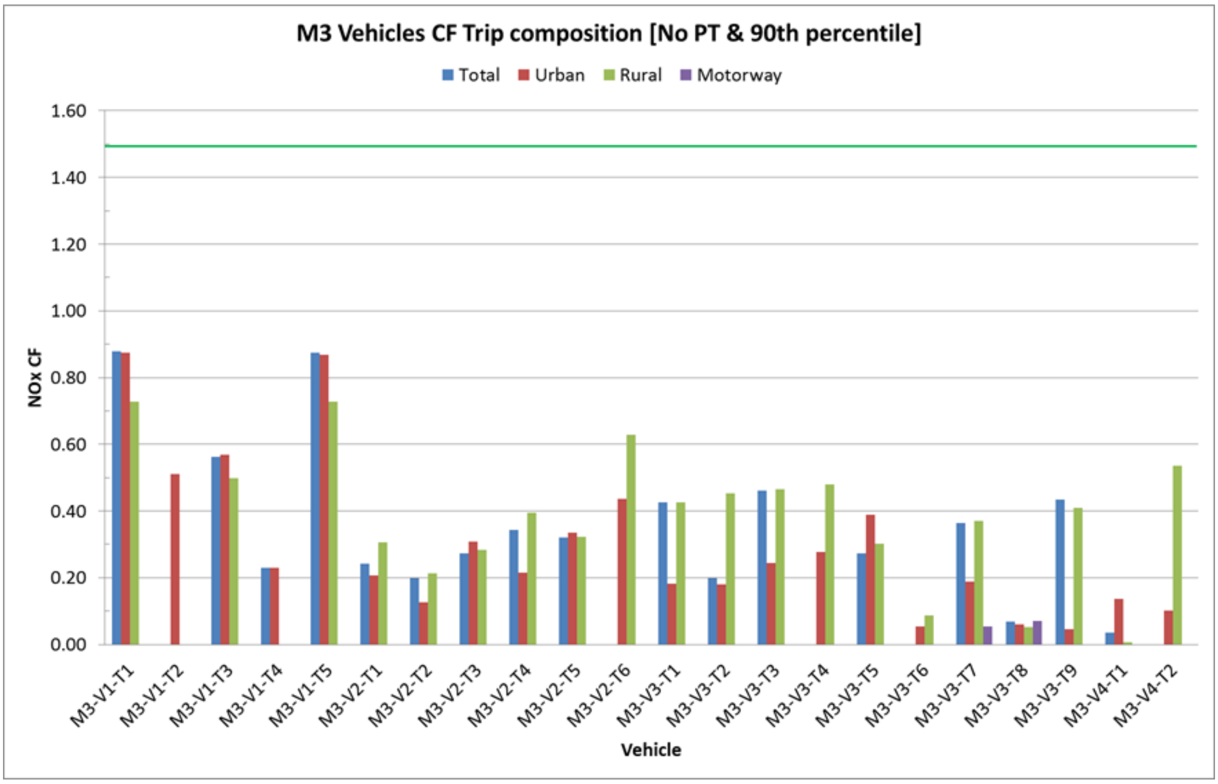


Figure 6-18 NOx emissions (CF) of the different components of the trip (U-R-M) for M3 (Class I) vehicle category

In general the distribution found when applying the operational binning; i.e. urban, rural and highway, is related to the trip composition as prescribed by the present legislation (see section 5.3.). For instance for M3 (Class I) vehicles, the trip must have an operation with the following distribution: 70% urban and 30% rural; as it can be seen, Figure 6-18 rarely show any values in the motorway binning portion.

On the other hand the distribution in terms of average per-cent contribution to the different components of the trip[1] indicates that in general all the analysed trips comply with the required legislated route composition (Figure 6-19). However the average velocities[2] of each of those route components are in general much higher than what is expected from the average velocity found in the combined data from the WHDC database for Europe (Urban: 21.6 km/h, Rural: 46.4 km/h and Motorway: 78.5 km/h) and the average velocity from the WHVC (Urban: 21.3 km/h, Rural: 43.1 km/h and Motorway: 76.2 km/h). This indicates the need to introduce in the description of the trip composition not only the shares of operation which is characterised by a vehicle speed range, but also to specify an average speed in that range. The methodology to calculate these average speeds need to be further discussed.

Figure 6-20 depicts the behaviour in terms of NOx emission of a vehicle which has performed similar trips but it the reverse order. In the first case, (a), the low operation share is performed at the beginning of the trip while in the second case, (b), is performed at the end after the motorway and rural shares. It is obvious that with independence of considering or not cold start (time < 1000 s), the emissions in the

[1] Calculated as in the case of table 2.

[2] The average velocity has been calculated by analysing the second-by-second instant speed of the trips

urban part of the trip (a) is larger than in the case (b). This seems to indicate the need to maintain the present legislative prescription of the trips order: i.e. urban followed by rural and motorway operation. In the case (b) the vehicle when arrives at the urban operation part of the trip has undergone a conditioning of the after-treatment system that is not the case in (a).

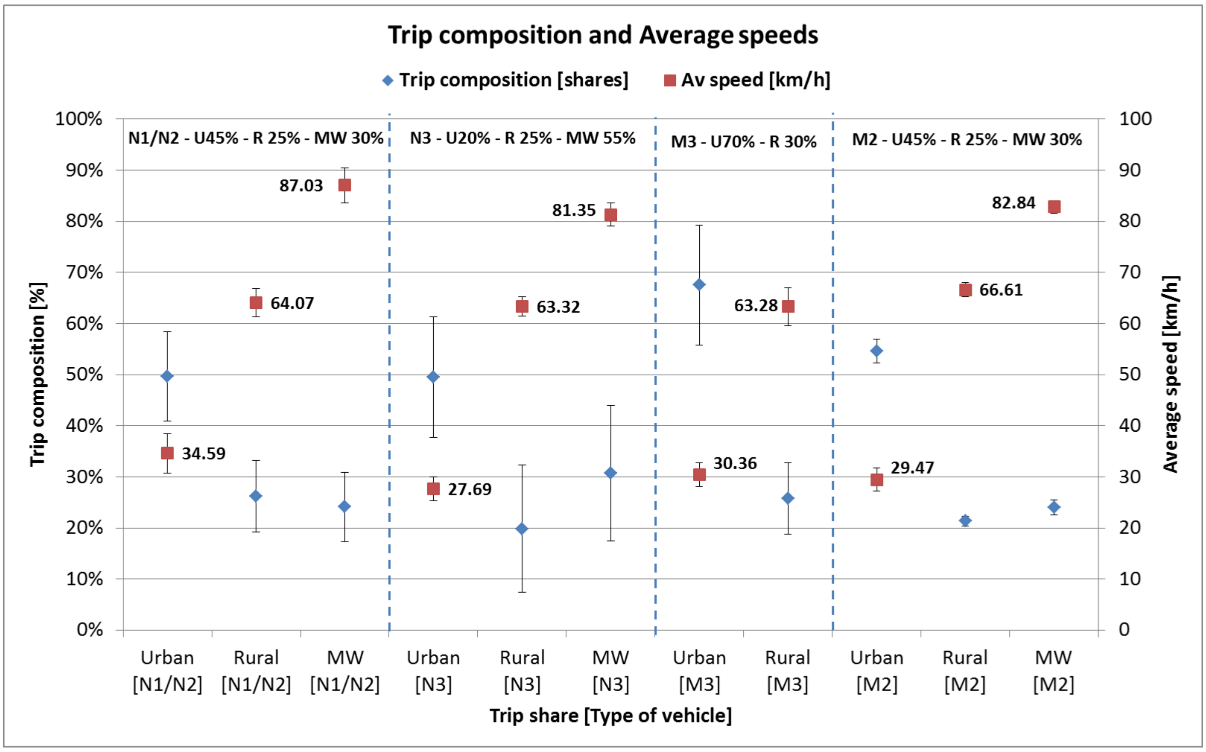
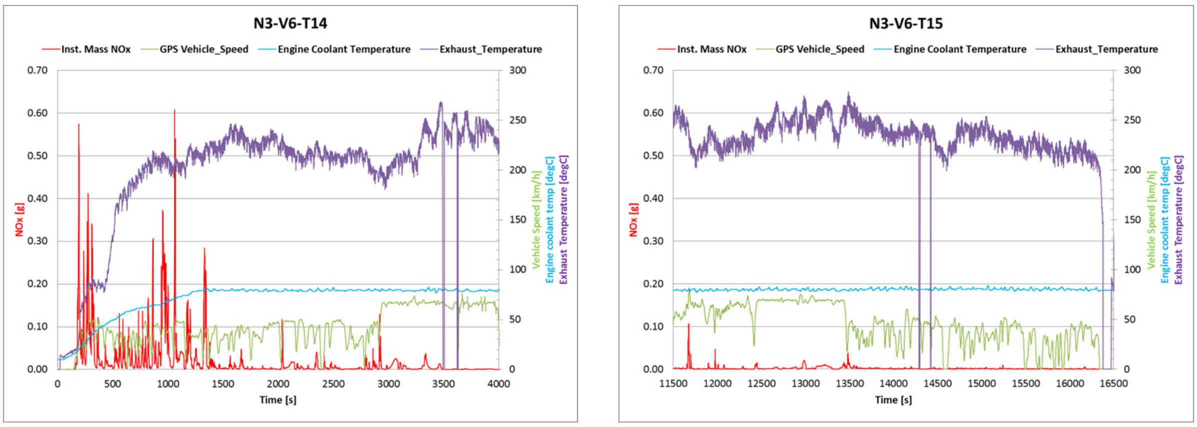


Figure 6-19 Shares of trip composition for the analysed trips for each vehicle category together with the average velocity in each of the trips share. The bar corrisponds to the standard deviation of the data set.



(a) (b)

Figure 6-20 Urban operation portion of two similar trips for the same vehicle (N3) indicating the difference of NOx emissions [g] found depending if the urban (low power operation) is at the beginning or at the end of the trip.

6.4. Vehicle payload

The vehicle payload is an important factor in the engine operation of a vehicle and therefore it was included in the elements to be evaluated in the present assessment program. However, the amount of available analysed data is not sufficient to reach a conclusion on the suitability of the present prescribed payload (50 to 60%) in the legislation.

Figure 6-21 depicts the analysis performed at various payloads in four different N3 vehicles, while Figure 6-22 compares directly the values of the different payloads for the same vehicle indicating that there is not a clear trend in their behaviour as they may strongly depends on the engine calibration and strategy chosen by the manufacturer.

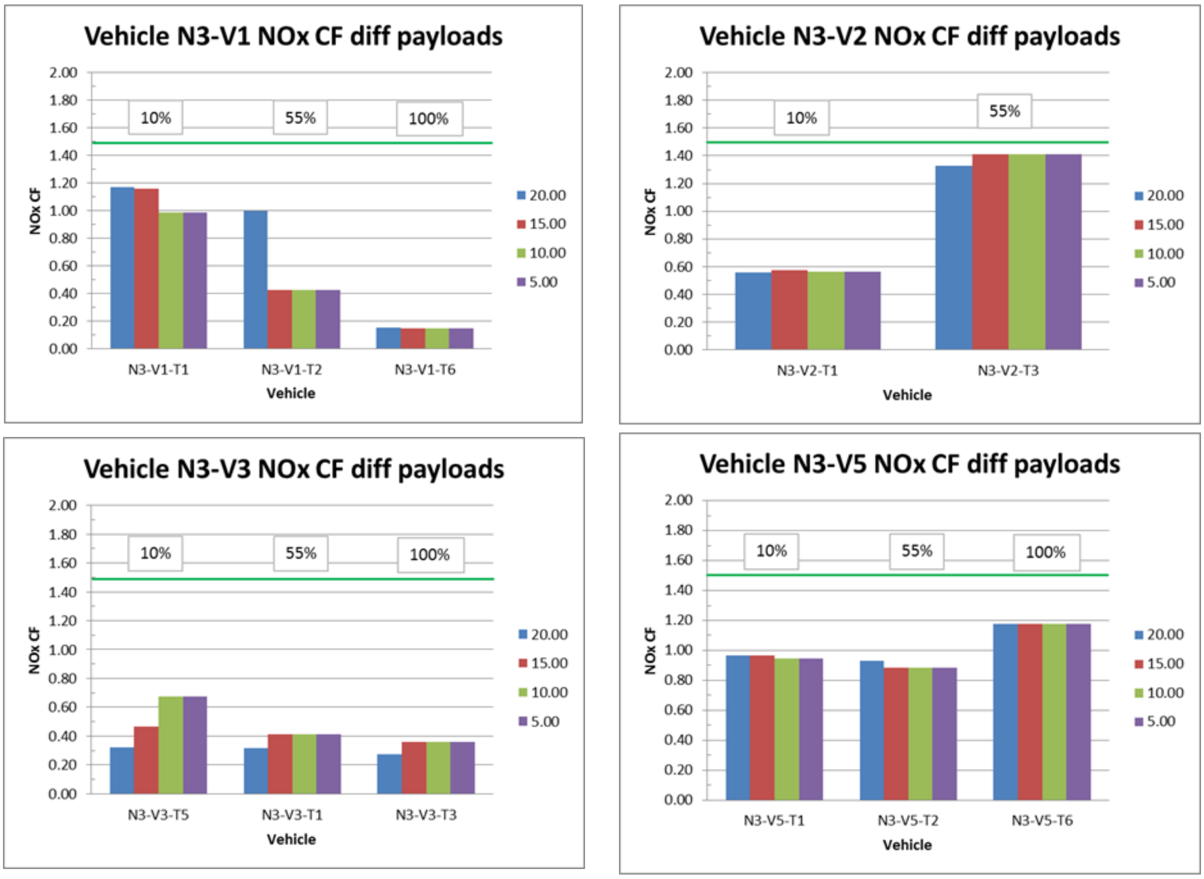


Figure 6-21 NOx emissions (CF) for different payloads. The figure also shows the behaviour at differetn power threshold. In all cases the 90th cumulative percentile has been used.

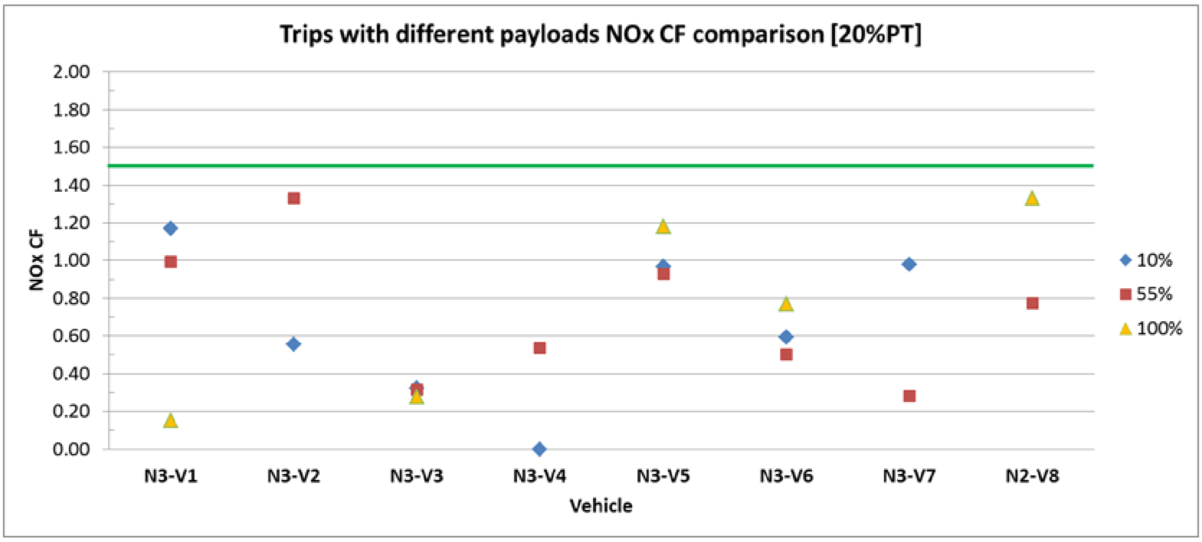


Figure 6-22 No clear trend is found when data is analysed for similar trips and different payloads. In all cases the 90th cumulative percentile has been used.

6.5. Objectives settings

In order to account for the nature of on-road testing which includes the variability of the testing conditions generated by among others the traffic conditions and the driver for a given test route, a 90% cumulative percentile was deemed the better indicator of the engine emission performance.

Figure 6-23 depicts the NOx CF, and the incremental percentage of windows above 90% cumulative percentile for some examples. These trip (test) data examples have been processed using the present boundary conditions; i.e. 20% power threshold and the exclusion of cold start. It can be seen that under these conditions, the use of the 90% cumulative percentile is a good indicator of the engine emission performance as it represents well the behaviour of the engine in the trip, possibly avoiding or giving unnecessary too much weight to operational areas with marginal high emissions.

Figure 6-24, Figure 6-25, Figure 6-26 and Figure 6-27 give an overview of the differences obtained in NOx CF using the 90% and 100% cumulative percentile for all the tests of the assessment program.

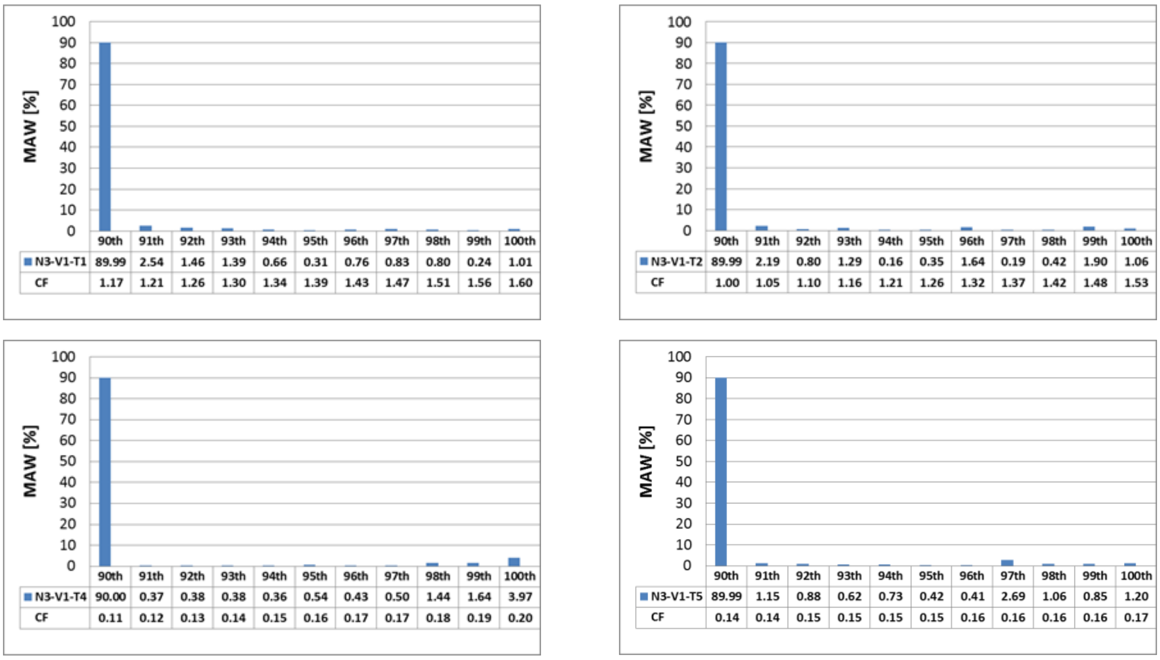


Figure 6-23 NOx conformity factors at different cumulative percentile together with the percentage of extra considered windows for each case.

Looking at the results depicted in the figures one can conclude that in general there is not large differences between the 90% and 100% cumulative percentile for N3 and M3 vehicle categories (applying the present boundary conditions; i.e. exclusion of cold start operation) being in most of the occasions below the maximum allowable CF (i.e. 1.5). This is not the case for N2 and M2 categories due to the 20% power threshold limit that leaves large portion of the low power operation out of the data processing and the 90% cumulative percentile then will essentially take only into consideration the rural and highway operations where these vehicles have as expected low NOx emissions (please keep in mind that in the case of M2 the comparison are made with a power threshold of 10% -green bars- as there were not enough valid windows at 20% (15%) power threshold conditions). Then the 100%

cumulative percentile will include some part of the urban operation and therefore the larger differences found in these categories of vehicles.

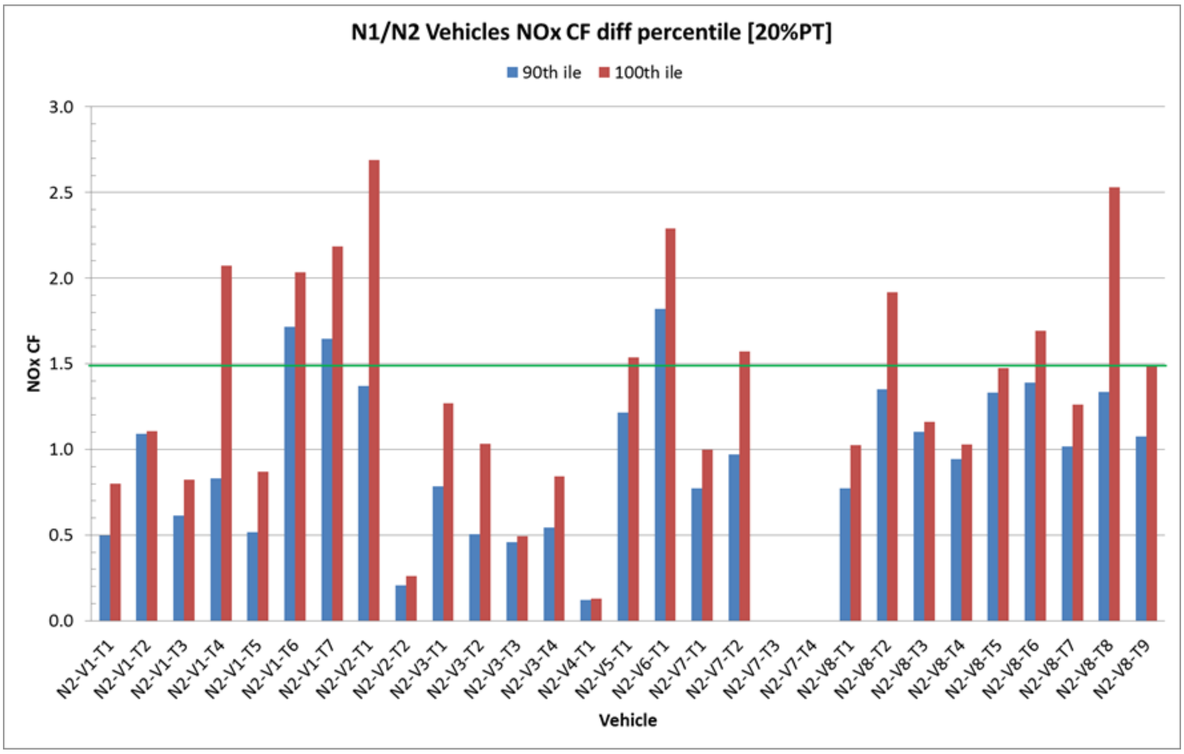


Figure 6-24 Differences in NOx emissions (CF) at the 90th and 100th cumulative percentile for N1/N2 vehicles.

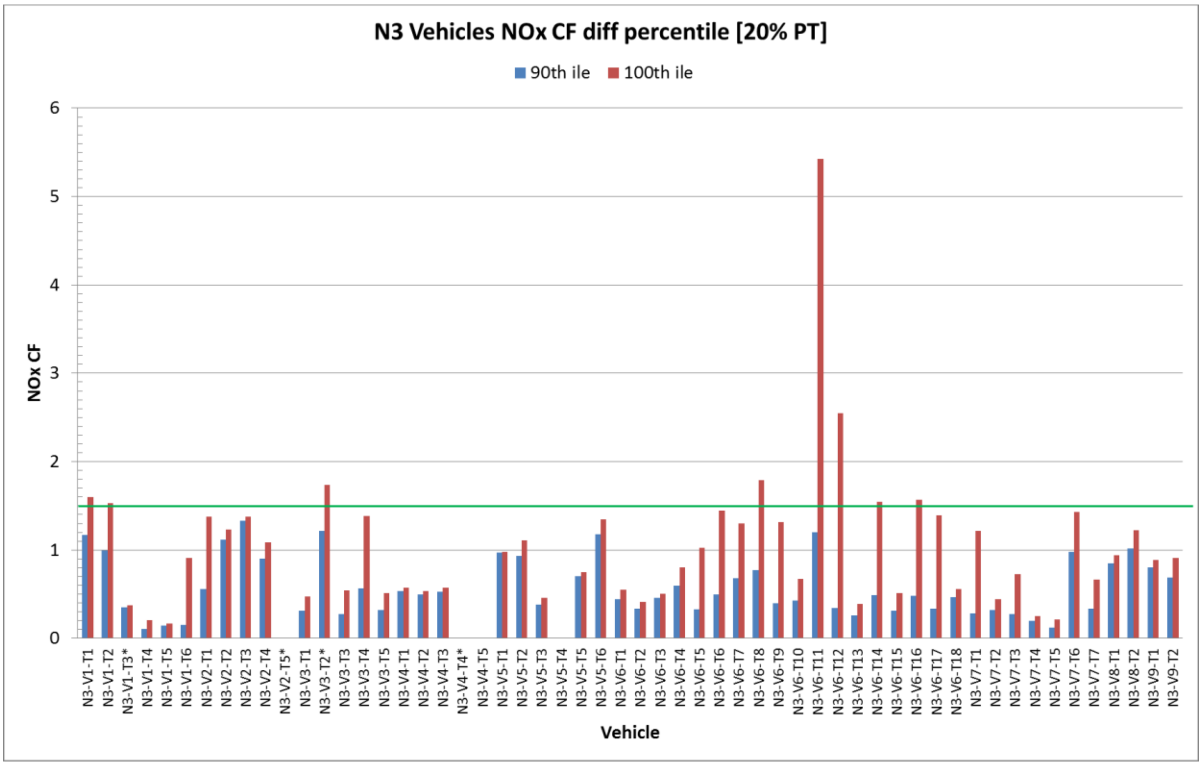


Figure 6-25 Differences in NOx emissions (CF) at the 90th and 100th cumulative percentile for N3 vehicles. Trips with an * indicate trips with a large percentage of idle (idle trips).

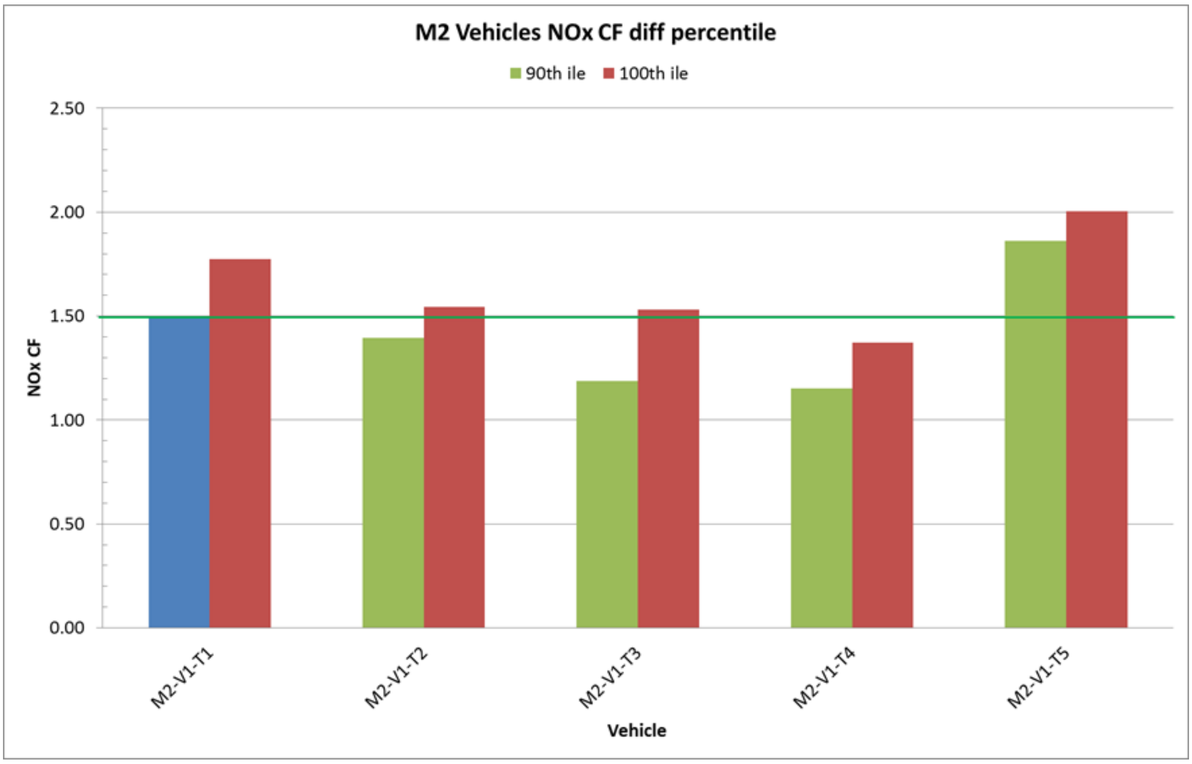


Figure 6-26 Differences in NOx emissions (CF) at the 90th and 100th cumulative percentile for M2 vehicles.

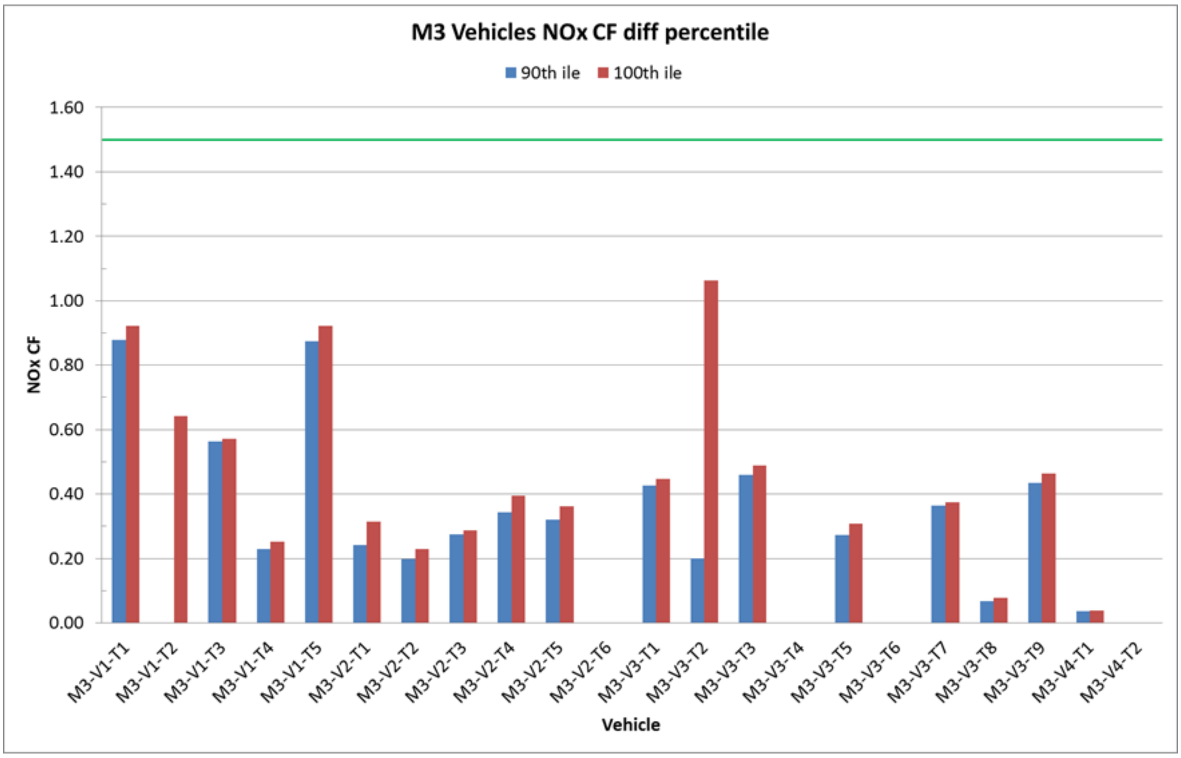


Figure 6-27 Differences in NOx emissions (CF) at the 90th and 100th cumulative percentile for M3 vehicles.

6.6. *Reference quantity (work or CO_2)*

To keep a strong link with the certification transient cycle, the work based approach for the MAW method was selected because it provides an 'energy based' evaluation, i.e. describes the emissions of the engine for a given quantity of energy. However the use of an alternative reference quantity for the MAW method which would not rely on the torque data broadcast on the vehicle network by the engine control units and whose accuracy is uncertain was also considered and investigated during the European Heavy-Duty Engines Conformity Testing based on PEMS (the so-called EU-PEMS Pilot Program). The program had as main aim to confirm and validate the robustness of the PEMS test protocol developed in the EU-PEMS Project as basis for the introduction of ISC provisions based on the PEMS approach in the European type-approval legislation.

Because of the linear relationship between CO_2 mass emission and the work of performed in the trips the CO_2 based was studied [7] in comparison with the work base methodology. The comparison found good agreement between both methods albeit it was conducted with both uncertain torque values from ECU (affecting the work based windows calculation) and uncertain reference CO_2 mass emissions (affecting the CO_2 based calculations). It needs also to point out that the comparison was performed on engines that were EUR IV and EUR V compliance.

The present PEMS assessment study re-visited this comparison between both methods but this time using EUR VI compliant engines/vehicles.

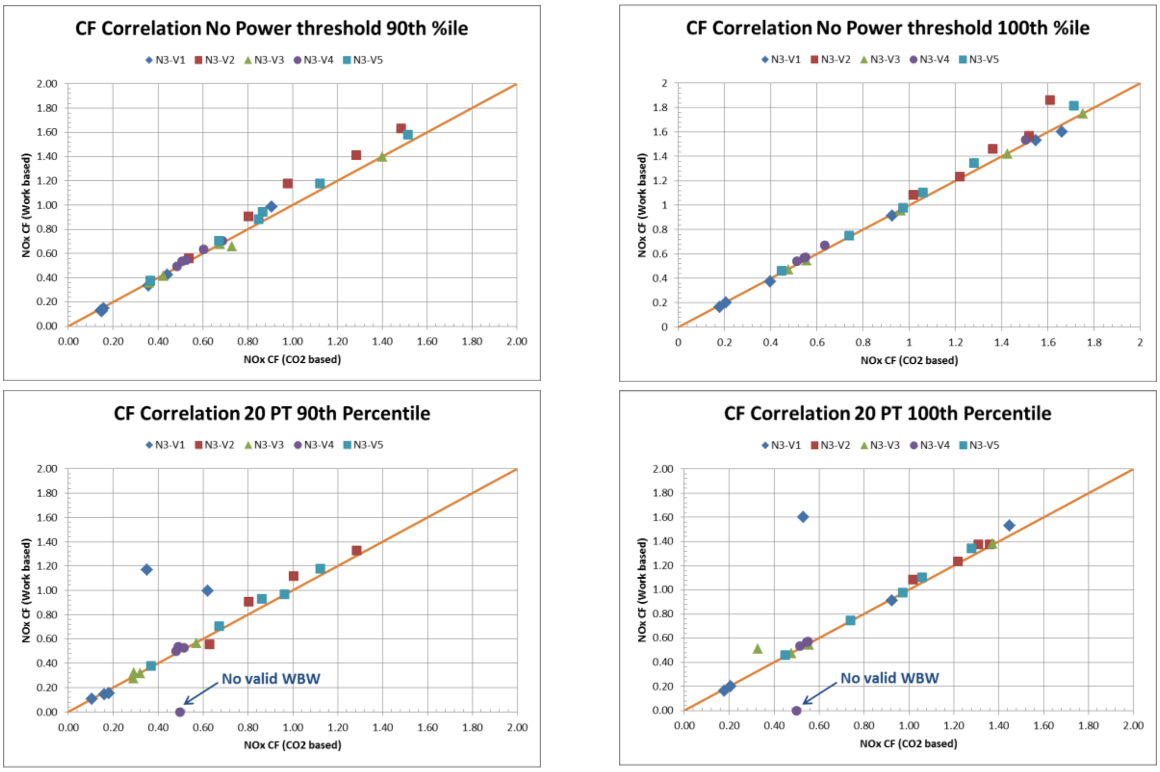


Figure 6-28 Correlation between NOx emisisons (CF) obtained using the work-based and CO_2 based MAW

Figure 6-28 shows a good agreement between both methods as it was expected from the previous studies performed during the EU-PEMS Pilot Program [7].

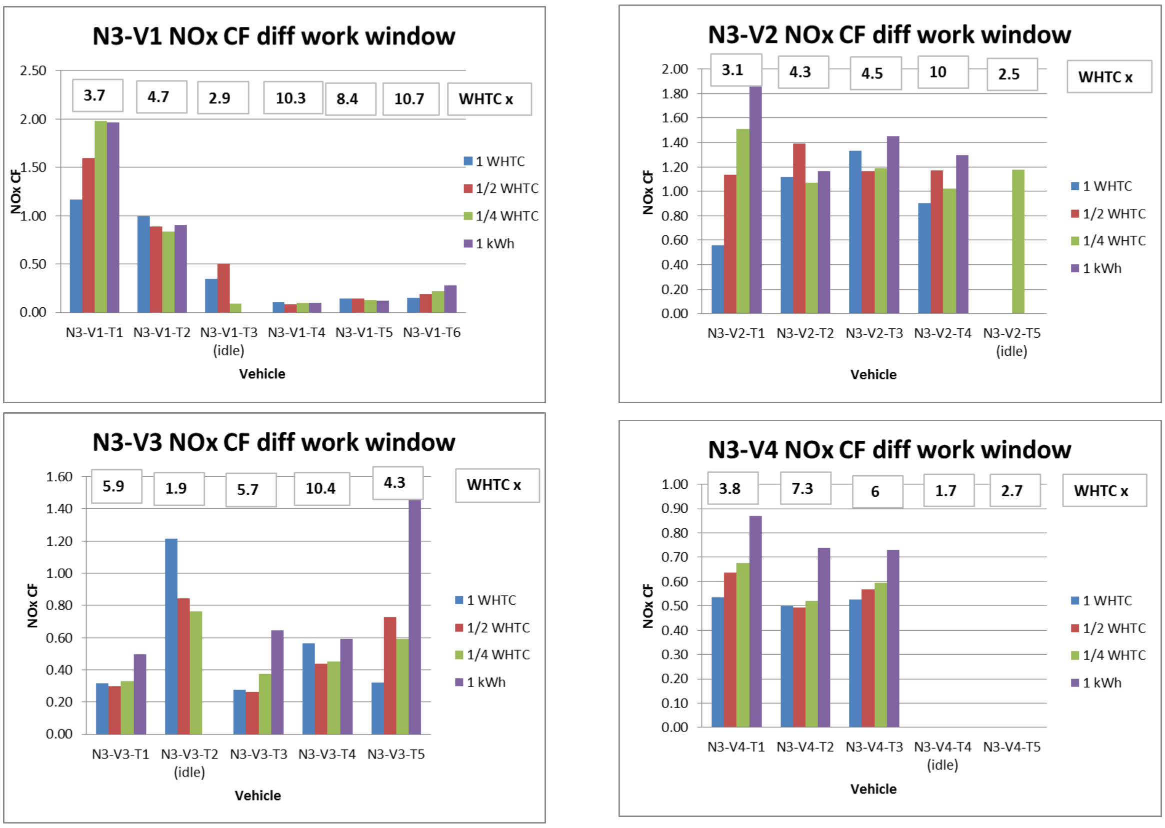
6.7. Impact of windows length definitions in work-based MAW

In the present legislation for ISC using PEMS, the length of the window (in the MAW-WBW) is defined to be equal to the work performed by the engine in the legislative cycle; i.e. the work performed at the WHTC cycle.

The present section studies the differences found when the WBW length is change to different values. The values considered were 1, ½ and ¼ WHTC together with a very small window of 1 kWh.

Figure 6-29 depicts the results of the exercise for some N3 vehicles in terms of CF using the present legislated boundary conditions (i.e. 20% power threshold, 90th cumulative percentile and exclusion of cold-start operations). Figure 6-29 also shows the total length of the different trips in term of number of WHTC reference work. It is apparent that in general as the window length is reduced the NOx CF increases due to a finer combing of the experimental data. However this is not sometimes the case because the 90th cumulative percentile operates by reducing the CF due to the increase of number of windows. If a large number of windows are having lower CF this impinges in the final value of the 90th cumulative percentile. From this data it seems reasonable the use of the work of 1 WHTC as the window length to analyse the data for ISC using PEMS methodology.

Although there is not a clear trend and in order to reduce the burden on testing it seems that the trip length of 5 WHTC is a good compromise between the amount of data available for analysis and the time required to obtain them (~ 2.5 hours).



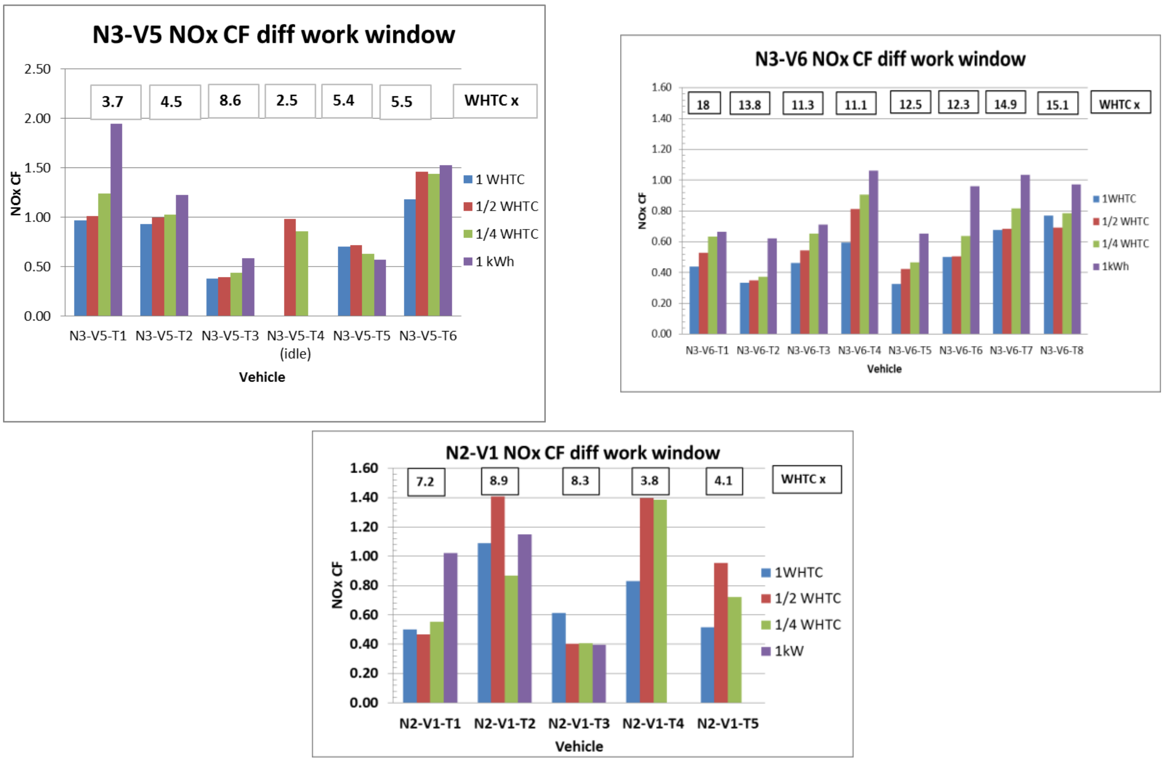


Figure 6-29 Analysis of different window lengths for the work-based MAW (1xWHTC, 1/2xWHTC, 1/4xWHTC and 1kWh). The figure also indicate the length of the trip in terms of the reference work.

6.8. Shortcomings of the analysis of emissions based on current legislation boundary conditions

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

6.8.1. Engine coolant temperature and power threshold

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

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

And Section 4.2.2 to the same Appendix:

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

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

Figure 6-30 shows trip N2-V7-T3 with the cumulative NOx in green, in which the percentage of NOx excluded from the final results of the analysis is pointed by the blue and red dotted lines. As it can be seen, the cold start excludes[3] 68.98% of the total amount of NOx produced in this trip; furthermore, 90.20% of total NOx (including the 68.98% from the CS) is left out due to the 20% power threshold boundary as mentioned above. Indeed this trip will not be considered valid because it does not reach 50% valid windows at 15% power threshold. The 50% valid windows are reached at a power threshold of 14.9% (purpled pointed line in Figure 6-30). Even allowing this power limit the amount of percentage of NOx excluded from the final results is well above 85%.

There are a few issues highlighted by this condition, first, we have a situation in which the legislation is excluding a substantial part of the NOx emitted by this vehicle due to an overlook of two conditions that appear every day on normal operation of this type of vehicle: cold start and low power operation; second, it highlights an issue that specifically N2 vehicles are currently suffering, this is that due to low power operation, after-treatment system activation temperature is hard to achieve, hence, non-negligible emissions are seen on the urban part of the test.

It is very important to stress the fact that combinations of these two boundaries exclude a non-negligible part of the NOx produced by this vehicle on this trip.

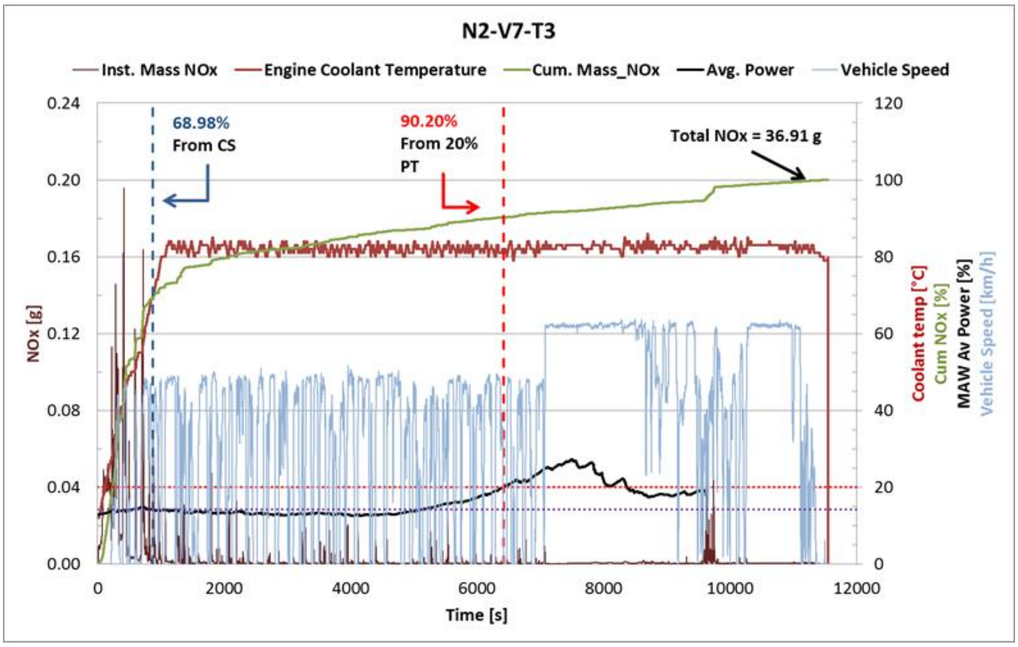


Figure 6-30 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N2 vehicle, because of either exclusion of cold-start operations or windows being valid if its average power is above the 20% (15%) of the maximum engine power (power threshold)

Another example on how the combination of the boundaries impact the amount of NOx to be analysed is being shown in Figure 6-31. This figure represents another N2

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[3] In this section the percentage is used to illustrate how much of the total emission is either considered or not in the data analysis. It does not prejudge the compliance of the vehicle with the present legislation as this report addresses the assessment of the procedure and not the vehicle/engine compliance (type approval).

vehicle, this time the exclusion from cold start is 12.21%, this is due to a shorten cold start phase as the coolant temperature at the beginning of the trip was of 33°C, compared to 12°C from the previous example. The NOx excluded due to the power threshold boundary condition (at 19% the trip reached 50% valid windows) is another 56.88%, adding to the 12.21% from the CS for a total of 69% shown on the figure.

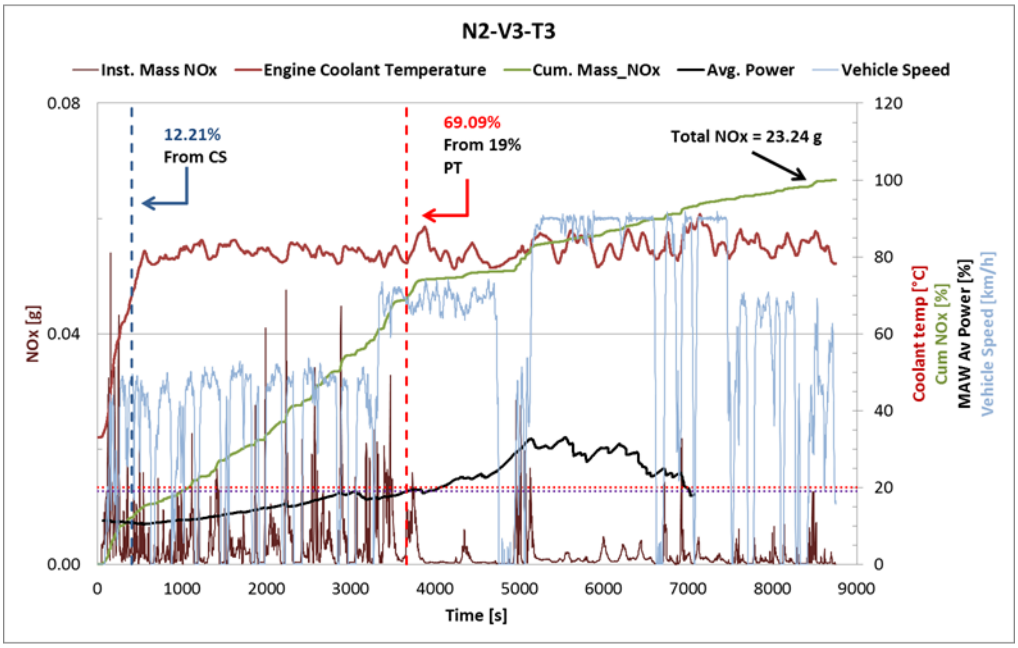

Figure 6-31 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N2 vehicle, because of either exclusion of cold-start operations or windows being valid if its average power is above the 20% (19% purple line) of the maximum engine power (power threshold)

The exclusions due to these boundary conditions are reflected for all the N1/N2 vehicles with cold start trips on Figure 6-32 below, the figure shows the percentages of NOx excluded due to cold start or power threshold. Please note that the highest excluded value (which in most cases on N1/N2 vehicles is the power threshold exclusion) already contains the smaller contribution by the second boundary condition (in most cases on N1/N2 the cold start exclusion).

As it can be seen, and due to the nature of the behaviour of N1/N2 vehicles and their power/mass ratio, the NOx exclusion biggest source on this type of vehicles is the 20% power threshold. This is not the case for N3 vehicles, Figure 6-33 and Figure 6-34, show typical NOx exclusion from trips performed with N3 vehicles.

Figure 6-33, shows the amount of NOx excluded from N3-V3-T4 vehicle test; both from power threshold and cold start. Combined, these two boundaries leave at least 57.42% of the total NOx produced by this trip out of the analysis (there is a part of the trip between about 1000 and 3000 seconds where the power is below the 20% power threshold and that has not been taken into account in these percentage calculations. In other words, the NOx exclusion has only taken the first time the power has gone past the 20% power threshold).

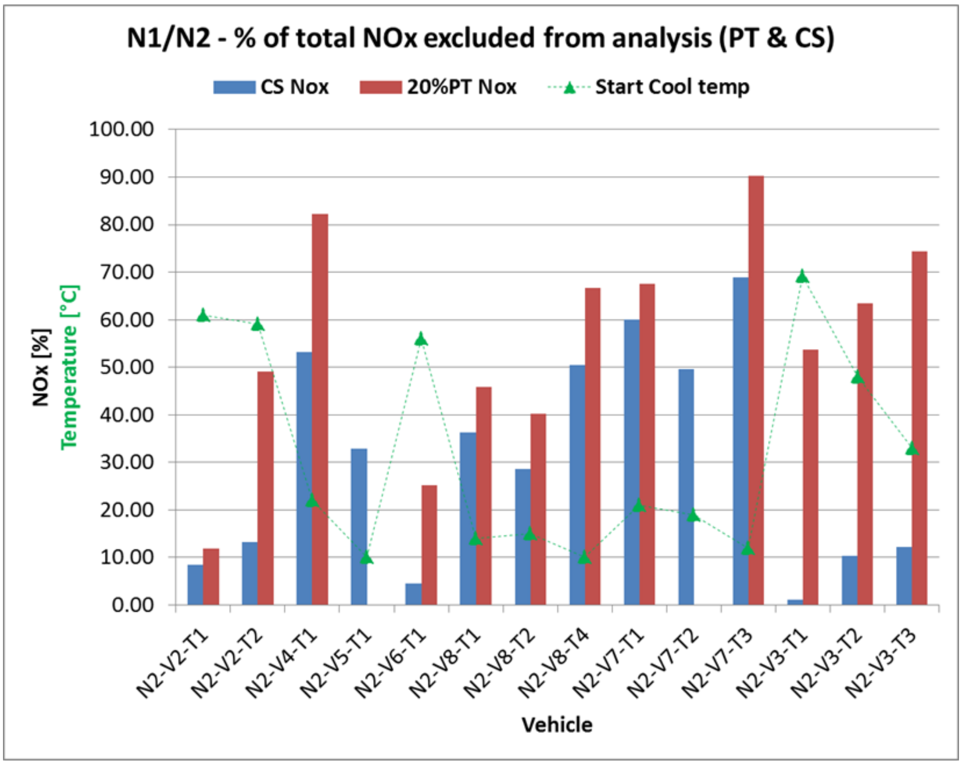

Figure 6-32 Percentage of NOx excluded by either the exclusion of cold-start operation or windows having an average power below the 20% maximum engine power (poer threshold), together with the starting coolant temperature (°C) for N1/N2 vehicles

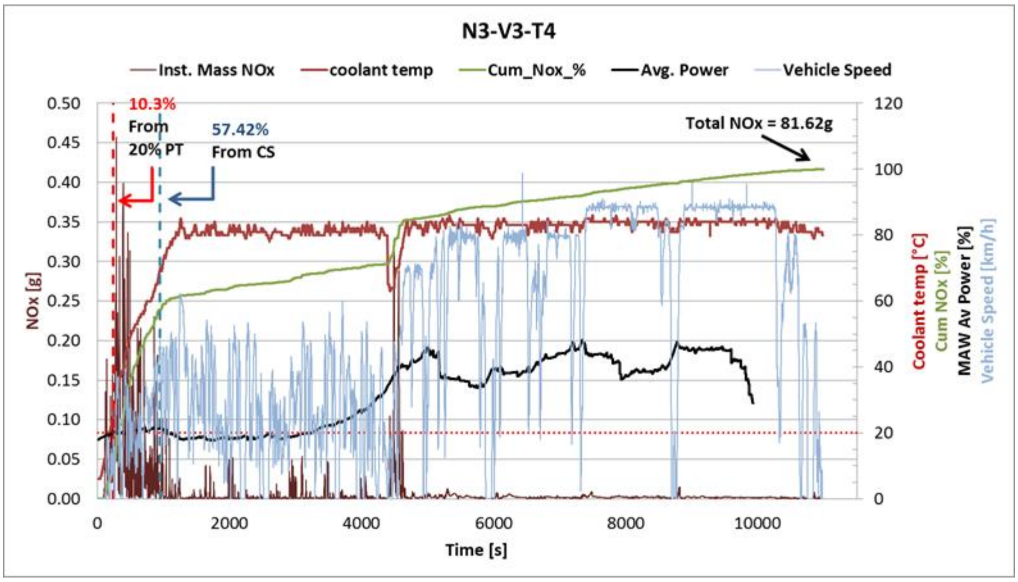

Figure 6-33 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N3 vehicle, because of either exclusion of cold-start operations or windows being valid if its average power is above the 20% (15%) of the maximum engine power (power threshold)

Figure 6-34 below, is another example of the behaviour of N3 vehicles under cold start conditions. For this particular trip more than half of the total NO_x emissions is not considered due to this boundary condition.

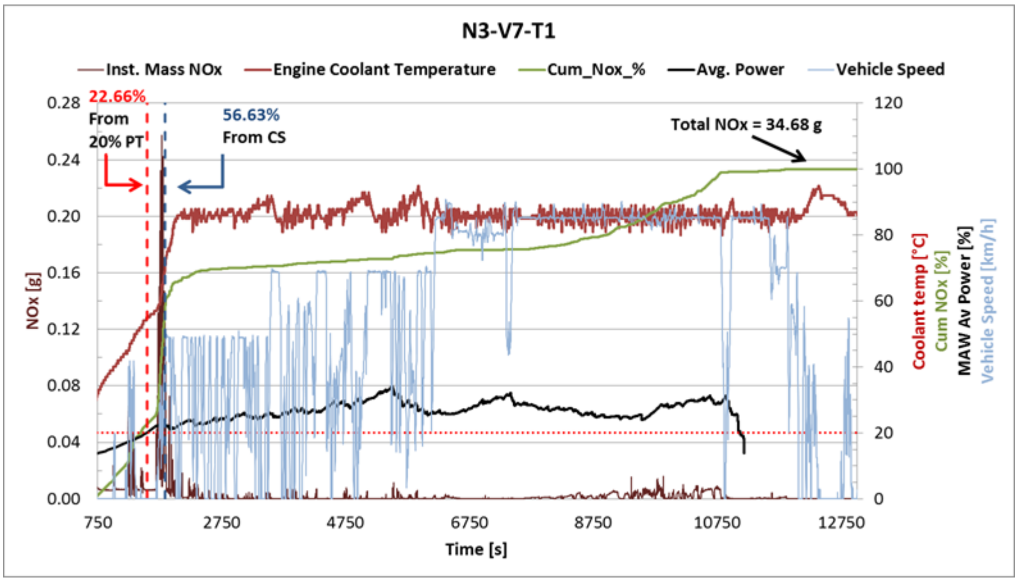

Figure 6-34 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N3 vehicle, because of either exclusion of cold-start operations or windows being valid if its average power is above the 20% (15%) of the maximum engine power (power threshold)

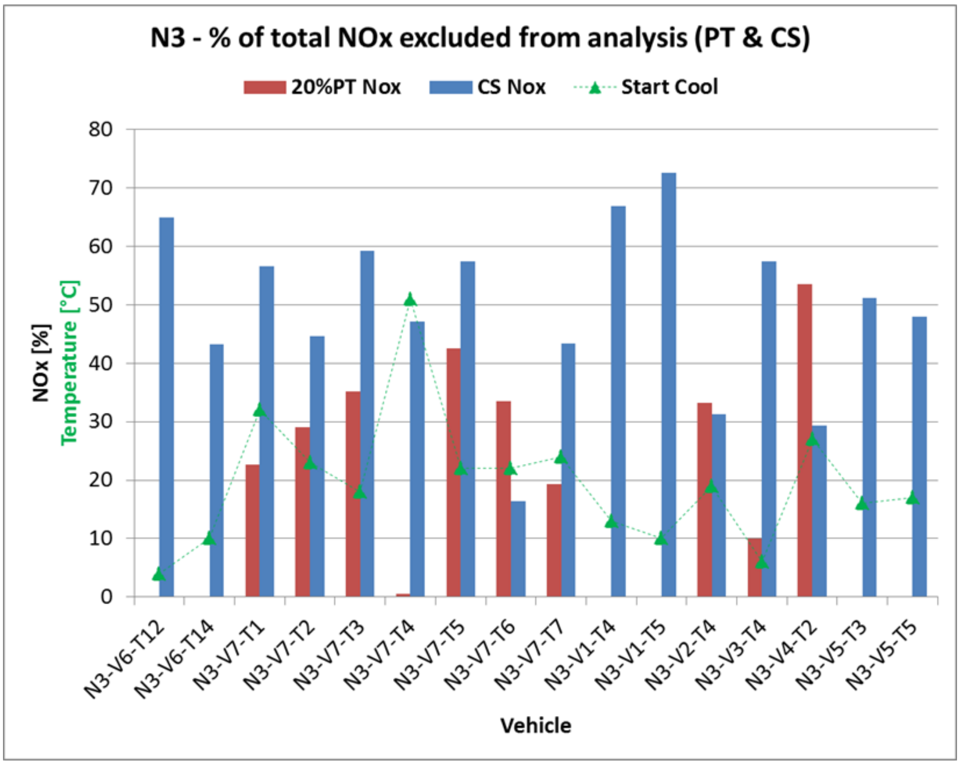

Figure 6-35 Percentage of NOx excluded by either the exclusion of cold-start operation or windows having an average power below the 20% maximum engine power (power threshold), together with the starting coolant temperature (℃) for N3 vehicles

Further to this, Figure 6-35 shows the general behaviour of N3 vehicles considering cold start operation. As it can be seen, contrary to the findings on N1/N2 vehicles, N3 vehicles tend to exclude more NOx from the cold start; this is because the power/mass ratio of the engines is reasonably well coupled and due to the weight of these vehicles, it is not difficult to achieve higher loads which forces a higher power exerted by the engine, hence its behaviour under cold start operation evidence a lack of activation temperature of the emissions after-treatment, namely SCR systems. As it can be seen, and as previously noted, the effect of cold start on emissions is a major contributor to the amount of NOx emissions produced by this type of vehicle; 17 to 74% of NOx produced in the analysed tests is excluded by no considering the cold start operation.

For M3 vehicles, Figure 6-36 represents the overview of the NOx excluded due to these boundary conditions, in general terms, M3 vehicles have a mix of percentages of NOx excluded, be it for cold start or power threshold, this means that the characteristics of the vehicle (mainly city buses) having its daily operation mainly in cities on urban driving conditions (most of the test have been ran to specified shares on the legislation for M3 Class I vehicles: 70% urban / 30% rural) show that the vehicle produces most of its NOx at the beginning of the trip while it is still warming up the engine; as the mode of operation of these vehicles is mainly at low speed, it demonstrates that most of this warming-up occurs at low power engine operation hence the close relationship between the cold start operation produced NOx and that from the power threshold.

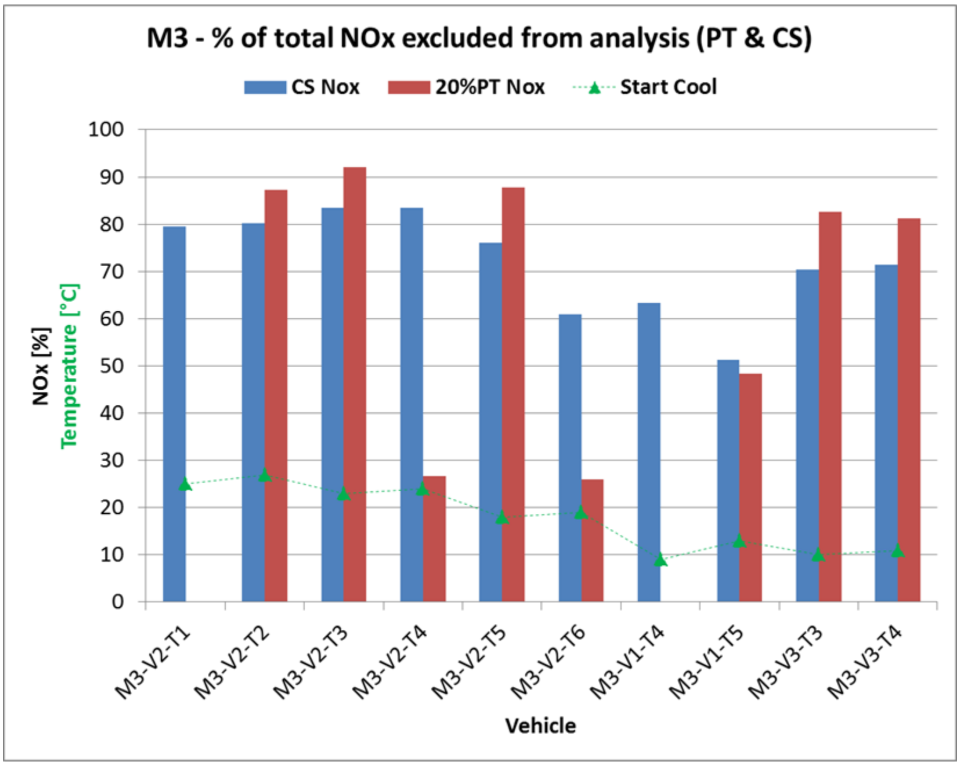

Figure 6-36 Percentage of NOx excluded by either the exclusion of cold-start operation or windows having an average power below the 20% maximum engine power (power threshold), together with the starting coolant temperature (℃) for M3 vehicles

On the other hand, M2 vehicles NOx exclusion shown in Figure 6-37 below, show behaviour closely related to the N2 vehicles, on which, the power threshold is the major source of NOx excluded in the analysis.

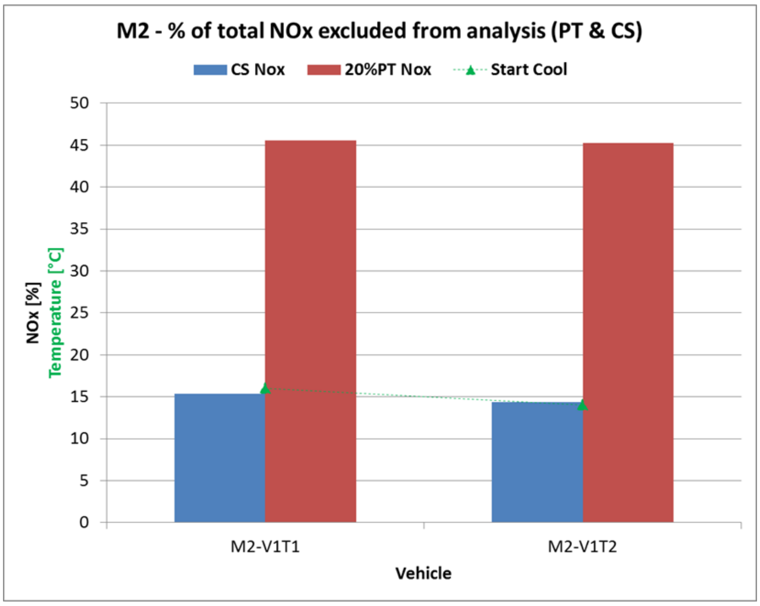

Figure 6-37 Percentage of NOx excluded by either the exclusion of cold-start operation or windows having an average power below the 20% maximum engine power (power threshold), together with the starting coolant temperature (°C) for M2 vehicles

6.8.2. 90th percentile and cold start

Figure 6-38 depicts the current boundary conditions applied to the MAW analysis described in the regulation 582/2011. As in previous figures, we are now aware of the importance of the consideration of cold start operation, the power threshold and the percentages of NOx produced on the trip and excluded from the analysis. Figure 6-38 combines also the 90th cumulative percentile objective setting. As previously explained in Section 6.5, the rationale behind having a robust statistical objective setting indicates a fair representation of the performance of the vehicle/engine under the trip. Under warm operation, this is the case with the 90th cumulative percentile; while under cold start conditions the perspective is different. Figure 6-38 represents the current situation and combines three boundary conditions that are effectively excluding 76.20% of NOx from the MAW analysis method.

Several iterations on the conformity factor result for this specific case are shown on Figure 6-39. The caption describes each of the approaches taken in order to portrait the effect of the different boundary conditions on the resulting conformity factor.

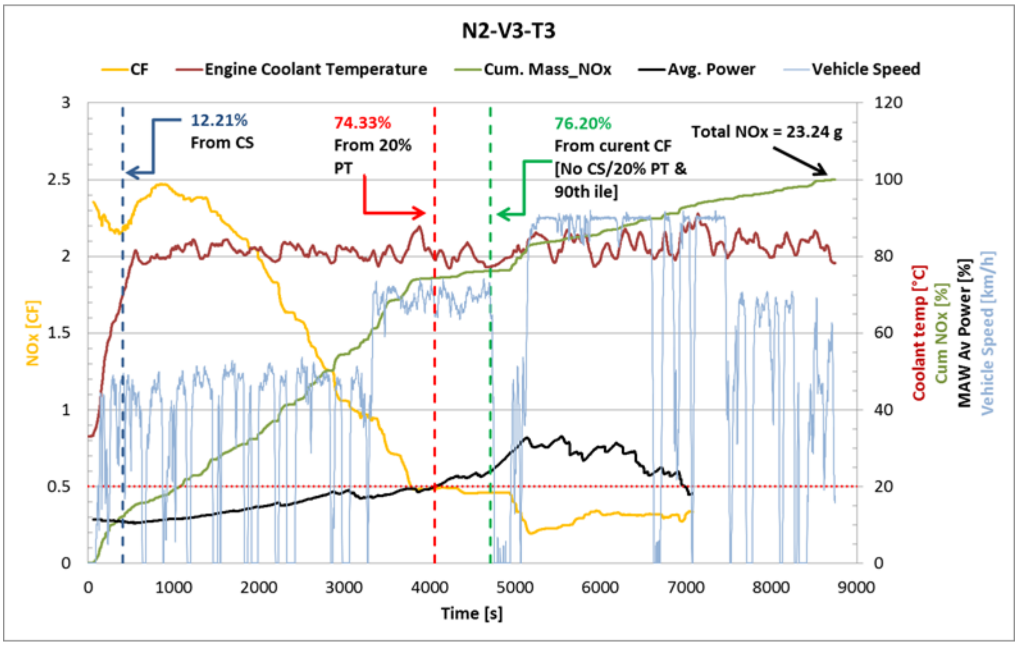

Figure 6-38 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N2 vehicle, because of either exclusion of cold-start operations, windows being valid if its average power is above the 20% (15%) of the maximum engine power (power threshold) or the 90th cumulative percentile.

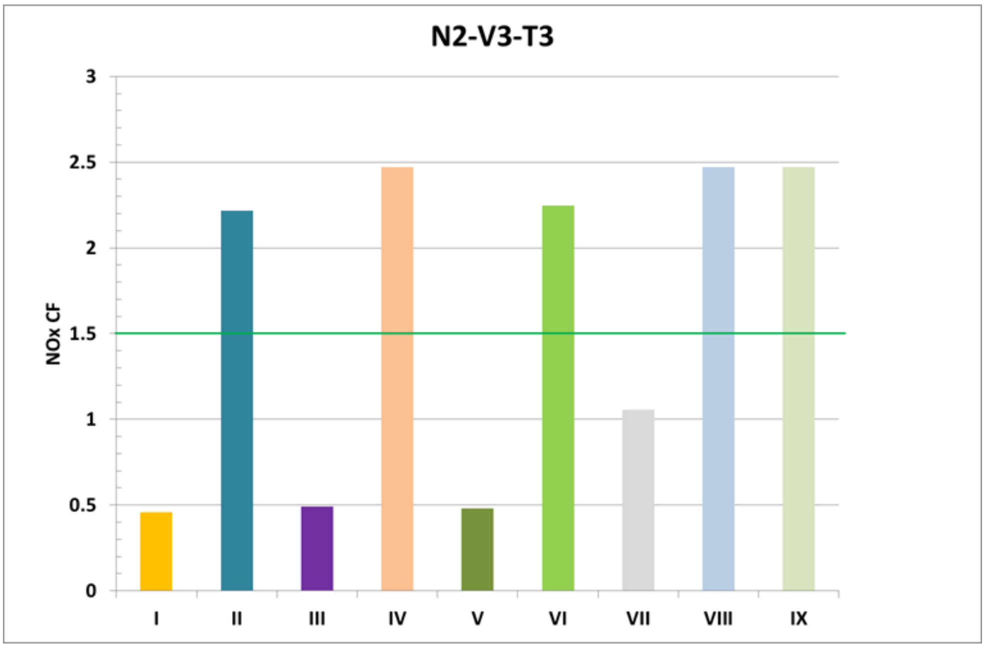

Figure 6-39 Study of the impact of different boundary conditions on a N2 vehicle. I. ISC as present [20%PT & 90th ile], II. No PT / 90th ile, III. 20% PT / 100th ile, IV. No PT / 100th ile, V. Total trip [CS + 20% PT & 90th ile], VI. Total trip [CS + No PT & 90th ile], VII. Total trip [CS + 20% PT & 100th ile], VIII. Total trip [CS + No PT & 100th ile], IX. Total trip [CS + No PT & 100th ile] $T_{coolant}$>20°C.

As it can be seen, the differences shown on Figure 6-39 are significant. Between the case I in which the conformity factor equals 0.45 considering the 3 boundaries mentioned above to case IV in which we are not considering any power threshold and we are taking the 100th percentile (still without taking the cold start into consideration) the conformity factor rises to 2.47. In this case it can be seen that the data analysis is very sensitive to the boundary conditions and it makes a difference between a vehicle comfortable pass under the 1.5 CF limit; to a situation in which the vehicle is not compliant. In this case is also important to point out that the maximum value of CF is located outside the cold start operation, hence the value of CF for case VIII which includes also the cold start operation is equal to that of case IV.

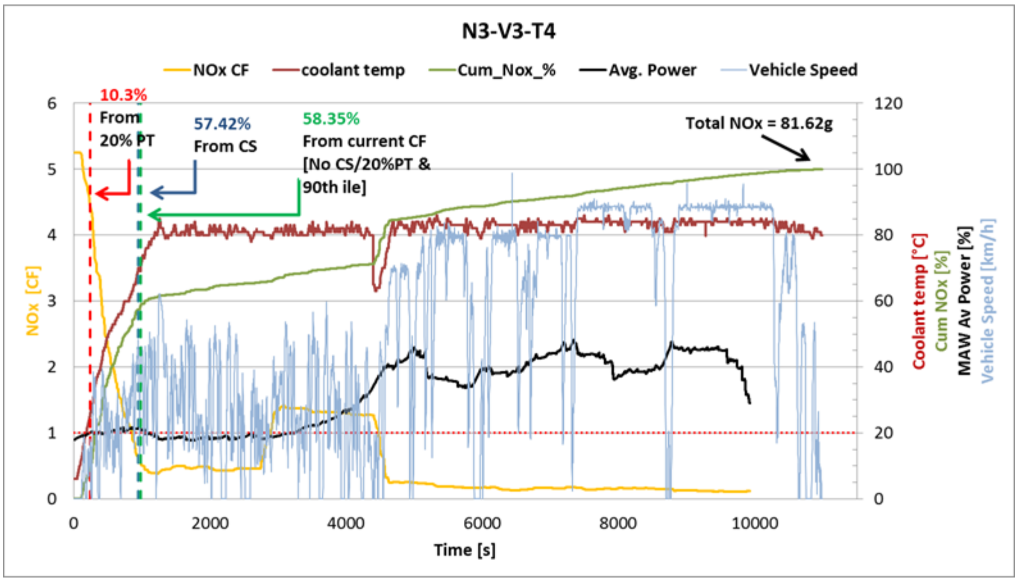

Figure 6-40 Percentage of cumulative (total) NOx emissions left out of the MAW analyisis of a N3 vehicle, because of either exclusion of cold-start operations, windows being valid if its average power is above the 20% (15%) of the maximum engine power (power threshold) or the 90th cumulative percentile.

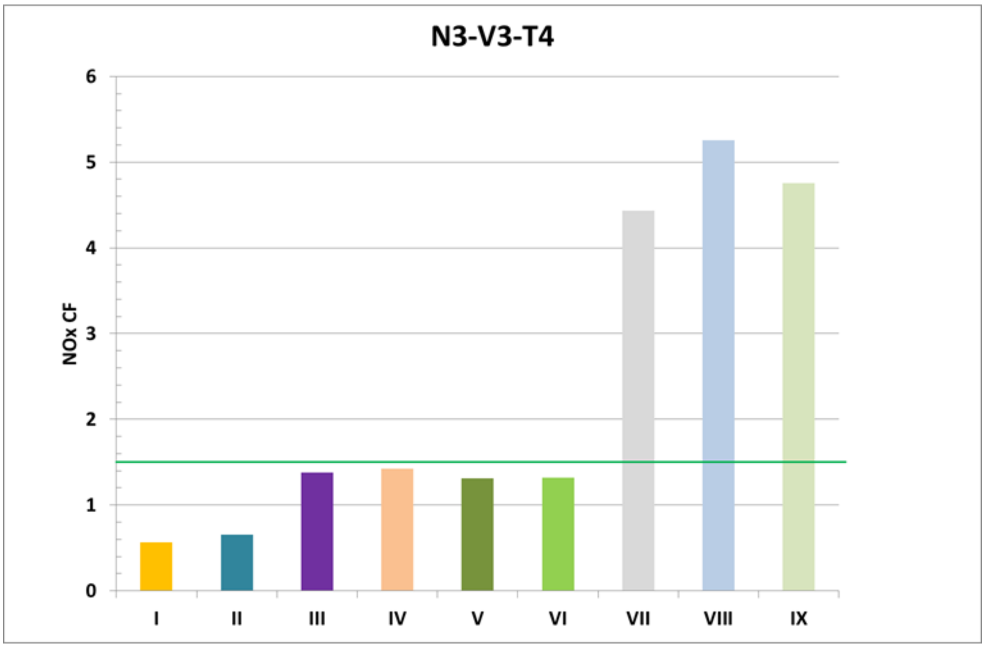

Figure 6-41 Study of the impact of different boundary conditions on a N3 vehicle. I. ISC as present [20%PT & 90th ile], II. No PT / 90th ile, III. 20% PT / 100th ile, IV. No PT / 100th ile, V. Total trip [CS + 20% PT & 90th ile], VI. Total trip [CS + No PT & 90th ile], VII. Total trip [CS + 20% PT & 100th ile], VIII. Total trip [CS + No PT & 100th ile], IX. Total trip [CS + No PT & 100th ile] $T_{coolant}$>20°C.

In Figure 6-40 and Figure 6-41, an N3 vehicle results are presented. In previous analysis, we also have seen the impact of CS and PT, further to this; the 90th percentile also contributes to a total exclusion of 58.35% of NOx produced. In this case (Figure 6-41) the difference between case IV and case VIII is quite substantial, this is because in the case of this specific N3 vehicle test, the cold start component is much larger than in the previously presented N2.

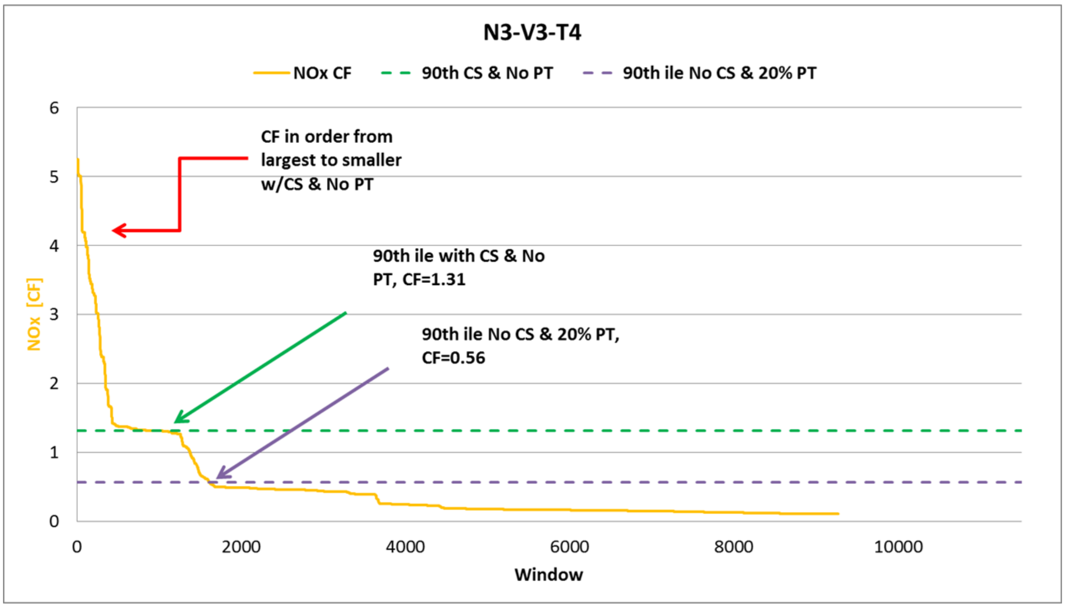

Figure 6-42 NOx conformity factor for each window of the MAW (ordered from maximum to minimum value) for the trip N3-V3-T4

As conclusion from the above discussion it would be fair to say that the 90th cumulative percentile is a robust representation for warm operations, nonetheless, it is not a good indicator for the cold start operation. By considering Figure 6-40 above and Figure 6-42 below and in the hypothetical case on which the cold start operation was taken into account without any power threshold for the MAW analysis, what it can be seen is an exclusion of the higher pollutant windows which belong to CS, this means that even taking into consideration the cold start without power threshold, using the 90th cumulative percentile will prevent the analysis to consider the most critical windows.

7. Conclusions

The following points can summarise the findings in the ISC PEMS assessment performed and reported in the above sections:

1. There is no basis for changing the present testing prescriptions on Payload (50% to 60%) as it seems not to be a clear relation between emissions and different payloads. However, vehicle emissions are to be effectively limited under all possible payloads to be in compliance with the legislative requirements.
2. In order to keep a close relation to the engine type-approval the Metrics (g/kWh) should be kept.
3. The Window Length (=1 WHTC) used in the MAW-WBW seems reasonable. No change seems appropriate.
4. Test duration shall be long enough to complete between 4 to 6 times the work performed during the WHTC or produce between 4 to 6 times the CO2 reference mass in kg/cycle from the WHTC as applicable.
5. The 90^{th} cumulative percentile approach applied concurrently to other limitations (power threshold and cold start) seems to unnecessarily eliminate from the assessment a significant portion of vehicle's operation in urban areas.
6. A robust assessment of urban emissions needs to be addressed and therefore the trip should always start with urban operation and the 20% (15%) power threshold needs to be at least lowered to 10% to ensure that all relevant types of urban driving are recognized and analysed during the PEMS testing.
7. Cold-start operation should be further assessed, as its exclusion seems to remove non-negligible NOx emissions from the PEMS data analysis.

8. Recommendations

8.1. Cold start

The data analysis presented in this PEMS assessment indicates that the current PEMS procedure does not properly address the cold-start operation. It was found that significant amounts of the total NOx emitted by vehicles/engines are excluded from the analysis because of the cold-start exclusion prescribed in the legislation [6].

Consideration of cold-start operations in the PEMS procedure needs further dedicated detailed studies that are outside the scope of the present report. Therefore it is recommended to launch a program devoted to addressing all aspects involved in the possible inclusion of cold-start operations in the PEMS procedure. Among those aspects and without being exhaustive one can mention: Auxiliary Emission Strategies (AES), boundary conditions to be applied, impact of the starting coolant temperature, etc.

During this PEMS assessment, the JRC has developed some potential procedures for the inclusion of cold start in the PEMS procedure. They are described and assessed in the annex (see Section 10).

8.2. Power threshold

This report demonstrates that the 20% (15%) power threshold results in a significant reduction of valid windows, mainly under urban operating conditions. It is therefore recommended to reduce it to at least 10%. This will significantly improve the evaluation of urban operation.

8.3. 90th cumulative percentile

The 90th percentile is a robust and sensible statistical concept to evaluate warm operation of the PEMS based data. However, it has been shown that the 90th percentile excludes non-negligible NOx emissions when evaluating cold start operation PEMS tests data. Therefore it is recommended that the choice of the appropriate cumulative percentile is studied during the cold start test program proposed in section 8.1.

8.4. Payload

This assessment has not found any specific trends with respect to the load that the vehicle carries during the PEMS tests on NOx emissions. Therefore the current legislated payload of 50-60% should be kept for PEMS testing with no further recommendations on this matter. Nevertheless, vehicle emissions need to be effectively limited under all possible payloads and the vehicle needs to be in compliance with Euro VI emission limits under all such operations.

8.5. Trip composition

This assessment has stressed the importance of including on the analysis the low power operation data which usually occurs on the urban (<50km/h) share of the trip. It has also shown that cold operation plays a significant part on the emissions performance of the engine at low power. Therefore, it is important to closely analyse the behaviour of the vehicle on the urban share of the trip under these conditions. It is recommended that the test trip is always started in urban, followed by rural and motorway operations without any possibility to alter this order. Furthermore the different parts of the trip shall be defined not only by a speed range but also be characterised by an average speed within the range.

9. References

[1] For the Term of Reference of the PEMS Assessment consult the CIRCABC page:

https://circabc.europa.eu/sd/a/8c8aae81-0e15-4b4e-8687-41f3f6850d2a/110831%20PEMS%20WG%20tor%20Draft_1st%20PEMS%20meeting.doc

[2] http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:167:0001:0168:EN:PDF

[3] 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

[4] COMMISSION REGULATION (EU) No 678/2011 of 14 July 2011 replacing Annex II and amending Annexes IV, IX and XI to Directive 2007/46/EC of the European Parliament and of the Council establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles (Framework Directive)

[5] Directive 2001/85/EC of the European Parliament and of the Council of 20 November 2001 relating to special provisions for vehicles used for the carriage of passengers comprising more than eight seats in addition to the driver's seat, and amending Directives 70/156/EEC and 97/27/EC (OJ L 42, 13.2.2002, p. 1).

[6] ANNEX II, Appendix 1. Paragraph 2.6.1 of COMMISSION REGULATION (EU) No 582/2011

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

[8] E/ECE/324/Rev.1/Add.48/Rev.6-E/ECE/TRANS/505/Rev.1/Add.48/Rev.6

(http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2013/R049r6e.pdf)

10. Annexes

10.1. Annex 1: Cold start (CS) methods I (JRC's proposal)

In order to be able to measure the regulated emissions during the period of cold start (cold start - as defined under paragraph 2.6.1 from Appendix 1 of Annex II as written on Reg 582/2011); JRC has defined 6 methods which can be explained as follows and they are assessed in section 10.2.

An eventual inclusion of cold-start operation in the PEMS procedure will need to include the appropriate temperature boundary conditions. This will be part of a more detailed dedicated study as already mentioned above (see section 8.1).

10.1.1. Method 1 – No cold-start emissions considered.

This method is defined in the current legislation under Annex II Paragraph 4.6.2 which states: "… Any cold start emissions may be removed from the emissions evaluation, in accordance with point 2.6 of Appendix 1".

10.1.2. **Method 2 – Consider cold emissions on the normal Moving Average Window (MAW) analysis.**

This method is defined by allowing the analysis tool (e.g. EMROAD, etc.) to consider all data present in the test PEMS file, even though the data is located inside the "cold-operation" area (Figure 10-1) as defined by paragraph 2.6.1 Appendix 1 of Annex II on Reg 582/2011.

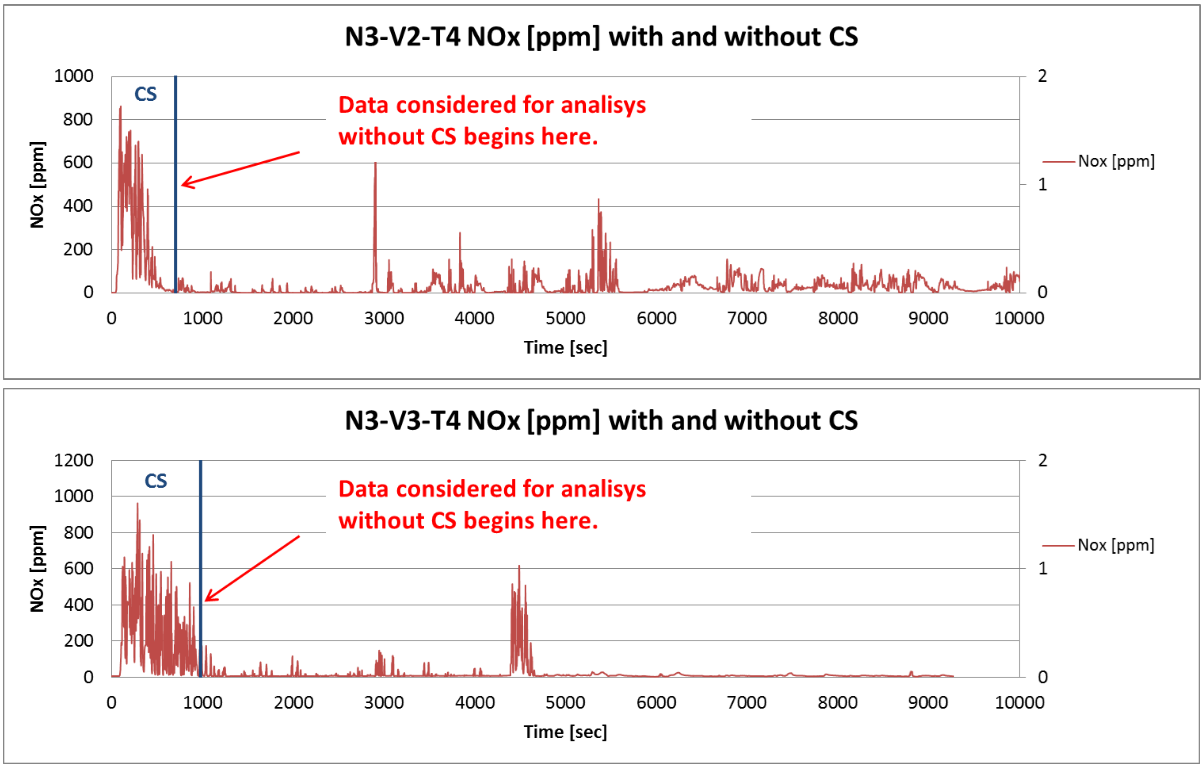

Figure 10-1 Point from which the data is considered for analysis with and without CS

To obtain a distribution of windows like the one shown on Figure 10-2:

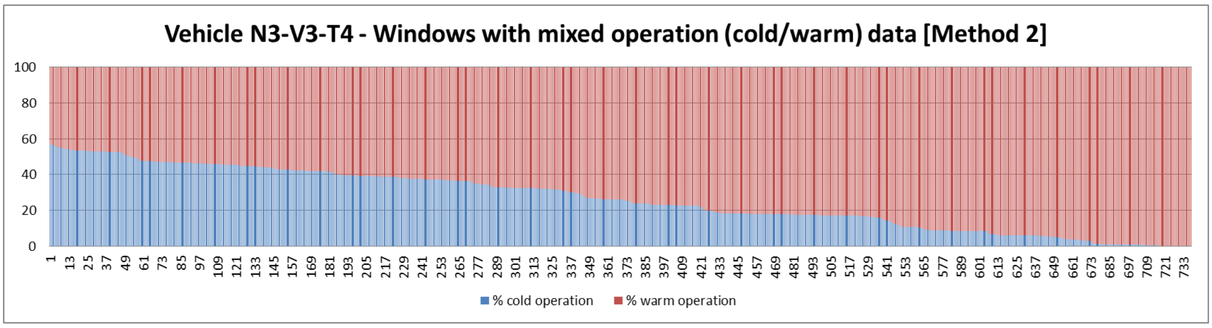

Figure 10-2 Distribution of data on different windows (blue – cold data, red – warm operation)

10.1.3. *Method 3 – Cold start operation as one single window*

This method defines the data inside the "cold-operation" area as a single window. This requires performing the following data operations:

a. Manually calculate the cumulative NOx produced while the coolant temperature is below 343K (70C), and divide it by the cumulative work done until that point. Divide the result by the current NOx limit to obtain a conformity factor ("cold-operation" CF).
b. Perform the normal warm operation MAW analysis. Obtain the 90th percentile "warm-operation" CF (EMROAD or the preferred analysis tool will do this calculation).
c. Manually weight the result in the following way:
    - 14% "cold-operation" CF'
    - 86% "warm-operation" CF'

The application of this method would need that no power threshold will be applied.

10.1.4. *Method 4 – Window average temperature analysis*

This method is based on the average temperature of the MAW (Figure 10-3), one has to analyse the windows that have an average temperature below 343K (70C), and perform 2 analyses:

a. Use the 90th percentile analysis approach to manually obtain a CF of the "cold-temperature" windows.
b. Use the 90th percentile analysis approach to manually obtain a CF of the "warm-temperature" windows.
c. Weight the result in the following way:
    - 14% "cold-operation" CF'
    - 86% "warm-operation" CF'

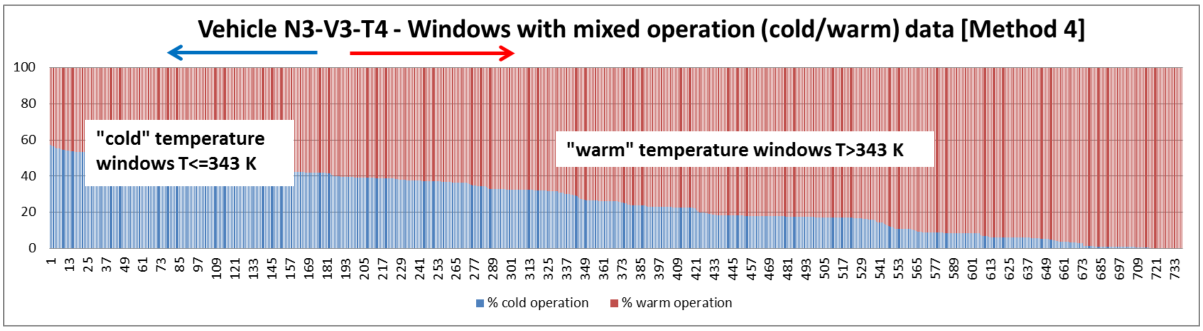

Figure 10-3 Distribution of the cold and warm temperature windows

10.1.5. Method 5 – Cold and warm start analysis using Reg. 49 Methodology (Annex 4B, 8.6.3) and 90th percentile.

This method is an approximation to the HD engine type-approval procedure to include cold start (see section 10.3):

In the case of PEMS data file the following must be performed:

a. Analyse the “cold start” trip (full data set with cold and warm operation) and obtain a CF.
b. Analyse the “warm” trip (only warm operation) and obtain a CF.
c. Weight the result in the following way:
    - 14% “cold-operation” CF’
    - 86% “warm-operation” CF’
d. The application of this method would need that no power threshold will be applied; this method uses the 90th cumulative percentile CF for both cold and warm calculations

10.1.6. Method 6 – Cold and warm start analysis using Reg 49 Methodology (Annex 4B, 8.6.3) and 100th percentile.

This method has been thought as the best approach to be able to measure cold-start operation emissions as shown on Figure 10-4; it also follows closely method 5 methodology with the following changes:

a. Analyse the “cold start” trip (full data set with cold and warm operation) and obtain a CF (100th percentile – max value).
b. Analyse the “warm” trip (only warm operation) and obtain a CF (100th percentile – max value).
c. Weight the result in the following way:
    - 14% “cold-operation” CF’
    - 86% “warm-operation” CF’
d. The application of this method would need that no power threshold will be applied; this method uses the 100th percentile CF for both cold and warm calculations.

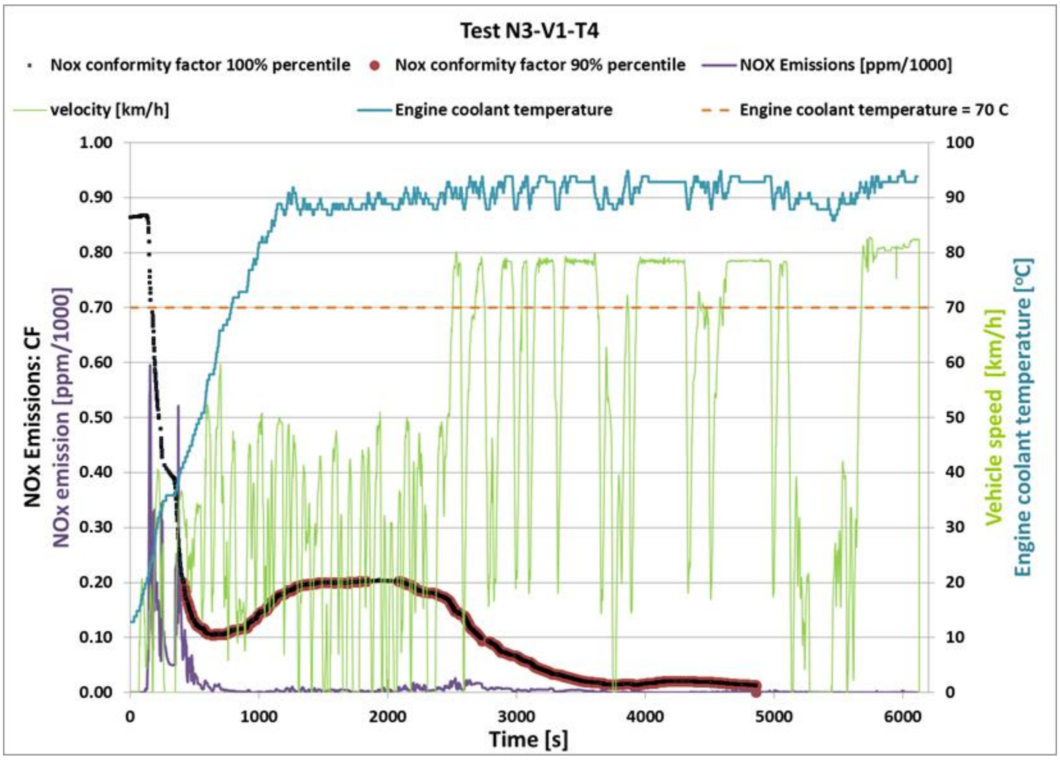

Figure 10-4 Cold-start operation highlighted emissions.

10.2. Assessment of the different methodology to address cold-start operation

This section reviews the advantages and drawbacks of the different proposed methodology to include CS operations as defined in the previous sections of this annex.

Method 1 is the business-as-usual approach and obviously does not address cold-start operations.

Taking in consideration cold start with **Method 2** follows the procedure and the current legislation definitions, it also does not compromise the results but it is not sensitive enough to highlight an engine/vehicle cold-start issue. In particular the use of the 90th cumulative percentile as it has been shown in previous sections will exclude most of the cold start operation area of the trip.

Method 3 defines the cold start as 1 window and weights it as the 14% of the total CF. This method uses two different metrics for cold and warm operations. Therefore, in order to keep consistency in the data processing between the different operational areas this approach does not seem to be an appropriate one.

Method 4 analyses the windows which have a coolant temperature below 343 K separately and uses 90th cumulative percentile CF. It also runs the risk of not having any window with low temperature (in the case the CS is too short). Therefore this approach does not seem to address appropriately the cold-start operation issue.

Method 5 follows closely the methodology of Reg 49 (Annex 4B, 8.6.3) but using the 90th cumulative percentile excludes quite a part of the cold-start operations as it has been indicated previously in this report (see Section 6.8.2).

In order to tackle the amount of NOx emissions excluded from the analysis due to the cold start boundary of 70°C (343 K), JRC has proposed Cold Start Method 6 (refer to Section 10.1.6). This method performs a thorough analysis of the data generated by a single PEMS trip with cold start included, and it follows the weighting of hot and cold operation used for the calculation of emissions in Reg. 49 (Annex 4B, 8.6.3)..

Method 6 follows closely the methodology used to weight the cold start phase of the WHTC engine test (see Section 10.3); the fundamental principle is to use the data acquired from the complete trip included the cold start operation and analyse it with the MAW method. Instead of defining the CF applying current defined boundaries (20%Pt, 90th cumulative percentile and coolant temperature T≥70°C), Method 6 requires to analyse the complete trip and uses the 100th cumulative percentile (or maximum) CF; further to this, a second analysis is ran only on the warm operation (T≥70°C) to be able to get its 100th cumulative percentile CF. Once both CFs' are obtained the "cold operation CF" is weighted to 14% (as the cold phase of the WHTC) and the "warm operation CF" is consequently weighted to 86%.

Figure 10-5 shows the result of applying the cold start methods listed on Section 10.1 for test N2-V3-T3. As it can be seen, the current ISC legislation with its boundaries (Method 1, Section 10.1.1) is far from representing the real vehicle situation in terms of NOx emissions. Method 6 portrays a situation on which the maximum CF is evaluated in order to obtain a real indication of the NOx emitted under normal everyday cold-start operation of the vehicle. The importance of including the cold-start operation as part of the PEMS procedure is because it should monitor the performance of the engine between the test performed at engine type approval (WHTC) and after a number of months/kilometres of vehicle usage (currently within the first 18 months and every 2 years after that; and no less than 25000km of use, Section 3.1 and 3.2 Annex II to Regulation 285/2011). Therefore it seems consistent that PEMS procedure must have the possibility to monitor the cold-start operation because of WHTC contains a cold-start operation phase (within defined boundaries conditions).

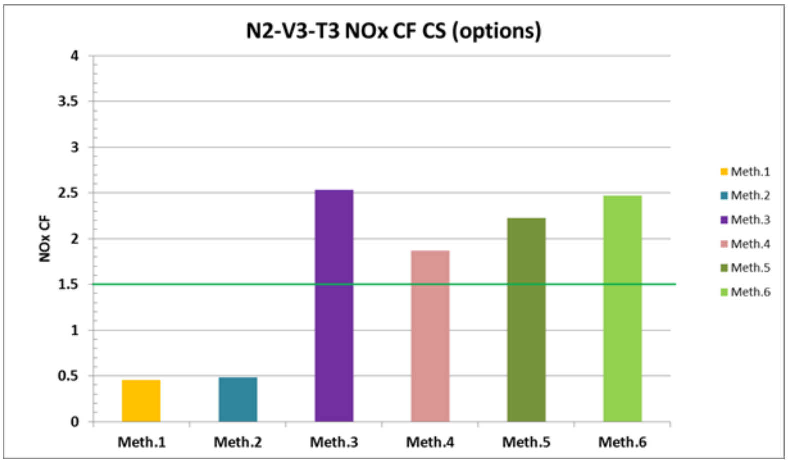

Figure 10-5 NOx CF obtained applying the different cold-start methods to a N2 vehicle test

Following the N2 example, Figure 10-6 shows the results of the evaluating methods from an N3 vehicle. As it can be seen, the extent of the coverage of Method 6 allows having a result which is closer to the real emissions of this type of vehicles. Further to this, Method 6 guarantees a full diagnostic of the emitting capabilities of the vehicle by preventing the current analysis boundaries to conceal excessive NOx emissions in some of the operational part of the trip. It is also important to point out that this method does not penalize those vehicles which emission strategy seems to better handle the cold-start operation.

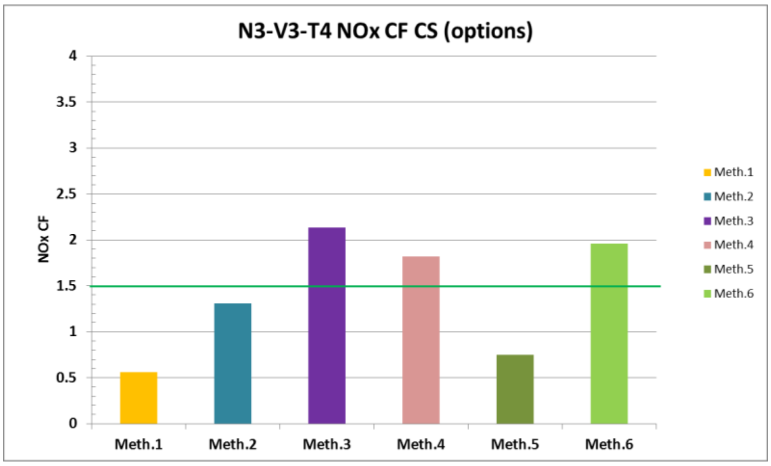

Figure 10-6 NOx CF obtained applying the different cold-start methods to a N3 vehicle test

Figure 10-7 represents an N3 vehicle with cold start operation where the coolant temperature at the beginning of the trip is 10°C.

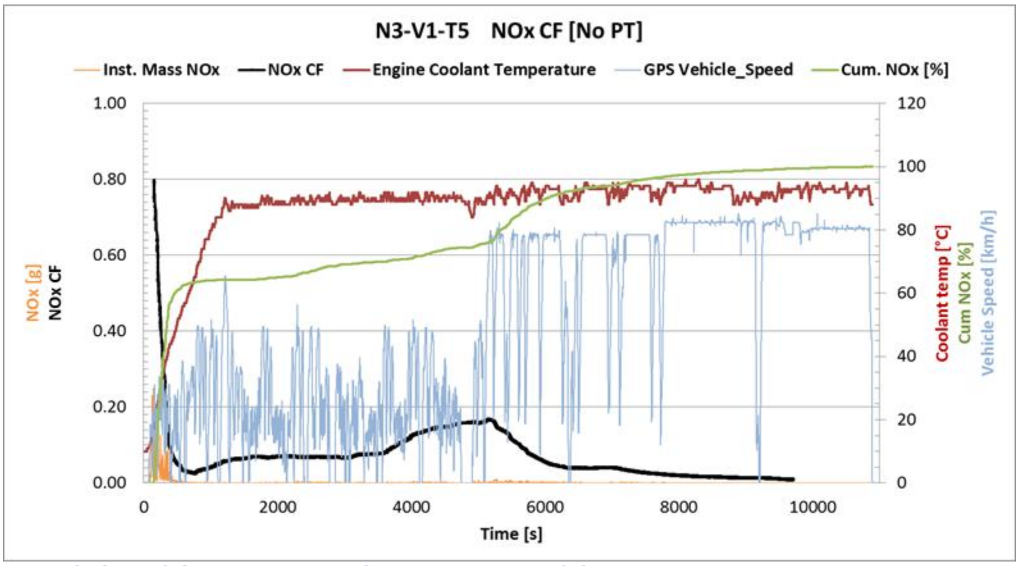

Figure 10-7 Relation of the NOx CF to other parameters of the N3-V1-T5 test

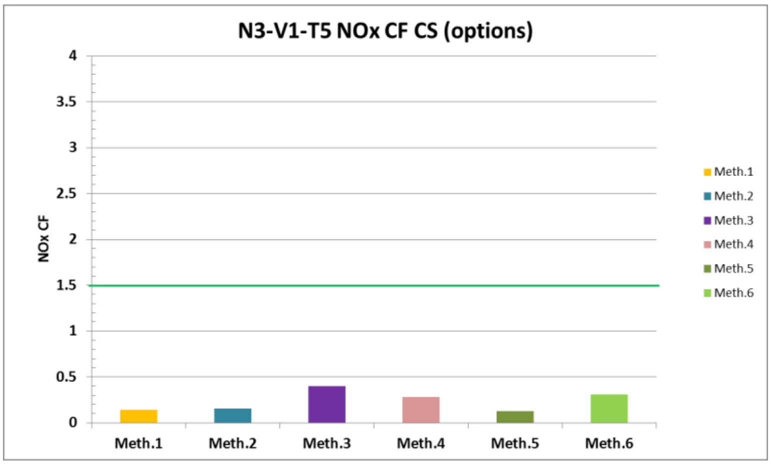

Figure 10-8 NOx CF obtained applying the different cold-start methods to N3-V1-T5 vehicle test

As it can be seen in Figure 10-8 that shows the results from the different evaluating methods on the complete set of data from N3-V1-T5; Method 6 does not worsen the results due to taking the power threshold and cold start boundaries, instead it enhances the accuracy of the ISC methodology to detect those vehicles that are not performing as well in this operational area.

10.3. Annex 2: Similarity between Reg 49 Cold start Methodology (Annex 4, 8.6.3) and JRC's proposal "Method 6"

The procedure to calculate the overall (weighted) specific emissions of the combination of the cold-start and warm-start tests of the WHTC cycle at engine type approval is described in paragraph 8.6.3 of Annex 4 (Test Procedure) to the UN ECE Regulation No. 49 [8] as follows:

"8.6.3. Calculation of the specific emissions"

The specific emissions e_{gas} or e_{PM} (g/kWh) shall be calculated for each individual component in the following ways depending on the type of test cycle.

For the WHSC, hot WHTC, or cold WHTC, the following equation shall be applied:

$$e = \frac{m}{W_{act}}$$

Where:

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

W_{act} is the actual cycle work as determined according to paragraph 7.8.6., kWh

For the WHTC, the final test result shall be a **<u>weighted average from cold start test and hot start test</u>** according to the following equation:

$$e = \frac{0.14 \cdot m_{cold} + 0.86 \cdot m_{hot}}{0.14 \cdot W_{act,cold} + 0.86 \cdot W_{act,hot}} \qquad \text{Eq. 1}$$

Where:

m_{cold} is the mass emission of the component on the cold start test, g/test

m_{hot} is the mass emission of the component on the hot start test, g/test

$W_{act,cold}$ is the actual cycle work on the cold start test, kWh

$W_{act,hot}$ is the actual cycle work on the hot start test, kWh

If periodic regeneration in accordance with paragraph 6.6.2. applies, the regeneration adjustment factors kr,u or kr,d shall be multiplied with or be added to, respectively, the specific emissions result e as determined in equations 69 and 70.

<u>JRC's ISC proposed cold start method 6</u>

CF is the conformity factor $CF = \frac{e}{L}$

Where:

e is the window brake-specific emission of the component, mg/kWh;

L is the applicable limit, mg/kWh.

<u>Cold Start Method 6</u> defines the final CF of the cold start operation as:

$$CF = 0.14 \cdot CF_{cold} + 0.86 \cdot CF_{hot}$$

Where:

CF_{cold} is the conformity factor at 100% cumulative percentile of the cold calculation

CF_{hot} is the conformity factor at 100% cumulative percentile of the hot calculation

The window length in the MAW is equal to the work measured over the reference laboratory transient cycle (W_{ref}).

$$CF = \frac{0.14 \cdot e_{cold} + 0.86 \cdot \ e_{hot}}{L}$$

$$e_{ISC-cold\ start} = L \cdot CF = \frac{0.14 \cdot m_{cold} + 0.86 \cdot m_{hot}}{W_{ref}}$$

Eq. 2

Eq. 1 ≈ Eq. 2 as the W_{ref} is the work measured over the reference laboratory transient cycle as by prescription[4]

$$0.85 \cdot W_{ref} \ \leq \ W_{act} \leq 1.05 \cdot W_{ref}$$

An eventual inclusion of cold-start operation in the PEMS procedure using the proposed “Method 6” will need to include the appropriate temperature boundary conditions. This will be part of a more detailed dedicated study as already mentioned above (see section 8.1). Annex 2 only addresses the formal equivalence between the assigned percentage to cold and warm emissions to obtain the final test’s specific emission in Regulation 49 [8] and that proposed in “Method 6”.

[4] Paragraph 7.8.6 of Annex 4 (Test Procedure) to the UN ECE Regulation No.49

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