European Commission

JRC TECHNICAL REPORTS

Real driving emissions: 2017 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty

Giechaskiel B., Clairotte M.,
Valverde V., Bonnel P.

2018

Joint Research Centre

EUR 29138 EN

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Contact information
Name: Barouch Giechaskiel
Address: European Commission, Joint Research Centre, via E. Fermi 2749, Ispra, I-21020 (VA), Italy
Email: barouch.giechaskiel@ec.europa.eu
Tel.: 0039 0332 78 5312

JRC Science Hub
https://ec.europa.eu/jrc

JRC109481

EUR 29138 EN

PDF ISBN 978-92-79-80384-0 ISSN 1831-9424 doi:10.2760/127122

Luxembourg: Publications Office of the European Union, 2018

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How to cite this report: Giechaskiel B., Clairotte M., Valverde V., Bonnel P., *Real driving emissions: 2017 assessment of PEMS measurement uncertainty*, EUR 29138 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80384-0, doi:10.2760/127122, JRC109481

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Foreword

Regulation (EU) 2016/427 (first regulatory package of the Real-Driving Emissions regulation, RDE1) introduced on-road testing with Portable Emissions Measurement Systems (PEMS) to complement the laboratory Type I test for the type approval of light-duty vehicles in the European Union (EU). Subsequently, Regulation (EU) 2016/646 (RDE2) introduced Real Driving Emissions (RDE) conformity factors for nitrogen oxides (NOx) emissions in two steps. Both regulations were consolidated in the World Harmonized Light Duty test Procedure (WLTP) Regulation (EU) 2017/1151 and further developed by Regulation (EU) 2017/1154 (RDE3), which also introduced an RDE conformity factor for the on-road test of ultrafine particle emissions. For the sake of simplicity, in the report whatever applies to the original RDE regulations applies also for their transposition into WLTP.

A temporary conformity factor of 2.1 for NOx tailpipe emissions may apply from September 2017 upon the request of the manufacturer. In a second step, a conformity factor of 1.5 will apply for all manufacturers from January 2020. This conformity factor requires full compliance with the Euro 6 limit (i.e., a conformity factor of 1), but allows a margin of 0.5 to account for the additional measurement uncertainty of PEMS relative to standard laboratory equipment. The recitals in the RDE regulations oblige the Commission to review the appropriate level of the final conformity factor in light of technical progress, a task that was undertaken by the European Commission's Joint Research Centre (JRC).

The objective of this report is to:

- Document review activities in 2015/2016 that led to an amendment of the RDE Regulation regarding the measurement performance of NOx analysers.
- Document review activities in 2017 regarding the PEMS measurement uncertainty for NOx.
- Outline the framework for the systematic review and revision of PEMS measurement uncertainties in the future.

Acknowledgements

The authors would like to acknowledge the RDE working group for their data contributions and their comments in support of the review of the PEMS measurement uncertainty margins.

Special acknowledgments to the colleagues from the European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), P. Dilara, and Directorate-General for Environment (DG ENV), V. Franco and Z. Kregar, for their comments.

Abstract

Regulation 2016/427 introduced on-road testing with Portable Emissions Measurement Systems (PEMS) to complement the laboratory Type I test for the type approval of light-duty vehicles in the European Union. A NOx conformity factor of 1.5 will apply from January 2020/2021. This conformity factor includes a margin of 0.5 to account for the additional measurement uncertainty of PEMS relative to standard laboratory equipment. Said margin (and also the PN margin, initially set at 0.5 by Regulation (EU) 2017/1154 (RDE3), has to be reviewed annually (Recital 10 of Regulation 2016/646). This report summarizes the first review of the NOx margin and lays out the framework for future margin reviews. Since the PN margin was first set in 2017, it was not included in the 2017 review exercise.

Based on experimental data received by the stakeholders, technical improvements of PEMS and assumptions of possible zero drift during the tests, a NOx margin of 0.24 to 0.43 was calculated.

1 Introduction

1.1 Overview of technical requirements for PEMS

A Portable Emission Measurement System (PEMS) generally consists of 1) pollutant analysers, 2) an exhaust flow measurement (EFM) device, 3) a positioning system, 4) auxiliary sensors (ambient temperature and pressure etc.), and 5) a power supply.

The distance specific emissions are calculated based on the signals from the analyser, the exhaust flow meter and the positioning system (with distance being derived from an instantaneous velocity signal). Regulation 2016/427 describes the technical requirements for PEMS measuring devices. These requirements result in a theoretical measurement **uncertainty** (more details will be given in **Chapter 4**). Details of the technical specifications can be found in the RDE Regulation or in the **Annex**.

The most important **requirements** prescribed in the RDE regulation for the analysers and the EFM that have direct impact on the PEMS measurement uncertainty are:

- Accuracy (at a specific concentration). For NOx (concentration measured by the analyser) and EFMs (concentration measured by the analyser) is set at 2% of the reading.
- Non-Linearity (differences at low – high concentrations): The permissible variability expressed as standard error of estimate (SEE) is set at 1% for NOx and at 2% for EFMs.
- Drift over time for zero and maximum concentration (span). For NOx, the permissible zero and span drift is set at 5 ppm and 2% of reading respectively. For EFMs it is set at 1%.

The comparison of the PEMS with the laboratory equipment on a chassis dynamometer is a check of the functionality of the complete PEMS once it is fully installed in the vehicle. In the context of RDE measurements, is called a "**validation of PEMS**" and is not meant to compare the respective measurement performance of the laboratory and the PEMS test principles. Such a validation test only ensures that the PEMS is correctly installed and functioning when its emissions over a WLTC are found to be within a reasonable range around the ones given by the CVS. The permissible tolerances of this validation are given in the RDE Regulation. For example, for NOx, the limits are set to ±15% or 15 mg/km, whichever is larger.

The scope of this review includes an investigation to confirm that these requirements are satisfactory - achieved by current PEMS equipment, and otherwise, whether some of them need to be revisited to reflect the level of performance of the instruments.

1.2 Rationale for the definition of the NOx conformity factor

Following Recital 10 of Regulation 2016/646, the final NOx conformity factor of 1.5 takes into account the **additional** measurement uncertainty related to the application of PEMS. The additional uncertainty introduced by the use of portable equipment should be evaluated relative to standard laboratory equipment at the level of the emission limit, i.e. at 80 mg/km for the case of NOx. To obtain a quantitative estimate of this additional measurement uncertainty, the JRC conducted in 2015 an assessment of PEMS and laboratory equipment based on the technical performance requirements laid down respectively for PEMS and laboratory equipment in the RDE Regulation 2016/427 and in UNECE Regulation 83. This assessment was complemented by a scenario analysis based on emission measurements conducted with 4 vehicles, ranging in engine displacement from 1.2 to 3.0 litres. The results that were presented to the RDE working group in October 2015 suggested that PEMS equipment might be subject to up to 30% higher measurement uncertainty than laboratory equipment (i.e., an uncertainty margin of 0.3), broken down as follows:

- 10% (margin 0.1) additional uncertainty resulting from the performance requirements for PEMS analysers, exhaust flow meter, and the vehicle speed signals.
- 20% (margin 0.2) additional uncertainty resulting from possible analyser drift affecting the second-by-second measurement of NOx concentrations during an on-road test.

This first assessment of the PEMs uncertainty margin for NOx was however limited to vehicles with 1.2 to 3.0 litre engines, and it assumed a gradual (linear) drift over the test. This meant that assuming a worst-case scenario for the drift (maximum allowable drift occurring from the beginning of the test) and taking into account the increased effect of drift (in mg/km terms) for engines with displacement above 3.0 litres, the uncertainty margins could, in some cases, exceed those quantified initially by the JRC. Taking these observations into account, the finally established NOx conformity factor of 1.5 can be regarded as a conservative estimate of the additional uncertainty of NOx emissions measured with PEMS for a very broad range of engine displacements. In any case, an annual review clause was introduced in the legislation in order to allow for further improvements and analysis.

Note: Analyser drift is virtually negligible in the laboratory, as the NOx (and rest pollutants) concentration in the sampling bags is determined once at the end of a test, before the measurement of the bag that collected the exhaust gas, rather than over longer periods on an instantaneous basis (typically at a frequency of 1 Hz) as it is done with PEMS.

1.3 Review activities and amendments implemented in 2016

The Commission organized in 2016 two stakeholder meetings dedicated on the issue of uncertainty of PEMS measurements in 2016: one on 8 January with all major PEMS manufacturers and a second one on 29 February with all interested RDE stakeholders. In these meetings, PEMS manufacturers expressed their support to reduce the maximum allowable zero drift for NOx analysers by 50% through a revision of Table 2, Point 6.1 of Appendix 1 of Regulation 2016/427. This table specified that the zero and span drift over a test had to be within 5 ppm or 2% of the reading. The provision used to apply individually to NO_2 and NO/NOx measurements. As NOx is calculated as the sum of the measured NO_2 and NO concentrations, the allowable NOx zero drift was thus 10 ppm. The revised provisions in Regulation 2017/1154 (RDE3) clarify that NOx concentrations are to be determined within a zero drift of 5 ppm. The amendment thereby lowers the permissible drift for NOx measurements by 50% compared to the original requirements in Regulation 2016/427 427 (in line with the recommendations of PEMS manufacturers), which in turn provides the scope for revising the PEMS uncertainty margin for NOx.

Based on the uncertainty assessment conducted by the JRC, the margin of 0.5 (or 50%) of the final NOx conformity factor consisted of the following components:

- Performance requirements as defined in Regulation 2016/427 (0.1 or 10%),
- Analyser drift as quantified by JRC (0.2 or 20%), and
- Worst-case drift effects (0.2 or 20%).

With the lowering of the permissible drift in half in RDE3, the analyser drift as quantified by JRC decreases ***theoretically*** to 0.2*50%=0.1 (or 10%). Likewise, the component of the margin that accounts for worst-case drift effects would decrease to 0.2*50%=0.1 (or 10%). However, experimental data are necessary to support the reduction of the margin due to the revised worst-case drift assumptions, and this was one of the objectives of the review activities that took place in 2017.

1.4 Review activities in 2017

The RDE Regulation obliges the European Commission to "keep under annual review the appropriate level of the final conformity factor in light of technical progress". To this end, "appropriate level" should be understood as the level of conformity factor that can be justified given the additional measurement uncertainty of PEMS which comply with the performance requirements of the RDE regulation, relative to the laboratory equipment. The term "technical progress" should be understood as improved PEMS measurement performance achieved in real-world use, and/or prescribed by more stringent regulatory RDE requirements.

The review of the PEMS measurement uncertainty should therefore focus on quantifiable error sources resulting from the technical performance requirements defined in the RDE regulation (e.g., for NOx analyser drift, specifically the footnote to Table 2 in Point 6.1 of Appendix 1 to Regulation 2016/427, accuracy of analysers and exhaust flow meters, or efficiency requirements for PN analysers). The variability of measured results related to RDE trip design, vehicle operating conditions, and data evaluation remain outside of the uncertainty margin and thus outside of the scope of the review.

In the context of the review of PEMS uncertainty margins, the following meetings took place in 2017:

- 2017-05-03: Teleconference of the margins sub-group (data input discussion)
- 2017-05-31: RDE meeting Brussels
- 2017-07-19: RDE meeting Brussels
- 2017-09-26: Teleconference of the margins sub-group (PEMS certification)
- 2017-11-08: RDE meeting Brussels (final presentation)

The 2017 review process followed 4 steps:

(i) Identification of the technical provisions in Appendices 1 and 2 of Regulation 2016/427 that are most relevant for the PEMS measurement uncertainty.

(ii) Evaluation of experimental data on how existing PEMS fulfil the technical requirements identified in (i) in laboratory and/or real-driving conditions.

(iii) Revision of selected performance requirements according to (ii).

(iv) Amendment of relevant RDE performance requirements for PEMS equipment according to (ii) and calculation of revised PEMS uncertainty margin for NOx.

Due to the recent introduction of Particle Number (PN) in RDE regulation (2017/1154 published in June 2017) and relatively recent introduction of commercial PN-PEMS, there was no evidence that the PEMS uncertainty margin for PN has changed since its initial determination. Therefore, the 2017 review of the PEMS uncertainty margin only addresses NOx measurements.

2 Experimental data

2.1 Overview of data

The official request for data from the RDE-LDV group participants took place on the 24th of March 2017. Data was received until the 26th of May 2017. Mid of September data from the RDE monitoring phase were also included in the JRC analysis, which was presented in May at the RDE group.

In the meantime, KIT (Karlsruher Institut für Technologie) launched a parallel independent study funded by the VDA (German Association of the Automotive Industry), which was originally planned to be finalized in August. KIT shared only a partial analysis and no data until the end of September 2017, so their results could not be used fully in this report. Nevertheless, the preliminary KIT results (and from others that gave detailed presentations like ACEA and JAMA) are compared to this analysis in **Chapter 4**.

The data used in the study came from 2 main sources:

- Voluntary submissions under the margins sub-group;
- Data from the RDE reporting and monitoring exercise.

2.1.1 Stakeholder-contributed data (margins sub-group)

The data received included (Table 2-1):

- 14 laboratories: consisting of 7 institutes, 2 instrument manufacturers, ACEA (4 OEMs), and JAMA (1 OEM). The data from another 2 labs were non usable (no comparisons with other instruments).
- 4 PEMS models/manufacturers: However, the majority of data produced by PEMS was from 2 manufacturers.
- 162 tests for zero/span drift evaluation.
- 162 cycles (>300 with sub-phases) from 101 vehicles for the validation tests.

No data from JRC was used in the analysis as it was desirable to base the 2017 analysis on others' experiences and at the same time see how far or close the 2015 estimations were. All received data was taken into account. No data was rejected. It was assumed that all tests were conducted under best engineering practice and there were no error or warning alarms from the instruments.

2.1.2 Monitoring data

The Commission also requested Member States (MS) Type Approval Authorities to provide the data collected during the monitoring period of RDE (Appendix 6 to Annex I to Regulation (EC) No 692/2008, Table 1). Data from 9 Member States were screened for data that could be used for the evaluation of the PEMS uncertainty margins (i.e. data that included a comparison with a reference laboratory system) (Table 2-2). From 415 RDE tests, 227 were usable for the drift evaluation. The data included also 66 "validations of PEMS" tests.

Some of the monitoring data were rejected for the following reasons:

- Drift values were exactly 0 or higher than the span value. This indicates that it is likely that no drift measurement took place (recorded values would be default/placeholders).
- Drifts were identical to those of previous measurements: This indicates that the same validation was used for a series of RDE tests (recorded values were carried over from a previous measurement).

Note: The PEMS manufacturers that were included in the studies are (alphabetically) AVL, HORIBA, MAHA, Sensors.

Table 2-1: Data received from the Margins sub-group.

Source		Drift	Validation	EFM	PEMS	Vehicles
ACEA	4 member OEMs	35	40	30	3 (unknown)	40
ADAC	Car club	1			1	1
AECC/Ricardo	Catalyst assoc.		26	2	1	2
AVL	Instr. manuf.	Yes		1	1	0
Bosch	Not usable*					
IFA		82	1		1	>1
IDIADA	Technical service	19	17		1	17
JAMA	1 member OEM		22	4	1	2
KTI	Not usable**					
Sensors	Instr. manuf.			44		
TUG	University		8	Yes	1	1
UK	Member state		38		1	38

* Data in presentation form and was asked not to be used

** Comparison data not available

Table 2-2: Data from the Monitoring phase. Some vehicles were tested in different configurations and for this reason the symbol ">" is used.

Source	Tests	Drift	Valid.	EFM	PEMS	Vehicles	Comment
Belgium	3	Yes	Yes	-		>2	
Czechia	63	Yes	Yes	-	2	>2	
France	155	Yes	No	-	1	>9	
Germany	114	Yes	Yes	-	2	>6	
Ireland	18	Yes	No	-	2	>1	
Italy*							Not usable
Netherlands*							Not usable
Spain	25	Yes	Yes		3	>4	
UK	37	Yes	Yes		2	>5	Diff. than Table 2-1
Total	415	227	66		4		

* Folders empty

3 Results

3.1 Validation

The comparison test between PEMS and chassis dynamometer laboratory (typically using the WLTC cycle) is called "**validation**" and the applicable rules are laid down in regulation 2016/427. It is recommended to validate the installed PEMS once for each PEMS-vehicle combination before or after the on-road test. For instance, the differences for NOx should be within 15% or 15 mg/km (whatever is larger).

3.1.1 Received data

For the validation comparisons the following data was used:

- 10 labs: 5 + ACEA (4 OEMs) + JAMA (1 OEM).
- 152 (302 with sub-phases) validation tests.

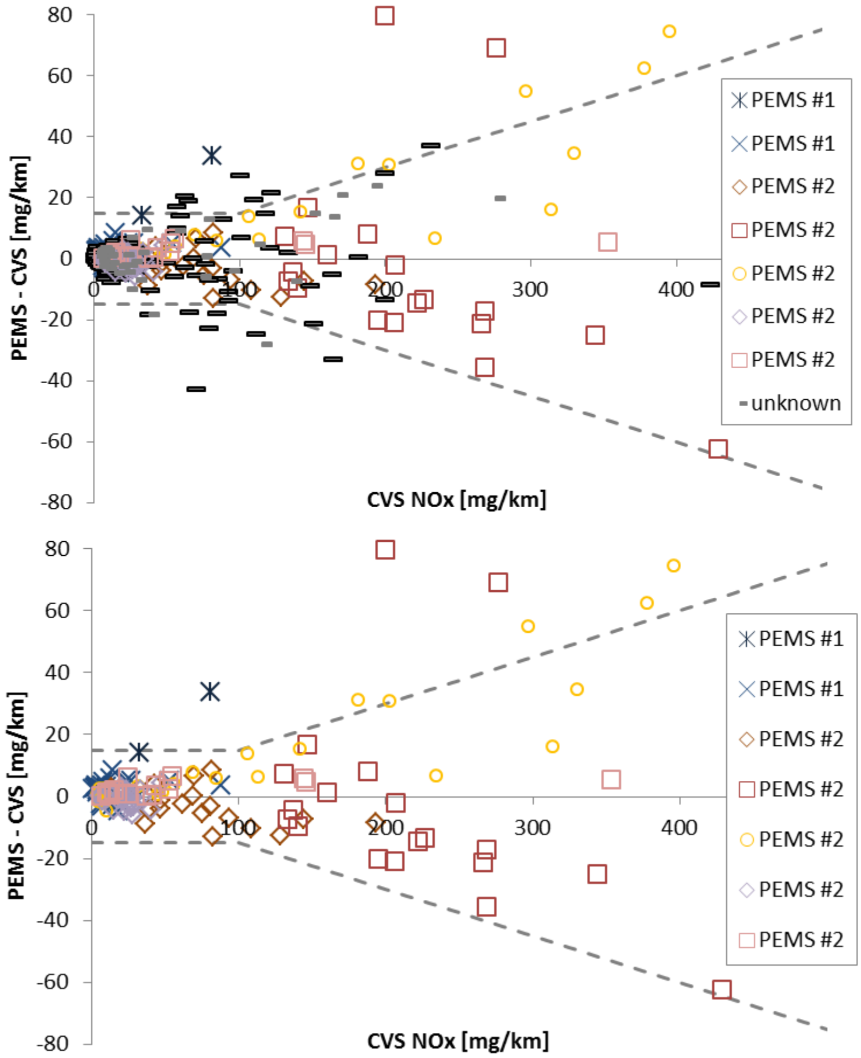


Figure 3-1: Validation test results for stakeholder-contributed data. The subplots cover a) all data (top) and b) tests where the manufacturer of the PEMS was reported (known) (bottom). Different symbols indicate different sources of data. The dotted lines mark the permissible difference of 15% or 15 mg/km between PEMS and CVS (bag results).

The results are presented in Figure 3-1a for all data and Figure 3-1b for tests where the model/manufacturer of the PEMS was reported (known) (two different manufacturers).

The results show that the majority of the data fall within the permissible range, but nevertheless, there are cases that exceed the permissible limits. The statistics will be discussed in the following paragraphs.

3.1.2 Monitoring data

The monitoring data included:

- Data from 7 Member States at more than 8 locations.
- 4 PEMS manufacturers.

Figure 3-2 presents the results. Only one test was outside the permissible tolerance.

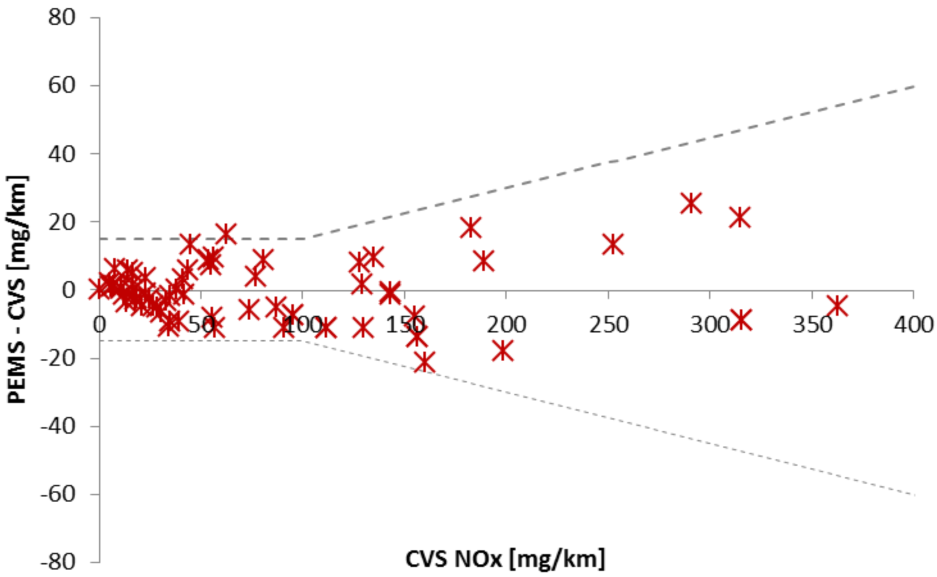


Figure 3-2: Validation test results included in the monitoring data. The dotted lines mark the permissible difference of 15% or 15 mg/km between PEMS and CVS (bag results).

3.1.3 Summary

All previous results and the statistics (pass/fail) are summarized in Table 3-1. The pass/fail was based on the permissible tolerance of 15 mg/km or 15% (whichever is larger) from the legislation and thus the uncertainty of the CVS measurement is also included.

The results indicate that for NOx approximately 95% of the validation tests are within the permissible requirements (i.e. they are below 15 mg/km or 15% whichever is larger from the reference laboratory NOx result). The results during the monitoring phase exhibit excellent compliance with the requirements of the validation test, i.e. the difference when measuring simultaneously PEMS and laboratory equipment. Therefore, the uncertainties in a laboratory testing environment between PEMS and laboratory equipment is adequately covered by the requirements of the validation test when measuring at the EURO 6 limit. The validation test does not include the uncertainty related to the distance, because this is taken from the dynamometer.

Table 3-1: Validation tests (pass/fail results).

	Stakeholder contributed		Monitoring
	Cycles	Sub-phases	Cycles
All (with unknown equipment)	152	302	
Outside permissible tolerance	9	26	
Not valid tests percentage	6.3%	8.6%	
All (with known equipment)	112	142	66
Outside permissible tolerance	6	9	1
Percentage of invalid tests	**5.4%**	**6.3%**	**1.5%**

Analysing separately the sub-phases of the test cycles showed only slightly higher percentages of tests exceeding the permissible levels (which currently apply for the whole cycle). Dedicated tests contributed by members of JAMA and ACEA showed however that low speed (exhaust flow) sub-phases may be more often outside the permissible limits (50% of the failed tests), which could indicate the presence of technical issues (e.g. non-linearity, lower accuracy of the EFM at low flow rates) of the PEMS and even the CVS. Checking separately each phase of the laboratory test cycle during the validation test might capture PEMS issues at very low or high flowrates or speeds. Figure 3-3 shows as an example the results of PEMS validation tests for different WLTC sub-phases.

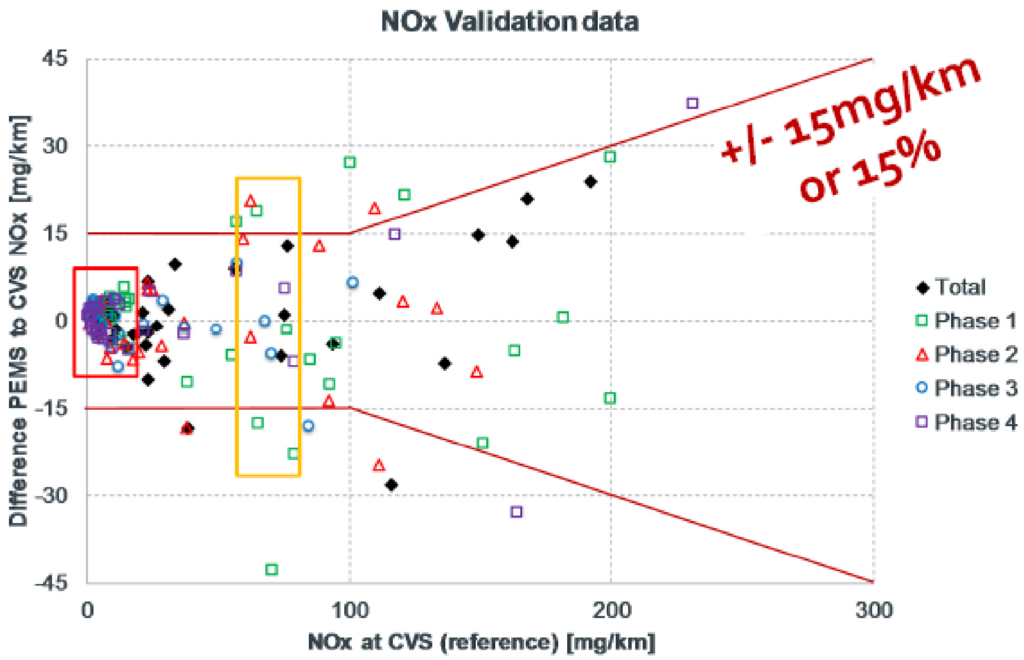


Figure 3-3: Differences of PEMS to CVS for different cycle phases. From ACEA presentation to the RDE group (31st of May, Brussels). Phases 1-4 stand for the WLTC sub-phases. The yellow rectangle is the area of the Euro 6 limit. The red rectangle is the area of very low NOx emissions.

3.2 NOx analyser zero drift

3.2.1 Regulation requirements

According to Regulation 2016/427 (RDE1) the permissible zero drift was set to 5 ppm for NO and 5 ppm for NO_2. In Regulation 2017/1154 (RDE3), based on the first review of the margins that took place in 2016, the requirements were changed and the permissible zero drift was set to 5 ppm for NOx ($NO+NO_2$). Thus the permissible zero drift was therefore effectively reduced by 50% with RDE3.

3.2.2 Zero drift evaluation

The actual drift based on experimental data was evaluated using the received data and the monitoring data. Three cases were examined for the NOx zero drift ($NO+NO_2$):

i) after the validation test in the laboratory at 23°C,

ii) after the real driving emissions test on the road, and

iii) after tests under environmental conditions outside the normal conditions (extended conditions).

Table 3-2 summarizes the number of tests, the sources and the statistics (mean, median, minimum and maximum values).

Table 3-2: Zero drift results from the margins sub-group or the monitoring phase at the laboratory, after an RDE test or at extended conditions. The results are sub-divided in all received results or results with reported PEMS model (known). Extended conditions are temperatures <0°C, or >30°C, or pressures changes greater than ±200 mbar.

	Received (margins sub-group)						Monitoring
ZERO	Laboratory (validation)		RDE		Extended		RDE
	All	Known	All	Known	All	Known	Known
Labs [#]	1+ACEA	1	3+ACEA	3	1	1	11
Tests [#]	36	1	119	89	1	1	228
PEMS [#]	3	1	4	3	1	1	4
Mean [ppm]	-2.9	-0.6	0.2	0.3	0.4	0.4	0.2
Median [ppm]	-0.1	-0.6	0.2	0.3	0.4	0.4	0.0
Min [ppm]	*-28.1*[*1]	-0.6	-7.3	-7.3	0.4	0.4	**-5**
Max [ppm]	2.5	-0.6	4.7	4.7	0.4	0.4	**8**
Failed [#]	6	0	1	1	0	0	2
Failed [%]	16.7%	0%	1.1%	0.8%	0%	0%	0.9%

[*1] indicates not enough warm-up time or other PEMS preparation procedure

One important point to note is that the mean zero drift is almost 0 (except the problematic case of laboratory validation with all PEMS equipment, where the mean is -2.9 ppm), indicating no systematic drift, and that probably the ±5 ppm scatter is due to random variation between various instruments. This was valid for all tests and those with known PEMS equipment. The worst zero drift results were observed in the monitoring data and was between -5 ppm to +8 ppm for RDE tests (only 2 tests outside the 5 ppm limit). Figure 3-4 shows all data dividing them for tests with and without unknown PEMS equipment.

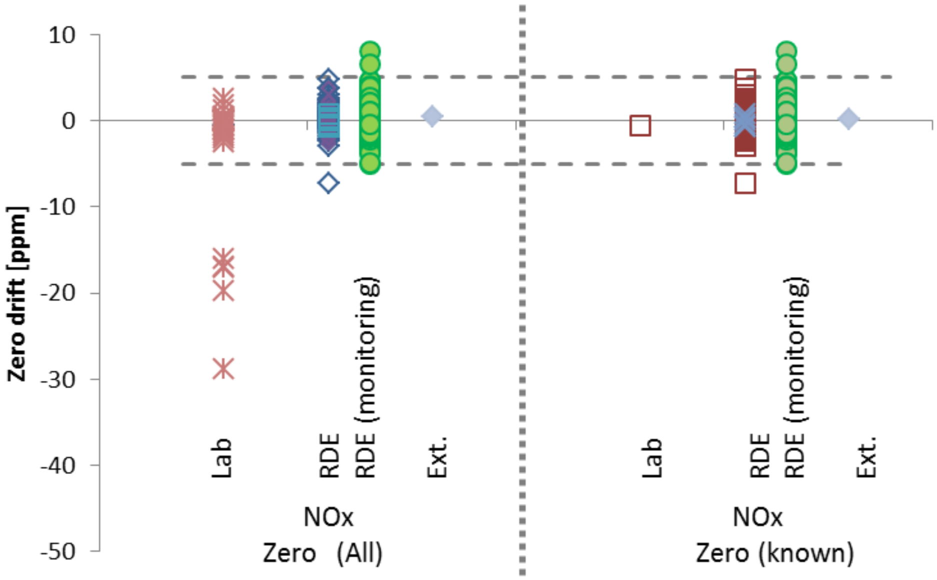


Figure 3-4: Zero drift results after tests in the laboratory, after RDE tests and at extended conditions (Ext.). In this graph extended conditions are temperatures below 0°C, or higher than 30°C, or pressures changes greater than ±200 mbar. Dotted lines show a 5 ppm drift.

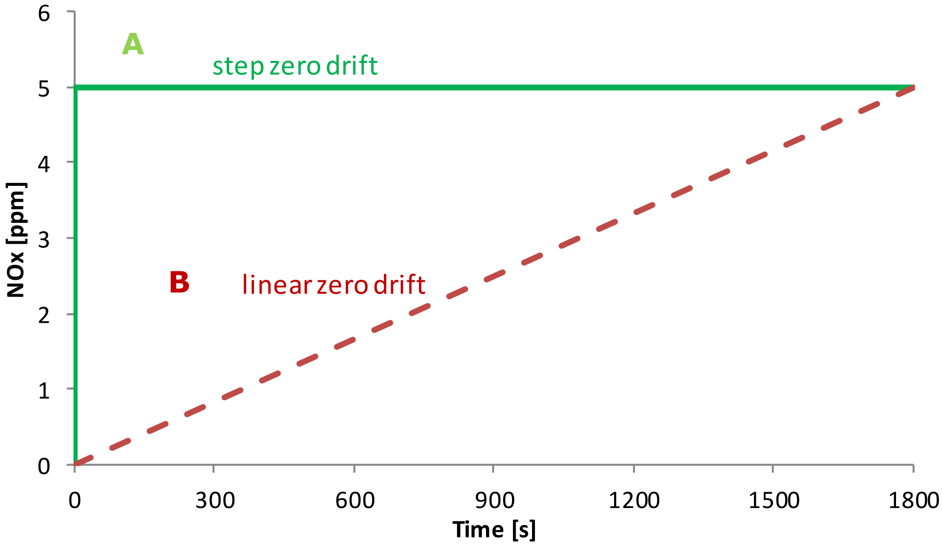
3.2.3 Implication of 5 ppm zero drift

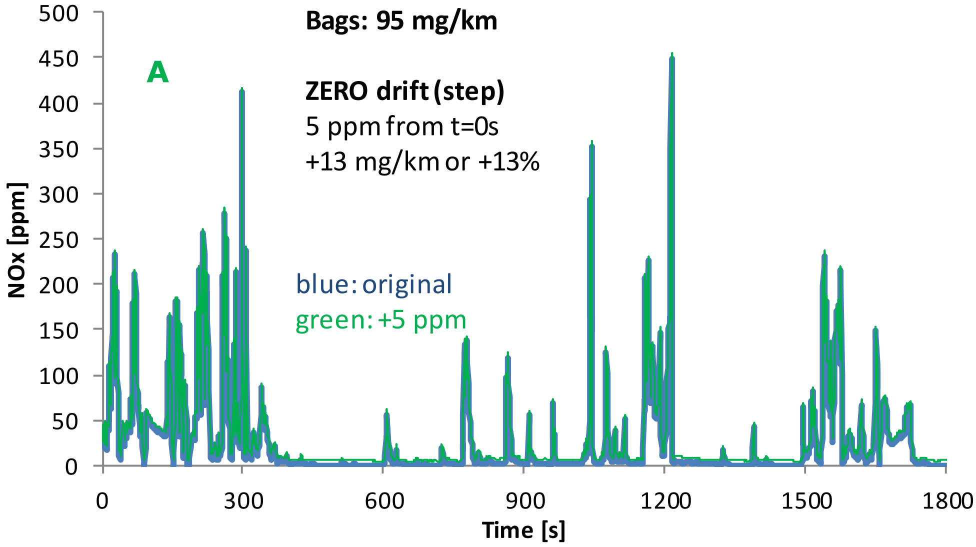
Comparing the zero drift before and after the test did not allow knowing how much it influences the uncertainty of the measurement, because it is not known when this drift built up over the test. Therefore, and to be able to assess this aspect, two scenarios of the zero drift were analysed:

A. A drift of 5 ppm happening immediately at the beginning of the test (t=0 sec) and remained constant for the whole test. A real time example is presented in Figure 3-5a. This scenario is called "step zero drift" and it represents an extreme assumption.

B. A drift happening linearly from the beginning of the cycle and reached 5 ppm at the end of the test (in this example after 1800 s, end of the WLTC) (Figure 3-5b). This scenario is called "linear zero drift" (as in the JRC 2015 study).

The two scenarios, for this example of Figure 3-5, were found to lead to an overestimation of the 'true' emissions (in the absence of drift) by 13 mg/km and 7.4 mg/km (respectively for step and linear drift) for a test in the laboratory of 30 minutes duration.





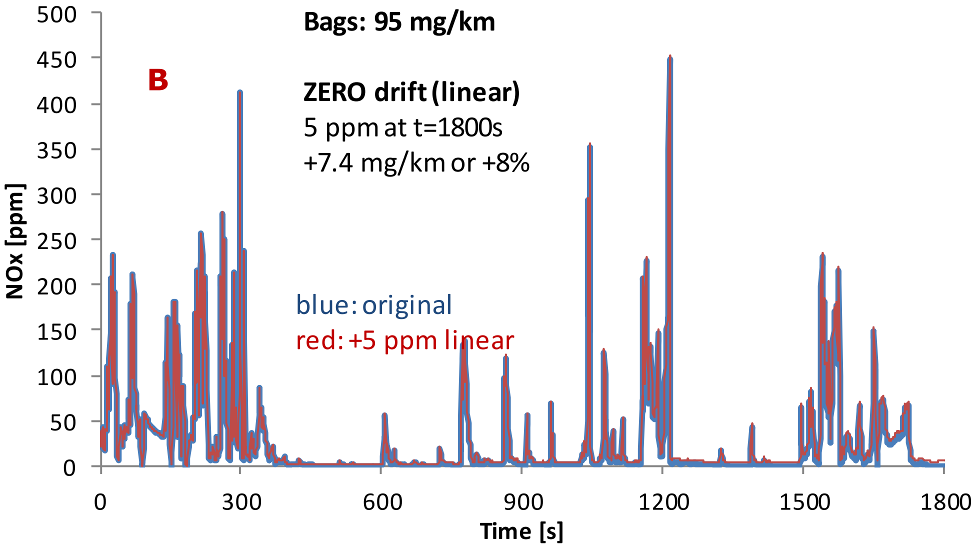
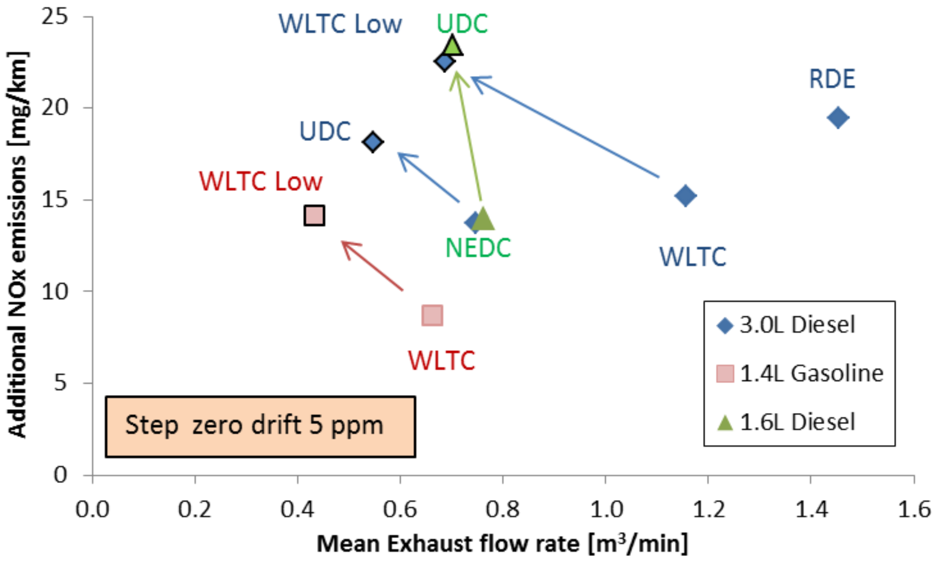


Figure 3-5: Real time example of a 5 ppm NOx zero drift a) drift over time b) NOx emissions and "step zero drift" (step increase of 5 ppm) c) NOx emissions and "linear zero drift" (linear increase up to 5 ppm).

A second influence that needs to be estimated is what happens when this drift happens for longer or shorter cycles and for different engine capacities. At a next step the drift effect was simulated for different driving cycles (NEDC, WLTC and RDE cycles) and different typical vehicles technologies (diesel or gasoline) with different engine capacities ranging from 1.4L to 3L. The exhaust flow rates were taken from actual vehicles.

Figure 3-6a shows the simulation results (additional NOx emissions) for a step increase of 5 ppm from time t=0 sec. The results are plotted in function of the mean exhaust flow rate. The arrows show the urban part of the respective cycles (e.g. UDC for NEDC, Low part for WLTC).



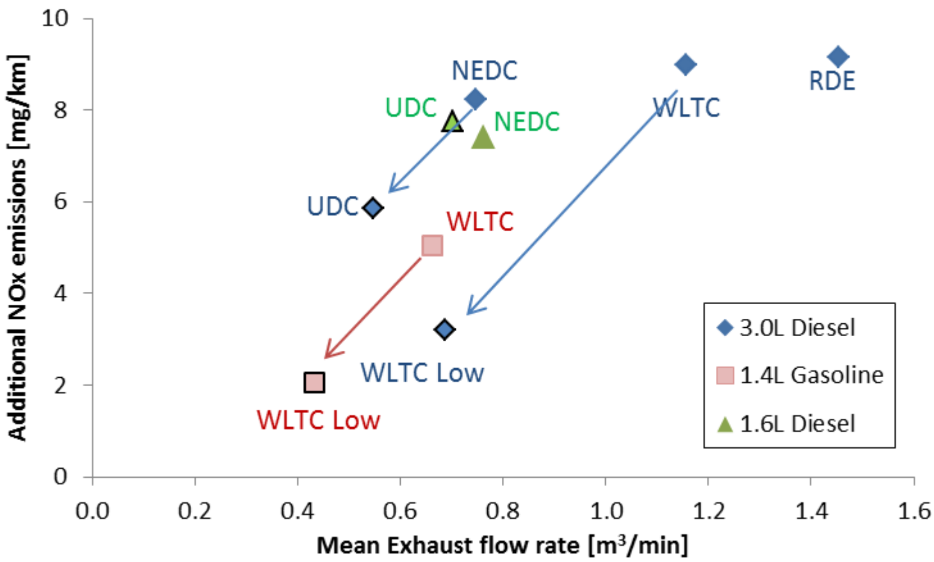


Figure 3-6: Effect of zero drift on final NOx emissions for different cycles and vehicles in function of the mean exhaust flow of the specific test: a) 5 ppm step increase from t=0 sec b) linear increase to reach 5 ppm at the end of the cycle. The arrows show the urban (low) part of the specific test cycles.

The results show:

- Larger engines have higher mean exhaust flow rates over a cycle and the 5 ppm drift results in a larger increase in NOx emissions in mg/km.
- For most cases the maximum 5 ppm zero step drift translates to <15 mg/km NOx emissions over typical cycles.
- A **worst case "step zero drift"** for the largest engines and/or urban conditions (where the mean speed/distance is low) could translate to 20-25 mg/km NOx, i.e. another 5-10 mg/km NOx with respect to the typical <15 mg/km NOx contribution of drift.

Figure 3-6b shows the simulation results for a linear increase of drift reaching 5 at the end of the cycle (i.e., t=1180 sec for NEDC, t=1800 s for WLTC or t>5000 sec for RDE). The results show:

- For all cases the linear 5 ppm drift translates to an increase of NOx emissions <10 mg/km.
- A **worst case drift** for the largest engines and/or urban conditions (where the mean speed and urban distance is low) was not observed. The drift effect at the urban part is negligible because the zero drift is very low at the beginning of the cycle under this scenario.

Assuming the worst-case "step zero drift" scenario A, zero drift has a contribution to the overall uncertainty of <15 mg/km for RDE trips in most situations. An additional contribution to the uncertainty in the range of 5-10 mg/km is observed for the largest engines and/or urban conditions.

Assuming the "linear zero drift" scenario B, zero drift has a contribution to overall uncertainty of <10 mg/km, and no extra uncertainty contribution is observed for the largest engines and/or urban conditions.

3.3 NOx analyser span drift

3.3.1 Regulation requirements

In Regulation 2016/427 (RDE1) the permissible span drift was set to 2% for NO and 2% for NO_2. In Regulation 2017/1154 (RDE3), based on the technical input provided by instrument manufacturers, the specifications were tightened to 2% for NOx ($NO+NO_2$).

The two analysers (for NO and NO_2) are typically calibrated at different concentration levels (NO with >2000 ppm and NO_2 with <500 ppm span gases). Therefore, the measurement uncertainty contribution due to span drift is determined in practice by the NO analyser, and the modification of the specifications does not significantly affect the measurement uncertainty.

3.3.2 Span drift evaluation

The actual span drift was evaluated using the received experimental data from the margins sub-group and the monitoring data. Three cases were examined for the span NOx drift ($NO+NO_2$):

i) after the validation test in the laboratory at 23°C,

ii) after the real driving emissions test on the road, and

iii) after changing the environmental conditions outside the normal conditions (extended conditions).

Table 3-3 summarizes the number of tests, the sources and the statistics (mean, median, minimum and maximum values). Figure 3-7 presents all data and distinguishes the tests with known or unknown PEMS equipment.

Table 3-3: Span drift results.

	Received (margins sub-group)						Monitoring
SPAN	Laboratory (validation)		RDE		Extended		RDE
	All	Known	All	Known	All	Known	Known
Labs [#]	1+ACEA	1	3+ACEA	3	2	1	11
Tests [#]	36	1	119	89	31	12	227
PEMS [#]	3	1	4	3	2	1	4
Mean [%]	0.0%	0.3%	-0.1%	0.1%	-0.2%	0.0%	-0.3%
Median [%]	0.1%	0.3%	0.1%	0.1%	-0.2%	0.0%	0.0%
Min [%]	-7.0%	0.3%	-5.0%	-0.7%	-8.9%	-0.3%	-9.3%
Max [%]	5.1%	0.3%	3.1%	0.9%	11.7%	1.5%	3.3%
Failed [#]	9	0	5	0	12	0	24
Failed [%]	**25%**	**0%**	**4.2%**	**0%**	**39%**	**0%**	**10.5%**

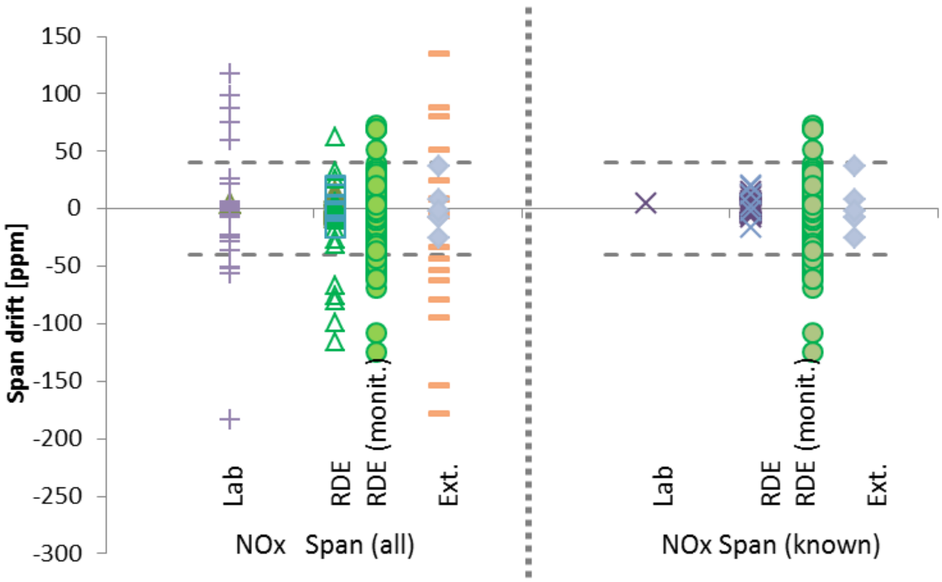


Figure 3-7: Span drift results after tests in the laboratory, after RDE tests and at extended conditions (Ext.). In this graph, extended conditions are temperatures below 0°C or higher than 30°C, or pressures changes greater than ±200 mbar. Dotted lines show approximately 2% drift (span gas 2000 ppm); the exact level depends on the span gas concentration. Each symbol refers to a different PEMS model. Symbols "+" and "-" are unknown PEMS.

The tests failed in the laboratory represent in general a high percentage of the tests (25%). However, the failed tests during the RDE tests was much lower (4.2%) indicating that there were issues with the PEMS in the laboratory (e.g. not enough stabilization time). The failed span checks during the monitoring phase were 10.5%. This percentage is relatively high, however 8.3% of the fails come from one specific manufacturer, thus indicating that some improvements are still necessary (and that such improvements are technically possible, since some other manufacturers show 0% failed tests). The failed tests were mainly due to high NO drift (span gas around 2200 ppm).

3.3.3 Implication of span drift

The effect of the span drift was examined with two extreme cases of 2% drift at 2500 ppm. The drift was assumed to be linear with values 0% at 0 ppm and 2% at 2500 ppm, but constant over time.

CASE L (Figure 3-8a) represents a case where the NOx emission spread during the whole cycle and, thus the low NOx concentrations relatively to the 2500 span concentration result in an overestimation of **only 0.1%** relative to the span drift**.**

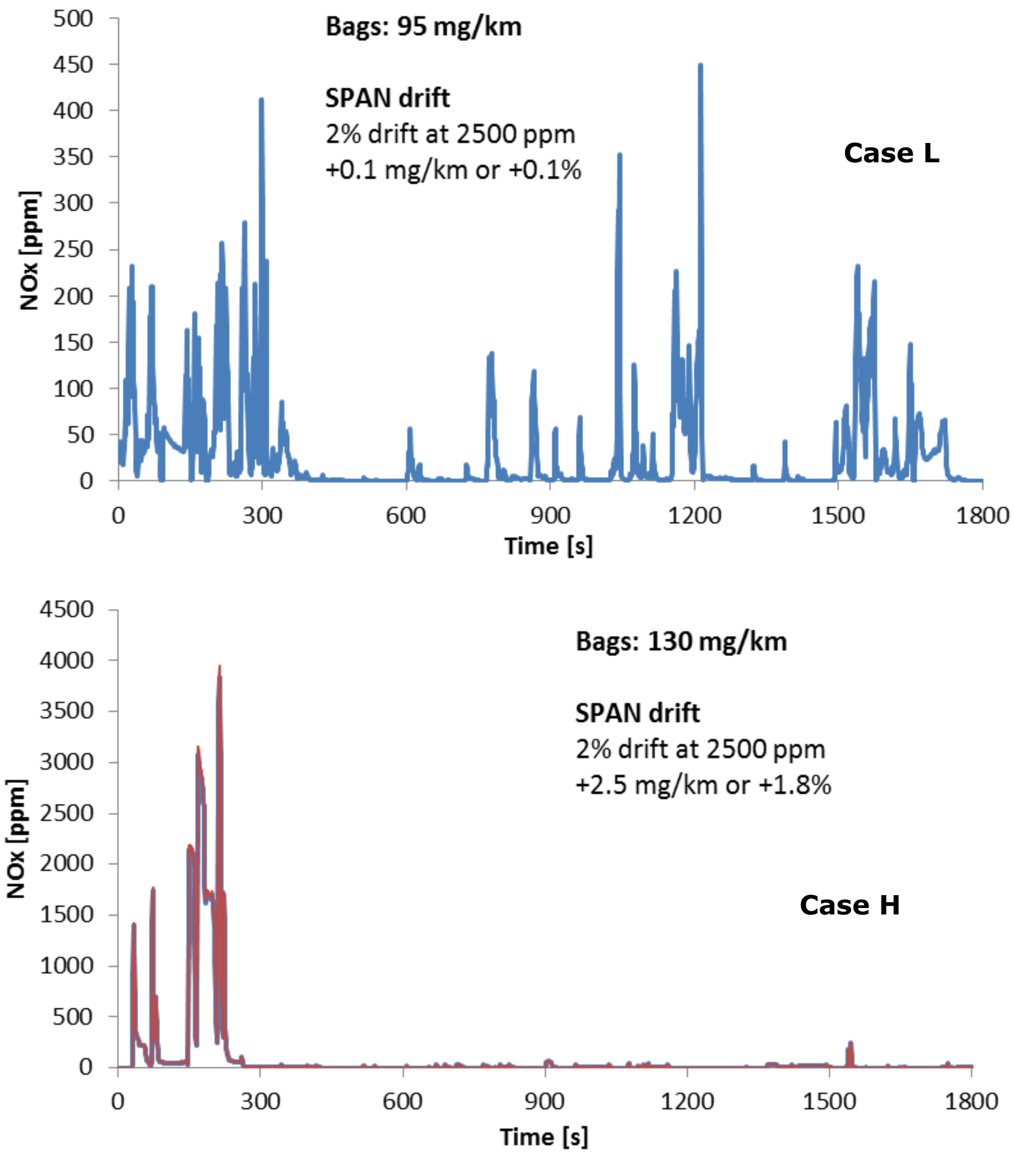


Figure 3-8: Real time examples of a 2% NOx span drift: a) NOx emissions during the whole test, b) high NOx emission events concentrated at the beginning of the test.

CASE H (Figure 3-8b) represents a case where high NOx emission events exceeding the span concentration occur at the beginning of the cycle. Even with some peaks with 3% error of the NOx concentration, the final overestimation of the emissions is **1.8%, lower than the permissible span drift (2%)**. Thus, the 2% permitted drift will result in <2% underestimation of the NOx emissions. However, one should note that the second scenario is based on a vehicle that would significantly exceed the EURO 6 emission limit.

The main conclusion of the span drift requirements is that the uncertainty coming from this component is small and the contribution less than the actual drift (<2%).

3.4 Exhaust flow measurement

Due to their principle of operation, EFMs have increased uncertainty when operating at low flow rates and highly dynamic flows. These conditions are characteristic of car exhaust. The exhaust flow is estimated by the EFM using differential pressure sensors corrected for density using the static pressure and temperature in the exhaust line. It is difficult to accurately estimate the exhaust density because of the rapid temperature changes observed in the exhaust. Additionally, the measured dynamic pressure must be correlated with exhaust flow using a correction factor K as part of the Bernoulli equation that the flow measurement principle is based on. This K constant is a function of Reynolds number (Re). The biggest difficulty is the small pressure difference at low flow rates that results in high uncertainty. Pressure pulsations can also have a significant effect upon the measurement quality at low flow rates.

One instrument manufacturer sent data on 44 light duty EFMS as received after more than 1 year of use, and compared them to a traceable standard (i.e. air measured with flow meters) (Figure 3-9). The results were within the regulation requirements, and indicated minimal (if any) drift even after 1 year.

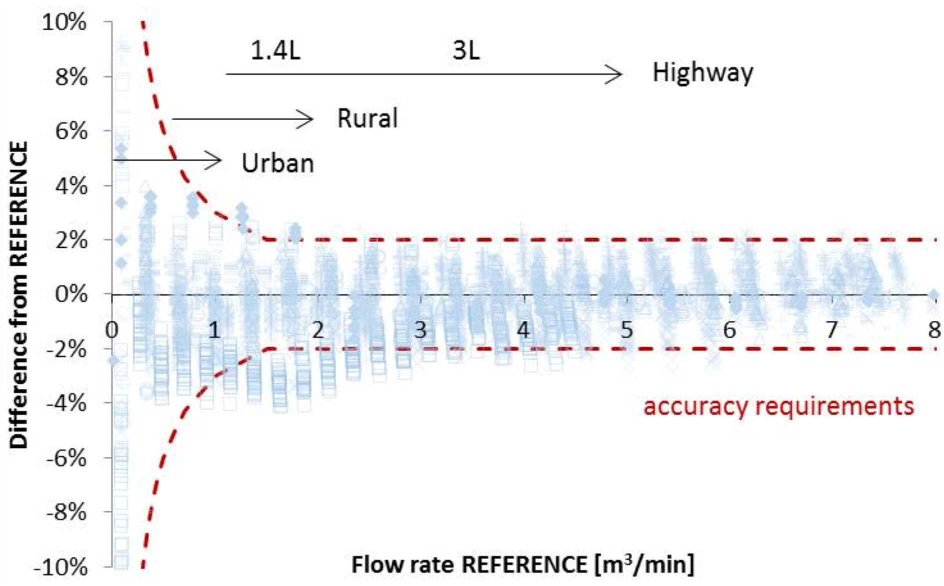


Figure 3-9: Checks of EFMs against a traceable standard at the instrument manufacturer's site after 1 year of use.

At idle the uncertainty was high in relative terms (>10%), but low in absolute values. For urban, rural conditions (flow rates <1 m^3/min) the uncertainty was less than 4%. For higher flowrates the uncertainty was <3% (compare this to the 3% currently specified in the RDE regulation from the linearity slope). In all cases, the standard error of estimate (SEE) was <0.5% of the maximum value (2% allowed in the regulation).

The received EFM evaluation data from the margin sub-group included comparisons with other EFMs, CVS estimated exhaust mass flow or engine intake air. These methods have an uncertainty at the same level as the examined EFMs, and cannot be considered traceable calibration data. Thus, these results are only indications of EFM uncertainty.

Table 3-4 summarizes the number of tests, the sources and the statistics (mean, median, minimum and maximum values). The differences ranged from approximately -30% to +20%. The mean differences were ±2%.

Figure 3-10 graphically shows all data points. In general, the differences were within 10%. Only at lower flowrates higher differences, as also mentioned above, can be seen. This could be due to EFM or reference instrument calibration errors and uncertainties at low flowrates.

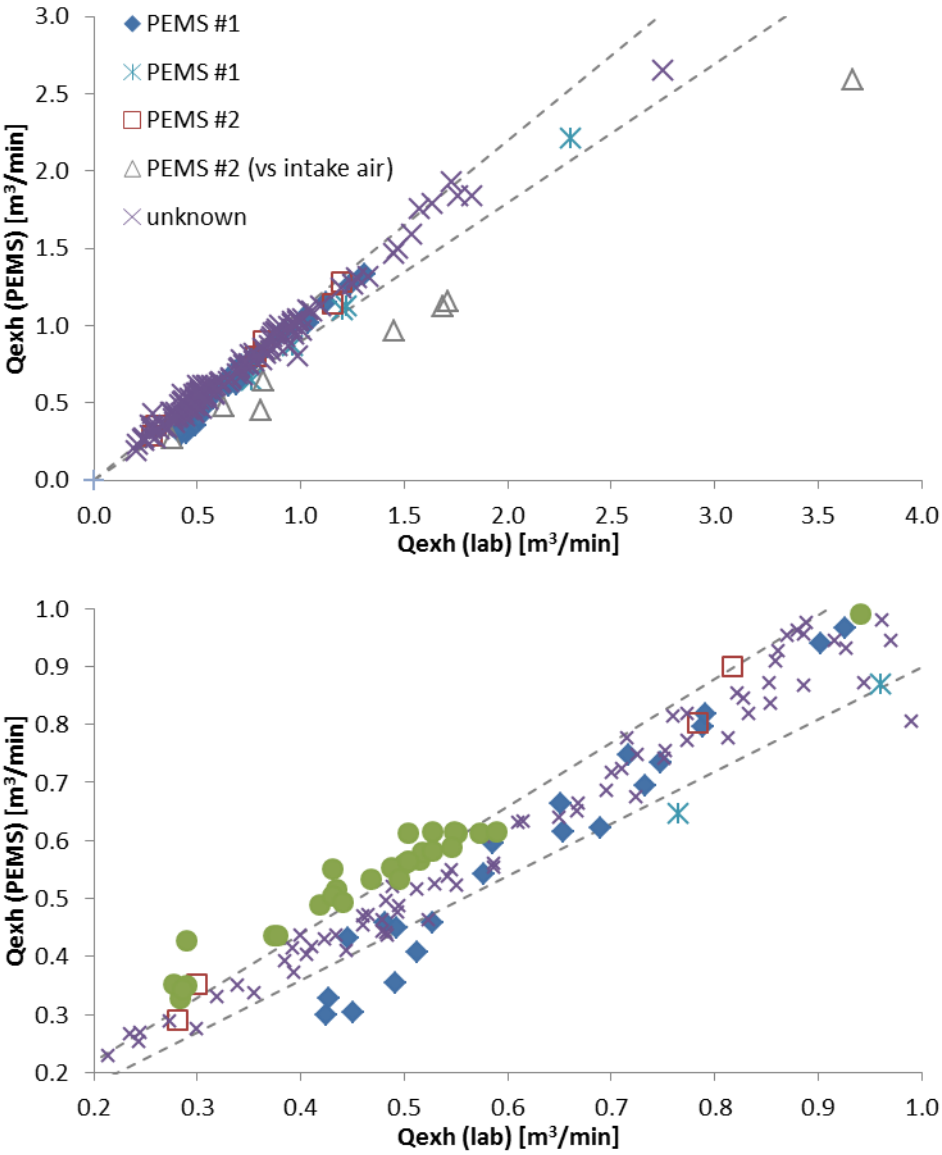


Figure 3-10: Comparison of EFMs with other EFMs or CVS estimated flows. a) all data, b) focus on flows <1 m^3/min. Green circles are results from one OEM/EFM.

For example, the CVS estimated flow is typically calculated from the difference of two flow rates which have an uncertainty of 2%. Assuming 10 m^3/min total flow rate (uncertainty 0.2 m^3/min) and 9 m^3/min dilution air flow rate (0.18 m^3/min), the calculated 1 m^3/min flow rate has an uncertainty of 0.27 m^3/min or 27%. Thus the high uncertainty of the EFM could be due to the high uncertainty of the other "reference" instrument used (e.g. other EFMs, CVS estimated exhaust mass flow or engine intake air).

Nevertheless, these data show that even though all market EFMs today fulfil the (static) legislation requirements, in real life transient operation the uncertainty could be higher (around 10%) than the previously estimated 4% uncertainty.

Table 3-4: EFM evaluation received data.

	All		**Known**	
Labs	**3+ACEA+JAMA**		**3+JAMA**	
PEMS	**2+ACEA**		**2**	
	Cycles	**Sub-phases**	**Cycles**	**Sub-phases**
Tests	48	175	20	37
Mean	1.8%	2.4%	-2%	-4.6%
Median	2.0%	2.3%	1.8%	-1.8%
Min	-32.6%	-32.6%	-32.8%	-32.8%
Max	21.7%	47.6%	17.4%	17.4%

4 Uncertainty calculations

4.1 Uncertainty equations

The emissions of a pollutant in the RDE regulation, e.g. NOx, E_{NOx}, are calculated from the following equation:

$$E_{NOx} = \frac{\sum u_{NOx} c_{NOx,i} q_{mew,i}}{d}$$

Eq. 4-1

Where

u_{NOx} is the ratio of the density of NOx and the overall density of the exhaust (constant)

$c_{NOx,i}$ is the NOx instantaneous measured concentration in the exhaust at time i [ppm]

$q_{mew,i}$ is the measured instantaneous exhaust mass flow rate at time i [kg/s]

d is the distance of the test [km]

For the estimation of the E_{NOx} uncertainty ($\varepsilon_{E,NOx}$) (in %), the error propagation rule for multiplication and division was used. This assumes random and uncorrelated to each other errors, which is a valid assumption (e.g. the error of the positioning system is not correlated to the NOx analyser). The constant u_{NOx} doesn't contribute to the relative uncertainty.

$$\varepsilon_{E_{NOx}} = \sqrt{(\varepsilon_{q_{mew}})^2 + (\varepsilon_{c_{NOx}})^2 + (\varepsilon_d)^2}$$

Eq. 4-2

Where

ε_{qmew} is the relative uncertainty of the exhaust mass flow rate [%]

ε_{cNOx} is the relative uncertainty of the NOx concentration [%]

ε_d is the relative uncertainty of the distance [%]

In order to find the uncertainty of each component of the equation, the technical specifications in the RDE regulation and experimental data were taken into account. For example, the uncertainty of the analyser and the EFM is determined by the accuracy, linearity (standard error requirement), the zero and span drift requirements (Figure 4-1).

The zero drift of the analyser (δ_{drift}) was analysed separately due to its significant effect on low level emissions. Note that this uncertainty is expressed in [mg/km] because the evaluation was in [mg/km]. The (absolute) uncertainty symbol is δ. Some additional uncertainties were also considered, such as time mis-alignment (ε_t), and effect of boundary conditions on instrumentation accuracy (ε_B).

All these additional uncertainties were added to the uncertainty estimation in order to find the maximum uncertainty. The reason is that there was no input regarding their contribution in real operation (e.g. how the drift evolves).

Finally the uncertainty of the CVS bag measurement was subtracted (δ_{CVS}), as the margin should cover the additional uncertainty of PEMS.

The final uncertainty $\delta_{F,E,NOx}$ [mg/km] for an emission level L [mg/km] is calculated:

$\delta_{F,E,NOx} = [\ \varepsilon_{E,NOx} + \varepsilon_t + \varepsilon_B\ ]\ L + \delta_{drift} - \delta_{CVS}$ Eq. 4-3

Extending this equation to different emission levels assumes that the uncertainties (relative or absolute) remain constant. This will be discussed in a next section.

A simplified schematic of the uncertainties considered is shown in Figure 4-1.

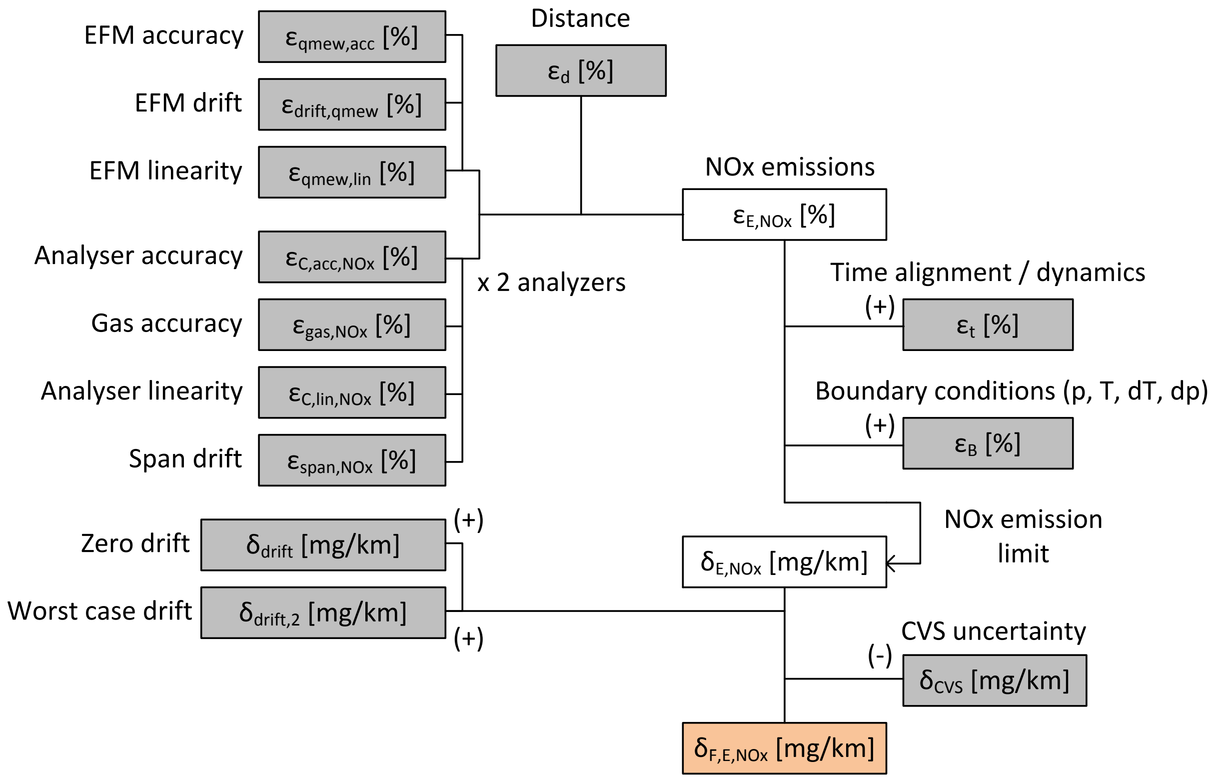


Figure 4-1: Uncertainties calculation scheme. Symbols (+) or (-) indicate that the errors are simply added or subtracted, without using the error propagation rule.

4.2 Sources of uncertainty

The uncertainty values are summarized in Table 4-1. The values were taken from the RDE regulation or experimental data. For definitions and details see **Annex**.

4.3 Uncertainty value

The uncertainties were expressed in both relative [%] and absolute levels [mg/km], because the analysis included components that the uncertainty was expressed in relative and absolute terms.

4.3.1 JRC 2015 study

Figure 4-2 shows the 2015 study graphically. The zero drift was assumed to be linear and was based on analysis of 1.2-3L engines. The higher than specified analyser uncertainty was based on real time comparisons of PEMS with modal analysers in the laboratory.

4.3.2 Review 2017

For 2017, based on the analysis of **Chapter 3**, the following two cases are based on:

- STEP increase of the zero drift (Figure 4-3), or
- LINEAR increase of the zero drift (Figure 4-4) (as in the JRC 2015 study).

The EFM uncertainty was increased from 4% to 10% to take into account the differences between EFMs in the market today and the difficulties checking them in practice. This was based on Figure 3-9. With more comparisons in the future this number could decrease to the theoretically expected value of 4%.

The EFM drift was probably negligible after one year of testing as shown in Figure 3-8. Nevertheless, the permitted 2% was kept in the calculations.

The EFM non-linearity uncertainty was estimated by the standard error of estimate (SEE). In all cases it was <0.5% from calibration max value; much lower than the maximum allowed of 2%, which was also considered in the uncertainty calculation.

The analysers' uncertainty was assumed to be the one estimated by the RDE accuracy limits (around 5%). This is slightly lower than the 2015 JRC study (8%), nevertheless it is in agreement with the data received in 2017. For example, JAMA compared PEMS with laboratory grade equipment (Figure 4-5a). The differences were on the order of <2% (at final emission level of 200 mg/km) to <10% (at final emission level of 10 mg/km), although second by second higher differences were observed (see Figure 4-5b, c). Thus at a level of 80 mg/km an uncertainty of 4.5% would correspond.

KIT did also a similar comparison in the laboratory and found differences on the order of 5-7% (effect on the final result <0.5 mg/km). It should be noted though that higher differences were found when PEMS were compared to each other: 16% for NO_2, 20-40% for NO. The effect on the final emissions were 10-11 mg/km, which could reflect the plus-minus range of uncertainty. Thus a 5% uncertainty for the NOx analysers (around 4 mg/km at levels of 80 mg/km) reflects the real time behaviour of the NOx analysers in the market.

Additionally a 1% non-linearity uncertainty for the gas analysers was considered (based on the SEE requirement of RDE).

The span drift was kept 2% (as required in RDE) because higher values that were determined in the received data would result in invalid tests.

The uncertainty of the gas used for calibrations was assumed to be 2%, as required in RDE. Discussions with gas cylinder producers confirmed that this uncertainty is <1.5%.

The distance uncertainty was kept 4% as in 2015 (no analysis in 2017), a value prescribed in the RDE (maximum allowed difference of the methods used to determine the distance).

The time alignment/dynamics uncertainty was kept 3%. Similar values were found from the limited number of real time data received in 2017 (all were laboratory tests, no tests from the road) (no figure shown).

The contribution of the boundary conditions (low or high temperatures and pressures) was considered negligible, based on the results received from one instrument manufacturer. A second instrument manufacturer had issues at different temperature and pressure conditions, but later resolved the issue.

In all cases a 3% uncertainty of the CVS laboratory measurements was subtracted as was also done on the 2015 analysis. This uncertainty was theoretically evaluated in the **Annex** and was found slightly higher. As no data were received for this topic it was decided to leave it 3% in 2017.

The two scenarios give an uncertainty of 24-43%. This uncertainty is split to the proportional PEMS uncertainty (15% or 12 mg/km) and the constant zero drift uncertainty (10 mg/km to 25 mg/km). The above analysis shows that the bigger influence on the uncertainty is the zero drift and whether one assumes that it happens in a step change at the beginning of the test (worst case) or gradually during the test. However there is lack of data proving whether any of the two scenarios is more plausible.

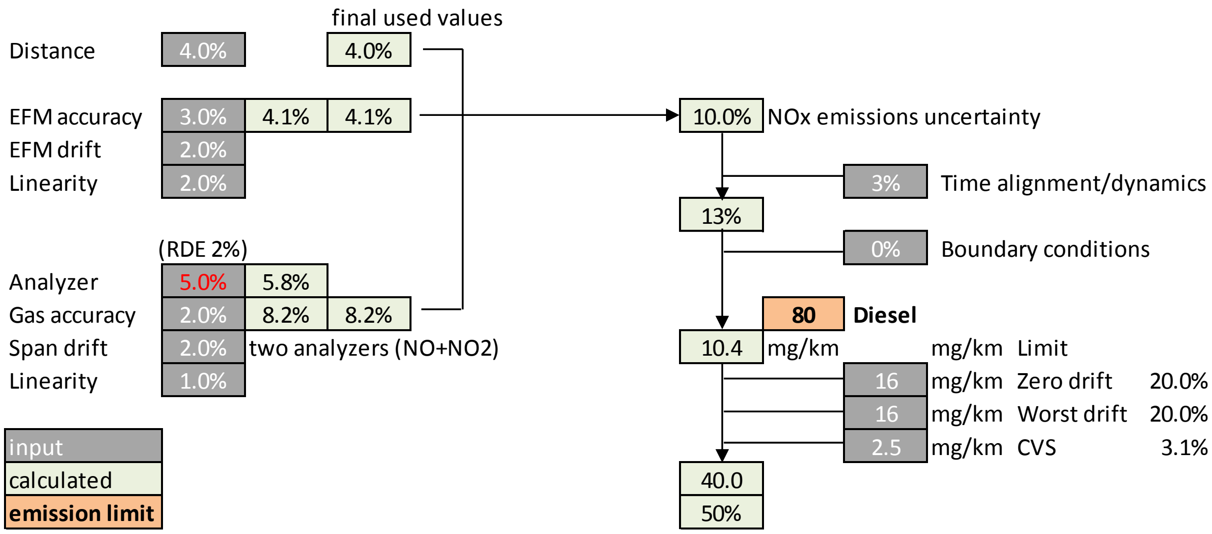


Figure 4-2: Margin as estimated in the JRC 2015 study.

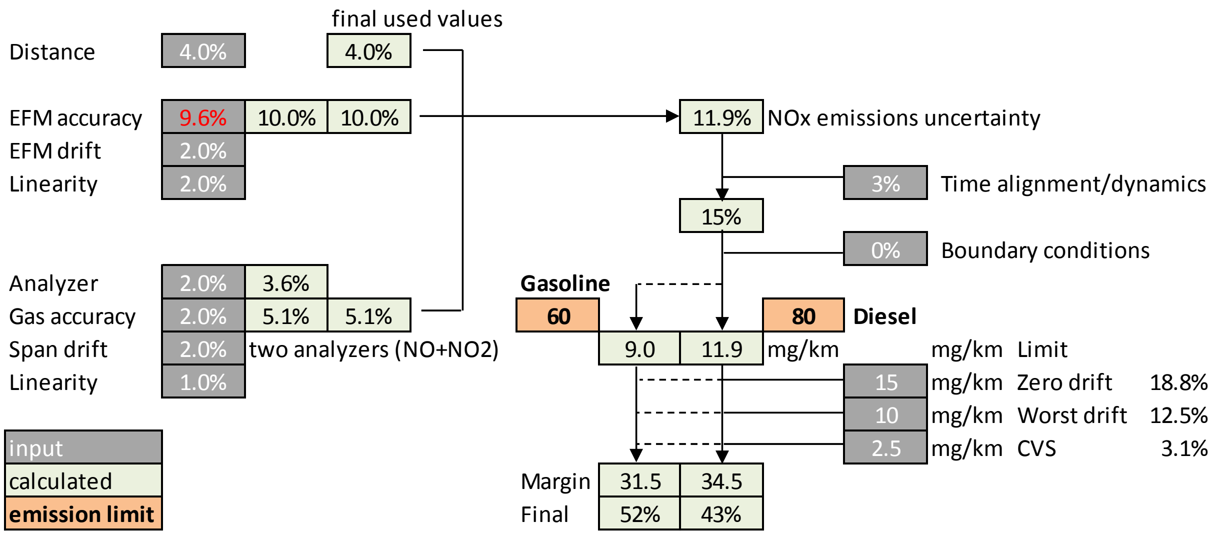


Figure 4-3: Scenario a: STEP increase of zero drift

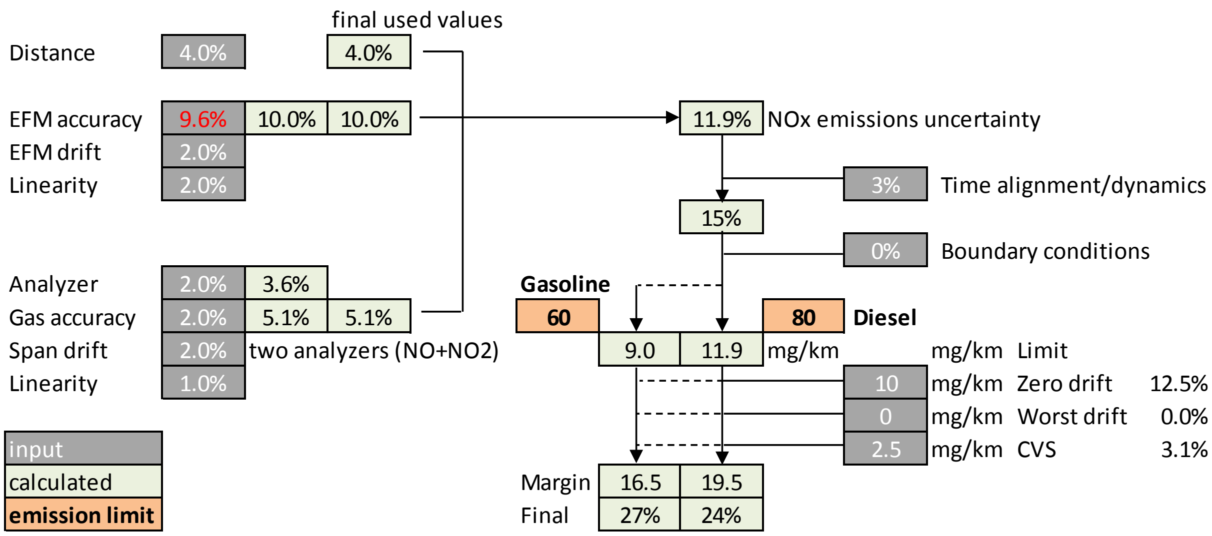


Figure 4-4: Scenario b: LINEAR increase of zero drift.

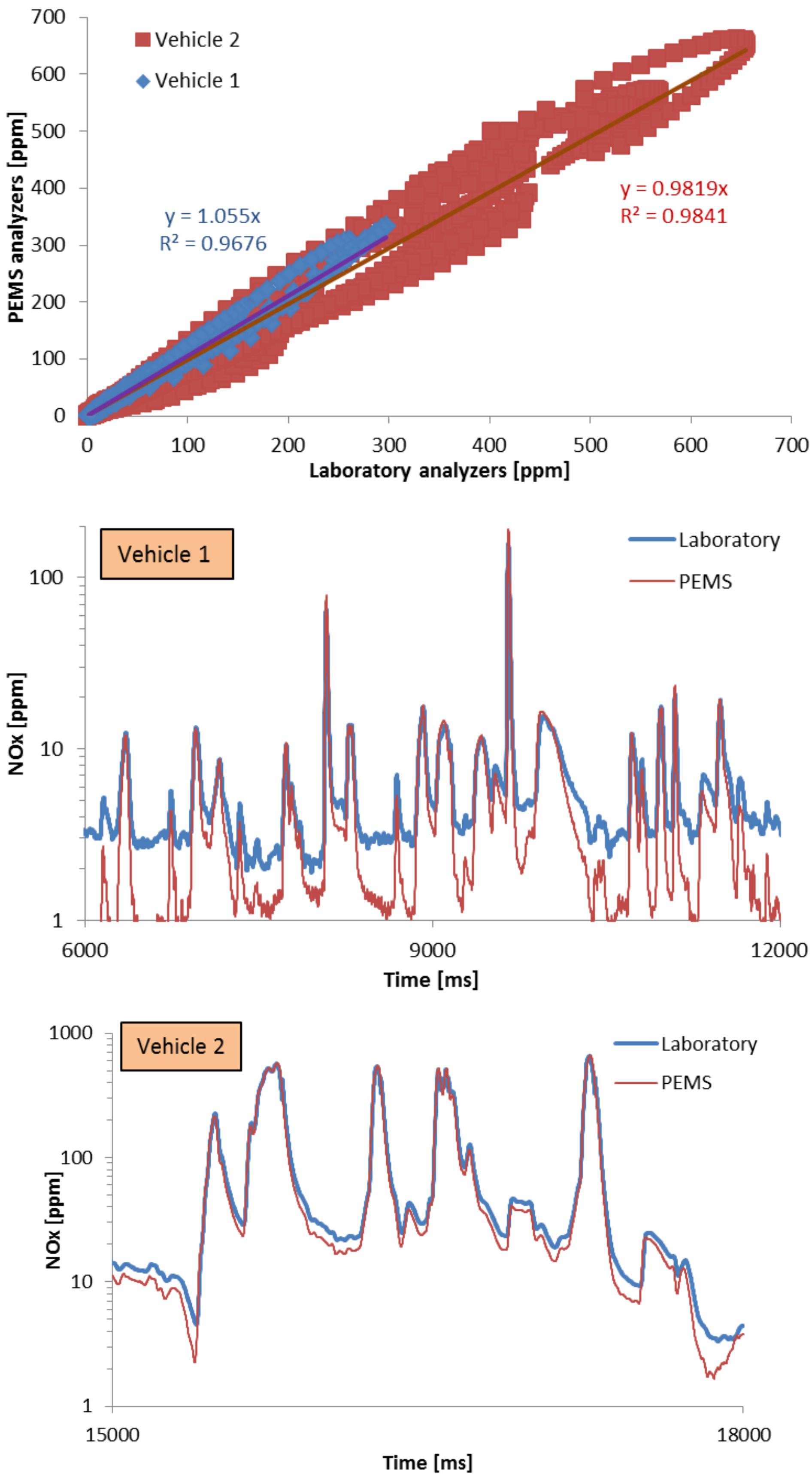


Figure 4-5: Comparison of PEMS with laboratory grade analysers: a) linear regression b) detail for vehicle 1 (low emissions), c) detail for vehicle 2 (high emissions). From JAMA input.

4.4 Margin at other emission levels.

The previous uncertainty estimations were based on values close to the emission limit. Extending the equation to lower levels is valid only if the values remain the same. The validity of this assumption is investigated in this section.

From all the components of Eq. 4-3 and Table 4-1, the only ones that could be variable are the EFM, the NOx analysers and the CVS.

Figure 4-6 shows the NOx analysers (in particular NO) measurement uncertainty based on the calibration certificates from 4 PEMS manufacturers. The uncertainty is well within 2% down to approximately 100 ppm and then gradually increases to approximately 5% at 10 ppm level. Based on Figure 3-8a, for emission levels of 80 mg/km, the NOx spikes are between 50 and 250 ppm. For 20 mg/km, the expected spikes would be between 10 and 60 ppm. In this case the NOx uncertainty would be on the order of 10% (and not 2%).

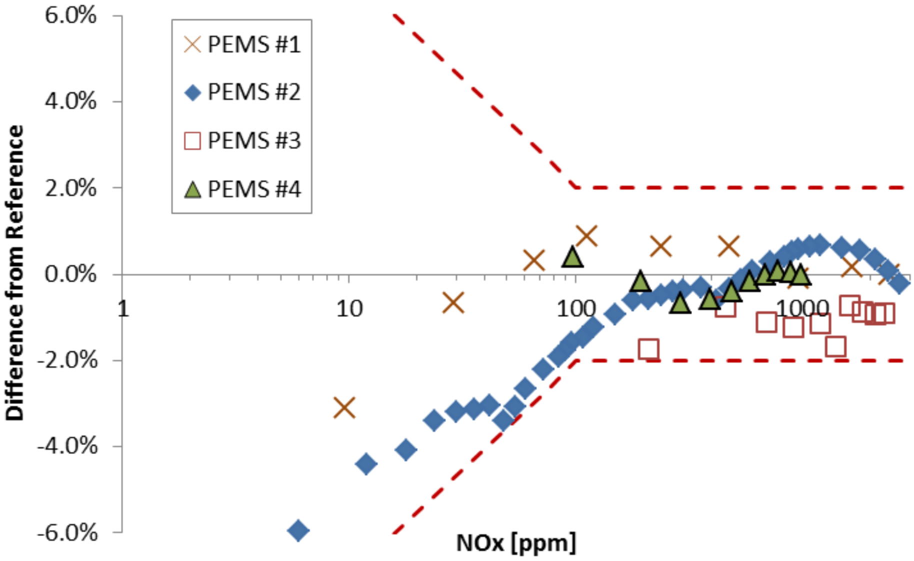


Figure 4-6: Measurement uncertainty of PEMS NOx analysers (data from 4 different PEMS manufacturers).

The EFM uncertainty was discussed in Figure 3-9. For high flowrates the uncertainty is 2-3%, increases at 4% for rural conditions (flow rates <1 m^3/min) and reaches 10% at idle conditions. However, the uncertainty should be independent of the emission levels as long as the vehicle's exhaust flow rate does not change.

The CVS uncertainty is discussed in the **Annex**. For 80 mg/km the uncertainty is 4-8% and at 20 mg/km increases to 13-32%.

Thus, it can be assumed that the relation of the additional PEMS uncertainty (compared to the CVS) at low emission levels remains at the same levels as at the current emission limit of 80 mg/km.

Based on this assumption, as the emission levels decrease below the limit value, such as when manufacturers may decide to declare a lower RDE_{max} in the certificate of conformity, the result of the PEMS will have higher relative uncertainty (expressed in %), but lower absolute uncertainty (expressed in mg/km). Figure 4-7 presents the uncertainty both in absolute and relative terms for different emission levels for the two scenarios.

In simple terms if one would measure a level of emissions of 20 mg/km with PEMS, the added margin would be 127% or 28 mg/km for scenario a (Step drift) or 52% or 13 mg/km for scenario b (Linear drift). In other words the possible PEMS measurement could be up to 48 or 33 mg/km for the two scenarios respectively.

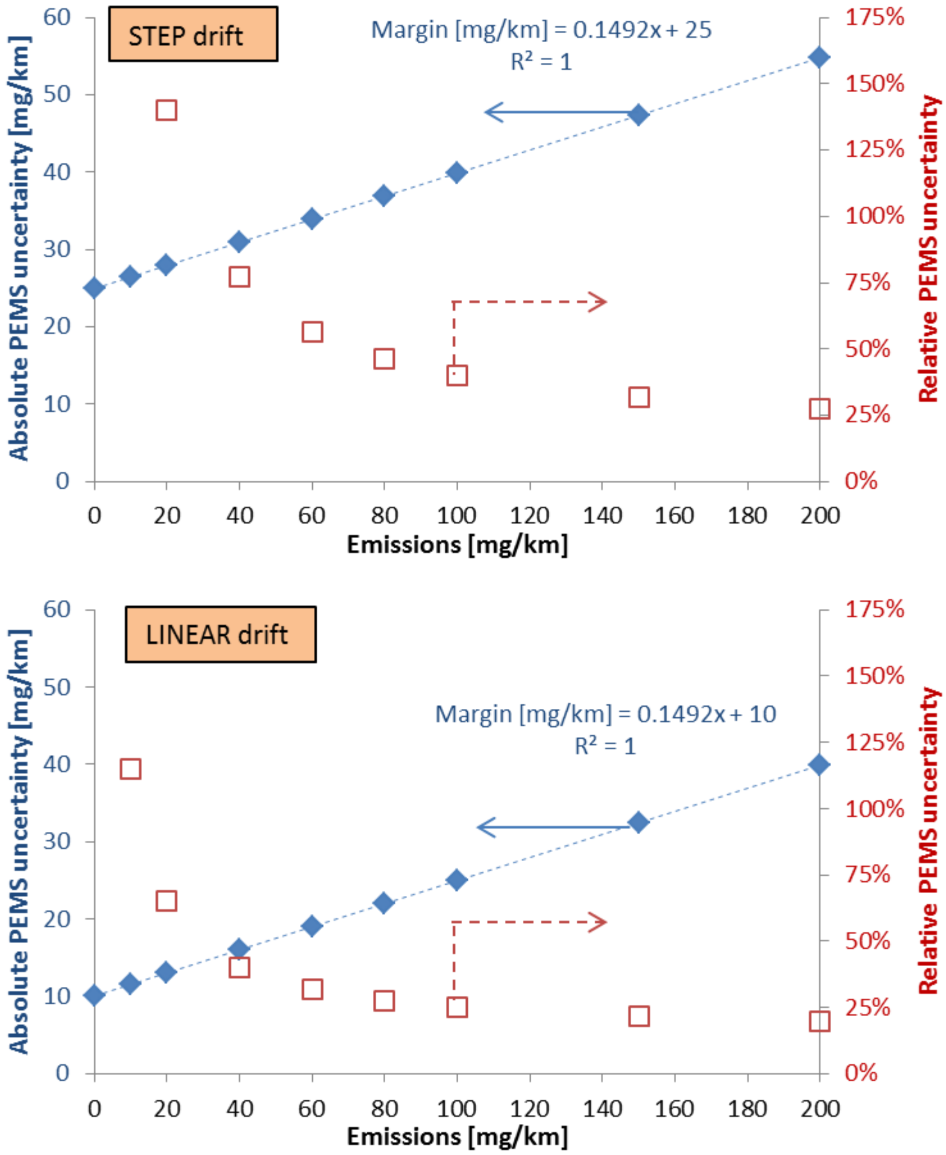


Figure 4-7: Relative and absolute uncertainty for different emission limits.

Table 4-1: Sources (components) of PEMS uncertainty, the technical requirements (RDE), uncertainties of the 2015 study and the error margin found experimentally in the 2017 review (Experimental). With bold the values used in the further analysis. In brackets uncertainty components not investigated in 2017.

Name	Symbol	RDE	2015	Experimental	Comment
EXHAUST FLOW METER (EFM)					
EFM accuracy	$\varepsilon_{qmew,acc}$	3%	2%	**10%**	Figures 3-10 (compared to non-traceable references)
EFM drift	$\varepsilon_{drift,qmew}$	2%	2%	**2%**	No drift after one year: Figure 3-9
EFM linearity	$\varepsilon_{qmew,lin}$	2%	2%	**2%**	Based on EFMs data SEE<0.5%max (Figure 3-9)
GAS ANALYSER					
Analyser accuracy	$\varepsilon_{C,acc}$	2%	5%	**2%**	Based on real time comparisons (Figure 4-5)
Analyser linearity	$\varepsilon_{C,lin}$	**1%**	1%	1%	Based on a few calibration certificates received
Span drift	ε_{span}	**2%**	2%	≤5%	Figure 3-7. Values >2% result in invalid test
Gas accuracy	ε_{gas}	**2%**	2%	(2%)	Based on gas cylinder manufacturers <1.5%
OTHER					
Distance	ε_{d}	**4%**	4%	(4%)	Max difference between distance methods
Dynamics	ε_{t}	time aligned	**3%**	3%	Based on JRC 2015 study. Confirmed with laboratory data.
Boundary conditions	ε_{B}	0%	0%	**0%**	Based on one PEMS manuf. data (Figures 3-4 and 3-7)
Analyser zero drift	δ_{drift}	5 ppm	16 mg/km	**10-15 mg/km**	Numbers show: Linear – Step drift (Figure 3-6)
Worst case drift	$\delta_{drift,2}$	-	16 mg/km	**0-10 mg/km**	Numbers show: Linear – Step drift (Figure 3-6)

5 Next steps

5.1 PEMS additional technical requirements

All analysis conducted so far assumed that the PEMS operate with similar uncertainty even under extended conditions (boundary conditions uncertainty was assumed 0%). In order to confirm that the measurement uncertainty and the relative margins correspond to the PEMS in the market, the margins sub-group is currently working on standardizing the required additional tests (e.g. changes of temperatures, pressures, vibrations) to prove compliance of the instruments also in extended conditions.

5.2 Review procedure in the following years

In the following years the review procedure shall follow a similar procedure:

- Collection of new data from all commercially available equipment and/or creation of other data through dedicated experimental campaigns (for Table 4-1).
- Confirmation with experimental data that the technical requirements are fulfilled both in laboratory and on the road.
- Assessment of each uncertainty according to the framework described in Figure 4.1. Adjustment of the framework if necessary.
- Identification of technical requirements that could be improved in legislation.
- Amendment of relevant RDE performance requirements for PEMS equipment and adapting the NOx conformity factor.

5.3 Further margins reduction

Reduction in the following years of the measurement uncertainty could be achieved by the following ways:

- Modification of technical requirements. For example, one possible is to reduce the accuracy requirement of the gas cylinders (from 2% to 1%) as required in WLTP. Another example would be to further reduce the permitted zero drift, or find data on when this zero drift actually happens, i.e. at the beginning of the test or gradually during the test.
- Better analysis of CVS uncertainty with experimental data.
- All campaigns showed mean values of drift of 0 ppm, indicating that there is no actual drift but any final zero check result is due to random variation. The current situation of the market instruments means that the drift will not be any more necessary to be added, but it could be taken into account with the typical uncertainty equations.

6 Conclusions

For the 2017 NOx margin evaluation, data were received from the margins sub-group and the monitoring phase.

From the 218 validation tests, 1.5-5.5% were outside the permissible tolerance of the regulation (15 mg/km or 15%, whatever is larger).

From the 384 zero drift tests, 2.1% were outside the permissible tolerance of 5 ppm. The mean and median values were <0.5 ppm indicating that there is no systematic error of the analysers.

The 5 ppm drift was simulated as a step drift of 5 ppm at t=0 or as a linear drift reaching 5 ppm at the end of the cycle. The simulations with engines of 1.4L to 3.0L engine displacement showed an overestimation of the emissions of approximately 10-25 mg/km, depending on the engine, cycle and drift pattern. Assuming a linear zero drift, the overestimation of the NOx emissions was <10 mg/km.

From the 413 span drift tests, 12.1% were outside the permissible tolerance of 2%. The majority of them failed 1) in the laboratory indicating improper usage of the PEMS, and 2) at extended conditions indicating that some instruments were not ready for low ambient temperatures (this issue was later corrected). Simulation of different tests showed that the span drift has a small effect on the final result (<2%).

Data from one instrument manufacturer showed that exhaust flow meters (EFMs) even after one year of use remain within the regulation requirements (3%). At low flow rates this uncertainty is around 4%. Other comparisons of EFMs with other EFMS or indirectly determined exhaust flows (e.g. from the dilution tunnel) gave differences on the order of 10% or even higher in a few cases, but since these other measurements contain uncertainties and are not traceable standards, this 10% is a probably an overestimation of the EFM uncertainty.

Based on the experimentally determined data and a theoretical analysis of the uncertainty, a total margin of 0.24-0.43 was calculated for emission level of 80 mg/km depending on whether one the zero drift happens gradually or with a step function at the beginning of the tests.

As the emission levels decrease, the result of the PEMS will have higher relative uncertainty, but lower absolute uncertainty.

References

Regulation 2016/427 (RDE 1)

Regulation 2016/646 (RDE 2)

Regulation 2017/1154 (RDE 3)

Regulation 2017/1151 (WLTP)

UNECE Regulation 83

List of abbreviations and definitions

ACEA	European Automobile Manufacturers' Association
ADAC	General German Automobile Club
AECC	Association for Emissions Control by Catalyst
CVS	Constant Volume Sampling
EFM	Exhaust mass Flow Meter
EGR	Exhaust Gas Recirculation
IFA	Institute for Powertrains & Automotive Technology (Vienna, Austria)
JAMA	Japan Automobile Manufacturers Association
KIT	Karlsruher Institut für Technologie (Germany)
KTI	Institute for transport sciences non-profit Ltd. (Hungary)
LNT	Lean NOx Trap
MS	Member State
NEDC	New European Driving Cycle
PEMS	Portable Emission Measurement Systems
PN	Particle Number
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
TUG	Technical University of Graz
UDC	Urban Driving Cycle
VDA	German Association of the Automotive Industry
WLTC	World Harmonized Light Duty Test Cycle
WLTP	World Harmonized Light Duty Test Procedure

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Annex

Technical requirements in Regulations EU 2017/1151 and 2017/1154

Definitions

"Accuracy" means the deviation between a measured or calculated value and a traceable reference value

"Noise" means two times the root mean square of ten standard deviations, each calculated from the zero responses measured at a constant recording frequency of at least 1,0 Hz during a period of 30 seconds.

"Precision" means 2,5 times the standard deviation of 10 repetitive responses to a given traceable standard value.

"Span" means the calibration of an analyser, flow-measuring instrument, or sensor so that it gives an accurate response to a standard that matches as closely as possible the maximum value expected to occur during the actual emissions test.

"Span response" means the mean response to a span signal over a time interval of at least 30 seconds.

"Span response drift" means the difference between the mean response to a span signal and the actual span signal that is measured at a defined time period after an analyser, flow-measuring instrument or sensor was accurately spanned.

"Validation" means the process of evaluating the correct installation and functionality of a Portable Emissions Measurement System and the correctness of exhaust mass flow rate measurements as obtained from one or multiple non-traceable exhaust mass flow meters or as calculated from sensors or ECU signals.

"Zero" means the calibration of an analyser, flow-measuring instrument or sensor so that it gives an accurate response to a zero signal.

"Zero response" means the mean response to a zero signal over a time interval of at least 30 seconds.

"Zero response drift" means the difference between the mean response to a zero signal and the actual zero signal that is measured over a defined time period after an analyser, flow-measuring instrument or sensor has been accurately zero calibrated.

"Linearity" means the verification of an instrument at ≥10, approximately equally spaced and valid, reference values (including zero).

Exhaust mass flow rate [kg/s] (≥1 Hz)

- Linearity (slope within 1.00 ± 0.03 over a stationary test, standard error ≤2% of max)
- Accuracy (within 2% of reading, 0.5% of full scale, or 1% of maximum calibrated flow)
- Precision (within 1% of maximum calibrated flow)
- Noise (within 2% of maximum calibrated flow)
- Zero and span drift (within 2% of the maximum value of the primary pressure signal over 4h)
- Rise time (<1 s)
- Response time (<3 s)
- Possible exclusion of data due to system maintenance (<1%)
- If calculated from air and fuel flow rate, the following requirements apply:
  - Linearity (slope within 1.00 ± 0.02 for air and fuel flow rate and 1.00 ± 0.03 for the calculated exhaust mass flow rate over a stationary test)

- Accuracy for air and fuel flow rate (within 2% and 0.02% for reading)

Worst case scenario: Accuracy 0.5% full scale for an EFM calibrated up to 5 m^3/min, translates to uncertainty of 0.025 m^3/min or 2% of reading. For 0.4 m^3/min the uncertainty is 6% and for 0.2 m^3/min is 12%.

Drift 2% pressure sensor means additional 2% uncertainty.

Pollutant concentration [ppm] (≥1 Hz)

- Error (Regulation 83): Less than 2% plus uncertainty of calibration gas
- Calibration gas uncertainty (Regulation 83): 2% (1% in WLTP)
- Linearity (slope within 1.00 ± 0.01 over a stationary test)
- Accuracy (within 2% of reading or 0.3% full scale)
- Precision (within 2% below 155ppm and 1% equal or above 155ppm)
- Noise (within 2% of full scale)
- Zero and span drift (analyser-dependent margins for compliance in the laboratory over 4h and on the road over the duration of a test) for NOx 5 ppm (zero) and 2% for span
- Rise time (≤3 s)
- Response time (≤12 s)
- Efficiency of NOx converters
- CO2 and water quench of CLD (≤2% full scale)
- Quench of NDUV analyser (5% of maximum test concentration; sample dryer to remove less than 5% of the original NO_2)
- Accuracy of gas and gas divider (within 2% of reading)

u value [kg/g] (tabulated)

Vehicle speed [km/h] (≥1 Hz)

- Accuracy (total trip distance determined via GPS, sensor, or ECU within 4%)
- Accuracy sensor (within 1% of reading)
- Accuracy ECU (distance of the validation test to deviate by <250 m when measured with ECU and roller bench)

General

- Leakage in the sampling line (≤0.5%)
- Calibration (1% of measurements may exceed the calibration range)
- Possible exclusion of data due to system maintenance (<1%)

Additional sources of uncertainty:

- Temperature measurements (accuracy within 2K absolute for T≤600 K or within 0.4% of reading if T>600K)
- Relative humidity (accuracy within 5% absolute)
- Absolute humidity (accuracy within 10% of reading or 1 g_{H2O}/kg dry air, whichever is larger)
- Ambient pressure (accuracy within 0.2 kPa absolute)

- Intrusivity (e.g., backpressure introduced by measuring exhaust mass flow rate and component concentrations)

- Changes in the exhaust composition within the sampling lines

- Miscellaneous error sources (electro-magnetic interferences, shocks, vibration, variability in ambient conditions, dust, external contamination)

- Malfunctioning of equipment under on-road test conditions

CVS uncertainty

The theoretical uncertainty of the gaseous pollutants bag result can be estimated by the formulas used to calculate the pollutants and the reported calibration uncertainties (or manufacturers specifications). The mass concentration of a gas pollutant Mi [g/km] is calculated as (UNECE Regulation 83 or WLTP Regulation 2017/1151):

$$M_i = \frac{V_{mix} \cdot Q_i \cdot k_h \cdot C_i \cdot 10^{-6}}{d}$$

Eq. A1

Symbol	Units*[1]	Explanation	Uncertainty
V_{mix}	[l]	volume of the diluted exhaust gas	0.5% (Annex 4a, App. 2, 2.2.11)
Q_i	[g/l]	density of the pollutant i	negligible
k_h	[-]	humidity correction factor (NO_x)	<2%*[2]
C_i	[ppm]	concentration of the pollutant i	2 ppm or 2%*[3]
d	[km]	distance	1% (Annex 4a, App. 1, 1.2.6)

*[1] All volumes refer to normal conditions 273.2 K and 101.33 kPa.

*[2] The correction is based on the measurement of humidity, pressure etc.

*[3] The concentration of the pollutant in the diluted exhaust gas is corrected by the amount of the pollutant i contained in the dilution air, thus the uncertainty is the combination of the two uncertainties (each 2% or 2 ppm for C<100 ppm) (Annex 4a, App. 3, 1.3.8).

For 80 mg/km NOx emission levels, around 9 ppm are expected to be measured in the bag. With a 2 ppm gas analyser measurement uncertainty the total uncertainty of the NOx emission measurements is 32% (26 mg/km). With current technology analysers a 0.2-0.5 ppm uncertainty is reasonable resulting in 4-8.5% uncertainty (3-7 mg/km).

At 20 mg/km NOx emission levels, the CVS uncertainty increases to 13-32% (2.5-6.5 mg/km).

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KJ-NA-29138-EN-N

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doi:10.2760/127122

ISBN 978-92-79-80384-0