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Real Driving Emissions (RDE): 2020 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty

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Contents

Preface

Since 2017 on-road testing is required for the type approval of vehicles (Regulation 2017/1151 and amendments). In order to take into account the extra measurement uncertainty of the on-board equipment when compared to laboratory ones, **conformity factors** are applicable to the on-road emissions. These conformity factors require full compliance with the Euro 6 limits but allow **margins** to account for the additional measurement uncertainty of on-board systems relative to standard laboratory equipment for NOx and particle number emissions. The recitals in the Real-Driving Emissions (RDE) regulations oblige the Commission to review the appropriate levels of the conformity factors in light of technical progress, a task that was undertaken by the European Commission's Joint Research Centre (JRC).

The objective of this JRC report is to:

- Document review activities in 2020 regarding the measurement uncertainty for NOx.
- Review the framework for the systematic review and revision of Portable Emission Measurement Systems (PEMS) measurement uncertainties.
- Propose the framework for the Particle Number (PN) margin and revise the current PN margin of 0.5.
- Propose possible improvements in the implementing regulation and related future margins.

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The authors would like to acknowledge R. Loos for providing the relative data for this report from the in-service conformity project, and A. Melas and T. Lahde for their comments on the particle number uncertainty.

The contribution of all the institutes with data for this report is highly appreciated (alphabetically): AIP, AVL, EMISIA, Green NCAP (GVI), Horiba, LAT, Sensors.

Authors

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Abstract

This report describes the 2020 assessment of the margins for the RDE (Real-Driving Emissions) results prescribed in the EURO 6 regulation. Margin is defined as the additional measurement uncertainty introduced by PEMS (Portable Emissions Measurement Systems) compared to the laboratory systems for a pollutant. The 2020 data collected by a series of EU testing houses showed in general very good performance of the PEMS in terms of NOx zero drift and laboratory validation results. In consequence, the framework to calculate the NOx margin was modified and together with the observed improvement of the exhaust flow meter's uncertainty, the NOx margin may now be decreased from 0.32 to 0.23. In practical terms, this value covers at least 95% of the worst cases, compared to the 99% of the previous report.

The data suggest that further reduction is possible by improving the permissible tolerances for the equipment in the regulation and the method by which the zero drift is taken into account. Under this future scenario the future NOx margin could be reduced to 0.10, but this requires first changes in the regulation.

In this report, the framework was further developed to analyse the Particle Number (PN) margin. Based on the analysis of this report the PN margin is now estimated to be 34% (0.34).

For further reductions of the PN margin a more holistic approach is necessary (e.g. bringing closer technical and calibration specifications of the PN-PEMS and the reference PMP systems).

1 Introduction

A major breakthrough in the European Union's (EU) regulations for light-duty vehicles was the introduction of Real-Driving Emissions (RDE) testing with Portable Emission Measurement Systems (PEMS). Commission Regulation (EU) 2016/427 (first regulatory act of the RDE regulation) introduced on-road testing with PEMS to complement the laboratory Type I test for the type approval of light-duty vehicles in EU. Subsequently, Commission Regulation (EU) 2016/646 introduced the not-to-exceed (NTE) concept, which equals the emission limit for the laboratory Type I test multiplied by a so-called conformity factor (CF). The CF requires full compliance with the Euro 6 limits but allows a margin to account for the additional measurement uncertainty of PEMS relative to standard laboratory equipment (CF = 1 + margin). CFs for NOx were introduced in two steps: A CF of 2.1 was applicable upon the request of the manufacturer from September 2017 to all new types (and September 2019 to all new vehicles), and a CF of 1.5 was applicable from January 2020 for new types (and January 2021 for all new vehicles). Recital 10 of the RDE Regulation 2016/646 prescribed that the European Commission should review the appropriate level of the final conformity factor in light of technical progress of PEMS; a task that was assigned to the European Commission's Joint Research Centre (JRC). Both regulations were consolidated in Regulation (EU) 2017/1151.

Regulation (EU) 2017/1154 (the third part of the RDE Regulations), introduced a RDE conformity factor for the on-road test of solid particle number (PN) emissions (CF=1.5), applicable already since 2017. The fourth part of the RDE Regulation 2018/1832 introduced on-road emissions testing as part of in-service conformity checks and slightly lowered the conformity factor for NOx based on an ad-hoc review of the PEMS measurement uncertainty performed by the JRC in 2018 (data from 2017) (Giechaskiel et al., 2018a,b) (CF=1.43).

In addition to proposing a reviewed value for the NOx margin, the 2018 JRC report laid out the framework for subsequent margin reviews. This methodological framework for calculating the additional uncertainty of the PEMS respect to laboratory equipment was based on the assessment of the individual uncertainty of the PEMS components (gas analysers, exhaust mass flow meter, etc.) and considering the error propagation rule.

The 2018 JRC report identified the zero drift of gas analysers (i.e. the difference in zero reading between the pre-test and the post-test) as a major contributor to the final value of the NOx margin. The lack of experimental data on zero drift throughout RDE tests was encountered assuming a step increase of the zero from the beginning of the test. Furthermore, the uncertainty of the exhaust flow meter (EFM) was higher than expected, and the effect of the boundary (ambient) conditions was not well characterized at the time. The review closed suggesting the following ways for further CF reductions:

- Improvement of the uncertainty framework: For example, in 2017 the mean values of drift were close to 0 ppm, indicating that there is not always a one-way drift but the final zero drift result is due to random variation, thus, the drift should not be added, but should be taken into account with the typical uncertainty equations.
- Modification of technical requirements. For example, one possible way would be to reduce the accuracy requirement of the gas cylinders (from 2% to 1%), or another example would be to further reduce the permitted zero drift (from 5 ppm to a lower value).
- Better understanding of real time drift or EFM uncertainty. For example, in 2017 it was assumed that the drift could happen at the beginning of the test or gradually during the test, but it was not tested.
- Better analysis of reference system's uncertainty with experimental data.

The 2020 report (2018/2019 data) addressed the three areas that needed better feedback (Valverde et al., 2020): EFM uncertainty, zero drift and effect of boundary conditions on PEMS. Dedicated on-road tests were conducted measuring the NOx zero drift of the analysers every 10-20 min during RDE compliant and non-compliant routes. Altitudes up to 1100 m were covered and temperatures within 0°C and 35°C. Lower temperatures (-7°C) and drastic changes of the temperature (-7°C to 23°C and vice versa) were better assessed in the laboratory. NOx zero drift hypothesis of a step drift occurring at the very beginning of the test and then being maintained along the duration of the test was not verified in any of the tests performed. No correlation with temperature, ambient humidity or altitude was found. Based on the worst experimental case scenario for zero drift of the JRC testing campaign and considering the effect on a vehicle with large engine displacement (largest effect in terms of NOx mass), an updated NOx margin of 0.32 was proposed.

The 2020 margin report will

- Document review activities in 2020 regarding the measurement uncertainty for NOx.
- Review the framework for the systematic review and revision of Portable Emission Measurement Systems (PEMS) measurement uncertainties.
- Propose the framework for the Particle Number (PN) margin and revise the current PN margin of 0.5.
- Propose possible improvements in the implementing regulation and related future margins.

2 Evaluation of test data

2.1 NOx (and CO) zero drift

Before the start of a test, the PEMS analysers (e.g. for NOx, CO) are “zeroed” with a gas that contains no pollutants (e.g. NOx, CO), typically N_2. Then at the end of the test the analysers are checked with the “zero” gas. A small difference is allowed, but if the post-test values exceed a threshold (e.g. 5 ppm for NOx), then the test is not valid.

2.1.1 Input data

Data were collected in the course of 2020 from various laboratories. In total 304 tests were made available.

Institutions: Pre- and post-zero tests were provided by JRC and DG-GROW contractors for In-Service Conformity (ISC), Euro 7 (CLOVE), and retrofit projects. JRC contributed 38% of the data. The majority of the rest tests came from four other labs (95% of the rest 62%). Another three labs provided the rest 5% of the data.

RDE / non-RDE: The non- RDE tests refer to tests which were not compliant with the RDE boundaries, or trips composition. Most of them were done at high altitude, dynamic driving, longer trips (up to 2.5 h), and trips with urban/rural/motorway shares outside the RDE specifications. There were no tests at temperatures <0°C. The non- RDE tests were 56% of the tests.

PEMS models: The tests included PEMS from three manufacturers AVL (44%), Horiba (45%), and Sensors (11%). These three manufacturers currently cover most of the market and were the only PEMS available throughout the year at the participating laboratories. Even though results from the fourth PEMS manufacturer are missing, there is a good coverage of the market with the data from the three manufacturers.

Table 1 summarises the data distributed in different categories.

Table 1. Number of available total tests and classifications.

Categories	Name	Number of tests
Institutions	JRC	115
	ISC	114
	CLOVE	75
Compliance	RDE	133
	Non-RDE	171
Models (Manufacturers)	AVL	135
	Horiba	136
	Sensors	33
Total tests		**304**

Source: JRC 2021

2.1.2 NOx zero drift results

The NOx zero results are summarised in the following figures. **Figure 1** plots the results separately for RDE compliant and non-RDE tests. The normalised distributions are almost identical, indicating no influence of dynamic driving, different shares of urban/rural/motorway parts, and altitude on NOx zero drift. **Figure 2** plots the results for different PEMS models. For all three models the distributions peak either at the 0 ppm to 1 ppm range or -1 ppm to 0 ppm range.

The results show that lowering the current 5 ppm NOx permissible zero drift at the end of the test would result in:

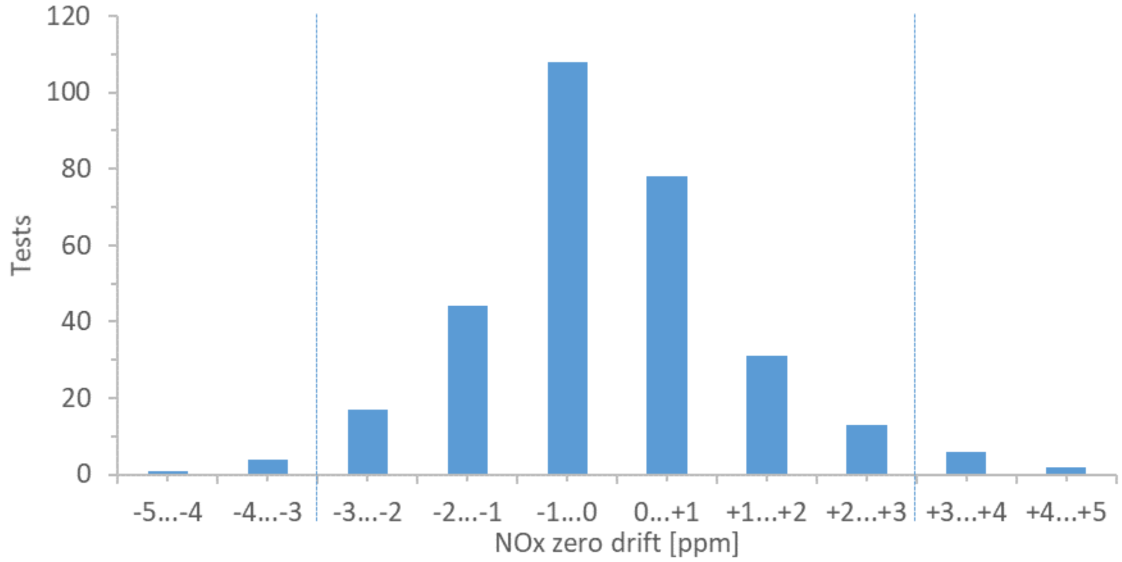
- Abs Drift <4 ppm 99.0% pass
- Abs Drift <3 ppm: 95.7% pass
- Abs Drift <2 ppm: 85.9% pass

The mean drift of the 304 tests was -0.1 ppm (median -0.2 ppm) with a standard deviation of 1.4 ppm. The distributions A and C were normally distributed (chi statistic of normality, p=0.05), while B not (skewed to the left).

The results clearly show that a maximum zero drift of 3 ppm would cover most cases (around 96%). These results further confirm that the current experimental worst case zero drift, which is based to 5 ppm drift, overestimates the NOx zero drift for most cases and therefore leads to an overestimation of the margin for most tests. This is further supported by the fact that the zero drift uncertainty considers large 3 L engines, which is also an overestimation for the vehicles in the market.

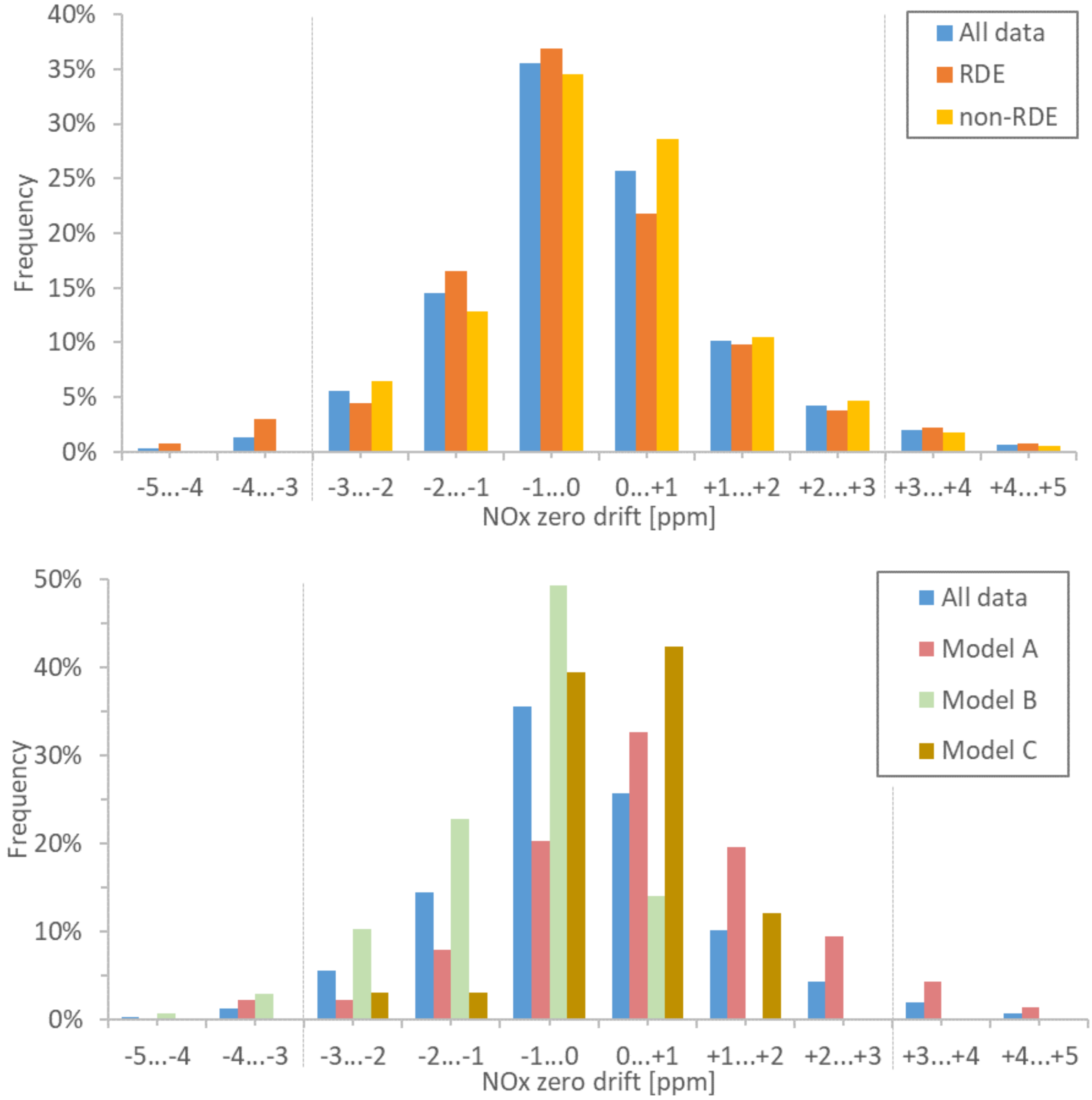
These findings suggest that a different approach should be followed in the future, i.e. the NOx zero drift of each single test should be corrected linearly before proceeding with the analysis of the results. The minimum zero drift as the current data support, should be reduced to 3 ppm. Current data shown above estimate that only 4-6% of the tests might need to be repeated because the zero drift might be higher than the allowed but this is bound to improve in the future.

Figure 1. Distribution of NOx zero drift of all 304 tests. Vertical lines show ±3 ppm zero drift.



Source: JRC 2021, Data from JRC and other institutes as explained in the main text.

Figure 2. Normalised distribution of NOx zero drift for total, RDE and non-RDE tests (upper panel) or different PEMS models (manufacturers) (lower panel). Vertical lines show ±3 ppm zero drift.



Source: JRC 2021, Data from JRC and other institutes as explained in the main text.

2.1.3 NOx zero drift conclusions

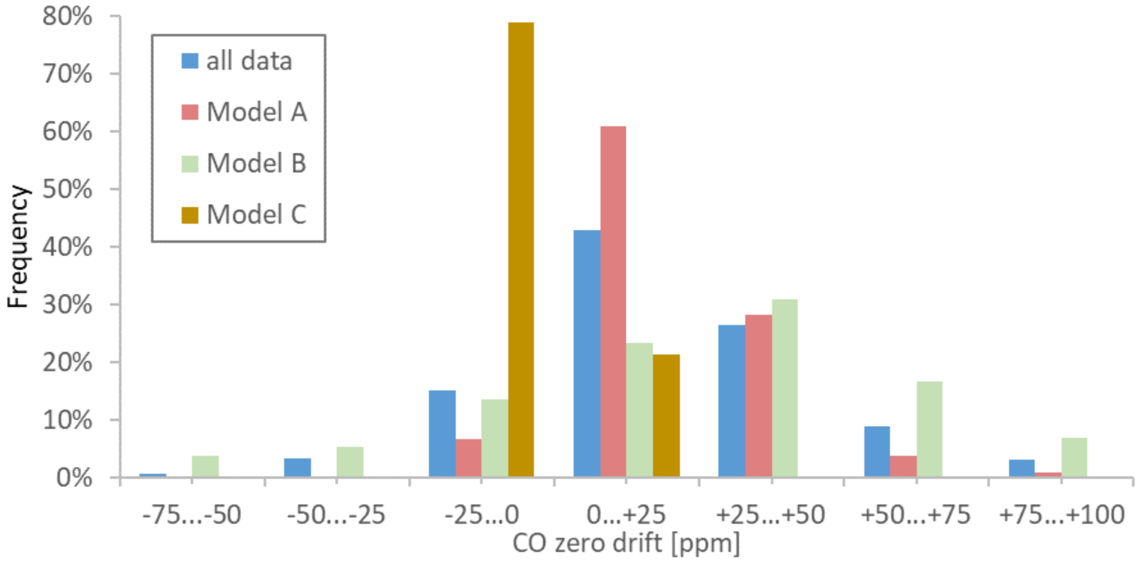
- Mean drift of 304 tests close to 0 ppm.
- No effect of dynamic and/or high altitude driving (all tests at temperatures >0°C).
- All manufacturers have drift within 3 ppm, each of them for at least >94% of the tests (combined 96%).
- The results are better than in the past, indicating better maintenance and/or procedures from the laboratories compared to the first years of PEMS implementation even though the PEMS used for testing are of the same technology and age.

2.1.4 CO zero drift results

The permissible zero drift of the CO analyser over a PEMS test is currently 75 ppm. Following a similar analysis for CO zero drift the main conclusions are,

- The overall CO drift distribution covered a range of -60 to 100 ppm. The distribution of CO drift followed a normal distribution for all manufacturers.
- The mean was 20 ppm (median 17 ppm) with standard deviation of 28 ppm.
- A few tests were >75 ppm (the permissible drift).
- 88% of the tests were within ±50 ppm.
- No change of the current maximum drift is suggested.

Figure 3. Normalised distribution of CO zero drift for total or different PEMS models (manufacturers).



Source: JRC 2021, Data from JRC and other institutes as explained in the main text.

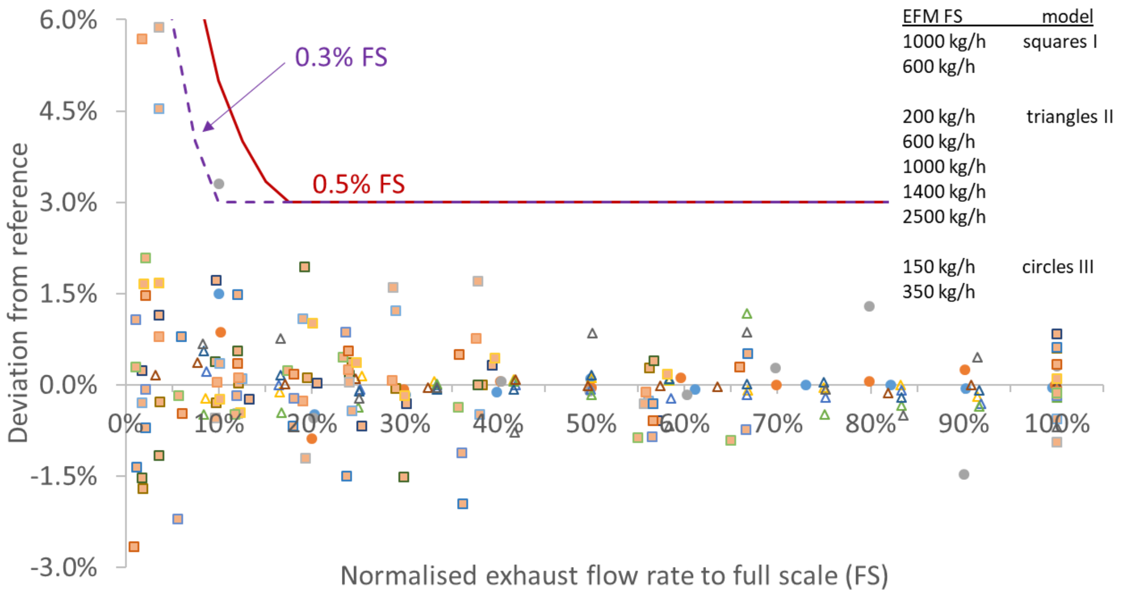
2.2 EFM uncertainty

This section reviews the uncertainty of the exhaust mass flow meters (EFM) by checking the uncertainty during their calibration by the manufacturers, and during their use on actual PEMS tests (on the road and during PEMS validation tests in the laboratory).

2.2.1 EFM calibration data

Input was received from three PEMS suppliers (AIP, AVL, HORIBA) and in total 28 calibration certificates were analysed. EFM calibration data from three PEMS models (manufacturers I, II, III) with different full ranges are summarised in **Figure 4**. The calibration data were normalised to the maximum flow rate of each flow meter (i.e. full scale). The limits in the regulation (3% or 0.5% of full scale, whatever is larger) are shown in the figure with a red line. Note that the 2% requirement in Reg. 2017/1151, was amended to 3% in Reg. 2018/1832. The calibration data fulfil the regulatory requirements. They show that the 2% is also fulfilled, but based on the 2017 data of re-calibration of EFMs after one year it is suggested to keep it to 3% (Giechaskiel et al., 2018a,b). Furthermore, it seems possible to reduce the 0.5% of full scale requirement to 0.3% of full scale.

Figure 4. EFM uncertainty based on calibration data from three PEMS suppliers (A, B, D). Lines show the positive EFM uncertainty based on technical specifications: 3% or 0.5% of full scale, whatever is larger.



Source: JRC 2021, Data based on calibration certificates from three PEMS suppliers, covering a wide range of exhaust flow rates (200 kg/h to 2500 kg/h).

2.2.2 EFM expected uncertainty

This section describes the typical range in which EFMs are usually used during RDE and WLTC tests based on a collection of data from the experimental JRC activity. The 200 total data of this section includes: 190 RDE tests from 13 positive ignition (P.I.) and 7 compression ignition (C.I.) vehicles, 10 laboratory tests from 6 P.I. and 3 C.I. vehicles.

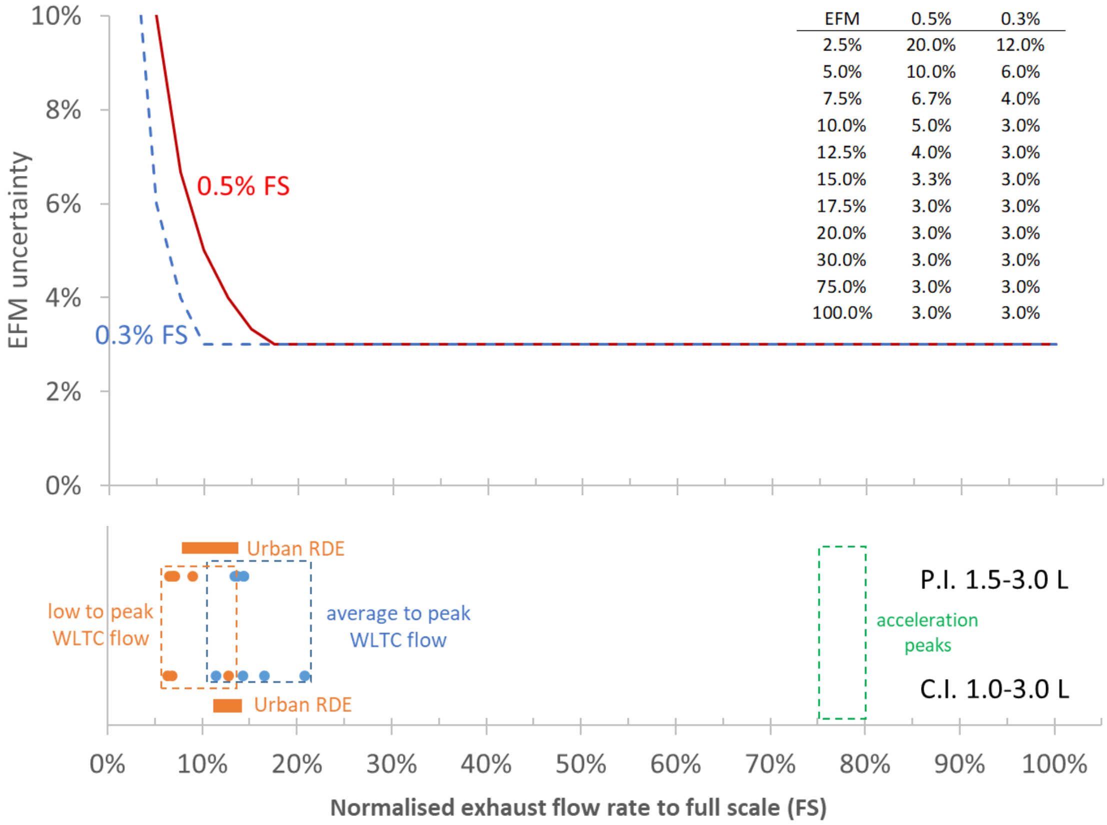
Figure 5 plots the EFM measurement range for WLTCs and RDE trips, normalising the EFM peaks during accelerations to 75% of the maximum EFM range (full scale). The normalisation to 75% is based on the regulation recommendation that the maximum exhaust flow rates during a test should cover at least 75% of the EFM range. Note that this normalisation decreased the actual used range for the dynamic tests that typically covered the whole EFM range.

The data are plotted separately for C.I. (diesel) and P.I. (gasoline, CNG) engines. The mean flow rate was used as it appropriately “weights” the accelerations (high exhaust flow rates) where they contribute significantly to the emissions. Furthermore, the analysis focused on the urban part where the flow rates are low (and the uncertainty is higher), plus the contribution of the cold start (high emissions) is significant.

The mean WLTC exhaust flow rate is around 10% to 22% of the EFM full scale, when the spikes during acceleration reach and slightly exceed 75% of the full scale. The lowest exhaust flow rates (for which the uncertainty is the highest) occur during the Low phase of the WLTC (mean speed 19 km/h). The flowrate in this condition ranges between 6.5% to 13% of the EFM full scale. Data based on actual RDE tests cover a range of 11-16% (C.I.) and 7-12% (S.I).

The inset of **Figure 5** gives the maximum calibration uncertainty for different flows normalised to the maximum flow rates. At the 5% EFM range the uncertainty is 10% (based on 0.5% of FS) or 6% if the requirement will be decreased to 0.3% of FS. At the 10% EFM range, which is the usual flowrate during RDE tests, the expected uncertainty of the EFM is 5% (or 3% with the 0.3% FS requirement).

Figure 5. Upper panel: EFM uncertainty in function of exhaust flow rate normalised to full scale. Lines and inset show the EFM uncertainty based on technical specifications: 3% or 0.5% of full scale, whatever is larger. **Lower panel:** Points show the mean exhaust flow rate for different phases of WLTC or RDE tests compared to the EFM full scale, when the spikes during accelerations slightly exceed 75% of EFM full scale. C.I.=Compression Ignition; FS=Full Scale; EFM=Exhaust Flow Meter; RDE=Real Driving Emissions; P.I.=Positive Ignition; WLTC=World harmonised Light vehicles Test Cycle.



EFM	0.5%	0.3%
2.5%	20.0%	12.0%
5.0%	10.0%	6.0%
7.5%	6.7%	4.0%
10.0%	5.0%	3.0%
12.5%	4.0%	3.0%
15.0%	3.3%	3.0%
17.5%	3.0%	3.0%
20.0%	3.0%	3.0%
30.0%	3.0%	3.0%
75.0%	3.0%	3.0%
100.0%	3.0%	3.0%

Source: JRC 2021: JRC internal data during PEMS validations (10 tests) and actual RDE tests (compliant and non-compliant) (190 tests), where the peaks were normalised to 75% of the EFM full scale,

2.2.3 EFM experimental uncertainty

During PEMS validations the performance of the complete PEMS may be compared against laboratory grade instrumentation. The performance of the EFM cannot be directly assessed during a PEMS validation test as the laboratory measurement of the exhaust mass flow is typically not performed via a traceable standard. Methods typically used (tracer, or total minus dilution air flow) also have uncertainty on the same range as the EFM.

The CO_2 validation test in the laboratory can be used as an estimation for the EFM uncertainty. Assuming:

$\varepsilon^2(validation) = \varepsilon^2(CO_{2,bags}) + \varepsilon^2(CO_{2,\ PEMS}) + \varepsilon^2(EFM) + \varepsilon^2(dynamics)$

then for a 10% difference between bags and PEMS CO_2 result, $\varepsilon(validation)$, a 3% uncertainty of the bags CO_2, $\varepsilon(CO_{2,bags})$, a 3% uncertainty of the PEMS CO_2 analyser, $\varepsilon(CO_{2,PEMS})$, and a 3% uncertainty of time alignment and dynamics, $\varepsilon(dynamics)$, then the EFM uncertainty, $\varepsilon^2(EFM)$, is 8.5%. Note that since the same distance is used for both PEMS and bags, this uncertainty is not considered.

This section evaluates the EFM performance through validation tests that were received from 10 labs (40 tests) plus the JRC validations (12 tests). The non-JRC data were from GVI (Green Vehicle Index) or Green NCAP project and DG-GROW's ISC and retrofit projects. The equipment was from AVL, Horiba and Sensors.

Figure 6 plots the comparisons of PEMS and bags CO_2 from the validation tests as absolute differences, while **Figure 7** as relative differences. From the 52 validations, 80% had below 5% difference of CO_2 between PEMS and bags. Three tests (6%) are above 7.5%. From those above 7.5%, two were positive differences (i.e. PEMS overestimating): one case was a hybrid vehicle and the other a CNG vehicle.

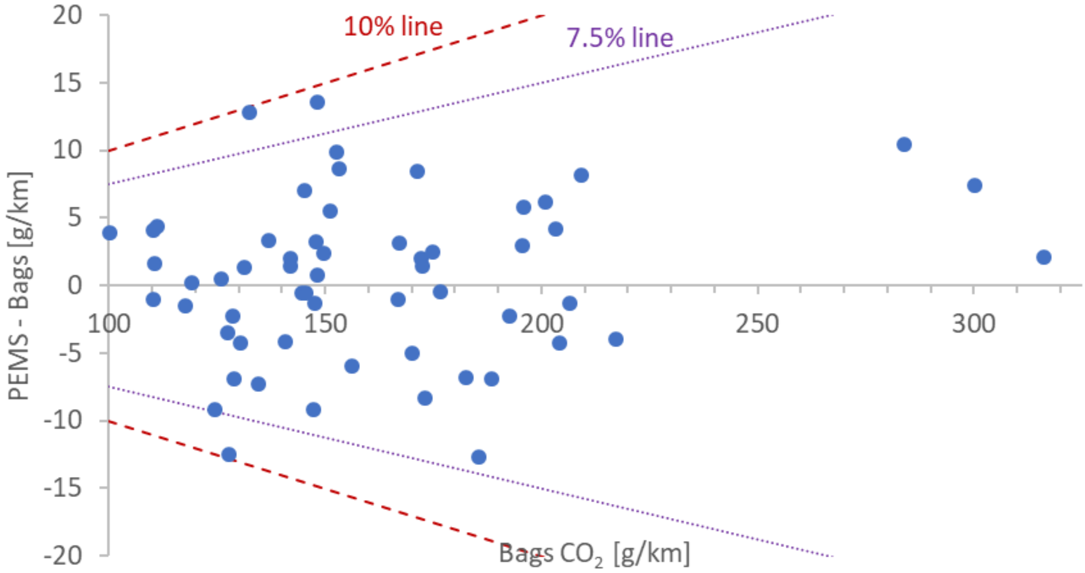
A 6% difference is the expected value for high flow rates, i.e. with EFM uncertainty 3%, PEMS and bags CO_2 uncertainty 3%, 3% time alignment. This was the case for CO_2 values >155 g/km (differences<5%), but not for lower CO_2 values. This indicates that the EFMs used for these cases might have been oversized. The 2020 data indicate 7.5% differences as the worst case of CO_2 values <155 g/km, with only a few exceptions.

These results are in agreement with the limited data in the literature, where in general agreement of better than 5% was found (Vu et al., 2020; Akard et al., 2020).

2.2.4 EFM conclusions

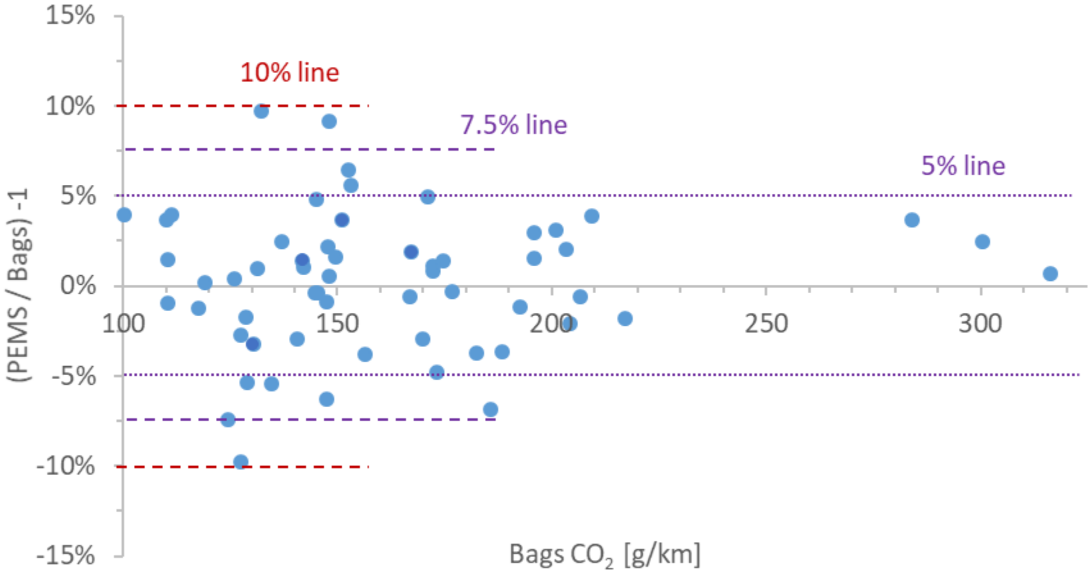
- The calibration certificates showed that the technical requirements for EFMs in the regulation can change from 0.5% of full scale to 0.3% of full scale (or 3%, whatever is larger).
- Experimental data of laboratory and on-road data showed that, assuming that the acceleration spikes reach 75% of the EFM's full scale, the lowest mean exhaust flow rates during urban operation range are between 6.5% to 16%. These flow rates translate to 7.7% (or 4.6% with the new requirements) to 3.1% (or 2% with the new requirements) uncertainty. If the spikes would cover a wider range of the EFM, then the uncertainty values would be lower. This means that with today's EFM technical requirements a 3-8% uncertainty is expected for the urban RDE tests. If the EFM technical specifications improve, then the EFM uncertainty could be reduced to 2-5%.
- Validation tests in the laboratory gave CO_2 differences between PEMS and bags of <5% for CO_2 values >155 g/km. For lower CO_2 values the majority of the cases was <7.5%. Note that the currently permissible tolerance of the CO_2 validations in the RDE regulation is 10%.

Figure 6. CO_2 validations as a proxy of EFM uncertainty. Red line shows the current permissible tolerances (10 g/km or 10%, whichever is larger).



Source: JRC 2021. Data from JRC and other institutes as described in the main text.

Figure 7. CO_2 validations as a proxy of EFM uncertainty. Red line shows the current permissible tolerances (10 g/km or 10%, whichever is larger).



Source: JRC 2021. Data from JRC and other institutes as described in the main text.

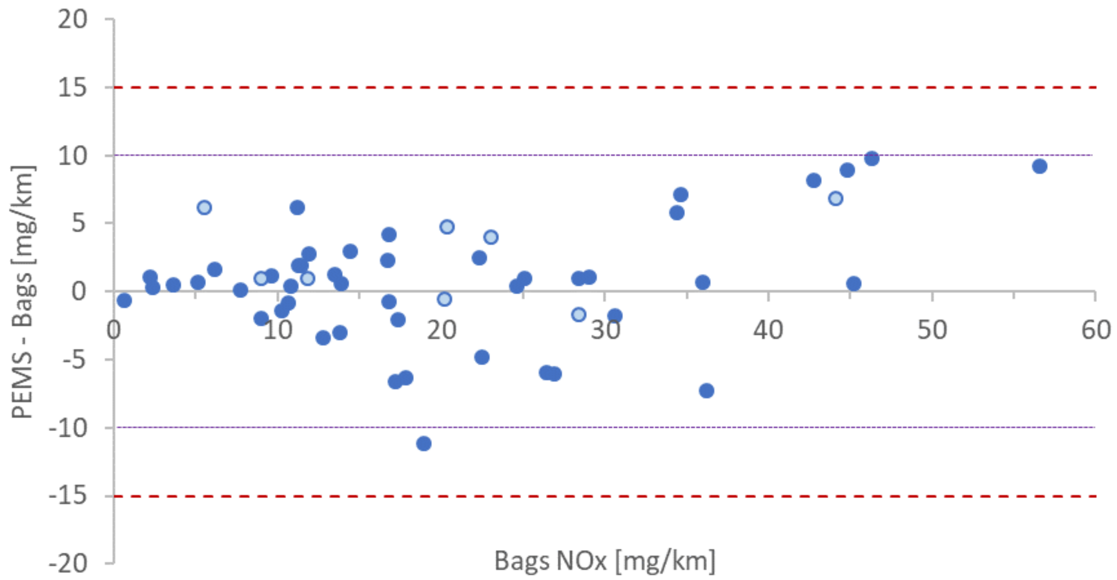
2.3 Rest validations

This section assesses the results of the PEMS validations for NOx, CO, and PN. The input of data was the same as for CO_2 validations described in the previous section.

Figure 8 plots the NOx validations. The emissions were below 60 mg/km (with a few exceptions >800 mg/km of older vehicles, not shown). The absolute differences between PEMS and bags were mostly <10 mg/km; lower than the 15 mg/km permissible tolerance. At levels below 30 mg/km the differences were within ±6.5 mg/km.

A recent study found differences ±15% (absolute emission levels were not reported) (Vu et al., 2020).

Figure 8. NO_x validations. Red line shows the current permissible tolerances (15 mg/km or 15%, whichever is larger).

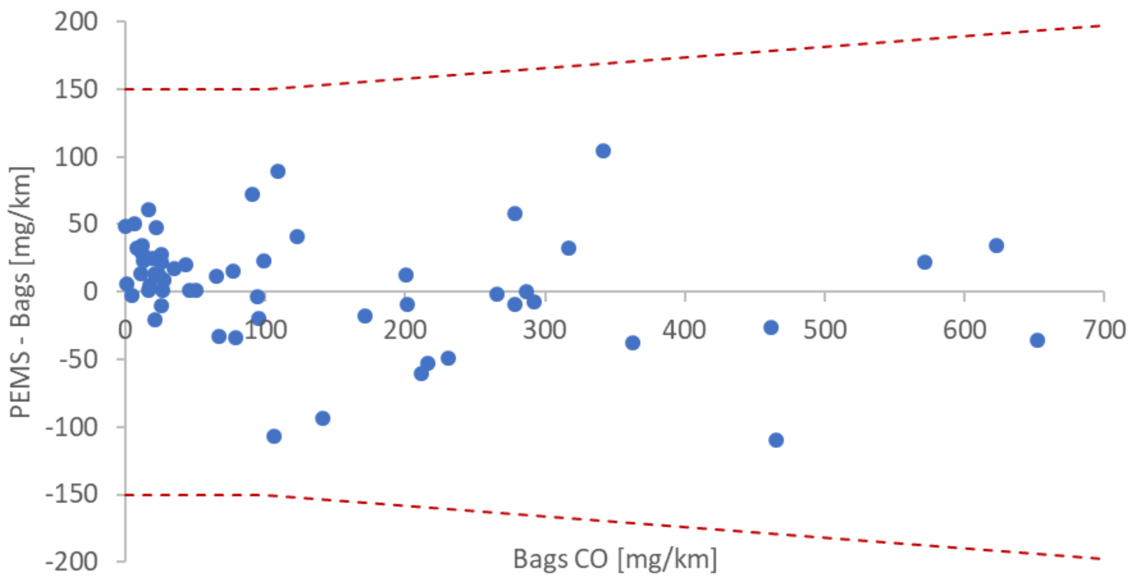


Source: JRC 2021. Data from JRC and other institutes as described in the main text.

Figure 9 plots the CO validations. The emissions were below 700 mg/km (one exception 1750 mg/km of an older vehicle). The absolute differences between PEMS and bags are <100 mg/km; only four higher than the 75 mg/km, and the majority of the points is within ±50 mg/km. At low range of CO emissions (<50 mg/km), the scatter of the validation points expressed as distance-specific emissions, remains.

A recent study found ±8% differences for a gasoline vehicle and 15% on average for a 6.7 L diesel vehicle (Vu et al., 2020).

Figure 9. CO validations. Red line shows the current permissible tolerances (150 mg/km or 15%, whichever is larger).

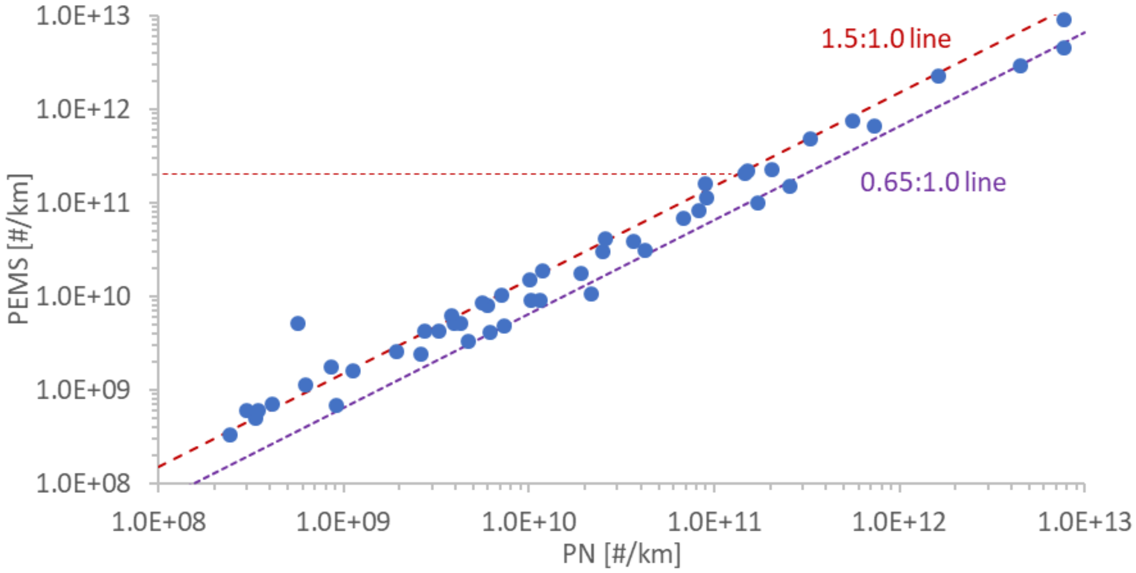


Source: JRC 2021. Data from JRC and other institutes as described in the main text.

Figure 10 plots the PN validations. The emissions ranged over five orders of magnitude. In general, the differences between PEMS and laboratory PN were within -35% to +50% with a few exceptions at low levels. The mean difference was 8% for >6 $\times 10^{10}$ p/km (16 data points), 3% for >1 $\times 10^{11}$ p/km (12 data points), Reducing the permissible tolerance to 40% would result in 3 points not respecting the permissible tolerances, while a tolerance of 42% would invalidate only one test. Reducing the absolute limit to 8×10^{10} p/km also did not change the results.

Recent studies also found differences on average <25%, with maximum differences <40% (Otsuki et al., 2019; Schriefl et al., 2020).

Figure 10. PN validations. Red line shows the current permissible tolerances (1×10^{11} p/km or 50%, whichever is larger).



Source: JRC 2021. Data from JRC and other institutes as described in the main text.

The conclusions from the rest validations are:

- The permissible tolerance of NOx validations could be reduced to 10 mg/km (from 15 mg/km) for emissions levels below 80 mg/km.
- The permissible tolerance of CO validations could be reduced to 100 mg/km (from 150 mg/km) for emissions levels below 700 mg/km.
- The permissible tolerance of PN validations could be reduced to 42% (from 50%) (or 8×10^{10} p/km, whichever is larger).

3 Framework for PEMS uncertainty

The framework for the calculation of the NOx PEMS measurement uncertainty was described in Giechaskiel et al. (2018a,b) (see details also in **Annex**). This chapter will discuss the recommended improvements.

The framework for particle number (PN) uncertainty will be separately presented.

3.1 Gaseous pollutants margin framework

3.1.1 Revised framework

The new framework is identical with the previous version with the only change that the dynamics and zero drift uncertainty are not added arithmetically, but taken into account with the error propagation rule (i.e. square root of sum of squares). Similarly, the CVS uncertainty is not subtracted, but reduced with the error propagation rule. Using the same input values as in the 2018/2019 study (Valverde et al., 2020), and reducing the EFM uncertainty from 10% to 7.5% (based on the 2020 data), the NOx margin is 23% (0.23), instead of 32% (0.32) (**Figure 11**).

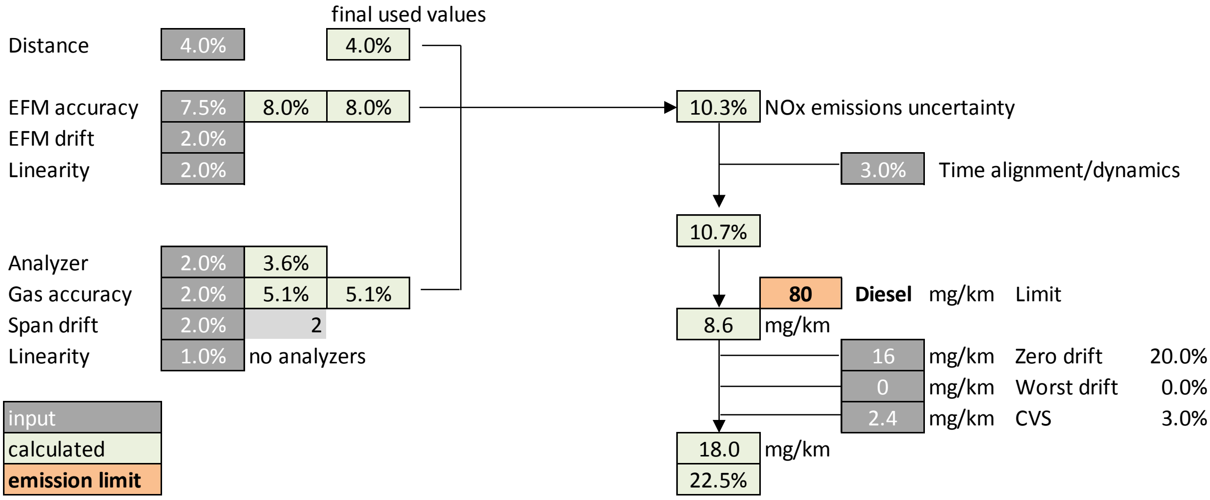
The modification of the framework is based on three years' experience that the zero drift is random and does not have a particular trend. Furthermore, this approach largely matches **the approach proposed by the standard under development for PEMS measurement uncertainty from the European Committee for Standardization** (CEN) (CEN, 2018).

In practical terms this change of the framework means that (at least) 95% of the cases are covered, compared to the 99% (with the CF=1.32) or 100% (with the CF=1.43) with the older framework.

It should be reminded that the zero drift of 16 mg/km was estimated based on 3 L engines, for which the EFM uncertainty was found to be on the 5% range (and not 7.5%). Vehicles with smaller engine displacement will have EFM uncertainty 7.5%, but on the other hand almost proportionally lower zero drift. Thus, **for both large and small engine displacement vehicles the 0.23 NOx margin covers >95% of the cases.**

More details and explanations can be found in the **Annex**.

Figure 11. Updated PEMS margin framework for NOx.



Source: JRC 2021.

3.1.2 Future NOx margin and related changes in the implementing regulation

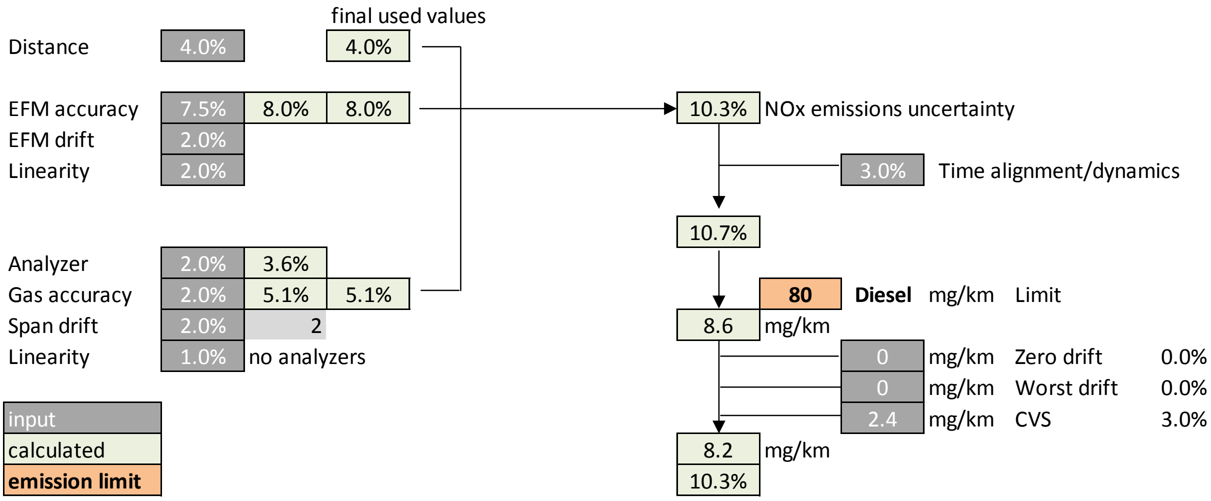
With the revised framework and slightly modified values the NOx margin is 0.23, still the main contributor is the NOx zero drift. The experimental data of **Chapter 2** confirmed once more that the NOx zero drift is distributed around 0 ppm, with 95% of the cases within -3 ppm and +3 ppm. Thus the 5 ppm drift case is overestimating the contribution of zero drift for at least 95% of the cases. We therefore suggest that the 5 ppm drift allowed by the Regulation is lowered to 3 ppm. For the PEMS tested, this is already achievable today.

Furthermore, the estimated maximum uncertainty NOx zero drift of 16 mg/km was based on 3 L engines, while the majority of the cases are smaller engines. Thus, a better approach would be to consider the zero drift of the specific RDE test. The under development CEN standard also suggests the linear drift as the best assumption for the calculation of the uncertainty. As was already done in the heavy-duty regulation, the best way forward is to correct the NOx signal taking into account the actual NOx zero drift linearly based on the pre- and post-test checks. Such a correction would decrease the final NOx emissions in case of positive NOx zero drift, but increase the final NOx emissions in case of negative NOx zero drift to reflect the real contribution of the zero drift in the results.

In order to further support this change and to minimize the uncertainty, the permissible tolerances of the validation tests should also be reduced. The NOx tolerances in validation tests should be reduced to 10 mg/km or 12.5% (=10/80), whichever is larger (from 15 mg/km or 15%, whichever is larger). Furthermore, the CO_2 tolerances in validation tests (as a proxy of the EFM uncertainty) should also be reduced to 7.5% or 10 g/km, whichever is larger (from 10% or 10 g/km, whichever is larger).

Following on this change the future NOx margin could be reduced to 0.10 (see **Figure 12**), where the NOx zero drift has been set to 0 mg/km.

Figure 12. Future PEMS NOx margin.



Source: JRC 2021.

3.2 Particle number (PN) margin framework

3.2.1 PN-PEMS uncertainty

The PN emissions when measured from the tailpipe with a PEMS (PN_{PEMS}), are calculated as:

$$PN_{PEMS,i} = 10^6\ C_{PEMS,i}\ Q_{exh,i}\ /\ \rho_{exh,i}$$

$$PN_{PEMS} = \Sigma\ PN_{PEMS,i}\ /\ D$$

where $C_{PEMS,i}$ is the instantaneous concentration of the PN-PEMS (p/cm^3) normalized at 0°C, $Q_{exh,i}$ is the instantaneous exhaust flow rate (kg/s), ρ_{exh} is the density of the exhaust (kg/m^3) at 0°C, and D is the distance (km).

The uncertainty of the concentration measured by the PN-PEMS, $\varepsilon(C_{PEMS})$, depends on the accuracy during the calibration $\varepsilon(C_{acc})$, the linearity $\varepsilon(C_{lin})$, and the drift that has occurred since the calibration $\varepsilon(C_{drift})$. This is the calibration uncertainty $\varepsilon(C_{PEMS,cal})$. In addition, the size $\varepsilon(size)$, and the boundary conditions uncertainty $\varepsilon(boundaries)$ should be taken into account. The boundary conditions consider environmental conditions (e.g. temperature, pressure, relative humidity) that can influence the instrument. For on-road tests, vibrations are also included in this category.

$$\varepsilon^2(C_{PEMS,cal}) = \varepsilon^2(C_{acc}) + \varepsilon^2(C_{lin}) + \varepsilon^2(C_{drift})$$

$$\varepsilon^2(C_{PEMS}) = \varepsilon^2(C_{PEMS,cal}) + \varepsilon^2(size) + \varepsilon^2(boundaries)$$

The size uncertainty $\varepsilon(size)$ takes into account the dropping efficiency at small sizes (for both CPCs and diffusion chargers) and increasing at large sizes (for diffusion chargers).

Assuming that the uncertainties of the signals of PN-PEMS, $\varepsilon(C_{PEMS})$, and exhaust flow, $\varepsilon(Q_{exh})$, remain the same every second (or taking the maximum uncertainty values), then the final uncertainty, $\varepsilon(PN_{TP})$, can be estimated from the equation:

$$\varepsilon^2(PN_{PEMS}) = \varepsilon^2(C_{PEMS}) + \varepsilon^2(Q_{exh}) + \varepsilon^2(\rho_{exh}) + \varepsilon^2(D) + \varepsilon^2(\mathrm{d}ynamics) + \varepsilon^2(losses)$$

Where $\varepsilon(D)$ is the distance uncertainty and $\varepsilon(\rho_{exh})$ is the exhaust gas density uncertainty. The losses uncertainty, $\varepsilon(losses)$, considers agglomeration, and thermophoresis that take place at the inlet of the instrument ($L_{TP\text{-}PEMS}$) because these losses are not taken into account during the calibration of the instrument at ambient temperature. It is assumed that there is no interference from volatile particles.

The dynamics uncertainty, $\varepsilon(dynamics)$, takes into account the time misalignment between Q_{exh} and C_{PEMS} and the different time responses of the two signals.

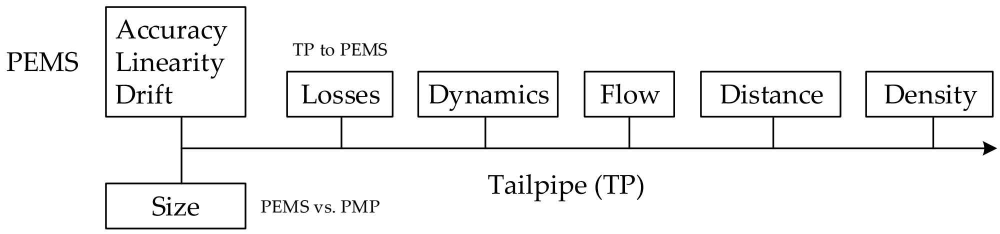
The last equation assumes that the effects of the dynamics and particle losses are random and not systematic. If it is known a priori that a specific system has a bias due to its characteristic, then the bias could be taken into account by adding it and not considering the error propagation rule. This could be for example the case of a system with known high or low thermophoretic losses compared to other systems. However, there are many approaches in the market (e.g. direct cold or hot dilution or use of a sampling line to the instrument) to draw conclusions about bias of a specific approach.

Finally, the PN margin is given by subtracting the PMP reference laboratory system uncertainty from the PN-PEMS uncertainty:

$\varepsilon^2(margin) = \varepsilon^2(PN_{PEMS}) - \varepsilon^2(PN_{PMP})$

Figure 13 summarizes the contributing parameters to the measurement uncertainty of a PN_PEMS at the tailpipe with a causal type diagram. The additional uncertainties, not included in the NOx framework are the particle losses and the size uncertainty. Particles, compared to gases, can be lost in the sampling lines. Furthermore, their size is unknown during a test and this uncertainty has to be considered

Figure 13. Schematic of parameters contributing to the measurement uncertainty for a PN-PEMS at the tailpipe. Additional uncertainties compared to gaseous pollutants: particle losses and particle size uncertainty. PEMS=portable emissions measurement system; TP=tailpipe.



Source: JRC 2021.

3.2.2 Input values

The values that were used for the PN uncertainty calculations are described below. The values are usually the positive part of the maximum permissible error in the legislation (±value). They include a coverage factor of k=2 (i.e. 95% coverage), assuming that the probability distributions are normal, thus they are expanded uncertainties. The values are representative for PN systems measuring from approximately 6×10^{10} p/km to 6×10^{12} p/km, i.e. close to the current emission limit (6×10^{11} p/km). Lower emissions are close to the background (zero) levels of the systems, so the relative uncertainty increases. Higher levels will have higher uncertainty due to particle losses (agglomeration).

PN-PEMS accuracy: The PEMS efficiency is calibrated by comparing the PEMS with a reference PNC_{Ref}, which typically has an accuracy around 5%. However, the technical requirements allow 15% tolerance. Thus, a 15% accuracy uncertainty was considered as appropriate.

PN-PEMS linearity: For PEMS a 15% uncertainty was assumed, the maximum allowed during the linearity checks.

PN-PEMS drift: There is no info regarding long term drift of PEMS (e.g. after one year of use), so a 10% drift was assumed, to cover cases of contaminated orifices, optics, drift of mass flow meters etc.

Boundary conditions: The effect of the boundary conditions (e.g. temperature, pressure, relative humidity, vibrations) was assumed to be 0% (i.e. there is no influence). This assumption is valid for systems measuring in the laboratory, where the conditions are controlled and stable. For on-road tests, this assumption is based on limited experimental data, showing that the instruments still respect their accuracy specifications (Valverde et al., 2020, Giechaskiel et al., 2016).

Distance: For on-road tests, a 4% error was assumed as in the case of NOx margin, i.e. the maximum allowed in the regulation: difference between GPS (global positioning system), reference sensor or validated ECU (electronic control unit) and reference distance from a map.

Exhaust flow: A 7.5% uncertainty was used at the calculations, based on the results of this report and the value that was used for the NOx assessment.

Dynamics: Some studies estimated the uncertainty of the dynamics by misaligning the exhaust flow and the PN signal by ±1 s (Giechaskiel et al., 2019). There was no tendency of the influence and the results were typically within ±5%, reaching in some cases ±10%. A max 5% value was considered for the tailpipe (and on-road) measurements because typically the misalignment cannot be more than 0.5 s. This value is slightly higher than the one for NOx (3%) in order to take into account the more dynamic signal of diffusion chargers.

Particle losses: This uncertainty considers the additional particle losses that are not taken into account during the calibration of the PEMS. These losses can take place at the sampling tube from the tailpipe to the PEMS ($L_{TP\text{-}PEMS}$), The PEMS regulation permits dilution at the sampling point or a sampling tube with residence time up to 3 s. For PEMS connected at the tailpipe, this tube must be heated to >100°C. The dilution can be at ambient temperature or heated. The combinations of possible losses are many and are instrument and setup specific. For this reason, a simplified approach was followed. The $L_{TP\text{-}PEMS}$ were assumed to originate from agglomeration and thermophoresis. The thermophoretic losses were estimated based on typical exhaust gas temperature profiles and assuming cooling to 100°C (until the entrance of the PN-PEMS (Giechaskiel et al., 2012a). This is the worst case, because in reality the final temperatures could be higher. The agglomeration losses were based on various particle number concentration profiles, typical for emission levels up to 1×10^{12} p/km. **Table 2** summarizes the results. For light-duty vehicles the losses were up to 14% mainly due to agglomeration at cold start. Thermophoresis played a small role at high speeds when the particle concentrations were also high.

Table 2. Examples of estimations of particle losses.

Category	**T_{max} (°C)**	**PN_{max} (p/cm^3)**	**Max losses (-)**
DPF (lab)	230	5×10^6	0-3%
GDI/PFI (lab)	260	7×10^7	3-14%
CNG (lab)	225	3×10^7	4-10%

CNG=Compressed natural gas; DPF=Diesel particulate filter; GDI=Gasoline direct injection; PFI=Port fuel injection.

Source: JRC 2021

Size: The size uncertainty includes the effect of the unknown size distribution, but also the possibilities allowed in the regulation, because ranges of permitted efficiencies are prescribed. It is not possible to derive this uncertainty comparing with the "true" inlet concentration, because the technical requirements (i.e. PN-PEMS efficiencies) result in different "measured" concentrations. Thus, the size uncertainty of PN-PEMS was estimated by comparing them to PMP systems, which are supposed to be more accurate and are still the reference systems.

The simulated system efficiencies are given in **Figure 14**. The left panel shows the experimental and simulated efficiencies of PMP reference laboratory systems. The efficiency of the PMP systems at each size was calculated as the product of the penetration of the VPR and the efficiency of the PNC. The penetration of the PMP system was also multiplied with the average PCRF of 30 nm, 50 nm, and 100 nm as required in the regulation. A PMP system, with low penetration (high losses), due to the average PCRF that is used, will overestimate the concentration of large particles (for this reason the efficiency is higher than 100%). Experimental data from calibration certificates from the two largest instrument manufacturers in Europe confirmed that the commercial systems are well within the technical specifications and the worst cases considered here.

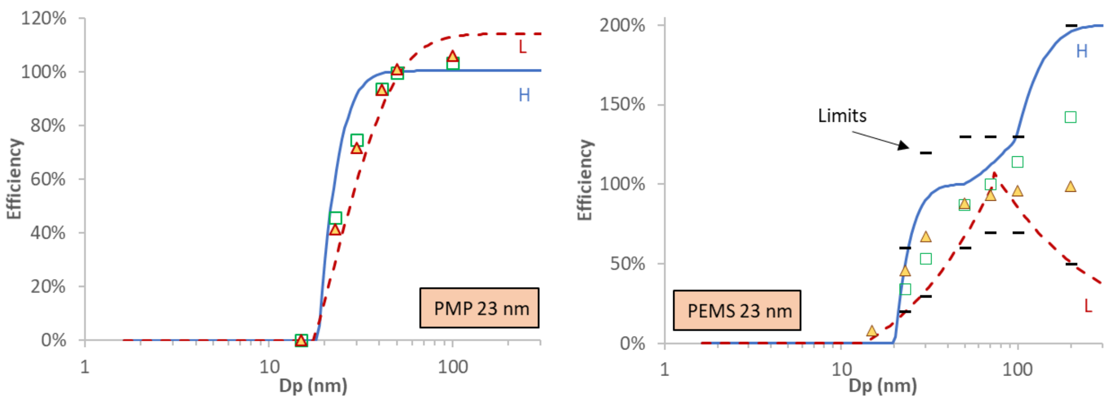
The right panel of **Figure 14** shows the experimental and simulated efficiencies for PN-PEMS. It should be noted that the simulated PN-PEMS efficiencies do not follow the higher or lower limits in the regulation, because the linearity has to give a slope of 1.00±0.15. Thus, there must be a size that there is perfect agreement with the reference instrument (efficiency 100%) at a size >45 nm. Experimental data confirmed that the commercial systems are well within the worst cases simulated.

The 23 nm systems measure >50% of the "true" inlet concentration when the Geometric Mean Diameters (GMDs) are larger than 25 nm, thus inlet concentrations with lower GMDs will have a big error on the absolute concentration, and in any case they are out of the scope of the regulation as the targeted cut-off size is 23 nm. The size range that was considered for the 23 nm systems was 25-70 nm, based on experimental data from various studies e.g. reviews (Giechaskiel et al., 2019b, 2012b).

Figure 15 summarises the expected maximum and typical (based on experimental data) differences between PEMS and PMP systems. The maximum difference between PN-PEMS (overestimating) and PMP (underestimating), can be 20% when the size distributions have GMDs 40-50 nm, 25% at 25 and 70 nm GMD and 30% at 80 nm (PEMS-PMP max). Note that this difference includes size uncertainty but also calibration flexibilities due to the range of permitted efficiencies. On the other hand, a PN-PEMS can be measuring 30-45% lower than a PMP system (PEMS-PMP min).

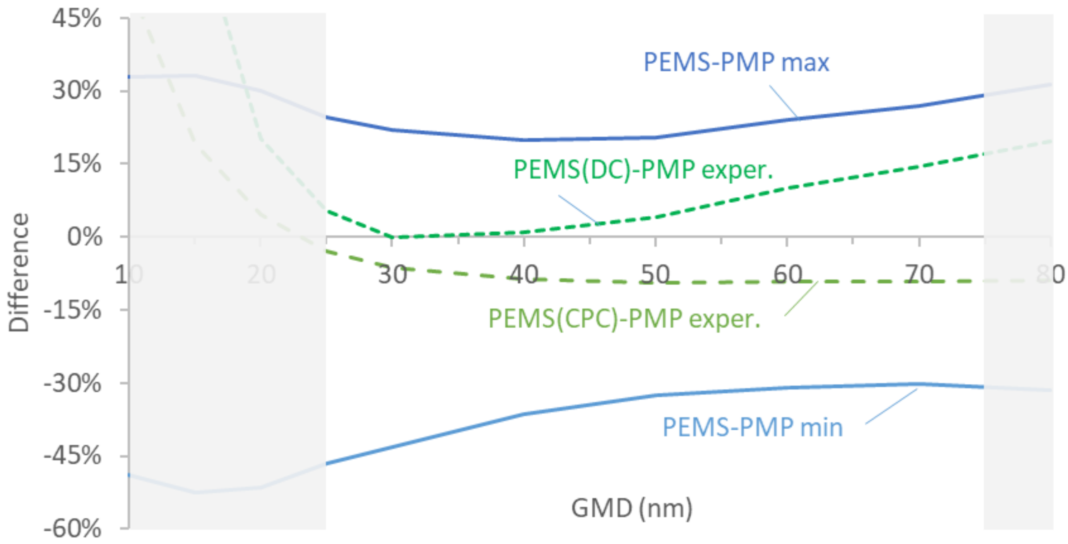
Based on the previous simulations, and assuming that the majority of the GMDs is in the 25-70 nm range, a 25% size uncertainty was assumed for the maximum differences between 23 nm PEMS-PMP systems,

Figure 14. Left panel: Simulated PMP (Particle Measurement Programme) system efficiencies corrected with the mean particle concentration reduction factor (PCRF) and the particle number counter (PNC) slope (i.e. normalized to the plateau region of the PNC). Two cases are shown: one with high efficiencies (low losses) (H) (blue continuous lines) and one with low efficiencies (high losses) (L) (red dotted lines). Symbols give experimental data from two instrument manufacturers. **Right panel:** Simulated PN-PEMS (Portable Emissions Measurement System) efficiencies. Two cases are shown: one with high efficiencies (H) (blue continuous lines) and one with low efficiencies (L) (red dotted lines). Symbols give experimental data from two instrument manufacturers, one based on diffusion charger (squares) and another on condensation particle counter (triangles).



Source: JRC 2021.

Figure 15. Simulated differences between PMP and PN-PEMS systems using the maximum permissible tolerances (max) or based on experimental data (exper.) with diffusion charger (DC) or condensation particle counter (CPC) based systems. At the grey area the systems measure <50% of the true particle concentration. GMD=geometric mean diameter; PEMS=portable emissions measurement system; PMP=particle measurement programme.



Source: JRC 2021.

PMP uncertainty: The uncertainty of the reference laboratory system was considered 18%. This values is supported by both theoretical and experimental data (Giechaskiel et al., 2012).

3.2.3 Results and discussion

The input values for the uncertainty equations (**3.2.1**) as discussed in the previous section (**3.2.2**) are summarized in **Table 3**. Note that as the maximum uncertainty values were used, these results can be considered as expanded uncertainty with a coverage factor of 2 (i.e. confidence level of 95%).

Table 3. PEMS uncertainty: maximum and typical values.

Component	**Symbol**	**PEMS 23 nm (max)**
Accuracy PN-PEMS	$\varepsilon(C_{acc})$	15%
Linearity PN-PEMS	$\varepsilon(C_{lin})$	15%
Drift PN-PEMS	$\varepsilon(C_{drift})$	10%
Boundaries	$\varepsilon(boundaries)$	0%
Size	$\varepsilon(size)$	25%
Particle losses (1)	$\varepsilon(losses)$	14%
Dynamics	$\varepsilon(dynamics)$	5%
Flow	$\varepsilon(Q_{exh})$	7.5%
Density	$\varepsilon(\rho_{exh})$	1%
Distance	$\varepsilon(D)$	4%

Calibration uncertainty	$\varepsilon(C_{PEMS,cal})$	**23%**
Total PN-PEMS uncertainty	$\varepsilon(PN_{PEMS})$	**39%**
PN margin	$\varepsilon(margin)$	**34%**

(1) Particle losses values for light-duty vehicles.
CNG=Compressed natural gas; DPF=Diesel particulate filter; GDI=Gasoline direct injection; PFI=Port fuel injection.

Source: JRC 2021

The 23 nm PEMS calibration uncertainty was calculated to be 23%. The total uncertainty measuring at the tailpipe was calculated to be around 39%,

A check for the proper operation of a PEMS is the "validation" test, where the PN-PEMS is compared to a laboratory PMP system. The combined uncertainty is 42%, which is calculated from the 39% PEMS uncertainty and 18% PMP calibration uncertainty (Giechaskiel et al., 2012b), The 42% value is close to the 50% permissible tolerance allowed in the regulation during a validation test. The 42% expected difference between PN-PEMS and PMP systems is in agreement with the 2020 validation tests presented in **section 2.3**, where all data but one was below 42%.

On the other hand, the PN margin, which takes the additional uncertainty of the PN-PEMS compared to the PMP system could be estimated by subtracting the PN-PEMS and PMP uncertainties. The difference gives 34%. **We suggest therefore that the PN margin is now set to 0.34.** The suggested margin does not need any change in the regulation, but is a more thorough assessment of the uncertainty compared to the past. Note that this value is a conservative upper limit because it assumes (i) that the particle losses are higher for the PMP systems at the dilution tunnel and (ii) that the efficiency curve of the PMP systems is lower at small and large sizes (i.e. underestimating compared to PEMS).

3.2.4 Future PN margin

There are three major contributors to the PN margin: (i) calibration uncertainties; (ii) size uncertainty; (iii) particle losses. One step in order to improve in the future could be to reduce the permissible calibration requirements for PEMS-PN equipment. However, a more holistic approach would be more efficient. Such approach would bring closer the PMP and PN-PEMS technical and calibration requirements, further reducing all contributors. This approach needs detailed development with involvement of the instrument manufacturers and is therefore out of the scope of this report. We recommend that this topic is better addressed at the PMP working group.

4 Summary of results

This report assessed the margins of the RDE (Real-Driving Emissions) regulation with data from year 2020. The data were mostly from JRC's and DG-GROW's projects, with the contribution from PEMS manufacturers and GVI (Green Vehicle Index) project.

Zero drift

The zero drift evaluation was based on 304 tests.

- The mean zero NOx drift was -0.1 ppm with a standard deviation of 1.4 ppm. Approximately 95% of the tests had drift <3 ppm.
- The mean zero CO drift was 20 ppm with a standard deviation of 28 ppm. Approximately 88% of the tests were within ±50 ppm.

EFM

The 28 EFM (exhaust flow meter) calibration certificates received from three PEMS manufacturers covering maximum flow rates from 150 kg/h to 2500 kg/h, showed that the technical requirements can change from 0.5% of full scale to 0.3% of full scale (or 3%, whatever is larger).

Experimental data of 10 laboratory and 190 on-road tests showed that, assuming that the acceleration spikes reach 75% of the EFM's full scale, the mean exhaust flow rates during urban operation range between 6.5% to 16%. These flow rates translate to 3.1-7.7% uncertainty based on the calibration certificates (or 2.0-4.6% with the stricter calibration requirements). The existing recommendation in the regulation that the maximum flow rate during a test should be at least the 75% of the EFM maximum range, should be obligatory.

Laboratory validations

Based on 52 validation tests in the laboratory, CO_2 differences between PEMS and bags (reference method that the Euro limits are based on) of <5% for CO_2 values >155 g/km were seen. For lower CO_2 values the majority of the cases was <7.5%. This value is an experimental approximation for the EFM uncertainty.

The NOx validations gave <10 mg/km differences between PEMS and bags, for emission levels <60 mg/km.

The CO validations gave differences less than 100 mg/km, lower than the permissible tolerance of 150 mg/km or 15%, whichever is larger.

The PN validations gave differences between PN-PEMS and PMP systems within 42% or 8×10^{10} p/km, whichever is larger (with one exception). Even at low levels the differences were around 50%. It should be mentioned that the validation differences include both the uncertainty of the PEMS and the reference system.

Framework for assessing the Margin

The framework for the assessment of the NOx margin was adjusted to take into account the zero drift and the time alignment uncertainty with the error propagation rule. This means that the value is not added, but taken into account with the square root of the squared sums. This change is based on more than three years of experience that the final zero drift value is random and partly the under development CEN standard for PEMS.

Based on this change, and the lower EFM uncertainty (from 10% to 7.5%), the NOx margin may be decreased already from 32% to 23%.

Reductions of the permissible tolerances (e.g. max zero drift 3 ppm instead of 5 ppm) and changes of the method for taking into account the zero drift in each individual test, as is already done in the heavy duty legislation, can further decrease the NOx margin in the future to 10%.

The framework was also modified to calculate the PN margin. Particle losses and unknown size uncertainties were added in the uncertainty estimation scheme (framework). Based on the current technical specifications, 25% size uncertainty and 14% particle losses uncertainty, the expected difference between PN-PEMS and PMP systems are 42% (PEMS uncertainty plus PMP uncertainty) and the PN margin (PEMS uncertainty minus PMP uncertainty) is 34% (0.34). Thus a reduction from the current margin of 0.50 to 0.34 is possible.

5 Summary of recommendations

Based on the 2020 data review report the following are recommended for the margins and the changes in the implementing regulation:

5.1 Margins proposal

The report supports the reduction of the NOx and PN margins without the need of any change in the regulation:

- The NOx margin can be reduced to 0.23.
- The PN margin can be reduced to 0.34.

5.2 Changes in Commission Regulation (EU) 2017/1151

The report supports some changes in the regulation that will further decrease the uncertainty and the resulting NOx margin.

5.2.1 EFM specifications

- The current text “The accuracy of the EFM, defined as the deviation of the EFM reading from the reference flow value, shall not exceed ± 3 percent of the reading, 0,5 % of full scale or ± 1,0 per cent of the maximum flow at which the EFM has been calibrated, whichever is larger”, should be replaced “The accuracy of the EFM, defined as the deviation of the EFM reading from the reference flow value, shall not exceed ± 3 percent of the reading, 0,3 % of full scale”.
- The current recommendation “It is recommended to select the EFM in order to have the maximum expected flow rate during the test covering at least 75 % of the EFM full range”, should be a requirement.

5.2.2 Zero drift requirements

- The NOx zero drift should be reduced from 5 ppm to 3 ppm.
- The NOx zero drift of each individual trips should be (linearly) corrected before the calculation of the emissions, following the method from the heavy-duty regulation.

5.2.3 Laboratory validations:

- The CO_2 permissible tolerance should be reduced to 7.5% (from 10%) or 10 g/km (whichever is larger).
- The CO permissible tolerance should be reduced to 100 mg/km (from 150 mg/km).
- The NOx permissible tolerance should be reduced to 10 mg/km (from 15 mg/km) or 12.5% (whichever is larger.
- The PN permissible tolerance should be reduced to 42% (from 50%) or 8×10^{10} p/km (whichever is larger.

5.3 Future margins

After implementation of the new changes in the regulation as suggested above, the margin framework can be used to calculate the future margin, which would bring the future NOx margin down to 0.10.

Regarding the future PN margin, more work needs to be done in reducing the tolerances of the technical and calibration specifications of the PN-PEMS and possibly the PMP reference systems. The topic should be addressed at the PMP group.

References

Akard, M., Gramlich, N., Nevius, T., and Porter, S. *Comparison of real-world urban driving route PEMS fuel economy with chassis dynamometer CVS results*. **2019**. SAE 2019-01-0762. doi:10.4271/2019-01-0762.

CEN/TC 301, 2018. Road vehicles. *Portable emission measuring systems (PEMS) performance assessment*. Proposal for European Standard, **2018**.

Giechaskiel B., Riccobono F., Mendoza P., Grigoratos T.; *Particle number (PN) - portable emissions measurement systems (PEMS): heavy duty vehicles evaluation phase at the Joint Research Centre (JRC)*, **2016**, EUR 28256 EN, doi: 10.2788/052796

Giechaskiel, B., Clairotte, M., Valverde, V. and Bonnel, P., *Real driving emissions: 2017 assessment of portable emissions measurement systems (PEMS) measurement uncertainty*., JRC report EUR 29138, Publications Office of the European Union, Luxembourg, **2018a**, doi:10.2760/127122.

Giechaskiel, B., Clairotte, M., Valverde-Morales, V., Bonnel, P., Kregar, Z., Franco, V., Dilara. P. *Framework for the assessment of PEMS (portable emissions measurement systems) uncertainty.* Environ. Res., 166, 251-260, **2018b**, doi: 10.1016/j.envres.2018.06.012

Giechaskiel, B., Arndt, M., Schindler, W., Bergmann, A., Silvis, W., Drossinos, Y., *Sampling of non-volatile vehicle exhaust particles: a simplified guide.* SAE International Journal of Engines 5, 379–399, **2012a**. https://doi.org/10.4271/2012-01-0443

Giechaskiel, B., Mamakos, A., Andersson, J., Dilara, P., Martini, G., Schindler, W., Bergmann, A. *Measurement of automotive nonvolatile particle number emissions within the European legislative framework: a review.* Aerosol Science and Technology 46, 719–749, **2012b**, doi: 10.1080/02786826.2012.661103

Giechaskiel, B., Lähde, T., Drossinos, Y. *Regulating particle number measurements from the tailpipe of light-duty vehicles: The next step?* Environ. Res., 172, 1–9, **2019a**. doi: 10.1016/j.envres.2019.02.006

Giechaskiel, B., Joshi, A., Ntziachristos, L., Dilara, P. *European regulatory framework and particulate matter emissions of gasoline light-duty vehicles: a review.* Catalysts 9, 586, **2019b**. doi: 10.3390/catal9070586

Khan, M.Y., Patel, M., Scott, N., Liew, C.M. et al. *Assessment of in-use solid particle number measurement systems against laboratory systems*. **2020**. SAE 2020-01-5074. doi: 10.4271/2020-01-5074

Otsuki, Y., Nakamura, H., Kojima, K., Kondo, K., Haruta, K. *Investigation in calibration procedures for portable and stationary solid particle number measurement systems.* **2019**. SAE 2019-01–1187. doi 10.4271/2019-01-1187

Schriefl, M.A., Nishida, R.T., Knoll, M., Boies, A.M., Bergmann, A. *Characterization of particle number counters based on pulsed-mode diffusion charging.* Aerosol Science and Technology 54, 772–789, **2020**. doi: 10.1080/02786826.2020.1724257

Valverde, V., Giechaskiel, B., Carriero, M. *Real driving emissions: 2018-2019 assessment of portable emissions measurement systems (PEMS) measurement uncertainty*, EUR 30099 EN, Publications Office of the European Union, Luxembourg, **2020**, ISBN 978-92-76-16365-7, doi:10.2760/06282, JRC114416

Vu, D., Szente, J., Loos, M., and Maricq, M. *How well can mPEMS measure gas phase motor vehicle exhaust emissions?* **2020**, SAE 2020-01-0369. doi:10.4271/2020-01-0369

List of abbreviations and definitions

C.I.	Compression Ignition
CF	Conformity Factor
CNG	Compressed Natural Gas
CPC	Condensation Particle Counter
CVS	Constant Volume Sampling
DC	Diffusion Charger
EFM	Exhaust Flow Meter
EU	European Union
FS	Full Scale
GDI	Gasoline Direct Injection
GMD	Geometric Mean Diameter
GVI	Green Vehicle Index
ISC	In-Service Conformity
JRC	Joint Research Centre
MPE	Maximum Permissible Error
NCAP	New Car Assessment Program
P.I.	Positive Ignition
PCRF	Particle Concentration Reduction Factor
PEMS	Portable Emissions Measurement System
PFI	Port Fuel Injection
PMP	Particle Measurement Programme
PN	Particle Number
PNC	Particle Number Counter
RDE	Real-Driving Emissions
TP	Tailpipe
VPR	Volatile Particle Remover
WLTC	Worldwide harmonised Light vehicles Test Cycle

List of figures

List of tables

Annexes

Annex 1. Detailed explanation of the updated JRC NOx margin framework

In the Guide to the Expression of Uncertainty in Measurement (GUM), Type A evaluation of uncertainty is defined as the method of evaluation of uncertainty by the statistical analysis of series of observations (experimental approach). Type B evaluation of uncertainty is defined as the method of evaluation of uncertainty by means other than the statistical analysis of series of observations (theoretical approach). This annex, based on Type B assessment, will estimate the PEMS measurement uncertainty under chassis dynamometer or on-road conditions based mainly on the input from the technical requirements in the regulation and/or data (experiments or input from previous years). The margin corresponds to the PEMS measurement uncertainty considering the inaccuracy of the reference method (i.e. CVS).

The emissions (e.g. of NOx), E, are calculated with the following equation:

$$E = \frac{\sum u\, c_i\, q_i}{d}$$

Where:

u is the ratio of the density (e.g. of NOx) and the overall density of the exhaust (constant for a fuel),

c_i is the pollutant (e.g. NOx) instantaneous measured concentration in the exhaust at time i [ppm],

q_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 emissions (e.g. of NOx) uncertainty (ε_E) (in %), the error propagation rule for multiplication and division can be used. This assumes errors are random and uncorrelated to each other, which is a valid assumption for a PEMS setup (e.g. the error of the GPS is not correlated to that of the analyser). The constant u does not contribute to the relative uncertainty ε_E: Due to the real time nature of the signals, an uncertainty due to time misalignment and dynamics (ε_t) has to be considered:

$$\varepsilon_E = \sqrt{\varepsilon_q^2 + \varepsilon_c^2 + \varepsilon_d^2 + \varepsilon_t^2}$$

where

ε_q is the relative uncertainty of the exhaust mass flow rate [%],

ε_c is the relative uncertainty of the pollutant (e.g. NOx) concentration [%],

ε_d is the relative uncertainty of the distance [%].

ε_t is the relative uncertainty of the time misalignment and dynamics [%].

In order to find the uncertainty of each component of the equation, the technical specifications can be taken into account (e.g. accuracy, linearity etc.). The most important requirements prescribed for the analysers and the exhaust flow meter (EFM) that have direct impact on the PEMS measurement uncertainty are (sources of uncertainty):

- Accuracy (at a specific concentration).
- Non-linearity (differences at low – high concentrations).
- Drift over time for zero and maximum concentration (span).

The effect of test/environmental conditions, such as temperature, altitude, vibration (called boundary conditions in the regulation) (δ_B) and the zero drift ($\delta_{c,drift}$) were calculated as absolute uncertainties, The (absolute) uncertainty symbol is δ. To convert the relative uncertainty ε to absolute uncertainty δ, the emission level L is needed. To calculate the maximum uncertainty the emission limit of 80 mg/km was used. Based on the experience of >3 years, these errors are also random and can be taken into account with the error propagation rule. The final instrument uncertainty $\delta_{F,E}$ [mg/km] is calculated as:

$$\delta_{E,F} = \sqrt{(\varepsilon_E L)^2 + \delta_B^2 + \delta_{c,drift}^2}$$

The margin is calculated from the instrument uncertainty subtracting the CVS uncertainty.

$$\delta_m = \sqrt{\delta_{E,F}^2 - \delta_{CVS}^2}$$

The expanded uncertainty $\delta_{m,exp}$ with k=2, corresponds to a confidence interval of 95%.

$$\delta_{m,exp} = k\ \delta_m$$

In the regulation, the technical requirements are the Maximum Permissible Error (MPE). Assuming normal distribution of errors, the conversion factor 2 can be used to convert the MPE to uncertainty. **Table A1** summarises the sources of uncertainty, the MPE (Maximum Permissible Errors) as given in the regulation and the final used values.

A simplified schematic of the uncertainties with the input of **Table A1** is shown in **Figure A1**. The result is NOx margin 0.23 (23.5%).

The zero drift uncertainty in mg/km depends on the exhaust flow rate. Assuming 8 mg/km drift of 1.5 L engines (instead of 16 mg/km for 3 L engines), the NOx margin is 0.16 (15.8%). Using k=3 (99% confidence interval), the margin is 0.24 (23.7%), thus the 0.23 proposed margin, even though has confidence interval of 95% for 3 L engines, it has almost 99% for 1.5 L engines. It should also be mentioned that the 7.5% EFM uncertainty for large engines is typically much lower (estimated to be 5% from the 2020 data), thus also for large engines the 0.23 margin has at last 95% confidence interval.

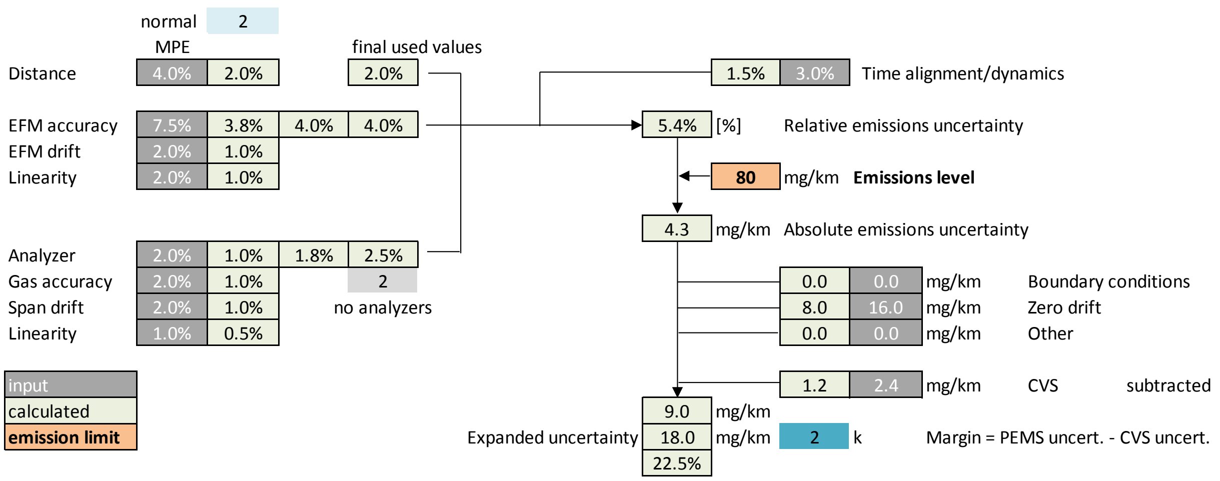
Table A1. Uncertainty sources and used values.

Uncertainty source	symbol	MPE	used
EXHAUST FLOW METER			
EFM accuracy	$\varepsilon_{q,acc}$	3%	4% (=7.5%/2)
EFM drift	$\varepsilon_{q,drift}$	2%	1%
EFM linearity	$\varepsilon_{q,lin}$	2%	1%
GAS ANALYSERS			
Analyser accuracy	$\varepsilon_{c,acc}$	2%	1%
Analyser linearity	$\varepsilon_{c,lin}$	1%	0.5%
Span drift	ε_{span}	2%	1%
Gas accuracy	ε_{gas}	2%	1%
OTHER			
Dynamics	ε_{t}	3%	1.5%
Distance	ε_{d}	4%	2%
Boundary conditions	δ_{B}	Included in zero drift	0 mg/km
Zero drift	$\delta_{c,drift}$	5 ppm	16 mg/km

MPE=Maximum Permissible Error.

Source: JRC 2021

Figure A1. Updated JRC NOx margin framework (showing more details on how to reach the expanded uncertainty).



Source: JRC 2021.

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