



Traceable uncertainty of exhaust flow meters embedded in portable emission measurement systems

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Abstract

Exhaust flow meters (EFM) measure the amount of exhaust gas during type approval tests of diesel and petrol fuelled vehicles. They are embedded in portable emissions measurement systems (PEMS), together with analysers which measure pollutants in the exhaust gas. The European Union adopted Real Driving Emissions legislation in 2016 - 2018 in which real-driving emission tests using PEMS are a requirement for type approval of vehicles. SI-traceable calibration of the exhaust flow meter and analysers in PEMS for real driving conditions is a challenging task. Currently a conformity factor is employed to acknowledge the fact that the calibration of PEMS components in accurately controlled laboratory conditions does not consider all factors contributing to overall PEMS uncertainty in a real-driving type approval test. The EFM uncertainty is a dominant uncertainty component in PEMS measurements. A need exists for traceable quantitative uncertainty characterization not limited to transients in the exhaust flow, flow pulsations, gas composition, temperature, and drift of the flow meter. As part of the European Metrology Programme for Innovation and Research (EMPIR) research project 19ENV09 "MetroPEMS", this paper (I) presents a generic uncertainty analysis of the EFM using state-of-the-art knowledge, and (II) presents first measurement results of quantitative and (partly) traceable assessment of factors contributing to the overall uncertainty of the EFM. While some experimental results show that the EFM matches legislative accuracy requirements, other experiments indicate that this is not generically proven for all possible on-road conditions in which the PEMS are used.

1. Introduction

Nitrogen Oxides (NO_x) and fine particles emitted from petrol and diesel fuelled vehicles are the leading causes of air pollution. The burden of internal combustion vehicles to the environment has decreased in recent years as a result of stricter regulations and the implementation of more effective pollution control systems. However, these reductions have not been as large as anticipated due to documentary emission standards not delivering the expected reductions under real-world driving conditions. In recognition of this, legislation was recently introduced by the European Commission for on-road real driving emission (RDE) tests using portable emission measurement systems (PEMS) [1]. PEMS tests are mandatory in the type approval (TA) process for light passenger and commercial vehicles sold in the European Union since 2016. The current light duty legislation follows the procedures described in the commission regulation (EU) 2017/1151 [2], which is also known as RDE3. This legislation was amended by 2017/1154 [3] and the commission regulation (EU) 2018/1832 [4], which is also known as RDE4. The on-road tests using PEMS introduced in 2016

complemented in-laboratory TA tests for light-duty vehicles [5]. The RDE regulation was amended afterwards to introduce conformity factors for NO_x (NO and NO₂) [6] and PN [2], respectively. These conformity factors establish "not to exceed" emission limits for on-road tests compared to laboratory tests [1]. The conformity factor acknowledges the fact that the calibration of PEMS components in accurately controlled laboratory conditions does not consider all factors contributing to overall PEMS uncertainty in an on-road type approval test. Uncertainty from the exhaust flow meter (EFM) is a dominant component in the uncertainty associated with PEMS on-road emission measurements of pollutants. Quantifying the EFM uncertainty accurately and traceably is very challenging. This explains why complete metrological validation of the EFM in on-road tests is lacking.

Notwithstanding the challenging nature of traceable EFM uncertainty assessment for on-road driving conditions, studies were performed providing quantitative uncertainty information. Giechaskiel et al. [7] conclude that EFMs match the requirements of the legislation at laboratory conditions, while



attributing a 10.4 % uncertainty to the EFM under more realistic (RDE driving test) conditions. They correctly indicate that the uncertainty is higher than the RDE accuracy requirement at 3 % [4]. Giechaskiel et al. [8] obtained 28 calibration certificates from 3 leading PEMS suppliers and concluded that the calibration data fulfil the regulatory requirements, in particular the 3 % accuracy requirement for a wide range of exhaust flow rates (200 kg/h to 2500 kg/h). Giechaskiel et al. [8] further use Constant Volume Sampling (CVS) CO₂ bag validation test data, which is part of a PEMS validation test, as proxy to quantify EFM uncertainty (untraceably) and arrive at ≤ 7.5 % uncertainty of the EFM flow measurement. However, to the knowledge of the authors, a comprehensive and metrologically validated uncertainty estimation of the EFM in on-road driving conditions does not exist.

The European Metrology Programme for Innovation and Research (EMPIR) research project 19ENV09 "MetroPEMS" [1] aims to develop the necessary metrology for PEMS (EFM + chemical analysers) to support newly introduced vehicle emission legislation for on-road TA RDE testing. For the EFM specifically, it is aimed to develop application-oriented calibration procedures and uncertainty budgets for PEMS EFMs for relevant carrier gases and to investigate the effect of dynamic flow behaviour on PEMS uncertainty. The project consortium combines state-of-the art PEMS testing and traceable calibration capabilities to obtain reliable quantitative EFM uncertainty contribution information from effects such as transients in the exhaust flow rate, flow pulsations, gas composition, temperature effects, and drift of the flow meter.

In this paper a generic EFM flow measurement uncertainty analysis for on-road driving conditions is presented, using information from the current state-of-the-art as found in literature. The analysis results in a comprehensive overview of influencing variables (potentially) affecting the EFM overall uncertainty and identifies where information is lacking. Experimental results are presented that quantify the EFM uncertainty from (I) traceable ambient air calibration under accurately controlled laboratory conditions, and (II) customary CVS PEMS validation tests. Further experimental results are presented on the effect that a pulsating flow can have on the EFM error and its associated accuracy. These results are then used in combination with the EFM flow measurement uncertainty analysis to infer first interpretations on achievable traceable uncertainty in on-road test-conditions while also identifying missing uncertainty information.

2. EFM flow measurement uncertainty analysis

Instantaneous emission measurement of the PEMS is expressed as [2]:

$$m_{gas,j} = u_{gas} \cdot c_{gas,j} \cdot q_{mew,j}, \quad (1)$$

where $m_{gas,j}$ is the mass (flow rate) of the exhaust component 'gas' [g/s] (e.g., NO_x or CO₂), j is the number of the instantaneous measurement, u_{gas} is the ratio of the exhaust component 'gas' and the overall density of the exhaust (given in [2], taking into account unit conversions), $c_{gas,j}$ is the measured concentration of the exhaust component 'gas' in the exhaust [ppm], $q_{mew,j}$ is the measured exhaust mass flow rate [kg/s]. Equation (1) is then integrated by methods defined in the RDE legislation and combined with the distance measurement to arrive at final emission results expressed in g/km of a pollutant (NO_x, CO, HC, CO₂, O₂, CH₄). Clearly, Equation (1) shows that the uncertainty of the emission measurement is proportional to the uncertainty of the EFM, which explains that large overall uncertainty of the EFM will manifest as a dominant uncertainty component in PEMS measurements. In Giechaskiel et al. [7] the EFM uncertainty is set at 10.4 % of reading for a total uncertainty in the NO_x conformity factor of 23 % to 44%, which in more recent years (2020 versus 2018) was recommended to be reduced to 23 % [8] (setting the EFM uncertainty at 7.5 %).

As part of the MetroPEMS project, a literature investigation into current EFM calibration procedures and its associated measurement uncertainty was performed [9]. It indicated that current practice is to calibrate, and possibly adjust, an EFM in ISO 17025 [10] accredited (SI-traceable) calibration laboratories, typically under controlled ambient conditions using air as calibration gas. Strictly speaking, the resulting uncertainty under RDE driving conditions is unknown, given that for many of the possible influencing factors no traceable quantitative uncertainty information was obtained. The following generic EFM flow measurement mathematical model was formulated:

$$\varepsilon_{RDE,test}^{EFM} = \varepsilon_{lab}^{EFM} + \sum_{i=1}^N \frac{(\delta q)_m^i}{q_m^{EFM}} \left(1 + \frac{\varepsilon_{lab}^{EFM}}{100} \right) 100 [\%] \quad (2)$$

where $\varepsilon_{RDE,test}^{EFM}$ is the (relative) error [%] of the EFM under RDE test conditions, ε_{lab}^{EFM} is the (relative) EFM error from (SI-traceable) laboratory calibration, $(\delta q)_m^i$ is the perturbation in EFM mass flow rate reading due to influencing variable i , with a total amount of N influencing variables, and q_m^{EFM} is the EFM mass flow rate reading without the effect from the influencing variable. It is noted that it is assumed, from the literature investigation, that EFMs are adjusted after laboratory calibration, i.e.,



ϵ_{lab}^{EFM} is set to zero, and that any remaining error is taken as uncertainty of the EFM.

Table 1 shows an example uncertainty calculation using Equation 2 and uncertainty sources identified in literature [9]. The red cells indicate influencing variables which were identified in literature, without having quantitative information on the uncertainty contribution on the EFM mass flow reading. The orange cells indicate influencing variables which are studied in the project to provide lacking information. With an ϵ_{lab}^{EFM} fulfilling the legal limit of its error staying within $\pm 3\%$, and, for the sake of illustration setting all uncertainties for which no information was found (red cells) to zero, an overall EFM uncertainty at about 5% is computed. In the next section it will be shown that pulsations can influence an EFM laboratory calibration, and this effect can be on the order of 10% for ϵ_{lab}^{EFM} .

Table 1: Example uncertainty calculation for ϵ_{lab}^{EFM} at $\pm 3\%$ and setting uncertainty contributions for which no literature information was found to zero (indicated with “-“). Uncertainty sources taken from [9].

Uncertainty source	Uncertainty contribution [%] ($k = 2$)
ϵ_{lab}^{EFM}	3.5
Altitude	0.6
Backpressure	-
Clogging (of Pitot tube)	-
Drift	2.3
Dynamic flow changes/flow transients	-
Electromagnetic influence	-
Flow profile	0.0
Gas composition	-
Humidity	-
Linearity	0.6
Leakage	-
Noise	-
Precision	-
Pulsations/vibrations	0.9
Recalibration frequency	-
Response time	-
Shocks	-
Tailpipe wind	-
Ambient temperature	0.2
Gas temperature	1.2
Temperature gradient	-
Zero drift	-
Uncertainty of $\epsilon_{RDE, test}^{EFM}$ ($k = 2$)	4.5 [%]

It is noted that little quantitative information was found in the literature on the uncertainty from gas composition and no quantitative information was found on the effect from dynamic flow changes.

3. Characterizing EFM accuracy

3.1 SI-traceable calibration

In the introduction literature statements on EFM accuracy were summarized. While some of these statements are based on calibration certificates, the original calibration certificates are not shown.

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Consequently, it is not clear (I) whether instruments were adjusted, and (II) what the calibration conditions were (type of gas, pressure, temperature, humidity). In order to establish a ground truth for tests and experiments done in the MetroPEMS project, an EFM from a market leading supplier was traceably calibrated in VSL’s ISO/IEC 17025 [10] accredited gas flow laboratory. Figure 1 shows the result. Air under atmospheric pressure, at an ambient temperature of $(20.0 \pm 0.5)^\circ\text{C}$ and a relative humidity of $(45 \pm 5)\%$ was used. Flow stability is ensured as part of the traceable calibration. The Calibration and Measurement Capability (CMC) is 0.15% of gas flow rate in the measuring range $15\text{ m}^3/\text{h} - 15\,000\text{ m}^3/\text{h}$. The EFM (relative) percentage error is computed as:

$$\epsilon_{lab}^{EFM} = \frac{q^{EFM} - q^{lab}}{q^{lab}} 100 \quad [\%] \quad (3)$$

where q^{EFM} is the volumetric flow rate [m^3/h] indicated by the EFM, and q^{lab} is the reference (SI-traceable) volumetric flow rate. From Figure 1 it can be seen that EFM errors are within the legal accuracy limit (roughly $\pm 3\%$) as required by RDE [4] under controlled laboratory conditions. Observed errors are about -2% for $450\text{ m}^3/\text{h}$ and above.

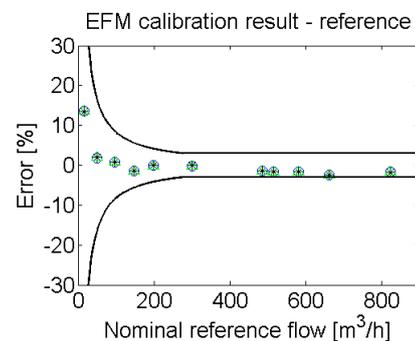


Figure 1: SI-traceable calibration result of an EFM. Symbols indicate the repeats ($N = 3$) of the calibration. CMC at 0.15%. Solid black lines indicate required accuracy from RDE [4].

3.2 Comparison with CVS

Traceable calibration of the EFM is prescribed (for TA) in RDE test procedures designed for passenger cars using a traceable standard “such as, e.g. a calibrated exhaust mass flow meter or a full flow dilution tunnel”. Currently, existing PEMS systems are validated against laboratory tests conducted with a dynamometer and the constant volume sampling (CVS) method utilizing a full flow dilution tunnel. The trip-based emissions acquired by the PEMS system are validated against the laboratory CVS results over the total trip with predetermined permissible tolerances. In the CVS method, the exhaust emissions of the test vehicle are diluted with filtered ambient dilution air, and the total diluted volume flow is set with CVS Venturis to form a constant volume flow. The samples over individual



test phases are collected into separate sample bags using a constant sample rate. By knowing the CVS system flow rate for each test phase, the mass of the measured exhaust components over a test are determined without knowing the vehicle exhaust mass flow or instantaneous emissions. Therefore, in the PEMS validation, the uncertainty of the EFM is accounted for in the total uncertainty of the PEMS device per exhaust component (c.f., Equation (1)) and not by the EFM uncertainty alone.

The determination of exhaust mass was determined at VTT's CVS test system by calculating the dilution rate between measured raw CO₂ emissions and the diluted CO₂ concentration value sampled from the CVS system. A simplified analysis was conducted by assuming that the density of the diluted exhaust mixture in the CVS is considered as constant, at 1.293 kg/m³ (at 0 °C – normalized temperature and pressure conditions). However, when measuring the instantaneous emissions in dynamic conditions, errors are introduced by variation in the time delay between the raw and the diluted sample measurements. Furthermore, during engine braking, corresponding errors are being amplified when no or very little exhaust flow takes place. As a result, when determining exhaust mass flows with a CVS system, most of the errors are caused by the dynamic behaviour in the exhaust flow. In addition, the measurement of the exhaust mass flow is not fully traceable in steady flow conditions either, despite the fact that the time related errors may be neglected. The EFM mass flow may in any case be compared with the CVS result in order to analyse the relative difference between several EFMs and the calculated exhaust mass by the CVS system.

In VTT's laboratory tests a real vehicle was operated on a chassis dynamometer. Two EFMs, one of which was used in the SI-traceable calibration (c.f., Figure 1), were attached downstream of the exhaust gas flow from the vehicle, between the vehicle tail pipe and the CVS system. The complete PEMS system was validated according to the WLTP protocol, meanwhile steady flow conditions were used for comparing the CVS results with the two EFM mass flow rate readings. Due to the known challenges in dynamic conditions, no direct comparison over the WLTC-tests for the EFMs are included in this study. For the steady flow tests, two different CVS-flow rates were used for each steady flow condition.

Table 2 shows relative errors of CVS flow rate versus q^{EFM} as determined in steady flow tests. For eight results out of twenty, relative errors are > 3 %. Note that the legal limit on the EFM accuracy is set roughly at ± 3 % of flow rate. Furthermore, a significant difference between the relative errors of the two EFMs was found throughout the tested flow FLOMEKO 2022, Chongqing, China

scale. When comparing the two EFM units, the results indicate that the largest relative differences were found for the lower exhaust flow rates, and the largest difference between the two EFMs is at ± 8 %, occurring at the lowest CVS setting and at exhaust flows corresponding with vehicle idle conditions. The relative errors between CVS and the EFM of Table 2 were computed using the definition of Equation (3), where q^{lab} now corresponds to the CVS flow rate.

Table 2: Relative errors of two EFMs with respect to the CVS flow rate in steady flow tests. Values reported are at normalized conditions (temperature at 0 °C).

CVS flow setting	CVS flow rate		Dilution rate	Relative error EFM 1	Relative error EFM 2
	m ³ /min	m ³ /h			
2.77	33.0	42.7	5.0	-2 %	6 %
2.77	60.1	77.7	2.8	-3 %	2 %
5.53	63.5	82.1	5.2	1 %	6 %
5.52	127.5	164.9	2.6	7 %	7 %
8.20	123.3	159.5	4.0	1 %	2 %
8.22	191.8	248.0	2.6	2 %	6 %
10.01	191.0	247.0	3.1	1 %	4 %
10.07	251.2	324.8	2.4	0 %	5 %
11.74	236.0	305.1	3.0	0 %	3 %
11.77	333.6	431.4	2.1	5 %	3 %

It is observed that relatively close flow points (e.g., 159.5 kg/h and 164.9 kg/h) acquired with different CVS flow settings can result in different errors of the exhaust mass flow rate. This can be explained by different CVS settings influencing the underpressure at the tailpipe (Figure 2). The changes in backpressure may influence vehicle behaviour, as a reduced tailpipe back pressure may increase the air flow through the engine. This effect suggests that the CVS system flow settings may introduce additional uncertainty in the PEMS validation if too high or too low flow settings are being implemented. The effect could possibly be avoided by pursuing reduction of factors influencing the pressure differences over the ambient air filters that affects the CVS backpressure. The above suggests that further work into calibration uncertainty of CVS validations of EFMs needs to be done in order to enable traceable calibrations with this method.

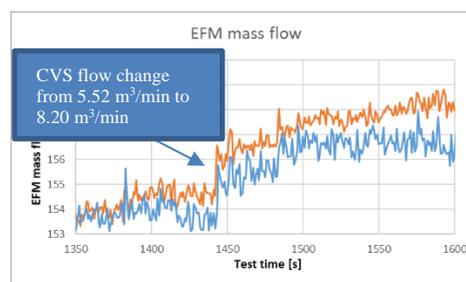


Figure 2: EFM mass flow traces with CVS flows at around 5.52 m³/min and at around 8.20 m³/min for a constant vehicle load.

4. Influence on EFM from flow pulsations

During the traceable calibration of the EFM, the 0.1 s EFM output data was continuously analysed. It was found that initially, due to the installation of the EFM, strong flow pulsations were present. This was mitigated to ensure steady flow conditions for the calibration of which the result is shown in Figure 1. Figure 3 shows the (flow rate dependent) pulsating flow (blue) and the flow with which the EFM was calibrated (black) versus time, as recorded by the EFM. An exploded view indicates a 1 s periodicity in the flow pulsations.

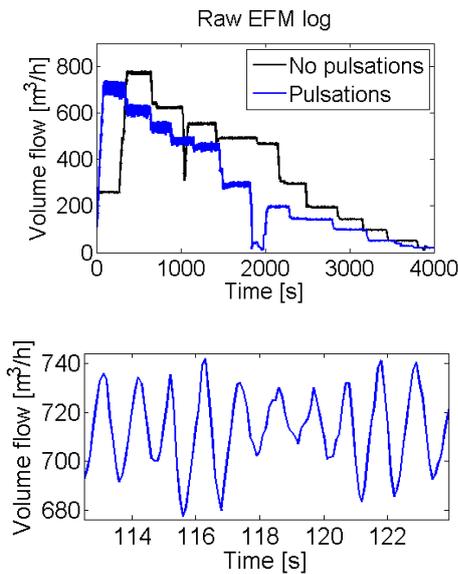


Figure 3: Raw EFM log output indicating flow rate dependent pulsations (top, blue) characterized by a periodicity of about 1 s (bottom).

Figure 4 shows the calibration result with the pulsating flow. A strong (i.e., > 10 %) effect on ε_{lab}^{EFM} is observed at the largest flow rate. Furthermore, the differences in repeats increase with flow rate and are on the order of a few percent at the larger flow rate. The corresponding Type A uncertainty is of the same order given the relatively small CMC at 0.15 %.

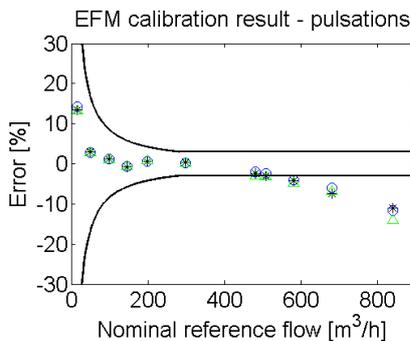


Figure 4: Calibration result of EFM when introducing flow pulsations. Symbols indicate the repeats ($N = 3$) of the calibration. Solid black lines indicate required accuracy from RDE [4].

5. Discussion

In order to arrive at traceable uncertainty of the EFM for on-road RDE test conditions, all unknown uncertainty sources should be (traceably) quantified or excluded reliably as a contributing factor. From the results presented it can be inferred that in an optimistic scenario, the RDE accuracy threshold of the EFM can be met, when there are no significant uncertainty contributions other than the error of the EFM during traceable calibration. In other scenarios, e.g., where pulsating flow has a strong effect on the EFM uncertainty (either in the lab or during a RDE test), the EFM uncertainty can be larger than the RDE accuracy threshold (at roughly $\pm 3\%$) and the current uncertainty employed for the determination of the conformity factor (say at 8 %). It can be speculated that a pulsating flow in a traceable laboratory calibration is not noticed, or the EFM is erroneously adjusted to compensate for errors introduced by the pulsating flow, that may be absent in an actual RDE test. This would then lead to a significant uncertainty source (e.g., at about 10 %, $k = 2$). From conversation with the supplier of the EFM, it was confirmed that no flow pulsations are observed in on-road conditions (except at idle conditions). Figure 5 shows that most of the flow rate in these typical on-road tests occurs below the flow rate at which a significant effect from pulsating flow was observed in the Figure 4 calibration (representative densities to convert mass flow rate to volume flow rate are at about 1.3 kg/m³ [2]).

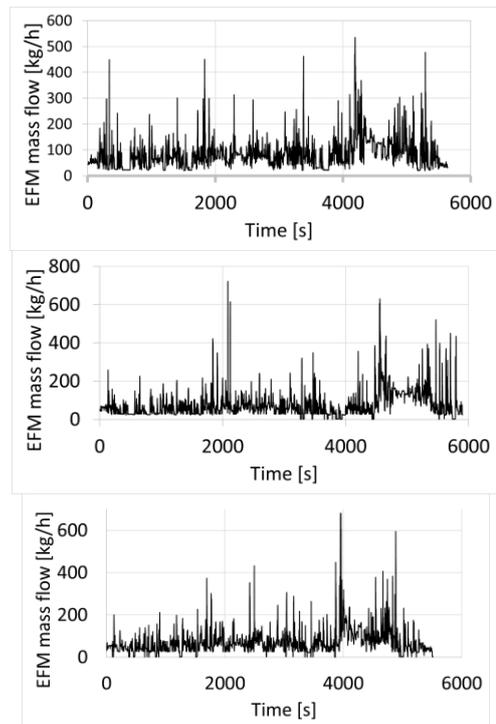


Figure 5: Measured exhaust mass flow rate [kg/h] versus time of three RDE real-driving tests.



To the best knowledge of the authors, in the current practice, comparing CVS measurements with the EFM measurements can only be an untraceable indicator of EFM uncertainty since fully traceable CVS systems do not seem to exist. Comparing relative errors from Table 2 with the SI-traceable calibration result from Figure 1 suggests that the CVS method would need to not only be made traceable, but also improved in order to achieve traceable uncertainties lower than, say, 1 % of flow rate in the EFM calibration.

6. Conclusion

While RDE requires a 3 % accuracy of the EFM [4], no SI-traceable datasets showing that this accuracy is achieved in on-road tests could be found. Further, the degree to which any adjustment of EFMs takes place is unknown from public data. The literature indicates that EFMs are calibrated, and presumably adjusted, in SI-traceable, ISO 17025 accredited, calibration laboratories under controlled ambient conditions and typically with ambient air as calibration gas. The resulting traceable uncertainty under RDE driving conditions is, strictly, unknown.

From the creation of the generic uncertainty budget for the EFM uncertainty in RDE test conditions it became clear that (traceable) uncertainty information on several influencing variables is lacking. In order to reliably quantify resulting uncertainty under RDE driving conditions all these sources should be quantitatively characterized or excluded as a significant uncertainty source.

In one experiment it was shown by SI-traceable calibration that an EFM matches the legislative accuracy requirement in controlled laboratory conditions. Results from another experiment, in which flow pulsations were introduced while keeping all other factors the same as in the first experiment, showed that the accuracy requirement was not met for flow rates above about 50 % of maximum flow rate.

Without fully traceable flow dilution tunnels the CVS method cannot be used for the traceable calibration of the EFM. This implies that this method can only be an untraceable indicator of EFM uncertainty.

Further research activities will be focussed on providing quantitative uncertainty information for influencing variables identified in the generic uncertainty budget including dynamic effects (transients) in the exhaust flow and gas composition.

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References

- [1] 19ENV09 MetroPEMS, "Publishable Summary for 19ENV09 MetroPEMS Improved vehicle exhaust quantification by portable emission measurement systems metrology," October 2020. [Online]. Available: https://www.metropems.ptb.de/fileadmin/documents/empir-2020/MetroPEMS/documents/19ENV09_Publishable_Summary.pdf. [Accessed 23 12 2021].
- [2] European Commission, "Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (RDE3)," *Official Journal of the European Union*, vol. 1151, p. 1–643, 2017.
- [3] European Commission, "Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles (RDE3)," *Official Journal of the European Union*, vol. 1154, pp. 1 - 25, 2017.
- [4] European Commission, "Commission Regulation (EU) 2018/1832 of 5 November 2018 amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) 2017/1151 (RDE4)," *Official Journal of the European Union*, vol. 1832, pp. 1 - 314, 2018.
- [5] European Commission, "Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)," *Official Journal of the European Union*, vol. 427, pp. 1 - 98, 2016.
- [6] European Commission, "Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)," *Official Journal of the European Union*, vol. 646, pp. 1 - 22, 2016.
- [7] 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," *Environmental Research*, vol. 166, pp. 251-260, 2018, <https://doi.org/10.1016/j.envres.2018.06.012>.
- [8] Giechaskiel B., Valverde V., Clairotte M., "Real Driving Emissions (RDE): 2020 assessment of Portable Emissions," EUR 30591 EN, Luxembourg: Publications Office of the European Union, 2021, ISBN 978-92-76-30230-8 (online), doi:10.2760/440720 (online), JRC124017.
- [9] M. Schakel, M. Zabihigivi and R. Pettinen, "Summary of current PEMS EFM (SI-traceable) calibration procedures and its associated measurement uncertainty for relevant carrier gases including an overview of (potentially) significant uncertainty sources in on-road emission tests," 19ENV09 MetroPEMS, 2021.
- [10] ISO/IEC 17025:2017(en), General requirements for the competence of testing and calibration laboratories, ISO, 2018.