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19ENV09 Improved vehicle exhaust quantification by portable emission measurement systems metrology (MetroPEMS)

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Partners (Lead partner in bold)	**VSL**, KIT, VTT, PTB
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1.0	9 February 2022	Draft	Menne Schakel (VSL)	First draft created. Request for feedback from KIT, VTT, PTB
2.0	23 February 2022	Updated	Menne Schakel (VSL), Wouter Stiphout (VSL)	Internal update after feedback. Typo's corrected
3.0	30 March 2022	Updated	Menne Schakel (VSL), Mitra Zabihigivi (KIT), Rasmus Pettinen (VTT)	Update following feedback from KIT and VTT. Text with 7.1 and 7.2 changed.
4.0	26 April 2022	Updated and approved	Menne Schakel (VSL), Wouter Stiphout (VSL)	Addition of text paragraph in 7.2. Acknowledgement included.

1 Contents

2 Introduction

This work was performed according to the Joint Research Project protocol of the "Improved vehicle exhaust quantification by portable emission measurement systems metrology" (shortname: MetroPEMS) project. One of the objectives of the MetroPEMS project is to develop application-oriented calibration procedures and uncertainty budgets for Portable Emission Measurement Systems (PEMS) exhaust flow meters (EFMs) for relevant carrier gases and to investigate the effect of dynamic flow behaviour on PEMS uncertainty.

This report follows from a literature investigation into the current state-of-the-art of PEMS EFM SI-traceable calibration procedures. From the literature investigation a generic EFM uncertainty budget was composed for on-road conditions. For some of the influencing variables quantitative uncertainty information could be found and incorporated into the uncertainty budget. For other influencing variables such information could not be found.

This deliverable is comprised of a definition of metrology terms chapter, followed by a brief description of the current legislative requirements, the currently employed SI-traceable calibration procedures, including a description of the EFM error and uncertainty, an overview of currently known uncertainty sources affecting the EFM error, a chapter culminating the information into a generic uncertainty budget for EFM uncertainty in on-road conditions, and finally a summary and conclusion chapter.

3 Definition of terms employed in metrology

In order to avoid confusion between the PEMS users and experts and the metrological community, definitions of measurement error, measurement uncertainty, measurement accuracy, and traceability are given following the international vocabulary of metrology [1].

Adjustment of a measuring system
Set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

Measurement accuracy
Closeness of agreement between a measured quantity value and a true quantity value of a measurand.

Measurement error
Measured quantity value minus a reference quantity value.

Measurement uncertainty
Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Metrological traceability
Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Figure 1 shows a schematic of EFM error and uncertainty.

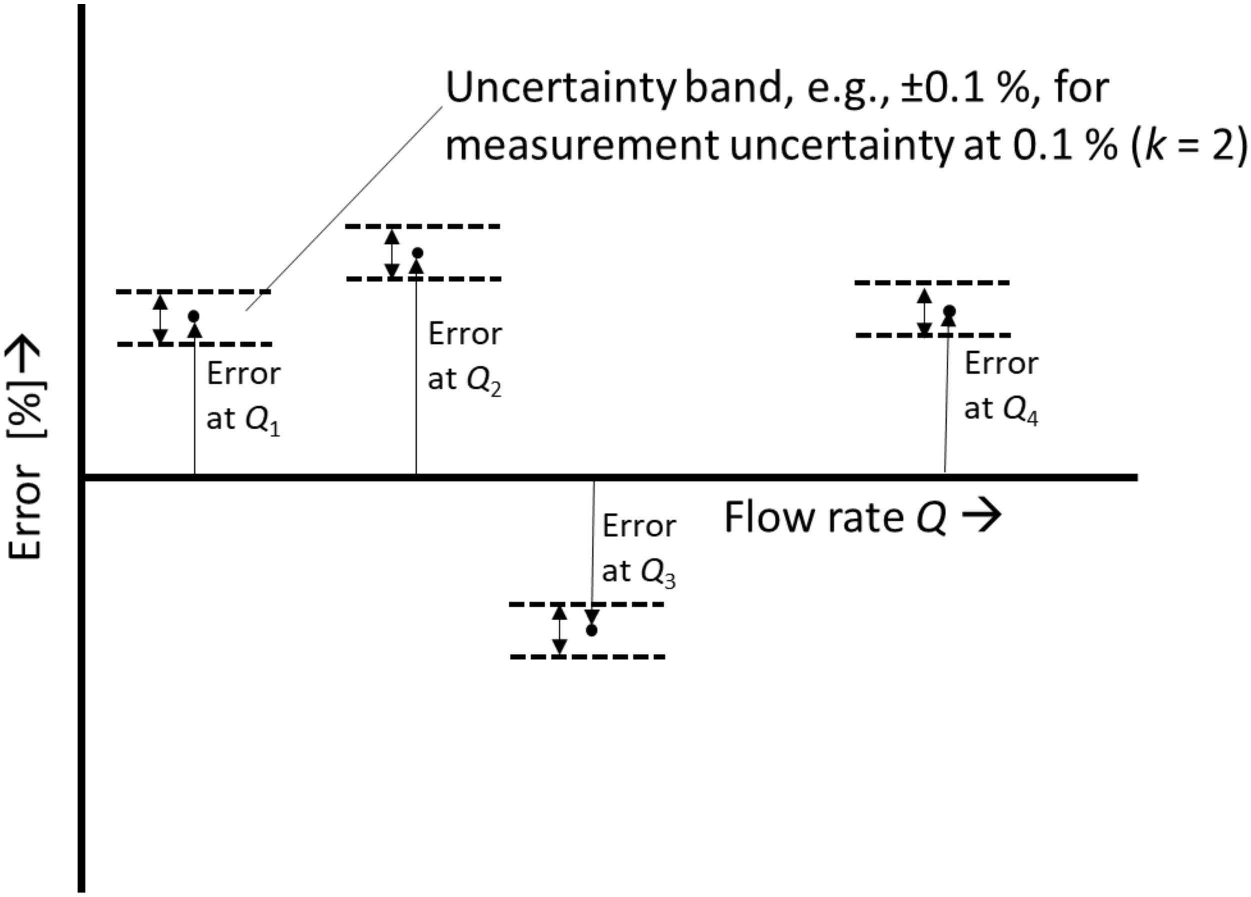

Figure 1: definition of error and uncertainty as employed in metrology.

The error is expressed as:

$$Error[\%] = \frac{q^{EFM} - q^{r}}{q^{r}} 100[\%] \qquad (1),$$

where q^{EFM} is the flow indicated by the EFM, and q^{r} is the reference flow. The units can be in terms of totalized mass (kg), mass flow rate (e.g., kg/s), and volume flow rate (e.g., m^3/h).

SI-traceable error is defined as the error of an EFM as established in a calibration against a SI-traceable reference. SI-traceable uncertainty is defined as the uncertainty of a calibration in which the error of an EFM is established against a SI-traceable reference.

Error and uncertainty are quantitative terms supplied with a calibration certificate of an instrument by an SI-traceable calibration laboratory. Accuracy is treated here as a more generic, at times qualitative, term.

4 RDE requirements

PEMS devices are used for measuring vehicle emissions in real life conditions, known as RDE tests (real driving emissions). PEMS tests are mandatory in the type-approval process for light passenger and commercial vehicles sold in the EU region since 2016. The current light duty legislation follows the procedures described in the commission regulation (EU) 2017/1151 [2], [3], which is also known as RDE3.

This legislation was amended by 2017/1154 [4] and the commission regulation (EU) 2018/1832 [5], which is also known as RDE4. RDE3 and RDE4 are taken as the basis to define the EFM requirements.

4.1 RDE EFM requirements

The required **accuracy** of the EFM is defined in RDE4, Annex III, Appendix 2 “Specifications and calibration of PEMS components and signals”, point 7.2.3 at 3 %:

“7.2.3. Accuracy

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.”

It is noteworthy that the accuracy requirement was set to a larger value from 2 % in RDE3 to 3 % in RDE4.

Traceability of the EFM is prescribed (for type approval) in RDE3, Annex IIIA, Appendix 2, 7.2.1:

“7.2.1. *Calibration and verification standards*

The measurement performance of exhaust mass flow meters shall be verified with air or exhaust gas against a traceable standard such as, e.g. a calibrated exhaust mass flow meter or a full flow dilution tunnel.”

In RDE3, Annex IIIA, point 3.1.1 it is prescribed that for type approval purposes independent measurement equipment (EFM) shall be used to determine exhaust mass flow.

Further requirements in RDE3/RDE4 apply to:

- **Installation requirements** (for complete PEMS):
  - leak-tight
  - minimization of effects from
    - electromagnetic interference
    - temperature
    - dust
    - vibrations

  RDE3, Annex IIIA, Appendix 1, 3.4.1
- **Backpressure**
  RDE4, Annex III, Appendix 1, 3.4.2
- **EFM range**: 75 % of EFM full range is maximum expected flow rate
  RDE4, Annex III, Appendix 1, 3.4.3
- **Linearity**: ≤ 2 % max
  Amendment to RDE3 [4], Annex II, Appendix 2, 3.2
- **Upstream/downstream pipe length**: max(4 diameters, 150 mm)
  RDE4, Annex III, Appendix 1, 3.4.3
- **Recalibration frequency:** ≤ 1 year
  RDE3, Annex IIIA, Appendix 2, 3.3; 7.2.2
- **Precision:** ≤ 1 per cent of the maximum flow
  RDE3, Annex IIIA, Appendix 2, 7.2.4
- **Noise:** ≤ 2 per cent of the maximum calibrated flow
  RDE4, Annex III, Appendix 2, 7.2.5
- **Zero and span drift**

RDE3, Annex IIIA, Appendix 2, 7.2.6 & 7.2.7

- **Rise time:** matching that of gas analysers and ≤ 1 second
  RDE3, Annex IIIA, Appendix 2, 7.2.8
- **Response to dynamic flow conditions:** "The gas flow rate used for the test shall cause a flow rate change of at least 60 per cent full scale of the exhaust mass flow meter…. The exhaust mass flow meter response time … shall be ≤ 3 seconds"
  RDE3, Annex IIIA, Appendix 2, 7.2.9

4.2 Not-to-exceed (NTE) values and conformity factors (CF)

In RDE3 and RDE4 (ANNEX III/Annex IIIA, 2.1), not-to-exceed (*NTE*) values are defined for a pollutant as follows:

$$NTE_{pollutant} = CF_{pollutant} \cdot EURO6_{emission,linit} \quad (2),$$

where *CF* is the conformity factor and further symbols and subscripts are taken as self-explanatory. The *NTE*-values apply to measurements from a RDE test under real driving conditions. The CF is defined as 1 + *margin*, where *margin* is a positive, real number. Thus, the *CF* accounts for the additional measurement uncertainty of PEMS relative to standard laboratory equipment. The margins are revised annually and from RDE3, Annex IIIA, 2.1.1:

"shall be revised as a result of the improved quality of the PEMS procedure or technical progress".

For the EFM, RDE3 & RDE4 do not state a value for the *CF*. The exhaust mass flow is not a pollutant in itself; however, it is a component in computing the mass emissions of pollutants.

Consequently, for computing $NTE_{pollutant}$ reliably, the accuracy of the EFM readings in actual on-road driving conditions must be known.

5 SI-traceable EFM calibration

5.1 Current practice of traceable EFM calibration procedure

The literature investigation did not yield calibration results with clearly stated SI-traceable measurement errors, uncertainties, statements on the conditions under which these calibrations are performed (e.g., by means of calibration certificates), and the manner in which the RDE requirement on traceable calibration (see section 4.1) is being fulfilled. The literature investigation did yield the indication that current practice is to calibrate, and possibly adjust, an EFM in ISO 17025 [6] accredited (SI-traceable) calibration laboratories. Typically (depending on the type of facility), SI-traceable calibrations are performed under controlled ambient conditions using ambient air as calibration gas. Typical calibration laboratory conditions correspond to atmospheric pressure and controlled temperature bands, e.g., at around 20 °C. RDE on-road moderate temperature and altitude conditions are defined as 0 °C – 30 °C and altitude ≤ 700 m, respectively. Extended conditions exceed these bands. (RDE3, Annex IIIA, 5.2, and Amendment to RDE3 [4], Annex II, 5.2.4, 5.2.5).

EFM calibration results using traceable flow dilution tunnels were not found. Laboratory equipment used in PEMS validations, such as Constant Volume Sampling, is typically not traceable [7] when operated in transient conditions.

5.2 SI-traceable EFM error and uncertainty

Giechaskiel et al. [8] 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 (accuracy) RDE requirement (see section 4.1). They observed differences between EFMs within about 10 % and indicate the difficulty of checking the accuracy in practice.

Giechaskiel et al. [7] 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 (see section 4.1), for a wide range of exhaust flow rates (200 kg/h to 2500 kg/h). While their conclusions are based on calibration certificates, calibration certificates themselves are not shown. Consequently, it is not clear (1) whether instruments were adjusted, and (2) what the calibration conditions were (type of gas, pressure, temperature, humidity). Typically (depending on the type of facility), SI-traceable calibrations are performed under controlled ambient conditions. Assuming that the calibrations were performed under ambient conditions reduced accuracy (i.e., > 3 % error) of the EFM under RDE test conditions could be expected. Giechaskiel et al. [7] further use Constant Volume Sampling CO_2 bag validation test data, which is part of a PEMS validation test, as proxy to quantify EFM uncertainty and arrive at ≤ 7.5 % uncertainty of the EFM.

González et al. [9] developed a flow meter based on a Pitot tube to measure the instantaneous average exhaust mass flow rate. They determine the Pitot factor by calibration with air under ambient conditions against a traceable laminar flow element (LFE), with stated accuracy of 0.64 % of reading. A manual from the manufacturer (Meriam) [10] describes the corrections that need to be taken into account to correct LFE flow readings for pressure, temperature, and humidity effects. No comments on the (additional) uncertainty introduced by applying the corrections could be found.

MetroPEMS partners have access to a calibration certificate of an EFM for a calibration performed under ambient conditions with air performed by an ISO 17025 [6] (SI-traceable) calibration laboratory. Measurement errors were within 2 %. The calibration certificate states that these errors are applicable after adjustment in as built state of the EFM. The datasheet specifying the technical specifications correspondingly states that the accuracy is ± 2 % of reading, (or 0.5 % of full scale, whichever is greater).

Note that in ISO 17025 7.8.4.1d [6] it is stated that results both before and after any adjustment shall be included into a calibration certificate, if available.

6 Literature overview of EFM uncertainty components

This section lists an overview of uncertainty sources as found in literature generically affecting the EFM under real driving conditions. References are included to distinguish legislative requirement/statements from literature sources based on measurements in laboratory conditions and/or real driving conditions.

Where applicable, quantification of the uncertainty is provided.

- **Accuracy**
    - 10 % - 11 % (projected under RDE test conditions, Giechaskiel et al. [8], Varella et al. [11], Giechaskiel et al. [12])

  - Giechaskiel et al. [7] obtained 28 calibration certificates from 3 leading PEMS suppliers and conclude that the 3 % accuracy requirement is met for a wide range of exhaust flow rates (200 kg/h to 2500 kg/h)
  - ≤ 7.5 % (using Constant Volume Sampling CO2 bag validation test data as proxy; Giechaskiel et al. [7])
  - 1 % (targeted with LFE; Guenther et al. [13], [14]), sometimes outside this threshold
  - Feist et al. [15] observe approximately 10 % median differences between measured intake air flow and fuel flow laboratory reference equipment and the EFM reading for a 76 mm diameter EFM and 3 % for a 102 mm diameter EFM. They state 5th percentile relative errors at -1 % and 95th percentile relative error at 11 %
  - Diep et al. [16] make crossplots between PEMS (Pitot) measurements and laboratory exhaust flow measurements (no statement on traceability of equipment), yielding a slope of 1.05 and 1.02, and state that test to test variability (between crossplots) is perhaps at ± 5 %
- **Altitude or ambient pressure**
  - 0 % effect of boundary conditions on NOx margin, but not directly on EFM (Giechaskiel et al. [7], [8])
  - 0.5 % of maximum flow mean zero error (Feist et al. [15])
  - > 0 % for unstated EFM type (European Automobile Manufacturers Association [17])
- **Backpressure**
  - Varella et al. [11] compromise between upstream and downstream pipe length (at least 4 diameters), and pressure drop by (not) reducing the tailpipe inner diameter
  - Shall not unduly increase the pressure at the exhaust outlet in a way that may influence the representativeness of the measurements (RDE4, Annex III, Appendix 1, 3.4.2)
- **Clogging (of Pitot tube)**
  - González et al. [9] note that clogging from moisture or particles should be prevented by the Pitot tube design
  - Effect from dust should be minimized (RDE3, Annex IIIA, Appendix 1, 3.4.1)
- **Drift**
  - Negligible, however set at 2 % (Giechaskiel et al [7], [8])
  - ± 0.5 % shift in error (targeted, Guenther et al. [13])
  - order 2 % shifts for J-Tec prototype exhaust meter, flow rate dependent (Guenther et al. [13])
- **EFM range**
  - 75 % of EFM full range is maximum expected flow rate (RDE4, Annex III, Appendix 1, 3.4.3)
- **Electromagnetic interferences**
  - Effect should be minimized (RDE3, Annex IIIA, Appendix 1, 3.4.1)
  - 0.3 % of maximum flow mean zero error (Feist et al. [15])
- **Flow profile & upstream/downstream pipe length**
  - 0 % effect of boundary conditions on NOx margin, but not directly on EFM (Giechaskiel et al. [7], [8])
  - 0.1 % to 0.5 % of maximum flow relative error against laboratory flow rate (Feist et al. [15])
  - González et al. [9] allow for 10 diameters of upstream pipe length and include a flow conditioner for their Pitot tube based EFM

    - González et al. [9] (Table 2) find 0.2% FS effect at idle conditions from using different downstream geometries (while upstream length and flow conditioning takes place). Differences in mass flow at idle at about 10 %
    - Varella et al. [11] include at least 4 diameters of upstream and downstream pipe lengths
    - Guenther et al. [13], [14] use 10 diameters upstream and 5 diameters downstream pipe lengths for flow conditioning
    - Max(4 diameters, 150 mm) upstream and downstream (RDE4, Annex III, Appendix 1, 3.4.3)
- **Gas composition**
    - Small for particular ultrasonic meter (unquantified statement from Guenther et al. [14])
- **GPS or distance**
    - Effect on NOx margin (4 % uncertainty), but not directly on EFM (Giechaskiel et al. [8])
    - Influencing variable on PEMS for real driving conditions (European Automobile Manufacturers Association [17])
- **Humidity**
    - Can create huge errors by condensation with particulate matter for Pitot tube based EFM (González et al. [9])
    - Influencing variable on PEMS for real driving conditions (European Automobile Manufacturers Association [17])
- **Linearity**
    - Standard error of estimate < 0.5 % of the maximum value (Giechaskiel et al. [8])
    - Average slope adjustments on the order of +4 % was reported by Feist et al. [15] for 7.6 cm and 10.2 cm diameter EFMs
- **Leaks**
    - Installation shall be leak-tight (RDE3, Annex IIIA, Appendix 1, 3.4.1)
- **Noise**
    - ≤ 2 per cent of the maximum calibrated flow (RDE4, Annex III, Appendix 2, 7.2.5)
- **Pulsations and/or vibrations**
    - 0 % effect of boundary conditions on NOx margin, but not directly on EFM (Giechaskiel et al [7], [8])
    - 0.2 % to 0.8 % of maximum flow relative error against laboratory flow rate for pulsation experiment in Feist et al. [15]
    - Negligible for vibration experiment in Feist et al. [15]
    - Effect should be minimized (RDE3, Annex IIIA, Appendix 1, 3.4.1)
    - González et al. [9] argue that pulsating flow is inherent to internal combustion engines and infer a mathematical model which includes engine speed as a variable
- **Precision**
    - ≤ 1 % of the maximum flow (RDE3, Annex IIIA, Appendix 2, 7.2.4)
- **Recalibration frequency**
    - ≤ 1 year (RDE3, Annex IIIA, Appendix 2, 3.3; 7.2.2)
- **Response time**
    - 0.1 s – 0.4 s for (reference) Ultrasonic meter (USM), within 0.5 s – 2.0 s for three other meter types comprising (another) USM, vortex shedding, and nozzle-based EFMs (Guenther et al. [14])
    - ≤ 3 seconds (RDE3, Annex IIIA, Appendix 2, 7.2.9)

  - Feist et al. [15] report 5th percentile relative errors "with respect to the median PEMS value for a given NTE (not-to-exceed, added) event, without direct reference to transient laboratory data" at -0.7 % and 95th percentile relative error at 0.6 %, whilst noting that they can be two to three times larger, and show "error surfaces" of PEMS exhaust flow rate error as % of EFM maximum flow versus PEMS median exhaust flow rate, with errors within ± 3 %
- **Shocks**
  - Effect should be minimized (RDE3, Annex IIIA, Appendix 1, 3.4.1)
- **Tailpipe wind**
  - Negligible (Feist et al. [15])
- **Temperature**
  - 0 % effect of boundary conditions on NOx margin, but not directly on EFM (Giechaskiel et al. [7], [8])
  - 0.2 % of maximum flow mean zero error (Feist et al. [15]) for ambient temperature fluctuations
  - Influencing variable on PEMS for real driving conditions (European Automobile Manufacturers Association [17])
  - Order 0.5 % - 1.0 % for unstated EFM type (indication from Guenther et al. [13])
- **Temperature gradient**
  - Influencing variable on EFM for real driving conditions (European Automobile Manufacturers Association [17])
  - Effect should be minimized (RDE3, Annex IIIA, Appendix 1, 3.4.1)
- **Zero drift**
  - Negligible, however set at 2 % (Giechaskiel et al. [7], [8])
  - Negligible, 0 kg/s before and after test (Valverde at al. [18]; resolution not stated)
  - Indication of minimal drift after 1 year of use (Giechaskiel et al. [19])
  - González et al. [9] correct for zero drift for a Pitot tube based EFM

7 EFM uncertainty in on-road conditions

7.1 Generic uncertainty budget

The term "generic" is used here to indicate that it applies to EFMs in general. The general uncertainty budget is not specific to the meter type (ultrasonic, Pitot) nor to a particular (unique) calibrated flow meter. Hence there is no measurement model that can readily be formulated based on the underlying physical principle. Rather, the uncertainty budget combines the uncertainty sources known to apply to EFMs from literature. The chapter 6 uncertainty sources are combined into a generic uncertainty budget because (1) the flow meter type about which uncertainty information is provided is not always stated, (2) a variety of flow meter types was used, (3) no calibration data(sets) applicable to a particular (set of) EFM(s) was found in the literature.

The following generic EFM flow measurement error mathematical model is formulated:

$$\varepsilon_{RDE,test}^{EFM}[\%] = \varepsilon_{lab}^{EFM}[\%] + \sum_{i=1}^{N} \frac{(\delta q)_m^i}{q_m^{EFM}} \left(1 + \frac{\varepsilon_{lab}^{EFM}[\%]}{100}\right) 100[\%] \qquad (3),$$

where $\varepsilon_{RDE,test}^{EFM}$ is the error of the exhaust flow meter (EFM) under RDE test conditions, $\varepsilon_{lab}^{EFM}$is the 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., $\varepsilon_{lab}^{EFM}$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 3. The white cells indicate influencing variables which were identified in literature for which quantitative uncertainty information was provided. 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 MetroPEMS project to provide this lacking information. With an ε_{lab}^{EFM} fulfilling the legal limit of its error staying within ± 3 %, and, for the sake of illustration setting all uncertainties for which no information was found (red cells) to zero, an overall EFM uncertainty in on-road conditions of about 5 % is computed. From the results presented it can be inferred that in this arguably optimistic scenario, the RDE accuracy threshold of the EFM can be met, if there are no significant uncertainty contributions other than the error of the EFM during traceable calibration.

Table 1: Example uncertainty calculation for ε_{lab}^{EFM} at ± 3 % and setting uncertainty contributions for which no literature information was found to zero. Uncertainty sources taken from Section 6. For setup of Table see EA-4/02 [20].

Quantity	Estimated value	Expanded uncertainty (*k* = 2)	Standard uncertainty (*k* = 1)	*k*	Sensitivity coefficient	Contribution to the standard uncertainty
ε_{lab}^{EFM} [%]	0.00	3.00	1.73	1.73	1.00	1.73
Altitude	0.00	0.50	0.29	1.73	1.00	0.29
Backpressure	0.00	0.00	0.00	2.00	1.00	0.00
Clogging (of Pitot tube)	0.00	0.00	0.00	1.73	1.00	0.00
Drift	0.00	2.00	1.15	1.73	1.00	1.15
Dynamic flow changes/flow transients	0.00	0.00	0.00	1.73	1.00	0.00
Electromagnetic influence	0.00	0.00	0.00	2.00	1.00	0.00
Flow profile	0.00	0.00	0.00	1.73	1.00	0.00
Gas composition	0.00	0.00	0.00	2.00	1.00	0.00
Humidity	0.00	0.00	0.00	2.00	1.00	0.00
Linearity	0.00	0.50	0.29	1.73	1.00	0.29
Leakage	0.00	0.00	0.00	2.00	1.00	0.00
Noise	0.00	0.00	0.00	2.00	1.00	0.00

Precision	0.00	0.00	0.00	2.00	1.00	0.00
Pulsations/vibrations	0.00	0.80	0.46	1.73	1.00	0.46
Recalibration frequency	0.00	0.00	0.00	1.73	1.00	0.00
Response time	0.00	0.00	0.00	2.00	1.00	0.00
Shocks	0.00	0.00	0.00	2.00	1.00	0.00
Tailpipe wind	0.00	0.00	0.00	2.00	1.00	0.00
Ambient temperature	0.00	0.20	0.12	1.73	1.00	0.12
Gas temperature	0.00	1.00	0.58	1.73	1.00	0.58
Temperature gradient	0.00	0.00	0.00	1.73	1.00	0.00
Zero drift	0.00	0.00	0.00	1.73	1.00	0.00
$\varepsilon_{RDE,test}^{EFM}$ uncertainty	4.50 % (*k* = 2)					
$\varepsilon_{RDE,test}^{EFM}$ =	(0.00 ± 4.50) %					

Table 2 populates the unknown uncertainty sources, indicated in red, using a random number generator to select values for $(\delta q)_m^i / q_m^{EFM}\ 100[\%]$ (*k* = 2) from a Gaussian distribution with zero mean and 1.5 standard deviation in this quantity. An overall EFM uncertainty in on-road conditions of about 9 % is computed (*k* = 2).

Table 2: Example uncertainty calculation for ε_{lab}^{EFM} at ± 3 % and randomly selecting uncertainty contributions for which no literature information was found from a Gaussian distribution with zero mean and 1.5 standard deviation $(\delta q)_m^i / q_m^{EFM}\ 100[\%]$ Uncertainty sources taken from Section 6. For setup of Table see EA-4/02 [20].

Quantity	Estimated value	Expanded uncertainty (*k = 2*)	Standard uncertainty (*k = 1*)	*k*	Sensitivity coefficient	Contribution to the standard uncertainty
ε_{lab}^{EFM} [%]	0.00	3.00	1.73	1.73	1.00	1.73
Altitude	0.00	0.50	0.29	1.73	1.00	0.29
Backpressure	0.00	1.99	0.99	2.00	1.00	0.99
Clogging (of Pitot tube)	0.00	3.04	1.76	1.73	1.00	1.76
Drift	0.00	2.00	1.15	1.73	1.00	1.15
Dynamic flow changes/flow transients	0.00	0.00	0.00	1.73	1.00	0.00
Electromagnetic influence	0.00	0.00	0.00	2.00	1.00	0.00
Flow profile	0.00	0.00	0.00	1.73	1.00	0.00

Gas composition	0.00	0.00	0.00	2.00	1.00	0.00
Humidity	0.00	0.00	0.00	2.00	1.00	0.00
Linearity	0.00	0.50	0.29	1.73	1.00	0.29
Leakage	0.00	1.22	0.61	2.00	1.00	0.61
Noise	0.00	1.39	0.69	2.00	1.00	0.69
Precision	0.00	2.01	1.01	2.00	1.00	1.01
Pulsations/vibrations	0.00	0.80	0.46	1.73	1.00	0.46
Recalibration frequency	0.00	0.15	0.08	1.73	1.00	0.08
Response time	0.00	1.75	0.88	2.00	1.00	0.88
Shocks	0.00	0.42	0.21	2.00	1.00	0.21
Tailpipe wind	0.00	0.00	0.00	2.00	1.00	0.00
Ambient temperature	0.00	0.20	0.12	1.73	1.00	0.12
Gas temperature	0.00	1.00	0.58	1.73	1.00	0.58
Temperature gradient	0.00	4.81	2.78	1.73	1.00	2.78
Zero drift	0.00	0.00	0.00	1.73	1.00	0.00
$\varepsilon_{RDE,test}^{EFM}$ uncertainty	8.84 % (*k* = 2)					
$\varepsilon_{RDE,test}^{EFM}$ =	(0.00 ± 8.84) %					

It is noted that since underlying datasets leading to the uncertainty statements found in literature were often not readily available, and since they pertain to different EFM flow meter (types), no assessment of correlations between uncertainty sources (e.g., flow profile and ε_{lab}^{EFM}) could be made.

It is further 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. The latter was included in the generic uncertainty budget since the MetroPEMS project partners and its stakeholders have identified dynamic flow changes as one of the uncertainty sources that need to be better characterized.

7.2 SI-traceable calibration of EFM and its uncertainty for relevant carrier gases

As described in section 5.1 the SI-traceable calibration is performed using ambient air under ambient conditions. In on-road test conditions, or in chassis dynamometer tests, the gas composition will be different in terms of its constituents (to contain NO, NO_x, CO, CO_2, HC, CH_4, H_20 and fine particles), temperature, pressure, and correspondingly, its density and viscosity. In general terms, this will affect the flow meter response, with concomitant additional uncertainty, and the behavior will be dependent on the flow meter type.

The fact that little quantitative information was found in the literature on the uncertainty of the EFM from gas composition (see section 6) indicates that more information is needed to quantify this uncertainty source.

Uncertainty analysis was performed for an averaging Pitot tube EFM. The following model, modified from Dobrowolski and Kabicinski [21], is applicable:

$$q_m^{EFM} = KA\rho\sqrt{\frac{2\,\Delta p}{\rho}} \quad (4),$$

where q_m^{EFM} is the EFM mass flow rate reading, A is the cross-sectional area of the EFM pipe, ρ is the exhaust gas density, and Δp the differential pressure measured by the averaging Pitot tube EFM. The flow coefficient K accounts for non-ideal conditions [22], (i.e., K = 1 in ideal conditions). It comprises (corrections for) effects from flow blockage, flow profile, nonlinearity, compressibility, and higher flow velocities [21]. Equation 4 yields the valuable insight that density uncertainty directly affects the uncertainty of the EFM mass flow rate. Since the effects covered by K involve the Reynolds and Mach number, the fluid viscosity and speed-of-sound also affect q_m^{EFM}. The different composition of the exhaust gas in on-road tests with respect to that used in (air) laboratory ambient calibration conditions can result in additional uncertainty of the EFM mass flow reading. This also holds for the different pressure, temperature, and humidity conditions in on-road tests with respect to the conditions under laboratory ambient calibration conditions.

Equation 3 was combined with RDE test data and thermodynamic modelling to quantify the density difference between air and exhaust gas density at laboratory conditions and RDE test conditions. Results are summarized in Table 3. Simplified gas compositions were used. It is seen that:

1. The density of the idealized exhaust gas is about 4 % higher than that of idealized ambient air.
2. Under RDE test conditions, with temperatures at 600 °C, the density is much smaller than under ambient conditions.

In equation 4 the density ρ converts volume flow rate to mass flow rate, the latter quantity is needed as prescribed in the RDE [2]. Density also appears in the denominator of the fraction in the square root, hence effectively any density error in the density will translate into a square-root dependent error in EFM mass flow rate. For this numerical example, one arrives at about 2 % of EFM error from having a different composition in RDE test conditions than in an air calibration. Both observations indicate that the density needs to be accurately determined. When computed from pressure and temperature, the uncertainties in these quantities will propagate into the mass flow reading uncertainty. As an example, taking typical EFM uncertainties at 2 mbar (k = 2) for pressure measurement, and at 1.5 °C (k = 2) for temperature measurement, it was found that the resulting combined uncertainty in the density estimation is at about 0.5 % of density at ambient laboratory conditions and at 0.3 % of density at typical RDE test conditions.

Table 3: Simplified compositions for RDE test exhaust gas composition and for ambient air. Corresponding computed densities are shown. Thermodynamic modelling was performed using NIST's REFPROP [23].

Simplified RDE test exhaust gas composition						
N_2 [mol %]	CO_2 [mol %]	H_2O [mol %]	O_2 [mol %]	CO [mol %]	CH_4 [mol %]	
78.10	12.00	8.64	0.60	0.60	0.06	
Density [kg/m^3] at 20 °C; pressure at 1.013 bara			1.253			
Density [kg/m^3] at temperature* 600 °C; pressure* at 1.013 bara			0.415			
Simplified ambient air composition**						
N_2 [mol %]	CO_2 [mol %]		O_2 [mol %]			Ar [mol %]
78.0878	0.04		20.9390			0.9332
Density [kg/m^3] at 20 °C; pressure at 1.013 bara			1.205			
Density [kg/m^3] at at temperature* 600 °C; pressure* at 1.013 bara			0.399			

* Typical values from RDE-test at KIT.
** See Table 1 in [24]. Value for N_2 adjusted.

Stationary flow CVS validations can be made traceable. In [7] it is stated that (independent) laboratory measurements of the exhaust mass flow typically have uncertainties of the same size as those of the EFM mass flow reading. To estimate the uncertainty for CVS validations of the EFM, an uncertainty assessment should be made, e.g., comprising uncertainty from pressure, temperature, humidity, gas composition, measurements and from any equation-of-state used for the density computation.

7.3 Relation SI-traceable calibration of EFM to on-road emission tests

In order to arrive at completely traceable uncertainty of the EFM for on-road RDE test conditions, all unknown uncertainty sources would need to be traceably quantified or excluded reliably as a contributing factor. Given the current metrological infrastructure, this is a challenging task (c.f., section 5.1).

The degree to which any adjustment of EFMs takes place is unknown from public data. Some literature data was found for the magnitude of drift. In current practice, typically, EFMs are calibrated each year as part of annual service of PEMS equipment. The lack of publicly available data on adjustment and drift of the annual calibration results limits the possibility to provide accurate uncertainty estimates for ε_{lab}^{EFM}in the generic uncertainty budget. Effectively, the uncertainty estimate of ε_{lab}^{EFM} is dictated by the legal requirement of (say) ε_{lab}^{EFM} staying within ± 3 % for each (re)calibration, and taking that value as the magnitude of uncertainty. In other words, since the values of ε_{lab}^{EFM} are not known from publicly available literature, a rectangular distribution for its value is chosen in the generic uncertainty budget. The ± 3 % was chosen based on literature indications cited above. Since many of the literature sources define upper bounds for the magnitude of uncertainty sources in on-road conditions mostly as percentages of q_m^{EFM}

reading, without specifying the value on $(\delta q)_m^i$, the final result for $\varepsilon_{RDE,test}^{EFM}[\%]$ is set at zero with an uncertainty estimate defined by these upper bounds.

Employing equation 3, and using ε_{lab}^{EFM}= 0 to indicate how the current SI-traceable calibration (of ε_{lab}^{EFM}) relates to on-road emissions tests, one arrives at:

$$\varepsilon_{RDE,test}^{EFM}[\%] = \sum_{i=1}^{N} \frac{(\delta q)_m^i}{q_m^{EFM}}\, 100[\%] \qquad (5).$$

It can then be seen that none of the uncertainty sources leading to $(\delta q)_m^i \neq 0$ in on-road conditions can be traceably and rigorously determined during the test unless they are simulated properly in fully traceable test benches.

7.4 Obtaining quantitative uncertainty information from the MetroPEMS project

The MetroPEMS project partners are targeting to quantify the fields marked orange in Table 1 and Table 2 in the timeframe 2022 – 2023 using the following calibration and PEMS test benches and test equipment:

- SI-traceable calibration of EFM under controlled ambient conditions using ambient air as calibration gas.
- SI-traceable calibration under controlled ambient conditions with pulsating flow.
- CVS stationary flow operation.
- (High temporal resolution) analysers for air humidity, CO, CO_2, NO, and NO_x.
- Transient dynamometer test bench.
- (High temporal resolution) traceable fuel flow sensor.
- PEMS CO_2-measurement.
- Dedicated test benches for elevated temperature tests.

It will be endeavoured to use the traceably calibrated EFM in untraceable test benches. Traceability in dynamic flow conditions, for example as dictated by the test cycle employed, can not be inferred from the SI-traceable calibration of the EFM since this calibration is performed under stationary flow conditions.

8 Summary and conclusion

While RDE4 requires a 3 % accuracy of the EFM, 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 study 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 uncertainty under RDE4 driving conditions is, strictly, unknown. Literature was found in which the EFM uncertainty was quantified using untraceable reference laboratory equipment, such as in the Constant Volume Sampling method. For the assessment of the conformity factor, which accounts for the additional measurement uncertainty of PEMS relative to standard laboratory equipment [4], the combined (total) uncertainty is set at about 8 % - 10 % [7], [8]. A list of uncertainty components applicable to RDE driving conditions, as identified from the literature study, was provided in section 6 of this report. Some literature sources provide quantification of uncertainty sources. Uncertainty components known or thought to affect the EFM in on-road conditions were comprised into a generic uncertainty budget. Since not all uncertainty sources can be quantified from literature, it is not possible to make reliable statements on EFM uncertainty in on-road conditions based on this work. In order to reliably quantify resulting uncertainty under RDE driving conditions all the uncertainty sources for which no quantitative information is available should be (traceably) quantified or excluded reliably as a contributing factor. A brief list was given on where the MetroPEMS project is targeting to provide lacking EFM uncertainty information.

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