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RESEARCH

Traceable Uncertainty of Exhaust Flow Meters Embedded in Portable Emission Measurement Systems

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Abstract
Portable emissions measurement systems (PEMS) are used in the type approval tests of diesel- and petrol-fuelled light-duty vehicles. PEMS measure the amount of pollutants emitted during on-road, real driving, and testing of a vehicle. PEMS are comprised of gas analyzers, which measure the concentration of pollutants in the exhaust gas, and exhaust flow meters (EFMs), which measure the amount of emitted exhaust gas during an on-road test. With the adoption of the real driving emissions (RDE) legislation in 2016–2018, usage of PEMS during on-road tests became mandatory in the European Union for the type approval of light-duty vehicles. For accurate assessment of pollutant emissions, SI-traceable calibration of PEMS equipment is required, which is typically performed under the carefully controlled conditions of a calibration laboratory. However, when using the PEMS equipment in real driving conditions on the road, additional factors contribute to the measurement uncertainty with respect to the laboratory measurement uncertainty as established during the SI-traceable calibration. For this reason, the RDE prescribes the usage of conformity factors to account for additional measurement uncertainty in real-driving-type approval tests. The pollutant emissions measurements are a combination of the gas analyzer measurements and the EFM flow measurement. The EFM measurement uncertainty contributes strongly to the overall pollutant emissions measurement uncertainties. Further, the EFM measurement uncertainty in on-road conditions is not fully characterized. Consequently, SI-traceable, quantitative information on on-road factors affecting measurement uncertainty is needed. Important factors potentially affecting EFM measurement uncertainty are exhaust flow transients, flow pulsations, gas composition, temperature effects, and flow meter drift. For an improved understanding of representative, SI-traceable, EFM measurement uncertainty (I) a generic uncertainty analysis is presented, which is obtained from performing an uncertainty analysis on state-of-the-art knowledge stemming from literature. This is followed by (II) presenting quantitative and partly traceable measurement results of experiments dedicated to the assessment of uncertainty from potentially significant factors contributing to the overall measurement uncertainty of the EFM in on-road conditions. Experimental results indicate that the EFM can match the (laboratory) accuracy limits as defined in the RDE. Other experimental results indicate that specific potential on-road conditions can affect the EFM such that the resulting overall measurement uncertainty exceeds the limit from the employment of the RDE-prescribed conformity factor.

Keywords Exhaust flow meters (EFM) · Portable emission measurement systems (PEMS) · Real driving emissions (RDE) · Uncertainty · Traceability

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1 Introduction

Emissions of nitrogen oxides (NO_x) and fine particles by petrol- and diesel-fuelled cars are leading to air pollution with detrimental effects to the human health. In recognition of the adverse effects of emissions from internal combustion engines, more effective pollution control systems and regulations with stricter limits on emissions have been implemented. However, the effectiveness of the stricter limits on the reduction of air pollution in on-road real driving conditions has been smaller than anticipated. This has led to the European Commission requirement of performing emissions measurements in on-road conditions. The requirement is part of the real driving emission (RDE) tests and implies that systems are in place to perform the emissions measurements in on-road conditions. Such systems are called portable emission measurement systems (PEMS) [1]. The requirement for on-road emissions measurements is part of the type approval (TA) process and compulsory (since 2016) for the light-duty vehicle category. RDE3 (Commission Regulation (EU) 2017/1151 [2]) is the legislation in which the procedures for light-duty vehicle TA are described. RDE3 was amended by Commission Regulation (EU) 2017/1154 [3] and subsequently by RDE4 (Commission Regulation (EU) 2018/1832 [4]). The requirement of performing on-road tests using PEMS was introduced in Commission Regulation (EU) 2016/427 [5]. Conformity factors are included in the RDE regulation. They are "not to exceed" emission limit multiplication factors for on-road tests with respect to laboratory tests. They exist for particle number emissions [2] and NOx (NO and NO_2) [6]. The conformity factors are larger than 1.0 and thereby indicate that the emissions measurements using PEMS with components calibrated under controlled laboratory conditions have larger uncertainty in the non-controlled on-road conditions where additional factors affect PEMS components' uncertainty. The exhaust flow meter (EFM) is a key component in the PEMS as it determines the mass of emitted gas from the exhaust. Its measurements are multiplied with the PEMS analyzers' pollutant concentration measurements to establish the emitted mass flow rate of the pollutants. Given the current state of technology, the EFM is a dominant factor in the total PEMS uncertainty, meaning that its uncertainty has a significant effect on the overall PEMS on-road measurement uncertainty of emitted pollutant mass flow rate. Quantifying the EFM on-road measurement uncertainty is a challenging topic. The conditions under which the EFM is calibrated, namely under carefully controlled laboratory conditions, are different from those on the road. The complete metrological validation, with the link to the SI units established in a manner representative for the on-road conditions in which the EFM is used, is therefore, to the best knowledge of the authors, lacking. Consequently, the EFM measurement uncertainty in on-road conditions is not well established.

Notwithstanding, important studies have been performed aimed at characterizing quantitatively the EFM uncertainty for on-road conditions. In Giechaskiel et al. [7], a 10.4% uncertainty estimate is made for the EFM under realistic (RDE driving test) conditions, while it is also concluded that the, say, ± 3% error limit is met under laboratory conditions. Thus, Giechaskiel et al. [7] attribute larger EFM measurement uncertainty to on-road conditions than to laboratory conditions. In Giechaskiel et al. [8], further EFM calibration results are presented where it is concluded that calibrations are within the 3% accuracy limit for a 200 to 2500 kg/h flow rate range. Giechaskiel et al. [8] also quantify EFM uncertainty (untraceably) through constant volume sampling (CVS) CO_2 bag validation test data used as a proxy and indicate that a ≤ 7.5% uncertainty for the EFM flow measurement is applicable. Pham et al. [9] compared partial flow dilutor mass flow rates with those recorded by EFMs and found an agreement to within ± 2%. However, to the best knowledge of the authors, a metrologically validated EFM uncertainty estimation, which inherently is comprehensive and transparent, and which is applicable to its on-road measurements, does not yet exist.

Schakel et al. [10] performed a literature study into the current state-of-the-art of (potential) influencing variables affecting the EFM flow measurement accuracy. The following influencing variables were studied or identified [10]: altitude (European Automobile Manufacturers Association [11], Feist et al. [12], and Giechaskiel et al. [7, 8]), backpressure (Varella et al. [13]), Pitot tube hole clogging (González et al. [14]), EFM drift (Giechaskiel et al. [7,, 8] and Guenther et al. [15]), dynamic flow changes/flow transients (Feist et al. [12] and Guenther et al. [16]), electromagnetic factors (Feist et al. [12]), flow profile (Giechaskiel et al. [7, 8], Feist et al. [12], González et al. [14], Guenther et al. [15, 16], and Varella et al. [13]), gas composition ([15]), distance (European Automobile Manufacturers Association [11] and Giechaskiel et al. [7]), humidity (European Automobile Manufacturers Association [11] and González et al. [14]), EFM linearity (Giechaskiel et al. [7] and Feist et al. [12]), leakage, noise, precision, pulsations/vibrations (Feist et al. [12], Giechaskiel et al. [7, 8], and González et al. [14]), recalibration frequency, shocks, tailpipe wind (Feist et al. [12]), ambient and gas temperature (European Automobile Manufacturers Association [11], Feist et al. [12], Giechaskiel et al. [7, 8], and Guenther et al. [15]), temperature gradient (European Automobile Manufacturers Association [11]), and zero drift (Giechaskiel et al. [7, 8, 17], González et al. [14], and Valverde et al. [18]).

In this paper, a generic EFM flow measurement uncertainty analysis for on-road driving conditions is presented. The analysis results in a comprehensive overview of influencing variables (potentially) affecting the EFM overall uncertainty in on-road conditions and identifies where information is lacking. The influencing variables, as reported in the literature, are listed and combined into an overall EFM uncertainty figure. The generic EFM flow measurement uncertainty analysis as obtained from literature is then complemented in this paper by presenting experimental results 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 effects from electromagnetic influences (III), ambient temperature (IV), and pulsating flows (V) on the EFM error and its associated accuracy. These experimental results are then used in combination with the generic EFM flow measurement uncertainty analysis to infer interpretations on achievable traceable total uncertainty in on-road test conditions, while also identifying missing uncertainty information. In the following sections, first, the development of the generic uncertainty budget is described, followed by a section to characterize the laboratory accuracy (I, II) of two EFMs and a section on the assessment of EFM flow rate uncertainty from electromagnetic influences (III), ambient temperature (IV), and pulsating flows (V). The paper finishes with a discussion section and a conclusion section.

2 EFM Flow Measurement Uncertainty Analysis

The RDE [2] prescribes that the instantaneous mass emissions, expressed in g/s, shall be determined by multiplying the instantaneous concentration of the pollutant under consideration, expressed in parts per million (or ppm), with the instantaneous mass flow rate, expressed in kg/s. This product is corrected by another multiplication with a u-value specific to the pollutant that expresses (I) the ratio of the pollutant density and the exhaust gas density and (II) unit conversions to convert ppm and kg/s units to the required output unit in g/s. Instantaneous emission measurements of the PEMS are thus expressed as follows [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 CO_2), 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 the unit conversions into account), $c_{gas,j}$ is the measured concentration of the exhaust component "gas" in the exhaust (ppm), and $q_{mew,j}$ is the measured exhaust mass flow rate (kg/s). To arrive at final emission results expressed in g/km of a pollutant (NOx, CO, HC, CO_2, O_2, and CH_4), Eq. (1) is integrated by methods defined in the RDE legislation and combined with the distance measurement. Clearly, Eq. (1) shows that the uncertainty of the emission measurement is proportional to the uncertainty of the EFM, which explains that the large overall total uncertainty of the EFM will manifest as a dominant uncertainty component in PEMS measurements. In Giechaskiel et al. [7], the EFM uncertainty was set at 10.4% of reading for a total uncertainty in the NOx conformity factor of 23 to 44%, which by 2020 was recommended to be reduced to 23% [8] (setting the EFM uncertainty at 7.5%).

Schakel et al. [10] performed a literature investigation into current EFM calibration procedures and their associated measurement uncertainties [10]. The study indicated that the current practice is to calibrate, and possibly adjust, an EFM in ISO 17025 [19] accredited (SI-traceable) calibration laboratories, typically under controlled ambient conditions using air as a calibration gas. Strictly speaking, the resulting total 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:

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

where $\varepsilon^{EFM}_{RDE,test}$ is the (relative) error (%) (with respect to the actual mass flow rate) of the EFM under RDE test conditions; ε^{EFM}_{lab} is the (relative) EFM error (%) from (SI-traceable) laboratory calibration; $\left(\delta q_m\right)^i$ is the perturbation in EFM mass flow rate readings due to influencing variable i, with a total amount of N influencing variables; and q^{EFM}_m 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^{EFM}_{lab} is set to zero, and that any remaining error is taken as the uncertainty of the EFM. Effectively, the $\pm 3\%$ error of the EFM flow rate legal accuracy limit defined in the RDE legislation is taken as the uncertainty value. RDE legislation further prescribes a ≤ 1-year recalibration of the EFM.

Table 1 shows an example uncertainty analysis using Eq. 2 and uncertainty sources as identified in the literature [10] and listed in Section 1. The red cells indicate (potential) influencing variables which were identified in the literature, but without quantitative information on the uncertainty contribution affecting the EFM mass flow reading. The green cells indicate influencing variables which were studied in this work to provide quantitative information on their influences. With an ε^{EFM}_{lab} 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 4.5% is computed. The $\pm 3\%$ error of the EFM flow rate legal accuracy limit defined in the RDE legislation is taken as a rectangular distribution, so that its $k = 2$ contribution is at about 3.5%. In the next section, it will be shown that pulsations can influence EFM laboratory calibrations, and that this effect can be on the order of 10% for ε^{EFM}_{lab}.

Table 1. Example uncertainty calculation for ε_{lab}^{EFM} at ± 3% and setting uncertainty contributions for which no literature information was found to zero (indicated with "-"). Literature uncertainty sources are taken from [10]

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

3 Characterizing EFM Accuracy

3.1 SI-Traceable Calibration

In Section 1, literature statements on EFM accuracy were summarized. While some of these statements are based on calibration certificates, the original calibration certificates were not shown in the cited sources. 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, two EFMs from two different market-leading suppliers were traceably calibrated in VSL's ISO/IEC 17025 [19] accredited gas flow laboratory. Air under atmospheric pressure, at an ambient temperature of (20.0 ± 0.5) °C and a relative humidity of (45 ± 5) %, was used. Flow stability is ensured as part of the traceable calibration. The calibration and measurement capability (CMC) is 0.15% of the gas flow rate ($k = 2$). The EFM (relative) percentage error was computed as follows:

$$\varepsilon_{lab}^{EFM} = \frac{q^{EFM} - q^{lab}}{q^{lab}} 100\,[\%] \tag{3}$$

where q^{EFM} is the mass flow rate (kg/h) indicated by the EFM, and q^{lab} is the reference (SI-traceable) mass flow rate. Figures 1 and 2 show the results (blue curves). From the figures, it can be seen that EFM errors are within the legal accuracy limit (roughly stated at ± 3%) as required by RDE [4] under controlled laboratory conditions. Also shown are the calibration results as supplied by the EFM manufacturers (black curves), which were also obtained in ISO 17025 accredited calibration laboratories. These errors are also within the RDE4 accuracy limit. In Figs. 1 and 2, the total calibration uncertainties (vertical intervals) are shown for both the manufacturer and VSL. The vertical intervals show the ± 95% probability limits of the measured EFM error (i.e., they indicate that there is a ± 95% probability that the EFM error lies between those limiting values). A difference in error beyond the intervals indicates a drift of the error curve.

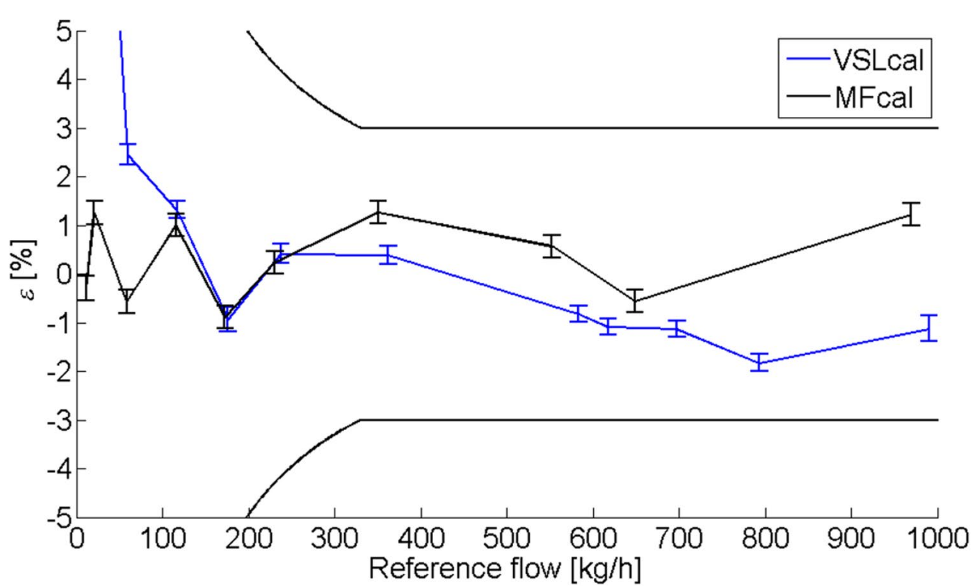

Fig. 1 SI-traceable calibration result of an EFM. Total calibration uncertainty is indicated by the vertical bars. Solid black lines indicate the required accuracy from RDE [4]

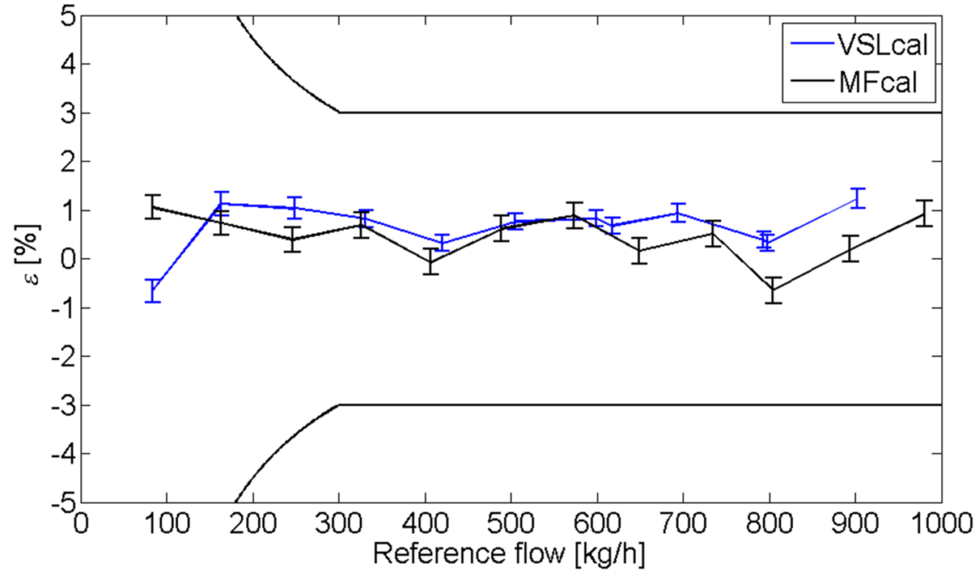

Fig. 2 SI-traceable calibration result of additional EFM. Total calibration uncertainty is indicated by the vertical bars. Solid black lines indicate required accuracy from RDE [4]

In Fig. 1, the drift indication is at 1–2% per year, while it is around 1% for Fig. 2. Note that in Table 1, drift uncertainty contribution values were based on literature sources (versus this work).

3.2 Comparison with CVS

The Euro 6 RDE protocol assigned for light-duty vehicles (i.e., passenger cars) determines the minimum requirements for the PEMS devices used in RDE testing. The protocol defines in detail the required installation and pre- and post-test procedures to be completed within an RDE test. As part of the process, the complete PEMS device including the non-traceable EFM should be validated under transient conditions in a laboratory environment using a chassis dynamometer utilizing a constant volume sampling (CVS) method. During the PEMS validation, the responses of PEMS and laboratory equipment are compared and validated against predetermined permissible tolerances. In the CVS method, the exhaust emissions are determined by introducing the tailpipe emissions into the CVS system, which dilutes the exhaust sample with filtered ambient dilution air. The total diluted exhaust volume flow is set with CVS Venturis to form a constant volume flow for individual test phases over the test cycle. The diluted exhaust concentrations are then sampled over individual test phases and are collected into separate sample bags using a constant sampling rate. By knowing the CVS system flow rate for each test phase, the mass of the measured exhaust components over a test is determined without the need to quantify the vehicle exhaust mass flow or momentary emission response. In the PEMS validation however, the uncertainty of the EFM is accounted for in the total uncertainty of the PEMS device per exhaust component (c.f., Eq. (1)) and not by the EFM uncertainty alone.

To enable direct back-to-back comparison of the response between the EFM and the CVS reading, the exhaust mass flow was not determined in transient operation but determined in static conditions using VTT's CVS test system instead. The exhaust mass flow introduced to the CVS was determined by calculating the dilution rate between measured raw CO_2 emissions and the diluted CO_2 concentration value sampled from the CVS system. The analysis was simplified by assuming that the density of the diluted exhaust mixture in the CVS is considered constant, 1.293 kg/m^3 (at 0 °C, normalized temperature and pressure conditions). Implementation of static conditions was in this case justifiable to remove any additional uncertainties. When measuring the instantaneous emissions, a (variable) time delay exists between the raw and the diluted sample measurements, caused by the unequal distance between the raw and diluted devices. This time delay is especially meaningful under transient conditions. Furthermore, dynamic flow changes from situations where the actual exhaust mass flow is close to zero, e.g. engine braking, cause significant time delays between raw and diluted measurements, introducing further errors in transient operation. Nevertheless, the quantification of the exhaust mass flow using a CVS is never fully traceable even in steady flow conditions because gas density in the CVS method is assumed to be constant based on the used test fuel (e.g. for petrol, a density value of 1.2931 kg/m^3 is used). Regardless of these issues, the EFM mass flow can be reliably compared with the CVS response by analyzing the systematic, relative differences between several EFMs and the calculated exhaust mass by the CVS system.

In the laboratory tests, a back-to-back comparison for two EFM devices was conducted against the CVS using a real vehicle on a chassis dynamometer. These EFMs, one of which was used in the SI-traceable calibration (c.f., Fig. 1), were installed, according to the RDE protocol, between the vehicle tailpipe and the CVS system. As described earlier, because transient conditions may introduce additional uncertainties between the readings recorded for EFMs and CVS, the back-to-back EFM-CVS tests included only steady-state testing. During these tests, multiple exhaust mass flow conditions and CVS flow settings were used. For each operation point, two different CVS-flow rates were used to compare the influence of changes in CVS backpressure.

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). SI-traceable EFM 1 calibration results are in Fig. 1. EFM 3 was an additional EFM used for this test. Table modified from [20]

CVS flow setting	Exhaust flow calculated using CVS		Dilution rate	Relative error, EFM 1	Relative error, EFM 3
m^3/min	m^3/h	kg/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%

Table 2 shows the recorded relative errors between the CVS flow rate compared to the q^{EFM} sampled in each operation/flow point. For eight results out of 20, the relative errors were above 3%. It is noteworthy that the permissible deviation determined in the RDE procedure on the EFM accuracy is set at ± 3% of the measured flow rate (but larger at relatively small flow rates, see the RDE [4]). Furthermore, the test results show that the deviation between the two EFMs was found to be inconsistent, yet significant throughout the given flow range. The largest difference between the two EFMs was 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 Eq. (3), where q^{lab} now corresponds to the CVS flow rate.

Another issue observed was that even within two relatively similar operation points, but by using different CVS flow settings (e.g. 159.5 kg/h and 164.9 kg/h), the deviation of the tested EFM varied. It was noted that the CVS settings, which directly impact the total CVS flow, may affect the predominant negative gauge pressure at the tailpipe (see Fig. 3). This could directly affect the sensitivity of the two EFMs, which were installed in series between the tailpipe and the CVS. The tail-pipe backpressure may additionally influence vehicle or engine behaviour, as a reduced back pressure may increase the airflow through the engine. This finding is especially important for the outcome of the PEMS validation, particularly if excessively high or low CVS flow settings are being implemented. The effect could possibly be avoided by minimizing the pressure differences over the ambient air filters that in turn minimizes the CVS backpressure. It is noted that the setup, including the EFM, was carefully checked for leaks. The above suggests that further work into the calibration uncertainty of CVS validations of EFMs

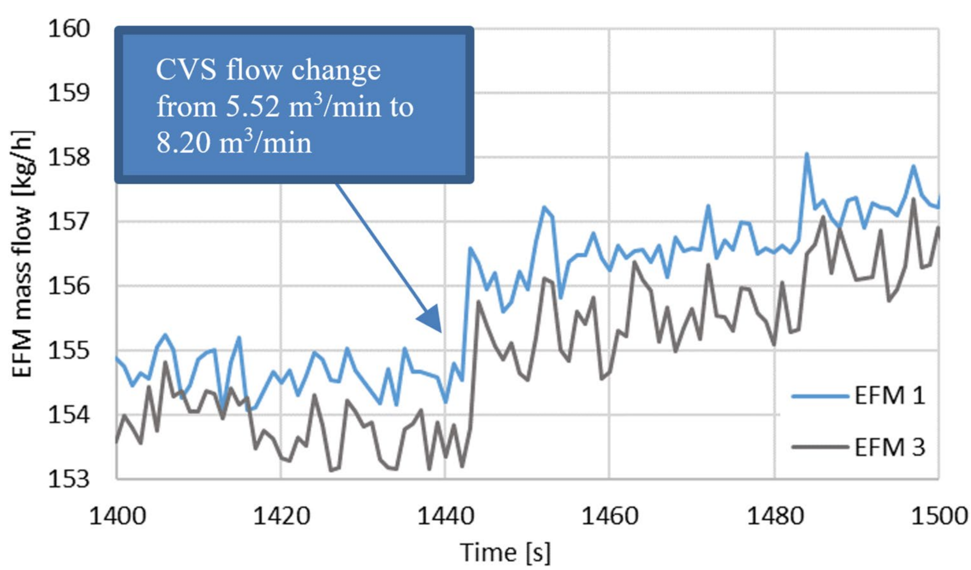

Fig. 3 EFM mass flow traces with CVS flows at around 5.52 m^3/min and at around 8.20 m^3/min for a constant vehicle load. Figure modified from [20]

needs to be done in order to enable traceable calibrations with this method.

4 Systematic Investigation into EFM Uncertainty Contributions

4.1 Electromagnetic Influences on EFM

The EFM for which the calibration result was shown in Fig. 2 was further tested to investigate the extent to which electromagnetic influences can affect its mass flow readings.

Tests were performed at NMi’s electromagnetic compatibility (EMC) test setup that can be categorized as follows:

- Conducted immunity tests
- Automotive pulse tests
- Radiated immunity tests

The conducted immunity tests were tests where a frequency sweep of 150 kHz up to 80 MHz is applied in 1% frequency steps, 10 Volt RMS, and a dwell time of 3 s. This signal was introduced through the various parts of the EFM setup to see if the resulting flow rate was affected by the disturbances.

The automotive pulse tests are standardized tests for the automotive industry according to ISO 7637–2011 [21]. Automotive pulse tests 1, 2a, 2b, 3a, and 3b from this ISO standard were performed. These tests simulate various malfunctions that a car can have, such as a sudden disconnection of the battery due to a loose wire, or a lightning strike hitting the car. The EFM is connected to the test-generating device by inserting the power supply of the EFM control box into the test-generating device. The tests can be performed at various levels of intensity. Level I/II tests were performed, which is sufficient for pre-compliance tests.

During the radiated immunity tests, a frequency sweep resembling the conducted immunity test was applied, but instead of conducting the EM frequencies through the device, an antenna was aimed towards the EFM to test the radiated immunity. The antenna went through the frequency range of 1 GHz up to 6 GHz in steps of 1% with a dwell time of 3 s. For one run, the antenna was placed in a horizontal position, and for a second run, in a vertical position.

Throughout all these tests, the recorded flow rate did not fluctuate notably, i.e., the natural variation of flow rate was not dependent on the presence of the tested EM influences.

4.2 Ambient Temperature Effect on EFM

The EFM for which the calibration result was shown in Fig. 2 was further tested to investigate the extent to which variations in ambient temperature can affect its mass flow readings.

The EFM and its control box were placed in a climate chamber (see Fig. 4). A blower (2) produced a flow rate of about 20 kg/h using 20 °C laboratory air. Hence, the flow rate is relatively low with respect to the EFM range (c.f., Fig. 2). Ambient temperatures were set in the climate chamber at – 10 °C, 0 °C, 20 °C, 30 °C, and 35 °C and a flow was generated. This range coincides with the extended (ambient) temperature conditions from the RDE, c.f., RDE3, Annex IIIA, 5.2.4 and 5.2.5 [2, 3]). Differences in the flow rate at 20 °C, $Q_{20\,°C}$, with respect to the flow rate at another ambient temperature are displayed in Fig. 5. For 20 °C, 30 °C, and 35 °C, no differences beyond two times the standard deviation of EFM flow rate were observed, while at 0 °C, a difference of about 2 kg/h is seen. The result at – 10 °C is not displayed, since the EFM flow rate and temperature readings were erroneous. Closer inspection of inlet and outlet EFM piping for the – 10 °C experiment indicated the presence of condensed water and icing in the EFM. For the determination of an error as given in Eq. 3, it is good practice to ensure that leak rates are negligible. No EFM errors with respect to the reference flow meter could be determined, because the setup was not sufficiently leak tight for the relatively low flow rates tested at about 20 kg/h.

Fig. 4 Climate chamber (1), blower (2), reference flow meter (3), and its data acquisition system (4). The EFM and its control box are located within the climate chamber. The green arrow indicates the flow direction

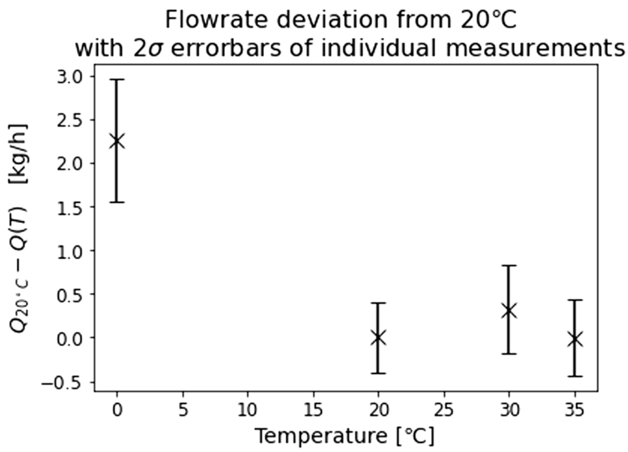

Fig. 5 Difference of EFM flow rate reading at set climate chamber ambient temperature and flow rate reading at set climate chamber ambient temperature of 20 °C. Within run two standard deviations in flow rate are indicated by the vertical bars

4.3 Flow Pulsation Influence on EFM

Raw output data was recorded during the SI-traceable EFM calibrations of Figs. 1 and 2. This is needed for the calibration itself, while it can also serve as a diagnostic of the quality of the exhaust flow meter measurement in its specific (calibration) installation. Before the EFM calibration results of Fig. 1 were obtained, a calibration experiment for the investigation of the EFM's sensitivity to flow pulsations was set up. Flow pulsations were deliberately introduced by installing the EFM on a rigid support and setting upstream valve positions such that flow pulsations are stimulated (versus dampened). Figure 6 (blue, pulsations) shows the raw recorded data for this setup and contrasts it with the raw recorded data of Fig. 1 (black, no pulsations). The latter was used to obtain the calibration results of Fig. 1. At the higher flow rates, pulsations can be seen in the blue graph which diminish as the flow rate becomes smaller, because the pulsations' pressure variations diminish naturally as the flow is

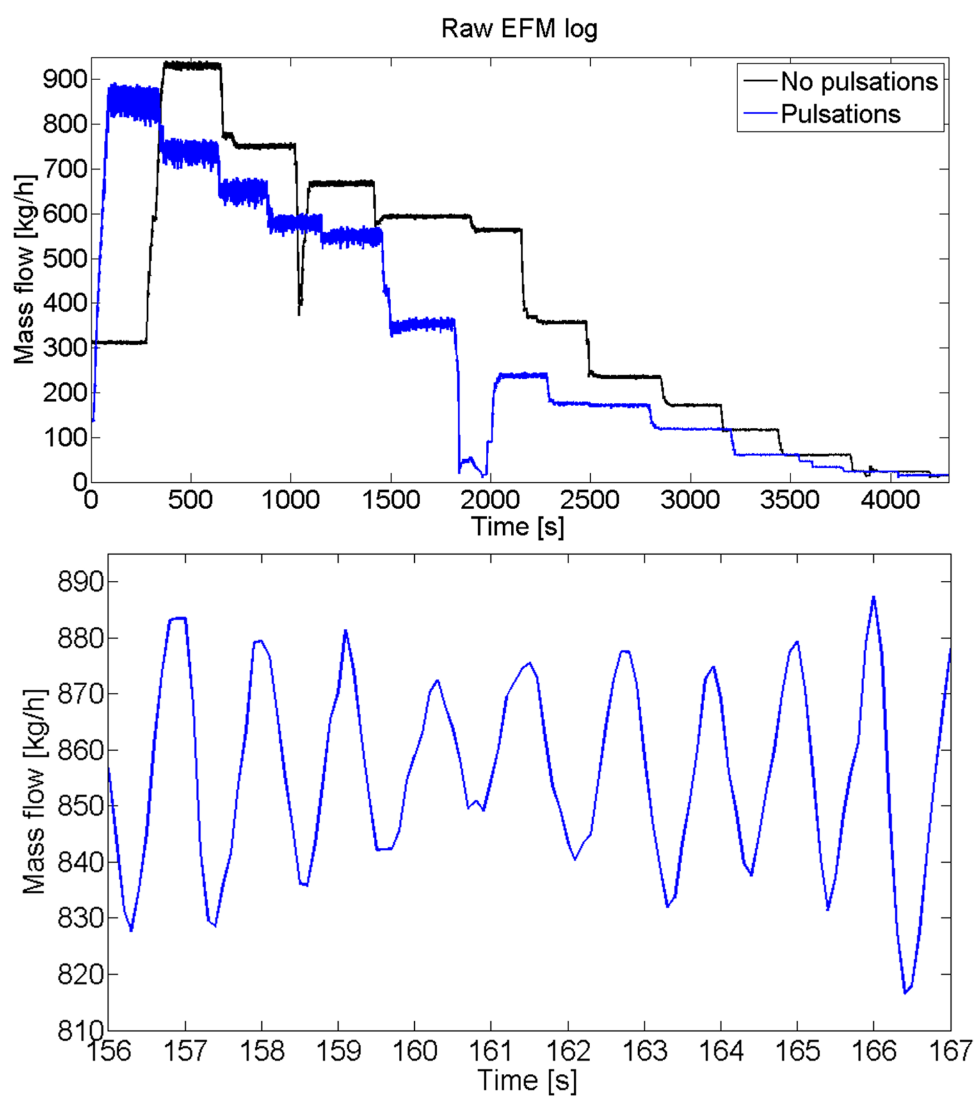

Fig. 6 Raw EFM log output indicating flow rate dependent pulsations (top) characterized by a periodicity of about 1 s (bottom)

reduced. An exploded view in the bottom graph shows that the pulsations show an approximate 1 s (or 1 Hz) periodicity. The EFM mass flow rate data was sampled at 0.1 s, which is sufficient to avoid aliasing of a 1 Hz signal.

When using the Fig. 6 pulsating flow EFM measurements as input to the SI-traceable calibration, the result of Fig. 7 is obtained. One can discern a potentially strong effect on the ε_{lab}^{EFM}, whose magnitude increases with flow rate to above 10%. The calibration uncertainty is indicated by the vertical bars, indicating a 95% confidence interval. The calibration uncertainty also increases with flow rate because the differences between ε_{lab}^{EFM} at the same flow rate (repeats) increase. Note that no individual repeat results are displayed. At the higher flow rates, the calibration uncertainties (vertical bars) are on the order of several %, which is large with respect to the much smaller calibration and measurement capability (CMC) at 0.15% ($k=2$, indicating a 95% confidence interval) of reference flow rate. In other words, the Fig. 7 high flow rate larger calibration uncertainties are caused by increasing high flow rate repeatability uncertainty.

5 Discussion

5.1 EFM Uncertainty Assessment for On-Road Driving Conditions

For a complete SI-traceable uncertainty estimation of the EFM for on-road RDE conditions, all factors (potentially) affecting its measurements must be identified and then quantified (e.g. by using SI-traceable reference measurement standards) or reliably excluded to affect its measurements for the specific conditions in which they were performed. The example uncertainty calculation presented in Table 1 can be perceived as an optimistic scenario. The laboratory SI-traceable accuracy limit (as defined in the RDE) is taken as the dominant uncertainty source, i.e., contributing most to the overall uncertainty calculation at the bottom of Table 1. Contributions of other (potential) uncertainty sources are either smaller or set to zero. In this case, the overall uncertainty calculation, applicable to the on-road conditions, is at 4.5% ($k=2$) well below the conformity factor, at about 8% (at the time of writing). Table 3 can be perceived as a pessimistic scenario. The overall uncertainty is at 17.9% ($k=2$) well above the conformity factor. It is a result from the large uncertainty contribution from flow pulsations, which is the dominant uncertainty source in this scenario. If flow pulsations affect the EFM measurements as indicated in Fig. 7 and Table 3, the EFM uncertainty in on-road RDE driving conditions is larger than what is accounted for in the conformity factor. Table 3 takes the worst-case number for the uncertainty from flow pulsations (see Section 5.3.5 for further discussion).

While the generic uncertainty budget presented in this paper gives insight into potential significant influencing variables affecting the EFM flow rate measurement in on-road conditions, it must be noted that a representative uncertainty estimate will require an analysis tailored to the specific EFM considering flow meter type (ultrasonic, averaging Pitot), size, model, manufacturer, serial number, and the circumstances in which it was operated (e.g. cold start, fuel type (e.g. gasoline/diesel), dynamic flow effects, and pressure/temperature effects).

5.2 CVS Validations of the EFM

To the best knowledge of the authors, in the current practice, comparing CVS measurements with the EFM

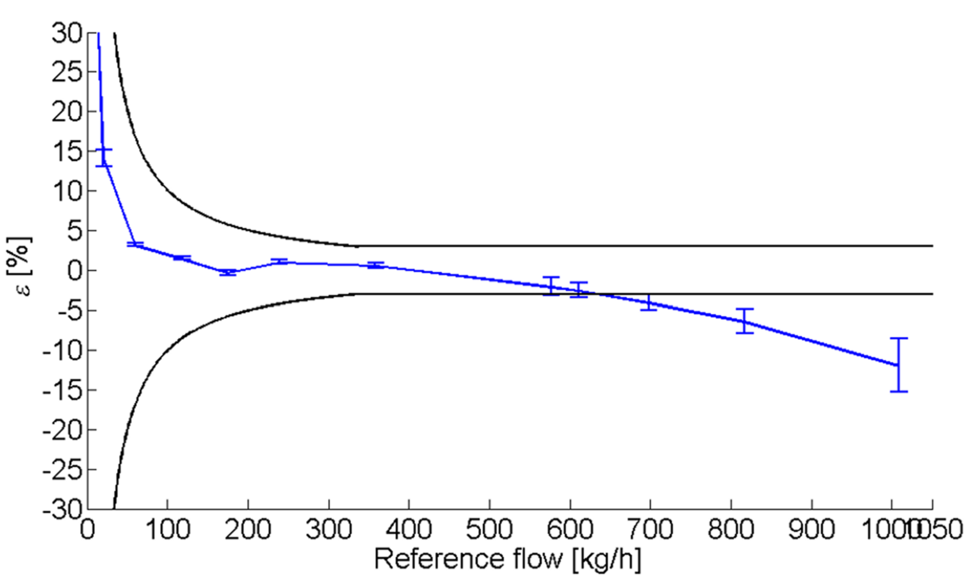

Fig. 7 Calibration result of EFM when deliberately introducing flow pulsations. Total calibration uncertainty is indicated by the vertical bars. Solid black lines indicate the required accuracy from RDE [4]

Table 3. Example uncertainty calculation for ε_{lab}^{EFM} at ± 3%, setting uncertainty contributions for which no literature information was found to zero (indicated with "-"), and including a (worst case) relative uncertainty for the effect from flow pulsations on the EFM. Literature uncertainty sources are taken from [10]

Uncertainty source	Uncertainty contribution [%] (k = 2)
ε_{lab}^{EFM}	3.5
Altitude	0.6
Backpressure	-
Clogging (of averaging Pitot tube)	-
Drift	2.3
Dynamic flow changes/flow transients	-
Electromagnetic influence	-
Flow profile	-
Gas composition	-
Humidity	-
Linearity	0.6
Leakage	-
Noise	-
Precision	-
Pulsations/vibrations	17.3
Recalibration frequency	-
Response time	-
Shocks	-
Tailpipe wind	-
Ambient temperature	-
Gas temperature	1.2
Temperature gradient	-
Zero drift	-
Uncertainty of $\varepsilon_{RDE,test}^{EFM}$ (k = 2)	17.9 [%]

measurements can only be an untraceable indicator of EFM uncertainty since fully traceable CVS systems do not exist. Furthermore, given the variability of relative errors between EFM 1 and EFM 3 in Table 2, the variability for relatively close CVS set points in Table 2, and when contrasting these results with the errors from the SI-traceable calibration in Figs. 1 and 2, it is inferred that the CVS method would need an improved accuracy in order to achieve uncertainties lower than, say, 1% of flow rate in the EFM calibration. Larger uncertainties can result in inconclusive EFM accuracy determination as a 3% threshold applies.

5.3 Insights into Uncertainty from EFM Drift, Electromagnetic Influences, Ambient Temperature, Pitot Tube Clogging, Flow Pulsations, Low Flow, and Line Pack Effects

From the experiments presented in this paper, insights into influencing variables (potentially) affecting the EFM flow rate readings were obtained.

5.3.1 EFM Drift

A difference in error beyond the uncertainty intervals indicates a drift of the error curve. In Fig. 1, the drift indication is at 1–2% per year, while it is around 1% for Fig. 2. Note that in Tables 2 and 3, drift uncertainty contribution values were based on literature sources (versus this work). The maximum 2% of drift interpreted from Fig. 1 coincides with the drift value chosen in [7, 8].

5.3.2 Electromagnetic Influences

No significant effects from electromagnetic influences on the EFM and its equipment were identified. The strongest intensity ISO 7637–2011 pulse tests were not performed, because the risk of creating a permanent malfunction of the EFM was deemed too high, given that further experiments were planned requiring the same EFM to be used. It is noted that Feist et al. [12] report a 0.3% of maximum flow mean zero error effect from electromagnetic interferences.

5.3.3 Ambient Temperature

The experimental results indicate that for ambient temperatures close to 0 °C and lower (partial) icing within the averaging Pitot tube holes can cause the EFM to produce erroneous or biased results. Presumably, such effects would only manifest just after a cold start in extended condition RDE tests, and only just after the engine has started after which the heated gas will cause the ice and condensed water to be removed. It is noted that ambient air at 20 °C was used in the experiments, while exhaust gas temperatures are typically on the order of several 100's of °C.

5.3.4 Averaging Pitot Tube Clogging

EFMs based on the averaging Pitot tube principle are well known to be potentially affected by clogging of their holes (e.g. dust/soot). The experimental results of this paper indicate that icing and/or condensed water can also result in clogging of the averaging Pitot tube holes resulting in erroneous EFM flow rate values. Caution should therefore be taken when using the EFM at extended RDE test conditions and when the exhaust gas is still below 100 °C.

5.3.5 Flow Pulsations

Based on Table 3 uncertainty calculation, one can speculate that flow pulsations can contribute strongly to the EFM measurements' total uncertainty in RDE driving conditions. Figure 1 calibration results were obtained in VSL's ISO 17025 accredited (SI-traceable) calibration laboratory, which is set up to calibrate all sorts of flow meters and for which steady flow conditions are a requirement. Importantly, this calibration laboratory is not an engine or chassis dynamometer test laboratory. This implies that the type of flow pulsations observed in Fig. 6 does not need to be representative for the conditions in which the EFM is used in on-road conditions, where it is embedded in the PEMS system and connected to the vehicle exhaust. Communication with the EFM manufacturer indicated that the type of (1 Hz) flow pulsations observed in Fig. 6 is not known to occur in on-road conditions. Figure 7 shows the magnitude of the effect from the flow pulsations on ε_{lab}^{EFM} increases with the flow rate. Figure 8 shows measured exhaust flow rates (kg/h) versus time for three RDE real-driving tests. The results show that most of the flow rates are coinciding with the lower flow rates of Fig. 7, where ε_{lab}^{EFM} is relatively unaffected by the flow pulsations. For light-duty vehicles, the > 200 kg/h mass flow rates correspond to short periods of acceleration and to very high-speed driving on motorways (say > 130 km/h) with relatively high fuel consumption (> 50 kg/h). This explains why on-road conditions for light-duty vehicles, as in Fig. 8, mostly correspond to < 200 kg/h mass flow rates.

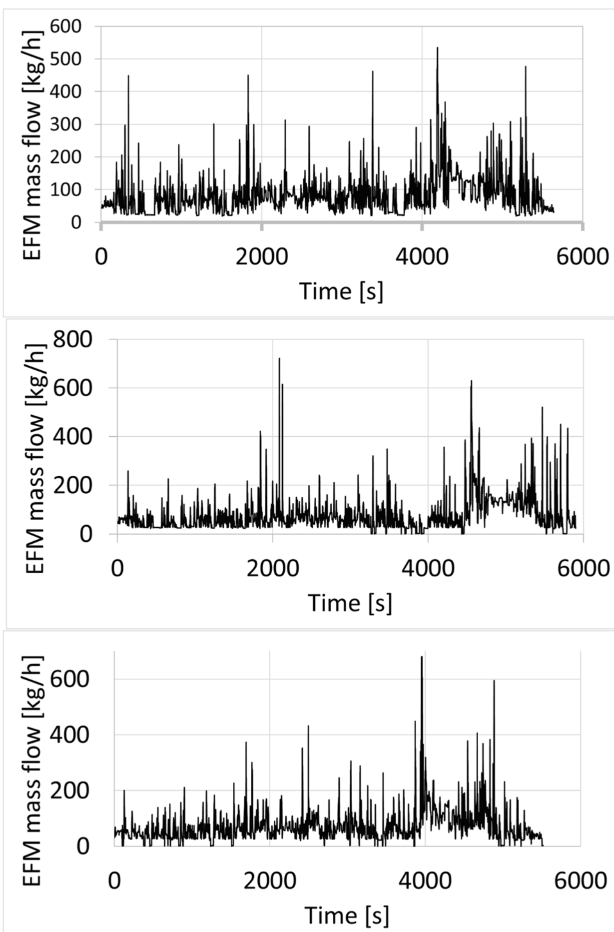

Fig. 8 Measured exhaust mass flow rate (kg/h) versus time of three RDE real-driving tests carried out on an SUV with a 2.0 L diesel engine with selective catalytic reduction (SCR) and Euro 6d calibration. Figure reproduced from [20]

5.3.6 Low Flows

Figures 1 and 2 show that the EFM accuracy limit as required by the RDE is less stringent than 3% at lower flows (approximately < 300 kg/h). Emitted pollutants can be particularly high after a cold start, when the exhaust mass flow is low. To ensure sufficiently low EFM uncertainty, three options may be considered: (I) the range (size) of the EFM may need to be reduced, (II) the measurement principle of the EFM may need to be changed to ensure larger rangeability (e.g. ultrasonic-based EFM), or (III) the existing EFM is carefully calibrated including its drift, speculating that a sufficiently low resulting EFM uncertainty is arrived at. It is noted that none of these options has been investigated in this work.

5.3.7 Line Pack Effects

In flow measurement, a well-known phenomenon that should be analyzed in terms of influence on flow meter error (c.f., Eq. (3)) when comparing two EFMs in series is the line pack effect. When the density changes within a fixed volume (the line pack) connecting the two EFMs, some mass is seen by the first EFM which is not seen by the second EFM. Especially when the pressure and temperature are changing over the time interval in which two EFMs are compared, line pack effects should be considered. The raw data leading up to Table 2 was analyzed and it was concluded that the flow meter error difference between the two EFMs in the series could not be attributed to line pack effects.

6 Conclusions

Research reported in the literature reveals that varied influencing variables can (potentially) affect the EFM flow readings for on-road conditions as applicable to TA tests. The literature investigation provided the insight that (traceable) uncertainty information on several influencing variables, as applicable to on-road conditions, is lacking. Consequently, the resulting traceable uncertainty under RDE driving conditions has still not been fully characterized. This in turn implies that the establishment of the conformity factors is accompanied with assumptions on several influencing variables affecting the EFM under on-road conditions, for which there is little or no information.

The generic EFM uncertainty analysis yielded a list of (potential) influencing variables, as obtained from literature, which are combined into an overall EFM uncertainty figure. However, for a representative EFM uncertainty, as applicable to a particular on-road test, a specific (versus general) EFM uncertainty analysis must be performed. Differences between EFMs, such as type of flow meter (ultrasonic, averaging Pitot), or serial number, can result in different outcomes. As an extreme example, for the sake of illustration, an EFM with a malfunction during the on-road test would result in a totally different uncertainty figure than one which does not have a malfunction.

RDE requires a 3% accuracy for the EFM [4]. The requirement implies that during the laboratory calibration of the EFM, the error should be within ± 3%, possibly after adjustment. However, no transparent SI-traceable calibration datasets were found in the literature that display that the 3% accuracy limit is met. Results on the accuracy of EFMs under controlled laboratory calibration conditions are reported in the literature; however, the underlying datasets are not shown. In this paper, complete and transparent calibration results were shown for two EFMs from two different market-leading suppliers, both of which were within the 3% accuracy limit under steady flow conditions. For one EFM, results from an experiment in which flow pulsations were introduced while keeping all other factors the same as in the calibration, showed that the accuracy requirement was not met for flow rates above about 50% of its maximum flow rate.

Without fully traceable flow dilution tunnels, the CVS method can not be used for the traceable calibration of the EFM. This implies that this method can only be an untraceable indicator of EFM uncertainty. Furthermore, SI-traceable calibration of the EFM by the CVS method seems impractical as a 3% accuracy must be shown, while variability in CVS results is observed from changed settings which should conceptually not cause any variation in the established EFM error.

Experiments dedicated to assessing the uncertainty contributions of potential influencing variables affecting the EFM flow rate measurement under on-road conditions provided the following insights:

- For the two EFMs tested, the indications of EFM drift were within the limit set in references [7] and [8].
- No effects were observed from electromagnetic influences for the tests presented, while one literature source did report an effect.
- Strong indications were found that ice and/or condensed water can affect EFMs that are based on the averaging Pitot tube measurement principle.
- Flow pulsations affected one EFM strongly at relatively high flow rates (> 200 kg/h). This occurred in a laboratory setting (versus an on-road test). Flow pulsations can be monitored relatively easily from the raw flow rate output. In a conversation with the supplier of the EFM, it was stated that no flow pulsations are observed in on-road conditions. This can be explained from the fact that, for light-duty vehicles, > 200 kg/h mass flow rates correspond to short periods of high acceleration and to very high-speed driving.
- To the best knowledge of the authors, line pack effects were not (yet) identified as possible influencing factors affecting the EFM error.

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Author Contribution MS, WS, and RP wrote the manuscript. MS prepared Figs. 1, 2, 6, and 7, and tables 1 and 3. WS prepared Figs. 4 and 5. RP prepared Fig. 3 and Table 2. ZY and UW prepared Fig. 8. MS, RP, and UW supported funding acquisition and project administration. All authors reviewed the manuscript.

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Data Availability Metadata of the manuscript is published here: https://zenodo.org/records/8299381.

Declarations

Ethical Approval Not applicable.

Competing Interests The authors declare no competing interests.

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