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MetroPEMS

Improved vehicle exhaust quantification by portable emission measurement systems metrology

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| Coordinator: Jorge Saturno, PTB | Tel: +49 531 592 3217 | E-mail: jorge.saturno@ptb.de | | | | | | | |
| Project website address: https://metropems.ptb.de | | | | | | | | | |
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1 Overview

Nitrogen Oxides (NO_x) and fine particles emitted from cars with combustion engines are the leading causes of air pollution. In recognition of this, EC legislation was introduced for on-road type approval (TA) real driving emission (RDE) tests using portable emissions measurement systems (PEMS). However, metrological validation has not been established. This project has provided insights and developed reference materials in order to support the accuracy and comparability of vehicle emission values procedures for metrological PEMS characterisation (for NOx, particle number (PN) and exhaust gas flow). This is particularly relevant for the accurate verification of vehicle emission limits in TA, and thus vital for (i) European vehicle manufacturers, (ii) the associated measurement device industries and (iii) the legislative bodies responsible for ensuring adequate air quality despite increasing traffic emissions.

There are still ongoing challenges in providing stable reference materials for low concentration fractions below 10 µmol mol⁻¹. An improved infrastructure for in-field performance validation of RDE PEMS devices was developed using an optical gas standard device. An instrument intercomparison across three laboratories revealed discrepancies in PN measurements, particularly for particles below 30 nm, and gas matrix influenced the gas dilution factor by up to 17 %. Regarding exhaust flow, meeting the 3 % accuracy legal limit in SI-traceable calibration for two EFM units was proven feasible, experiments with pulsations indicated limitations for flow rates exceeding approximately 50 % of the maximum, although this pulsation type is uncommon in on-road conditions. The project successfully assessed PEMS performance in real-world conditions. As part of the recommendations, special attention should be given to tuning PEMS devices to specific emission matrices and to refining analyser drift criteria in current RDE regulations.

2 Need

The European car industry currently provides jobs to more than 6 % of the employable population. It is a growing sector of European economy that produces a trade surplus of \in 90.3 billion. Furthermore, it is predicted that for decades to come, vehicles powered by internal combustion engine remains dominant over electrically driven ones, which in 2018 have only reached a 2.0 % share of the total registered vehicles across the EU. The burden of internal combustion vehicles to the environment has decreased in recent years thanks to stricter regulations and the implementation of more effective pollution control systems. However, these reductions have not been as large as anticipated due to emission standards not delivering the expected reductions under real-world driving conditions. As a result, this sector is still responsible for an important amount of NO_x and fine particles. According to the latest European Environment Agency (EEA) report, severe violations of World Health Organization (WHO) air quality guidelines (AQG) for Particulate Matter (PM₁₀ and PM_{2.5}) were recorded in almost all EU Member States. Moreover, for NO₂, 88 % of concentrations observed at traffic stations were above AQG limit values.

In 2016, an additional TA test procedure called RDE test was introduced by the EC. This is an on-road test using PEMS and complements in-laboratory TA tests for light duty vehicles. This regulation was amended later to introduce conformity factors for NO_x and PN. These conformity factors establish "not to exceed" limits for on-road tests compared to laboratory tests. Currently, PEMS measurement uncertainties are expected to be considered in the conformity factors. From 2020, new conformity factors apply to TAs and therefore there is increasing need from end-users (e.g., car manufacturers) for the development of accurate and metrologically validated calibration standards and guidelines for vehicle emission on-road TA RDE testing. Conformity factors are expected to be adjusted down to 1.0 with the introduction of the Euro 7 regulations.

3 Objectives

The overall goal of the project was to develop the necessary metrology for PEMS to support newly introduced vehicle emission legislation for on-road TA RDE testing. The specific objectives of the project were:

- To develop traceable methods to validate and calibrate portable NO_x emissions measurement systems (PEMS), in particular for NO₂, for concentrations from below 10 µmol/mol up to at least 2500 µmol/mol. This should include the generation of a 'state-of-the-art' PEMS with respect to high accuracy reference gases, development of improved gas standards, calibration methods and uncertainty evaluations, as well as the validation of commercial NO_x-PEMS.
- To evaluate the performance of commercial particle number (PN) PEMS by comparison with traceable PN facilities; to include the characterisation of i) linearity and counting efficiencies ii) particle size dependence (at least up to 10⁴ particles/cm³ and four sizes), iii) dynamic flow behaviour including the determination of aerosol sampling and handling effects.



- To develop application-oriented calibration procedures and uncertainty budgets for PEMS exhaust flow meters (EFM) for relevant carrier gases and to investigate the effect of dynamic flow behaviour on PEMS uncertainty.
- 4. To quantify the correlation between: i) RDE-PEMS measurements and laboratory dynamometer test results, ii) individual PEMS "channels" for CO₂, CO, NO, NO₂, PN, exhaust mass flow and iii) validated 'golden' (reference) PEMS and commercially available PEMS.
- 5. To facilitate the take up of the technology and standards developed in the project by the measurement supply chain (instrument and car manufacturers, accredited calibration laboratories), standards developing organisations (e.g., CEN, ISO) and end users (automotive industry).

4 Results

4.1 Extending amount fraction capabilities of high accuracy primary reference materials of NO₂

Improving gravimetrical gas standards

For low NO₂ amount fractions reference materials (particularly < 10 μ mol mol⁻¹), one of the largest sources of problems in the preparation of static standards is the presence of water (H₂O) which reacts with NO₂ to create nitric acid (HNO₃). The mechanism for the hydrolysis of NO₂ under atmospheric conditions is well described in the literature and is shown below:



Figure 1. Relative amount of NO₂ dimer (N₂O₄) as a function of temperature and partial pressure of the monomer.

2 NO₂ + H₂O + surface \rightarrow HNO₃ + HNO₂

Due to the ubiquity of water and its affinity for surfaces, the thermodynamically favourable hydrolysis of NO₂ within high pressure cylinders is a big problem for the stability of NO₂ reference standards. As amount fractions increase the dimer, dinitrogen tetroxide (N₂O₄) becomes increasingly more abundant (for example, at 20 °C 100 µmol mol⁻¹ and 1000 µmol mol⁻¹ NO₂ contains 0.1 % and 0.8 % N₂O₄ respectively). This produces analytical challenges as the temperature conditions and the analyser used for certification both affect the amount fraction of N₂O₄ and hence the analytical result (see **Error! Reference source not found.**). To achieve sufficiently low uncertainties needed for accurate PEMS calibration improved methodologies for characterising these major impurities (HNO₃ and N₂O₄) in NO₂ reference materials are required. In the case of HNO₃ a deeper understanding of the formation and evolution of this impurity, as well as methods to suppress its formation are needed.

To characterise HNO₃, NPL developed an alternative approach to determine the HNO₃ amount fraction in NO₂ reference standards by the difference between the total NO_y and NO_x (HNO₃ = NO_y – NO – NO₂). The NO_y and NO amount fractions were measured by Chemiluminescence Detector (CLD), and the NO₂ amount fraction was measured by NDUV or Cavity Attenuated Phase Shift (CAPS) spectroscopy. LNE and NPL utilised the developed methods to quantify the HNO₃ amount fraction in the NO₂ reference standards produced in the project.

LNE, Air Liquide and NPL produced 15 low amount fraction NO₂ reference standards in two different cylinder types with NO₂ amount fractions of 1 (13 reference standards) and 10 (two reference standards) µmol mol⁻¹ in a matrix of synthetic air. The developed NO₂ reference standards were assessed for stability over a period of 12 months by LNE and NPL. For the 1 µmol mol⁻¹ standards a decrease in NO₂ amount fraction was observed for all mixtures after 12 - 22 months (0.1 - 13.1 %), and varying amounts of HNO₃ (1 - 70 nmol mol⁻¹), NO (0 - 1 nmol mol⁻¹) and water (200 - 320 nmol mol⁻¹) were observed. For the 10 µmol mol⁻¹ standards tested, NO₂ losses of 3.5 % were observed after 12 months, with a sum of 70 - 110 nmol mol⁻¹ NO and HNO₃ observed in the standards. Despite taking measures to remove as much water as possible during preparation, the persistence of water in the reference standards led to high levels of impurities which affected the long-term stability of the mixtures, particularly at 1 µmol mol⁻¹. As a result of the effect that water had on stability, the reference standards had large uncertainties when considering the NO₂ drift over time - based on the data, the uncertainty on the amount fraction of NO₂ for the 1 µmol mol⁻¹ NO₂ in synthetic air standards produced by LNE was 8 % after 13 months, 13 % after 12 months for the standards produced by NPL, and 5.4 % after 22 months for the standards produced by Air Liquide. Based on the data, the uncertainty on the amount fraction of NO₂



for the 10 μ mol mol⁻¹ NO₂ in synthetic air standards produced by NPL was 3.5 % after 14 months. Due to the challenges in removing and avoiding reintroducing water during preparation and handling, and the non-linear decay profile for NO₂ that results, an alternative approach to determine the analytical amount fraction of NO₂ after waiting for most of the reaction with water to occur (100 days after preparation) could be considered. If a dynamic standard with a low uncertainty is used, it should be possible to achieve the uncertainties required.

LNE, Air Liquide and NPL participated in a comparison of 1 µmol mol⁻¹ NO₂ in synthetic air reference standards which was hosted by NPL. The protocol for the comparison was written following recommendations from the key comparison CCQM-K74.2018 and was the first successful implementation of this comparison approach. Each partner provided one standard and measured the stability before and after the comparison. The stability results were interpolated to estimate the amount fraction of NO2 at the time of the comparison measurements conducted at NPL, and the submitted results were compared to the reference values measured by NPL. The results submitted by Air Liquide and NPL had good agreement with the comparison values, with the interpolated results being comparable to the reference values within the expanded uncertainties (k = 2). However, there was a small discrepancy between the results submitted by LNE and the comparison value, although the relative uncertainties were much smaller for the results submitted by LNE compared to Air Liquide and NPL, and if the same relative uncertainties were applied to LNE's results good agreement would have been obtained between these values as well. Approximately 3 % biases were observed between the partners results and the comparison results (3 % above for LNE; 3 % below for Air Liquide and NPL). Based on the results it cannot be firmly concluded which values are "correct", but rather highlights the need for improved preparation and measurement techniques for all the partners to achieve adequate accuracy and good comparability. Possible reasons for the discrepancies could be preparation bias, measurement bias and/or incorrectly estimated uncertainties. Working together and directly comparing cylinders allowed these biases to be observed, while also allowing the comparison of preparation and analytical approaches between the laboratories which would not have been possible if they were working independently.

VSL in collaboration with PTB developed a spectroscopic method to accurately characterise N2O4 using an FTIR spectrometer equipped with a SilcoNert® 2000coated absorption cell. Experiments performed using high amount fraction (500 - 2500 umol mol⁻¹) NO₂ reference standards demonstrated that the system was able to detect the dimer impurity along with HNO3 with a good signal to noise ratio. The developed approach was disseminated to NPL and VSL and both partners utilised the method to quantify the N₂O₄ amount fraction in the high amount fraction NO₂ reference standards produced in the project.



Figure 2. Algorithm for assessing the NO₂ amount in mixtures. Amount of the NO₂ monomer is calculated using the integrated intensities of well-separated bands and comparing the results with the data from HITRAN database. The choice of the spectral features depends on the amount fraction range. In the concentrated samples the strong fundamental band at 1600 cm⁻¹ is saturated, hence the combinations at 2900 cm⁻¹ should be used.

Absorption spectroscopy in the middle infrared region allows to evaluate not only the amount of the NO_2 monomer and dimer, but also gives estimates for the sample impurities. **Figure 2** shows the simplified algorithm for assessing the NO_2 amount in mixture depends on the amount fraction range using infrared spectrum.

VSL, NPL and Air Liquide produced nine high amount fraction NO₂ reference standards with NO₂ amount fractions of 500 (two reference standards), 1500 (one reference standard), 2000 (five reference standards) and 2500 (one reference standard) µmol mol⁻¹ in a matrix of synthetic air. Only VSL produced reference standards at all the amount fractions. The NO₂ reference standards were assessed for stability and the presence of the dimer by VSL and NPL using FTIR. The NO₂ amount fraction for all the reference standards was found to be stable over the 12-month stability period, however the analytical methods employed had relative uncertainties of 1.8 % for NPL and 2.5 % for VSL. The measured N₂O₄ amount fractions were relatively stable for all the reference standards, ranging from 0.4 % relative to the gravimetric NO₂ amount fraction at 500 µmol mol⁻¹ to 1.9 % for 2500 µmol mol⁻¹. VSL also measured approximately 1 % relative HNO₃ in the high amount fraction binary NO₂ reference standards, along with traces of CO and CO₂.



Air Liquide and VSL performed a theoretical thermodynamic and kinetic study of the reversible gas phase dissociation of N₂O₄ to NO₂ for ten mixtures (100 – 2000 µmol mol⁻¹) at different temperatures (15 – 30 °C, in steps of 1 °C) and pressures (800 – 1200 mbar, in steps of 100 mbar). VSL also performed measurements using FTIR which were largely in line with the results from the modelling considering the relatively large uncertainty (5 %) of the model, although deviation from the model at higher amount fractions was observed where the actual N₂O₄ measured was lower than predicted from the model (see Figure 2 below).



Figure 2: N₂O₄ amount fraction as function of the NO₂ gravimetric amount fraction. The red line shows the values derived from the equilibrium model and the blue points are the FTIR measurement results of the gas standards developed within MetroPEMS by VSL.

The position of equilibrium is strongly dependent on the temperature, with less N_2O_4 and more NO_2 observed at elevated temperatures. For example, for a 2000 µmol mol⁻¹ NO_2 mixture, the N_2O_4 amount fraction is about 25 % higher at 20 °C than at 23 °C. The equilibrium position is much less dependent on pressure. The time taken to reach equilibrium was evaluated to be less than 1 millisecond under standard conditions and so could be considered instantaneous for most practical purposes.

VSL and Air Liquide produced six multicomponent reference standards of NO₂ (500 – 2400 μ mol mol⁻¹), NO (900 – 2400 μ mol mol⁻¹), CO (0.5 – 4.5 cmol mol⁻¹) and CO₂ (14 – 18 cmol mol⁻¹) in a matrix of nitrogen and measured the stability for 12 months. The amount fractions of the components were stable within the uncertainties for the 12-month period tested, although a bias of approximately 1.5 % at 2400 μ mol mol⁻¹ NO and 2.5 % at 500 μ mol mol⁻¹ NO was observed. In the multicomponent reference standards VSL measured approximately 1 % relative nitrous acid (HNO₂) rather than HNO₃. This is a new finding. Traces of water and formic acid were also observed.

Calibration and validation approach for RDE-PEMS

PTB applied a state-of-the-art traceable calibration method for NO_x amount fractions on the golden PEMS and the dTDLAS developed by TU-DA. It utilised static and dynamic NO₂ reference standards and cross-validation using NDUV. The standard reference method for NO_x is based on chemiluminescence EN14211:2012, however the use of a CLD with catalytical converter might not be recommended in certain scenarios. Since CLD is an indirect method for NO₂, catalytical conversion of NO₂ to NO is required for NO₂ determination, and it is carried out based on the assumed ratio of NO and NO₂. Hence, without NO, single NO₂ is not properly detected by CLD at some ranges. For example, in the PTB setup, a commercial CLD was running properly for NO₂ only up to 100 µmol mol⁻¹ amount fraction when there was no NO in the mixture. Therefore, more investigation on CLD to use for SI-traceable NO₂ amount fraction (e.g., above 100 µmol mol⁻¹) without a certain ratio of NO present is needed. Nevertheless, NO amount fractions alone can be directly measured irrespective of the range and calibrated against a gas standard without any proportion of NO₂ present. A detailed investigation of a commercial CLD is part of a planned publication by PTB, where the MetroPEMS project will be fully acknowledged.

NPL developed and built a portable dynamic dilution system based on sonic nozzles for the dilution of high amount fraction NO₂ reference standards. The system comprised of two diluent and eight parent sonic nozzles resulting in the possibility to generate 755 dynamic standards from a single parent reference standard. To assist with nozzle combination selection, software was written to optimise the selection based on criteria set by the user including flow rate requirements and the final dynamic standard amount fraction and uncertainty



requirements. The system was calibrated volumetrically and validated gravimetrically using CO, tested with CO, CO₂, NO and NO₂ and showed good agreement with static standards. The uncertainty of the generated dynamic standards depends on the standard uncertainty of the parent reference standard. When parent standards with an uncertainty of < 0.2 % were employed, the overall dynamic standard uncertainty was < 0.5 %. The developed dynamic dilution system was used to generate an independent reference for stability measurements and to calibrate the "golden PEMS" device.

NPL investigated the analytical measurement bias resulting from the matrix gas composition for the "golden PEMS" unit, testing four different matrix gas compositions (synthetic air; nitrogen; 0.5 cmol mol⁻¹ CO and 14 cmol mol⁻¹ CO₂ in nitrogen; 4.5 cmol mol⁻¹ CO and 18 cmol mol⁻¹ CO₂ in nitrogen). The response of the PEMS was found to be very sensitive to matrix gas composition, with up to 20 % and 30 % variation in NO and NO₂ sensitivity respectively. Significant non-linearity was also observed for the PEMS response to NO and NO₂ reference standards in a nitrogen matrix, however a linear relationship was observed for NO₂ reference standards in a synthetic air matrix. As NPL and PTB both independently found these biases in the analytical measurement of up to 30 % due to the matrix effect, this could not be included as an uncertainty component. Instead, the matrix effect should be more thoroughly evaluated and corrected for, and the uncertainty of this correction should then be included in the uncertainty budget. Another possibility is to use other measurement technologies with lower cross sensitivities, that support the use of a physical model to reduce the effort on characterisation.

To reduce the uncertainty of PEMS measurements, an analytical and mobile transfer standard is required to preserve the uncertainties obtained in the laboratory to the application of the PEMS in RDE testing. The analytical transfer standard is required to maintain performance while withstanding the exhaust system of a vehicle which experiences high temperatures (up to 850 °C), significant pressure changes (several hundred mbar in a fraction of a second), and a corrosive environment from the exhaust gases and particle content. TU-DA in collaboration with PTB developed an upgraded optical measurement cell for the simultaneous measurement of NO and NO₂ amount fractions using direct Tuneable Diode Laser Absorption Spectroscopy (dTDLAS). Studies were carried out and recommendations made on the options to operate the dTDLAS spectrometer as an analytical transfer standard or an optical gas standard (OGS), as well as to facilitate testing at the metrological test stand at PTB. The thermal stability and robustness of the optical setup was successfully tested using the test stand and a new White cell concept with 0.7 m path length showed high stability with the potential to be increased to 2.1 m. After further optimisation, absorption spectra of NO and NO₂ showed low noise and good agreement with the fitting model during laboratory testing. During further field tests using the test stand at PTB, different amount fractions of NO and NO₂ (100 – 2500 µmol mol⁻¹) were measured, and the dTDLAS results were in a good agreement with the reference values. Relative uncertainties of 10 % and 6.3 % were estimated for NO and NO₂ respectively, and in both cases the most significant uncertainty contributions were determined to be coming from the line intensity (98 % to 63 % contribution to the overall uncertainty) and line area (2 % to 36 % contribution to the overall uncertainty) used to determine the amount fractions. As such, to further improve the uncertainty of the dTDLAS measurements, further work is required to improve the uncertainty in the molecular line strength. The comparison to the reference values of the gravimetric gas standards (bottles) showed linear agreement. The deviations of the NO and NO₂ amount fraction results from the reference (i.e., 1.6 % for NO₂ and 5 % for NO) are much smaller than the overall uncertainties discussed above. TU-DA further upgraded the optical setup of the dTDLAS and optimised the size and robustness of the electronic periphery to make it suitable for mobile application as a mobile transfer standard. The new setup was tested in a measurement campaign at VTT and compared to stationary measurement equipment at VTT and the golden PEMS using the test stand and compared to the golden PEMS during RDE tests. The upgraded dTDLAS device was able to measure NO and NO₂ species in-situ and simultaneously with high temporal and amount fraction resolution (capable of measuring transient changes from tens to thousands of µmol mol⁻¹). The upgrades to the dTDLAS also improved the sensitivity of the instrument by a factor of two by improving the robustness through complete fibre coupling and improved thermal management.

The results of WP1 mark the still ongoing challenge to provide stable reference materials for the low amount fraction less than 10 µmol mol⁻¹. The calibration efforts undertaken on the golden PEMS showed the current situation of lack of metrologically-sound methods for guarantying a traceable calibration of RDE PEMS measurements. An improved infrastructure that allows in field performance validation of RDE PEMS devices was developed by means of an optical gas standard device.

Summary of the key outputs and conclusions for objective 1

• Static mixtures containing NO₂ at concentrations of 1 and 10 µmol mol⁻¹ were prepared and subjected to stability assessments over durations exceeding 12 months. The primary influence on uncertainties



was identified as the presence of H₂O impurity. Nevertheless, the attainment of target uncertainties was found to be feasible through the implementation of dynamic standard preparation techniques.

- A spectroscopic method to accurately characterise N₂O₄ in high amount fraction NO₂ reference standards was developed using an FTIR spectrometer.
- High amount fraction NO₂ standards were found to have stable dimer and nitric acid impurities over a period of > 12 months.
- The analytical measurement bias resulting from the matrix gas composition was investigated by testing four different matrix gas compositions. The response of the PEMS was found to be very sensitive to matrix gas composition, with up to 20 % and 30 % variation in NO and NO₂ sensitivity respectively.

This objective was successfully achieved.

4.2 Metrological validation and performance tests of PN-PEMS devices

Linearity and counting efficiency

Linearity and counting efficiency for PN measured by PEMS were determined in the different laboratories by following the European Commission Regulation (EU) 2017/1154. A round robin campaign involving three different NMIs was organised to compare results using the national primary standards for PN.

Polydisperse soot aerosol particles generated by a miniCAST soot generator was used in all linearity measurements. As a reference instrument, a faraday cup aerosol electrometer was used. For counting efficiency, different monodisperse sizes were produced, following the regulation specifications.

The multiple charge correction was estimated in different ways, as detailed in ISO 27891. Diffusion losses were evaluated according to the transport tubes and bents in the different setups that were used in the different experiments.

The linearity measured in the inter-comparison at different NMI laboratories is shown in Figure 4. Four different measurements were done during the course of the project: at METAS, NPL and two times at PTB. The results of all the linearity measurements are within the regulation limits: slope between 0.85 and 1.15 for a least-square linear regression and a coefficient of determination (R^2) > 0.950.



Figure 4. Linearity response obtained at different NMIs for polydisperse soot aerosol particles.

A comparison of linearity for monodisperse aerosol particles was done for different mobility diameters selected by a DMA. The results are shown in Figure 5. The smaller the particle size, the larger the discrepancies found among the different measurements done at the different NMIs. For example, for 23 nm CMD, there is a difference larger than 15 % between NPL and PTB, this decreases to < 6 % for 30 nm, which is within the expected range observed in previous comparisons. For particles larger than 50 nm, the three measurement results approach each other within 5 %.



Figure 6 shows the counting efficiency curve for monodisperse aerosol with the following CMD: 23, 30, 50, 70, 100 and 200 nm. The measurements done in the different laboratories show a good agreement and all fall within the regulatory limits, shown in the figure. The diameter where there is 50 % efficiency, d_{50} , was determined by applying a fit to the whole data set and corresponds to 23.8 nm, which is close to the nominal d50 for PEMS' CPC (23 nm).



Figure 5. Linearity results and linear fits corresponding to different monodisperse aerosol particles.





Figure 6. Counting efficiency for different monodisperse aerosol particles with diameters from 23 to 200 nm.

Volatile particle removal

Volatile removal efficiency (VRE) of PEMS was determined by measuring the upstream and downstream concentrations of semi-volatile tetracontane particles using two reference CPCs.

| | | 30 nm | | 50 nm | | | | |
|-------|--------------------------------------------------|----------------------------------------------------|---------|--------------------------------------------------|----------------------------------------------------|--------|--|--|
| | Upstream concentration (cm ⁻³) | Downstream concentration (cm ⁻³) | VRE | Upstream concentration (cm ⁻³) | Downstream concentration (cm ⁻³) | VRE | | |
| METAS | 103 592 | 12.67 | 99.99 % | 25 192 | 0.0038 | 100 % | | |
| NPL | 65 292 | 0.005 | 100 % | 56 366 | 0.0014 | 100 % | | |
| РТВ | 68 752 | 349 | 99.5 % | 9 150 | 71 | 99.2 % | | |

Table 1. Volatile removal efficiency for 30 and 50 nm tetracontane particles measured at three different laboratories.

The results shown in Table 1 meet the regulation requirement of a VPR factor larger than 99 %. Although, the amount of tetracontane particles downstream of the PEMS unit was slightly larger for the PTB measurements, the VRE was still within the limits.

Particle penetration efficiency

The particle penetration efficiency is not included in the European Commission Regulation (EU) 2017/1154 but was part of the parameters to be tested in this project to understand the particle dilution and measurement process within the PEMS instrument. The results, shown in the table below, indicate that larger particles are more efficient in being transported through the piping and dilution system compared to the smaller particles. To determine the penetration efficiency factor, the gas dilution factor is required, also shown in the table below. The gas dilution factor was measured for certified CO_2 (5%) and was in the order of 49 – 59, as measured in two different laboratories.



| Particle mobility diameter (nm) | Penetration efficiency (%) - NPL | Penetration efficiency (%) - PTB | | | | |
|---------------------------------|-------------------------------------|-------------------------------------|--|--|--|--|
| 23 | 42 ± 3 | 56 ± 5 | | | | |
| 30 | 50 ± 4 | 67 ± 5 | | | | |
| 50 | 59 ± 4 | 77 ± 5 | | | | |
| 70 | 58 ± 4 | 81 ± 6 | | | | |
| 100 | 64 ± 5 | 78 ± 6 | | | | |

| Table 2. | Particle | penetration | efficiency | for different | mobility diameters |
|----------|----------|-------------|------------|---------------|--------------------|
|----------|----------|-------------|------------|---------------|--------------------|

In-field linearity check

For a PN linearity check in the field it was necessary to deploy a particle generator and dilution system in the RDE workshop at VTT. The PN concentration upstream of the PEMS was measured by using a reference CPC. This setup was able to provide PN concentrations in the range from 5×10^3 to 1.2×10^7 cm⁻³. Four different linearity tests were performed before and after RDE tests (two before and two after). The results can be seen in Figure 7. All the linear fits fulfilled the regulatory requirements in terms of scope and coefficient of determination. Although we observed changes in the slope values before and after RDE tests, there is no conclusive evidence of an aging effect on the sensitivity of the PEMS PN sensor. The in-field linearity check realised in this project resulted in a relative expanded uncertainty of 16 % (k = 2) for PN concentration measured by a CPC-based PEMS.



Figure 7. Linearity checks performed before and after RDE tests. PEMS is compared to a reference CPC.

Summary of the key outputs and conclusions for objective 2

- An instrument intercomparison was done for linearity, particle counting efficiency and particle concentration dilution factor in three different laboratories. The largest discrepancies between the measurements were found for particles with diameter below 30 nm.
- The gas dilution factor, needed for determining particle penetration efficiency, was found to be influenced by the gas matrix, with deviations up to 17 %.

This objective was successfully achieved.



4.3 Application-oriented PEMS EFM calibration procedures and uncertainty budgets

Uncertainty from the exhaust flow meter (EFM) is a dominant component in the uncertainty associated with PEMS on-road emission measurements of pollutants, which can be understood from the instantaneous emission measurement of the PEMS expression as defined in the RDE regulation [1]:

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

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 [1], 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) 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 [2].

The approach taken to address the third objective is schematically depicted in Figure 8. A literature study was conducted 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 (left side of Figure 8). For some of the influencing variables quantitative uncertainty information could be found and incorporated into the uncertainty budget (number displayed). For other influencing variables such information could not be found (no number displayed). In the generic uncertainty budget, effects that were studied as part of the project are indicated with green highlighting, while those for which no quantitative uncertainty information could be found from literature, nor were investigated in the project are indicated in red. The panel on the right entitled "Dedicated EFM uncertainty experiments" indicates how the guantitative uncertainty information highlighted in green in the generic uncertainty budget was obtained. Experimental and calibration capabilities of partners KIT, VSL, and VTT were combined to obtain information from influencing variables in dedicated setups. In a first step, VSL calibrated the EFM in controlled laboratory circumstances to establish a groundtruth by calibration of the EFM to be tested, ensuring the proper functioning of the EFM and knowing the SItraceable measurement error and uncertainty prior to subjecting it to any influencing variable, such as vibrations, dynamic flow effects, or elevated gas temperatures. Following steps were comprised of dedicated experiments at the KIT transient dynamometer setup, the VTT dynamometer setup, and in VSL laboratories.



Figure 8. Schematic of the research plan to address the third objective to estimate uncertainty in representative RDE-driving conditions comprising (I) application-oriented calibration procedures, (II) for relevant carrier gases, and (III) to investigate the



uncertainty from dynamic flow effects on the EFM. The total uncertainty listed in the bottom row of the generic uncertainty budget is for illustrational purposes only.¹

Figure 9 illustrates an example of the investigation into the effects from influencing variable pulsations. Figure 9 (left) displays the "calibration"² of an EFM. A strong (i.e., > 10 %) effect on the EFM error 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 total calibration is of the same order given the relatively small Calibration and Measurement Capability (CMC) at 0.15 % of flow rate [5]. Figure 9 (right) 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 9 (left).



Figure 9: Calibration result of EFM when introducing flow pulsations (left) [4] and flow rates recorded by the EFM during on-road tests (right). Total calibration uncertainty in the left figure is indicated by the error bars. Solid black lines indicate required accuracy from RDE [1].

Best capabilities were combined by the collaborating participants to yield the most EFM uncertainty information for on-road conditions possible: KIT investigated EFM uncertainty from dynamic flow (load) changes, gas temperature, and variable gas composition. VTT investigated the relation between CVS-validations of the EFM and the (independent) SI-traceable calibration result, and EFM uncertainty from dynamic flow (load) changes using a fast-responding fuel intake sensor and the link to the requirement set out in the RDE. VSL performed the SI-traceable (check) calibrations, and EFM uncertainty from electromagnetic radiation effects, pulsating flows, and ambient temperature effects.

The work resulted in the following conclusions taken mostly from [4,7]:

- No SI-traceable datasets showing exhaust flow meters fulfilling the 3 % accuracy legal limit in on-road test conditions nor in laboratory conditions were found in literature.
- The 3 % accuracy legal limit was fulfilled in SI-traceable calibration for two EFMs calibrated in MetroPEMS, in calibration laboratory (controlled) environment.
- For the two EFMs tested, the indications of EFM drift are within the limits set in Joint Research Centre literature [5,6].

¹ The generic EFM uncertainty budget should be tailored to specific EFM (flow meter type (ultrasonic, averaging Pitot), size, model, manufacturer, and serial number), and the circumstances in which it was operated (e.g., cold start, assoling/discal_dupamic.flow.affacts_and_prossure/temperature.affacts) to estimate the uncertainty in a specific op_road

gasoline/diesel, dynamic flow effects, and pressure/temperature effects) to estimate the uncertainty in a specific on-road test.

² The quotes indicate that the Figure 9 (left) result cannot formally be considered a calibration because the metrological requirements for obtaining the calibration result are not met when the pulsations occur.



- Legal limit was not met for flow rates above about 50 % of the maximum flow rate in an experiment where pulsations were introduced. The type of pulsations studied is not known to be observed in onroad conditions.
- No effects were observed from electromagnetic influences for the tests presented, while one literature source did report an effect.
- No systematic influences on EFM measurement were distinguished from: measuring range, exhaust gas temperature, or load changes.
- Strong indications were found that ice and/or condensed water can affect EFMs based on the averaging Pitot tube measurement principle.
- To the knowledge of MetroPEMS researchers so-called line pack effects are not considered in EFM performance studies, e.g., when placing them in series. Particularly due to the large temperature changes that can occur, some of the relative differences between EFM readings may be attributable to line pack effects.
- 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.

During the final stakeholder workshop recommendations for improving EFM uncertainty were formulated as follows:

- SI-traceability and calibration
 - Analyse, quantify and record drift of the EFM and completely register adjustments of calibration factors. Repeated SI-traceable laboratory calibrations should provide the required information. Ensure recalibration interval is fit-for-purpose given accuracy requirement.
 - The generic EFM uncertainty budget should be tailored to the specific EFM (flow meter type (ultrasonic, averaging Pitot), size, model, manufacturer, and serial number), and the circumstances in which it was operated (e.g., cold start, gasoline/diesel, dynamic flow effects, and pressure/temperature effects) to estimate the uncertainty in a specific on-road test.
 - Make transparent how EFM volume flow is converted to EFM mass flow by density. Take uncertainty from density measurement and computation into account.
 - Consider the current 3 % (of reading) EFM accuracy requirement as defined in the RDE as the lower limit for EFM's based on the averaging Pitot tube principle. Improved accuracy of averaging Pitot's will have to be shown.
- Analyse the EFM raw recordings for indications of flow pulsations. It applies both to calibrations as when using the EFM in any type of test.
- Avoid circumstances where clogging of Pitot tube holes (by icing or dust) can occur.
- Analyse line pack/density effects when comparing EFMs in series (or alternative). Differences observed may be (partly) explainable from density changes in the interconnecting volume between the devices.

When relating to the objective 3 of the EFM, the application-oriented calibration procedure and uncertainty budget are provided by considering that the generic uncertainty budget, including the SI-traceable EFM calibration, should be tailored to the specific EFM (flow meter type (ultrasonic, averaging Pitot), size, model, manufacturer, and serial number), and the circumstances in which it was operated (e.g., cold start, gasoline/diesel, dynamic flow effects, and pressure/temperature effects) to estimate the uncertainty in a specific on-road test. The effects from dynamic flow changes and from variable carrier gases were investigated by comparison of integrated mass flows for a variety of PEMS-systems, vehicle types (petrol, diesel, and hybrid), and exhaust gas mixtures. No definite quantitative figures on uncertainty influences could be provided; rather improvements in the EFM verification procedures were proposed.

Summary of the key outputs and conclusions for objective 3

• An uncertainty budget in representative RDE-driving conditions was provided and the 3 % accuracy legal limit was fulfilled in SI-traceable calibration for two EFM units.



• In experiments introducing pulsations, the legal limit was not met for flow rates exceeding approximately 50 % of the maximum. It's worth noting, though, that the specific type of pulsations investigated is not known to occur in on-road conditions.

This objective was successfully achieved.

4.4 Real-world assessment of PEMS performance

The main motivation for the work related to real-world assessment of PEMS performance was to validate and to define factors affecting the performance of PEMS devices. Another main element for the work was to study the correlation for PEMS response between laboratory and RDE measurements. This evaluation was performed both on a system level and for the individual PEMS channels, CO₂, CO, NO, NO₂, PN, exhaust mass flow. The collective goal was to quantify the correlation between i) RDE-PEMS measurements and laboratory dynamometer test results, ii) individual PEMS "channels" for CO₂, CO, NO, NO₂, PN, exhaust mass flow and iii) validated 'golden' (reference) PEMS and commercially available PEMS.

Experimental evaluation of PEMS performance

The performance evaluation of the PEMS devices was performed by setting up a test matrix consisting of both in laboratory tests and RDE measurements. The PEMS devices were evaluated by VTT and DTI between 2021 and 2023 using real world applications, i.e., with four Euro 6 emission class passenger cars. The tests were executed in two countries, Finland, and Denmark with close support from project partners, PTB, NPL, VSL and KIT. During the work four PEMS devices were evaluated, three commercially available PEMS devices and the project PEMS device, known as the goldenPEMS. The PEMS devices evaluated may be divided by device technology into two device types (called type 1 and type 2). One commercial PEMS device had remained stationary in each country for the whole test period (one type 1 PEMS in both countries), meanwhile two of the PEMS devices (type 2 PEMS devices), one commercial PEMS and the goldenPEMS were sent between the two countries for back-to-back testing with the type 1 PEMS devices, whenever applicable. The performance evaluation started in Finland, where the two different PEMS types were installed in series. This process was repeated for two vehicles in each country. Then a series of CVS validations in laboratory conditions were conducted using the WLTC cycle, followed by a series of RDE tests. After the evaluation was completed in Finland, the type 2 PEMS device was sent to Denmark for further testing evaluation. There, type 1 and type 2 PEMS devices were similarly tested with two other vehicles in RDE conditions. This process was repeated for both the commercial type 2 PEMS device and the goldenPEMS device. The test campaigns were timed such that device robustness of PEMS type 1 could be studied and any deterioration effects of e.g. device ageing or other factors could be assessed. Therefore, all tests conducted with the commercial devices type 1 were scheduled such that the device would be either as close to its annual service interval, or tested just after the annual service, as shown in Figure 10Error! Reference source not found.. The main subjects studied during the experimental testing:

- PEMS analyser pre- and post- test response.
- In laboratory testing, CVS validations with WLTC.
- Back-to-back comparison of PEMS devices in RDE conditions.
- Correlation of PEMS response between WLTC- and RDE-testing.
- Assessment of different PEMS device technologies in terms of individual channels.
- Performance of goldenPEMS.



EURAME¹

Figure 10. An overview of the test principle conducted between 2021 – 2023.

Summary of PEMS analyser pre- and post- test drift response

The drift response of PEMS devices were monitored throughout a three-year period, between years 2021 - 2023. The analyser drifts for the PEMS device, which was most extensively used are shown in Figure 11. The results may be summarised as the following:

- The results obtained between 2021 2023 suggest that any changes in the overall condition of the PEMS devices may be identified based on long term pre/post response trends.
- The current limits for the permissible analyser drifts were generally well met even with aged devices.
- Based on long term tests, permittable pre/post-test threshold for gaseous components could be reduced from 2 % to sub 1 % limit depending on device technology
 - \circ ND-IR drift was typically within ± 0.5 % (Figure 11 a.)
 - \circ ND-UV drift was typically within ± 0.2 % (Figure 11 b.)
- The ADC based PN analyser suffered from continuous internal errors. Rapid deterioration occurred between the service intervals, which prevented to successfully conduct pre/post testing.
 - When working properly, the typical zero values was below 1000 #/cm³ with relatively modest analyser drifts.



Figure 11. Span drift results for PEMS type 1 ND-IR based CO_2 and CO analysers and ND-UV based NO, NO_2 and NO_x from 28 PEMS tests.

Summary of CVS validations

Three PEMS devices in total were tested in laboratory conditions using a chassis dynamometer and a CVS system. The deviations for the two PEMS types compared to CVS results are shown in Table 3. Any cells marked in yellow exceed the permissible tolerances of Euro 6e regulation. Additionally, values marked in red exceed the permissible tolerances defined in the RDE4 regulation.



The general observations obtained from the PEMS validations in laboratory conditions are:

- When working as designed, the performance of the current commercial PEMS devices was typically well within the permissible tolerances defined in the RDE4 and Euro 6e regulation.
- For PEMS devices used in this work, the ageing effects affected the device performance case by case. E.g., not all ND-IR units face identical problems.
- Type 1 PEMS ND-IR and ND-UV units were found robust throughout the three-year period, meanwhile type 2 ND-IR suffered from issues with a pre-used device as seen in Table . The ND-IR for the goldenPEMS (type 2 based PEMS) was however satisfactory.
 - PN PEMS response varied greatly depending on the vehicle exhaust emissions.
 - The tested ADC faced challenges with permissible deviation when the test object produces PN emissions close to the emission limit.

| | | | | | | | PEMS TYPE 1 | | | | PEMS TYPE 2 | | | | |
|------------------------------|-----------------------|-----------------------|------|---------------|---------------|--------------------------------------|-------------|------------------------------------|---------------------|--------------------------------------|-----------------------|------------------------|---------------------|-----------------------------|-----------------------|
| Test information CVS results | | | | | | PEMS Deviation compared to CVS [abs] | | | | PEMS Deviation compared to CVS [abs] | | | | | |
| | PEMS type 1 status | PEMS type 2 status | Year | CO2 [g/km] | CO [mg/km] | NOx [mg/km] | PN [#/km] | ND-IR CO ₂ (g/km) | ND-IR CO (mg/km) | ND-UV NOx (mg/km) | ADC PN (10^11#/km) | ND-IR CO2 (g/km) | ND-IR CO (mg/km) | CLD + PAS NOx (mg/km) | CPC PN (10^11#/km) |
| Diesel | Aged | | 2021 | 124.1 | 11 | 19 | 1.0E+09 | 5 | 167 | 4 | 0.00 | | | | |
| Diesel | Used, serviced | Used, serviced | 2021 | 130.6 | 7 | 26 | 1.7E+09 | 2 | 4 | 5 | 0.01 | 14 | 7 | 7 | 0.0 |
| Diesel | Aged | Used, serviced | 2022 | 122.4 | 13 | 35 | 3.6E+10 | 10 | 10 | 5 | 0.33 | 14 | 1 | 12 | 0.3 |
| Diesel | Aged | goldenPEMS | 2023 | 127.0 | 11 | 28 | 1.0E+09 | 6 | 5 | 8 | 0.00 | 3 | 2 | 3 | 0.0 |
| Gasoline | Aged | | 2021 | 165.3 | 83 | 27 | 4.5E+11 | 6 | 10 | 2 | 2.27 | | | | |
| Gasoline | Used, serviced | Used, serviced | 2021 | 166.3 | 144 | 31 | 2.4E+11 | 8 | 8 | 2 | 1.07 | 27 | 19 | 8 | 2.1 |
| Gasoline | Used, serviced | Used, serviced | 2021 | 159.6 | 94 | 22 | 2.3E+11 | 7 | 10 | 3 | 0.87 | 28 | 13 | 0 | 1.9 |
| Gasoline | Aged | goldenPEMS | 2023 | 160.4 | 96 | 25 | 3.0E+11 | 5 | 4 | 5 | 1.52 | 5 | 11 | 0 | 0.2 |
| Gasoline | Aged | goldenPEMS | 2023 | 159.9 | 86 | 25 | 3.0E+11 | 5 | 3 | 4 | 1.34 | 4 | 12 | 0 | 0.2 |

Table 3. WLTC test results for laboratory reference with respective PEMS deviations for three tested PEMS devices



Summary of RDE testing

The performance of the two different PEMS types were compared back-to-back in RDE conditions. The data of the RDE tests were analysed based on both momentary and trip based emissions. The main findings from RDE tests may be summarised as the following:

- CO₂ was found problematic for the hybrid vehicle due to different response time of analysers. For all other vehicles CO₂ was detected adequately by both PEMS systems.
- CO concentration was sometimes extremely high at engine startup. However, the mean concentrations were well below legal limits for all vehicles tested. The overall agreement between the two PEMS systems was found good except for the gasoline hybrid.
- NO was detected reasonably well by both PEMS types.
- NO₂ was typically less than 4 ppm average which was not detected well by Type 1 (NDUV).
 - Signal drift for ND-UV NO₂ was significant and contributed with a majority of recorded NO₂.
- Negative values of CO and NO2 are sometimes indicated by the PEMS sensors. PEMS Type 1 records these values as negative, PEMS Type 2 records them as zero. PEMS Type 1 can therefore produce a negative end-result, while Type 2 cannot as shown in the example, Figure 12.
- Measurement of exhaust mass flow was challenging on hybrid gasoline vehicles due to high flow and high moisture at startup. For other vehicles, the readings correlated well.
- Measured PN can vary by more than ±50 % depending on measurement system. However, the difference between vehicles is much larger, up to several orders of magnitude.





Figure 12. Average NO₂ emissions recorded by PEMS type 1 and PEMS type 2 in 24 RDE tests.

Correlation of PEMS response between WLTC- and RDE-testing

The correlation between in laboratory (WLTC) and RDE testing was analysed based on data from the individual PEMS channels obtained in WLTC and RDE respectively. The results indicated that the correlation between laboratory dynamometer and RDE tests was more evident for some emissions components than others. The findings of these trends may be summarised per PEMS channel as the following:

- CO₂ Despite agreement for the two PEMS devices was typically satisfactory, no evident correlation between the deviation obtained in WLTC and RDE was found as seen in Figure 13. The difference in analyser response was concluded to be rather dependent of vehicle/fuel type.
- CO The deviation for analyser response was found relatively random especially for results with low trip CO emissions. The agreement between the two PEMS devices typically improved for higher CO emissions and vice versa. Despite high deviation in vehicle CO emissions, the response between the two PEMS devices in WLTC was found similar as in RDE as shown in Figure 13b.
- NO_x All vehicles typically produced relatively low NO_x emissions during normal operation. In these cases, the two PEMS types agreed within ± 12 % both in laboratory and in RDE testing. The difference between the device response was lowest (ca. 3 4 %) for one of the gasoline vehicles measured in RDE conditions. The results showed that ND-UV unit in these cases typically recorded higher NO_x results compared to the PAS device. Challenges in device agreement were seen when extremely low or high NO_x emissions were emitted as seen in Figure 14a.
- PN The response between the two PN PEMS devices was found dependent on recorded PN emissions. Best agreement between the two PEMS types were recorded when the vehicles would produce total PN around 1*10¹¹ #/km. Meanwhile the ADC based PN device agreed better with the CVS result for tests producing lower PN. The deviation between CVS results and PN PEMS was lower for the CPC based PN device for tests with higher PN emissions. The results suggest that the two PN PEMS devices may be tuned for different concentrations. The data produced both in laboratory and in RDE conditions indicate similar trends regardless of test condition, as seen in Figure 14b.
- EFM The deviations between the two EFM devices were generally relatively minor. In WLTC, lower exhaust mass was produced, but the deviations recorded were within the values obtained in RDE as shown in in Figure 15a. However, the EFMs agreed generally better for the diesel vehicle compared to the gasoline counterparts. This was a result of engine characteristics, as the diesel engines lack throttling effects. This in turn results that the lowest exhaust mass produced by the engine typically remain above the last 3 % of the measuring range as seen from one example recorded in Figure 15b.





Figure 13 a) *Relative deviation for CO between the two PEMS types compared to CVS. b*) *Deviation in trip-based CO results between the two PEMS device types in WLTC and in RDE conditions.*



Figure 14 a) Deviation in trip- based NO_x results between the two PEMS device types in WLTC and in RDE conditions. b) Deviation in trip-based PN results between the two PEMS device types in WLTC and in RDE conditions.



Figure 15 a) Deviation in cumulative EFM results between the two PEMS device types in WLTC and in RDE conditions. b) Deviation between PEMS type 2 and PEMS type 1 EFM reading in relation to the exhaust mass collected from PEMS type 2 data.

Summary of the key outputs and conclusions for objective 4 - Deployment, development and implementation of golden standards and goldenPEMS

During the MetroPEMS project, partners studied, developed and deployed golden measures for a commercially available PEMS device. For example, AirLiquide, LNE, NPL and VSL developed several golden gas standards explicitly for NO₂ in synthetic air (SA) matrix. NPL studied and created novel procedures for gas PEMS calibration and data correction. PTB and NPL developed a transfer standard for PN calibration. VSL and KIT studied any potential factors for improving the quality of EFM devices. Some of the main procedures were



directly implemented during the in-field tests conducted in Finland and Denmark. The main conclusions for the implementation of the goldenPEMS may be summarised as the following:

- NO₂ Calibration for the PAS based analyser was found unstable. Not planned, non-linear corrections could be applied due to excessive drift for original golden calibration that was found. Because of this, only linear corrections for analyser response were possible. However, implementation of golden NO₂ gas standards in SA matrix increased the stability of the analyser drift recorded from the pre/post-tests. This effect was more significant in colder ambient conditions. Because modern vehicles produce very low NO₂ concentrations and thus low NO₂ emissions, the impact of applied golden corrections implemented for NO₂ was typically relatively low. In fact, the characteristics and type of NO₂ analyser were concluded to be more significant, nonlinear drift during the tests, which contributed to increased NO₂ emissions. This was not the case for the goldenPEMS, which was only slightly affected by the gas adjustments used as shown in Figure 16.
- PN Currently, only zero response for PN is checked during the PEMS/RDE test procedure. The activities
 implemented in this project successfully demonstrated solutions enabling in field linearity checks for PN PEMS
 analysers. The linearity check was conducted using a soot generator. As reference, a laboratory grade CPC
 was used.
- EFM Because the lower end of the measuring range is known to be challenging for pitot-based EFM devices, alternative procedures for defining exhaust mass flow in the low flow conditions were compared. One method, which was tested in detail, was a fuel consumption-based method. The fuel consumption data were extracted using a high frequency, traceable fuel meter installed in the vehicle fuel line. Since an estimation of fuel composition and air-to-fuel ratio was possible, the momentary exhaust mass flow could be calculated based on these variables. The method proved to be highly potential, albeit further amendments and work would be required from the regulation and technical point of view. Biggest challenges are related to determination of fuel composition, which has a key role in scaling the produced exhaust mass.



Figure 16. An example of momentary NO₂ response for the goldenPEMS with applied standards compared to the NO₂ response for the ND-UV based PEMS type 1 device in a RDE test.

This objective was successfully achieved.

5 Impact

The project's outcomes were disseminated to stakeholders and industrial end users through public training courses and workshops focusing on good practices and methods for PEMS calibration. Three different training activities were organised during the course of the project: MetroPEMS stakeholder workshop (December 2020), MetroPEMS technical training course (August 2023) and MetroPEMS final workshop (August 2023).

In addition, the project was disseminated via publications at scientific conferences and in scientific journals as well as via trade journals such as AWE International.

Project outputs have been also presented at international conferences such as ETH conference on nanoparticles 2021, 2022, and 2023, Zurich, Switzerland; European aerosol conference 2023, Malaga, Spain; Flomeko conference on Flow measurement 2022. China; International Aerosol Conference 2022, Greece and Metrology for Climate Action conference (WMO-BIPM) 2022, online.



The main outputs of this project are improved standards for the determination of NO/NO₂ concentrations, PN and exhaust mass flow (objectives 1-3), real-world comparison of PEMS performance (objective 4) and the production of calibration guidelines for PEMs. The improved calibration standards include static and dynamic references, as well as transfer standards. These improved reference standards and the real-world assessment of PEMS performance will significantly advance and improve confidence in the traceability of PEMS measurements. The project outcomes were presented to two different standardisation committees including the Particle Measurement Programme of the United Nations Economic Commission for Europe (2022 and 2023) and the EURAMET TC-Flow (2021).

The project outputs are available via the website <u>https://metropems.ptb.de</u>. Additionally, dissemination also took place via LinkedIn. Metadata and reports generated in the project are openly made available on Zenodo <u>https://zenodo.org/communities/metropems/</u>.

Impact on industrial and other user communities

The most recent regulations on RDE for TA have put significant pressure on research and development throughout the whole automotive manufacturing supply chain. This project has created impact by supporting this research and developments and by providing traceable calibration methods as well as a support infrastructure for NO_x/NO₂ (objective 1), PN emission measurements (objective 2), and EFM (objective 3). These traceable calibration methods were tested in real-world applications (objective 4) and calibration guidelines were produced. The consortium has good connections with PEMS manufacturers and included them as part of the project's stakeholder committee. The project's outputs are useful to industrial end users and provide enhanced quality procedures to measure vehicle exhaust emission using PEMS.

This project extended the measurement capabilities of the participating NMIs, by the development of a support infrastructure for NO_x, PN and EFM. This includes improved flow calibration services for PEMS exhaust flow for VSL, new measurement services for primary reference materials of NO₂ from 1 – 2500 μ mol/mol for NPL and VSL, and new calibration services for PN-PEMS for PTB, NPL and METAS. In addition, PTB has introduced a 'golden' PEMS calibration service for use by end-users.

Impact on the metrology and scientific communities

The partners in this consortium were active in the BIPM Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) Working Group on Gas Analysis (GAWG) and EURAMET Technical Committee of Metrology in Chemistry (TC-MC), therefore the outputs of this project were presented to both groups. The improvements of high accuracy primary reference materials of NO₂ and the validation of PEMS PN measurements will support future activities of the metrology community to assure comparability among SI traceable standards, e.g., via key comparisons. Improved NO₂, PN and exhaust flow calibration and measurement capabilities have been made available to the scientific community via NPL, PTB and VSL.

Impact on relevant standards

The TCs predominantly targeted by this project were ISO/TC 158 (Gas Analysis), ISO TC24/SC4, WG12 on aerosol measurements and CEN TC 264 Air quality. The partners are members of these committees and ensured that the knowledge developed within the project was fed to the committees. This interaction ensured that the project's outputs were fed directly into the standardisation activities, and the requirements emerging from the standardisation committees were used to refine the project in order to maximise its impact.

Longer-term economic, social and environmental impacts

Vehicle emissions contribute to atmospheric PM, NO_x and tropospheric ozone pollution, which in turn affect the climate, human health and agricultural yields. In particular, diesel combustion vehicles produce a significant amount of NO_x. Stricter European regulations have been established to tackle emissions, however, it has been found that vehicles were emitting under real-world driving conditions as opposed to laboratory tests and therefore current results are not fully comparable. By providing high quality reference standards and traceability to PEMS measurements, this project supports the improvement of air quality across the EU and will potentially facilitate their uptake by other countries that adopt similar TA tests for light-duty vehicles.

In addition to the environmental benefits, economic and social impacts are also expected. The European car industry is a growing sector that provided the EU with a trade surplus of \in 90.3 billion in 2018. The European TA regulations for light duty vehicles require these to be tested by RDE PEMS. Therefore, the creation of calibration guidelines and a metrological infrastructure for such testing is essential to provide confidence in the results.



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This list is also available here: <u>https://www.euramet.org/repository/research-publications-repository-link/</u>

8 Contact details

Jorge Saturno, PTB

Tel: +49 531 592 3217

E-mail: jorge.saturno@ptb.de