# On-road emission measurements beyond type approval PEMS

Norbert Ligterink[1], Michal Vojtisek,[2] Uilke Stelwagen[1], Sam van Goethem[1]

[1] Sustainable Transport and Logistics, TNO, The Hague, 2595 DA, The Netherlands

[2]Center for Sustainable Mobility, Czech Technical University in Prague, Technicka 4, 160 00 Prague, Czech Republic

Keywords: PEMS, NOx, MAF, RDE, FTIR 3-5 key words

Presenting author email: norbert.ligterink@tno.nl

## Introduction

Exhaust emissions from internal combustion engines used in cars, trucks and various mobile machinery remain one of the most important sources of air pollution in metropolitan areas. The increasing discrepancy between legal emission limits and real-world emissions is partly due to engine design and calibration deficiencies, a manufacturing defect common to all vehicles of the same certification family, and partly due to the contribution of excess emitters, vehicles with high emission levels due to spontaneous defects and tampering. The new type-approval procedure, Real Driving Emissions (RDE) tests, are carried on the road, with portable emissions monitoring systems (PEMS) used to measure tailpipe emissions. These have been adopted in major legislations for automobiles (RDE) and heavy vehicles (PEMS ISC). Moreover, older vehicles may develop undetected malfunctions, which require emission measurements.

The currently applied PEMS have, however, some constraints and limitations. Firstly, contemporary PEMS measure only the "classic" pollutants, such as nitrogen oxides ($NO_x$). However, there appears to be a need to expand the on-road measurements to emerging pollutants of concern, such as ammonia ($NH_3$), e.g., relevant for eutrophication, and nitrous oxide ($N_2O$), a strong greenhouse gas. Secondly, the measurement of hot and pulsating exhaust gas flow with PEMS has been shown to have limitations. Within RDE emission legislation a 43% uncertainty margin is included based on the observed inaccuracies in PEMS measurements. This margin has been reduced to 32%, and a further reduction to 23% has been recently proposed by JRC. The European Commission aims to bring this margin down to zero, which is met with great opposition, from the collection of observed issues with the current PEMS equipment. In this paper other on-road emission measurement techniques are discussed that can help us to overcome these limitations of PEMS, via alternative approaches.

The PEMS designed for type approval testing currently include four gaseous pollutants: CO and $CO_2$, typically measured by a non-dispersive infra-red (NDIR) spectroscopy, and NO and $NO_2$, typically measured by non-dispersive ultra-violet (NDUV) spectroscopy or by chemiluminescence. On modern diesel engines, CO emissions are hardly an issue, and $CO_2$ concentrations can be inferred, albeit with an accuracy penalty, with a wide-band oxygen sensor mounted in the exhaust, if the fuel composition is known. In-situ $NO_x$ sensors, frequently used on engines with selective catalytic reduction (SCR) devices, have been shown to provide a reasonably accurate determination of the concentrations of either $NO_x$, or $NO_x$ plus some other reactive nitrogen species, in the exhaust. For practical purposes of identifying problematic vehicles and/or operating regimes, simple devices using in-situ $NO_x$ and oxygen sensors, coupled with OBD-derived flow, can be used in lieu of PEMS.

With the deployment of $NO_x$ aftertreatment technologies and advanced and alternative fuels, additional gaseous pollutants are worthy of consideration: potent greenhouse gases methane ($CH_4$, from methane based fuels) and $N_2O$ (formed mainly in $NO_x$ aftertreatment devices, like SCR); $NH_3$ and potentially other reactive nitrogen species, produced in three-way catalysts and SCR systems; aldehydes associated with ethanol addition in fuels. Most of the mentioned compounds, as well as all regulated compounds measured by type approval grade PEMS, can be measured with Fourier Transform Infra-Red (FTIR) analysers, already approved for laboratory measurements of $NH_3$ and $N_2O$ measurements, with several instruments being also demonstrated and validated, at least for some pollutants, on the road.

The current legislative approach mandates a direct exhaust measurement with a device based on the difference between static and dynamic pressure. This technique provides a direct measurement right at the sampling point, eliminating errors associated with conversion and residence time of gases in the vehicle exhaust system, but it has downsides: It requires a reasonably laminar flow, achieved by a relatively considerable length of straight pipe. As the pressure difference is proportional to the square of the mean velocity of the measured gas, its useful range is about one order of magnitude, which is close to, or even less than, the ratio between exhaust flow at full load and that at idle.

In this paper alternative measurement approaches are discussed. This includes determination of the exhaust flow from measured or computed flow of intake air or fuel. For that purpose also separate flow sensors have been installed. In

addition, using a trace gas, and a known dilution of the exhaust gas is discussed as a simple alternative. Attaching a pitot tube to the exhaust also allows to measure the exhaust gas flow. Retrieving intake air flow or fuel flow reported by the engine through on-board diagnostics (OBD) interface, when such data are available and reliable, is the simplest and the least intrusive method. The quality of different OBD signals can be tested by simple calibration methods, for example, with a flow measurement system attached to the engine air inlet.

## 1. Analysis of $NO_x$ sensor amplitude data

Sensor measurements can assist, possibly replace, the PEMS measurements. In the case of deviations of the PEMS system from a sensor reading, this can be reason to investigate the measurement accuracy further. Automotive sensors have been around for many years now, and are intended to assist or control the emission aftertreatment systems. Typically they last for 2000 to 5000 hours. To show the capabilities and limitations of such sensors, the in-line offset determination is discussed. In case of a suspected sensor failure, the sensors are re-calibrated at TNO in the laboratory.

Hypothesis

The amplitude distribution of $NO_x$ sensor data may contain information on the functioning of the sensor. In particular, shifts in the distribution of the low $NO_x$ amplitudes during motoring ($O_2$>19%, no fuel injection) might indicate sensor drift due to aging or damage over time and might be used as a sensor data quality indicator or a precursor of sensor failing.

Approach

The $NO_x$ sensor data of three broken/failed $NO_x$ sensors were analysed together with the data of two still functioning sensors. The five used sensors are same brand and type $NO_x$ sensors as used in TNO SEMS monitoring of vehicle emissions. All five sensors for this analysis were used in $NO_x$ emission monitoring in five same brand, similar type tractor-semi-trailer trucks during prolonged real-world driving use over many months.

*Table 1 SEMS $NO_x$ sensor overview from the sensor database*

| Sensor Nr | Sensor ID | Data period | Current state | Valid NOx samples (@1Hz) | Hours | Nr of graphs |
|---|---|---|---|---|---|---|
| 1 | 1-06-190407-000002 | 2019-09-04 to 2020-02-13 | broken | 1210460 | 336.2 | 4 |
| 2 | 1-06-190329-000004 | 2020-04-07 to 2020-06-30 | broken | 1403048 | 389.7 | 5 |
| 3 | 1-06-190407-000007 | 2019-08-23 to 2020-07-24 | broken | 5068399 | 1407.9 | 17 |
| 4 | 1-06-190107-000018 | 2019-12-11 to 2020-10-22 | functioning | 2911792 | 808.8 | 10 |
| 5 | 1-06-190329-000002 | 2018-08-27 to 2021-03-03 | functioning | 22510597 | 6252.9 | 76 |

Method

Depict and visually analyse the time history of a sensors' amplitude distribution by plotting a series of amplitude distribution graphs for consecutive data sections of 300k valid (raw/uncalibrated) $NO_x$ samples at 1Hz (in ppm). Each data section is thus equivalent to about 83 hours driving/engine runtime. Hence, for each sensor a series of four to 76 graphs resulted, giving a visual impression of developments over time for the amplitude distribution of the NOx values acquired by the sensor.

In order to emphasize the low $NO_x$ values during motoring, the analysis was repeated for valid $NO_x$ samples for which the simultaneous $O_2$ values were above 19%. For these latter graph series, the first and last graph per series are shown in Figure 1 and Figure 2. Additionally for each graph series a video clip of the consecutive graphs was made in an attempt to better visualise developments over time in the $NO_x$ amplitude distribution for each sensor. All sensors show a limited offset, or zero, value change over time.

Conclusion

Repeated visual analysis of all graph series as well as the corresponding video clips did not reveal any obvious changes in the $NO_x$ sensor amplitude distributions, neither for those of the valid $NO_x$ samples nor for those of the valid NOx samples for which the simultaneous $O_2$ values were above 19%, that might be attributable to sensor drift, damage or aging. Though changes over time are observable, they are not consistently different for the three broken sensors from the two still functioning sensors. Also consistent drift of lower amplitudes was not observed.

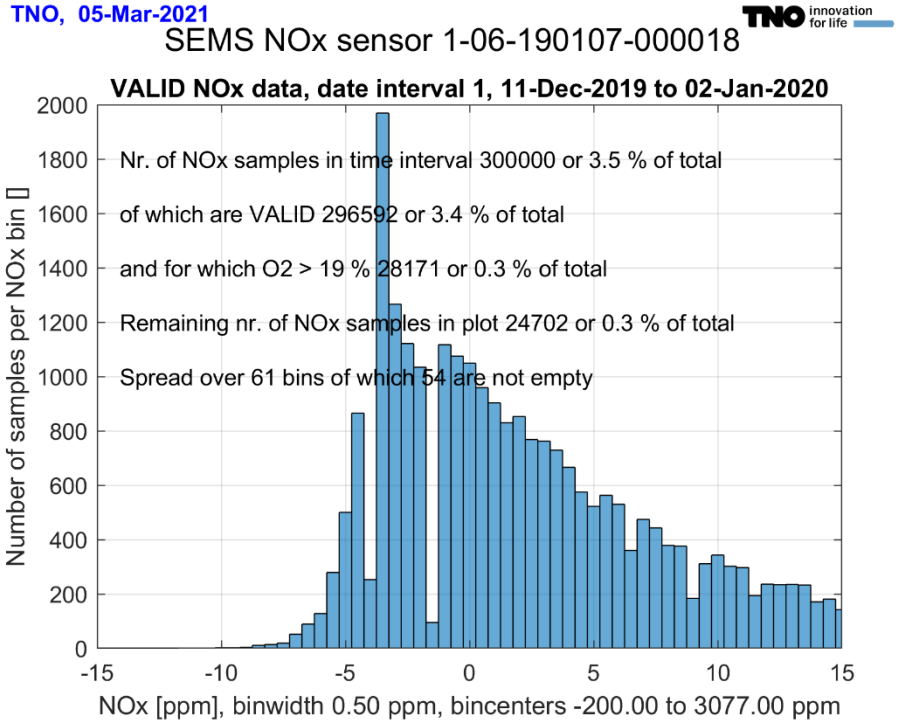


*Figure 1* ***Sensor 4****, NOx amplitude distribution of valid samples with $O_2$>19%, time section 1 of 10.*

Sensor 4 is taken as an example. The offset seems about -3 ppm, with a measurement spread (based on the left flank) of about +/- 3 ppm. Since the left flank does not change over the 800 hours of operation, it is likely that spread in the right-hand side of the peak around 0 ppm $NO_x$ is related to variation in engine operation and actual residual $NO_x$ concentrations.

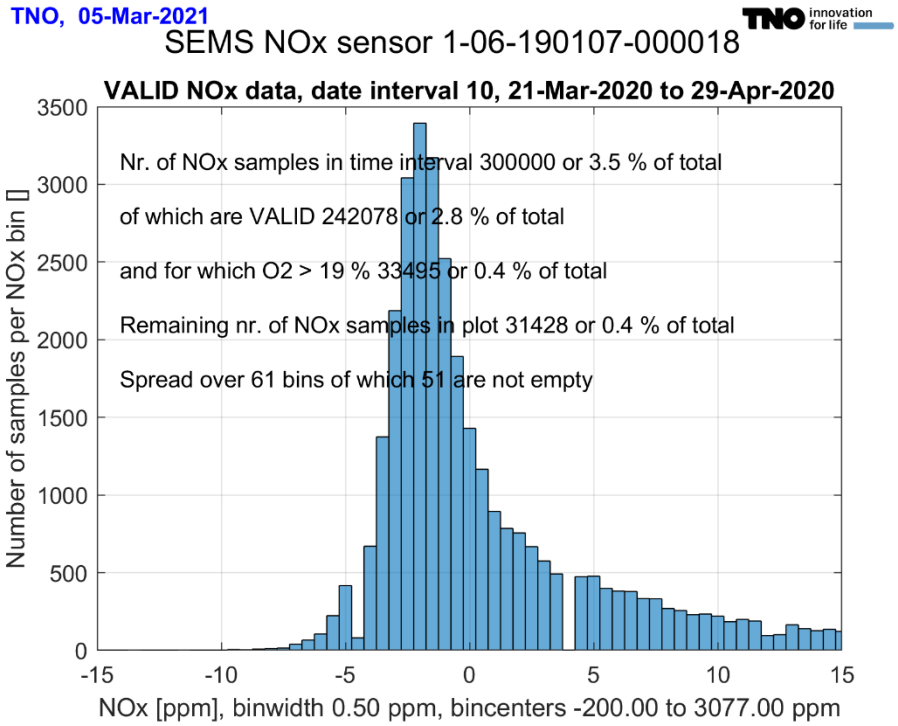


*Figure 2* ***Sensor 4****, NOx amplitude distribution of valid samples with $O_2$>19%, time section 10 of 10, after 800 hours.*

It should be noted that a deviation of the $NO_x$ concentration, as deduced from this magnitude of offsets, of 5 ppm is roughly 10-15 mg/km for a medium size passenger car. The current prescribed drift accuracy in the regulation is 5 ppm. Hence, sensors may help to ensure that a temporary drift is detected.

## 2. Using inlet mass airflow (MAF) to estimate $NO_x$ exhaust emissions

Hypothesis

The mass airflow (MAF) and $NO_x$ sensors in a modern vehicle can be used to estimate the exhaust flow rate and thus the $NO_x$ emission mass flow rate in exhaust with an accuracy comparable to that of PEMS. The MAF sensor operates in the inlet at ambient conditions, and seems to react more quickly to the flow variations.

Approach

Show possibilities by combining the simultaneously measured PEMS and SEMS signals in a diesel, Euro 6 passenger car during a TNO RDE testing trip. The SEMS system is based on automotive sensors added to the exhaust line, in combination with the signals on the OBD. The sensors are calibrated independently. The OBD signals are sometimes validated in the workshop, by temporary adding a second calibrated MAF sensor. These MAF sensors use a thermo-resistive method, which works well in clean ambient air.

Method

Calculation of the exhaust flow rate ($EFM_{OBD}$) including the fuel burnt during the combustion can be done by combining the mass air flow ($OBD_{MAF}$) and the OBD O2 concentration as follows.

$$EFM_{OBD}[g/s] = MAF_{OBD}*(1 + 0.067*(20.8 – O_{2\text{-}OBD}[\%])/20.8)$$

The oxygen in ambient air is about 20.8%. The difference from the 20.8% is the oxygen used in combustion. The factor 0.067 is the reciprocal of the stoichiometric air fuel ratio (AFR), which is the maximum mass of fuel that can be added to air in stochiometric combustion. This factor depends on the fuel composition; 0.067 is an approximate value for gasoline and diesel fuel. But in many of the legislation this composition is also assumed. Figure 3 shows the corresponding time signals (1 Hz) for the entire RDE trip with the diesel, Euro 6 passenger car, converted.

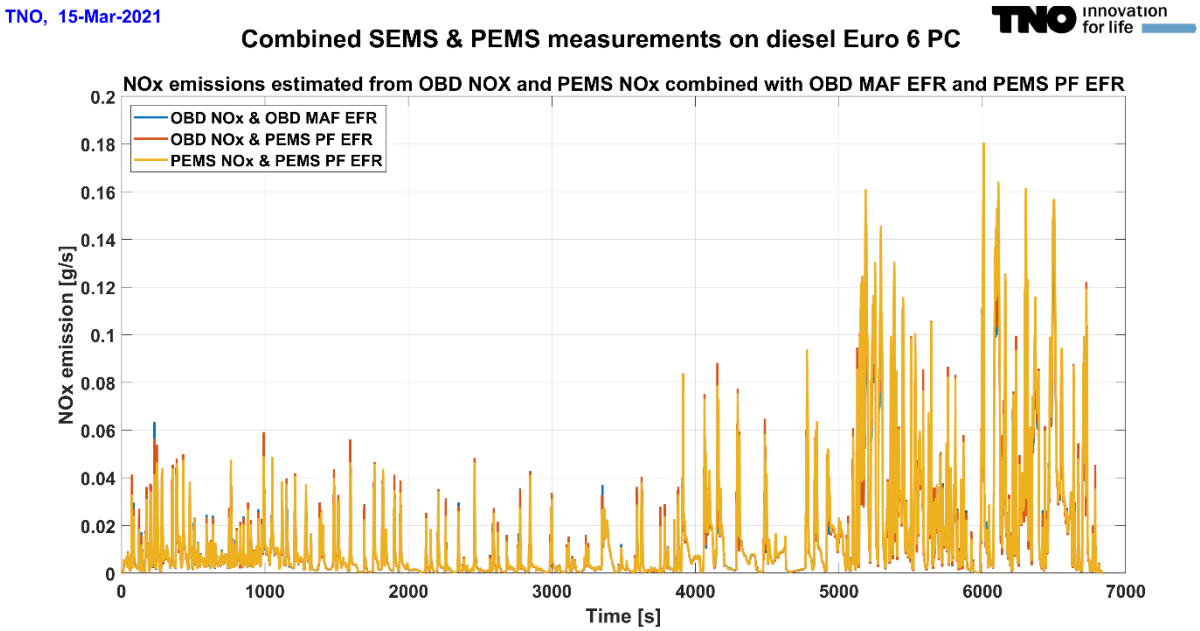


*Figure 3 The three NOx emission rates plotted together.*

Next, by combining the $NO_x$ concentration and the MAF-based exhaust flow rate the $NO_x$ emission rate follows.

$$NO_{x\text{-}OBD}[g/s] = (\rho_{NO2}/\rho_{exhaust\ gas})*NOx\ [ppm]*MAF_{OBD}[g/s]*(1 + 0.067*(20.8 – O_{2\text{-}OBD}[\%])/20.8)$$

Where $\rho_{NO2}$ and $\rho_{exhaust\ gas}$ are the densities of $NO_2$ and diesel exhaust gas, respectively, in standard conditions. The density of exhaust gas is within 1% the same as the density of air. Similarly, the PEMS $NO_x$ concentration and the PEMS PF exhaust flow rate ($EFM_{PEMS}$) can be combined to yield the PEMS $NO_x$ emission rate ($NO_{x\text{-}PEMS}$).

$$NO_{x\text{-}PEMS}[g/s] = (\rho_{NO2}/\rho_{exhaust\ gas})*NOx\ [ppm]*EFM_{PEMS}[g/s]$$

The aforementioned two estimates of the $NO_x$ emission rates are plotted together, with a mixed OBD/PEMS variant as well, in Figure 4 which again shows the time signals for the entire RDE trip. The similarity between the three signals looks favourable. Because of the used scale, of almost two hours driving time, it is impossible to tell how good the similarity is and where and how large the differences are.

Therefore, in Figure 4 cumulative versions of the three signals, hence the estimated $NO_x$ emissions in grams as functions of time, are given, which clearly show how the differences grow during the trip and also indicate that the differences grow faster at higher speeds. Figure 5 is a zoomed in version of Figure 3, showing five minutes of driving time on the motorway, which clearly illustrates that the differences mainly occur at higher speeds. This result is without the correction of the span and offset of the $NO_x$ sensor.

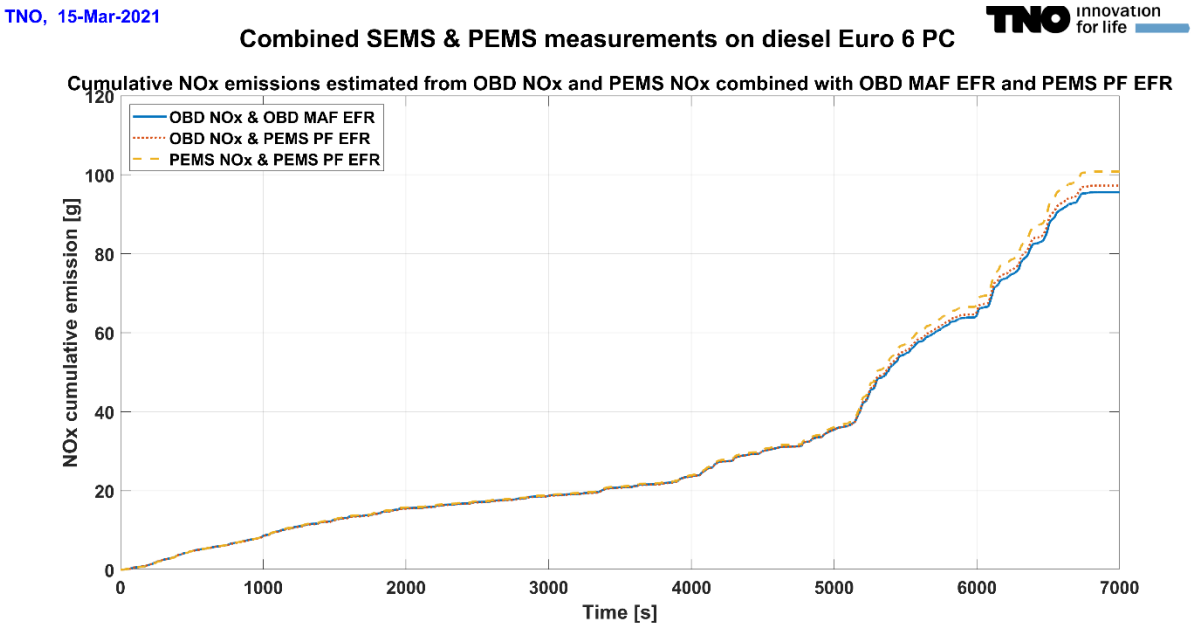


*Figure 4 The three cumulative NOx emissions plotted together. The concentration measurements give the largest deviation, the flow measurements deviate within 2%, over a long RDE test. But actual deviations occur at higher velocity and dynamics around 5000-6000 seconds.*

Conclusion

The MAF airflow and $NO_x$ sensors can be used to estimate the exhaust flow rate and thus the $NO_x$ emission mass flow rate in exhaust with an accuracy comparable to that of PEMS. Zooming in on the sections in which the deviations occur (see Figure 5), it can be noted that the PEMS flow is somewhat higher in the peaks than the MAF, and the PEMS smoothens the variations observed in the MAF. The MAF is therefore a useful tool to ensure deviations in the flow measurements are detected. If the measurement principles are extended, the measurement of inlet airflow could be a suitable and robust alternative to measuring in the hot, wet and pulsating exhaust gas, with variable composition.

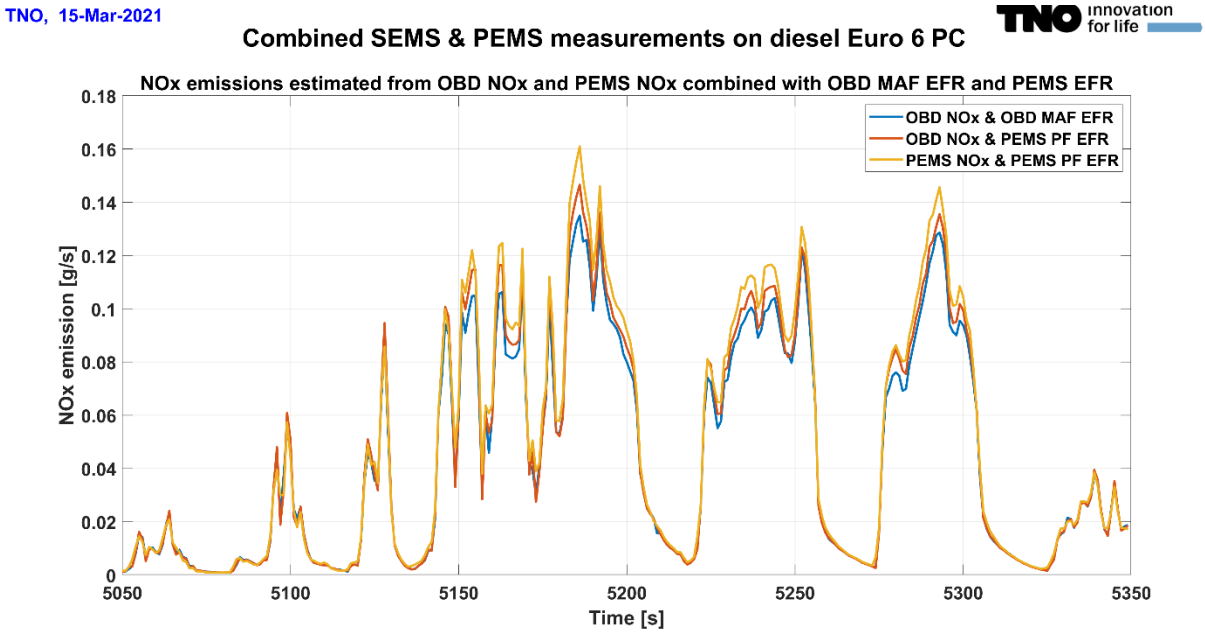


*Figure 5 Zooming in to five minutes of the three NOx emission rates shows where the differences occur.*

## The use of FTIR

Likewise as the use of concentration sensors and MAF sensors, the FTIR (Fourier Transform Infrared spectrometer) allows for quality control beyond the current PEMS systems. Unlike instruments working at a specific wavelength, an FTIR can store the complete mid infra-red absorption spectra, which can be, at a later time, re-analysed for the concentrations of additional gases of interest. The measurement of all gases of interest simultaneously, with one instrument, simplifies both the measurement procedure and the post-processing. Several FTIR have been successfully used on the road, ranging from simple, compact instruments to laboratory instruments carefully installed in a test vehicle. The mass and power consumption of the smaller systems are comparable to those of type-approval grade PEMS. The relatively small amount of liquid nitrogen (tenths of a litre) for detector cooling is well contained and no process gases are required during the testing, making the FTIR a relatively safe instrument suitable for on-road measurements.

There are two major caveats with FTIR. One is the possible distortion of the spectra due to contamination of the optics, excessive vibrations and jolts, fluctuations in various temperatures (instrument case, optical cell, sample, etc.), and other reasons. The quality of the spectra can be checked by evaluating certain regions of the spectra and/or by comparing the concentrations of at least some gases for which reference measurement is available ($CO_2$ calculated from exhaust gas oxygen sensor, $NO_x$ measured by a sensor in exhaust).

The second caveat is that the measured absorption spectra is the sum of the absorptions of all absorbing compounds, and that the contributions of each compound are calculated from often overlapping individual absorption spectra obtained by deconvolution of the measured spectra. Therefore, detection limits, uncertainties, or even the capability to obtain a meaningful reading for a given compound, are specific to the composition of the mixture. For example, the detection limit achieved with a mixture of calibration gas with dry nitrogen is unlikely to be achieved in the presence of several orders of magnitude higher concentrations of $CO_2$ and water vapor. This is, however, a known issue, common to both on-road and laboratory measurement, and is dealt with, to various degree of success, by spectroscopy specialists.

Since the FTIR is the preferred candidate instrument for Euro-7/VII legislation, to incorporate $NH_3$ and $N_2O$ measurements, it is important to also ensure that the capabilities of FTIR are used to improve the measurement accuracy, and disqualify substandard measurements. Several $N_2O$ measurements with FTIR indicate that this strong greenhouse gas contributes about 5% to the $CO_2$-eq emissions of diesel vehicles equipped with an SCR. If $N_2O$ is only regulated in the laboratory, there is a risk that on-road $N_2O$ emission levels are not curbed.

From the FTIR spectra themselves many aspects can be deduced. For example, misalignment, vibrations, noise, inlet gas composition, cross-correlations, light intensity fluctuations, temperature variations, fouling, etc. If such elements are taken into consideration, and possibly analysed in post-processing, it may reduce the risk of large measurement errors. In the best case, the actual measurement uncertainty can be deduced from the spectra themselves.

## Conclusions

On-road emission measurements are, per definition, in an uncontrolled environment. Validating the measurement equipment in the laboratory, against laboratory equipment has its limitations, as often pointed out by the automotive industry, in the discussions on RDE legislation. This is not related to the average or general results, taken by JRC as the basis for the margin, but to the risk of a deviation results, possibly due to an undetected measurement problem. It is therefore essential to develop techniques to have real-time, on-board, quality control of the measurement systems.

Moreover, measurement alternatives, such as using inlet air flow, rather than exhaust gas flow, may improve the robustness of emission measurements and allow for a move towards lifetime monitoring. In the latter case, with sensor based measurements, the PEMS is only needed for validation.

The development of Euro-7 legislation, incorporating other emission components, is an opportunity to fundamentally improve the on-road measurement systems. It should no longer be bringing laboratory equipment instrument to on-road measurements. Instead, robustness should arise from real-time quality control, that can detect deviations in the results. Using two independent on-road measurement principles in conjunction, as shown here, can be at the basis of these improvements.