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Real Driving Emissions: 2018-2019 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty

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Authors

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Abstract

Previous research of a proper margin value for Nitrogen Oxides to account for the additional measurement uncertainty of Portable Emissions Measurement Systems (PEMS) as compared to standard laboratory equipment in the context of the Real Driving Emissions (RDE) Regulation identified zero drift as an important component of uncertainty.

This report describes an experimental campaign carried out by the Joint Research Centre during 2018 and 2019 to assess zero drift of PEMS gas analysers under real life operation. The instruments considered in the analysis, from four large manufacturers, cover probably the whole PEMS market in Europe. The tested instruments belong to the generation of PEMS currently available in the market.

The results of the testing campaign (measuring zero every 10-20 min on the road) showed that there is not a systematic positive or negative drift, neither a systematic step nor linear drift for any of the pollutants considered (NO, NO_2, CO_2, CO) for all PEMS manufacturers tested. On most of the tests performed, the zero drift for NOx is lower than 3 ppm under a variety of ambient temperature and humidity conditions. Additional tests done on more stringent environmental conditions (high altitude mountain driving) show a similar pattern for zero drifts of all pollutants. Vehicle technology (spark ignition or compression ignition), PEMS installation location (cabin or trailer hook), ambient temperature and humidity, and altitude do not appear to be critical elements affecting the zero drift as results are similar for all the aforementioned conditions.

In general, the evidence gathered during the campaign does not verify the worst case drift scenario used to define the 0.43 NO_X margin, and it can be used to justify a further reduction of the margin value. Based on the worst case scenario for zero drift of the JRC testing campaign and considering the effect on a vehicle with large engine displacement (largest effect in terms of NOx mass), the updated NOx margin that is proposed is 0.32.

1 Introduction

Regulation (EU) 2016/427 (first regulatory package of the Real Driving Emissions regulation, RDE1) introduced on-road testing with Portable Emissions Measurement Systems (PEMS) to complement the laboratory Type I test for the type-approval of light-duty vehicles in the EU. Subsequently, Regulation (EU) 2016/646 (RDE2) introduced Real Driving Emissions (RDE) conformity factors (CF) for nitrogen oxides (NO_X) emissions. The CF requires full compliance with the Euro 6 limits but allows a margin to account for the additional measurement uncertainty of PEMS relative to standard laboratory equipment (CF = 1 + margin). NOx CFs were introduced in two steps: CF_{step1} = 2.1 applicable upon the request of the manufacturer from September 2017 to all new types (and September 2019 to all new vehicles), and CF_{step2} = 1.5 applicable from January 2020 for new types (and January 2021 for all new vehicles). Both regulations (RDE1 and RDE2) were consolidated in the Worldwide harmonised Light-duty vehicles Test Procedures (WLTP) Regulation (EU) 2017/1151 and further developed by Regulation (EU) 2017/1154 (RDE3), which also introduced an RDE conformity factor for the on-road test of solid particle number (PN) emissions (CF = 1.5). Recital 10 of the RDE Regulation 2016/646 foresees that the European Commission reviews the appropriate level of the final conformity factor in light of technical progress of PEMS; a task that has been assigned to the European Commission's Joint Research Centre (JRC). The fourth and last RDE regulatory package Regulation (EU) 2018/1832 (RDE4) updated the NOx CF_{final} to 1.43 based on an ad-hoc review of the PEMS measurement uncertainty performed by the JRC in 2017 (Giechaskiel *et al.*, 2018).

In addition to proposing a reviewed value for the NOx margin, the 2017 JRC report laid out the framework for subsequent margin reviews. This methodological framework for calculating the additional uncertainty of the PEMS respect to laboratory equipment is based on the assessment of the individual uncertainty of the PEMS components (gas analysers, exhaust mass flow meter, positioning system, etc.) and considering the error propagation rule along the cascade of measurement systems in real life operating conditions.

The 2017 JRC report identified the zero drift of gas analysers (i.e. the difference in zero reading between the pre-test and the post-test) as a major contributor to the final value of the margin. The lack of experimental data on zero drift throughout RDE tests did not allow quantifying its influence on the uncertainty of the measurement. Therefore, two scenarios of the zero drift were hypothesized in order to calculate the margin:

- A linear drift, in which zero drift occurs linearly from the beginning of the test and reaches 5 ppm (maximum permissible zero drift for NO_X) at the end of the test (120 minutes, which is the maximum duration of an RDE test).
- A step drift (worst case scenario), in which the 5 ppm of NOx drift occurs immediately at the beginning of the test and remains constant for the whole duration of the test. The step drift hypothesis was considered for the establishment of the 0.43 margin to be used from 2020.

The objective of this report is to provide technical evidence of the zero drift from a dedicated experimental campaign performed by JRC on PEMS units of four instrument providers covering all commercially available systems in Europe. In addition, the effect of ambient conditions (temperature and altitude) on the performance of the PEMS and, the uncertainty of the exhaust flow meter is discussed based on the PEMS testing activity of the JRC in the context of Market Surveillance pilot project (Valverde *et al.*, 2019).

A new value for the NOx margin is proposed in light of the experimental results.

2 Experimental data

2.1 Zero drift campaign

2.1.1 PEMS used in the campaign.

With the aim of quantifying the zero drift of gas analysers under working operating conditions a set of dedicated PEMS tests have been performed by JRC in the period May 2018 to January 2020.

PEMS units of the four main instrument manufacturers in Europe were used: AVL-MOVE, HORIBA OBS-ONE, AIP-PEMS (Gen 2), and SENSORS SEMTECH LDV. All the instruments correspond to PEMS units that are commercially available in the market (i.e., not prototypes but existing technology in the market).

The testing included three different units of AVL-MOVE and one unit of HORIBA OBS-ONE, all belonging to JRC. In addition, one unit of AIP-PEMS and one unit of SENSORS SEMTECH LDV, provided by AIP Automotive (Haldenwang, Germany) and SENSORS (Erkrath, Germany), respectively were used in the testing campaign.

The units of the four instrument manufacturers fulfil the technical requirements for PEMS as established by the RDE regulation (Appendix 2). **Table 1** summarises the measurement principles of the PEMS used.

Table 1. Measurement principles of the gas PEMS instruments used in the zero drift campaign

PEMS manufacturer	**AVL**	**HORIBA**	**AIP**	**SENSORS**
CO/CO_2 analyser	NDIR (^{1})	NDIR (^{1})	NDIR (^{1})	NDIR (^{1})
NO analyser	NDUV (^{2})	CLD (^{3})	CLD (^{3})	NDUV (^{2})
NO_2 analyser	NDUV (^{2})	Calculated from NO and NOx	PAS (^{4})	NDUV (^{2})

(^{1}) NDIR: Non-Dispersive Infrared Detection.
(^{2}) UV: Non-Dispersive Ultra-Violet Detection.
(^{3}) CLD: Chemiluminiscence Detection.
(^{4}) PAS: Photoacoustic Spectroscopy.

Source: JRC, 2020.

2.1.2 Zero drift testing procedure.

For each test, the PEMS unit was installed on-board of the vehicles following the manufacturer's recommendations, either inside the cabin or on the trailer hook (**Figure 1**). The testing was performed following the best practices for the preparation, the execution, and the follow-up of emissions tests with PEMS as described in Valverde and Bonnel (2018) with a single PEMS unit per test. The vehicle with the PEMS installed was soaked inside a facility with an ambient temperature between 20°C and 25 °C. For two of the tests performed in January 2020 with the SENSORS unit, when the ambient temperature was ~ 0 °C, the PEMS and the vehicle were soaked in the exterior to avoid abrupt changes of temperature following the manufacturer's operational requirements.

The standard pre-test and post-test procedures were systematically followed on all tests. The PEMS was set to sample from the vehicle exhaust following the regulated procedures. A nitrogen (N_2) bottle, fulfilling the specifications of Sub-Annex 5 of Annex XXI to Regulation 2017/1151, was placed on-board of the vehicle (**Figure 1**) and at regular intervals of 10 to 20 minutes (depending on the test and the instrument), zero response checks were performed while the vehicle was running following a predefined route. The N_2 bottle was connected to the zero inlet of the instrument. By this means, the zero drift was directly measured along the duration of the test under real life operation conditions (thus considering the effects of vibrations, temperature and humidity, altitude, etc. on the zero drift of the analysers). For the tests done with the AVL-MOVE, each zero check lasted ~ 90 seconds, - 120 seconds for the OBS-ONE, ~ 100 seconds for the AIP-PEMS, and ~ 90 seconds for the SENSORS.

The campaign covered three routes: 2 RDE compliant routes (RDEc in **Table 2**), and 1 route with only urban drive uphill and downhill a mountain of ~ 1100 masl (HighAlt in **Table 2**). Additional details on the RDE compliant routes (ESP and LAB) and the altitude route (SAC) are detailed elsewhere (Valverde *et al.*, 2019). On the altitude route, the cumulative positive elevation gain (1700 m/100 km) exceeded the permissible RDE limit (1200 m/100 km) and it was driven in order to measure zero drift under stringent conditions of use and assess potential influence of the altitude on the operation of the PEMS. In order to collect as much data as possible the sampling was not stopped at the end of the routes but when the vehicle re-entered the facilities just prior to the post-test procedure, which lead to measurements beyond the 2-hour limit set on the RDE regulation.

In total, 27 zero drift tests were performed during the campaign on running vehicles. Three tests were done with the HORIBA OBS-ONE (mounted on a C-segment, diesel passenger car, with an engine displacement of 1560 cc); four tests were done on the AIP-PEMS (on a D-segment, diesel passenger car with an engine displacement of 1968 cc); and four tests were performed with the SENSORS SEMTECH LDV (on a multi-purpose diesel vehicle, with an engine displacement of 1968 cc). Sixteen tests were performed with AVL-MOVE units: five tests with unit AVL-1, seven with AVL-2, and four tests with the unit AVL-3. The AVL-MOVE units were mounted on a variety of vehicles including 6 passenger cars (segments B and C) and 1 light commercial vehicle. Details on instruments, frequency of zero checks, vehicles and ambient conditions during each test are presented in **Table 2**.

The testing took place around the JRC Ispra site in Northern Italy in the period of May to October 2018 (AVL-MOVE units), August-October 2019 (HORIBA OBS-ONE unit), November 2019 (AIP-PEMS), and January 2020 (SENSORS SEMTECH LDV).

Figure 1. Overview of PEMS installations on the trailer hook for the three PEMS instruments assessed: a) AVL-MOVE, b) HORIBA OBS-ONE, c) AIP-PEMS, d) SENSORS SEMTECH LDV and e) fixation of N_2 bottle on-board the vehicle.

Source: JRC, 2020.

In order to further assess the zero drift, additional tests were performed with the AVL, HORIBA, and SENSORS systems on static vehicles.

On one hand, three tests were done at constant ambient temperature with AVL and HORIBA units. During the first static test with the AVL-MOVE, the vehicle was kept with the engine off, whereas in the second test, the vehicle was switched on and kept on idling with high idle accelerations every 20-30 min for the duration of the test. Both tests were performed on vehicle 5 with AVL-1 mounted in the cabin (**Table 2**) and the vehicle was kept inside the testing facility to avoid influences of varying ambient conditions. One additional static test was performed with the HORIBA OBS-ONE mounted in the cabin of a vehicle that was kept inside the facility at constant ambient temperature with the engine off along the test. All static tests had pre-test and post-test properly performed and zero checks were done every 10-15 minutes for a duration of 2 hours. All components of the PEMS were installed and used as if the vehicle was running an RDE test.

On the other hand, additional static tests were performed with the HORIBA, the SENSORS, and the AVL PEMS to assess the effect of a gradual change of ambient temperature on the zero drift. PEMS units were soaked in a climatic chamber at an ambient temperature of 23 °C, the pre-test calibration was also performed at 23 °C. Then, periodic zero response checks were performed at a regular interval of 10 minutes while the ambient temperature was set to reach -7 °C (reached after 90-100 minutes). The post-test was performed at -7 °C. Then, a pre-test was performed at -7 °C and the zero drift was measured for ~ 60 minutes at a constant -7 °C temperature (only for HORIBA and SENSORS). Then, on both instruments, zero drift was measured on the ramp-up of the ambient temperature from -7 °C to 23 °C (~ 60 minutes). On this third test, the pre-test was performed at -7 °C and the post-test at 23 °C. The test done on the AVL-1 unit was done independently from the PEMS of the other manufacturers, and it also included a test to check the zero drift change when the ambient temperature was set to increase gradually from -7 °C to 23 °C.

Table 2. Overview of testing conditions including PEMS installation location (PEMS loc.), ambient temperature (T) and relative humidity (RH) range and average (av.) conditions. The characteristics of the vehicles are fully described in Valverde et al., (2019) using the same vehicle codes except for tests 19-30.

Test #	Vehicle id	Fuel type	Eng. disp. [cc]	Route type	PEMS id	PEMS loc.	Zero check freq. [min]	Range (av.) T [°C]	Range (av.) RH [%]
T01	VW040	Gasoline	1395	RDEc	AVL-1	Hook	15	17-24 (18)	58-90 (82)
T02	NN009	Gasoline	1197	RDEc	AVL-2	Hook	15	15-20 (18)	60-80 (73)
T03	NN009	Gasoline	1197	RDEc	AVL-2	Hook	10	10-20 (14)	39-72 (60)
T04	OL002	Diesel	1248	RDEc	AVL-3	Cabin	15	17-23 (20)	58-80 (73)
T05	PT011	Diesel	1499	RDEc	AVL-2	Cabin	15	22-24 (23)	38-52 (46)
T06	OL003	Diesel	1598	RDEc	AVL-1	Cabin	10	14-21 (17)	56-83 (72)
T07	FT061	CNG	2999	RDEc	AVL-3	Cabin	15	24-36 (28)	22-61 (47)
T08	VW040	Gasoline	1395	HighAlt	AVL-1	Hook	15	15-24 (20)	57-88 (70)

Test #	**Vehicle id**	**Fuel type**	**Eng. disp. [cc]**	**Route type**	**PEMS id**	**PEMS loc.**	**Zero check freq. [min]**	**Range (av.) T [°C]**	**Range (av.) RH [%]**
T09	NN009	Gasoline	1197	HighAlt	AVL-2	Hook	10	17-24 (21)	47-73 (58)
T10	NN009	Gasoline	1197	HighAlt	AVL-2	Hook	10	12-21 (17)	33-60 (45)
T11	OL002	Diesel	1248	HighAlt	AVL-3	Cabin	15	15-25 (22)	49-78 (62)
T12	PT011	Diesel	1499	HighAlt	AVL-2	Cabin	15	25-32 (29)	24-42 (34)
T13	OL003	Diesel	1598	HighAlt	AVL-1	Cabin	10	17-25 (22)	46-67 (54)
T14	OL003	Diesel	1598	HighAlt	AVL-1	Cabin	10	17-23 (21)	51-68 (58)
T15	FT061	CNG	2999	HighAlt	AVL-3	Cabin	15	24-34 (30)	23-46 (33)
T16	FT060	LPG	1368	HighAlt	AVL-2	Cabin	15	15-27 (23)	46-91 (62)
T17	OL003	Diesel	1598	Static	AVL-1	Cabin	15	22-23 (22)	39-42 (40)
T18	OL003	Diesel	1598	Static	AVL-1	Cabin	15	19-19 (19)	38-39 (39)
T19	-	Diesel	1560	RDEc	HORIBA	Hook	15	14-23 (17)	44-76 (62)
T20	-	Diesel	1560	HighAlt	HORIBA	Hook	15	16-23 (20)	41-68 (54)
T21	-	Diesel	1560	HighAlt	HORIBA	Hook	15	11-23 (15)	50-92 (74)
T22	-	Gasoline/Electric	2487	Static	HORIBA	Cabin	15	26-26 (26)	71-72 (72)
T23	-	Diesel	1968	RDEc	AIP	Hook	20	8-18 (11)	47-94 (79)
T24	-	Diesel	1968	RDEc	AIP	Hook	20	11-19 (12)	46-89 (77)
T25	-	Diesel	1968	HighAlt	AIP	Hook	20	4-13 (7)	71-99 (98)

Test #	Vehicle id	Fuel type	Eng. disp. [cc]	Route type	PEMS id	PEMS loc.	Zero check freq. [min]	Range (av.) T [°C]	Range (av.) RH [%]
T26	-	Diesel	1968	HighAlt	AIP	Hook	20	3-17 (7)	73-99 (99)
T27	-	Diesel	1968	RDEc in.soak	SENSORS	Hook	15	5-15 (7)	20-25 (22)
T28	-	Diesel	1968	RDEc out.soak	SENSORS	Hook	10	-1-13 (6)	30-87 (60)
T29	-	Diesel	1968	HighAlt in.soak	SENSORS	Hook	10	7-19 (11)	16-49 (30)
T30	-	Diesel	1968	HighAlt out.soak	SENSORS	Hook	10	8-16 (12)	17-45 (32)
T31	-	-	-	Static	SENSORS	-	10	23 to -7	30-50
T32	-	-	-	Static	SENSORS	-	10	-7	50
T33	-	-	-	Static	SENSORS	-	10	-7 to 23	20-70
T34	-	-	-	Static	HORIBA	-	10	23 to -7	30-50
T35	-	-	-	Static	HORIBA	-	10	-7	50
T36	-	-	-	Static	HORIBA	-	10	-7 to 23	20-70
T37	-	-	-	Static	AVL-1	-	10	23-7	30-50
T38	-	-	-	Static	AVL-1	-	10	-7 to 23	20-60

Source: JRC, 2020.

2.1.3 Zero drift under drastic ambient temperature changes.

The RDE regulation defines a set of boundary conditions outside which, on-road tests with PEMS are not considered valid to assess emissions compliance against the limits. The valid ambient temperature conditions range from -7 °C to 35 °C and are defined to cover most of the European driving conditions, and to meet the temperature ranges in which PEMS can operate properly. In addition, vehicles and PEMS can be soaked at the same range of temperatures including soaking in the exterior and in the interior of buildings. This range of possibilities enables the option to test a vehicle on the road at cold ambient temperature (-7 °C) whereas its soak and pre-test has been performed inside a facility at controlled ambient temperature (e.g., 25 °C). The same situation can occur at the end of the RDE test: a vehicle tested at cold ambient temperature in the road may be driven inside a facility with much warmer temperature than outside. This drastic change of operating conditions of PEMS instruments (i.e., changing up to 40 °C in few seconds) could affect their measurement performance.

In this context, three ad-hoc tests were performed to evaluate the effect on zero drift. One test was performed with one of the units of AVL-MOVE (AVL-1) on board the cabin of a diesel passenger car, with an engine displacement of 1597 cc, and two others with the OBS-ONE unit in the cabin of a passenger car (**Table 2**). For the test done with the AVL-MOVE, the vehicle was soaked at ambient temperature inside a facility (~25 °C). After the pre-test operation, the vehicle was quickly driven (few seconds) inside a climatic chamber with an ambient temperature of -7 °C and a relative humidity of 70%. The vehicle was kept with the engine off and the PEMS was set to perform zero response checks every 10 minutes with an N_2 bottle connected in the zero inlet of the PEMS. In between zero checks, the PEMS was sampling ambient air. The post-test was performed inside the climatic chamber and the zero drift was assessed.

The first test with the HORIBA-OBS ONE replicated the test protocol described above for the AVL-MOVE with the following differences: the vehicle was soaked at 21 °C and the climatic chamber was set to operate at -2 °C and a relative humidity of 80%. Also the vehicle was driven inside the climatic chamber using the electric motor of the vehicle. In the second test with HORIBA OBS-ONE, the vehicle was soaked inside the climatic chamber at -7 °C, the pre-test and main test were performed at that same temperature and after two hours, the vehicle was driven out of the climatic chamber using the internal combustion engine to perform the post-test check at an ambient temperature of 23 °C. Zero response checks were performed every 20 minutes.

2.2 JRC PEMS data from market surveillance pilot project activities

Over recent years, the JRC has continuously measured light-duty vehicle's tailpipe emissions with PEMS in support of the development of the RDE regulation; the improvement of test protocols to identify defeat devices; and to assess emissions compliance in preparation of the in-service conformity and market surveillance duties. The on-road data gathered throughout 2018 on 19 Euro 6 vehicles with different powertrains, accounting for 185 PEMS tests, has been used to analyse the effect of weather conditions (ambient temperature and humidity), altitude, and PEMS location (in cabin or in the trailer hook) on the zero drift of gas analysers and drift of the exhaust mass flowmeter. For this set of 185 tests, the zero drift, as measured only from the pre-test and post-test measurements, is assessed. Although no intermediate and periodic zero response checks were performed during those tests the large number of tests considered provide a robust approach to the analysis of zero drift in real operation of the PEMS under a wide range of operating conditions.

The test routes, vehicles, and test conditions are detailed elsewhere (Valverde *et al.*, 2019). All considered tests were performed with the AVL-MOVE units described in section 2.1.1. The tests fulfilled the RDE regulation requirements for instruments, pre-test and post-test procedures, and calibration gases. Most routes complied with RDE requirements for driving dynamics, shares of operation, altitude gain, etc. whereas, some others did not (exceed v*a_pos95 limits, exceed cumulative positive elevation gain, exceed time duration, not compliance with shares of operation per bin, etc.).

All the PEMS tests conducted throughout 2018 have been systematically included in the analysis disregard if their zero drift was above or below the permissible tolerances. Tests where a regeneration of the diesel particle filter was identified have been also included in the analysis. **Table 3** summarises the PEMS tests considered in the campaign.

PEMS validation consists in comparing the emissions of a given vehicle when driven on the chassis dynamometer as measured simultaneously by the PEMS and laboratory standard equipment. The PEMS validation procedure is fully described in the RDE regulation (Appendix 3). During the routine activity in the JRC, PEMS validations as performed in order to check the correct installation and functionality of the PEMS. The data of 23 PEMS validations performed on a variety of vehicles using the 3 AVL units on two different JRC laboratories (VELA2 and VELA8) is also considered in this PEMS margin assessment to evaluate the performance of the exhaust flowmeter (EFM).

The results of the zero drift of NO and NO_2, and NOx were evaluated for different conditions of PEMS installation location, ambient temperature and humidity, altitude, and fuel type of vehicles, and are included in the analysis in chapter 4 below.

Table 3. Overview of JRC 2018 PEMS test for Market Surveillance pilot project. The characteristics of the vehicles are fully described in Valverde et al., (2019) using the same vehicle codes.

Vehicle code	# of PEMS tests	PEMS id	PEMS location
FD009	10	AVL- 1	Cabin
LA002	8	AVL- 1	Cabin
OL003	9	AVL- 1	Cabin
RT012	6	AVL- 1	Cabin
SA002	9	AVL- 1	Cabin
TA008	5	AVL- 1	Cabin
VW040	13	AVL- 1	Trailer hook
VW042	12	AVL- 1	Trailer hook
FT060	11	AVL- 2	Cabin
HI002	8	AVL- 2	Cabin
PT011	15	AVL- 2	Cabin
SI001	8	AVL- 2	Cabin
ST001	6	AVL- 2	Cabin
NN009	10	AVL- 2	Trailer hook
VO006	11	AVL- 2	Trailer hook
FT061	12	AVL- 3	Cabin
OL002	9	AVL- 3	Cabin
LR001	12	AVL- 3	Trailer hook
MB010	11	AVL- 3	Trailer hook

Source: JRC, 2020.

3 Results of the zero drift campaign

The results of the zero drift campaign are reported per PEMS manufacturer in the order of execution of the tests. In all plots in this section, the vertical brown dashed lines indicate the minimum (90 minutes) and maximum (120 minutes) time duration of an RDE test according to the RDE regulation. The results presented for NOx correspond to the sum of the absolute value of the zero drift of NO and the absolute value of the zero drift of NO_2.

3.1 AVL-MOVE

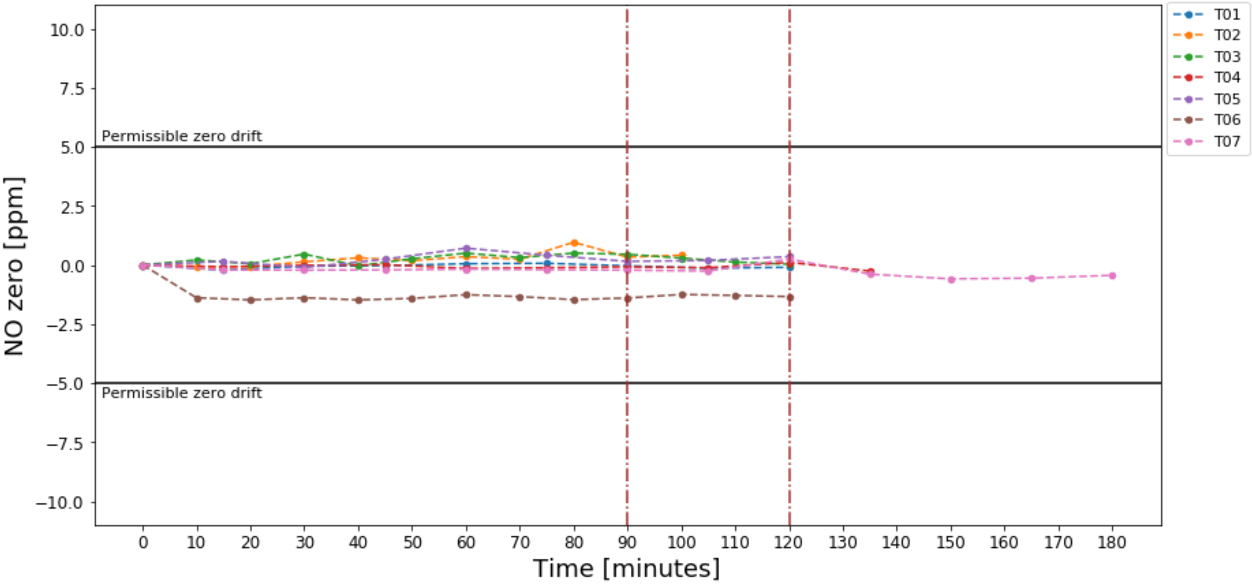
The zero drift for all measured gases (NO, NO_2, CO_2, CO) between the pre-test and the post-test fulfil the permissible zero drift limits on 12/16 tests considered in the report (< 5 ppm for NO/NO_2/NO_X, < 2000 for CO_2, and 75 ppm < for CO). One test (T03) slightly failed the CO zero drift (78 ppm), and three tests exceeded the NO_2 zero drift (T13 had a positive exceedance 6.7 ppm, whereas T06 and T10 had a negative drift -5.3 and -6.1 ppm, respectively at the non-RDE compliant routes).

Results on zero drift are analysed both inside (RDEc) and outside RDE boundary conditions (HighAlt). The three PEMS units were tested on both types of routes (**Table 2**). The data presented correspond to the values reported as zero response for each pollutant by the PEMS software (i.e., average of the zero value over the zero response time). NO and NO_2 zero drift are assessed individually and in combination as Nitrogen Oxides (NO_X).

3.1.1 Nitrogen monoxide NO

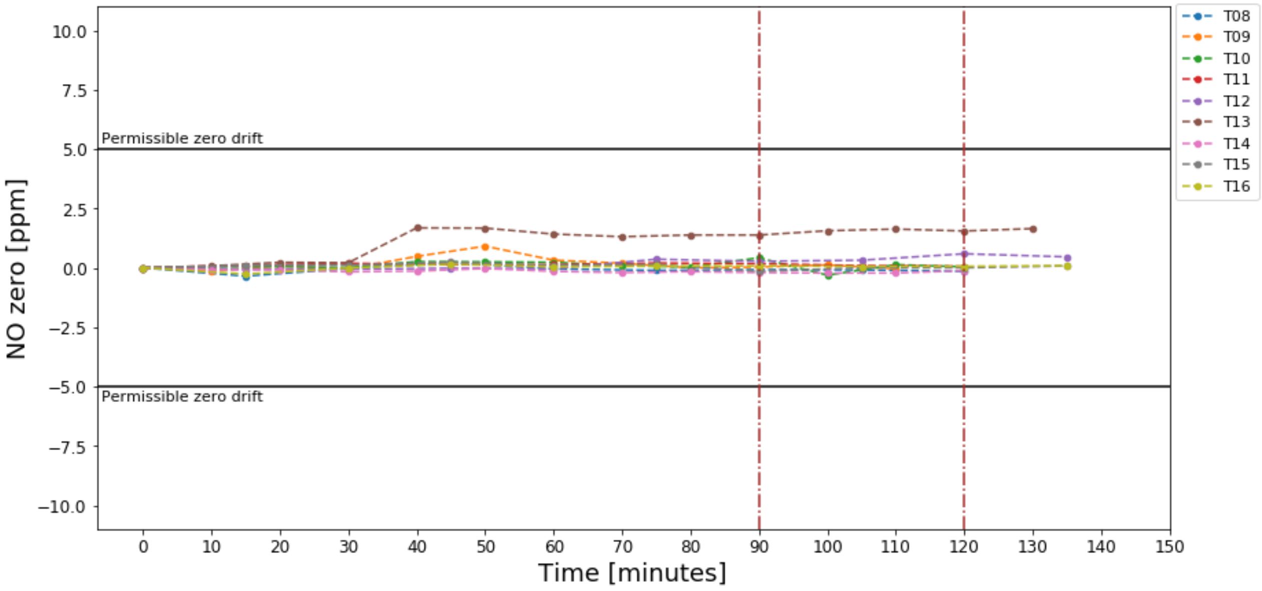
NO zero drift is lower than ±2 ppm on all tests on all intermediate zero checks, both when operated in RDE compliant routes (**Figure 2**), and in the high altitude route (**Figure 3**), with 14/16 tests displaying a zero drift within ±1 ppm on all intermediate steps. NO zero drift is always below the permissible value allowed by the regulation and both positive and negative values for zero drift are registered along the duration of the trip. As a general trend for all tests done NO zero drift is stable around 0 ppm with little variability among vehicles and routes. The largest drift is observed when the PEMS was mounted in the cabin of vehicle OL003, with a negative -1.5 ppm step drift occurring at the beginning of the test (T06) and a positive +1.5 ppm step zero drift after 30 minutes (T13).

Figure 2. NO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 3. NO zero drift over the high altitude route



Source: JRC, 2020.

3.1.2 Nitrogen dioxide NO_2

All tests on RDE compliant routes except T06 (**Figure 4**) and on high altitude except T10 and T13 (**Source:** JRC, 2020.

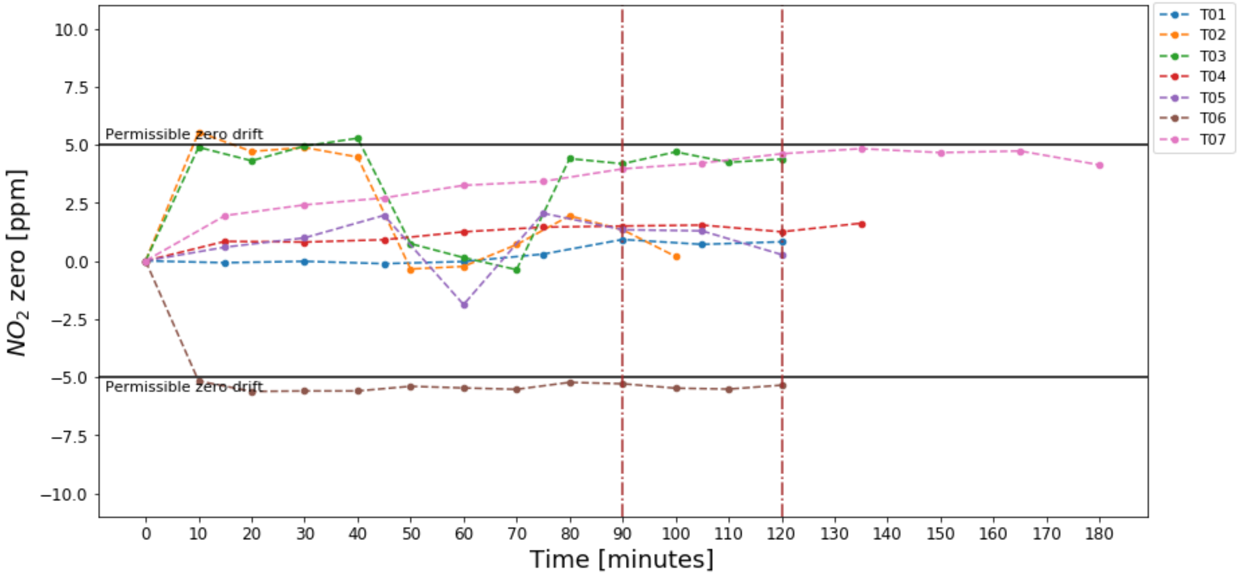
Figure 5) had an NO_2 zero drift at the end of the test within the permissible zero drift. As for NO drift, test T06 had a negative NO_2 step drift within the first ten minutes of the test (-5.2 ppm) and the stayed stable along the test leading to an invalid test at the end of the test. Similarly as for NO, T13 registered a positive step drift of NO_2 (7.8 ppm) between 30 and 40 minutes. From that point, the NO_2 drift remained stable around 7 ppm and led to the invalidation of the test for excess of zero drift. It is remarkable that the same PEMS unit (PEMS1 in the cabin of vehicle OL003) had a positive (T13) and a negative (T06) drift exceeding the permissible ±5 ppm on tests performed on consecutive days.

For the valid tests (i.e., NO_2 drift at the end of the test within ±5 ppm), most of the intermediate zero response checks had an NO_2 drift below ±5 ppm for both RDEc and HighAlt routes. However, for RDEc tests, there is no general pattern for NO_2 zero drift since some tests display little variability from 0 ppm (T01, T04, T05) while others have a linear positive drift (T07) that reaches circa 5 ppm after two hours of test, whereas for two tests (T02 and T03) there was a positive step drift slightly beyond 5 ppm on the first zero response checks of the tests that went to 0 ppm again on the checks done after 50 minutes. Both T02 and T03 were tests done with the PEMS mounted on the trailer hook but because T01 was also a test with an installation on the trailer hook and showed no drift, no direct relationship can be established between step drifts occurring along the test and the PEMS installation location.

HighAlt routes displayed a similar behaviour as RDEc ones with little zero drift on certain tests with installations in the trailer hook and in the cabin (T08, T11, T14), up and down steps in some other tests (T09, T10, T12), and a step drift of -5 ppm occurring after 40 minutes of drive that is maintained until the end of the test (T16). It is worth noting that T09 is the only valid test during which an exceedance of the permissible zero NO2 drift (6 ppm) is observed.

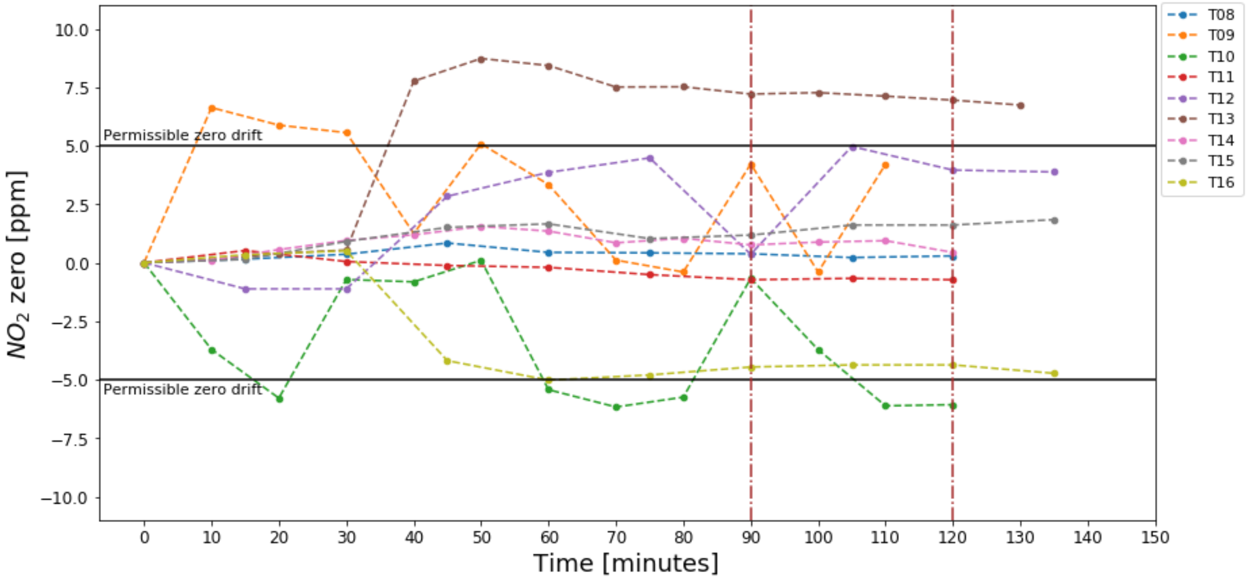
The tests with largest NO_2 zero drift (either steps or linear), occurred on vehicles with spark ignition (T02, T03, T07, T09, T10, T16) and compression ignition (T06, T12, T13). This observation points to the fact that the NO_2 drift is independent from vehicle ignition and fuel type.

Figure 4. NO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 5. NO_2 zero drift over the high altitude route



Source: JRC, 2020.

3.1.3 Nitrogen oxides NO_X

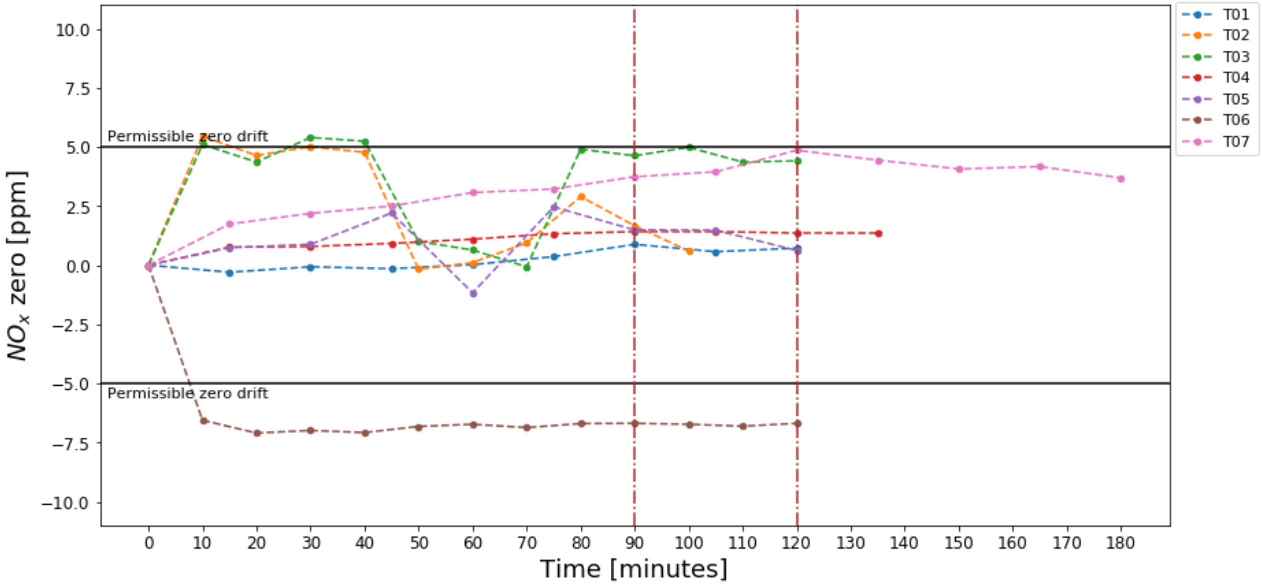
The permissible zero drift for NO_X is established in the RDE regulation to 5 ppm for the combination of NO and NO_2 since not all PEMS are technically designed to measure both pollutants individually. In the case of the AVL-MOVE units used in this campaign both pollutants are measured and observations show that NO_2 has larger zero drift than NO and hence it is responsible for a larger share of the NO_X measurement uncertainty. It is also important to remember that the NO_2 fraction of the NO_X emissions is not negligible, ranging 5-20% on gasolines and up to 50% for modern diesel vehicles equipped with oxidising catalysts (O'Driscoll *et al.*, 2018, Suarez-Bertoa *et al.*, 2019). It is therefore very important to measure accurately both NO and NO_2.

When combined, the NO_X zero drift repeats essentially the behaviour of the NO_2 zero drift described in section 3.1.2. Under RDE boundary conditions (**Figure 6**), all tests have a NO_X zero drift below the permissible 5 ppm in all zero checks except for T02 and T03, when NOx zero drift is slightly above 5 ppm between minutes 20 and 40 of the test, and T06, when a -6.6 ppm step is registered since the beginning of the test. A more erratic

NOx zero drift behaviour is observed on the high altitude tests (**Figure 7**) in particular for tests T09, T10 and T12 where several up and down steps are measured throughout the duration of the tests.

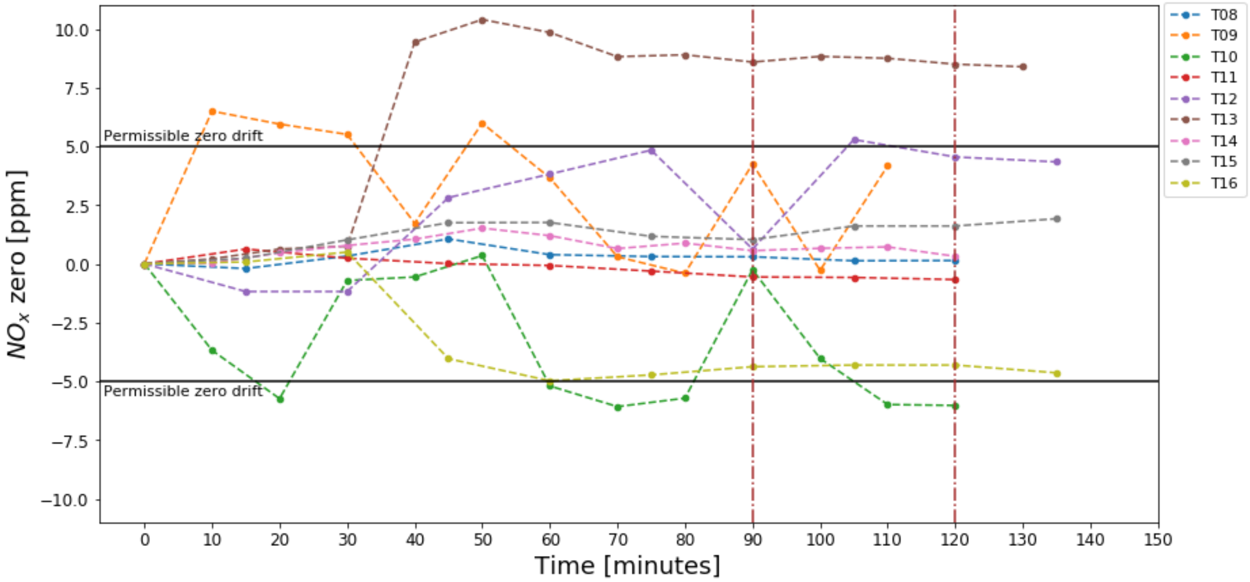
Considering all tests done inside and outside the RDE boundary conditions, it is important to note that the step drift hypothesis for positive NO_X zero drift is not verified (assuming a positive drift occurring at the beginning of the test and being maintained all over it). With the data available, the worst NO_X zero drift lies between linear and step drift hypotheses defined by Giechaskiel *et al.*, (2018).

Figure 6. NO_X zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 7. NO_X zero drift over the high altitude route

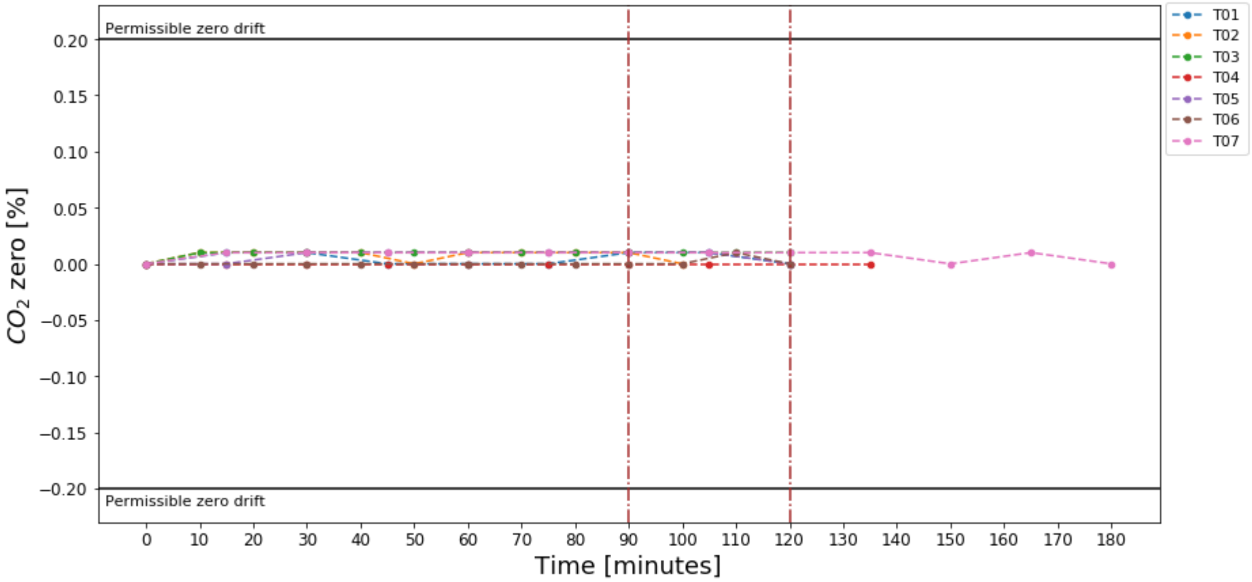


Source: JRC, 2020.

3.1.4 Carbon dioxide CO_2

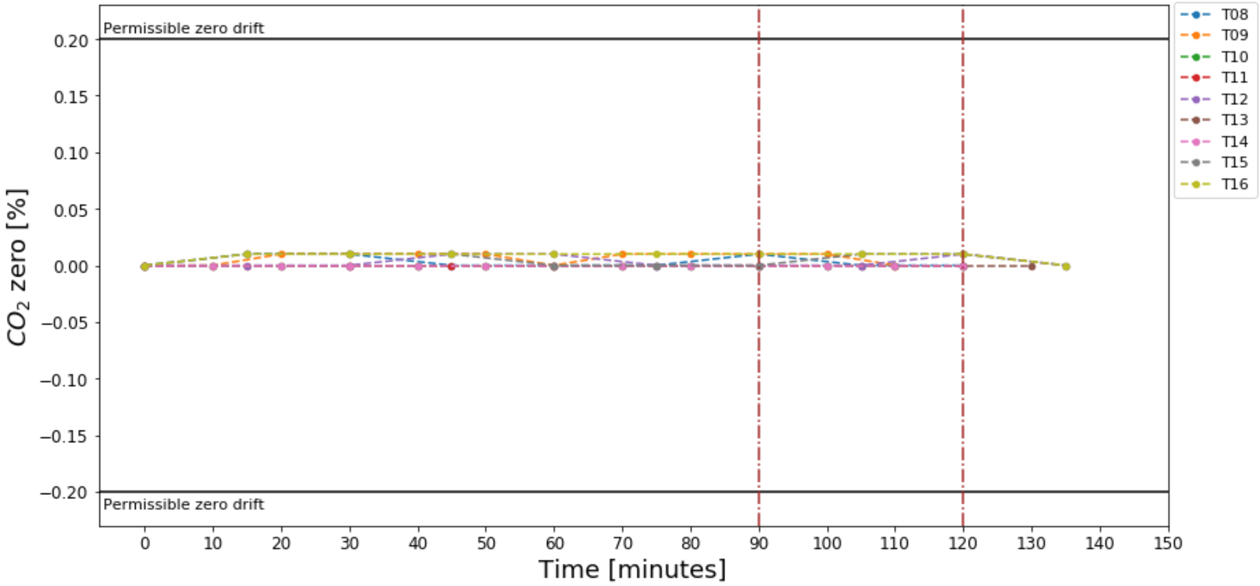
CO_2 zero drift is < 100 ppm on all tests and all zero intermediate checks, showing low variability among different tests. Although there is some slight variations of the zero response within a given test (from 0 ppm to 100 ppm), the zero drift is one order of magnitude lower than the permissible CO_2 zero drift (2000 ppm). Results are similar for tests done on RDE compliant routes (**Figure 8**) and on the high altitude tests (**Figure 9**). No differences are observed on CO_2 zero drift among different routes, PEMS installation location or vehicles.

Figure 8. CO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 9. CO_2 zero drift over the high altitude route



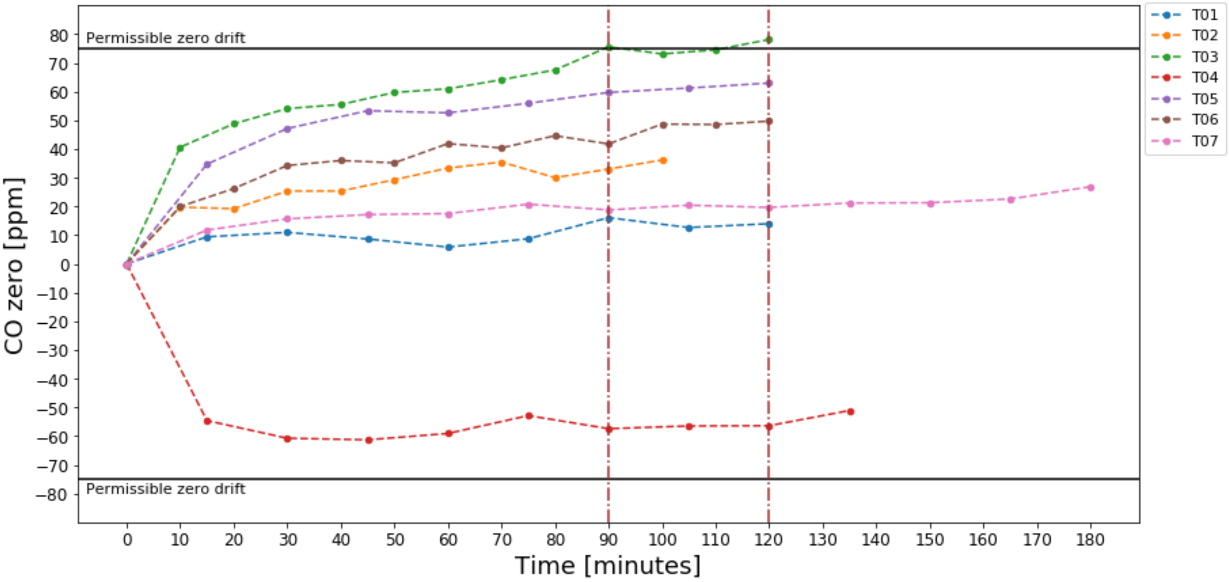
Source: JRC, 2020.

3.1.5 Carbon monoxide CO

CO has no margin assigned in RDE regulation. However, since it is currently measured with PEMS its zero drift is also assessed.

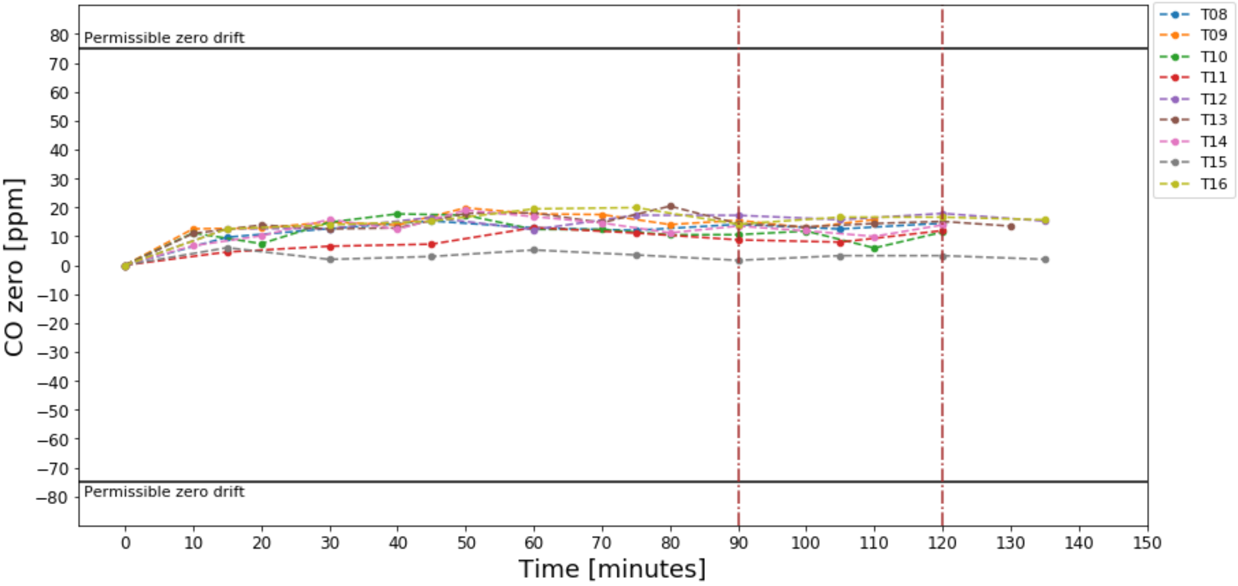
From the tests performed in the campaign with the AVL-MOVE, CO zero drift is always within its permissible range allowed by regulation (±75 ppm), except for test T03 which slightly exceeds the limit after 2 hours. For most of the intermediate zero checks, both for tests within RDE boundaries (**Figure 10**) and in the high altitude route (**Figure 11**), CO zero drift lies within ±25 ppm and it is quite stable around 0 ppm. It is worth noting that except for 1 test (T04) the drift is always positive. Two tests show a positive step zero drift (T03, T05) which occurs early in the test and then the drift is increasing linearly until the test end. It is assumed that the CO zero drift is larger on the RDEc tests than on the HighAlt ones, as the former were performed in the morning when the warming-up period of the PEMS was not necessarily long enough to allow a proper operation of the CO analyser (as it was the case on the afternoon tests on the HighAlt route). A longer warm-up time of PEMS has been implemented to avoid this issues as a consequence of this analysis.

Figure 10. CO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 11. CO zero drift over the high altitude routes



Source: JRC, 2020.

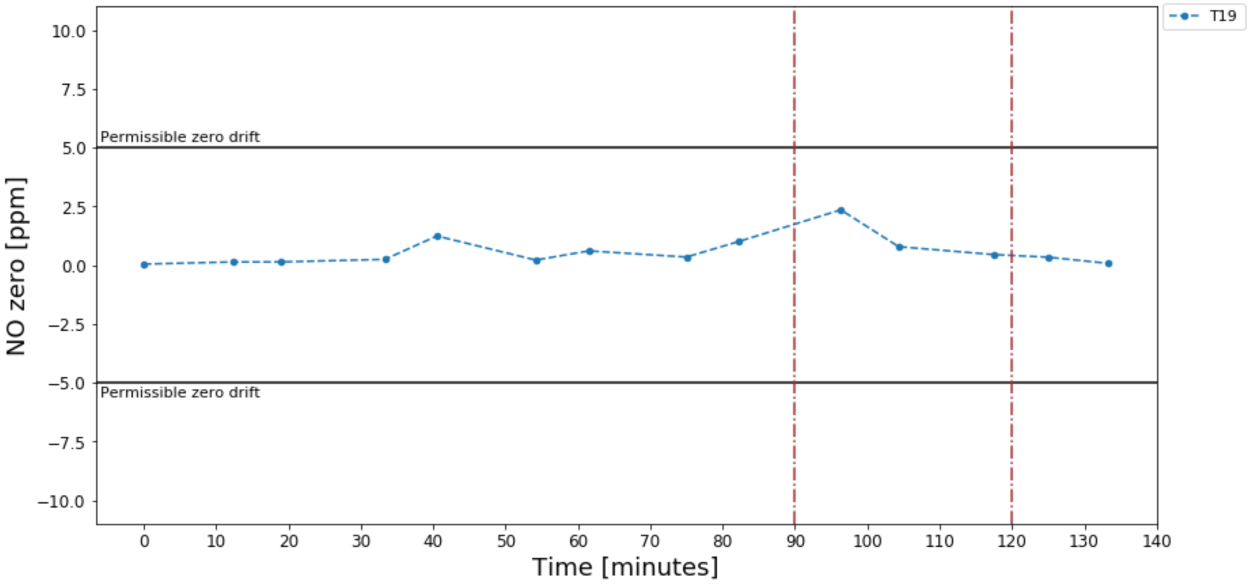
3.2 HORIBA OBS-ONE

Zero response checks were performed every ~15 minutes. The zero values reported in the intermediate checks were calculated as the average of the zero response over the zeroing period.

3.2.1 Nitrogen monoxide NO

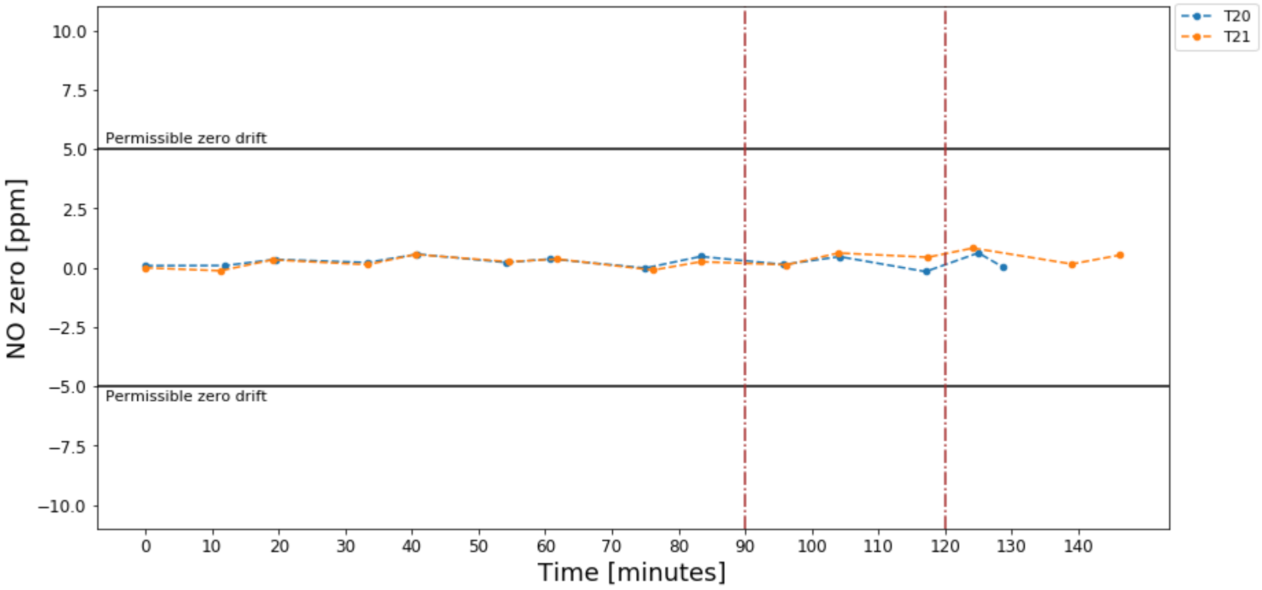
On the RDEc test (**Figure 12**), the NO zero drift is lower than 2.5 ppm along the trip and does not show a linear positive drift as several upwards and downwards steps are measured. On the HighAlt route (**Figure 13**), both tests show no drift for NO with intermediate zero response checks below 1 ppm.

Figure 12. NO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 13. NO zero drift over the high altitude route

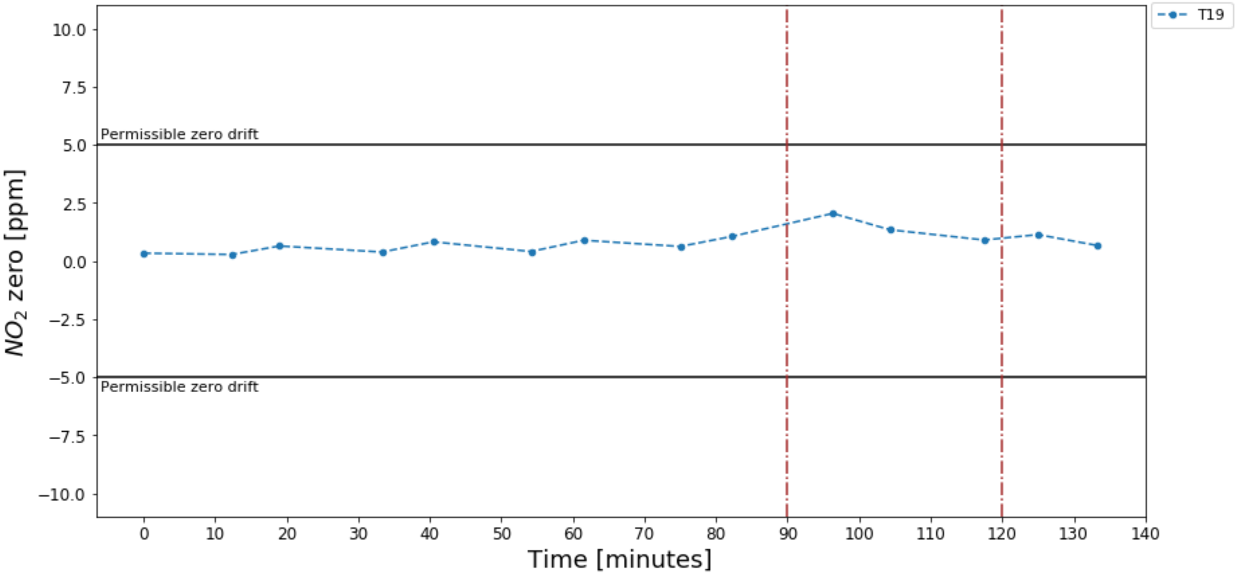


Source: JRC, 2020.

3.2.2 Nitrogen dioxide NO_2

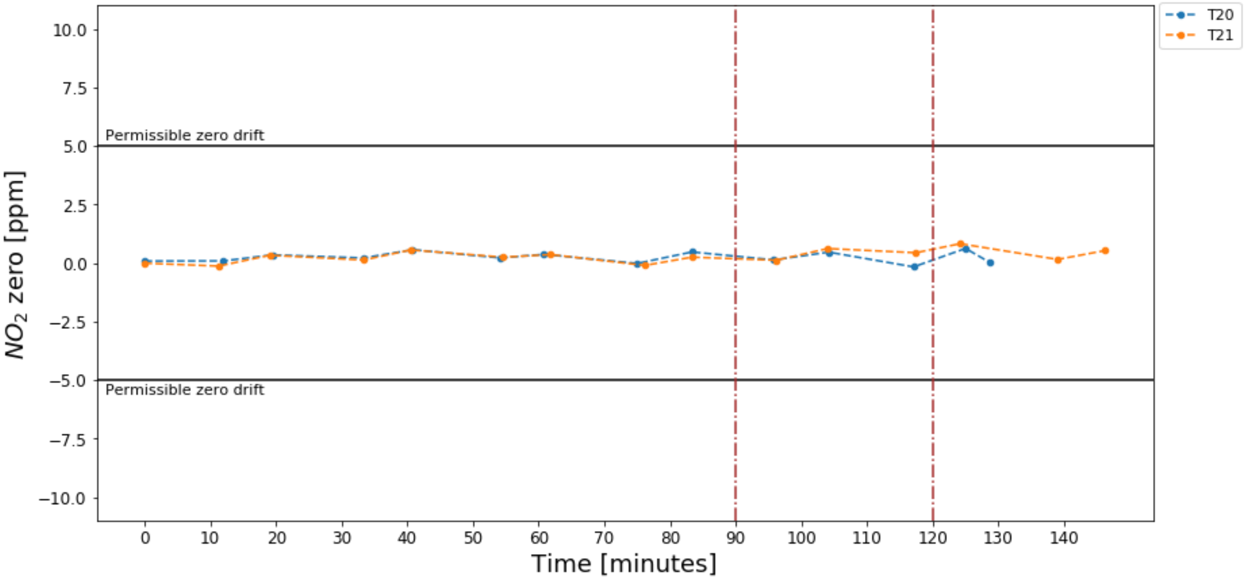
The results for NO_2 are calculated from the difference of NOx and NO. The NO_2 zero drift with the HORIBA OBS-ONE shows a similar behaviour as the one described for NO: less than 2.5 ppm an all intermediate stages on all tests performed, both RDEc (**Figure 14**) and HighAlt (**Figure 15**).

Figure 14. NO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 15. NO_2 zero drift over the high altitude route

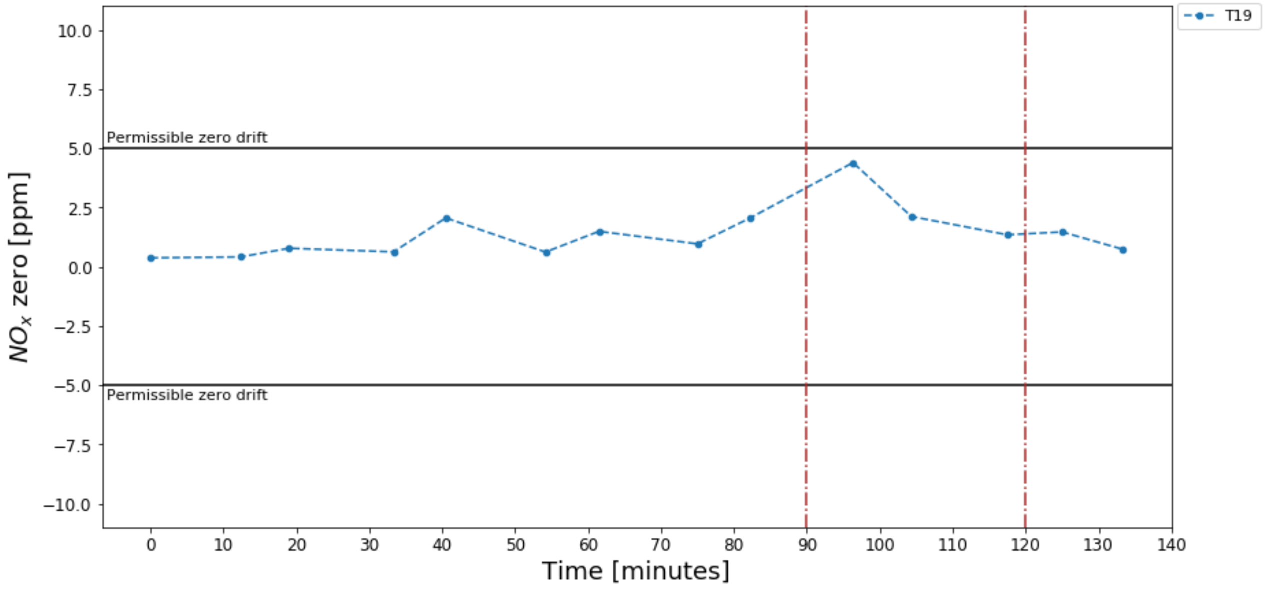


Source: JRC, 2020.

3.2.3 Nitrogen oxides NO_X

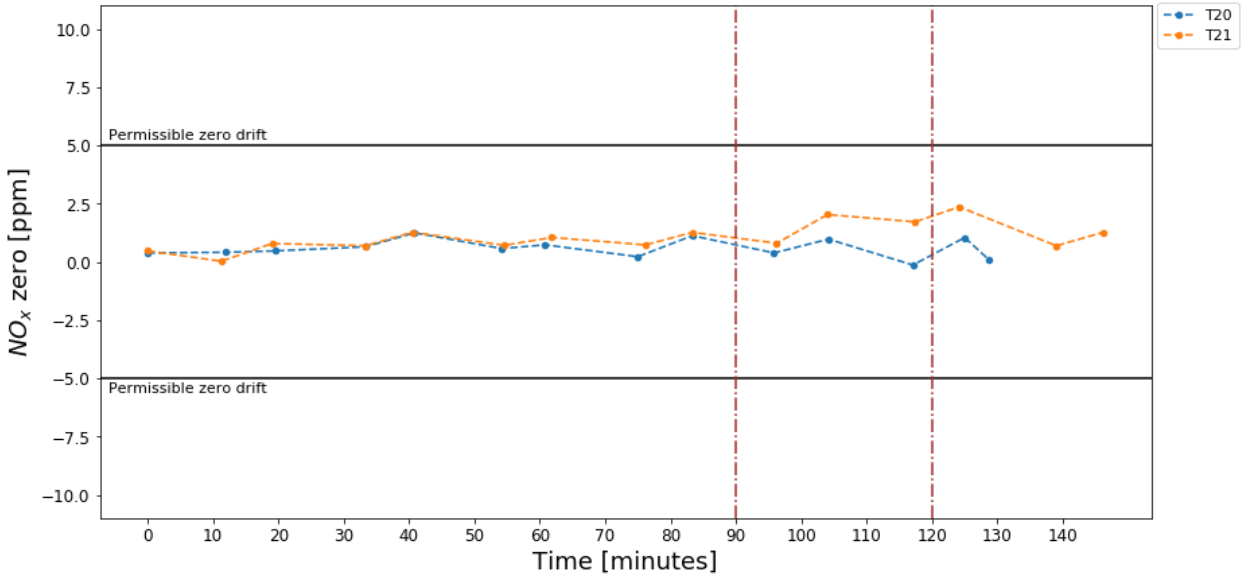
In the case of the HORIBA OBS-ONE unit tested, NO and NOx analysers are equally responsible of the total NOx drift observed in the RDEc route (**Figure 16**) and in the HighAlt tests (**Figure 17**). On all intermediate NOx response checks, the NOx drift is below the permissible NOx drift for the whole test and the maximum NOx drift is ~ 4.5 ppm. This maximum NOx drift is reduced at the post-test. Considering all tests done with the HORIBA instrument inside and outside the RDE boundary conditions the step drift hypothesis for positive NO_X zero drift is not verified. Also, no particular effect of altitude is observed on NOx zero drift.

Figure 16. NO_X zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 17. NO_X zero drift over the high altitude route

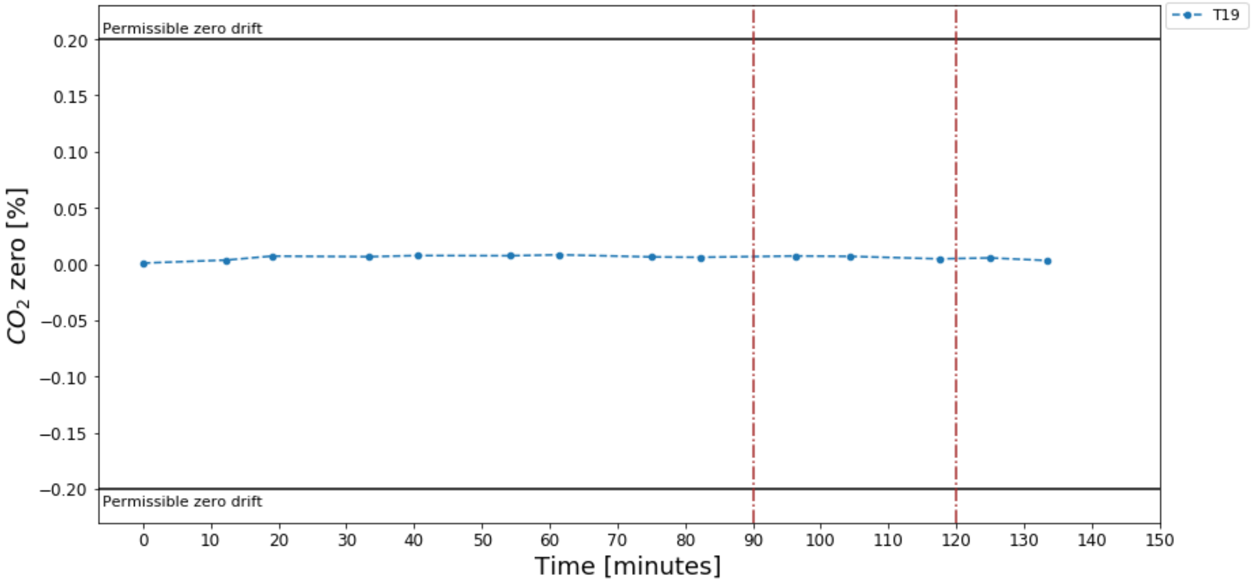


Source: JRC, 2020.

3.2.4 Carbon dioxide CO_2

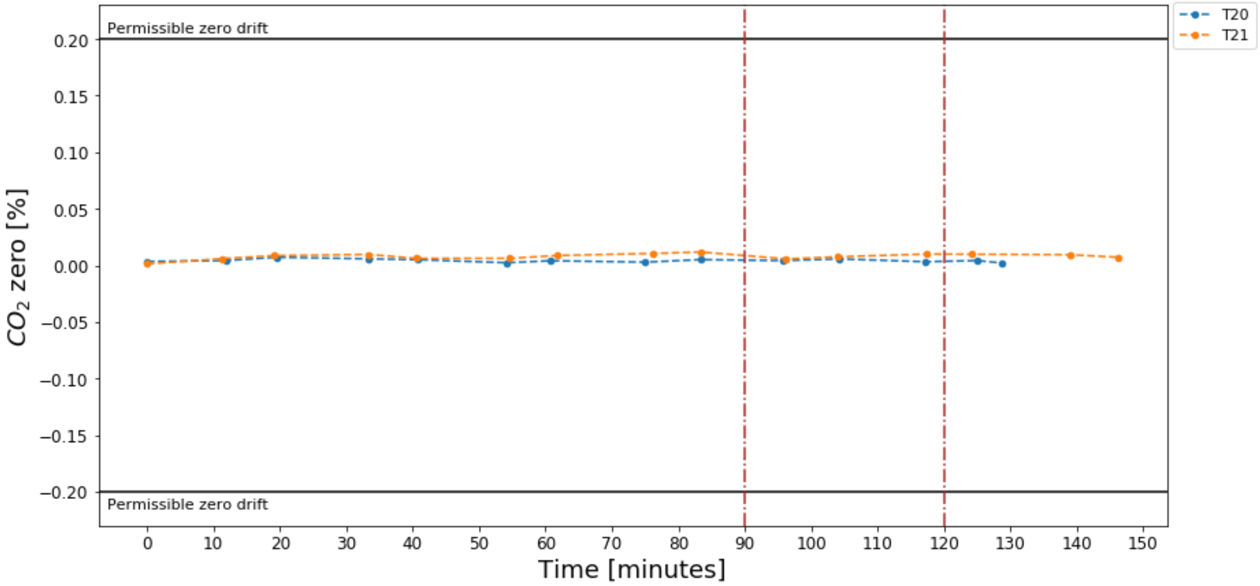
CO_2 zero drift is < 100 ppm on all tests and all zero intermediate checks, showing low variability among different tests. Although there is some slight variations of the zero response within a given test (from 0 ppm to 100 ppm), the zero drift is one order of magnitude lower than the permissible CO_2 zero drift (2000 ppm). Results are similar for tests done on RDE compliant routes (**Figure 18**) and on the high altitude tests (**Figure 19**).

Figure 18. CO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 19. CO_2 zero drift over the high altitude route

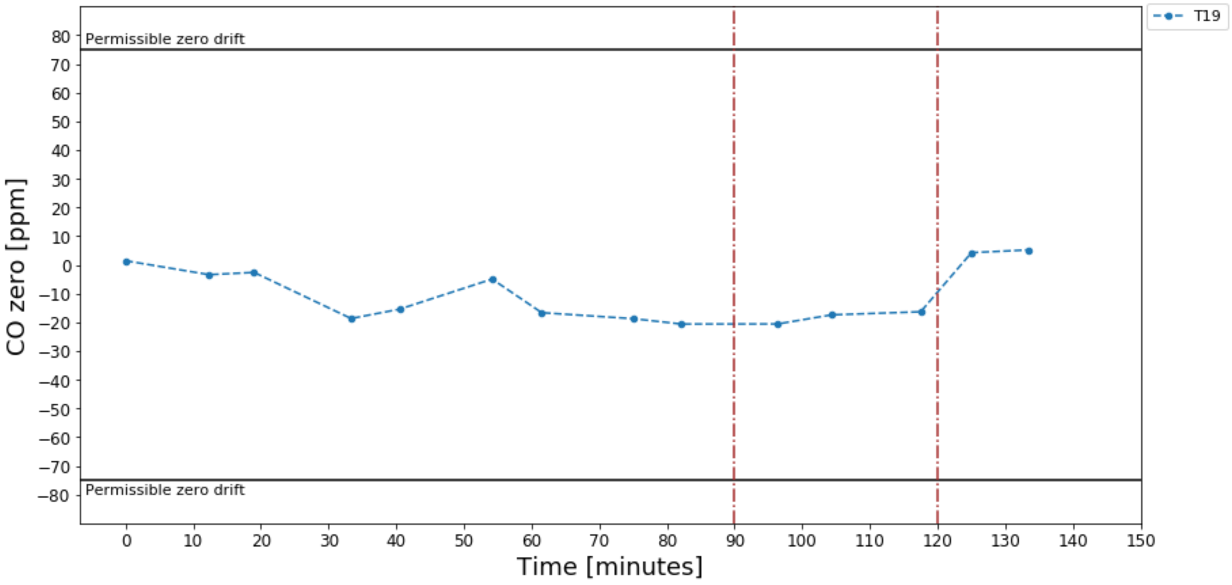


Source: JRC, 2020.

3.2.5 Carbon monoxide CO

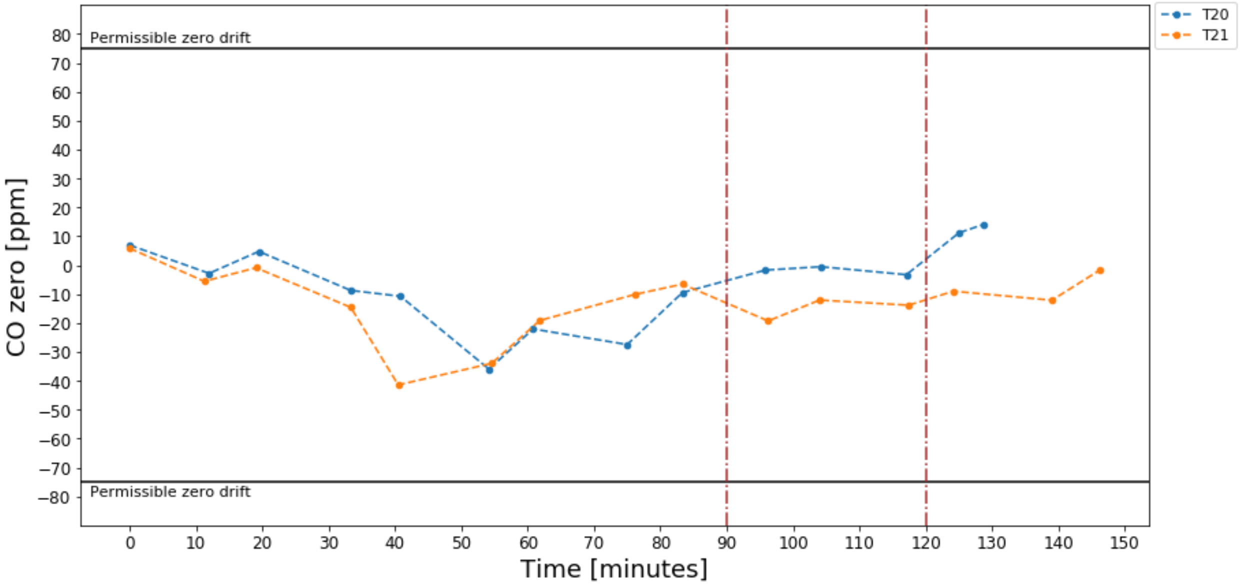
The CO zero drift is always within its permissible range allowed by regulation (±75 ppm) in the three tests performed with the HORIBA OBS-ONE unit. The measured CO drift is mainly negative and reaches a minimum value of -20 ppm on the RDEc test (**Figure 20**) and -50 ppm on the HighAlt tests (**Figure 21**). No step or linear drift is systematically observed in the tests performed. All intermediate zero checks are also within the permissible drift limit.

Figure 20. CO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 21. CO zero drift over the high altitude routes



Source: JRC, 2020.

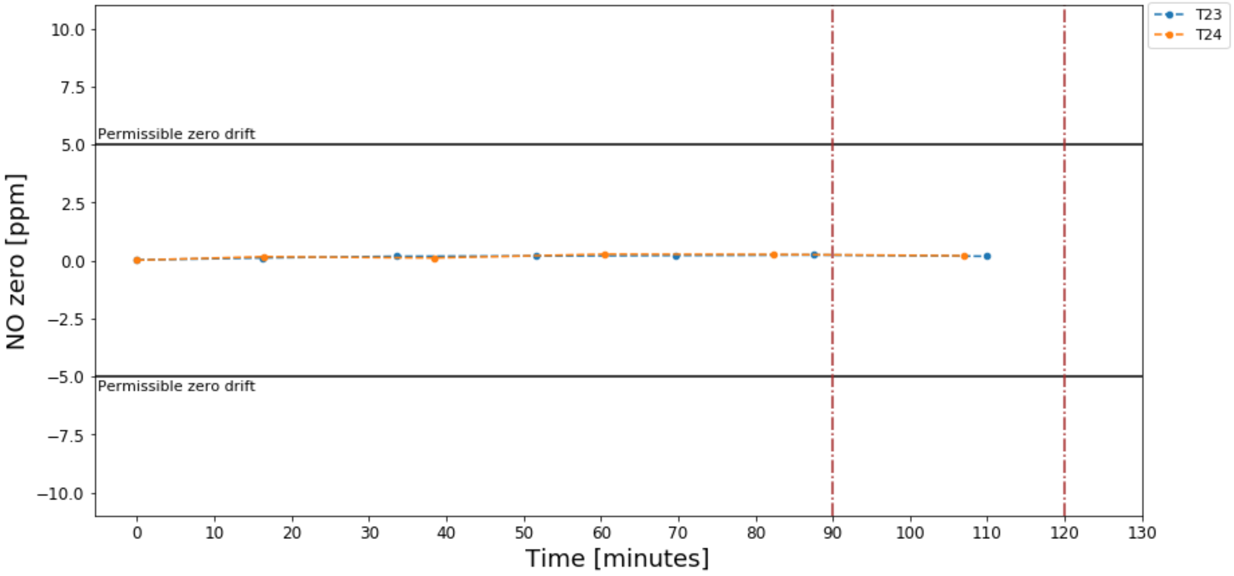
3.3 AIP-PEMS (Gen 2)

The zero response checks reported in this section were calculated as the average values of zeroing time as the PEMS does not automatically report those values. The zero drift of all analysers were within the permissible tolerances in all intermediate checks as well as in the post-test.

3.3.1 Nitrogen monoxide NO

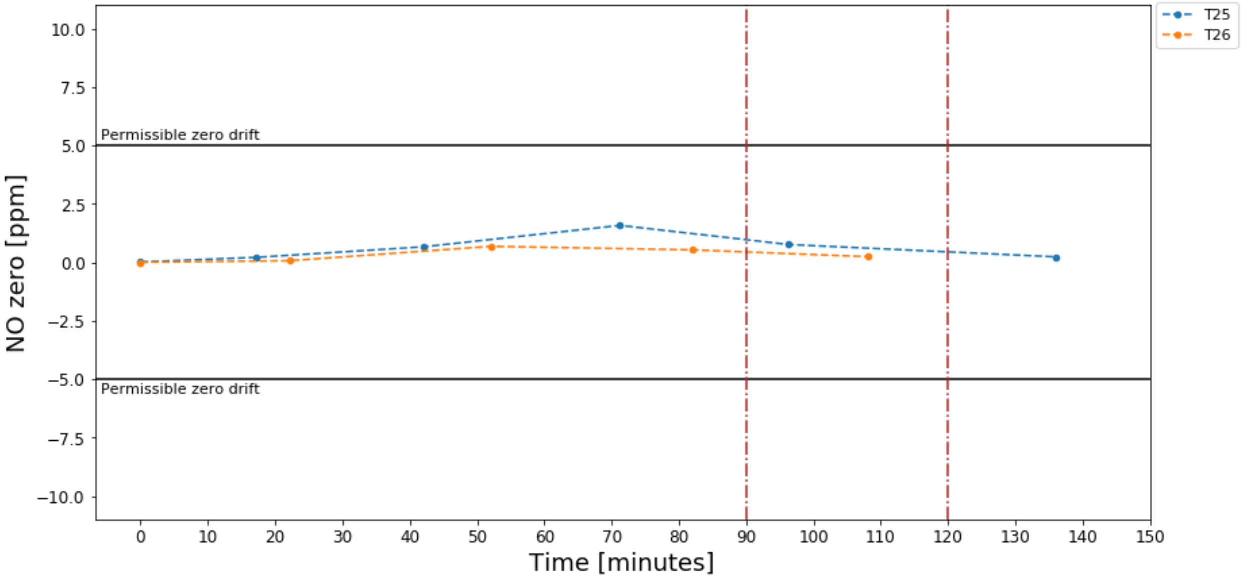
The AIP-PEMS shows no drift for NO on RDEc routes (**Figure 22**) and a maximum of 1.5 ppm in the altitude section of the HighAlt test in one out of two tests performed (**Figure 23**.). The two repetitions of each test are almost identical which proves a good reliability of the analyser.

Figure 22. NO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 23. NO zero drift over the high altitude routes

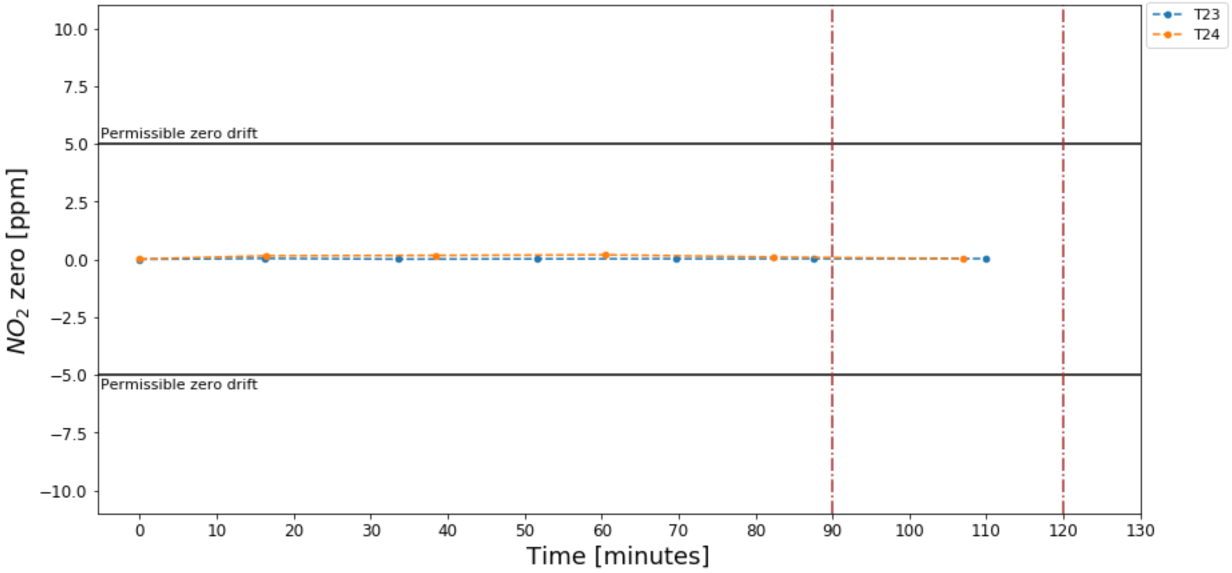


Source: JRC, 2020.

3.3.2 Nitrogen dioxide NO_2

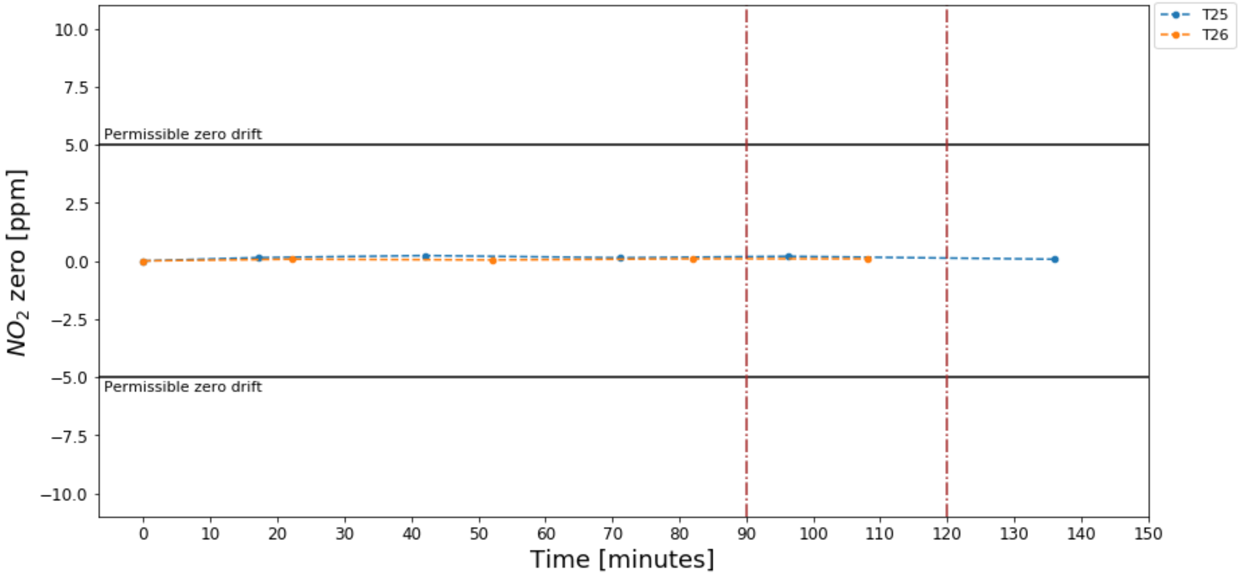
The AIP-PEMS has no zero drift for NO_2 showing consistently a value lower than 0.2 ppm on all intermediate checks on tests in RDEc routes (**Figure 24**) and HighAlt routes (**Figure 25**). Despite the harsh ambient conditions in which the HighAlt tests were performed (heavy rain, ~ 7 °C ambient temperature, and altitude reaching 1100 m), the analyser of NO_2 (Photoacoustic Spectroscopy) shows no sign of drift.

Figure 24. NO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 25. NO_2 zero drift over the high altitude routes

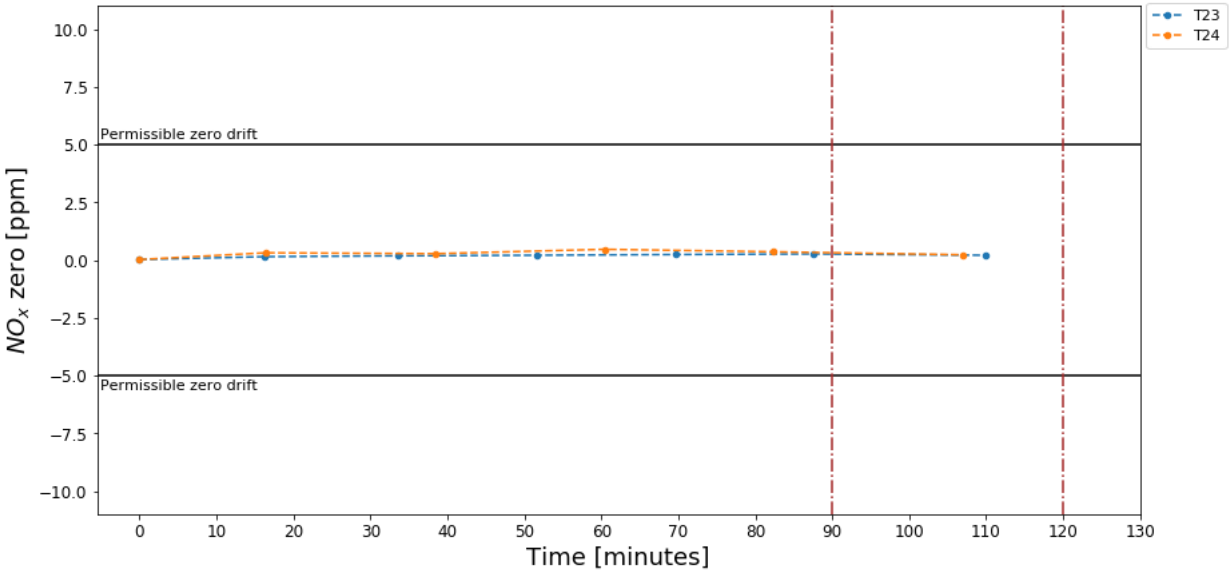


Source: JRC, 2020.

3.3.3 Nitrogen oxides NO_X

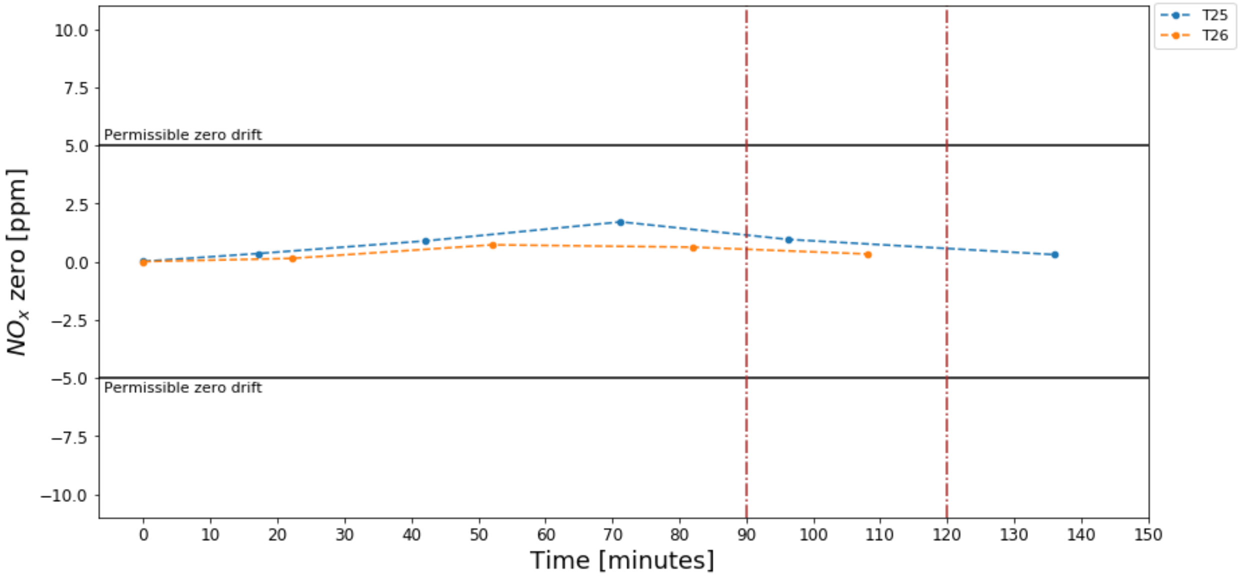
In the AIP-PEMS, the NO analyser is the main responsible of the observed NOx zero drift as the NO_2 analyser reading is systematically close to 0 (max 0.2 ppm). In all testing conditions (**Figure 26**, **Figure 27**), the intermediate NOx response checks are lower than 2 ppm. No worst case NOx step drift is observed for this instrument.

Figure 26. NOx zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 27. NOx zero drift over the high altitude routes

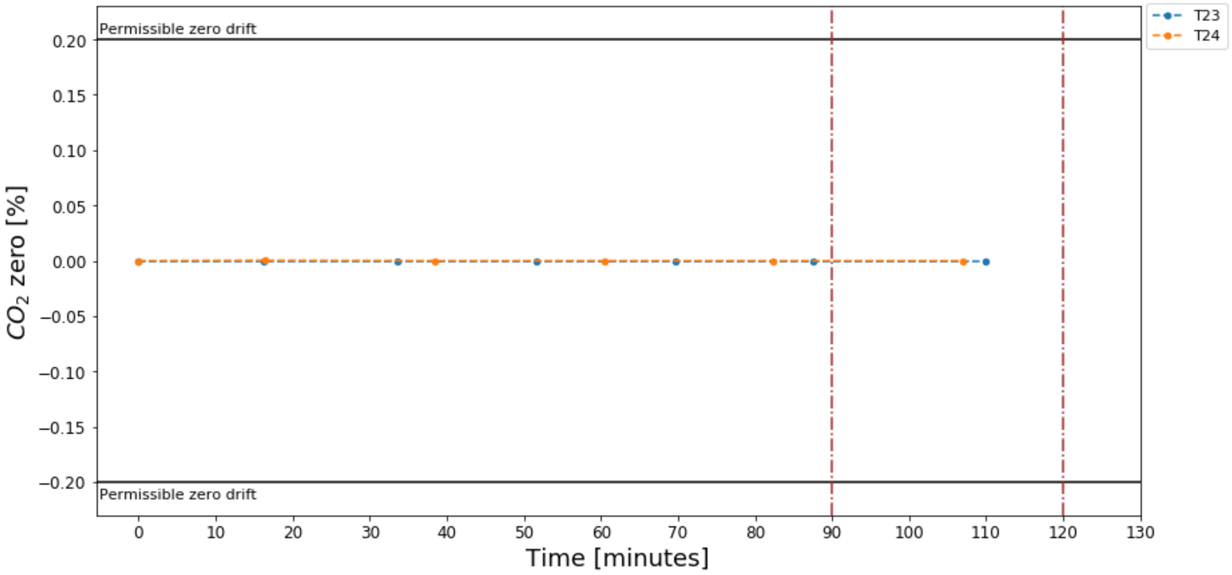


Source: JRC, 2020.

3.3.4 Carbon dioxide CO_2

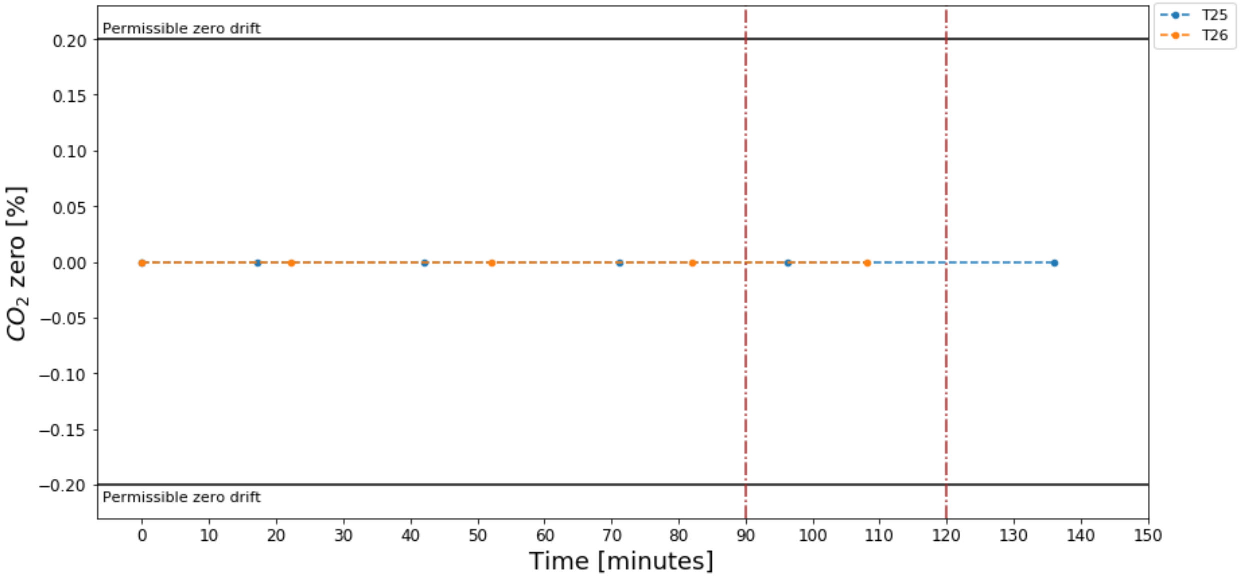
The CO_2 analyser of the AIP-PEMS is not affected by zero drift on any of the zero response checks performed or on the RDEc routes (**Figure 28**) or in the HighAlt ones (**Figure 29**). As for other instruments, the maximum zero drift measured is 100 ppm, which is one order of magnitude lower than the permissible zero drift for CO_2.

Figure 28. CO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 29. CO_2 zero drift over the high altitude routes

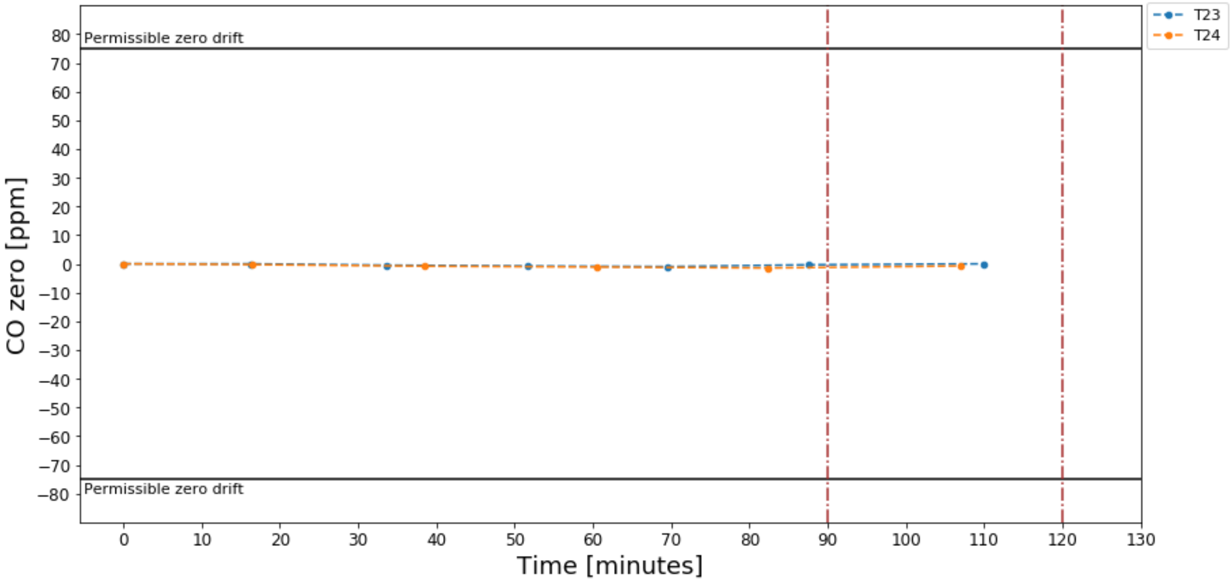


Source: JRC, 2020.

3.3.5 Carbon monoxide CO

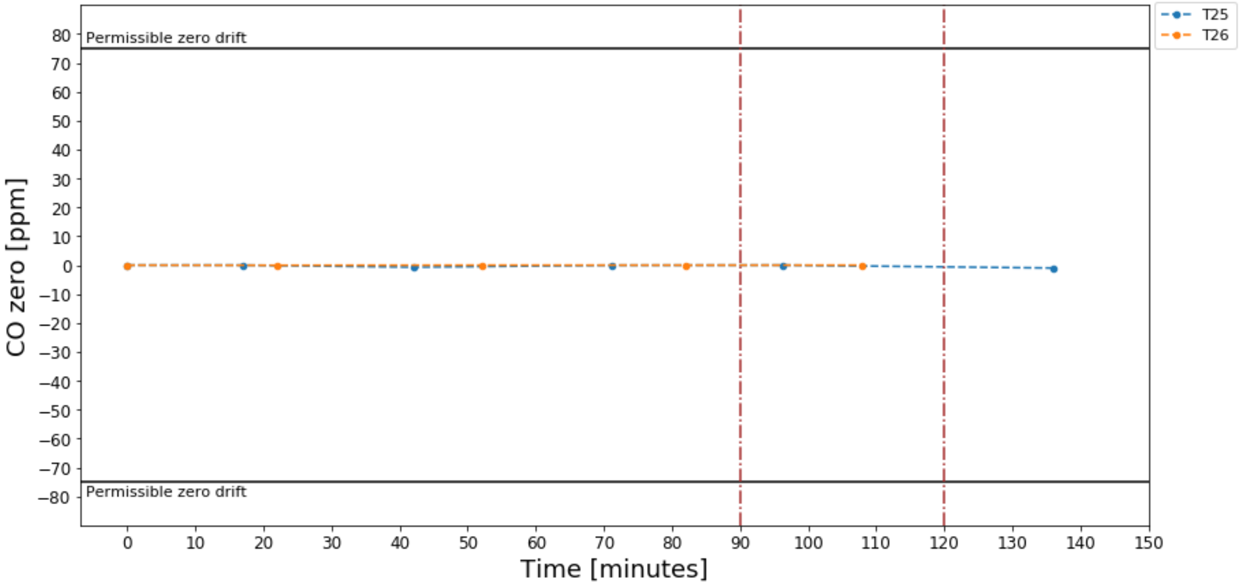
All four tests performed with the AIP-PEMS show essentially no zero drift for CO (**Figure 30**). All registered intermediate zero drift values are negative or null and the minimum intermediate response drift is -2 ppm. The analyser does not show any particular response to the altitude tests (**Figure 31**).

Figure 30. CO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 31. CO zero drift over the high altitude routes



Source: JRC, 2020.

3.4 SENSORS SEMTECH LDV

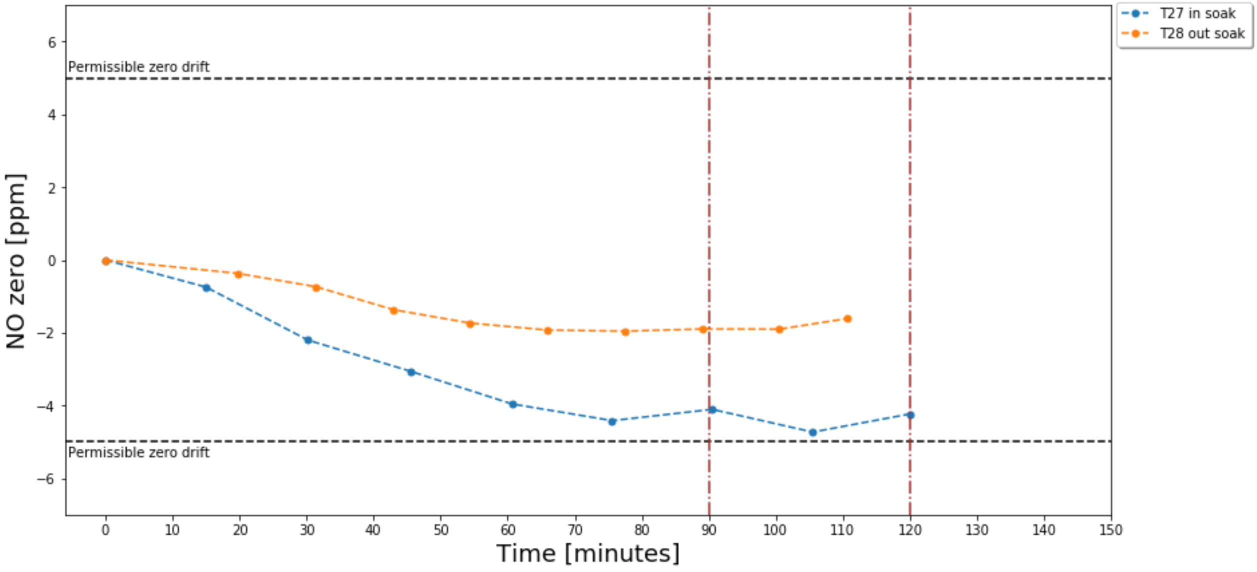
Two sets of tests were performed with the SENSORS SEMTECH LDV. Tests T27 and T29, were done with the pre-test performed inside the JRC facility, where the instrument had soaked at an ambient temperature of 20 °C. The vehicle, with the PEMS installed on the trailer hook was then driven for the tests at an ambient temperature of ~0 °C. Despite the zero drift for NO, and NO_2 between the pre-test and the post-test on both tests were lower than 5 ppm individually for each analyser, the combination of both led to an exceedance of the permissible NOx zero drift. For that reason, and following the PEMS manufacturer requirement, a new set of tests was performed (T28 and T30) on the following day, where the instrument was soaked at an ambient temperature similar to the testing temperature (~ 0 °C) and the pre-test was also performed at that temperature. For the tests performed in these conditions, the NO, NO_2, and also NOx zero drifts where within permissible tolerances at the end of the test.

The zero response checks reported in this section were calculated as the average values of zeroing time as the PEMS does not automatically report those values. The CO analyser of the instrument was not operating at the time of the tests.

3.4.1 Nitrogen monoxide NO

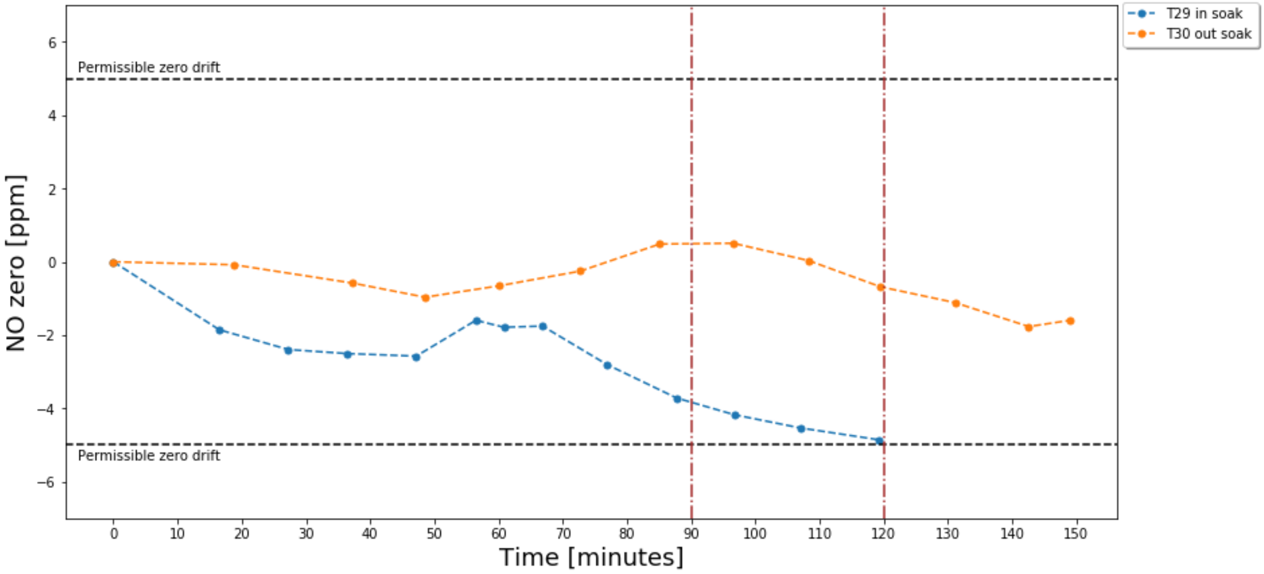
NO zero drift is lower than ±2 ppm on the tests where the pre-test was performed at external ambient temperature (T28, **Figure 32**, T30 **Figure 33**) on all intermediate zero checks, on the RDE compliant test and in the altitude test. For the tests where the pre-test was performed inside the facility, the NO analyser tended to drift linearly towards -5 ppm, almost reaching this value at the end of the two hours' drive.

Figure 32. NO zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 33. NO zero drift over the high altitude route

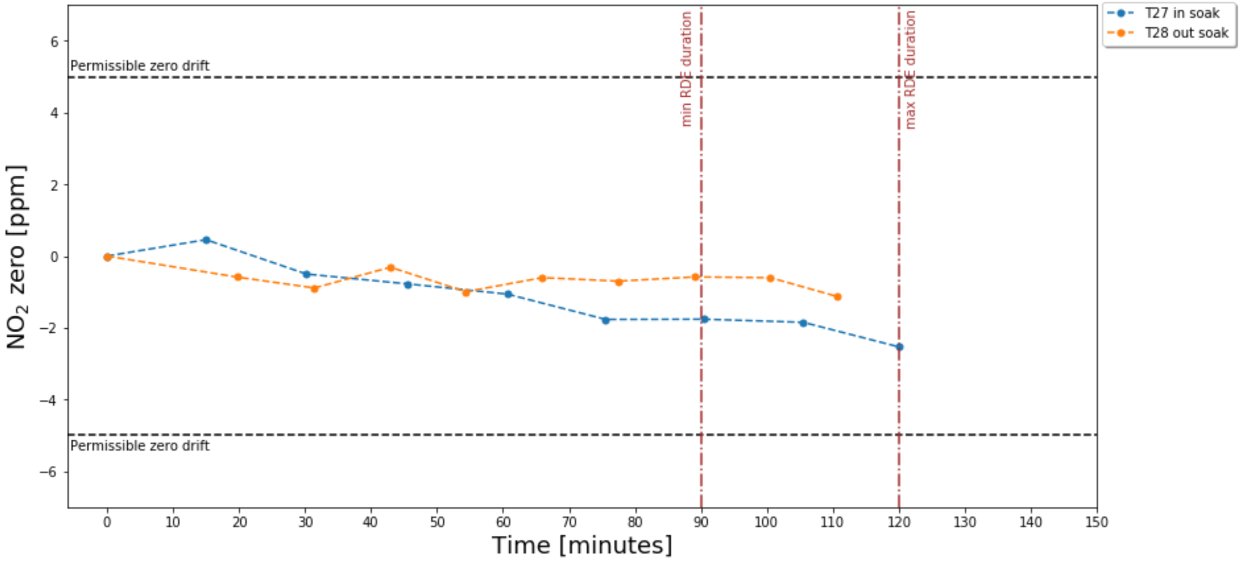


Source: JRC, 2020.

3.4.2 Nitrogen dioxide NO_2

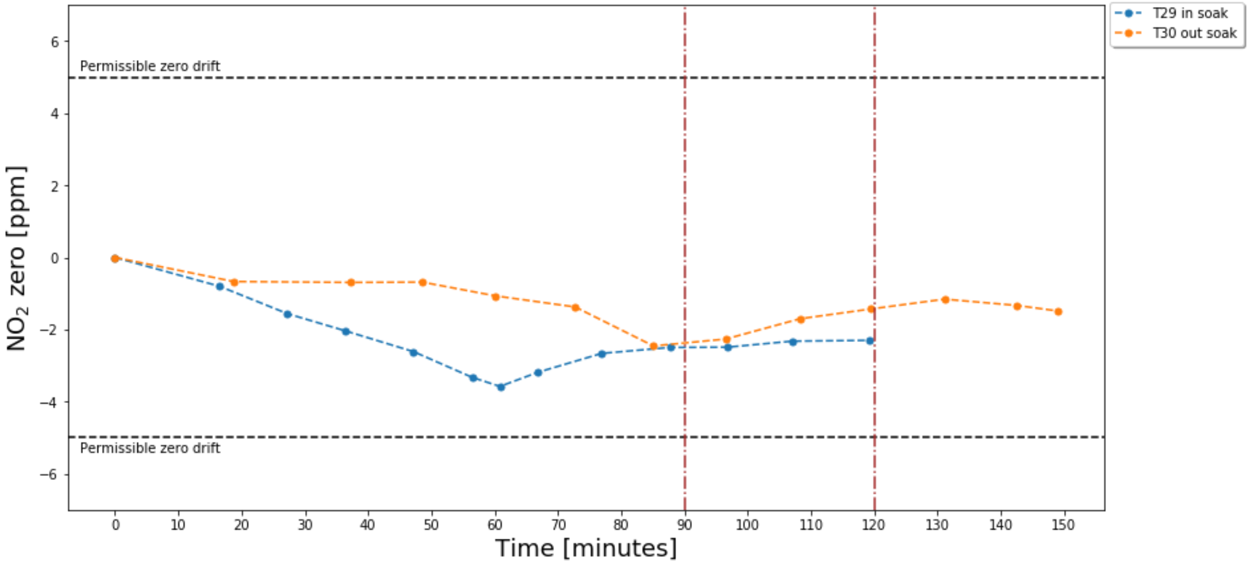
The intermediate NO_2 zero checks were within the permissible drift for all tests in all conditions (max drift -3.5 ppm). The NO_2 zero tend to drift to negative values, particularly on tests done with soak at very different ambient temperature than test temperature, both on the RDE compliant route (**Figure 34**) and on high altitude (**Figure 35**).

Figure 34. NO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 35. NO_2 zero drift over the high altitude route

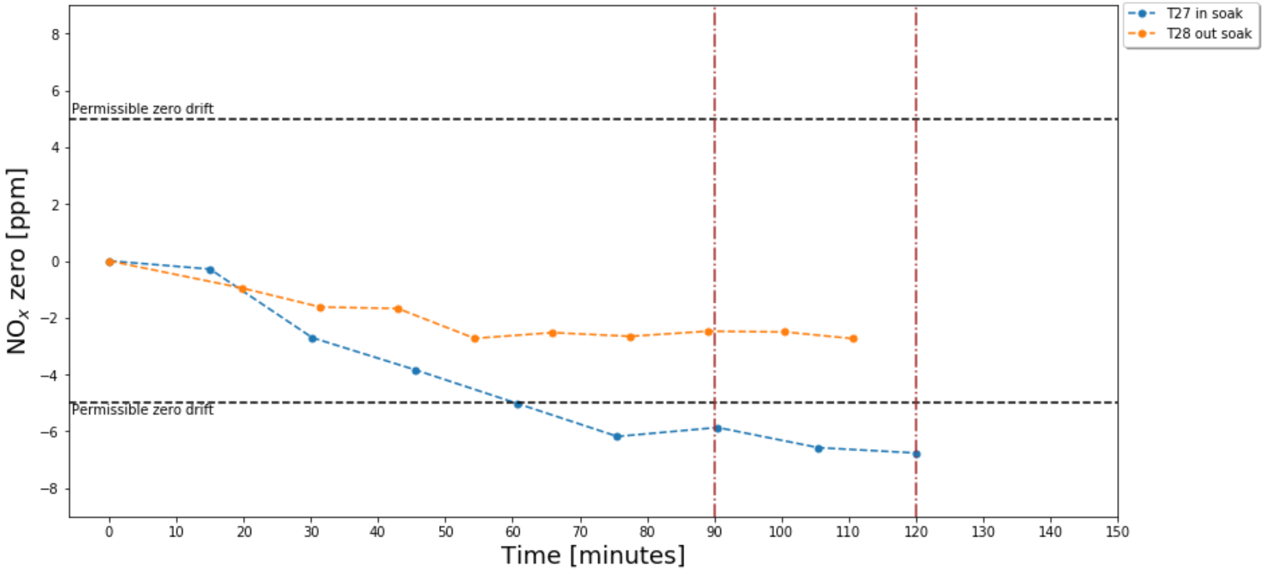


Source: JRC, 2020.

3.4.3 Nitrogen oxides NO_X

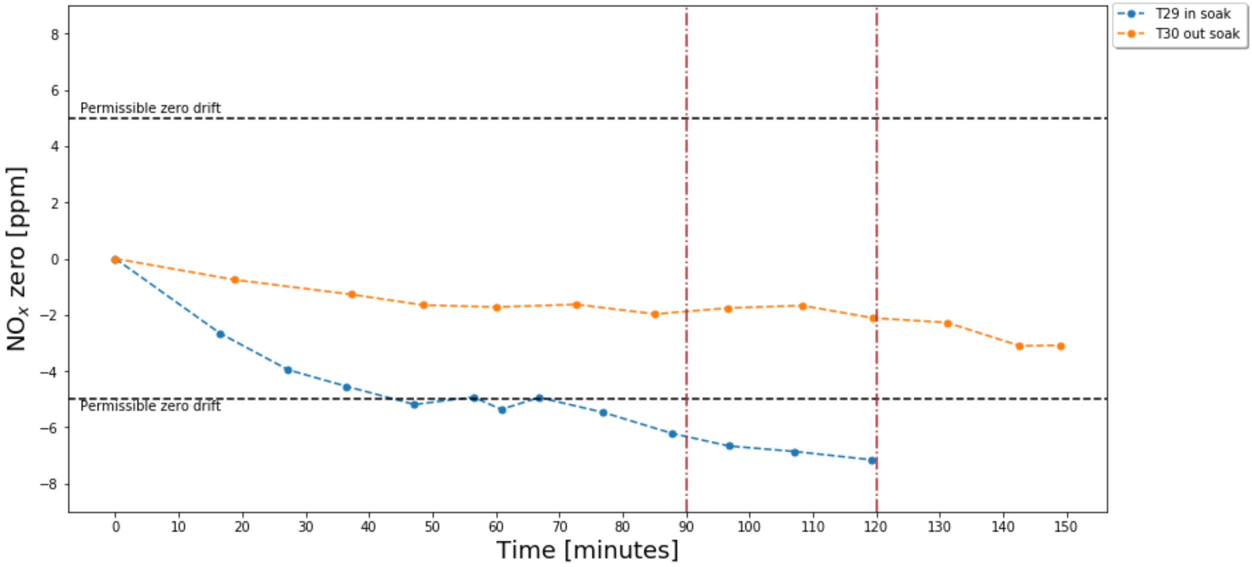
When combined, the NO_X zero drift of all four tests done with the SENSORS PEMS are negative (**Figure 36**, **Figure 37**). The NOx zero exceeds the permissible 5 ppm on the tests done with soak and calibration done inside the facility, whereas the tests with similar ambient conditions have a final zero drift within the tolerance. No effect of altitude is seen on intermediate zero checks. Also, T28 and T30 show that under cold conditions of the test, if the instrument is soaked and calibrated following the requirements of the PEMS manufacturer, no particular effect of ambient temperature is observed on NOx zero drift. No step drift was verified on any of the tests even when the instrument was exposed to a drastic change in the temperature operation condition.

Figure 36. NO_X zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 37. NO_X zero drift over the high altitude route

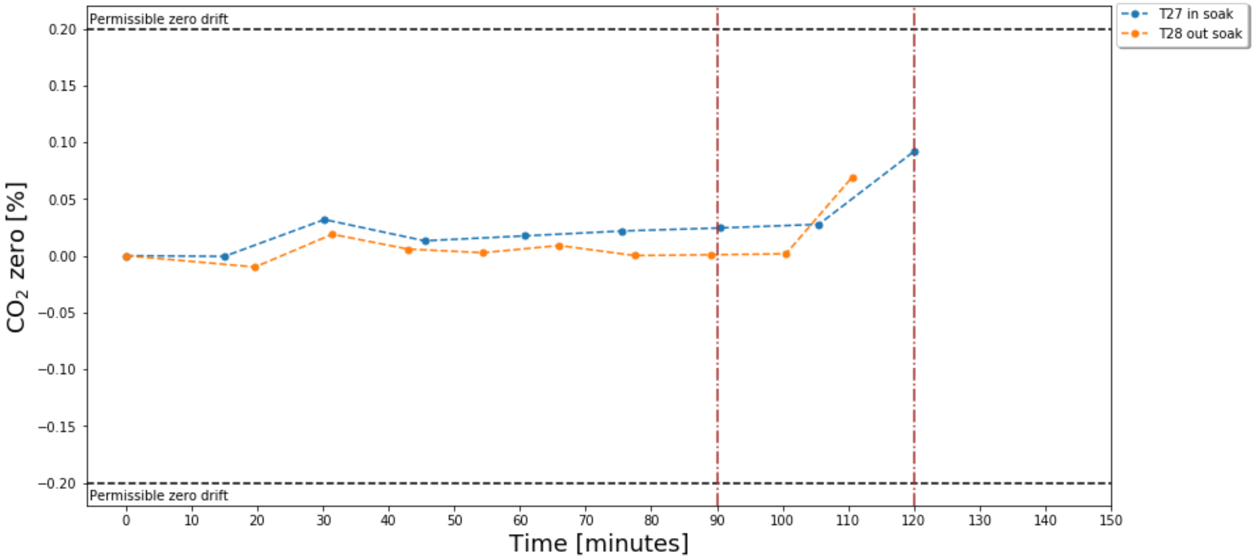


Source: JRC, 2020.

3.4.4 Carbon dioxide CO_2

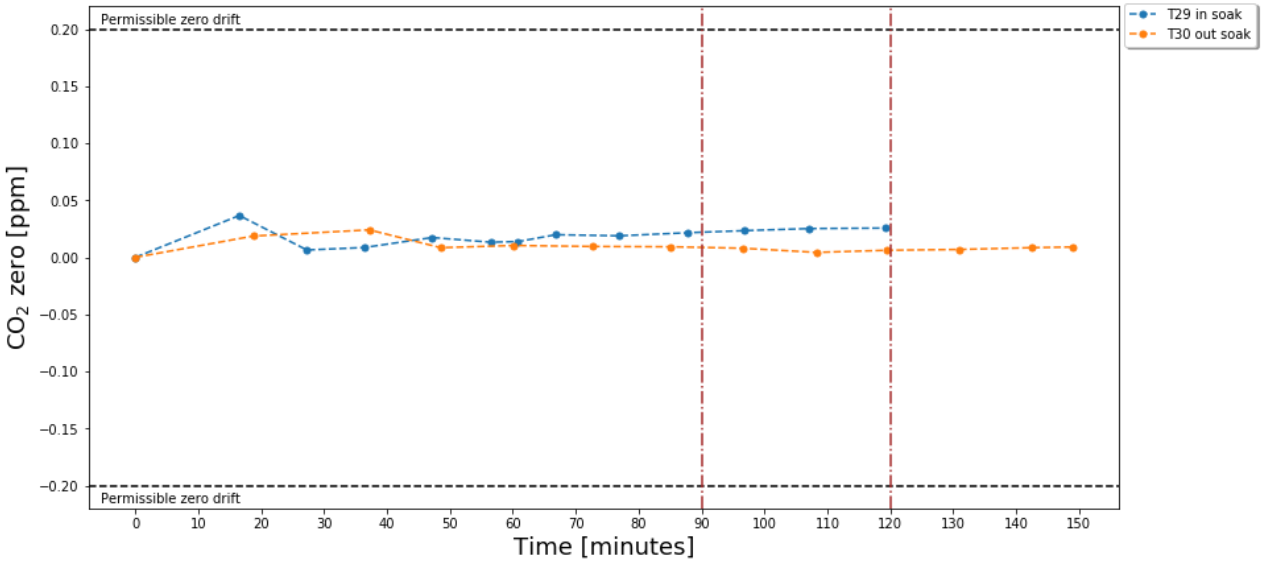
The zero drift of the CO_2 analyser of the SENSORS SEMTECH LDV is within the permissible tolerance on all intermediate zero checks performed on all tests, including the RDE compliant routes (**Figure 38**) and the high altitude tests (**Figure 39**). No effect of altitude or change of temperature is observed on the zero response of the CO_2 analyser.

Figure 38. CO_2 zero drift over RDE compliant routes



Source: JRC, 2020.

Figure 39. CO_2 zero drift over the high altitude route



Source: JRC, 2020.

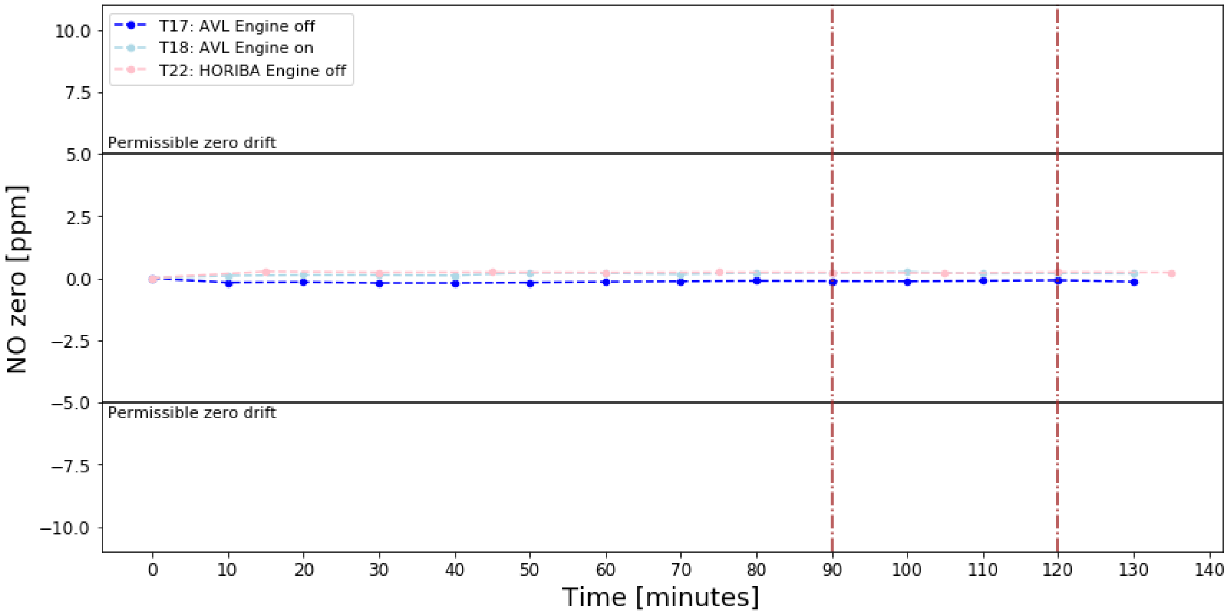
3.5 Static tests

3.5.1 Constant ambient conditions

This section provides an overview of the results for the three tests done with the PEMS performing zero checks at an interval of 10/15 minutes on a static vehicle for 2 hours at constant temperature (2 tests with AVL-MOVE, and 1 test with HORIBA OBS-ONE). All three tests fulfil the permissible zero drift limits for all measured gases (NO, NO_2, CO_2, CO) between the pre-test and their respective post-tests.

NO zero response checks lie within ±0.3 ppm on all three tests. The one with the AVL-MOVE in which the vehicle was kept idling (engine-on) and the one with the HORIBA OBS-ONE show positive values for NO zero, whereas the one with the engine-off on the AVL-MOVE displays negative values (**Figure 40**).

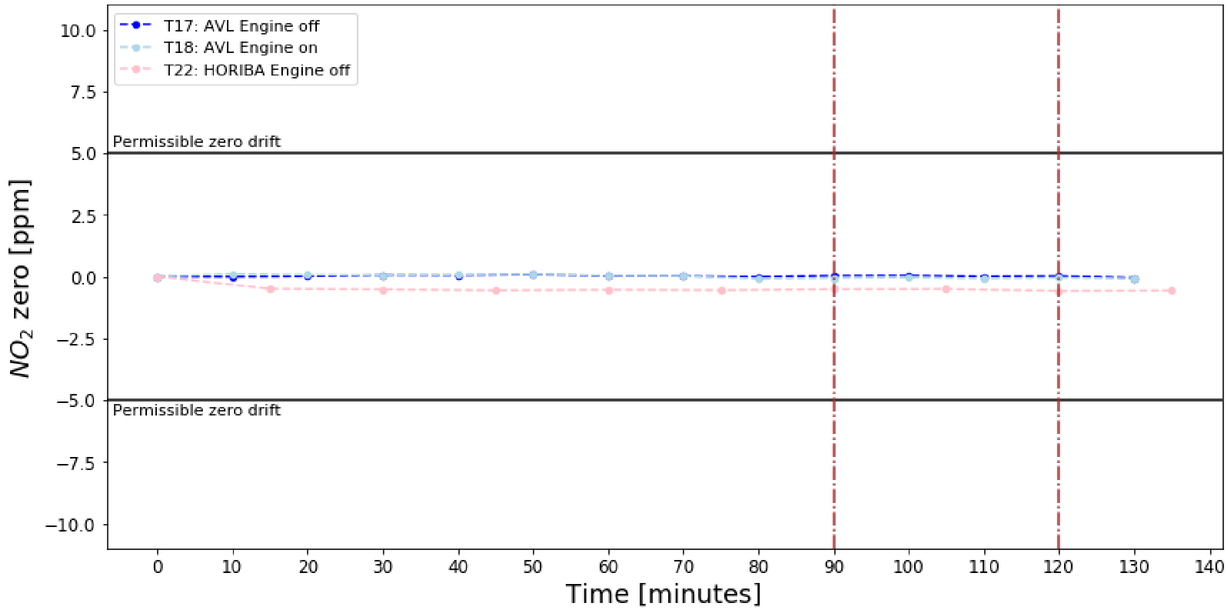
Figure 40. NO zero drift checks for static tests



Source: JRC, 2020.

The NO_2 zero response checks performed on both PEMS oscillate around 0 ppm (max 0.1 ppm and min -0.6 ppm, **Figure 41**). No increase/decrease trend is observed for NO_2 zero drift along the testing time.

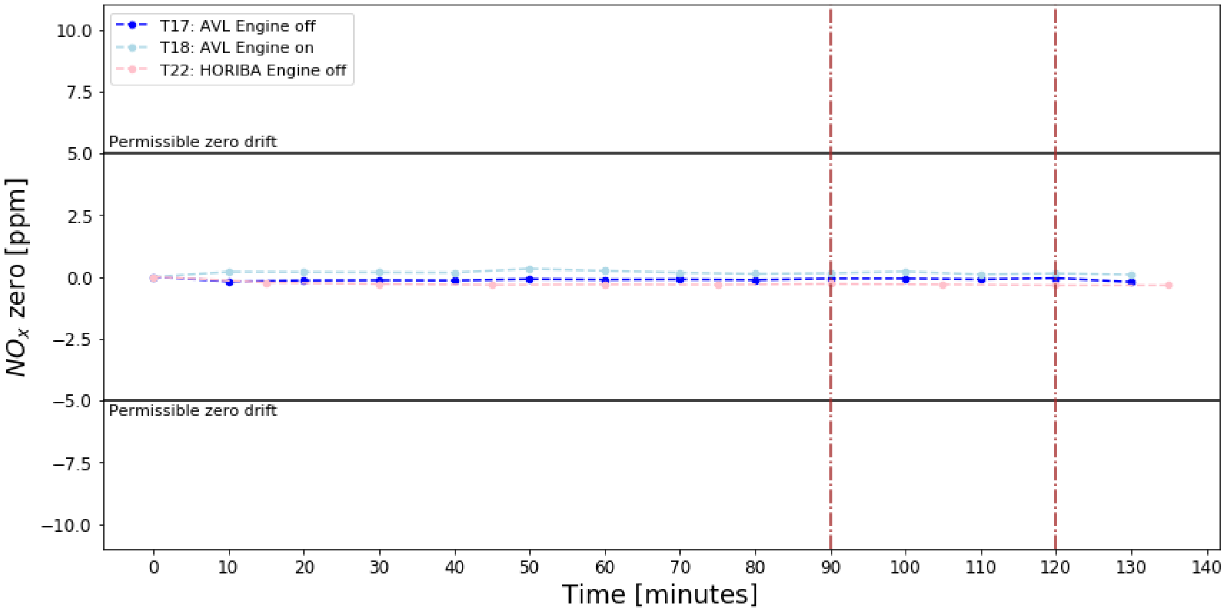
Figure 41. NO_2 zero drift checks for static tests



Source: JRC, 2020.

The same pattern described for NO applies for NO_X zero drift with intermediate checks within ±0.3 ppm (**Figure 42**). In contrast with the tests done with the vehicle running, on the static tests, the zero drift for NO_X is dominated by the NO component. The NOx drift is similar on both tests performed with the AVL-MOVE which points to the fact that engine on or engine off (i.e., exhaust gas flowing through the analysers) does not play a significant role in the zero drift.

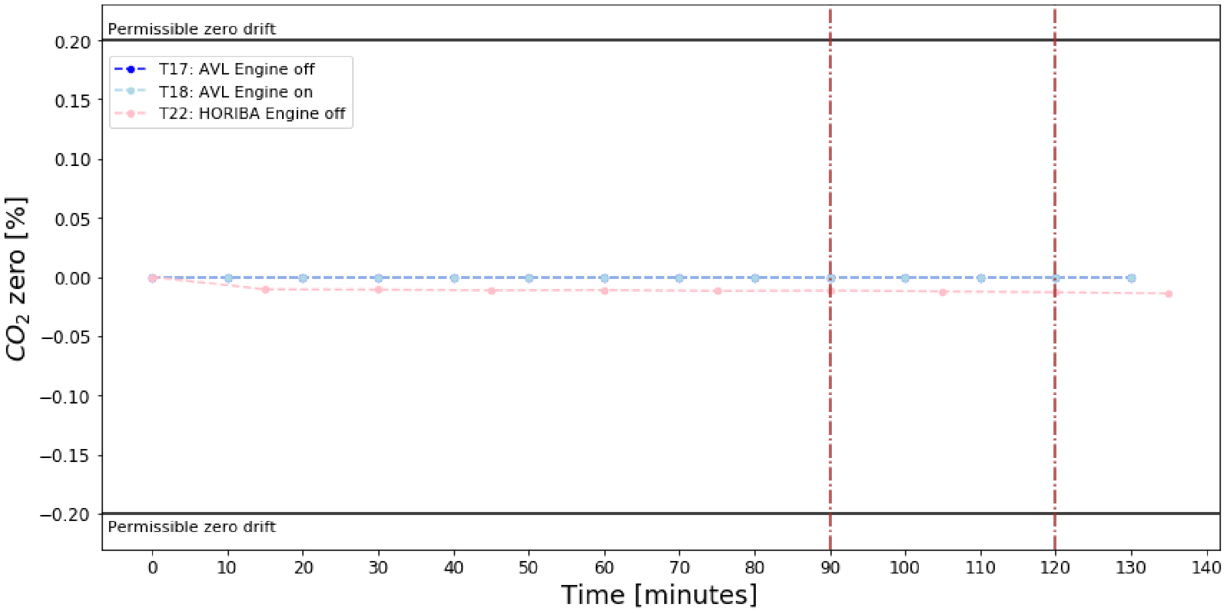
Figure 42. NO_X zero drift checks for static tests



Source: JRC, 2020.

On both tests with the AVL-MOVE the CO_2 zero drift of all intermediate checks was below the detection limit and reported as 0 ppm by the instrument. On the test done with the HORIBA instrument, the CO_2 drifted linearly from 0 to -140 ppm (**Figure 43**). This zero drift is however, one order of magnitude lower than the permissible CO_2 zero drift.

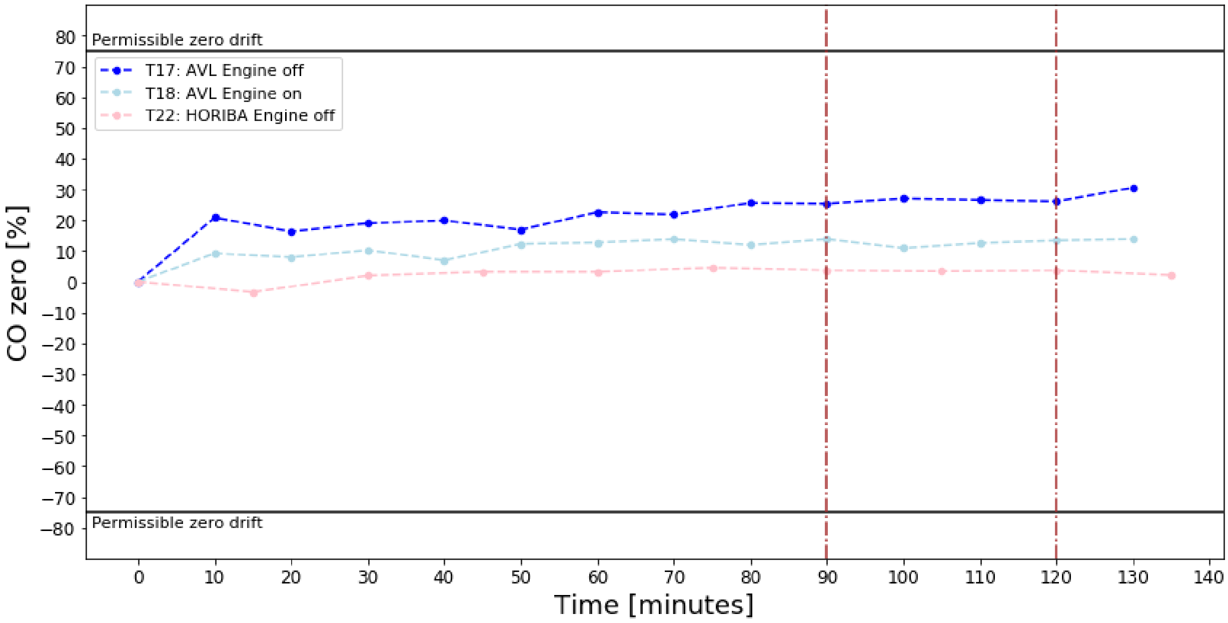
Figure 43. CO_2 zero drift checks for static tests



Source: JRC, 2020.

Finally, the zero drift behaviour for CO is similar for both tests performed with the AVL-MOVE with a positive step drift occurring just at the beginning of the test followed by a smooth positive linear drift until the test end reaching 31 ppm and 14 ppm for the engine-off and engine-on tests, respectively (**Figure 44**). In the case of the engine-off test the first step drift is 20 ppm whereas in the engine-on it is 10 ppm. The results of T01 are almost identical to the engine-on test, with a step of 10 ppm in the first zero check, and a maximum drift of 14 ppm at test end. The test done with the HORIBA PEMS has a stable behaviour with intermediate zero values in the range of ± 5 ppm with up and down values.

Figure 44. CO zero drift checks for static tests



Source: JRC, 2020.

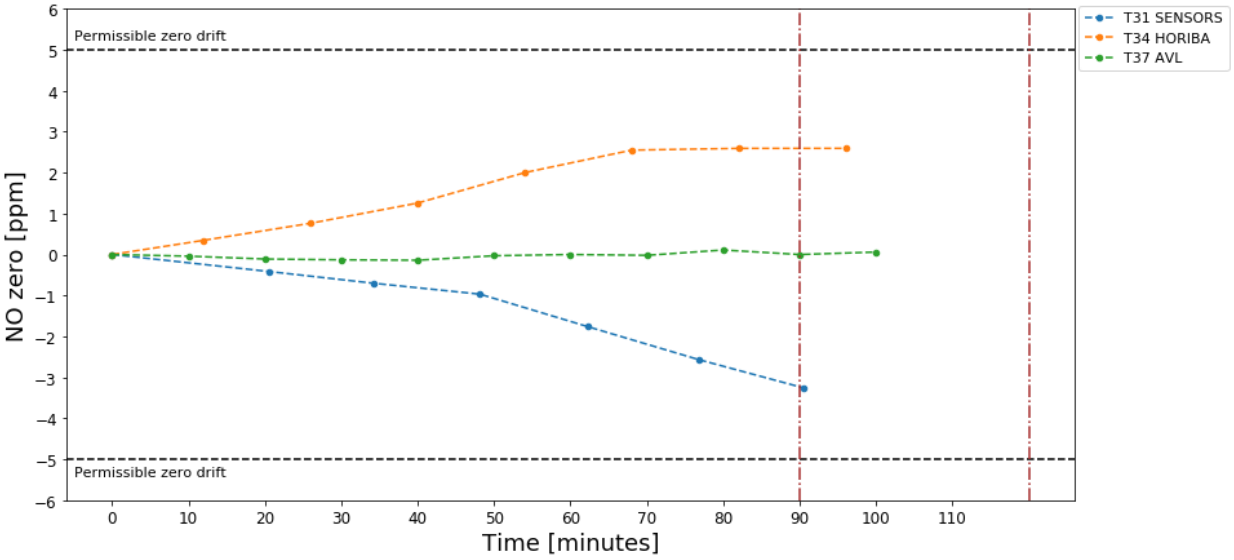
3.5.2 Gradual changes of temperature

This section presents the zero drift tests done in static conditions, when PEMS instruments where exposed to a i) a gradual change of ambient temperature from ~ 23 °C to -7 °C ii) a constant temperature of -7 °C, and iii) a change of ambient temperature from -7 °C to 23 °C. The focus is on NO, NO_2 and NOx.

3.5.2.1 Temperature change from 23 °C to -7 °C

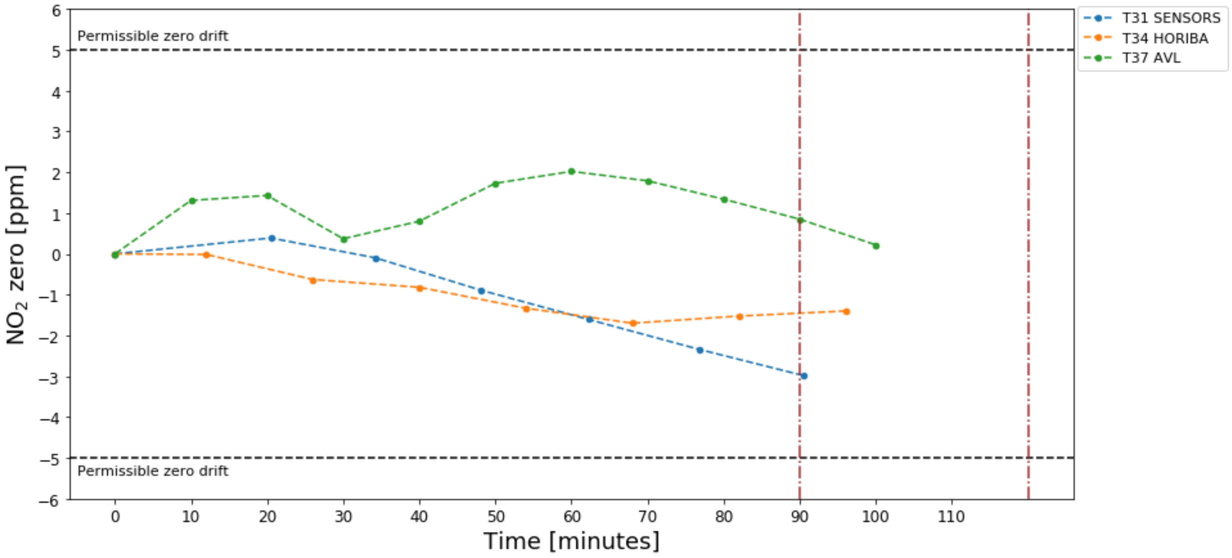
The pre-test was performed at an ambient temperature of ~ 23 °C. Then the climatic chamber was set to change its temperature to reach -7 °C. The temperature was reached after ~ 90-100 minutes. For the AVL and HORIBA instruments NO (**Figure 45**), NO_2 (**Figure 46**), and NOx (**Figure 47**) zero drift intermediate checks were within the permissible tolerances throughout the test, with maximum values < 3 ppm. It is worth noting that on the HORIBA PEMS the drift of NOx is virtually zero as the NO and NO_2 readings had opposite trends. In the case of the SENSORS PEMS, both NO and NO_2 analysers tended to drift toward negative values, reaching ~ -3 ppm each after 90 minutes, resulting in an exceedance of the zero drift tolerance for NOx at the end of the test (which would invalidate the test).

Figure 45. NO zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from 23 °C to -7 °C



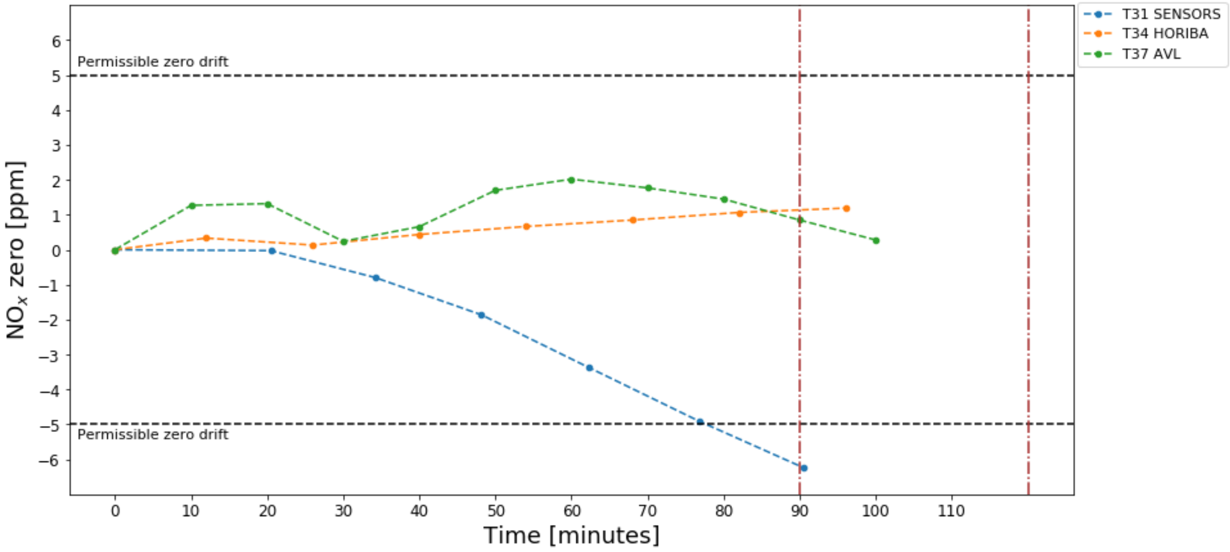
Source: JRC, 2020.

Figure 46. NO_2 zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from 23 °C to -7 °C



Source: JRC, 2020.

Figure 47. NOx zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from 23 °C to -7 °C

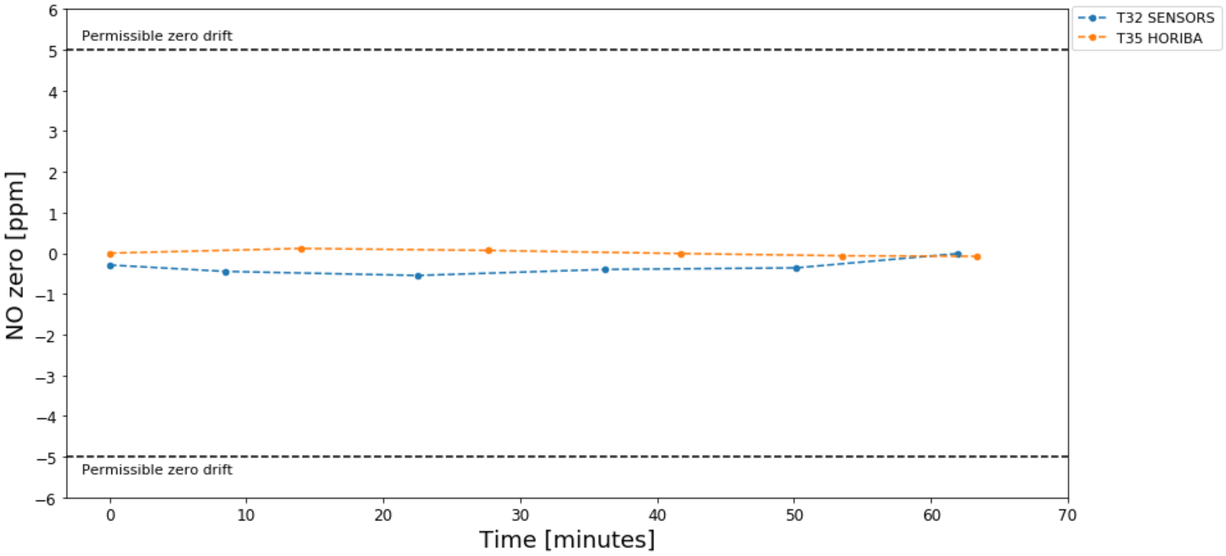


Source: JRC, 2020.

3.5.2.2 Constant -7 °C temperature

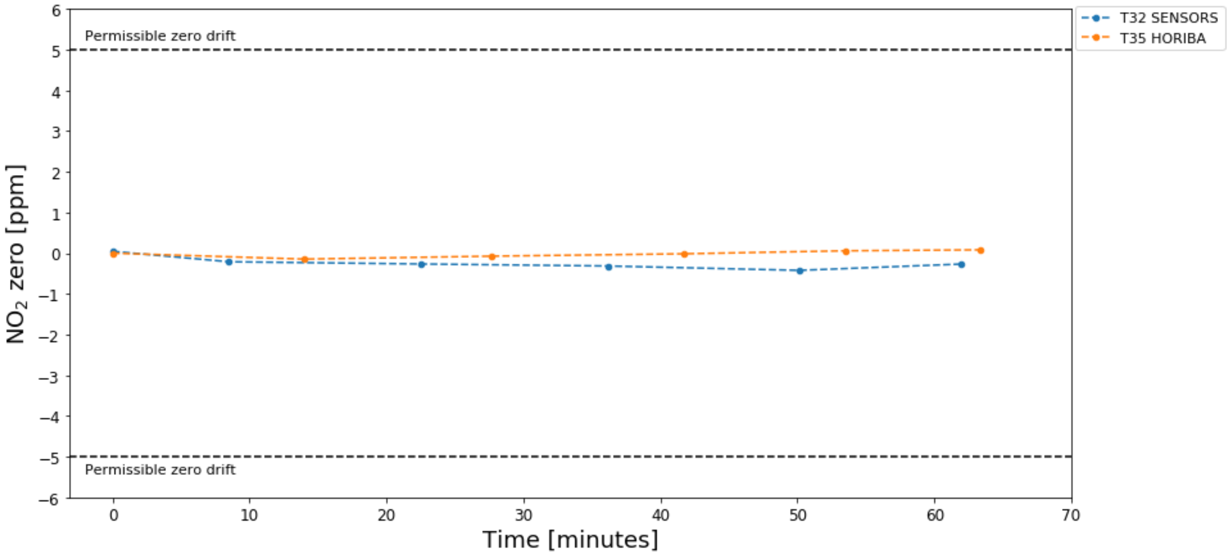
This test was performed immediately after the one described in the previous section. The instrument was calibrated at -7 °C and the zero checks were performed every 10 minutes for over an hour. In these conditions, the two tested instruments (HORIBA and SENSORS), showed no drift either for NO (**Figure 48**), NO2 (**Figure 49**), or NOx (**Figure 50**). The maximum intermediate zero drift was less than 1 ppm, which proves that the low ambient temperature does not have an influence on the zero drift when the pre-test is performed at similar temperature than the test temperature.

Figure 48. NO zero drift checks for static tests in a climatic chamber where ambient temperature was kept constant at -7 °C



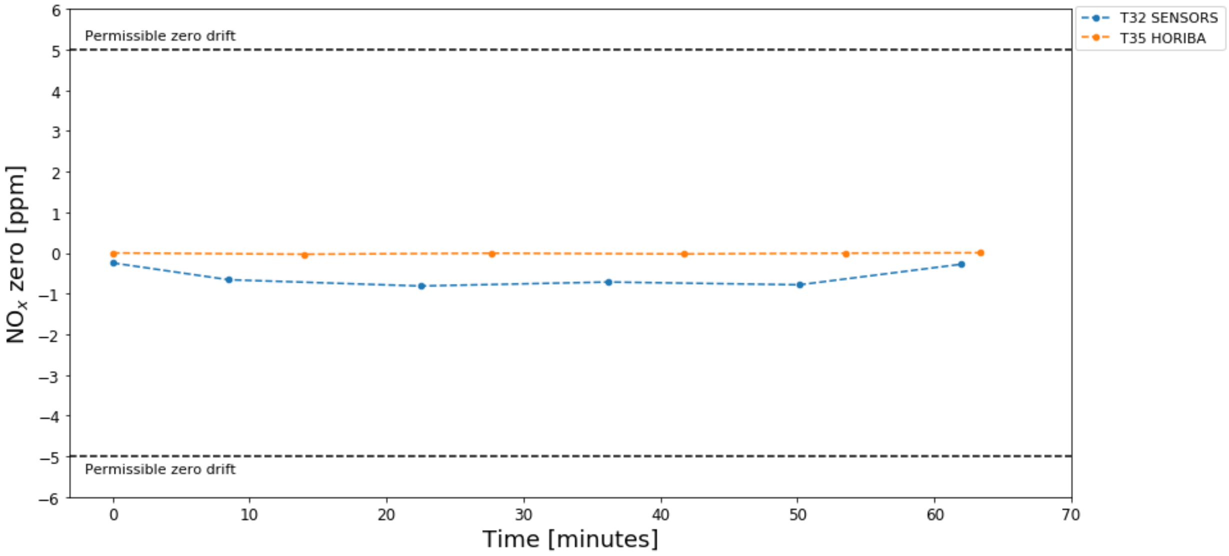
Source: JRC, 2020.

Figure 49. NO_2 zero drift checks for static tests in a climatic chamber where ambient temperature was kept constant at -7 °C



Source: JRC, 2020.

Figure 50. NOx zero drift checks for static tests in a climatic chamber where ambient temperature was kept constant at -7 °C

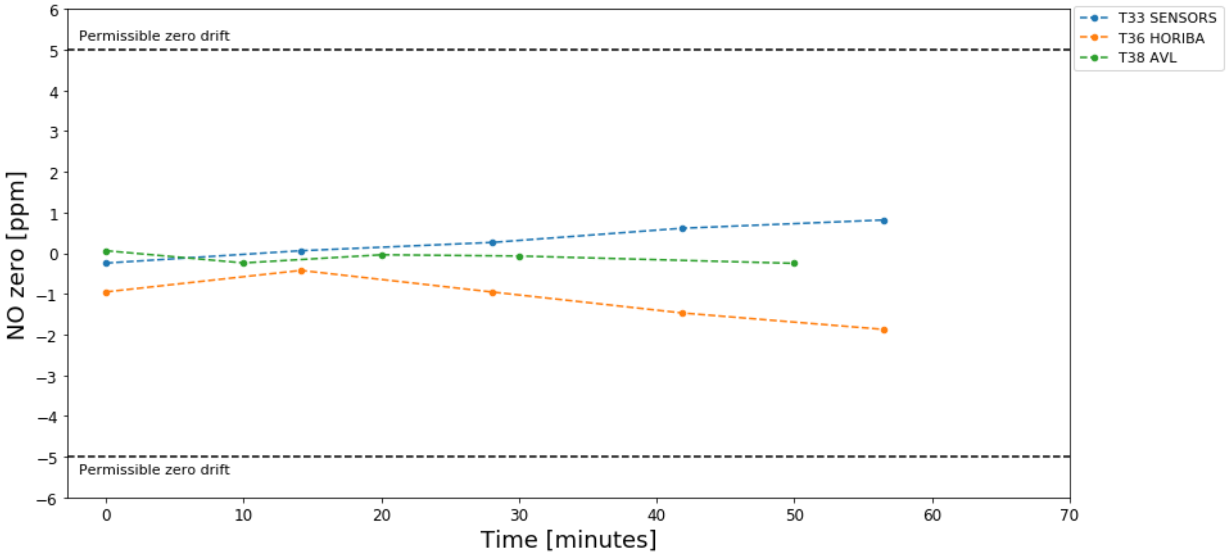


Source: JRC, 2020.

3.5.2.3 Temperature change from -7 °C to 23 °C

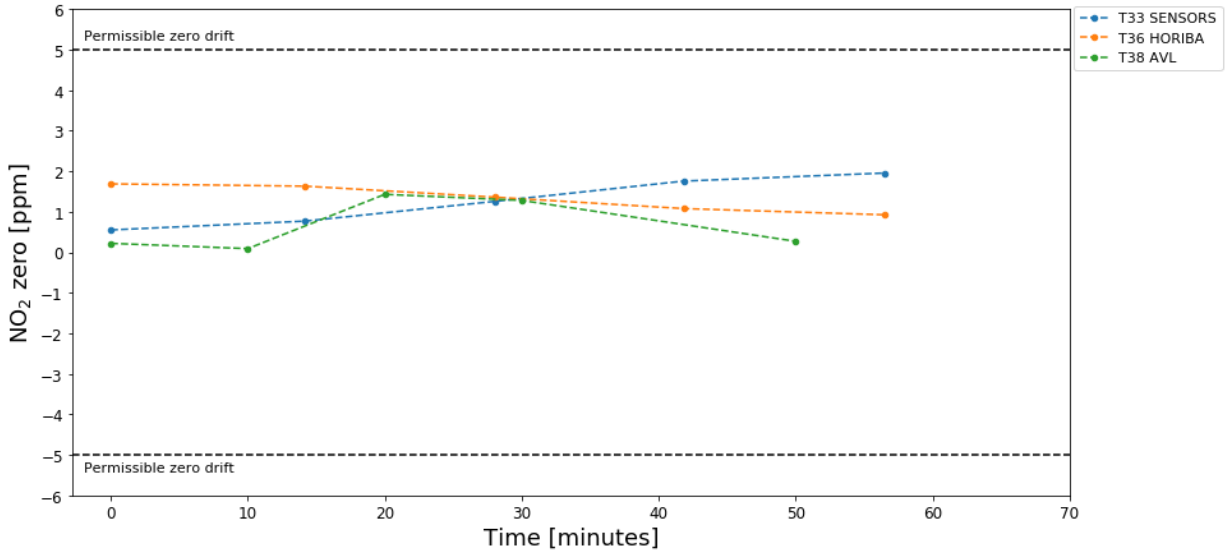
The ramp-up of the ambient temperature in the climatic chamber was performed quicker than the ramp-down from 23 °C to -7 °C. Despite this fact, the zero drift of NO (**Figure 51**), NO_2 (**Figure 52**), and NOx (**Figure 53**) remained well within the permissible tolerances with less than 3 ppm. No specific trend is observed for the set of PEMS tested with slight linear positive drift of the SENSOR, for both NO and NO2 and some up and down oscillations around 0 ppm for the AVL and HORIBA instruments.

Figure 51. NO zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from -7 °C to 23 °C



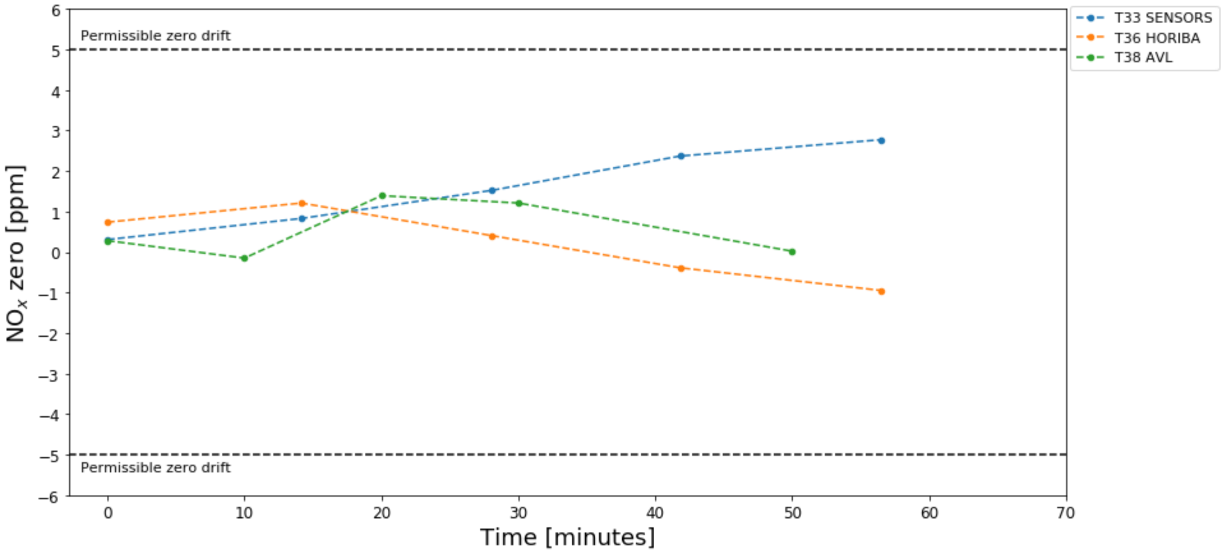
Source: JRC, 2020.

Figure 52. NO_2 zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from -7 °C to 23 °C



Source: JRC, 2020.

Figure 53. NOx zero drift checks for static tests in a climatic chamber where ambient temperature was gradually changed from -7 °C to 23 °C



Source: JRC, 2020.

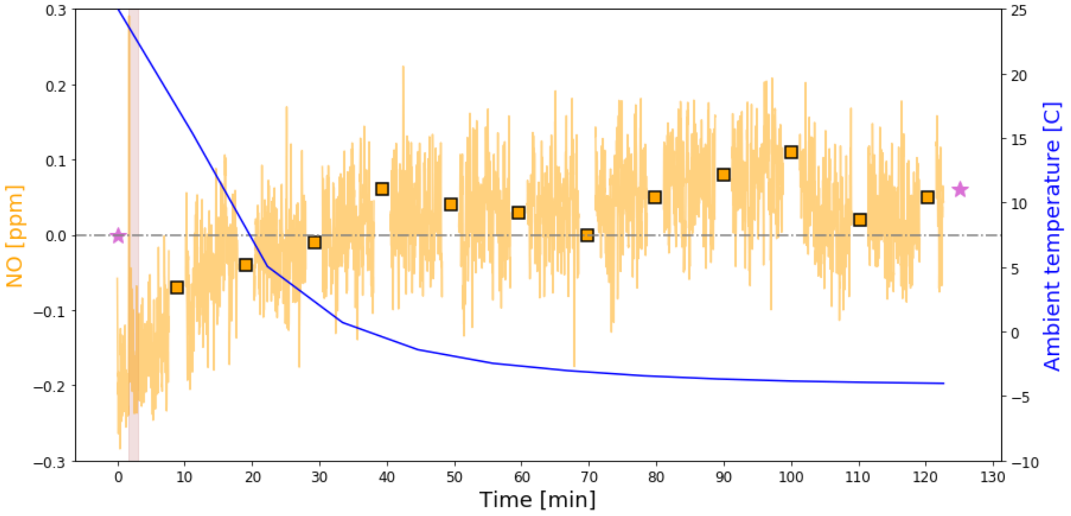
3.5.3 Drastic temperature changes

3.5.3.1 Test with AVL-MOVE

The results of the test with the AVL-MOVE are shown in **Figure 54** for NO, **Figure 55** for NO_2, **Figure 56** for NOx, **Figure 57** for CO_2 and **Figure 58** for CO, respectively. All figures in this section display the ambient temperature as measured by the weather station of the PEMS. Although the test cell ambient temperature was set to -7 °C, the weather station of the PEMS took circa 100 minutes to get its reading stabilised (and it reached -5 °C). The pink stars in the plots represent the pre-test and post-test zero reading for each pollutant. The squares show the reading of the intermediate zero response checks. The vertical brown rectangle immediately after the pre-test shows the time at which the engine of the vehicle was switched on to move it inside the climatic chamber. Finally, the coloured line represents the reading of the PEMS which shall correspond to the exhaust during and shortly after the engine-on time, and ambient air in the climatic chamber along the duration of the test.

The NO zero drift during the whole test is one order of magnitude lower than the permissible zero drift and it oscillates around ± 0.1 ppm (**Figure 54**). Immediately after the pre-test done with N_2 gas, the reading of ambient air is -0.15 ppm, whereas in the climatic chamber, the reading is stable at 0.1 ppm. No particular change in reading is observed after the drastic change of temperature.

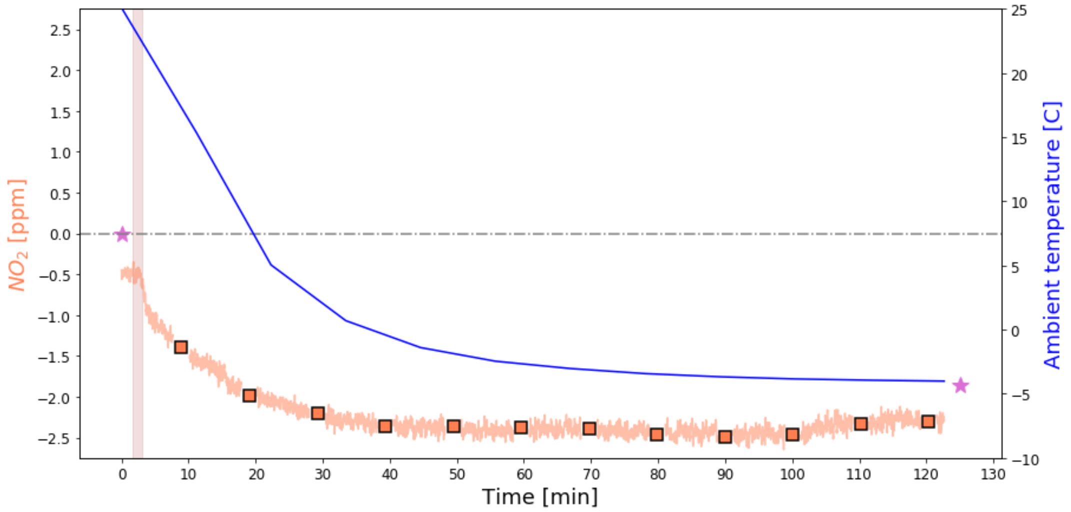
Figure 54. NO zero drift checks for static tests with drastic change of temperature – AVL-MOVE



Source: JRC, 2020.

All NO_2 intermediate zero checks lay within the permissible zero drift (**Figure 55**). The first NO_2 intermediate zero check is -1.5 ppm and then the NO_2 drift decreases asymptotically until the end of the test (-2.5 ppm). The NO_2 reading of ambient air has a -0.5 ppm drop after the pre-test, and then again after driving the vehicle inside the climatic chamber, there is an additional -0.5 ppm drop.

Figure 55. NO_2 zero drift checks for static tests with drastic change of temperature – AVL-MOVE

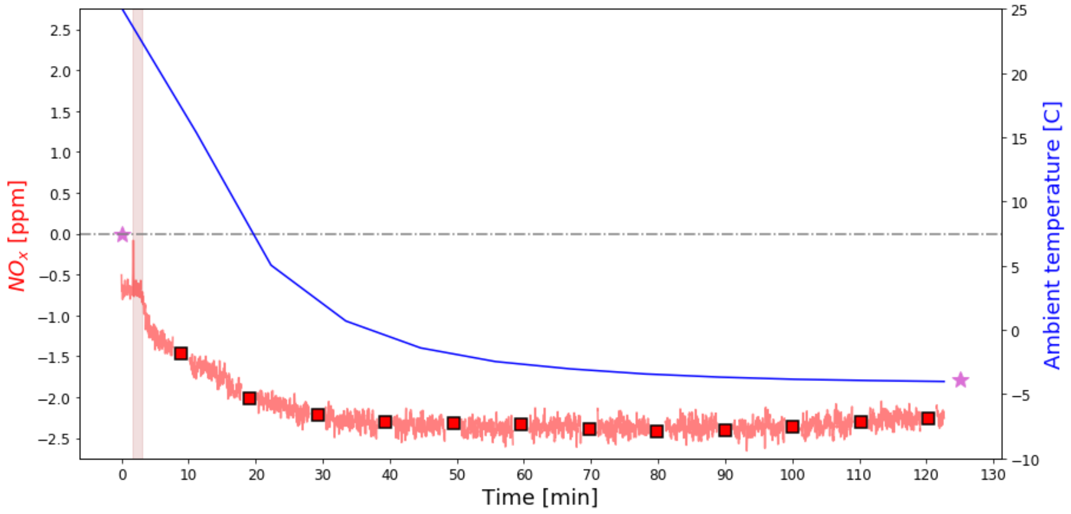


Source: JRC, 2020.

All intermediate NOx zero checks are within the permissible zero drift (**Figure 56**). The NOx zero drift is dominated by the NO_2 drift and it reaches a minimum of -2.5 ppm after 1.5 hours of test. As for NO_2, the ambient air reading has a drop of circa -0.5 ppm after the pre-test, and another one after the drastic change of temperature.

The main outcome of the experiment is that the NOx zero reading of the PEMS is -2.5 ppm at cold ambient conditions (-7 °C) and that there is a -0.5 ppm step in the reading under a drastic change of temperature.

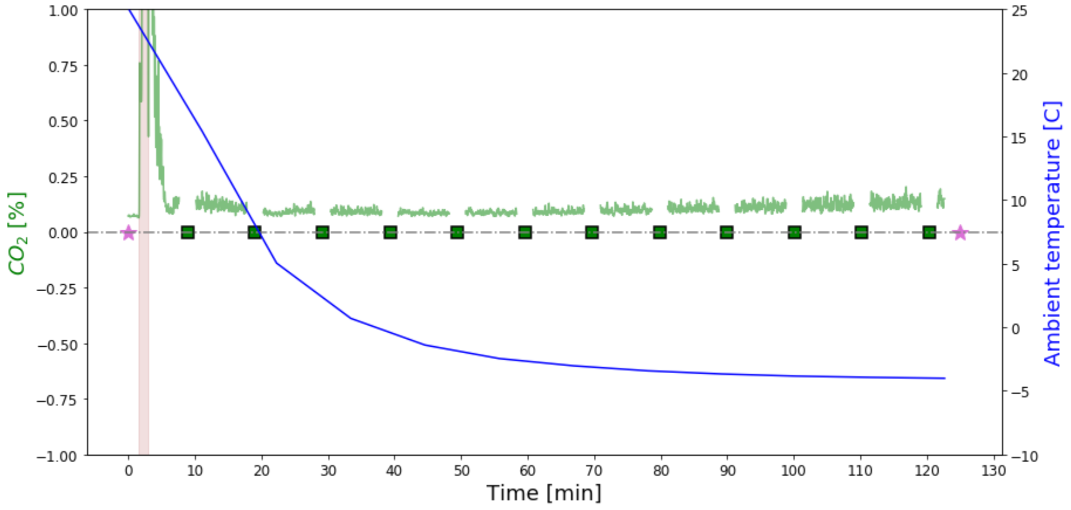
Figure 56. NOx zero drift checks for static tests with drastic change of temperature – AVL-MOVE



Source: JRC, 2020.

The intermediate CO_2 zero checks show systematically 0 values along the test (**Figure 57**). It can be therefore understood that the change in ambient temperature and the operation at -7 °C do not affect the zero CO_2 reading of the PEMS.

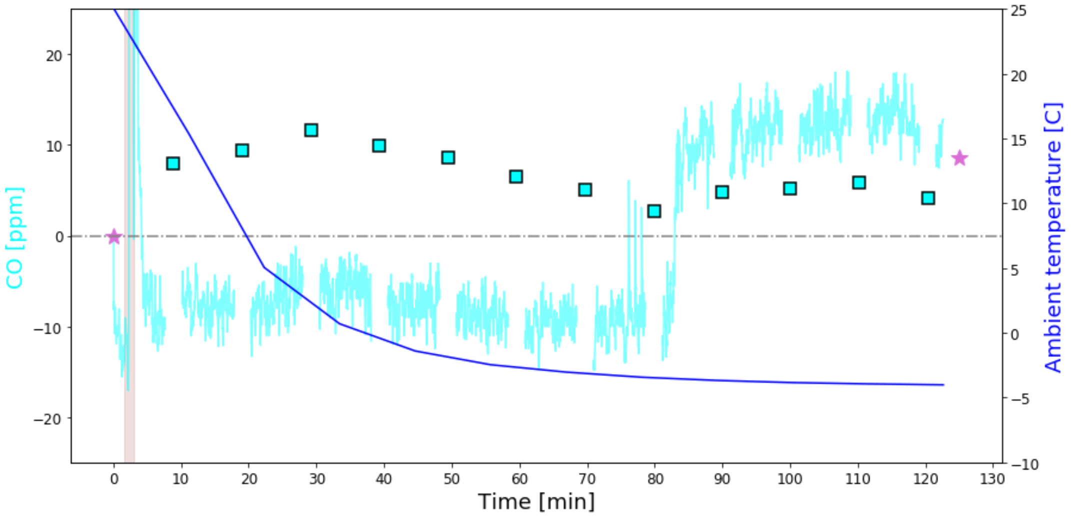
Figure 57. CO_2 zero drift checks for static tests with drastic change of temperature – AVL-MOVE



Source: JRC, 2020.

All the CO intermediate zero checks are within the permissible zero drift and the maximum value is < 15 ppm. After the drastic change of temperature, the reading of CO in the ambient air does not seem to be affected (**Figure 58**). Interestingly, after 80 minutes of the test, the reading of CO in the ambient air rises quickly from -10 ppm to 10 ppm despite the fact that the test conditions were not changed.

Figure 58. CO zero drift checks for static tests with drastic change of temperature – AVL-MOVE



Source: JRC, 2020.

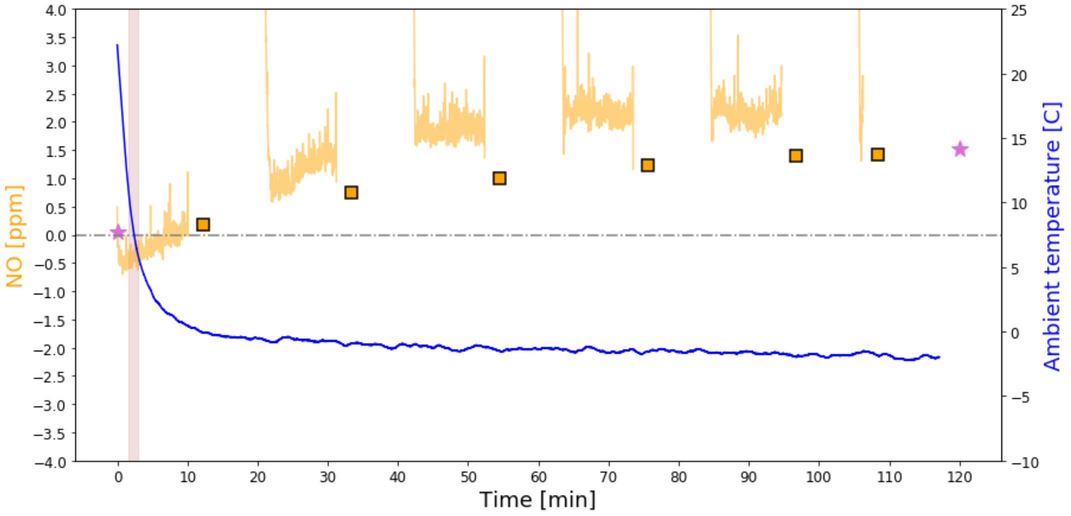
3.5.3.2 Tests with HORIBA OBS-ONE

The results of the tests with the HORIBA OBS-ONE are shown in **Figure 59** to **Figure 63** (for the test starting at 21 °C and changing quickly to -2 °C) and **Figure 64** to **Figure 68** (for the test starting at -7 °C and finishing at 23 °C). All figures in this section display the ambient temperature as measured by the weather station of the PEMS, which for the HORIBA instrument shows a quick response and stabilises quicker than the AVL-ONE. The pink stars in the plots represent the pre-test and post-test zero reading for each pollutant. The squares show the reading of the intermediate zero response checks. The vertical brown rectangle immediately after the pre-test on the first test shows the moment in which the vehicle was driven electrically inside the climatic chamber. On the second test, the brown rectangle before the post-test shows the time in which the combustion engine was switched on to take the car out of the climatic chamber. Finally, the coloured line represents the reading of the PEMS which shall correspond to the exhaust during and shortly after the engine-on time, and ambient air in the climatic chamber along the duration of the test.

Test 1

The first test with the HORIBA PEMS shows a gradual increase of NO zero along the test (**Figure 59**), which reaches asymptotically 1.5 ppm after 100 minutes of test. The reading of ambient air of the NO analyser shows a gradual increase during the first 40 minutes, although no drastic change is observed after the drastic change of ambient temperature.

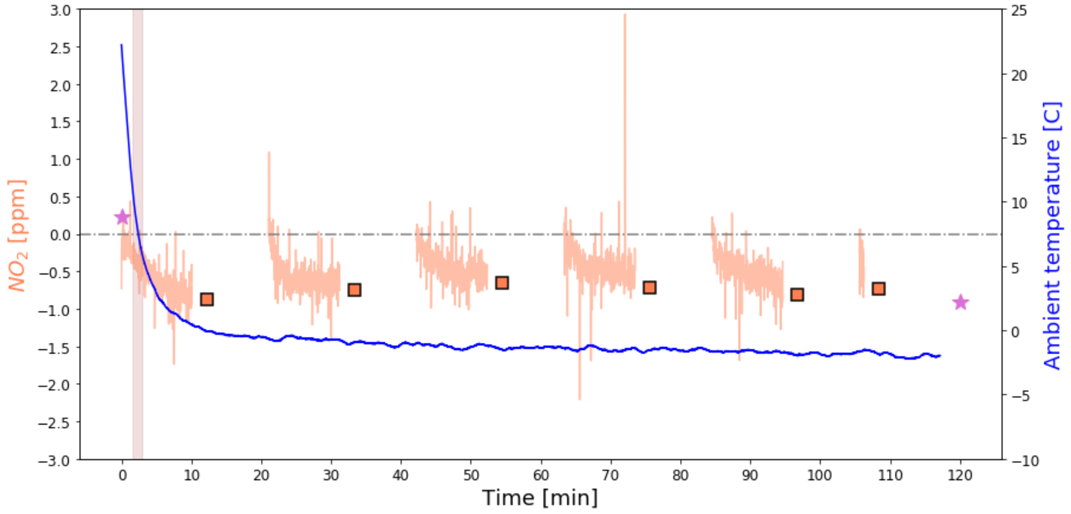
Figure 59. NO zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

All the intermediate NO_2 zero checks are < -1 ppm and no particular effect of the thermal shock is observed (**Figure 60**).

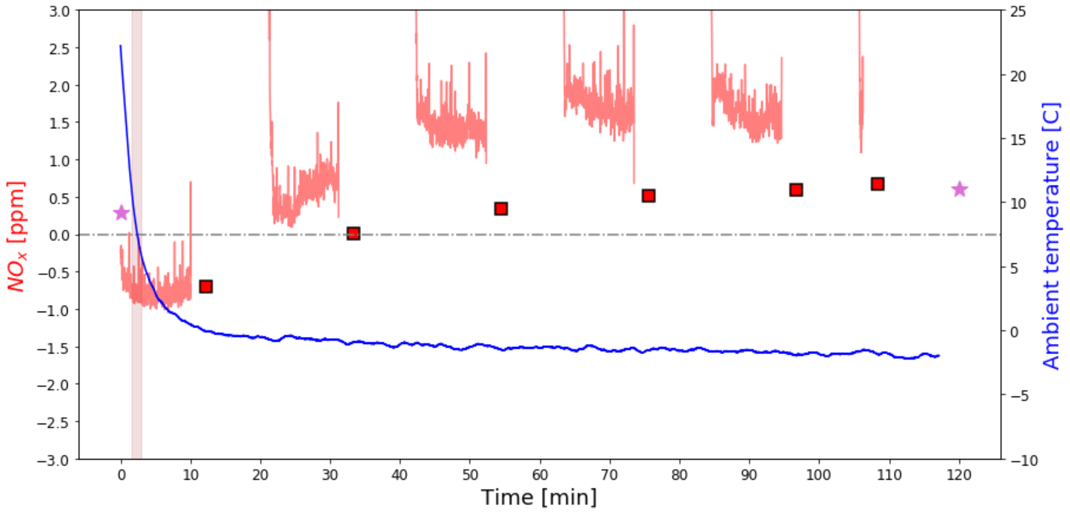
Figure 60. NO_2 zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

The HORIBA OBS-ONE has a zero drift of -1 ppm of NOx throughout the test, well within the permissible tolerance (**Figure 61**). As compared to the AVL-MOVE, the contribution to the total NOx zero drift in the HORIBA system is higher for NO and lower for NO_2. No particular problem is identified on the NOx drift neither for operating in cold conditions or for being exposed to a drastic change in ambient temperature.

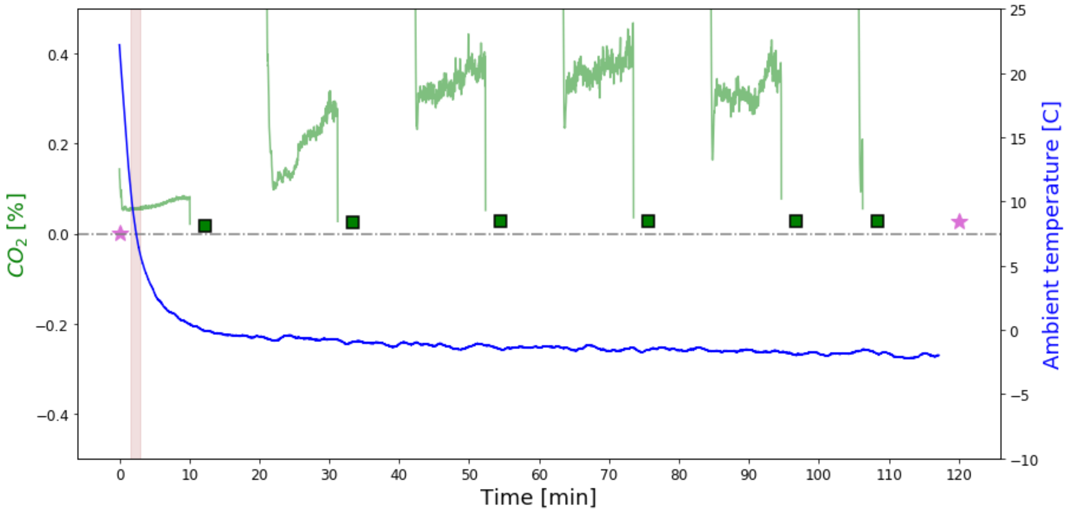
Figure 61. NOx zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

The CO_2 zero drift of the test is 0.02 %, one order of magnitude lower than the permissible zero drift (**Figure 62**). The zero drift of the instrument is stable throughout the test and no particular issue is observed as a consequence of the change in the operating temperature.

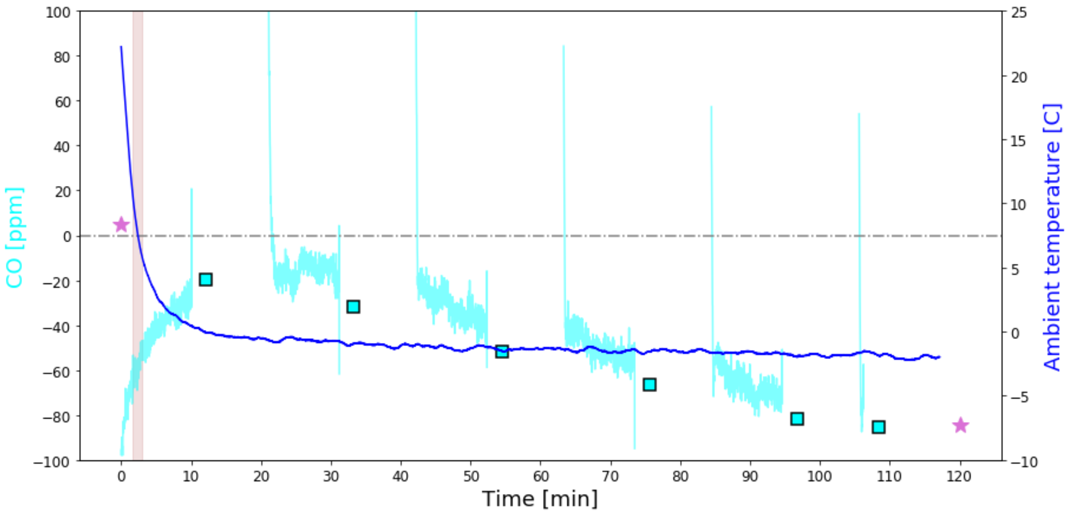
Figure 62. CO_2 zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

The CO zero drift of the HORIBA OBS-ONE exceeds the permissible zero drift for CO at post-test (-85 ppm), which invalidates the test (**Figure 63**). The CO zero drift decreases gradually along the test. The reading of the ambient CO also decreases gradually in the same proportion. From the observation of this test it is possible to detect a measurement issue when the PEMS is operated at low temperature as compared to the same test performed at 23 °C (**Figure 44**).

Figure 63. CO zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE

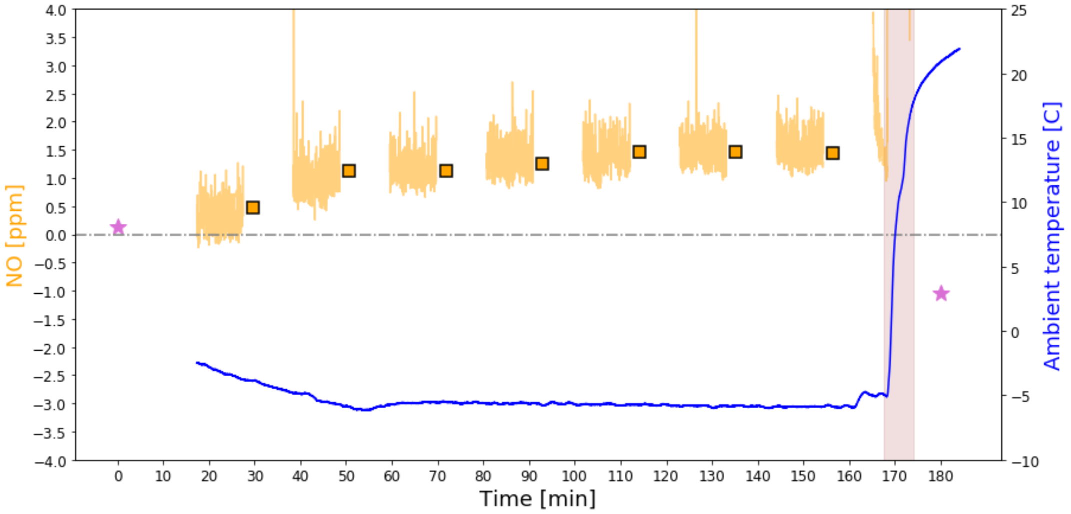


Source: JRC, 2020.

Test 2

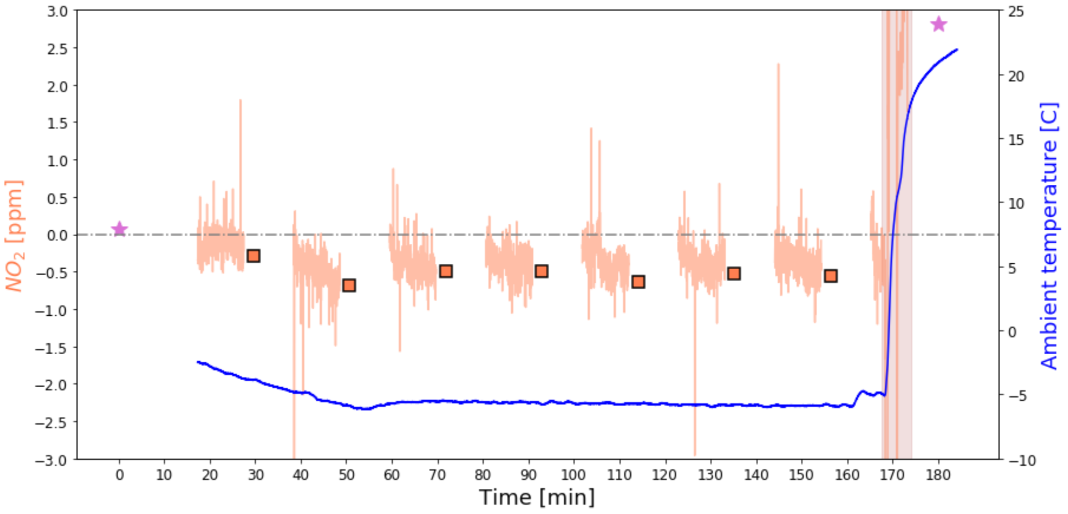
The second test with the HORIBA OBS-ONE shows a similar behaviour as the one reported for the first test for what regards NO zero drift: there is an asymptotical increase of NO intermediate zero readings until 1.5 ppm (**Figure 64**). However, the post-test which is done at an ambient temperature 30 °C higher than the temperature of the test shows a -3 ppm jump as compared to the last intermediate zero check. Despite this jump, the NOx zero drift is within the permissible tolerance.

Figure 64. NO zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



All the intermediate NO_2 zero checks performed while the vehicle is inside the climatic chamber at -7 °C are < -0.5 ppm and no issue is observed caused by the cold conditions of the test on the zero drift. However, the post-test which is performed after the thermal shock has a 3 ppm jump respect to the previous zero check (**Figure 65**). This jump is essentially the counterpart of the one observed for NO as NO_2 is calculated from NO and NOx for this PEMS. Despite this behaviour, the test is valid as the permissible limits for zero drift are not exceeded.

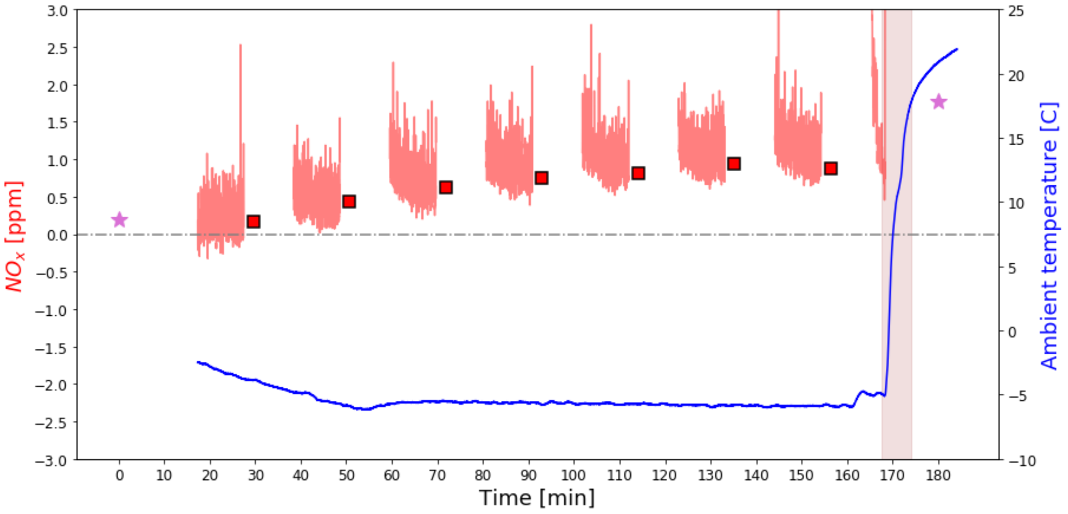
Figure 65. NO_2 zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

When considering the NOx, the HORIBA OBS-ONE operates well in cold conditions, with a zero NOx drift which is stable around 1 ppm along the test and despite the drastic change in temperature, the final NOx drift is below 2 ppm, which is less than half of the permissible zero drift (**Figure 66**).

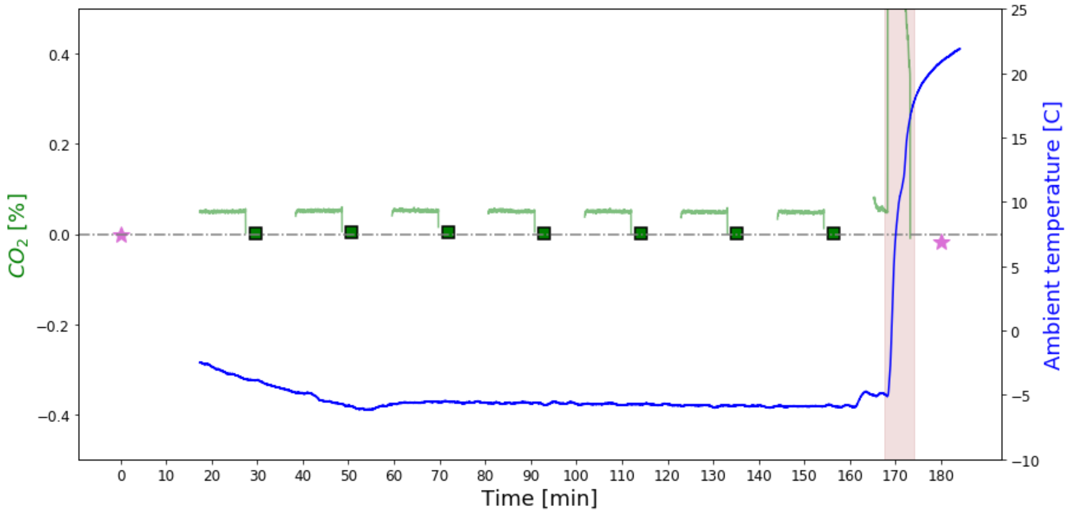
Figure 66. NOx zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

As for Test 1, the CO_2 zero drift during the test at -7 °C is circa 150 ppm, one order of magnitude lower than the permissible zero drift. No particular effect on the drift is observed at the end of the test after the thermal shock (**Figure 67**).

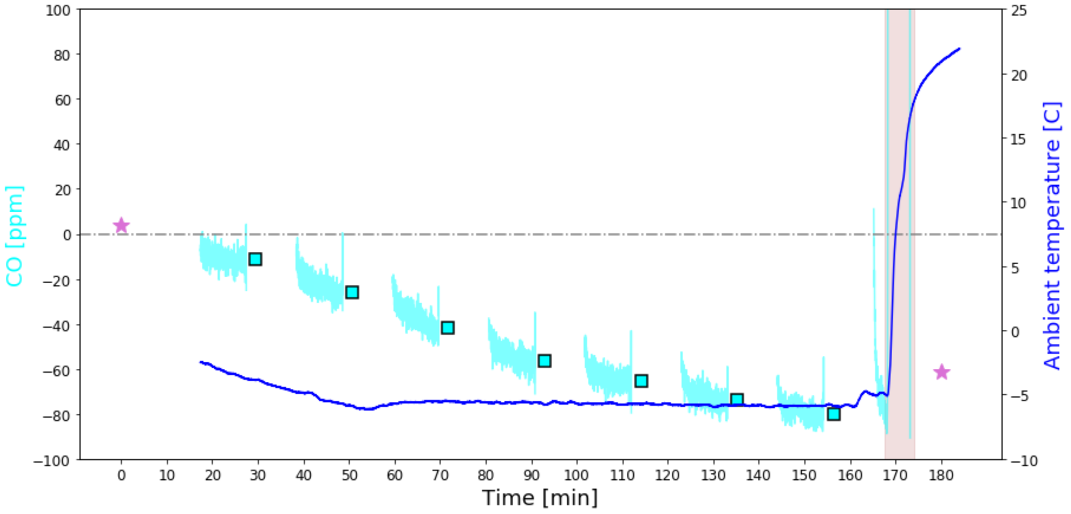
Figure 67. CO_2 zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

The CO zero drift decreases linearly along the time of the test, exceeding the permissible -75 ppm after two hours of test confirming that at -7 °C the instrument tends to drift negatively (**Figure 68**). In addition, it is important to notice that after taking the vehicle out of the climatic chamber, the post-test zero check for CO has a small positive jump which brings the final CO drift again within permissible tolerance (i.e., this test shall be invalidated but because of the effect of the drastic change in temperature on the analyser, the test is valid)

Figure 68. CO zero drift checks for static tests with drastic change of temperature – HORIBA OBS-ONE



Source: JRC, 2020.

As a conclusion of the tests done with drastic change of temperature for what regards NOx, both PEMS intermediate and final zero drift checks were within permissible tolerances. No particular issue was observed while operating in cold temperatures. When the test is done in cold conditions and the PEMS is then exposed at post-test at much higher ambient temperature, the analysers may be affected although still complying with the permissible limits. As a general recommendation the pre and post-tests should be done at similar ambient temperature than the one occurring during the test and exposing the PEMS to drastic thermal changes shall be avoided to prevent measurement issues.

4 Evaluation of JRC PEMS activity

This section presents i) the results of zero drift of NO, NO_2 and NOx for the on-road data gathered throughout 2018 on 19 Euro 6 vehicles totalizing 185 PEMS tests, ii) the outcomes of PEMS validations, and iii) an assessment of the zero drift of the exhaust mass flowmeter based on experimental data gathered by JRC in 2018. All tests were conducted with the AVL MOVE units.

4.1 Zero drift of NO, NO_2, and NOx

The NO zero drift for 185 PEMS tests has a mean and median lower than 0.25 ppm, which is one order of magnitude lower than the permissible drift (5 ppm) (**Table 4**). Only one of the 185 tests had an NO zero drift exceeding 5 ppm.

The average zero drift of NO_2 is slightly above 0.5 ppm, and 90% of the tests have a NO_2 drift within ±5 ppm.

The combined NOx zero drift is on average 2.0 ppm, less than half the permissible NOx zero drift. Roughly 90% of the PEMS tests performed had a NOx zero drift below 5 ppm. The NO_2 zero drift has a larger contribution to the total NOx drift.

In general terms, the results show that the zero drift between the test-start and the test-end are well within the tolerances foreseen in the regulation and that both analysers operate as expected when considering a large number of tests.

Table 4. NO, NO_2 and NOx zero drift from the JRC 2018 PEMS test campaign (n = 185).

[ppm]	Mean	Std. deviation	Median
NO	0.223	0.606	0.180
NO_2	0.544	2.494	0.390
NOx	2.034	2.176	1.135

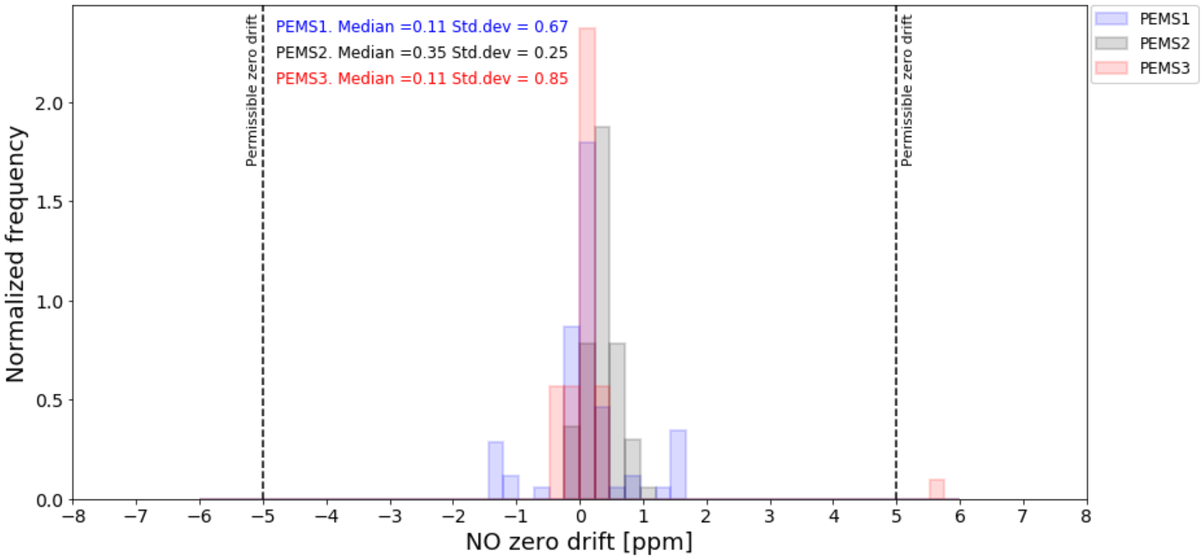
Source: JRC, 2020.

The distribution of the zero drift for NO, NO_2, and NOx per each of the three PEMS units used in the campaign are shown in **Figure 69**, **Figure 70**, and **Figure 71**, respectively. The three instruments have a similar behaviour for NO, with a modal distribution of zero drift centred in 0 ppm and a standard deviation of less than 1 ppm.

Regarding NO_2, PEMS AVL-3 has a median drift of 1.5 ppm, whereas the other two units have a median drift of 0 ppm. Most of the exceedances of the 5 ppm permissible tolerance correspond to the unit PEMS AVL-1.

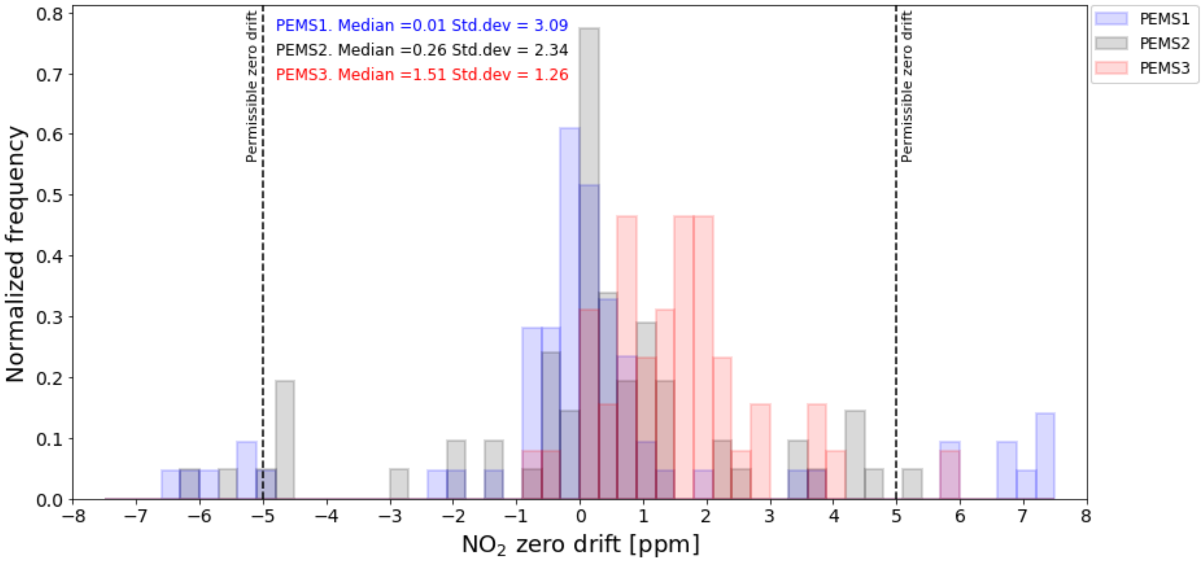
When combining the zero drift of both analysers, the NOx zero drift is lower than 3 ppm for the three PEMS units, with a median zero drift of 1 to 2 ppm. The maximum NOx zero drift from the campaign was 9.5 ppm (**Figure 71**).

Figure 69. NO zero drift of PEMS tests performed by JRC on 2018 as function of PEMS instrument



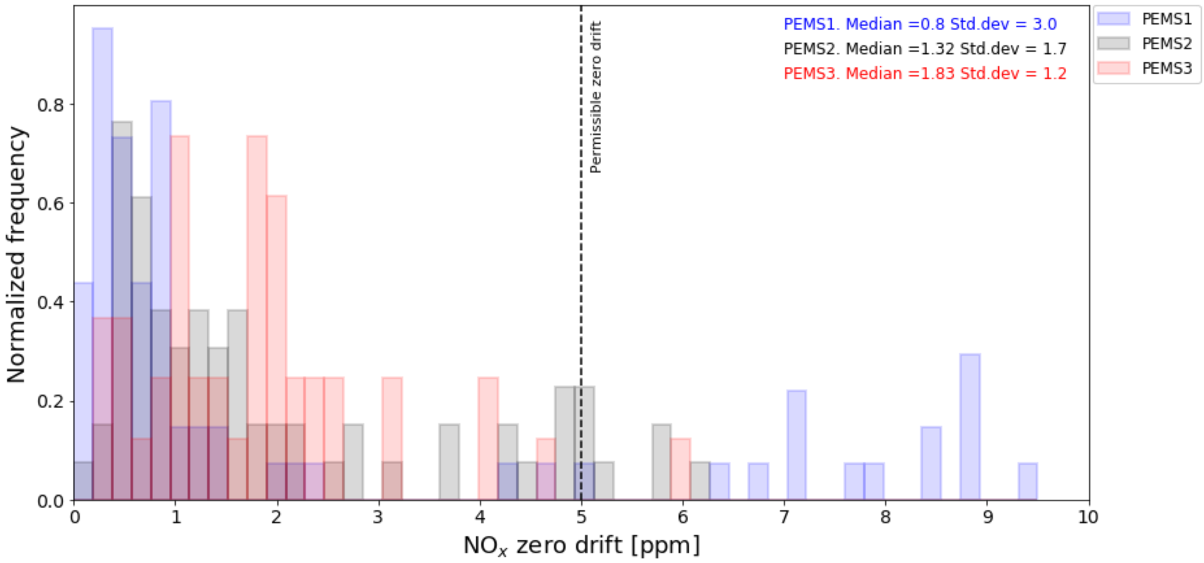
Source: JRC, 2020.

Figure 70. NO_2 zero drift of PEMS tests performed by JRC on 2018 as function of PEMS instrument

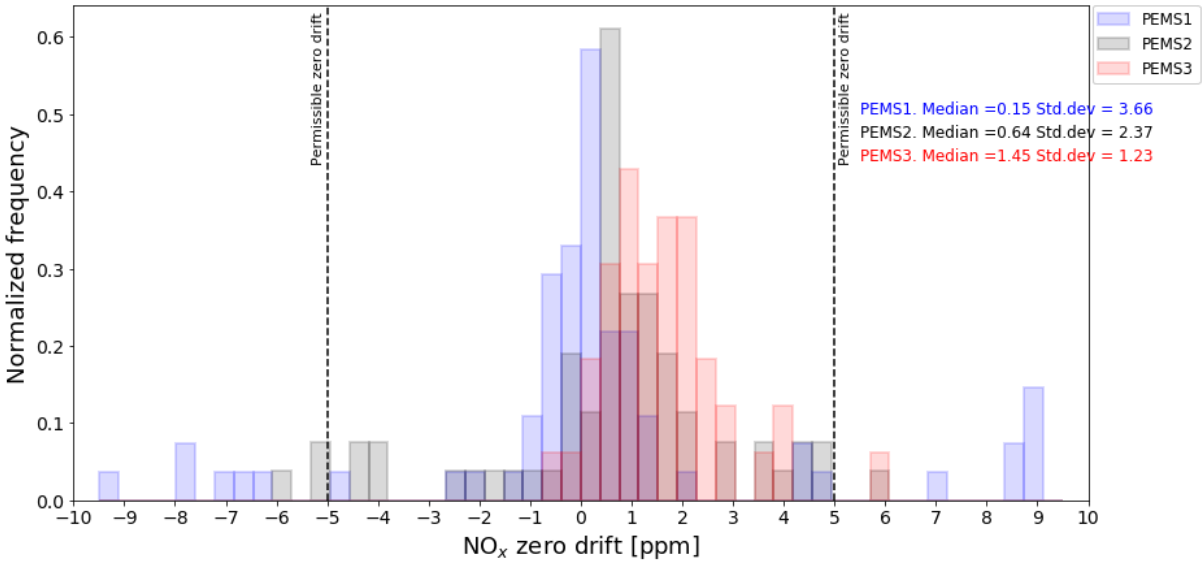


Source: JRC, 2020.

Figure 71. NOx zero drift of PEMS tests performed by JRC on 2018 as function of PEMS instrument top) NOx zero calculated as sum of absolute NO and NO_2 zero drifts. bottom) NOx zero calculated as sum of NO and NO_2 zero drifts.



Source: JRC, 2020.



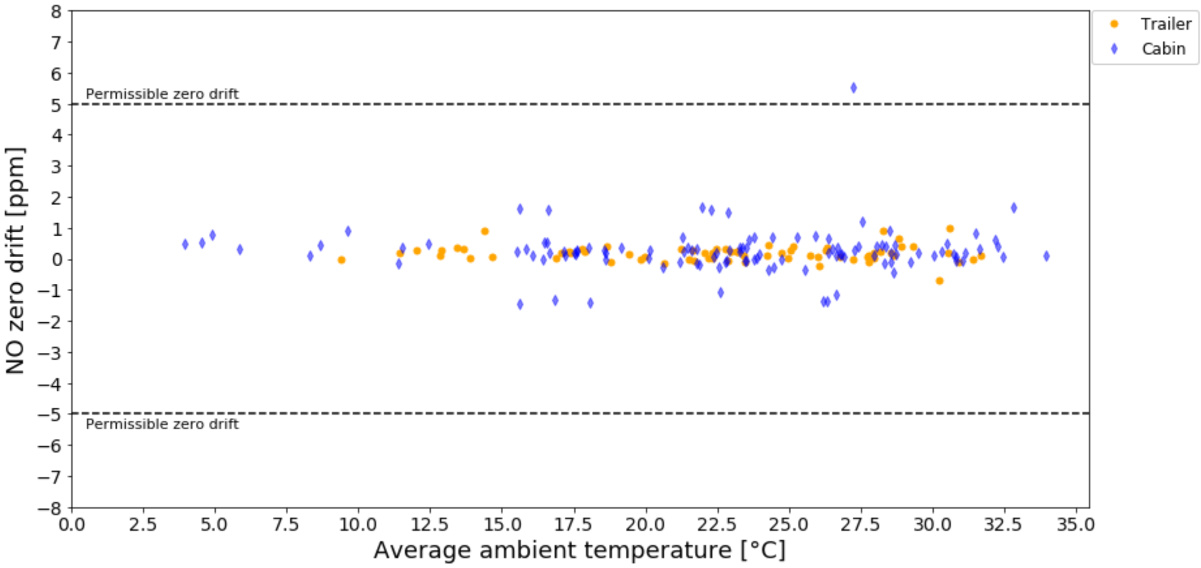
Source: JRC, 2020.

The influence of ambient temperature, ambient humidity, and PEMS installation location on NO, NO_2, and NOx zero drift was analysed using the JRC 2018 test campaign data. **Figure 72** shows that PEMS tests were performed over the 2018 year on a range of average ambient temperature from 3 °C to 33 °C, and 16% to 95% relative humidity. On that range of conditions, no effect of ambient temperature or ambient humidity is seen on the NO zero drift value. From the location of the PEMS point of view, no specific trend is observable in the NO zero drift with most of the data within ±2 ppm, when the unit is installed in the trailer hook and in the cabin.

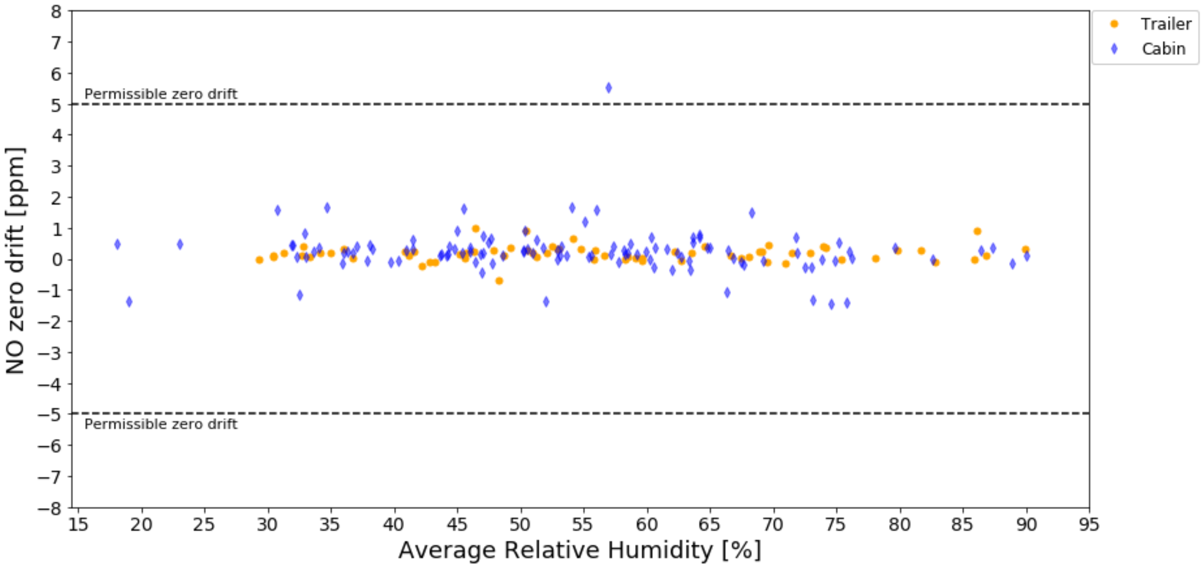
The NO_2 zero drift does not show correlation either with average ambient temperature and ambient humidity (**Figure 73**). Despite the fact that all exceedances of the NO_2 zero drift tolerance (5 ppm) occur at temperatures above 15 °C, no correlation exist between ambient temperature and NO_2 drift. The exceedances of NO_2 zero drift occur both when the PEMS is installed on the trailer hook or in the cabin.

For NOx, the same observations done for NO_2 apply: no correlation between zero drift and ambient temperature and relative humidity is seen in the 2018 data. Also, the exceedances of the 5 ppm tolerance occur when the PEMS is installed in the trailer hook and in the cabin (**Figure 74**).

Figure 72. NO zero drift of PEMS tests performed by JRC on 2018 as function of PEMS installation location and top) ambient temperature, bottom) ambient humidity



Source: JRC, 2020.

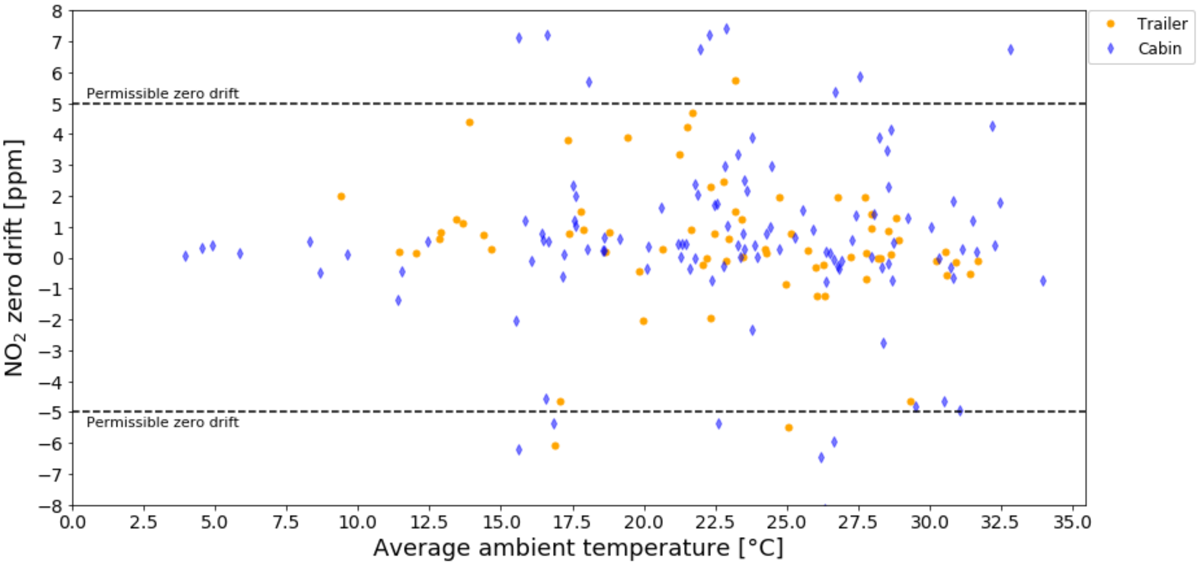


Source: JRC, 2020.

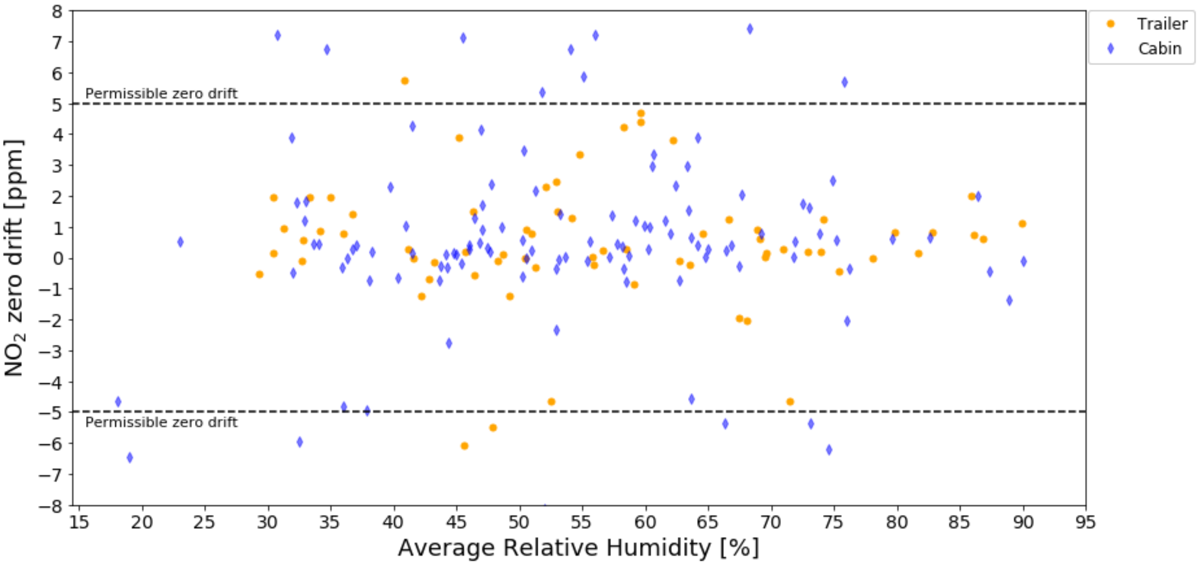
Among the different test routes used by the JRC on its 2018 campaign, it is possible to differentiate tests done in moderate altitude conditions (altitude up to 700 meters above sea level) and the SAC test, which includes ~20 minutes (~20% of the test duration) in extended conditions reaching a maximum altitude of 1100 meters above sea level (Annex 1C, Valverde *et al.*, 2019). The comparison of the NO (**Figure 75**), NO_2 (**Figure 76**), and NOx (**Figure 77**) zero drift between tests done in moderate conditions (176 tests) and partially in extended altitude conditions (SAC = 19 tests) shows similar distributions with virtually no distinction on the zero drift between tests. These results build on the idea that operation in altitude does not affect the zero drift behaviour of gas analysers.

From the JRC 2018 PEMS campaign data, it can be concluded that there is no particular effect of boundary conditions on the NOx zero drift: the NO and NO_2 analysers have a zero drift below the permissible tolerance over a wide range of ambient humidity and ambient temperatures (although not sub-zero tests are considered). Also, the PEMS installation location shows no particular effect on the NOx zero drift with an overall good performance of the PEMS when operated both in the trailer hook and in the cabin. Tests done in extended altitude conditions (> 700 and up to 1100 meters above sea level) have similar zero drift values than tests done at moderate altitude conditions. Vibrations, which affect the PEMS in any of the installation locations, are considered in these testing conditions, which reproduce RDE tests, and no specific effect is observed on NOx zero drift.

Figure 73. NO_2 zero drift of PEMS tests performed by JRC on 2018 as function of PEMS installation location and top) ambient temperature, bottom) ambient humidity

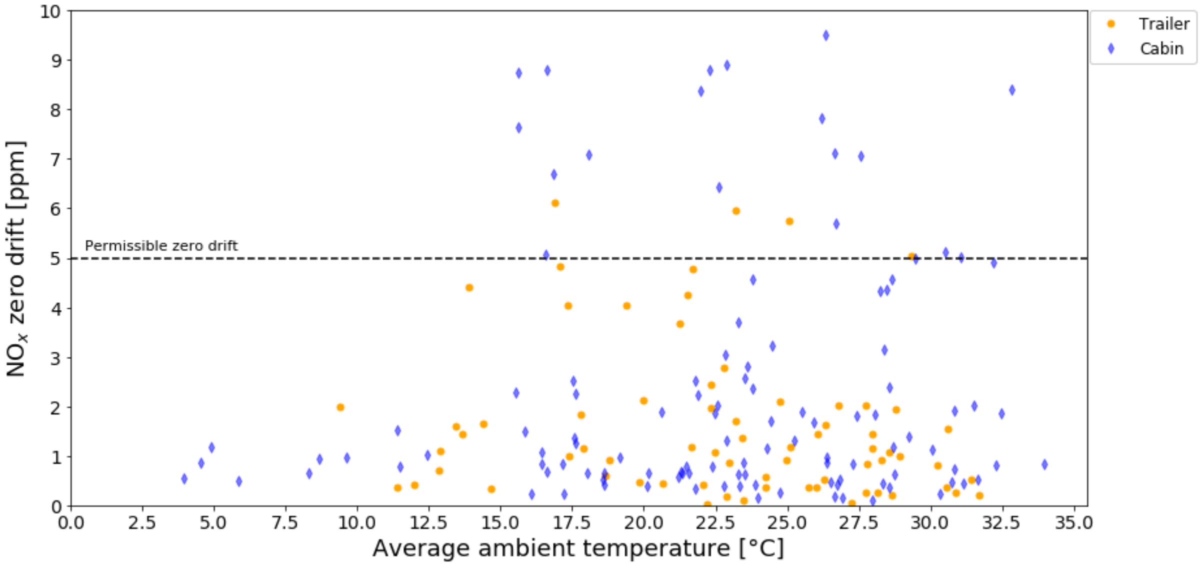


Source: JRC, 2020.

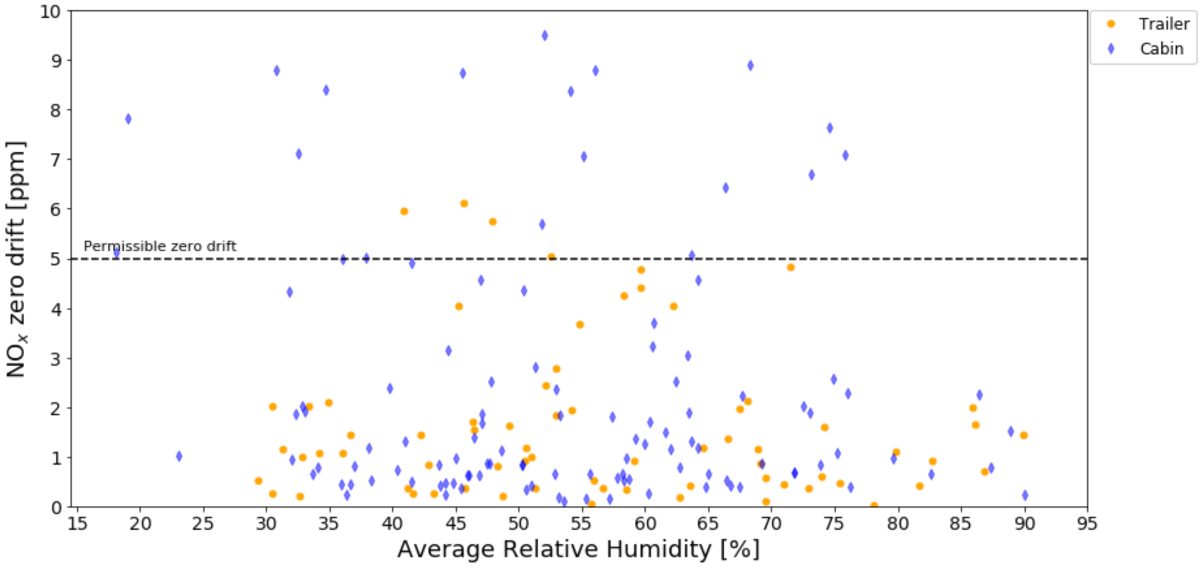


Source: JRC, 2020.

Figure 74. NOx zero drift of PEMS tests performed by JRC on 2018 as function of PEMS installation location and top) ambient temperature, bottom) ambient humidity

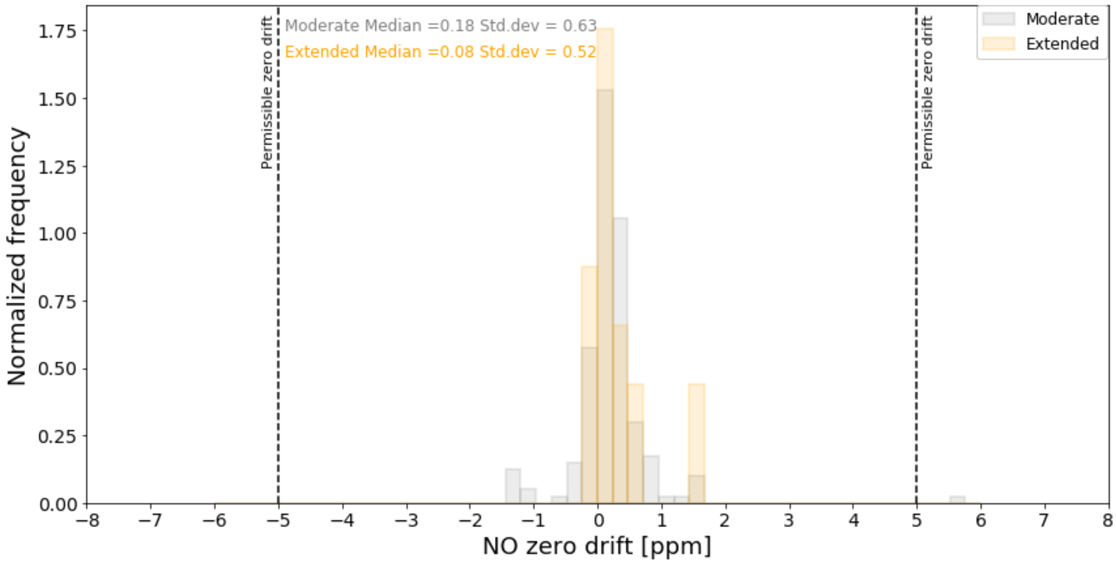


Source: JRC, 2020.



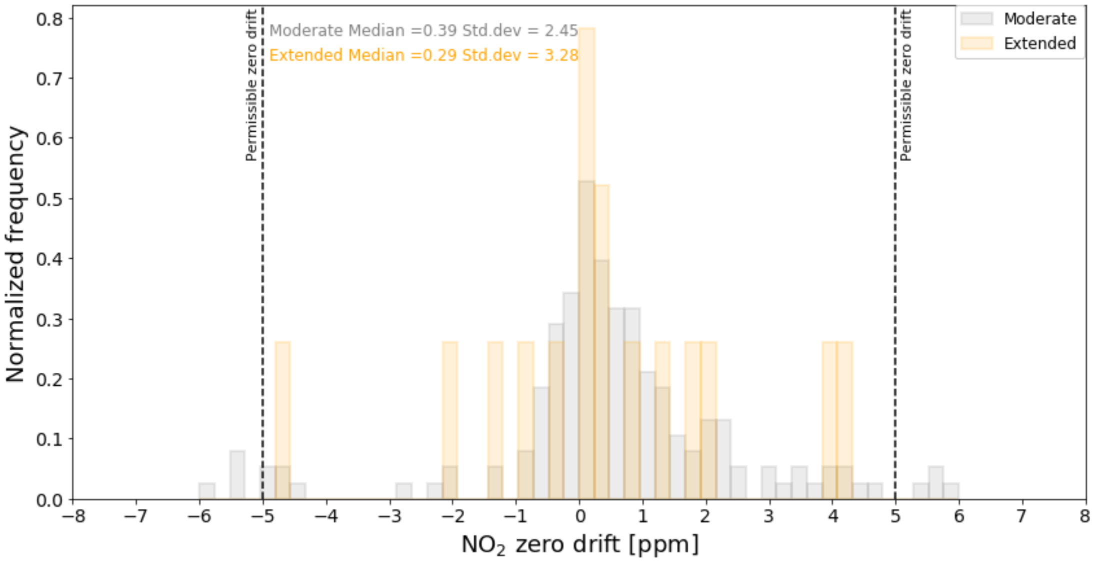
Source: JRC, 2020.

Figure 75. NO zero drift of PEMS tests performed by JRC on 2018 as function of altitude



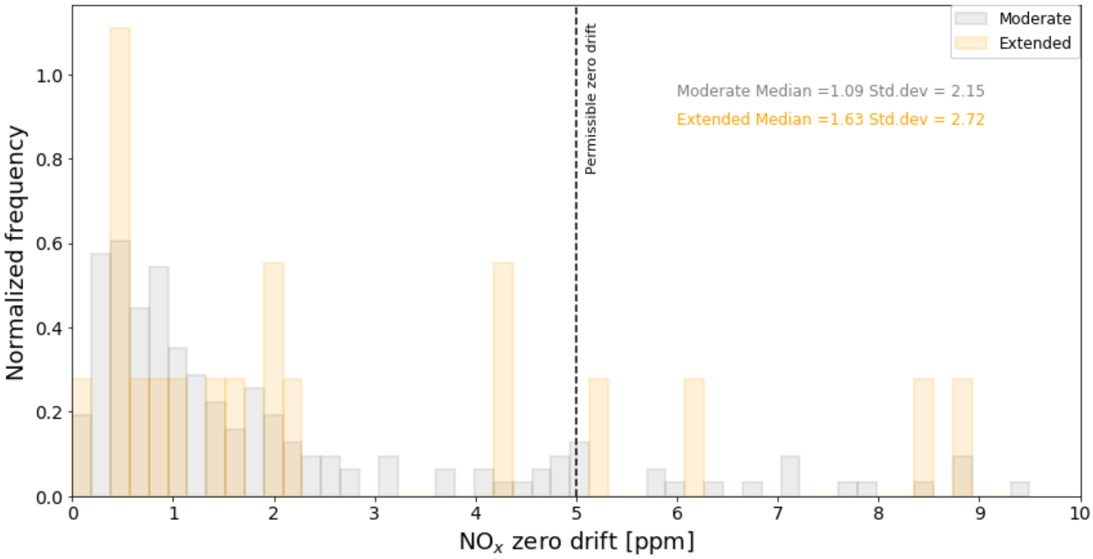
Source: JRC, 2020.

Figure 76. NO₂ zero drift of PEMS tests performed by JRC on 2018 as function of altitude

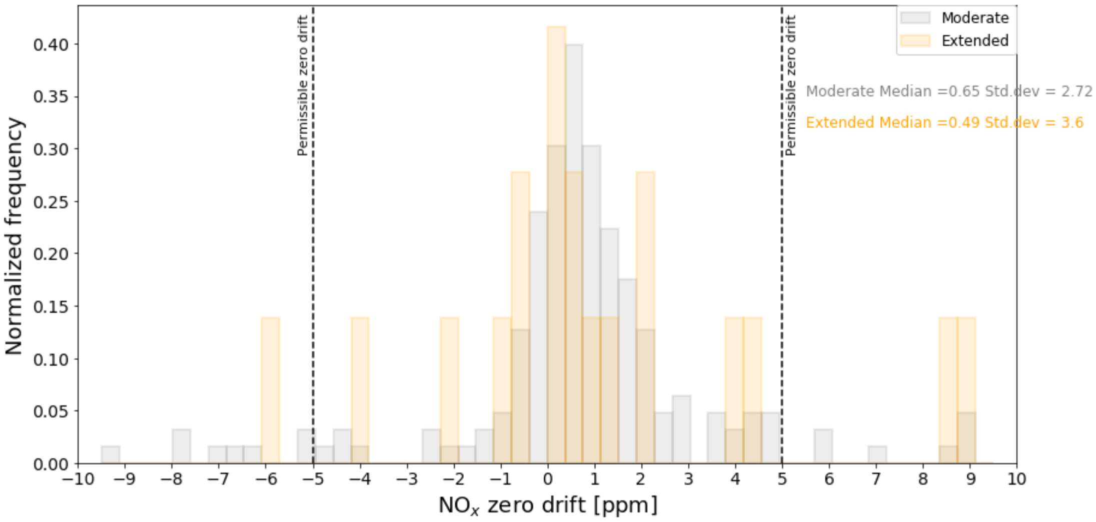


Source: JRC, 2020.

Figure 77. NOx zero drift of PEMS tests performed by JRC on 2018 as function of altitude top) NOx zero calculated as sum of absolute NO and NO$_2$ zero drifts. bottom) NOx zero calculated as sum of NO and NO$_2$ zero drifts.



Source: JRC, 2020.



Source: JRC, 2020.

4.2 PEMS validations

It is of common practice at JRC that a PEMS installation on-board a vehicle is validated by performing a comparison of the main parameters (emission concentrations, exhaust mass flow, and distance) against laboratory grade equipment in the VELA facilities. The PEMS validations are usually done either following the NEDC or the WLTP test procedures, fulfilling the requirements laid down in EU regulations for what regards the settings of the chassis dyno and the PEMS. Validation tests were performed on a cold or a hot vehicle, and the ambient temperature of the test cell varied from 14 °C to 25 °C, depending on the test. The relative humidity in the test cell was in all cases ~ 50%, and no NOx humidity correction was applied to the PEMS measurements. Two different JRC laboratories were used to perform PEMS validations: VELA2 with HORIBA instrumentation and VELA8 with AVL instrumentation. The validations were done with the three PEMS units from AVL introduced in the experimental section. All validation tests were performed with their specific pre-test and post-test, and in all cases, the NO, NO$_2$, and NOx zero drift were within the permissible limits.

Depending on laboratory availability and testing agenda, the PEMS validation is performed either before or immediately after the test campaign with the PEMS. In 2018, 26 PEMS validations were performed on a total of thirteen vehicles: twelve passenger cars and one light commercial vehicle. The PEMS validations covered all tested powertrains: diesel (5 vehicles), gasoline GDI (2), gasoline PFI (3), LPG (1) and CNG (2).

Figure 78 shows the results of the validation tests for NOx in terms of distance-specific emissions (top figure for absolute values respect laboratory bag values, and bottom for relative differences). The failure rate of the PEMS for NOx was ~4%, with a single test exceeding the permissible absolute tolerance (15 mg/km) and relative tolerance (15% of the laboratory reference) simultaneously. This specific test was performed on a standard NEDC cycle with a warm engine on a diesel Euro 6b vehicle. A previous validation repetition of the same PEMS installation on the NEDC cold test was within the permissible relative tolerance (11% deviation of the PEMS respect the laboratory).

For all other validation tests, independently from the test cycle used, the vehicle powertrain, the engine temperature condition at the test start, and the ambient temperature, the NOx measurement from the PEMS was within the permissible difference respect the one measured by the laboratory instrumentation. In general, the largest absolute difference occurred on vehicles with the highest NOx emissions of the tested fleet: Euro 6b diesel vehicles. On the other hand, the largest relative difference was measured on vehicles with low NOx emissions: gasoline (PFI) vehicles.

In the plots of **Figure 78**, the codes in the x-axis correspond to a combination of powertrain (D: diesel, G: gasoline), test cycle (N: NEDC, W: WLTP, IDC: Indian driving cycle), and test condition (C: cold engine condition, H: hot engine condition). A numeric value at the end of the code indicates the repetition number.

For the other gases measured with the PEMS (CO, CO_2 **Figure 79**) there is also a good performance of the analysers in laboratory conditions with low number of tests outside the permissible tolerances (< 5% for single analysers). When considering all analysers at the same time, the exhaust mass flow meter and the distance as measured from the OBD, the PEMS validation failure ratio from the 2018 JRC test campaign raised to 12%.

A PEMS validation test performed in VELA2 over a WLTP with a unit of AVL-MOVE (AVL-1) at an ambient temperature of -7 °C resulted in a passed validation, with all gaseous emissions within permissible tolerances (**Table 5**). Two additional PEMS validation tests were performed with the AIP PEMS over a WLTP test in VELA8 at an ambient temperature of 23 °C and -7 °C. Both tests were valid: zero drift of analysers was within the permissible tolerance and absolute and relative distance-specific lab to PEMS differences were also lower than regulated thresholds for all pollutants.

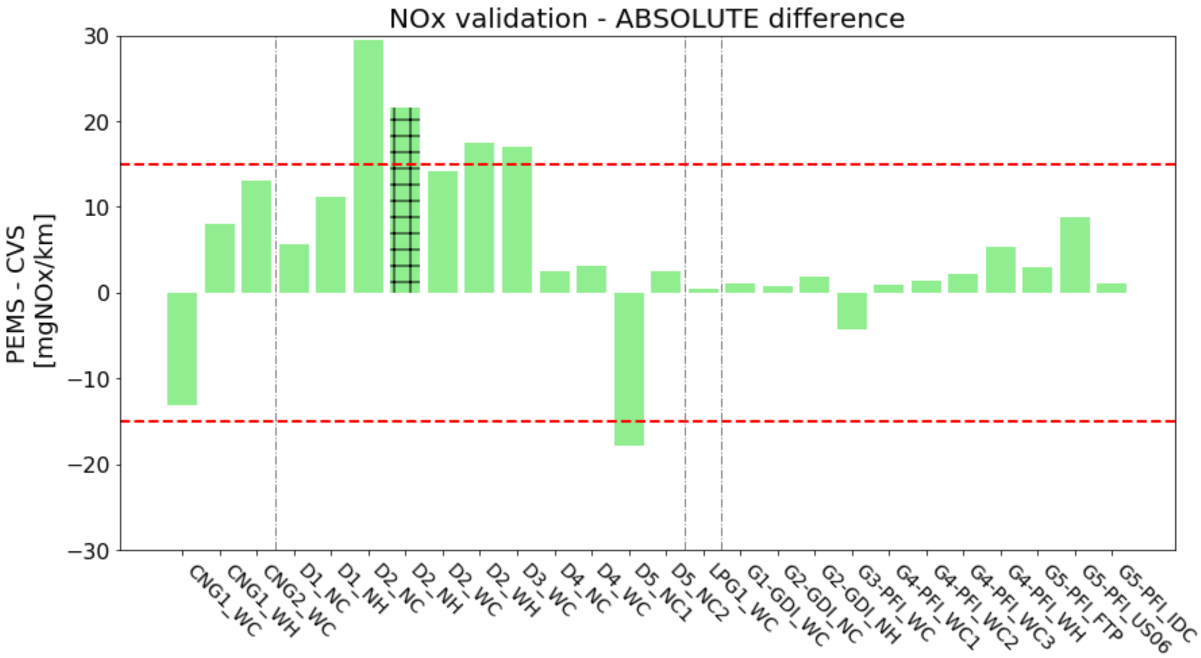
Table 5. Results of PEMS validation test performed at -7 °C

	Laboratory	**PEMS**	**Absolute difference**	**Relative limit [%]**	**Criteria**
CO [mg/km]	454.2	409.5	-44.7	-9.8	Pass
CO_2 [g/km]	140.9	144.50	3.6	2.6	Pass
NOx [mg/km]	37.2	36.2	1.0	-2.7	Pass

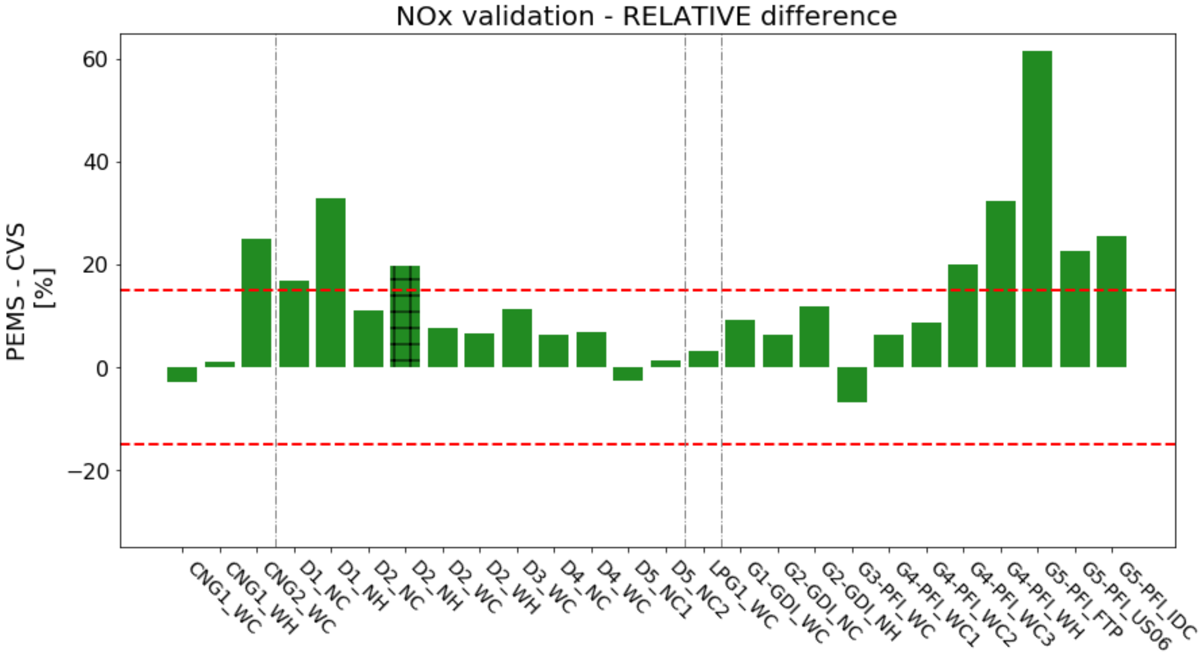
Source: JRC, 2020.

It can be concluded that in the laboratory, when the ambient conditions are stable and PEMS are not exposed to stressful conditions, the NO and NO_2 analysers perform well with no specific effect on the drift.

Figure 78. Validation of NOx measurement with PEMS against laboratory grade equipment from 2018 JRC PEMS activity top) absolute difference, bottom) relative difference. The red dotted lines indicate the permissible tolerances for NOx on PEMS validation tests. The hatches indicate the failed PEMS validation.

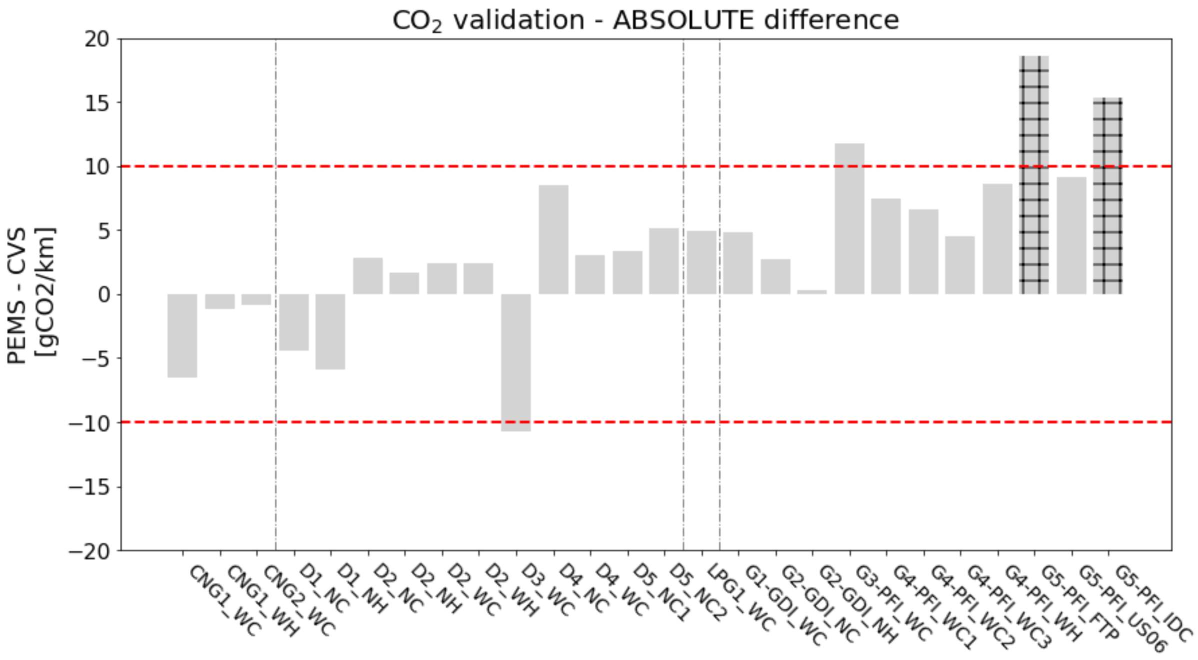


Source: JRC, 2020.

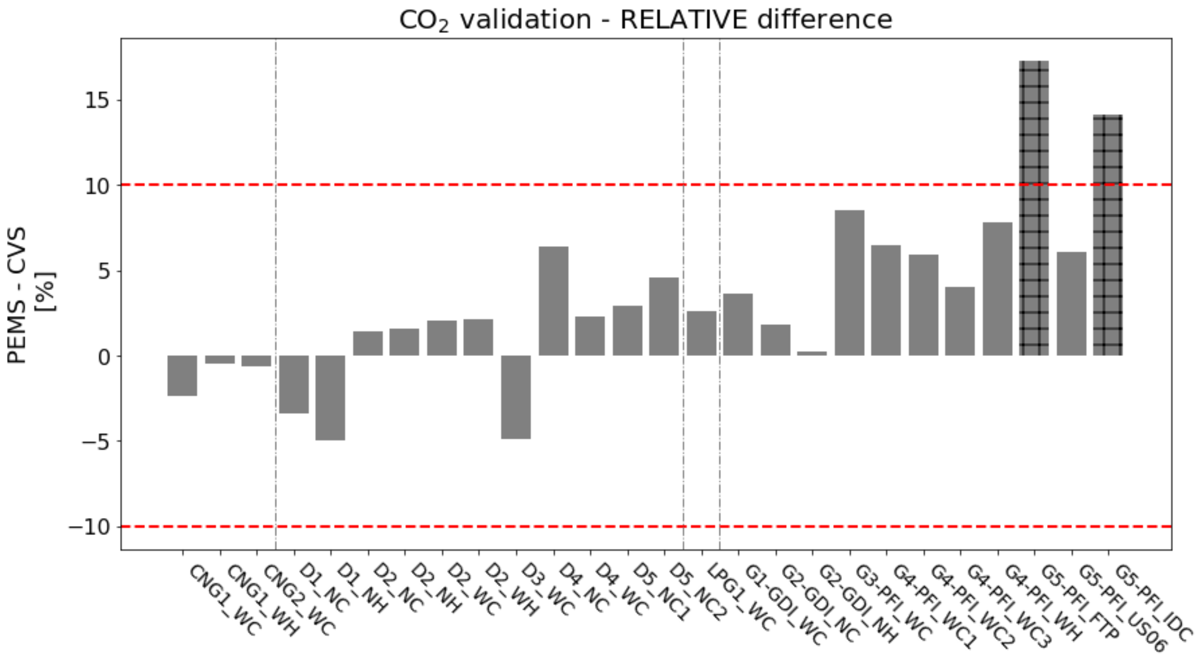


Source: JRC, 2020.

Figure 79. Validation of CO_2 measurement with PEMS against laboratory grade equipment from 2018 JRC PEMS activity top) absolute difference, bottom) relative difference. The red dotted lines indicate the permissible tolerances for CO_2 on PEMS validation tests. The hatches indicate the failed PEMS validation.



Source: JRC, 2020.



Source: JRC, 2020.

4.3 Zero drift of the exhaust mass flowmeter

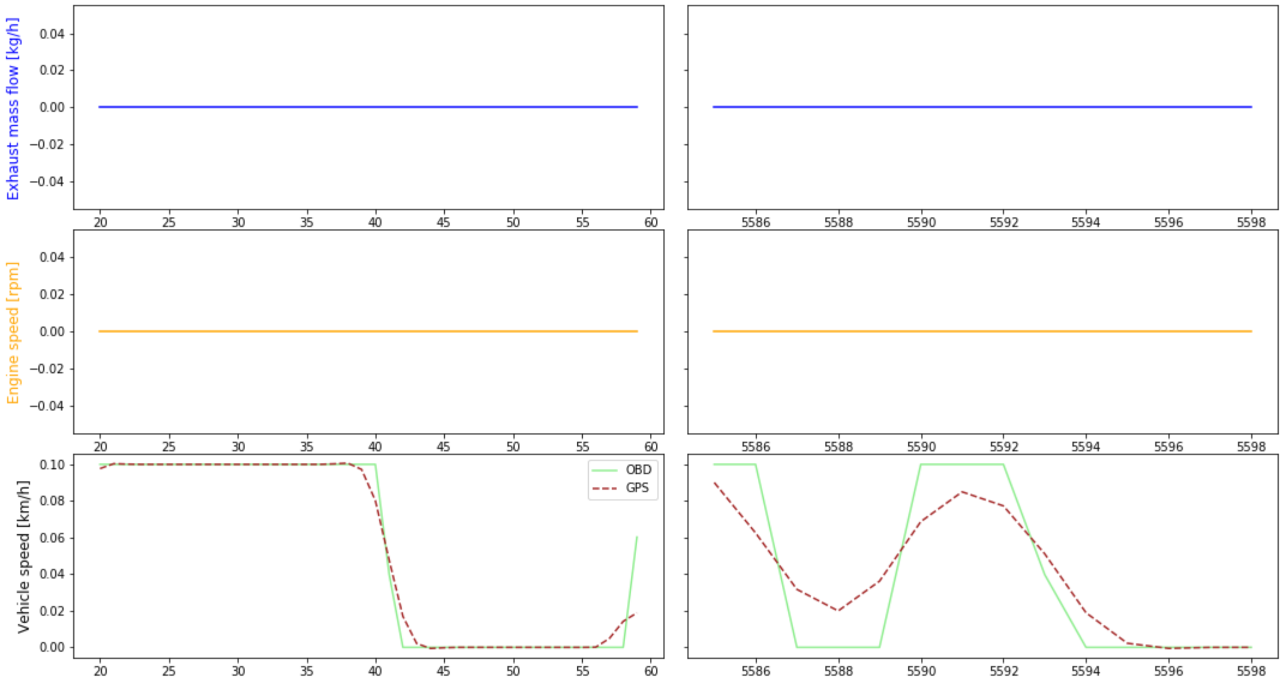
Prior to the test-start, as defined in RDE regulation (EU 2018/1832) for conventional internal combustion engine vehicles by the first ignition of the thermal engine (engine speed > 50 rpm, and exhaust mass flow > 3 kg/h), the recording of test parameters shall be launched so that all emissions are computed in the test. In the same way, the recording of the test parameters shall continue after the test-end. It is a general procedure at

JRC to launch the recording circa 1 minute before the test-start and finish it circa 1 minute after the test-end to make sure that all information from the test is properly logged and registered. During these two moments, the exhaust mass flowmeter (EFM) is operational and it is logging. As the thermal engine is off, the expected measurement from the EFM is 0 kg/h.

Using the date of the JRC 2018 PEMS campaign, a preliminary assessment of the zero drift of the EFM was performed by comparing the average measurement of the EFM before the test-start, and after the test-end.

The 185 PEMS tests of the campaign, showed the same pattern for what regards exhaust mass flow. As an example, **Figure 80** shows that the EFM measured 0 kg/h when the engine was off before the test and after the test. This could be interpreted as a lack of drift in the EFM measurement of the exhaust mass flow.

Figure 80. Exhaust mass flow measurement, engine speed, and vehicle speed, measured immediately before the test-start (left column) and immediately after the test-end (right column) of a representative PEMS test.



Source: JRC, 2020.

Regarding the validation of the measurement of exhaust mass flow from the EFM of the PEMS against the laboratory equipment, **Table 6** presents the main indicators of the correlation for 20 tests done at JRC in 2018 on a variety of vehicles. All tests were performed using AVL-MOVE units. It is important to notice that the laboratory measurement is not a traceable standard and therefore the analysis on the EFM performance is based on the best surrogate available. For the dataset considered, there is a good correlation between the exhaust mass flow of the PEMS and the measured with the laboratory equipment with an average r^2 of 0.945. Also the intercept and the slope parameters, which provide information on the correlation at low flows and throughout the range of flows, respectively comply well with the permissible tolerances defined in the regulation. It is noticeable that for most tests, the slope is lower than 1, which means that at higher speeds, when the exhaust mass flow is large, the EFM of the PEMS tends to underestimate the flow as compared to the laboratory.

Further data from vehicles with larger engine displacement and other instruments would provide a better understanding of the EFM performance. Based on the data considered it is reasonable to keep the current approach regarding the uncertainty of the EFM in the PEMS margin determination.

Table 6. Overview of the performance of the exhaust mass flow measurement with PEMS against laboratory exhaust flow estimation from JRC 2018 PEMS validations.

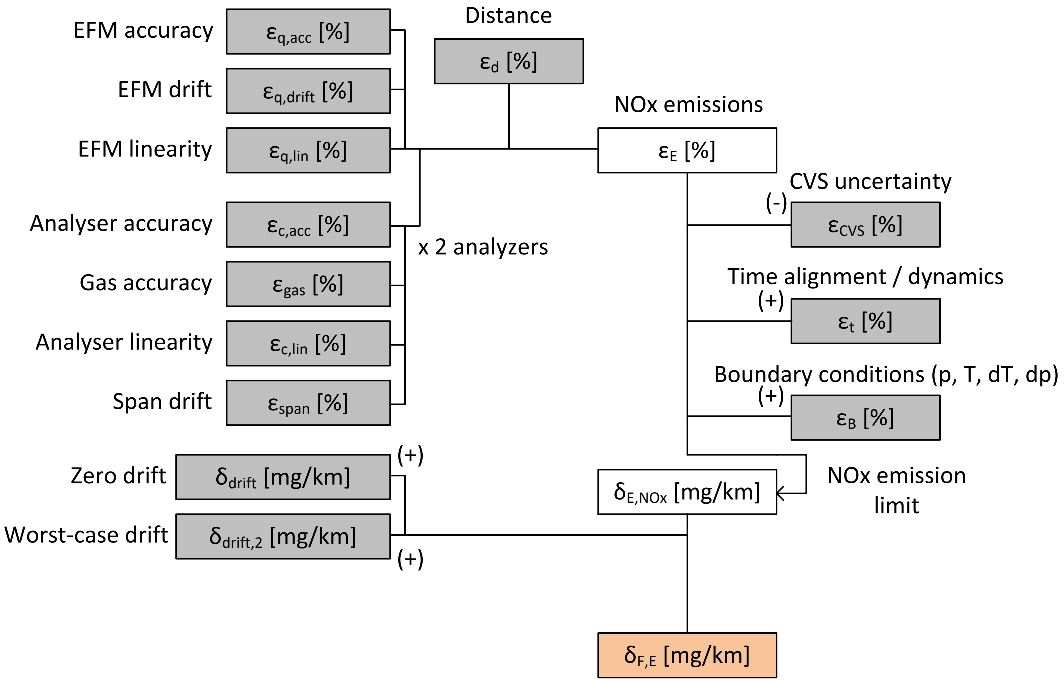
n = 20	**r^2**	**a_1 slope**	**a_0 intercept**	**SEE**
Permissible tolerance	≥ 0.90	[0.925/1.075]	[-3.0/3.0]	0.1
Average	0.945	0.929	1.347	0.017
Median	0.968	0.933	1.067	0.018
Outside limit [%]	5	30	10	0

Source: JRC, 2020.

5 NOx margin proposal

The calculation framework for the 2018/19 review follows the 2017 concept (**Figure 81**). The PEMS measurement uncertainty is calculated based on the error propagation of its components (analysers, exhaust flow meter (EFM) and GPS). In addition, the effect of the time alignment, dynamics and boundary conditions and the zero drift are considered. These uncertainties are added due to lack of information on their contribution to the PEMS uncertainty.

Figure 81. Margin estimation framework.



Source: JRC, 2020.

The focus of this review was on parameters that assumptions had to be made in 2017 due to lack of data:

- EFM
- Zero drift
- Effect of boundary conditions

For this chapter the PEMS manufacturers will be referred to as:

- PEMS A: AVL MOVE and the three units A1, A2, A3
- PEMS B: HORIBA OBS-ONE
- PEMS C: AIP
- PEMS D: SENSORS SEMTECH LDV

Table 7 summarises the dedicated zero drift results of this study (i.e. measuring the zero level every 10-20 min) in the laboratory (chassis dynamometer). The tests (PEMS not measuring exhaust gas) showed small drift under laboratory conditions with maximum ±2.5 ppm drift under extreme changes of the temperature (excluding PEMS D that failed the test). The effect of altitude and vibrations was not assessed in the laboratory.

Table 7. Laboratory (chassis dynamometer) assessment of NOx zero drift and influence of temperature. NOx zero drift check every 10-20 min. Influence of altitude or vibrations was not assessed in the laboratory. G=Gradual, S=Step change of temperature.

Laboratory	**Baseline**	**Temperature**		
	20-25°C	**23 °C to -7 °C**	**-7 °C**	**-7 °C to -23 °C**
PEMS A1	±0.3 ppm (**Figure 42**)	G: <2 ppm (**Figure 47**) S: -2.5 ppm (**Figure 56**)	-	G: <2 ppm (**Figure 53**)
PEMS B	±0.3 ppm (**Figure 42**)	G: +1.0 ppm (**Figure 47**) S: +1.0 ppm (**Figure 61**)	Negligible (**Figure 50**)	G: <2 ppm (**Figure 53**) S: <2.0 ppm (**Figure 66**)
PEMS C	-	-	-	-
PEMS D	-	G: -6.0 ppm (**Figure 47**)	-1 (**Figure 50**)	G: +3 ppm (**Figure 53**)

Source: JRC, 2020.

Table 8 summarises the dedicated zero drift results of this study (i.e. measuring the zero level every 10-20 min) on the road during RDE tests. The RDE test (with vehicle exhaust) covered a range of temperatures between 0 and 36°C and an altitude up to 1100 m. The vibrations were the normal vibrations (and shocks) of RDE tests. The results are summarized in **Figure 82** (RDE compliant routes) and **Figure 83** (high altitude routes).

Table 8. On-road assessment of NOx zero drift and influence of temperature, altitude and vibrations. NOx zero drift checks every 10-20 minutes.

On-road (RDE)	**Temperature (Figure 82)**	**Altitude (1100 m) (Figure 83)**	**Vibrations**
PEMS A1-3	10-36°C (**Figure 6**)	15-34°C (**Figure 7**)	included
PEMS B	14-23°C (**Figure 16**)	11-23°C (**Figure 17**)	included
PEMS C	8-19°C (**Figure 26**)	3-17°C (**Figure 27**)	included
PEMS D	0-13°C (**Figure 36**)	7-16°C (**Figure 37**)	included

Source: JRC, 2020.

Figure 82. On-road NOx zero drift tests (RDE compliant routes).

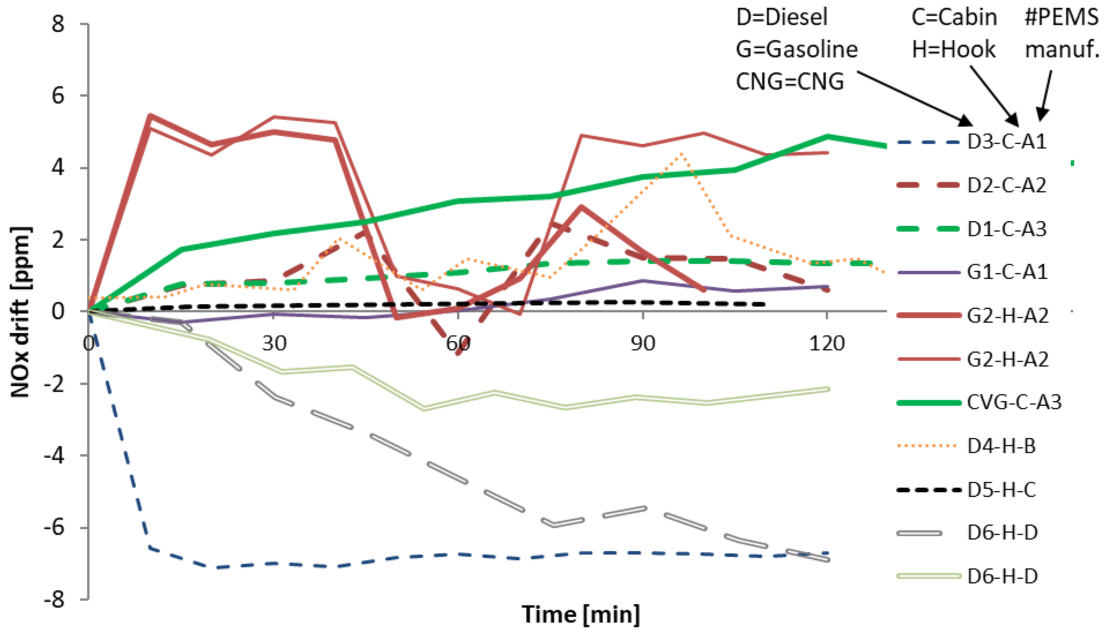
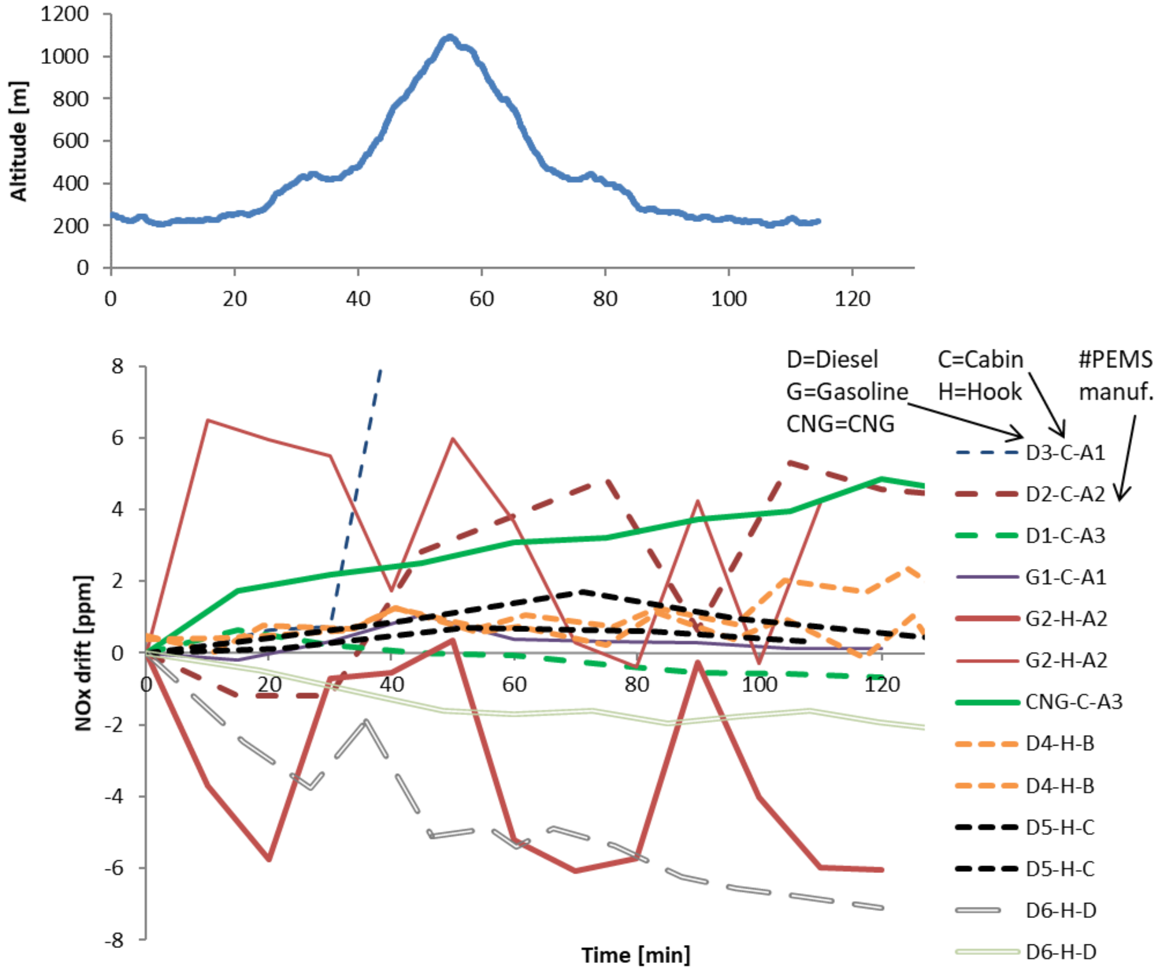


Figure 83. On-road NOx zero drift tests (non-RDE compliant routes with high altitude). Top) altitude profile bottom) NOx zero drift



Source: JRC, 2020.

Table 9 summarises the results of the indirect tests (i.e. only pre- and post test info is available) at the laboratory validations (PEMS measuring exhaust gas). The tests covered a temperature range of 14-25°C, but no altitude or vibrations influence. The zero drift assessment of the EFM was possible in the laboratory though. The results indicate that under laboratory conditions no drift is seen.

The mean slope, an indication of the EFM accuracy, was 0.93 (**Table 6**). However, the comparison was done with estimation of flow from the laboratory, which also has high uncertainty. Comparison of the PEMS CO_2 with the laboratory CO_2 is also an indication of the EFM accuracy (according to the future CEN). This comparison was within 10 g/km of CO_2 for 24 of the 26 validations (**Figure 79**).

Table 9. Laboratory (chassis dynamometer) assessment of pre-post validation tests NOx zero drift. The altitude and vibrations influence was not assessed.

Laboratory	**14-25°C (RH 45-55%)**	**Temp.**	**EFM**
PEMS A1-3	96% passed (23 validations) (**Figure 78**)	100% passed (1 validation)	No drift
PEMS B	100% passed (1 validation)	-	
PEMS C	100% passed (2 validations)	100% passed (2 validations)	No drift
PEMS D	-	-	

Source: JRC, 2020.

Table 10 summarises the results of the on-road indirect tests (i.e. only pre- and post test info is available). The RDE tests covered a temperature range of 3-33°C and an altitude of up to 1100 m. For the on-road tests the typical vibrations and shocks were also included. Drift higher than 5 ppm happened in <10% of the tests.

Table 10. On-road assessment of pre-post RDE NOx zero drift and influence of temperature, altitude and vibrations. Results based on 185 tests (PEMS A), 2 tests (PEMS C). 19 tests at high altitude (PEMS A).

On-road	**Baseline**	**Temperature / Humidity**	**Altitude (1100 m)**	**Vibrations / hook-cabin**	**EFM**
PEMS A1-3	90% <5 ppm (**Figure 71**)	3-33°C (**Figure 74**a) 16-95% (**Figure 74**b)	84% <5 ppm (**Figure 77**)	included	No drift (**Figure 80**)
PEMS B	-	-	-	-	
PEMC C	No drift	-	-	-	No drift
PEMS D	-	-	-	-	

Source: JRC, 2020.

Based on these experimental results the input for the assessment of the PEMS measurement uncertainty is summarized in **Table 11**.

- EFM: The EFM uncertainty was kept 10%. The EFM drift was negligible, but it was kept 2% (max. allowed in the regulation).

- Boundary conditions: As the influence of the boundary conditions was not clear and in most cases any effect was absorbed during the zero drift checks, it was decided to set it zero and include it in the zero drift.
- Zero drift: The zero drift was assessed using the zero drift curves of **Figure 82** and the respective exhaust flow rates of the vehicles used. An example is given in **Figure 84**. The maximum effect was 10 mg/km. In order to estimate a worst case scenario, the worst case experimentally determined drift (G2-H-A2) was combined with the maximum exhaust flow rate assessed (the CNG van). The result was 16 mg/km at the urban part. Thus, in order to cover large engines and/or urban conditions a 6 mg/km worst case drift was considered. It should be mentioned that there could be cases that the effect of the zero drift will be higher than this experimental worst case drift (i.e. step drift of large engines). These cases should be <<1%.

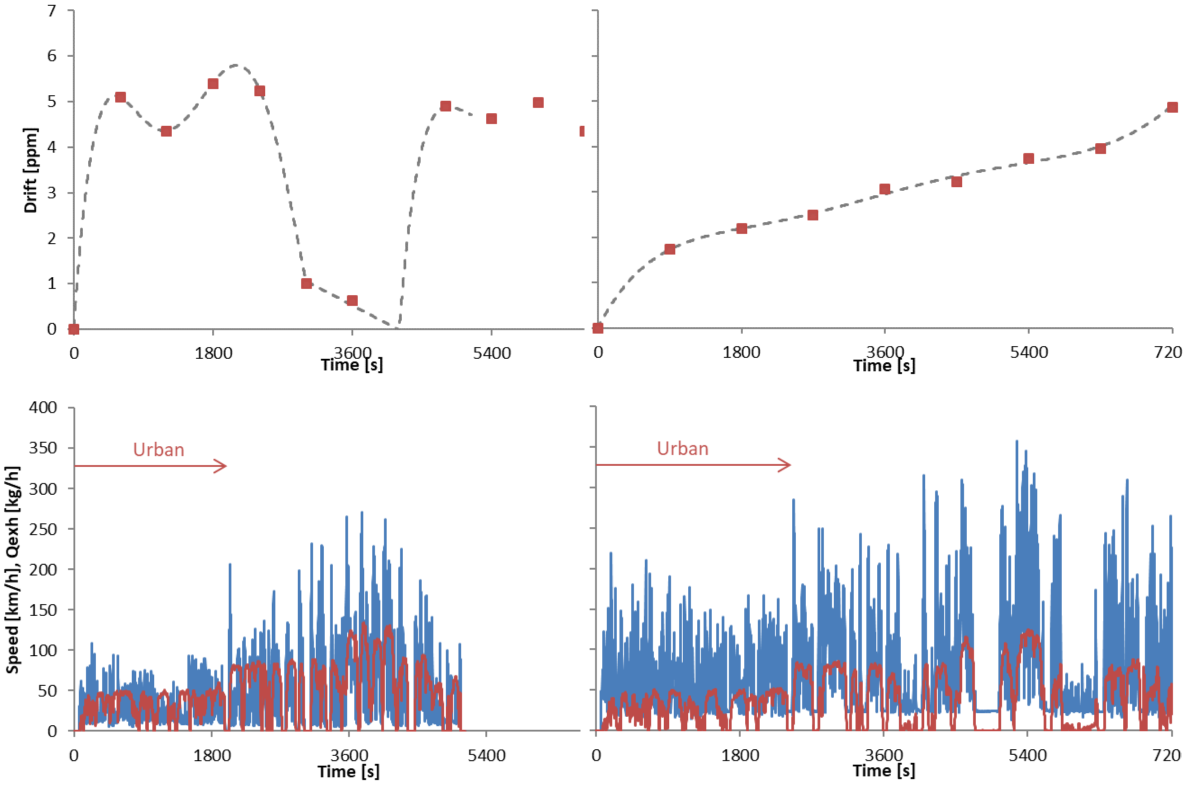
Table 11. Sources (components) of PEMS measurement uncertainty, as specified by the measurement performance criteria laid out in RDE regulation and as estimated from the experimental uncertainties from the 2018-9 review.

Name	Symbol	RDE	2017 review	Comments
		EXHAUST FLOW METER (EFM)		
EFM accuracy	$\varepsilon_{q,acc}$	3%	10%	**Table 6**
EFM drift	$\varepsilon_{q,drift}$	2%	negligible	**Table 10**
EFM linearity	$\varepsilon_{q,lin}$	2%	1.8%	**Table 6**
		GAS ANALYSERS		
Analyser accuracy	$\varepsilon_{c,acc}$	2%	not examined	
Analyser linearity	$\varepsilon_{c,lin}$	1%	not examined	
Span drift	ε_{span}	2%	not examined	
Gas accuracy	ε_{gas}	2%	not examined	
		OTHER		
Distance	ε_{d}	4%	not examined	
Dynamics	ε_{t}	time aligned	not examined	
Boundary conditions	ε_{B}	0%	included in zero	**Table 8**
		ZERO DRIFT		
Analyser zero drift	δ_{drift}	5 ppm	10 mg/km	**Figure 84**
Worst-case drift	$\delta_{drift,2}$	-	6 mg/km	**Figure 84**

Source: JRC, 2020.

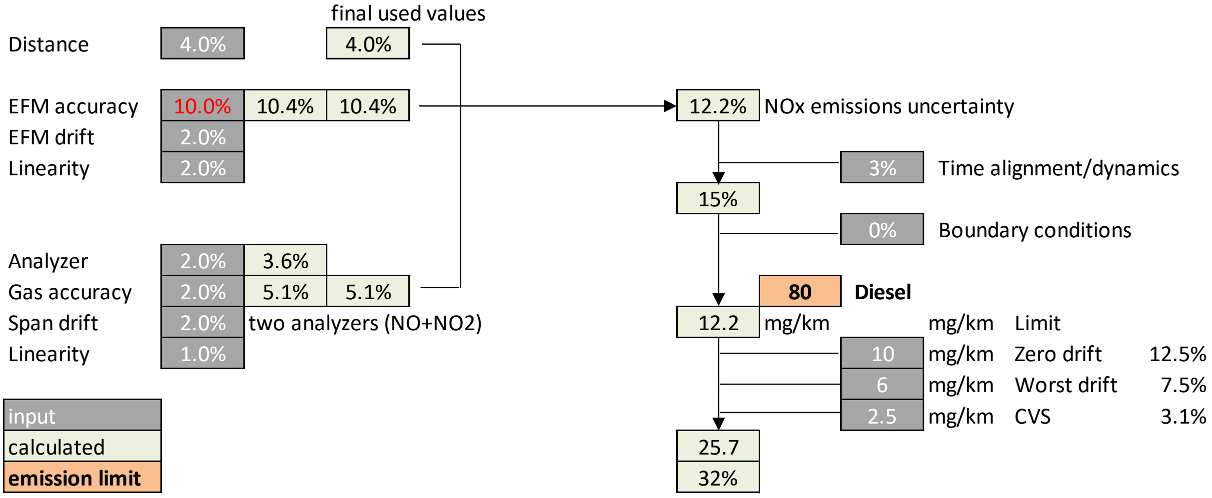
The final calculations for the NOx margin are shown in **Figure 85**. The result is 32% at an emissions level of 80 mg/km.

Figure 84. Examples of inputs for calculation of NOx zero drift. Left: G2-C-A2 NOx zero drift urban 6.3 mg/km and total RDE 4.0 mg/km. Right: CNG-C-A3 NOx zero drift urban 5.9 mg/km and total RDE 9.2 mg/km. Combining the experimental worst case drift with the high exhaust flow rate NOx zero drift urban 15.9 mg/km and total RDE 11.3 mg/km are calculated.



Source: JRC, 2020.

Figure 85. Calculation of the NOx margin based on the results of this study.



Source: JRC, 2020.

6 Conclusions

The PEMS measurement uncertainty framework of 2017 identified three areas that needed better feedback: EFM uncertainty, zero drift and effect of boundary conditions on PEMS.

In this measurement campaign these areas were addressed with special emphasis on the zero drift.

Dedicated on-road tests were conducted measuring the zero drift of the analysers every 10-20 min during RDE compliant and non-compliant routes. Altitudes up to 1100 m were covered and temperatures within 0 °C and 35 °C. Lower temperatures (-7 °C) and drastic changes of the temperature (-7 °C to 23 °C and vice versa) were better assessed in the laboratory.

The results of the test campaign did not show a uniform behaviour of the zero drift among tests, instruments, and pollutants. There is no systematic positive or negative drift, neither a systematic step nor linear drift.

In a given route with a specific PEMS unit, the drift for one gas analyser is independent from the drift of another gas analyser.

For the range of tested temperatures (0 °C – 35 °C) tests done under similar temperature and humidity conditions resulted in no drift or significant drift, pointing to the fact that there does not seem to exist a relationship between the measured zero drift at a given step of the trip and the ambient temperature and humidity conditions. Also, the results of zero drift in the high altitude route are similar to those observed on the RDE compliant routes.

The drastic thermal changes affected one of the PEMs manufacturers only, although in conditions not foreseen by the PEMS manufacturer.

Not negligible zero drift is observed in tests done in vehicles with spark ignition as well as with compression ignition pointing to the fact that there is not particular influence of the vehicle technology on the drift.

Tests where the PEMS was mounted on the trailer hook had a similar behaviour in terms of drift as tests where the PEMS is mounted inside the vehicle.

NO_X zero drift hypothesis of a step drift occurring at the very beginning of the test and then being maintained along the duration of the test is not verified in any of the tests performed. The observations of the campaign can justify further reducing the margin for NO_X on RDE tests.

Based on the worst case scenario for zero drift of the JRC testing campaign and considering the effect on a vehicle with large engine displacement (largest effect in terms of NOx mass), the updated NOx margin that is proposed is 0.32.

References

Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (RDE1). Official Journal of the European Union L 82/1.

Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (RDE2). Official Journal of the European Union L 109/1.

Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008. Official Journal of the European Union L 175/1.

Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC of the European Parliament and of the Council as regards real-driving emissions from light passenger and commercial vehicles (Euro 6) (RDE3). Official Journal of the European Union L 175/708.

Commission Regulation (EU) 2018/1832 of 5 November 2018 amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) 2017/1151 for the purpose of improving the emission type approval tests and procedures for light passenger and commercial vehicles, including those for in-service conformity and real-driving emissions and introducing devices for monitoring the consumption of fuel and electric energy (RDE4). Official Journal of the European Union L 301/1.

Giechaskiel, B., Clairotte, M., Valverde, V. and Bonnel, P., *Real driving emissions: 2017 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty.*, JRC report EUR 29138, Publications Office of the European Union, Luxembourg, 2018, doi:10.2760/127122.

O'Driscoll, R., Stettler, M., Molden, N., Oxley, T. and ApSimon, H., *Real world CO_2 and NO_X emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars*, Science of The Total Environment, Vol 621, 282-290, 2018, doi:10.1016/j.scitotenv.2017.11.271

Suarez-Bertoa, R., Valverde, V., Clairotte, M., Pavlovic, J., Giechaskiel, B., Franco, V., Kregar, Z., Astorga, C., *On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test*, Environmental Research, Vol 176, 108572, 2019, doi: 10.1016/j.envres.2019.108572

Valverde, V., Bonnel, P. *On-road testing with Portable Emissions Measurement Systems (PEMS). Guidance note for light-duty vehicles.*, JRC report EUR 29029, Publications Office of the European Union, Luxembourg, 2018, doi:10.2760/08294.

Valverde, V., Clairotte, M., Bonnel, P., Giechaskiel, B., Carriero, M., Otura, M., Gruening, C., Fontaras, G., Pavlovic, J., Martini, G., Suarez-Bertoa, R., Krasenbrink, A. *Joint Research Center 2018 light-duty vehicles emissions testing - Contribution to the EU market surveillance: testing protocols and vehicle emissions performance.*, JRC report EUR 29897, Publications Office of the European Union, Luxembourg, 2019, doi:10.2760/155802.

List of abbreviations and definitions

CF	Conformity Factor
EFM	Exhaust flow meter
EU	European Union
GDI	Gasoline direct injection
JRC	Joint Research Center
NOx	Nitrogen oxides
PEMS	Portable Emissions Measurement Systems
PFI	Port-fuel injection
PN	Particle Number
RDE	Real Driving Emissions
VELA	Vehicle Emissions LAboratory
WLTP	Worldwide harmonised Light-duty vehicles Test Procedures

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