Preliminary Uncertainty assessment

RDE Task Force on Uncertainty Evaluation

1 October 2015

European Commission, Joint Research Centre (JRC), Institute for Energy and Transport

Deviations between lab and RDE testing

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Systematic deviations between RDE and lab test conditions (1)

Uncertainty in the coverage of permissible test conditions (2)

Uncertainty in the evaluation of test conditions (3)

Measurement uncertainty relative to lab (4)

(1) Systematic deviations between RDE and lab test conditions

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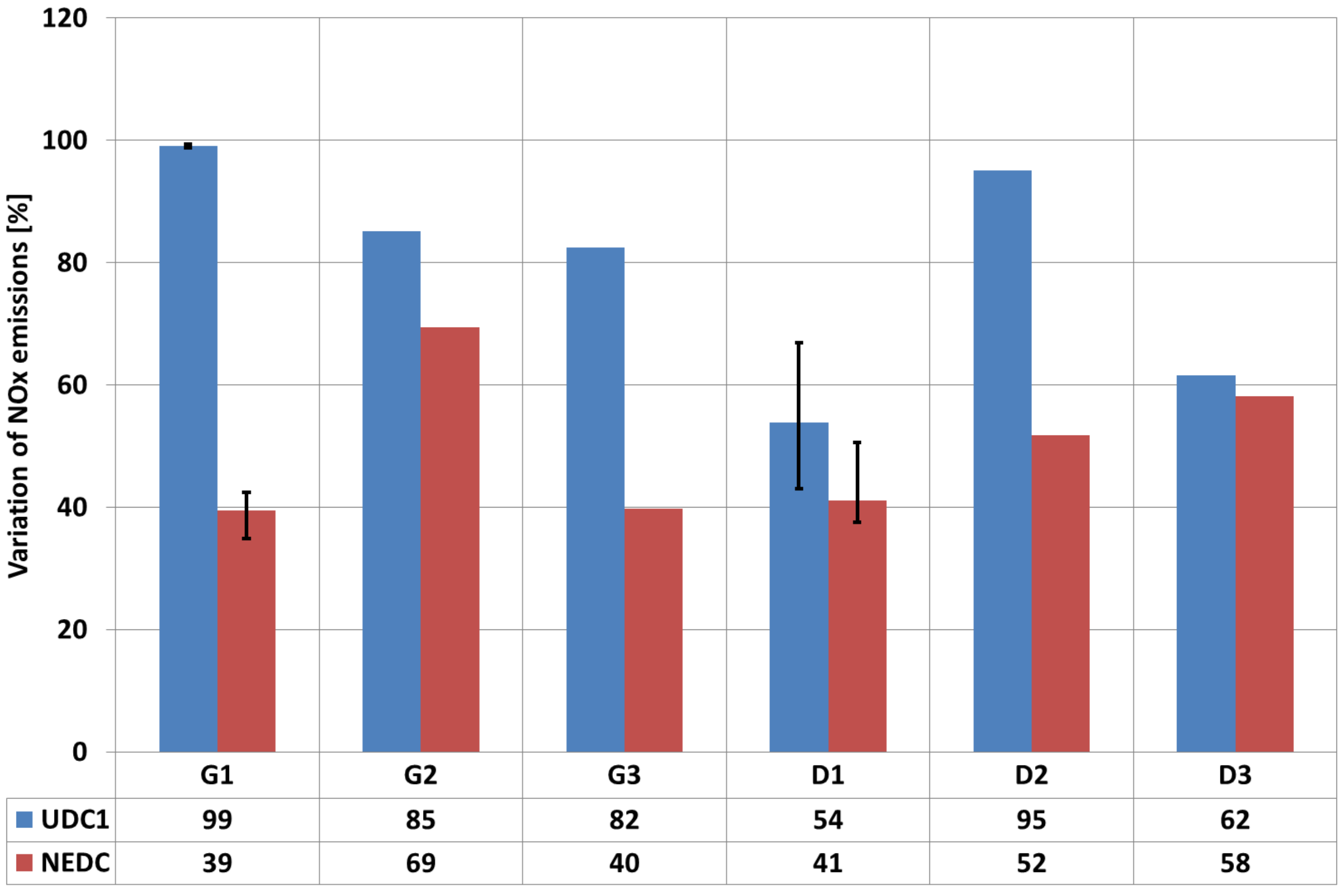
- 6 Euro6 vehicles:
  - ✓ 3 spark ignition engines featuring a TWC
  - ✓ 3 compression ignition engines with DOC+DPF+SCR
- Lab tests:
  - ✓ A total of 20 tests: 10 cold and 10 hot
  - ✓ Cold and hot cycles, per vehicle, performed with same dyno setings and test mass
  - ✓ Hot tests: $T_{oil} \geq 60$degC
- Cold vs. Hot NEDC deviations:
  - ✓ UDC1 (first NEDC 195s) percent deviation of NO_x emissions
  - ✓ Total NEDC (bags analysis) percent deviation of NO_x emissions
  - ✓ Percentage deviations:

$$Deviation\ [\%] = \frac{NO_{x,cold} - NO_{x,hot}}{NO_{x,cold}} * 100$$

(1) Systematic deviations between RDE and lab test conditions

Deviations over UDC1 (modal data) and NEDC (bags analysis)



- Error bars represent the maximum and minimum variation per vehicle
- Negligible error bars indicate single tests
- Significant deviations over both UDC1 and NEDC when comparing cold and hot cycles.
- Further investigations (?)

Average deviation over NEDC: 50 ± 12%

(1) Systematic deviations between RDE and lab test conditions

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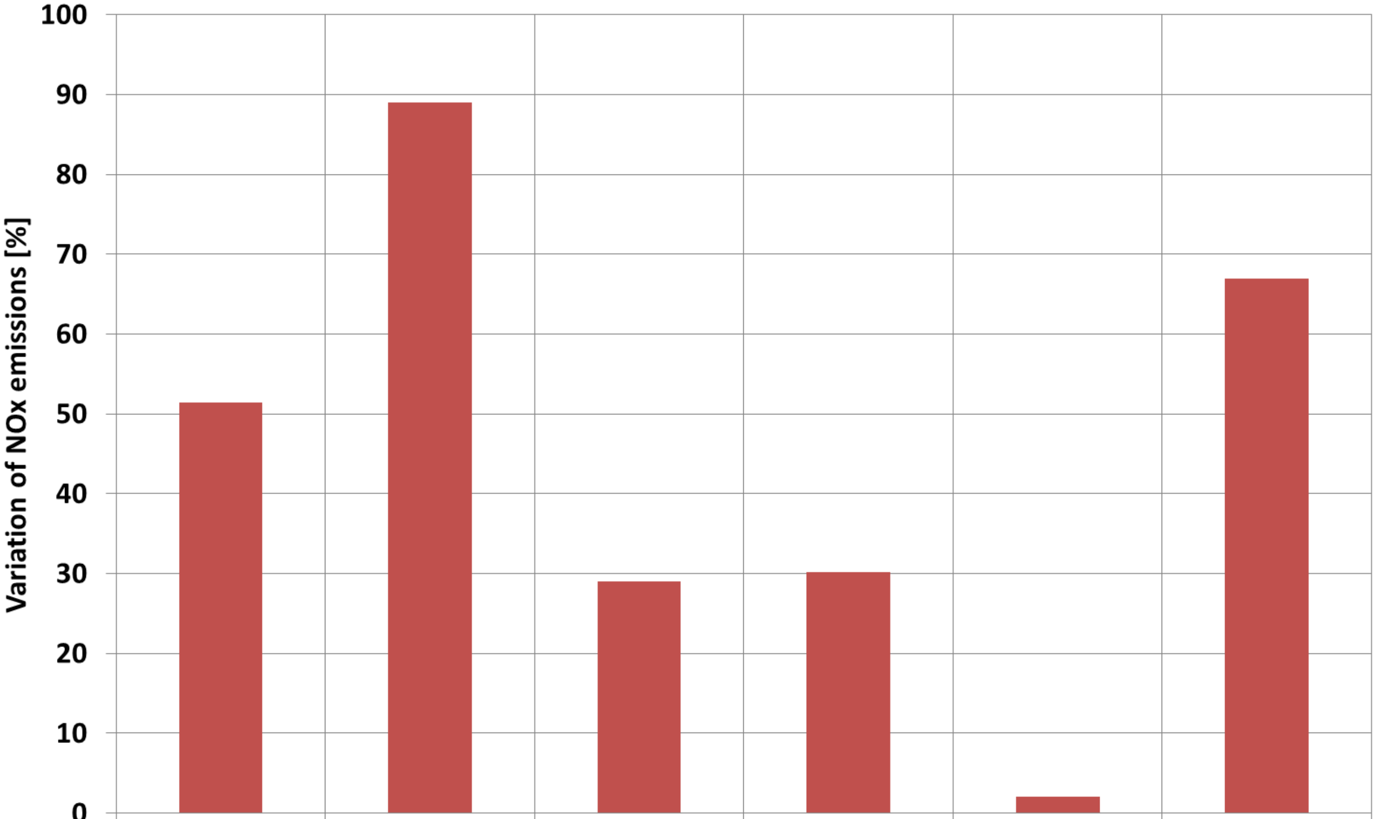
NEDC: Deviations modal cold-start vs. simulated hot start



	G1	G2	G3	D1	D2	D3
NEDC	51	89	29	30	2	67

- Further investigation (?)

Average deviation over NEDC: 45 ± 32%

(2) Uncertainty in the coverage of permissible test conditions

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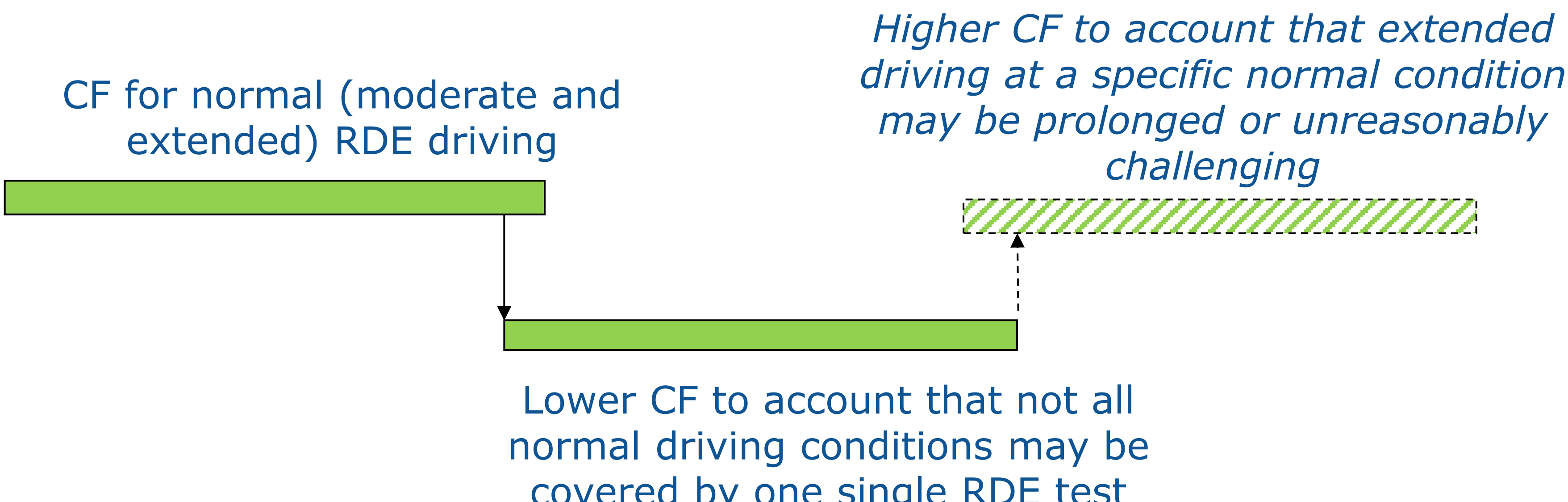
- Any valid RDE test likely covers only a part of the permissible test conditions
- Uncertainty of approving a “dirty” vehicle results because permissible conditions may have not been covered during a test
- The resulting uncertainty could be accounted for by lowering the CF (similar approach taken in durability requirements)



(3) Uncertainty in the evaluation of test conditions

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Sources of uncertainty

- Verification of temperature and altitude
- CO_2 emissions over the WLTC
- Conversion of CO_2 emissions into power at the wheel via Willans lines
- Human error in trip selection

Parameters are not used to calculate emissions but only to determine permissible test conditions

Parameter uncertainty small and potentially negligible with respect to the measured pollutant emissions

(1) Measurement uncertainty

What are the differences between PEMS and lab tests?

- (1) Measurement principle: Modal measurements of raw exhaust, using fast gas analyzers and flow meters (PEMS) vs. bag measurements on diluted exhaust (lab)
- (2) Measurement conditions: PEMS measurements under a wider range of conditions, e.g., temperature, ambient pressure, humidity, vibration

- Lab measurements associated with uncertainty that is absorbed by the Euro 6 limit; RDE conformity factors could absorb the additional (not the absolute) uncertainty of RDE PEMS testing relative to standard lab testing
- Effect of (2) difficult to quantify (EPA measurement allowance program) but potentially small

(1) Measurement uncertainty

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Bag measurement

$$E = \frac{V_{mix} * Q_i * k_h * C_i * 10^{-6}}{d}$$

PEMS

$$E = \frac{\sum c * q * u}{d}$$

Compound uncertainty

C_i - bag component concentration
Q_i – density of component
V_{mix} – volume diluted exhaust gas
k_h – humidity correction factor (NOx)
d - test distance
Compound uncertainty

c - instantaneous component concentration (modal raw exhaust)
q - instantaneous exhaust flow rate
u – fraction density component/ density exhaust
d - test distance
Compound uncertainty

Measurement uncertainty - lab

Symbol	Units[1]	Explanation	Uncertainty
V_{mix}	[l]	volume of the diluted exhaust gas	0.5% (Annex 4a, App. 2, 2.2.11)
Q_i	[g/l]	density of the pollutant i	negligible
k_h	[-]	humidity correction factor (NO_x)	<2%[2]
C_i	[ppm]	concentration of the pollutant i	>2%[3]
d	[km]	distance	1% (Annex 4a, App. 1, 1.2.6)

[1] All volumes refer to normal conditions 273.2 K and 101.33 kPa.

[2] The correction is based on the measurement of humidity, pressure etc.

[3] The concentration of the pollutant in the diluted exhaust gas is corrected by the amount of the pollutant i contained in the dilution air, thus the uncertainty is the combination of the two uncertainties (each 2% or 2 ppm for C<100 ppm) (Annex 4a, App. 3, 1.3.8; R83).

Compound uncertainty: 3% of measurement (for high measurement range)

Measurement uncertainty - lab

- **Example: less than 100 ppm in bag; 2ppm uncertainty for low concentrations, else 2%**

		Typical values			2 ppm error Values at the limits			0.5ppm error* Lower uncertainties		
Pollutant		Value	Uncertainty		Value	Uncertainty		Value	Uncertainty	
HC	mg/km	50	28	56%	100	28	30%	100	7.2	7.2%
CO	mg/km	300	50	17%	1000	50	5.5%	1000	17	1.7%
NO_x	mg/km	100	28	28%	60	28	47%	60	7.2	12%
CO_2	g/km	115	2.8	2.5%	45	1.3	2.9%	45	1.3	2.9%
PM	mg/km	1	0.2	20%	5	0.2	4%	5	0.2	4%
PNx10^11	p/km	1	0.2	20%	6	1.2	20%	6	1.2	20%

**0.5ppm error at low concentrations instead of 2 ppm based on experimental data of >10 years*

Expected error (2 σ) between 2 ppm and 0.5ppm: ≤25% at 60 mg/km

General overview - lab

2 ppm 0.5 ppm

Pollutant		Euro 6	RDE	Theory	Theory*	CUNA	VELAs	B/D/TP
THC	mg/km	100	15	28	7	18	5	8
CO	mg/km	1000	150	50	17	64	60	80
NO_x	mg/km	60	15	28	7	31	5	10
CO_2	g/km	120	10	3	3	11	5	4
PM	mg/km	4.5		0.2	0.2	2.5	0.5	
PN	#/km	6		0.2	0.2	2.4	3	

CUNA *is the mean of the standard deviations of the available data for each pollutants plus one standard deviation (Italian inter-laboratory exercise)*

VELA 1 and 2 *give the mean difference between the two laboratories plus one standard deviations.*

B/D/TP *give the mean difference between* ***B****ag with* ***D****iluted or* ***T****ailpipe real data plus one standard deviation*

Measurement uncertainty - PEMS

Exhaust mass flow rate [kg/s] (measured at ≥1 Hz)
- Linearity (slope within 1.00 ± 0.03 over a stationary test)
- Accuracy (within 2% of reading, 0.5% of full scale, or 1% of maximum calibrated flow)
- Precision (within 1% of maximum calibrated flow)
- Noise (within 2% of maximum calibrated flow)
- Zero and span drift (within 2% of the maximum value of the primary pressure signal over 4h
- Rise time (≤1 s)
- Response time (≤3 s)
- Possible exclusion of data due to system maintenance (<1%)
- If calculated from air and fuel flow rate, the following requirements apply:
  - linearity (slope within 1.00 ± 0.02 for air and fuel flow rate and 1.00 ± 0.03 for the calculated exhaust mass flow rate over a stationary test)
  - Accuracy for air and fuel flow rate (within 2% and 0.02% for reading)

Component concentration [ppm] (measured at ≥1 Hz)
- Linearity (slope within 1.00 ± 0.01 over a stationary test)
- Accuracy (within 2% of reading or 0.3% full scale)
- Precision (within 2% below 155ppm and 1% equal or above 155ppm)
- Noise (within 2% of full scale)
- Zero and span drift (analyzer-dependent margins for compliance in the laboratory over 4h and on the road over the duration of a test)
- Rise time (≤3 s)
- Response time (≤12 s)
- Leakage in the sampling line (≤1%)
- Calibration (1% of measurements may exceed the calibration range)
- Possible exclusion of data due to system maintenance (<1%)
- Additional requirements:
  - Efficiency of NO_x converters
  - Gas interferences during CO measurements (≤2% or ≤50ppm, whatever is larger)
  - CO_2 and water quench of CLD (≤2% full scale)
  - Quench of NDUV analyzer (5% of maximum test concentration; sample dryer to remove less than 5% of the original NO_2)
  - Accuracy of gas divider (within 2% of reading)

***u* value [kg/g]** (tabulated)

Time alignment based on cross-correlation

Vehicle speed [km/h] (≥1 Hz; measured and time aligned)
- Accuracy (deviation of total trip distance determined via GPS, sensor, or ECU within 4%)
- Accuracy sensor (within 1% of reading)
- Accuracy ECU (distance of the validation test to deviate by less than 250 m when measured with ECU and roller bench

Component mass emissions [g/s] (≥1 Hz; calculated)

Instantaneous distance-specific emissions [g/km] (≥1 Hz; calculated)

Additional sources of uncertainty:
- Temperature measurements (accuracy within 2K absolute for T≤600 K or within 0.4% of reading if T>600K)
- Relative humidity (accuracy within 5% absolute)
- Absolute humidity (accuracy within 10% of reading or 1 gH_2O/kg dry air, whichever is larger)
- Ambient pressure (accuracy within 0.2 kPa absolute)
- Intrusivity (e.g., backpressure introduced by measuring exhaust mass flow rate and component concentrations)
- Changes in the exhaust composition within the sampling lines
- Miscellaneous error sources (electro-magnetic interferences, shocks, vibration, variability in ambient conditions, dust, external contamination)
- Malfunctioning of equipment under on-road test conditions
- Inaccuracy in the concentration of calibration gases

(1) Measurement uncertainty in detail

Compounding PEMS measurement errors

Exhaust mass flow rate [kg/s]: 4% overall uncertainty of instantaneous measurements
- Considering only measurements with exhaust flow meters and disregarding requirements for air and fuel flow rate
- Assuming that linearity and accuracy on the one hand and precision and noise on the other hand are equivalent to each other; the parameter with the lowest uncertainty (i.e, 2% and 1% respectively) determined the permissible uncertainty margin
- Assuming that precision and noise are implicitly verified when determining linearity and accuracy

Component concentration [ppm]: 8% overall uncertainty of instantaneous measurements
- Assuming that linearity and accuracy on the one hand and precision and noise on the other hand are equivalent to each other; the parameter with the lowest uncertainty (i.e, 1% respectively) determined the permissible uncertainty margin
- Assuming that precision and noise are implicitly verified when determining linearity and accuracy
- Assuming an over-all uncertainty of 2% related to the item 'additional requirements'
- Assuming a maximum of 1% uncertainty related to leakage
- Assuming that the drift requirements for the actual on-road test are relevant; it is permissible to zero the analyzer prior to verifying the span drift; the drift-related uncertainty is analyzer dependent but may amount to 4% uncertainty

u values: small and potentially negligible

Component mass emissions [g/s]: 9% overall uncertainty
- Disregarding errors from misalignment of signals

Vehicle speed [km/h]: 4%

Instantaneous distance-specific emissions [g/km]: 10% overall uncertainty
- Disregarding errors from misalignment of signals and analyzer drift

Measurement uncertainty lab vs. PEMS (in the laboratory)

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Bag measurement

$$E = \frac{V_{mix} * Q_i * k_h * C_i * 10^{-6}}{d}$$

Bag component concentration: 2%
Density of component: negligible
Volume diluted exhaust gas: 0.5%
Humidity correction factor (NOx): 2%
Test distance: 1%
Compound uncertainty: 3%

PEMS

$$E = \frac{\sum \boldsymbol{c} * \boldsymbol{q} * \boldsymbol{u}}{\boldsymbol{d}}$$

Instantaneous component concentration: 8%
Instantaneous exhaust flow rate:4%
u-value: negligible
Test distance: 4%
Compound uncertainty: 10%

Additional uncertainty PEMS testing: ≈ 7%

Additional measurement uncertainty PEMS

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- Time alignment
- Analyzer drift during a test
- Water condensation in exhaust line (?)

Time alignment

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Appendix 4; Point 3 – Time correction of parameters

Analyzers

- The recorded traces of all component concentrations shall be time corrected by reverse shifting according to the transformation times of the respective analyzers

EFM

- The exhaust mass flow rate measured with an exhaust flow meter shall be time corrected by reverse shifting according to the transformation time of the exhaust mass flow meter

Speed

- Vehicle speed shall be time aligned with the exhaust mass flow rate by means of cross-correlation between the exhaust mass flow rate and the product of vehicle velocity and positive acceleration
- **Reference point: Exhaust outlet (?)**

Time alignment

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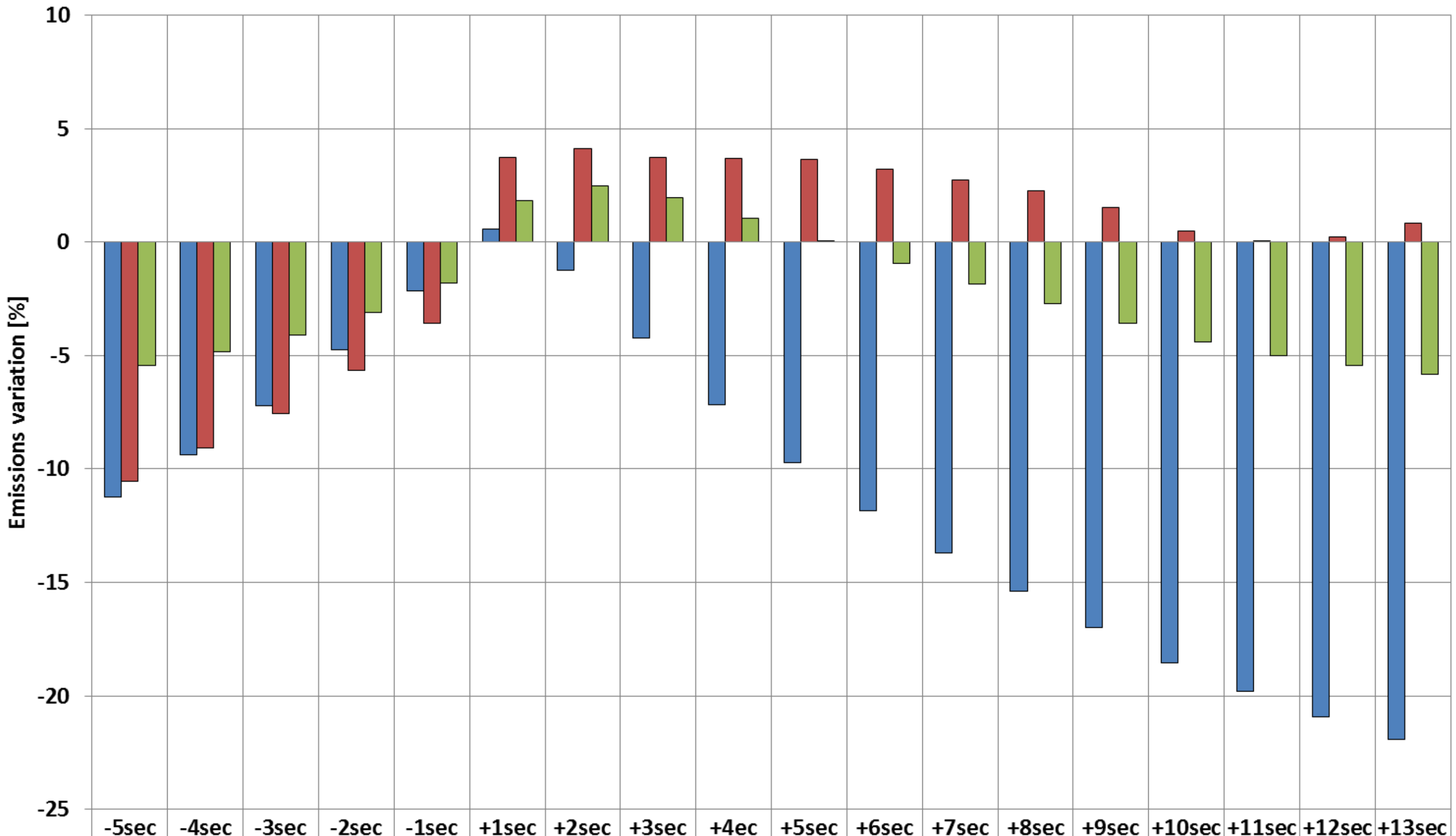
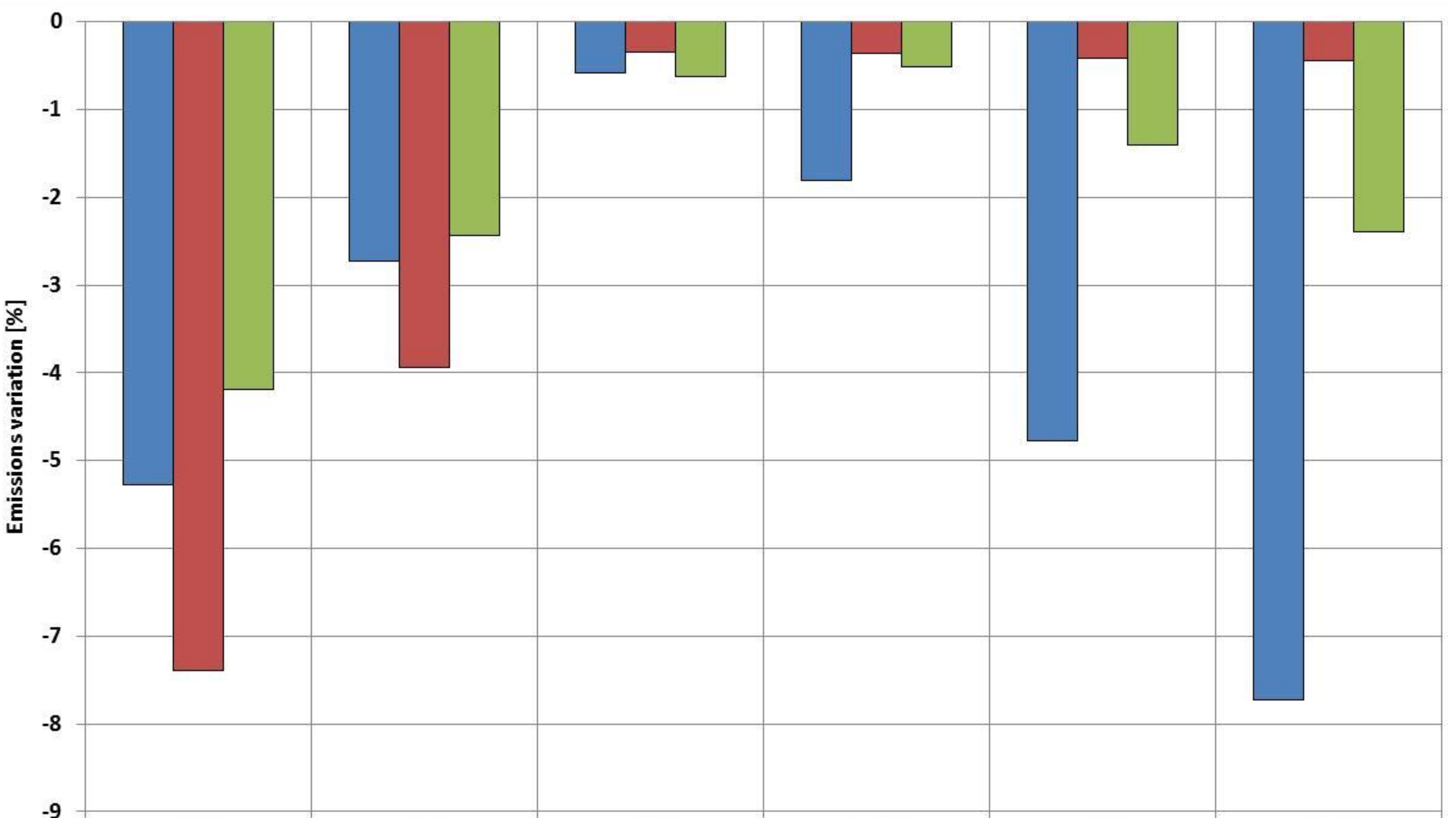


	-5sec	-4sec	-3sec	-2sec	-1sec	+1sec	+2sec	+3sec	+4ec	+5sec	+6sec	+7sec	+8sec	+9sec	+10sec	+11sec	+12sec	+13sec
NOx	-11.25	-9.35	-7.20	-4.73	-2.15	0.58	-1.24	-4.22	-7.19	-9.71	-11.84	-13.72	-15.40	-17.00	-18.53	-19.80	-20.93	-21.94
CO	-10.55	-9.08	-7.57	-5.65	-3.59	3.74	4.10	3.73	3.68	3.64	3.22	2.72	2.28	1.53	0.48	0.03	0.24	0.82
CO2	-5.42	-4.85	-4.10	-3.11	-1.81	1.84	2.49	1.96	1.04	0.04	-0.94	-1.85	-2.71	-3.57	-4.39	-4.99	-5.42	-5.82

- **Misalignment of >1-2s is unlikely**
- **Resulting uncertainty likely to be <3-5%**

Time alignment



	-3sec	-2sec	-1sec	+1sec	+2sec	+3sec
NOx	-5.28	-2.72	-0.58	-1.81	-4.77	-7.72
CO	-7.39	-3.94	-0.35	-0.36	-0.41	-0.45
CO2	-4.19	-2.43	-0.63	-0.51	-1.41	-2.39

- **Misalignment of >1-2s is unlikely**
- **Resulting uncertainty likely to be <3-5%**

Analyzer drift over a test

Pollutant	Zero response drift	Span response drift [(1)]
CO_2	≤2000 ppm per test	≤2% of reading or ≤2000 ppm per test, whichever is larger
CO	≤75 ppm per test	≤2% of reading or ≤75 ppm, per test, whichever is larger
NO_2	≤5 ppm per test	≤2% of reading or ≤5 ppm per test, whichever is larger
NO/NO_X	≤5 ppm per test	≤2% or reading or ≤5 ppm per test, whichever is larger
CH_4	≤10 $ppmC_1$ per test	≤2% or reading or ≤10 $ppmC_1$ per test, whichever is larger
THC	≤10 $ppmC_1$ per test	≤2% or reading or ≤10 $ppmC_1$ per test, whichever is larger

Analyzer drift

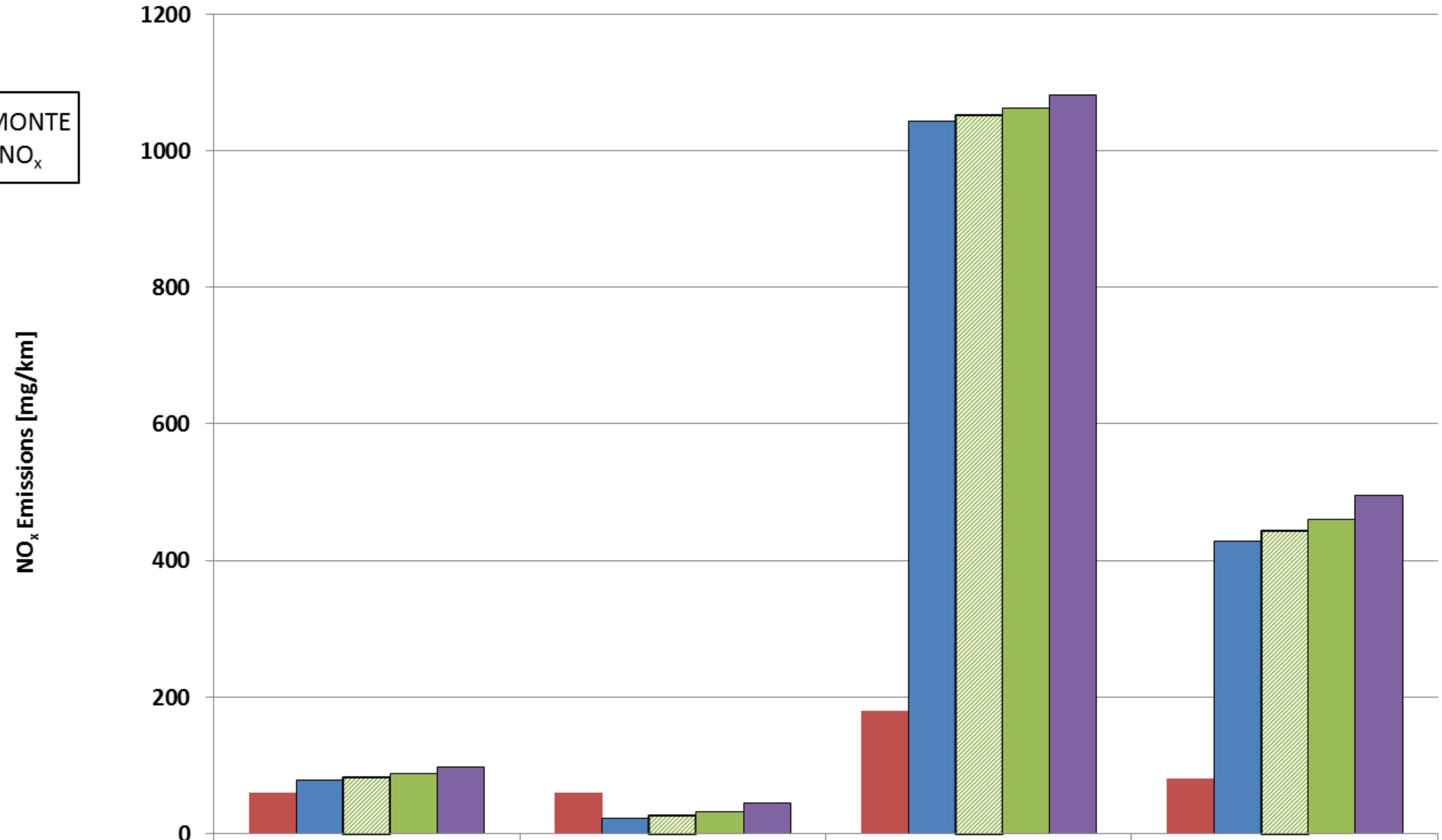
Scenario analysis

- **(a) Linear drift over a test up to 50% of the permissible limit**
- **(b) Linear drift over a test up to the permissible limit**
- **(c) Instantaneous drift at test start up to the permissible limit**

- **Drift can occur in both positive and negative directions**
- **Scenario (a) may represent worst case analyzer drift**

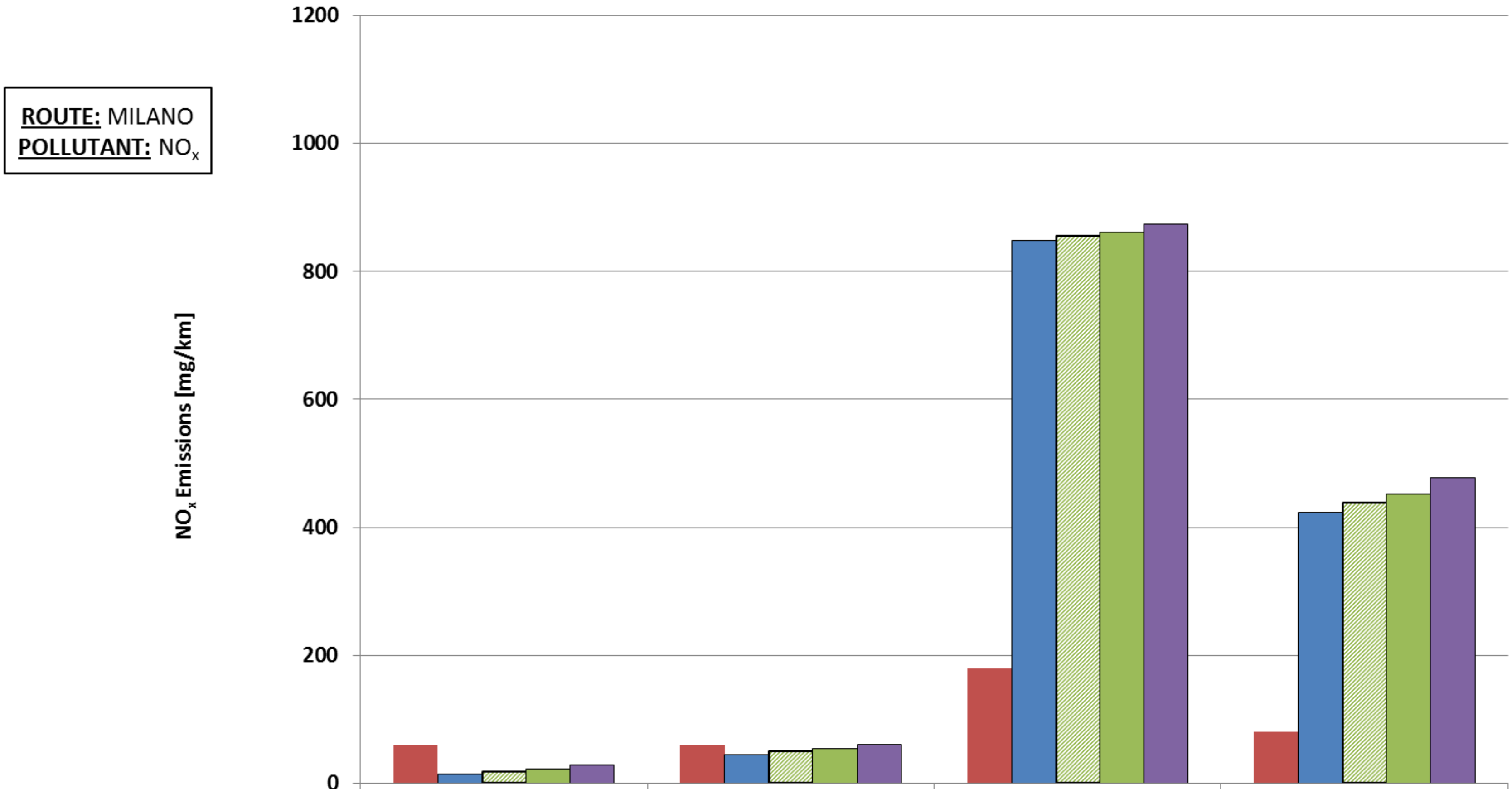
Analyzer drift

ROUTE: SACROMONTE
POLLUTANT: NO_x



	1.2l_AT_GASOLINE	2.0l_AT_GASOLINE	1.4l_MT_DIESEL	3.0l_AT_DIESEL
EMISSIONS LIMITS [mg/km]	60.0	60.0	180.0	80.0
NO DRIFT [mg/km]	77.8	22.1	1043.4	428.1
DRIFT LINEAR at 50% permissible	82.8	27.0	1053.0	443.7
DRIFT LINEAR [mg/km]	87.8	32.0	1062.5	459.3
DRIFT STEP [mg/km]	97.3	44.0	1081.7	494.6

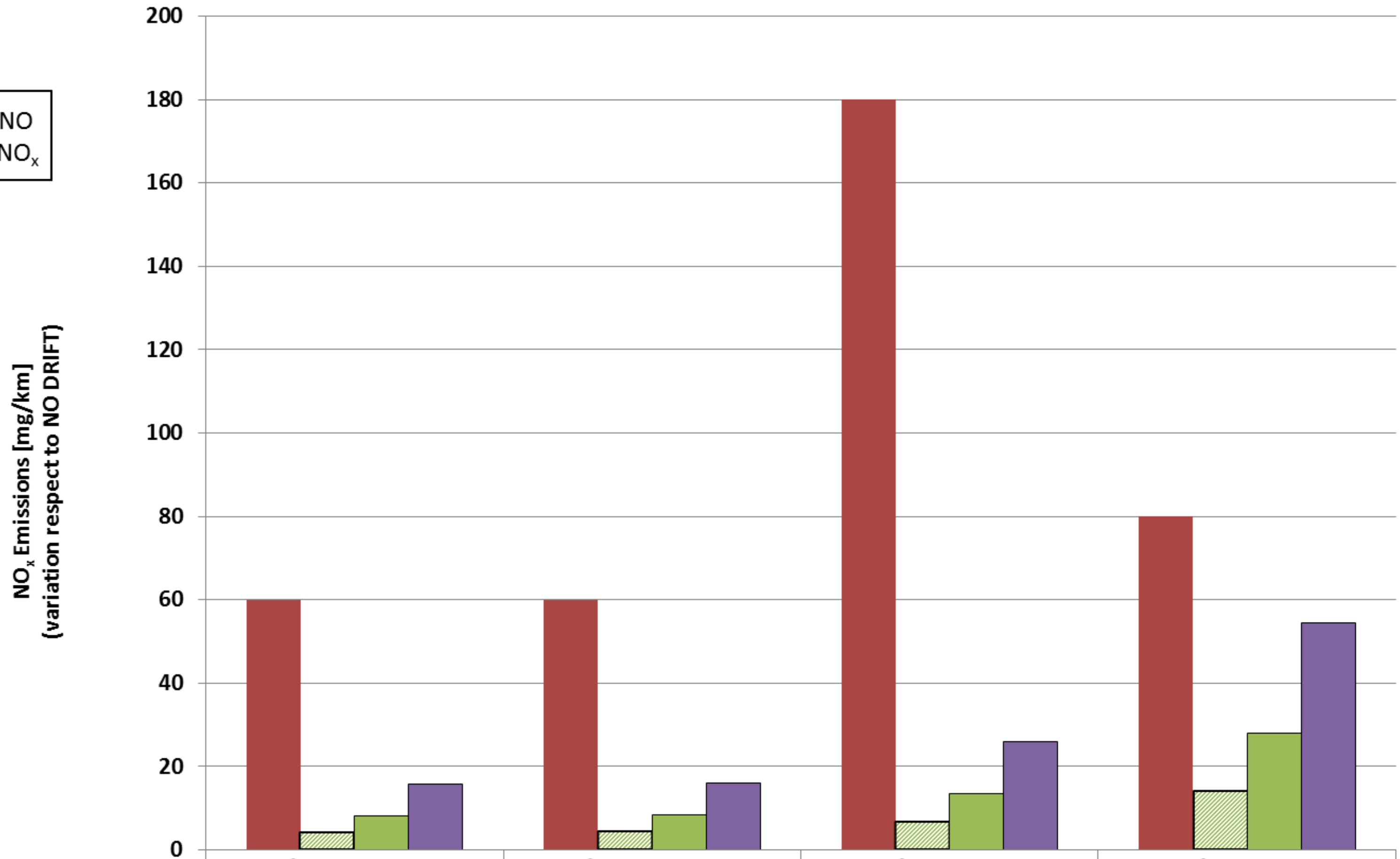
Analyzer drift



	1.2l_AT_GASOLINE	2.0l_AT_GASOLINE	1.4l_MT_DIESEL	3.0l_AT_DIESEL
EMISSIONS LIMITS [mg/km]	60.0	60.0	180.0	80.0
NO DRIFT [mg/km]	13.6	45.4	848.3	423.8
DRIFT LINEAR at 50% permissible	17.6	49.6	855.0	437.8
DRIFT LINEAR [mg/km]	21.7	53.8	861.7	451.8
DRIFT STEP [mg/km]	29.5	61.4	874.3	478.1

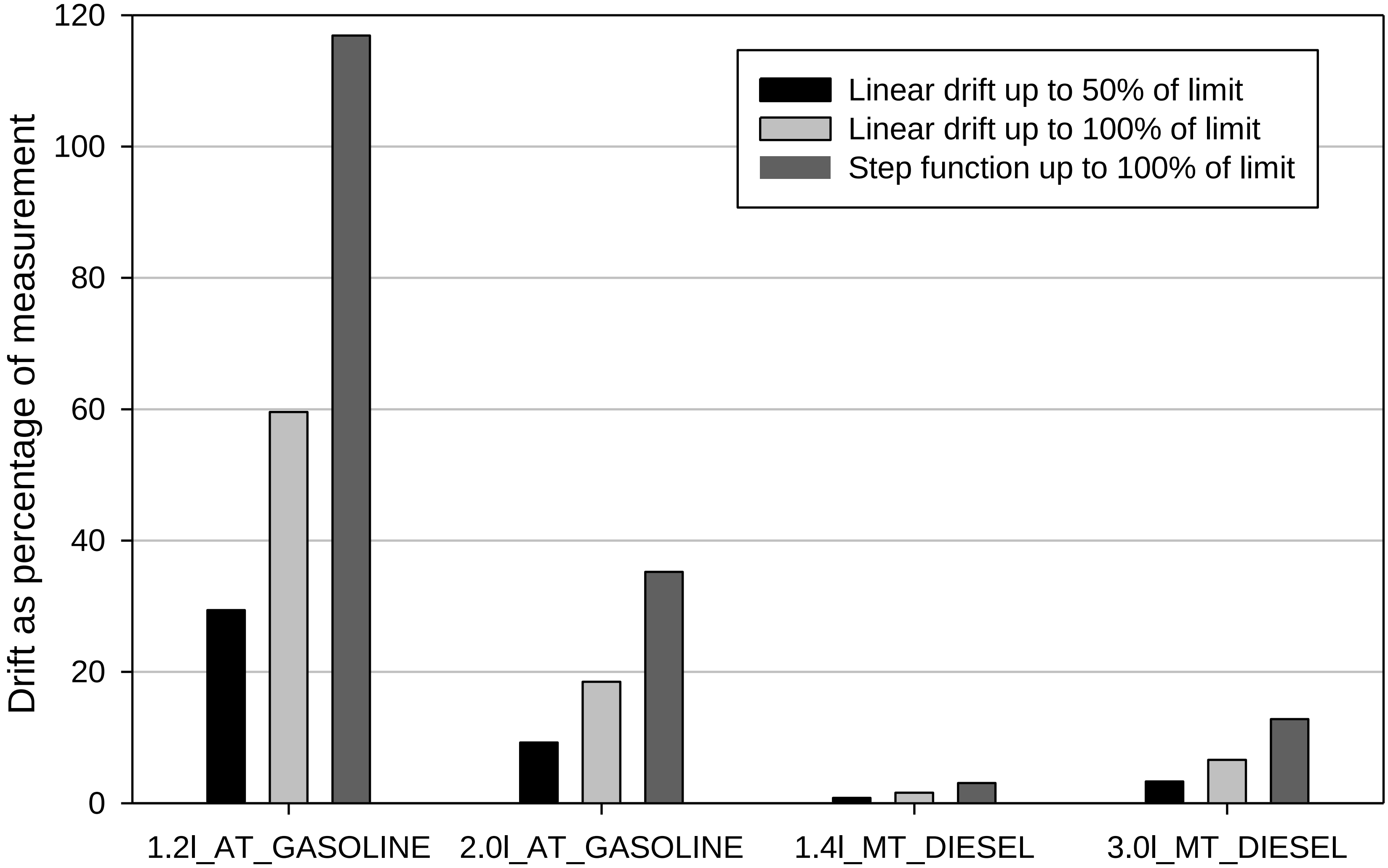
Analyzer drift

ROUTE: MILANO
POLLUTANT: NO_x



	1.2l_AT_GASOLINE	2.0l_AT_GASOLINE	1.4l_MT_DIESEL	3.0l_AT_DIESEL
EMISSIONS LIMITS [mg/km]	60.0	60.0	180.0	80.0
DRIFT LINEAR at 50% permissible	4.0	4.2	6.7	14.0
DRIFT LINEAR [mg/km]	8.1	8.5	13.4	28.0
DRIFT STEP [mg/km]	15.8	16.0	26.0	54.4

Analyzer drift



Conclusions

- PEMS may introduce an additional uncertainty compared to lab measurements of **7% (at Euro 6: 6 mg NOx/km)**
- **In addition:**
  - misalignment of signals may add **<3% uncertainty (at Euro 6: 2-3mg NOx/km)**
  - Analyzer drift over an on-road test may add **<20% (at Euro 6: 5-15 mg NOx/km)**

Additional PEMS measurement uncertainty:

≤30% (≤25 mg NOx/km)

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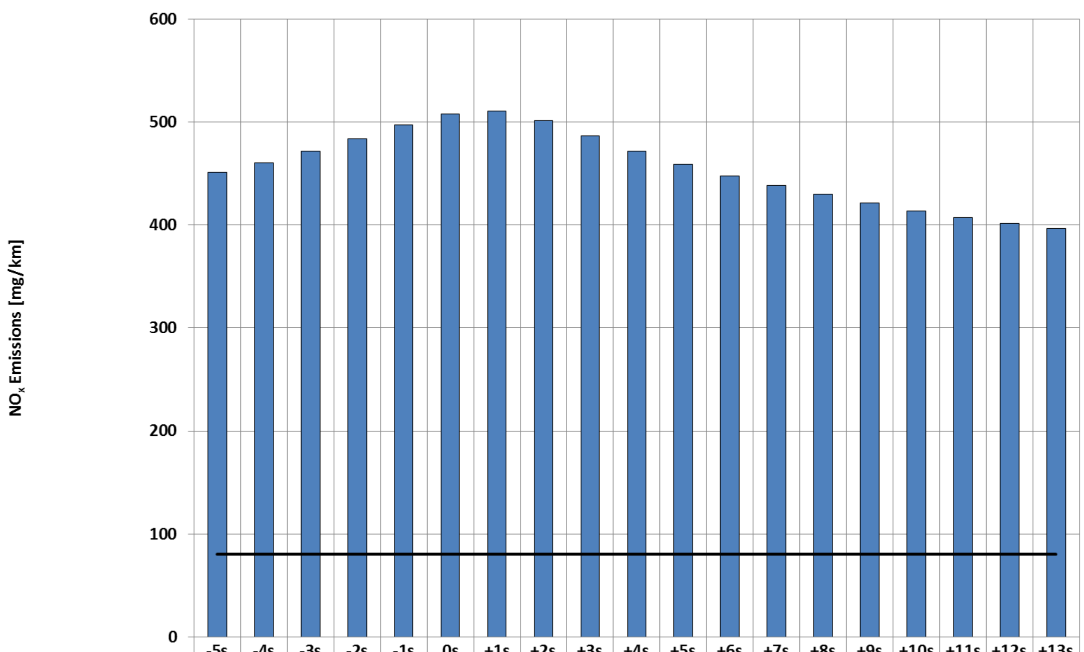
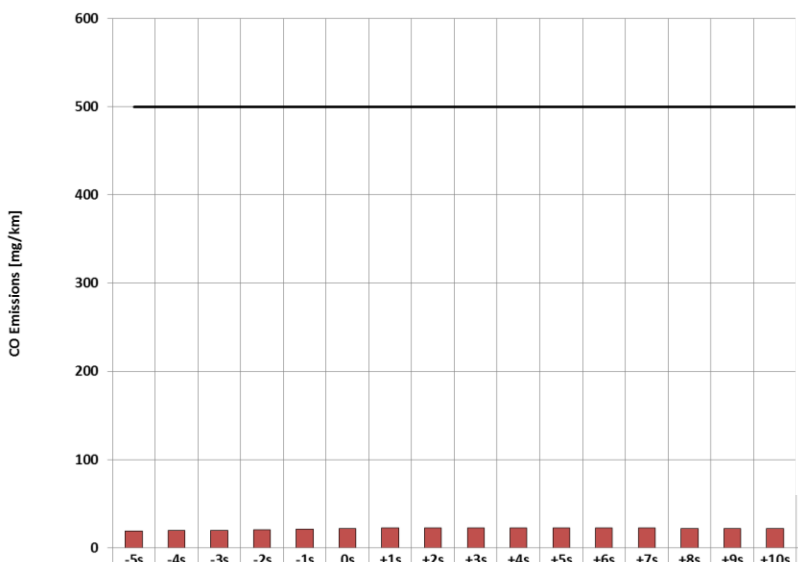
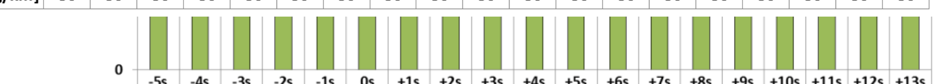
2.0l DIESEL EU6
TIME ALIGNMENT



	-5s	-4s	-3s	-2s	-1s	0s	+1s	+2s	+3s	+4s	+5s	+6s	+7s	+8s	+9s	+10s	+11s	+12s	+13s
NOx	451.0	460.6	471.5	484.1	497.2	508.1	511.1	501.8	486.7	471.6	458.8	447.9	438.4	429.8	421.7	414.0	407.5	401.7	396.6
EU6 Limit [mg/km]	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80



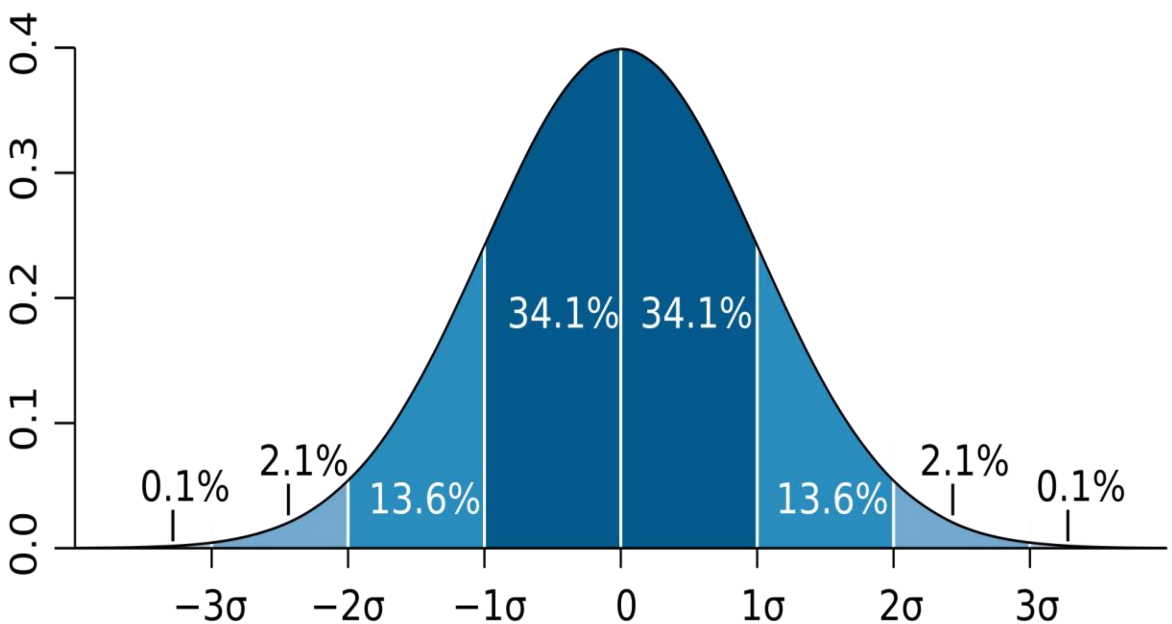
	-5s	-4s	-3s	-2s	-1s	0s	+1s	+2s	+3s	+4s	+5s	+6s	+7s	+8s	+9s	+10s	+11s	+12s	+13s
CO	19.33	19.65	19.98	20.39	20.84	21.61	22.42	22.50	22.42	22.41	22.40	22.31	22.20	22.11	21.94	21.72	21.62	21.67	21.79
EU6 Limits	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500



	-5s	-4s	-3s	-2s	-1s	0s	+1s	+2s	+3s	+4s	+5s	+6s	+7s	+8s	+9s	+10s	+11s	+12s	+13s
CO2	145.0	145.9	147.0	148.5	150.5	153.3	156.1	157.1	156.3	154.9	153.4	151.9	150.5	149.1	147.8	146.6	145.6	145.0	144.4
Fleet average	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130

Principle considerations

- Random errors scatter around the actual value
- Systematic errors deviate in one direction from the actual value
- Error intervals relate to a probability that a measured value remain within a certain margin around the actual value
- RDE performance standards for PEMS are binding – error within 3σ



Source: Wikipedia (2015)