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A miniature Portable Emissions Measurement System (PEMS) for real-driving monitoring of motorcycles

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Tables

Table S1. Summary of laboratory and Mini-PEMS instrumentation, see main article for details.

Compound/ Parameter	Laboratory	Mini-PEMS
CO_2 CO	NDIR	NDIR
THC	FID	NDIR
NO, NO_2	CLD	ECC
Exhaust flow	Calculated	Calculated
RPM	ECU/electric	Optical/electric
MAP	Not available	Piezo-resistive
GPS	NA	5Hz
PM	NA	Forward scattering
PN	PMP	Ionization chamber
Exhaust T	Thermocouples	Thermocouples

Table S2. EU emission limits for the 2-wheelers under study. Limit values for vehicle 2 and 3 refer to motorcycles with maximum rated speed < 130 km/h. The new WMTC driving cycle was used instead of the type-approval driving cycle for motorcycles, see main article for details.

Vehicle	Vehicle type	Emission standard	HC [g/km]	HC+NOx [g/km]	CO [g/km]	NOx [g/km]	Type-approval test cycle
1	Moped	Euro 2	--	1.2	1	--	R47-Ph2
2-3	Motorcycle	Euro 3	0.3	--	2	0.15	R40-EUDC (optional WMTC)

Table S3. Coefficient of determination relating Mini-PEMS and bench instrumentation for exhaust concentrations of pollutants and exhaust flow (speed density method against CO_2 tracer method). Notes: [(1)]Tests performed with Mini-PEMS No. 2.

Test	Vehicle	Cycle	R^2					
			HC	CO	NOx	CO_2	O_2	Exhaust flow
1	1	R47	0.740	0.552	0.745	0.661	N/A	0.64
2	1	R47	0.614	0.392	0.857	0.682	N/A	0.71
3	1	WOT	0.788	0.950	0.762	0.873	N/A	0.74
4	1	WOT	0.399	0.872	0.724	0.813	N/A	0.75
5	2	WMTC	0.885	0.913	0.855	0.883	0.937	0.63
6	2	WMTC	0.963	0.938	0.834	0.819	0.880	0.60
7	2	WMTC	0.761	0.790	0.863	0.868	0.933	0.63
5 (1)	2	WMTC	0.882	0.912	0.897	0.868	0.892	NA
6 (1)	2	WMTC	0.939	0.736	0.649	0.405	0.649	NA
7 (1)	2	WMTC	NA	NA	NA	NA	NA	NA
8	3	WMTC	NA	0.962	0.866	0.861	0.904	0.61

5

Table S4. Driving cycle phase dependant deviations between raw exhaust concentrations ([ppm]) measured by the Mini-PEMS and bench instrumentation. Dev = deviation, MAPD = mean absolute percentage deviation, min/max = minimum/maximum deviations. Notes: [(1)] Tests performed with the additional Mini-PEMS No. 2. Dev = deviation, MAPD = mean absolute percentage deviation, min/max = minimum/maximum deviations.

Test	Vehicle	Cycle	Start	HC Dev		CO Dev		NOx Dev		CO2 Dev	
				Phase 1 [%]	Phase 2 [%]	Phase 1 [%]	Phase 2 [%]	Phase 1 [%]	Phase 2 [%]	Phase 1 [%]	Phase 2 [%]
1	1	R47	Cold	-30	36	-6	10	6	47	4	6
2	1	R47	Hot	-23	30	4	22	-2	-8	2	0
MAPD	1	R47	-	27	33	5	16	4	28	3	3
5	2	WMTC	Cold	-6	19	15	7	25	17	-1	0
6	2	WMTC	Cold	-13	49	11	2	9	10	0	0
7	2	WMTC	Hot	-3	-14	7	4	8	9	-1	0
MAPD	2	WMTC	-	8	27	11	4	14	12	1	0
8	3	WMTC	Cold	-28	91	17	10	37	13	-1	0
MAPD	All	All	-	**17**	**40**	**10**	**9**	**14**	**17**	**2**	**1**
Min	All	All	-	-30	-14	-6	2	-2	-8	-1	0
Max	All	All	-	-3	91	17	22	37	47	4	6
5[(1)]	2	WMTC	Cold	-9	16	6	6	12	15	-1	0
6[(1)]	2	WMTC	Cold	-35	-17	5	19	9	21	0	1
7[(1)]	2	WMTC	Hot	-16	-34	1	8	-2	12	1	-1
MAPD	2	WMTC	-	20	22	4	11	8	16	1	1

Table S5. Comparison of emissions factors measured with the standard test cell instrumentation (Bench) and the Mini-PEMS during legislative test cycles (WMTC and R47) on the roller bench. Constant volumetric efficiency was assumed; see text for details. Notes: [(1)] Tests performed with the additional Mini-PEMS No. 2. Dev = deviation, MAPD = mean absolute percentage deviation, min/max = minimum/maximum deviations.

Test	Vehicle	Cycle	Start	HC			CO			NOx			CO2		
				Bench [g/km]	PEMS [g/km]	Dev [%]	Bench [g/km]	PEMS [g/km]	Dev [%]	Bench [g/km]	PEMS [g/km]	Dev [%]	Bench [g/km]	PEMS [g/km]	Dev [%]
1	1	R47	Cold	0.21	0.20	-2	2.68	2.83	6	0.14	0.15	8	65.59	70.33	7
2	1	R47	Hot	0.19	0.21	11	3.93	4.34	11	0.09	0.08	-17	59.23	61.01	3
MAPD	1	R47	-	-	-	**7**	-	-	**8**	**-**	**-**	**13**	**-**	**-**	**5**
5	2	WMTC	Cold	0.12	0.11	-5	0.81	0.84	3	0.14	0.12	-13	72.47	70.60	-3
6	2	WMTC	Cold	0.11	0.12	5	0.74	0.75	1	0.13	0.11	-18	73.77	74.43	1
7	2	WMTC	Hot	0.06	0.04	-21	0.56	0.53	-5	0.12	0.09	-21	71.86	69.77	-3
MAPD	2	WMTC	-	-	-	**10**	-	-	**3**	**-**	**-**	**17**	**-**	**-**	**2**
8	3	WMTC	Cold	0.12	0.13	4	0.90	0.89	-1	0.13	0.10	-23	57.16	54.37	-5
MAPD	All	All	-	-	-	**8**	**-**	**-**	**4**	**-**	**-**	**17**	**-**	**-**	**4**
Min	All	All	-	-	-	-21	-	-	-5	-	-	-23	-	-	-5
Max	All	All	-	-	-	11	-	-	11	-	-	8	-	-	7
5[(1)]	2	WMTC	Cold	0.12	0.12	5	0.81	0.90	11	0.14	0.13	-8	72.47	79.17	9
6[(1)]	2	WMTC	Cold	0.11	0.09	-19	0.74	0.90	20	0.13	0.13	-2	73.77	84.11	14
7[(1)]	2	WMTC	Hot	0.06	0.04	-29	0.56	0.60	6	0.12	0.10	-17	71.86	77.58	8
MAPD	2	WMTC	-	-	-	**18**	**-**	**-**	**12**	**-**	**-**	**9**	**-**	**-**	**10**

Table S6. Phase dependant deviations between emissions factors measured with the standard test cell instrumentation (bench) and the Mini-PEMS during legislative test cycles (WMTC and R47) on the roller bench. Variable volumetric efficiency was assumed; see text for details. Notes: [(1)]Tests performed with the additional Mini-PEMS No. 2. Dev = deviation, MAPD = mean absolute percentage deviation, min/max = minimum/maximum deviations.

Test	Vehicle	Cycle	Start	HC Dev		CO Dev		NOx Dev		CO2 Dev	
				Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
				[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
1	1	R47	Cold	-34	37	-17	7	-24	20	-9	5
2	1	R47	Hot	-23	34	-11	7	-22	-22	-4	-4
MAPD	1	R47	-	28	36	14	7	23	21	7	5
5	2	WMTC	Cold	-2	-1	13	15	9	-1	13	3
6	2	WMTC	Cold	0	31	19	10	-7	-2	12	10
7	2	WMTC	Hot	-4	-26	15	7	-9	-7	11	1
MAPD	2	WMTC	-	2	19	16	10	8	4	12	5
8	3	WMTC	Hot	-25	42	-4	-4	-18	-16	1	-6
MAPD	All	All	-	**15**	**29**	**13**	**8**	**15**	**12**	**8**	**5**
min	All	All	-	-34	-26	-17	-4	-24	-22	-9	-6
max	All	All	-	0	42	19	15	9	20	13	10
cold vs hot				94		-38		-22		-39	
5[(1)]	2	WMTC	Cold	-3	0	7	15	-8	-2	13	5
6[(1)]	2	WMTC	Cold	-25	-21	13	29	-8	7	12	13
7[(1)]	2	WMTC	Hot	-21	-40	3	12	-30	-9	12	2
MAPD	2	WMTC	-	16	20	7	19	15	6	12	7

Table S7. Phase dependant deviations between emissions factors measured with the standard test cell instrumentation (bench) and the Mini-PEMS during legislative test cycles (WMTC and R47) on the roller bench. Constant volumetric efficiency was assumed; see text for details. Notes: [(1)] = Tests performed with the additional Mini-PEMS No. 2. Dev = deviation, MAPD = mean absolute percentage deviation, min/max = minimum/maximum deviations.

Test	Vehicle	Cycle	Start	HC Dev		CO Dev		NOx Dev		CO2 Dev	
				Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
				[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
1	1	R47	cold	-30	46	-11	15	-20	27	-3	12
2	1	R47	hot	-17	44	-4	16	-17	-17	3	3
MAPD	1	R47		24	45	7	15	18	22	3	7
5	2	WMTC	cold	-2	-12	13	-5	2	-18	12	-10
6	2	WMTC	cold	1	13	17	-10	-12	-20	11	-4
7	2	WMTC	hot	-2	-36	16	-11	-11	-23	13	-11
MAPD	2	WMTC		2	20	15	8	9	20	12	8
8	3	WMTC	hot	-18	34	9	-8	-13	-25	10	-12
MAPD	All	All	-	**12**	**31**	**12**	**11**	**13**	**22**	**9**	**9**
min	All	All	-	-30	-36	-11	-11	-20	-25	-3	-12
max	All	All	-	1	46	17	16	2	27	13	12
cold vs hot				**163**		**-9**		**72**		**-1**	
5[(1)]	2	WMTC	Cold	9	-2	17	6	-3	-9	25	1
6[(1)]	2	WMTC	Cold	-16	-26	24	18	-3	-2	24	9
7[(1)]	2	WMTC	Hot	-10	-43	15	3	-24	-16	26	-1
MAPD	2	WMTC	-	**12**	**23**	**19**	**9**	**10**	**9**	**25**	**4**

Table S8. Non-volatile particle emissions from the full dilution tunnel (CVS) with lower size of 10 nm (CVS10). Total number of particles (including volatiles) inferred from Mini-PEMS ionization chamber measurement, and emission factors inferred from Mini-PEMS (No.1) light scattering detector.

Test	Vehicle	Cycle	CVS10	CVS23	Mini-PEMS Ioniz. chamber [#/km]	Mini-PEMS light scatter [mg/km]
1	1	R47 hot	4.02×10^{11}	9.87×10^{11}	5.50×10^{11}	0.40
2	1	R47 hot	8.43×10^{11}	2.88×10^{11}	1.46×10^{12}	0.34
3	1	WOT	8.55×10^{11}	2.15×10^{11}	1.42×10^{12}	0.36
RDE-1	1	On-road			4.37×10^{11}	0.44
RDE-2	1	On-road			3.43×10^{11}	0.35
RDE-3	1	On-road			4.20×10^{11}	0.42

Table S9. Non-volatile particle emissions from the full dilution tunnel (CVS) with lower size of 10 nm (CVS10) or 23 nm (CVS23) and total particle emissions with lower size of 6 nm (CVS_T_23) measured with an Engine Exhaust Particle Sizer (EEPS), and particulate matter (PM) mass with the filter method from the CVS. Total number of particles (including volatiles) and PM inferred from Mini-PEMS ionization chamber measurement, and PM inferred from Mini-PEMS light scattering detector. Note that the PEMS and CVS tests were conducted on different days and are not directly comparable.

Veh.	Cycle c=cold	PM [mg/km]	CVS10 [#/km]	CVS23 [#/km]	CVS_T_6 [#/km]	PEMS IC [#/km]	PEMS IC [mg/km]	PEMS LS [mg/km]
1	R47 c	1.99	2.1×10^{12}	1.1×10^{12}	3.0×10^{12}	1.5×10^{12}	0.50	0.34
2	WMTC c	1.78	8.6×10^{11}	4.7×10^{11}	1.2×10^{12}	4.8×10^{11}	0.48	0.82
3	WMTC c	0.41	1.7×10^{11}	6.4×10^{10}	2.2×10^{12}	1.1×10^{11}	0.13	0.04

IC=ionization chamber, LS=Light scattering

Figures

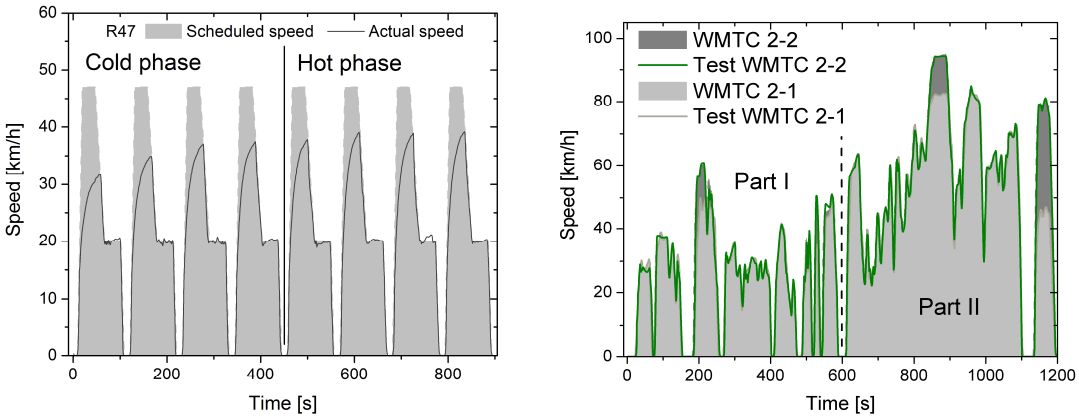


Figure S1. Legislative speed profiles (grey shaded area) and examples of actual test speed for driving cycles ECE-R47 (left panel), WMTC type 2-1 and WMTC 2-2 (right panel) run by vehicles 1, 3 and 2, respectively; see text for details.

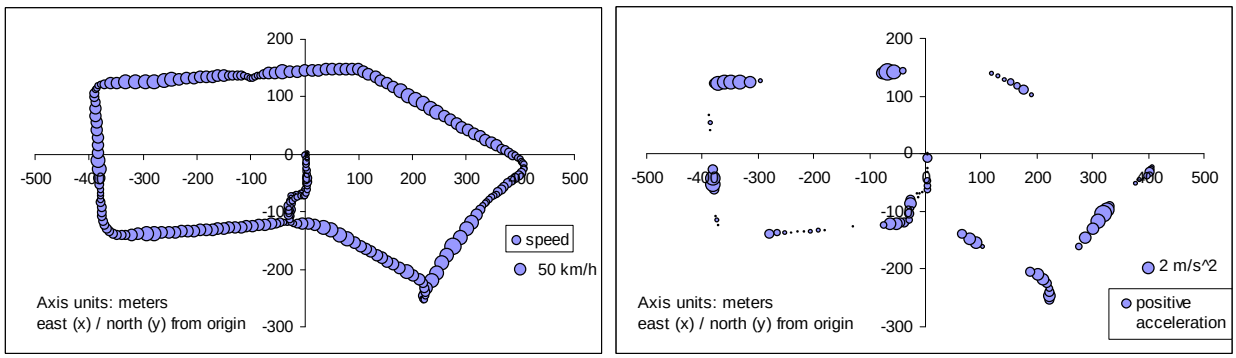


Figure S2. Top view of on-road trips geometry ([m]) with size-coded speed (left panel) and positive acceleration (right panel) for Vehicle 2. The vehicles had to pass 3 stop road-signals and 2 roundabouts.

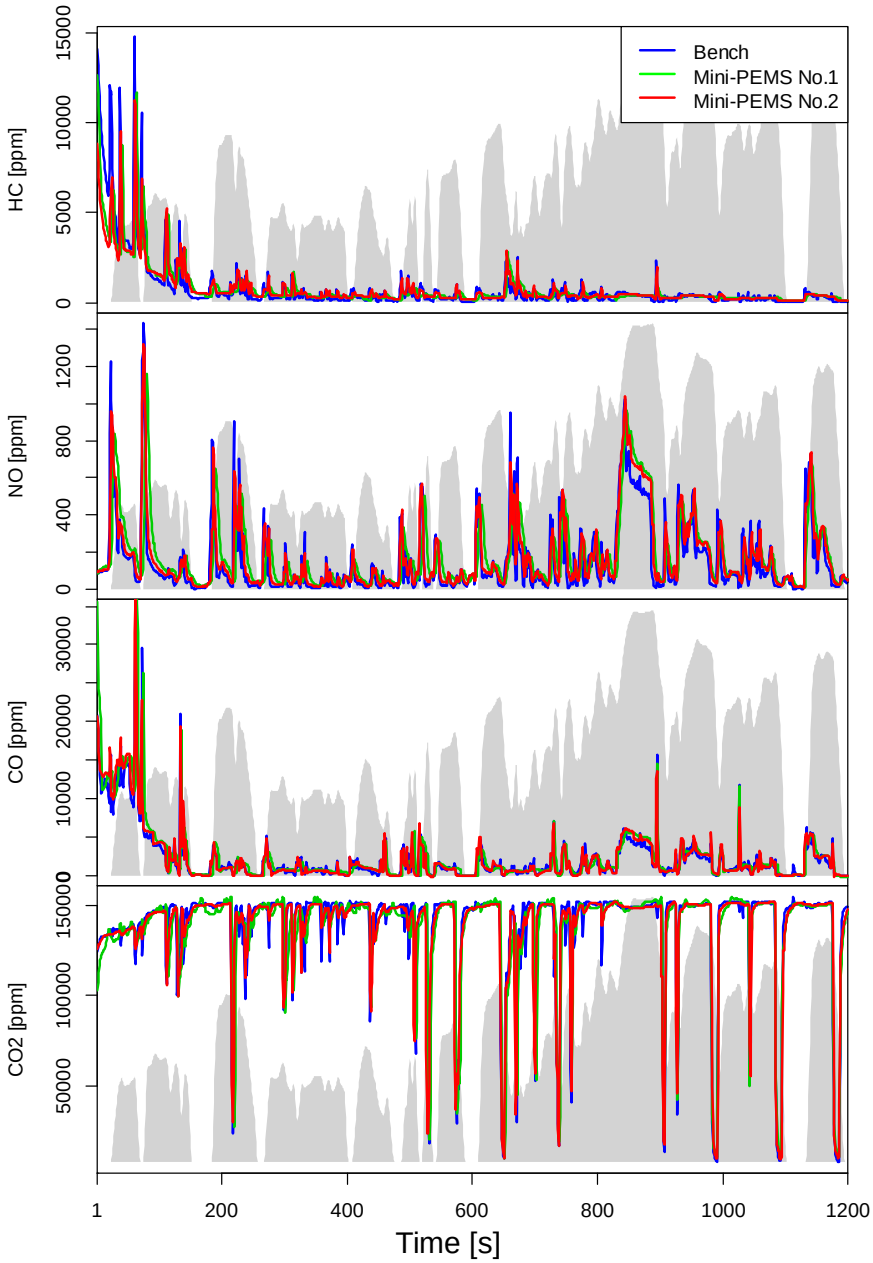


Figure S3. Raw exhaust concentrations of HC, NOx, CO and CO_2 from bench instrumentation and from the two Mini-PEMS for Vehicle 2 during a cold-start WMTC (Test 5).

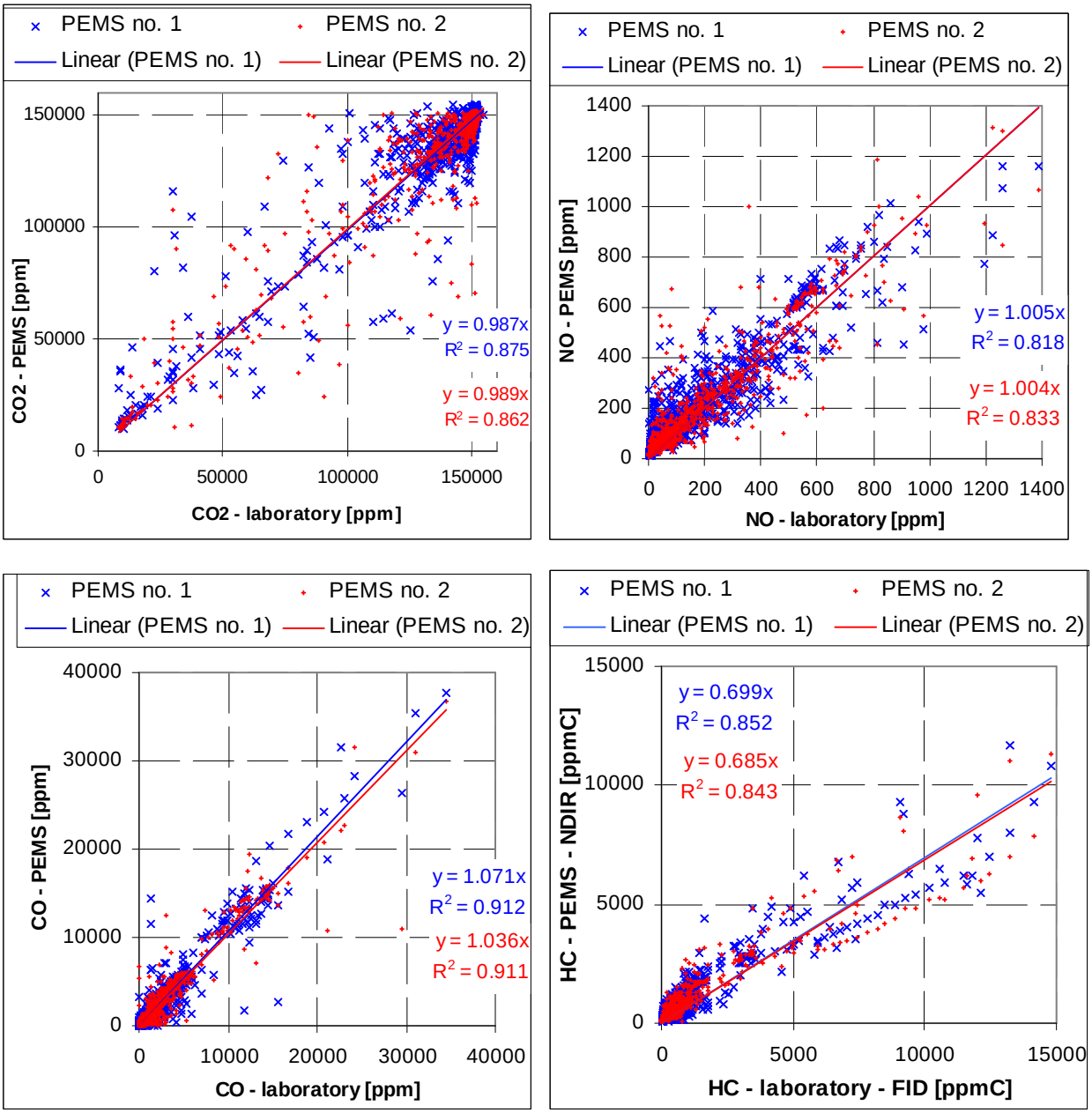


Figure S4. Comparison between pollutant concentrations measured by the two Mini-PEMS and the laboratory instrumentation for Test 5. Regression lines are shown with intercept forced through zero, yielding lower correlations compared to Table S4.

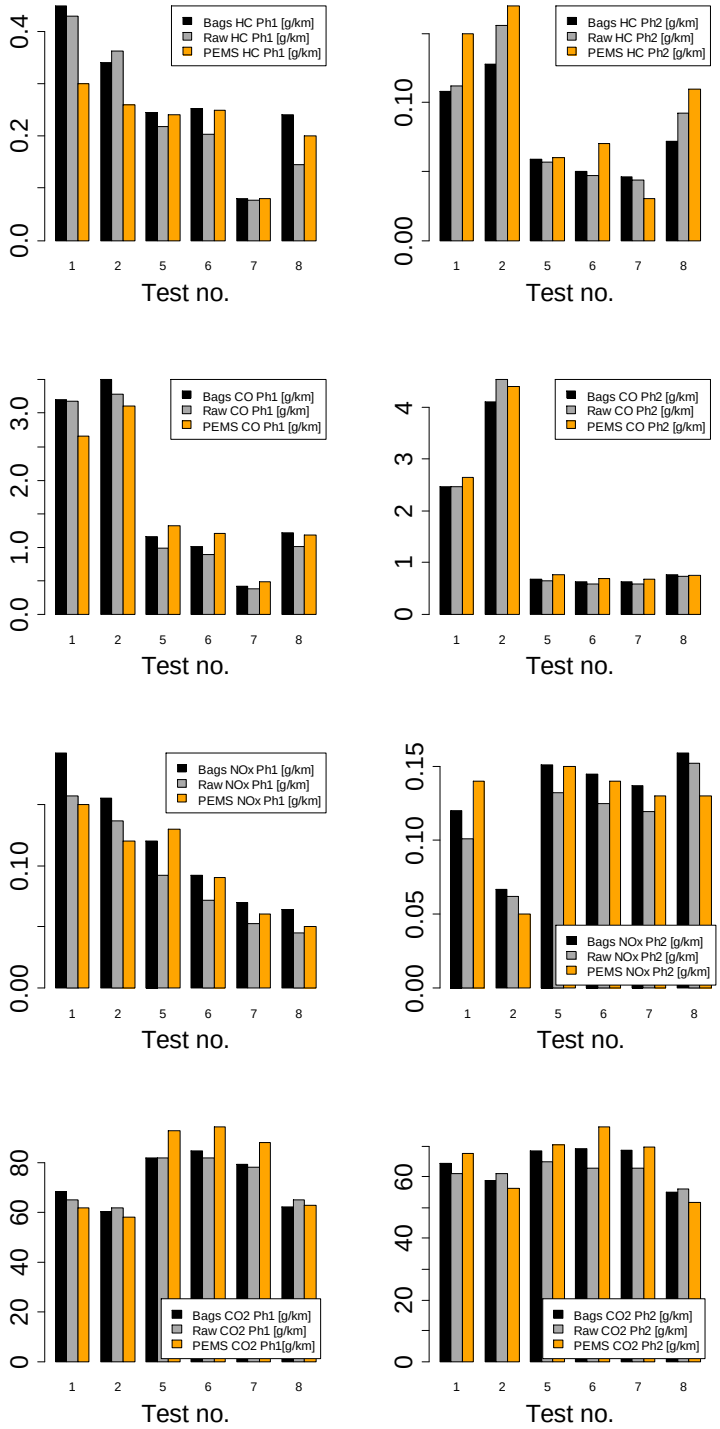


Figure S5. Emission factors from the legislative method (diluted exhaust, bag sampling), the raw exhaust with bench instrumentation, and Mini-PEMS No.1.

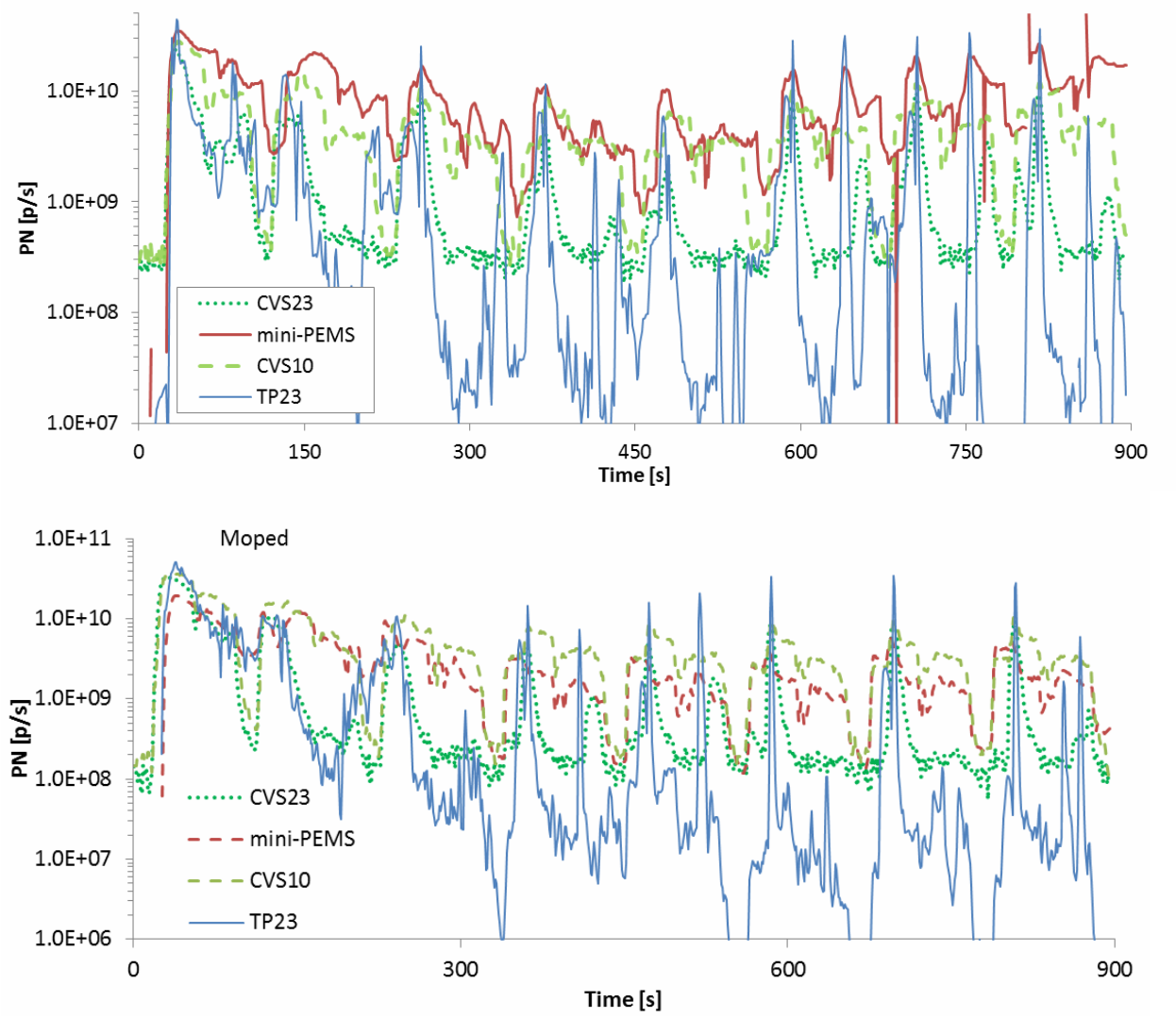


Figure S6: Comparison of particle number emission rates determined from the mini-PEMS exhaust flow and concentrations of all particles measured by the ionization chamber with the total number of non-volatile particles measured at the CVS with 10 and 23 nm cut-offs and at the tailpipe with a 23 nm cut-off. Two different R47 tests shown (summary statistics in Table S8).

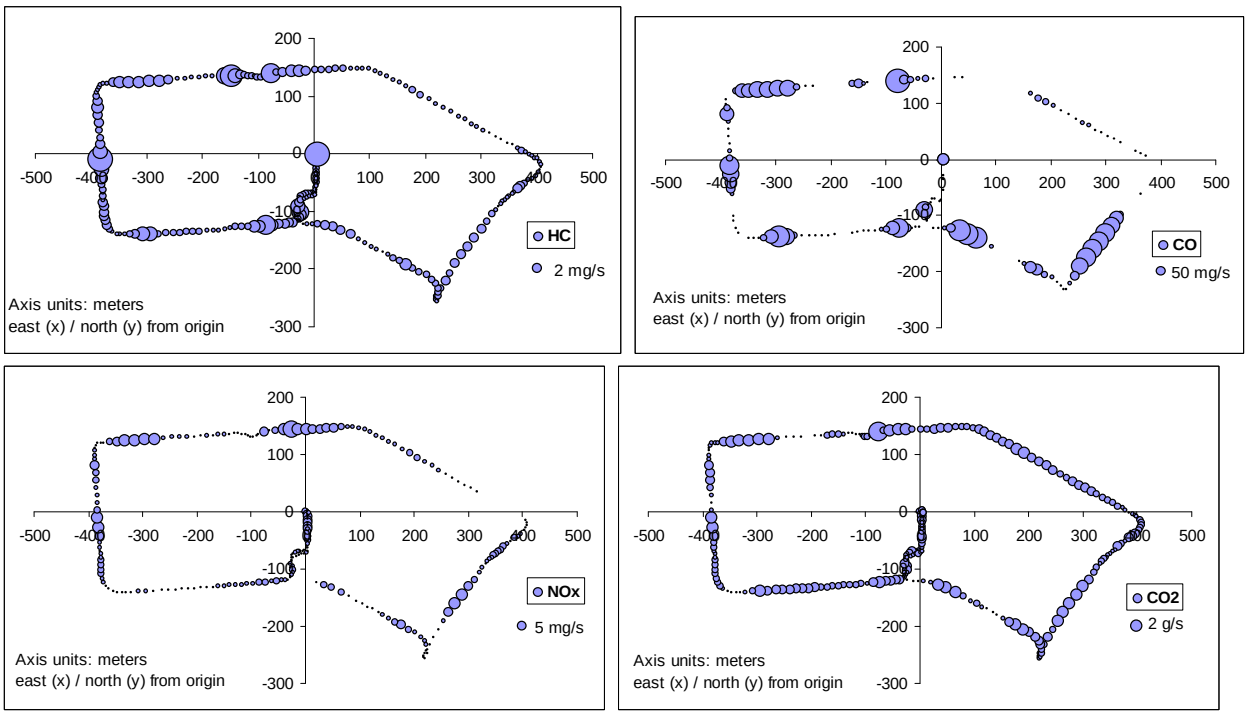
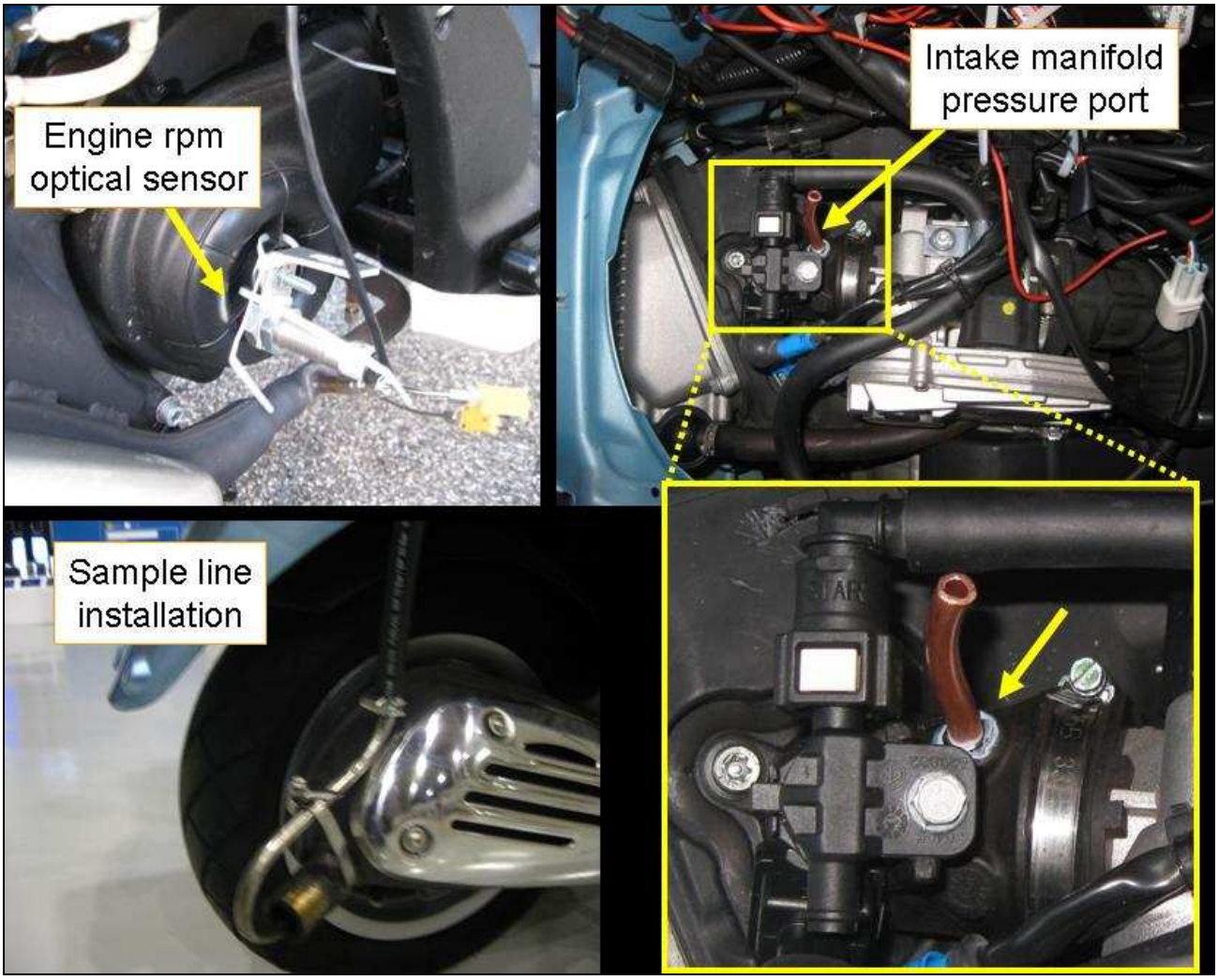


Figure S7. Top view of the on-road trip geometry with size-coded instantaneous mass emissions rates of HC, CO, NOx and CO2 averaged on three runs of Vehicle 2. See details in Chyba! Nenalezen zdroj odkazů.).

Pictures

Picture S1. Example of Mini-PEMS No. 1 installed on 2-wheelers during tests on the road (left) and during roller bench tests (right).



Picture S2. Engine speed sensor, intake manifold pressure port, exhaust sampling (bottom left), and MAP sensor inlet (bottom right).

Picture S3: Example of validation test for Mini-PEMS No.1 and No. 2. Mini-PEMS No. 1 was installed on-board of the vehicle during emission roller bench tests.