

On-road and laboratory regulated and unregulated pollutants from three different plug-in hybrid vehicles – part 1: gaseous emissions

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Supplementary Information

1. Tables

Table S1 – RDE route details for selected examples

	RDE	Motorway
Total trip duration (min)	103	117
Total trip distance (km)	91.1	187.7
Average speed (km/h)	52.8	95.6
Average temperature (°C)	21.6	30.8
Average rel. humidity (%)	72.1	34.9
Average altitude (m)	251.8	219.6
Urban distance (km)	35.5	15.0
Rural distance (km)	29.1	18.1
Motorway distance (km)	26.5	154.6

Table S2 – List of performed experiments

	Vehicle #1	Vehicle #2	Vehicle #3
<i>Laboratory tests</i>			
WLTP procedure @23°C (CD+CS)	Yes	Yes	Yes
WLTP procedure @ -10°C (CD+CS)	Yes	Yes	Yes
WLTC test @ 40°C (CS)	No	Yes	Yes
<i>On-road tests</i>			
RDE route test	CD100, CD50*, CD25, CS, BatCh	CD100, CD50, CD25, CS, BatCh	CD100, CD50, CD25, CS, BatCh

RDE route test – soak out	CD100*	No	No
Motorway route test	CS	CS (+FTIR for unregulated pollutants)	CS
<i>WLTP: Worldwide Harmonised Light-Duty Vehicles Test Procedure, CD: charge depleting, CS: charge sustaining, CDXX: charge depleting with initial SOC of high voltage battery equal to XX, BatCh: Battery charging mode, * user selectable mode equal to electric; in all other cases is the default one.</i>			

Table S3 – Tested vehicles

Vehicle ID	Vehicle #1	Vehicle #2	Vehicle #3
Fuel	Gasoline	Gasoline	Gasoline
Traction	ICE + Electric Motor	ICE + Electric Motor	ICE + Electric Motor
Injection	DI	DI	DI
Emission control system	TWC + GPF	TWC + GPF	TWC + GPF
Registration	2020	2020	2020
Mileage (km)	3092	2977	14360
Euro standard	Euro 6d-ISC	Euro 6d-TEMP-EVAP-ISC	Euro 6d-ISC
ICE size (cm ³)	1598	1499	1598
Electric range (km)	61	52	61
<i>ICE: internal combustion engine, DI: direct injection, TWC: three way catalyst, GPF: gasoline particulate filter</i>			

Table S4 – Data summary

VEHICLE #1 – On-road tests								
Route	Conditions @ test start	Average T _{ambient} (°C)	Mode of operation	SOC @ start	User selectable mode	NOx (mg/km)	CO (mg/km)	CO ₂ (mg/km)
RDE	Cold	14	CS	0%	Default	15	219	170
RDE	Cold	11	CD	100%	Default	7	172	96
Motorway	Hot	14	CS	0%	Default	16	1173	190
RDE	Cold	8	CD	100%	Default	10	170	93
RDE	Cold	10	CD	100%	Electric	18	242	156
RDE	Cold	15	CD	50%	Electric	19	244	147
RDE	Cold	14	CD	100%	Default	21	285	151
RDE	Cold	11	CD	25%	Default	17	287	159
RDE	Cold	5	CD	100%	Default	16	200	101
RDE	Hot	10	CS	0%	Battery charging	16	603	315
RDE (soak out)	Cold	3	CD	100%	Electric	9	287	114
RDE	Hot	10	CS	0%	Battery charging	17	515	308
RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery								

VEHICLE #2 – On-road tests

Route	Conditions @ test start	Average T _{ambient} (°C)	Mode of operation	SOC @ start	User selectable mode	NOx (mg/km)	CO (mg/km)	CO ₂ (mg/km)
RDE	Cold	27	CD	100%	Default	12	88	107
RDE	Hot	31	CD	25%	Default	23	174	179
RDE	Cold	25	CD	100%	Default	14	247	104
Motorway	Hot	31	CS	0%	Default	17	1091	209
RDE	Hot	31	CS	0%	Battery charging	32	365	232
RDE	Cold	32	CD	50%	Default	19	79	139
RDE	Cold	26	CS	0%	Default	28	202	175
RDE	Cold	28	CS	0%	Default	18	167	172
RDE	Hot	33	CS	0%	Battery charging	26	310	256
RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery								

VEHICLE #3 – On-road tests

Route	Conditions @ test start	Average T _{ambient} (°C)	Mode of operation	SOC @ start	User selectable mode	NOx (mg/km)	CO (mg/km)	CO ₂ (mg/km)
ESP	Cold	20	CS	0%	Default	15	349	205
ESP	Cold	20	CS	0%	Default	15	312	208
ESP	Hot	28	CS	0%	Battery charging	13	676	347
ESP	Cold	22	CD	100%	Default	8	150	94
ESP	Cold	22	CD	100%	Default	11	210	78
ESP	Hot	25	CD	25%	Default	13	281	156
ESP	Hot	27	CD	50%	Default	9	299	134
Motorway	Hot	27	CS	0%	Default	23	2383	212
ESP	Cold	22	CS	0%	Default	15	262	176
ESP	Hot	24	CS	0%	Battery charging	13	465	297
RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery								

VEHICLE #1 – Laboratory tests

Test type	NOx (mg/km)	CO (mg/km)	THC (mg/km)	NMHC (mg/km)	CH ₄ (mg/km)	NH ₃ (mg/km)	<C ₅ (mg/km)	C ₅ (mg/km)	AHC (mg/km)
Tests @ 23°C									
WLTC CD3	13	178	18	4	1	2	1	4	2
WLTC CD4	10	221	10	0	n/a	n/a	n/a	n/a	n/a
WLTC CS	25	332	8	7	1	4	1	5	2
Weighted	5	67	4	1	n/a	n/a	n/a	n/a	n/a
Tests @ -10°C									
WLTC CD1	15	440	60	42	4	4	6	19	10
WLTC CS	12	740	54	48	5	15	8	24	12

RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery, THC: total hydrocarbons, NMHC: non-methane hydrocarbons, <C₅: hydrocarbons with less than 5 carbon atoms, C₅: hydrocarbons with 5 carbon atoms, AHC: aromatic hydrocarbons.

VEHICLE #2 – Laboratory tests

Test type	NOx (mg/km)	CO (mg/km)	THC (mg/km)	NMHC (mg/km)	CH ₄ (mg/km)	NH ₃ (mg/km)	<C ₅ (mg/km)	C ₅ (mg/km)	AHC (mg/km)
Tests @ 23°C									
WLTC CD3	15	380	13	12	1	3	1	2	2
WLTC CD4	13	284	5	4	n/a	n/a	n/a	n/a	n/a
WLTC CS	11	333	12	10	1	6	1	2	1
Weighted	3	95	3	3	n/a	n/a	n/a	n/a	n/a
Tests @ -10°C									
WLTC CD1	75	431	57	41	3	12	5	13	3
WLTC CS	82	746	73	67	5	21	11	19	15
Tests @ 40°C									
WLTC CS	84	589	19	17	2	4	2	2	4

RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery, THC: total hydrocarbons, NMHC: non-methane hydrocarbons, <C₅: hydrocarbons with less than 5 carbon atoms, C₅: hydrocarbons with 5 carbon atoms, AHC: aromatic hydrocarbons.

VEHICLE #3 – Laboratory tests

Test type	NOx (mg/km)	CO (mg/km)	THC (mg/km)	NMHC (mg/km)	CH ₄ (mg/km)	NH ₃ (mg/km)	<C ₅ (mg/km)	C ₅ (mg/km)	AHC (mg/km)
Tests @ 23°C									
WLTC CD3	16	132	9	8	1	1	1	0	2
WLTC CD4	16	161	1	1	n/a	n/a	n/a	n/a	n/a
WLTC CS	21	274	9	7	1	2	1	2	2
Weighted	5	59	3	2	n/a	n/a	n/a	n/a	n/a
Tests @ -10°C									
WLTC CD1	5	380	63	58	4	1	7	20	13
WLTC CS	18	880	59	53	6	23	8	24	16
Tests @ 40°C									
WLTC CS	14	433	8	6	1	4	1	2	2

RDE, motorway as defined in experimental section and Table S1, CD: charge depleting, CS: charge sustaining, SOC: state of charge of HV battery, THC: total hydrocarbons, NMHC: non-methane hydrocarbons, <C₅: hydrocarbons with less than 5 carbon atoms, C₅: hydrocarbons with 5 carbon atoms, AHC: aromatic hydrocarbons.

2. Figures

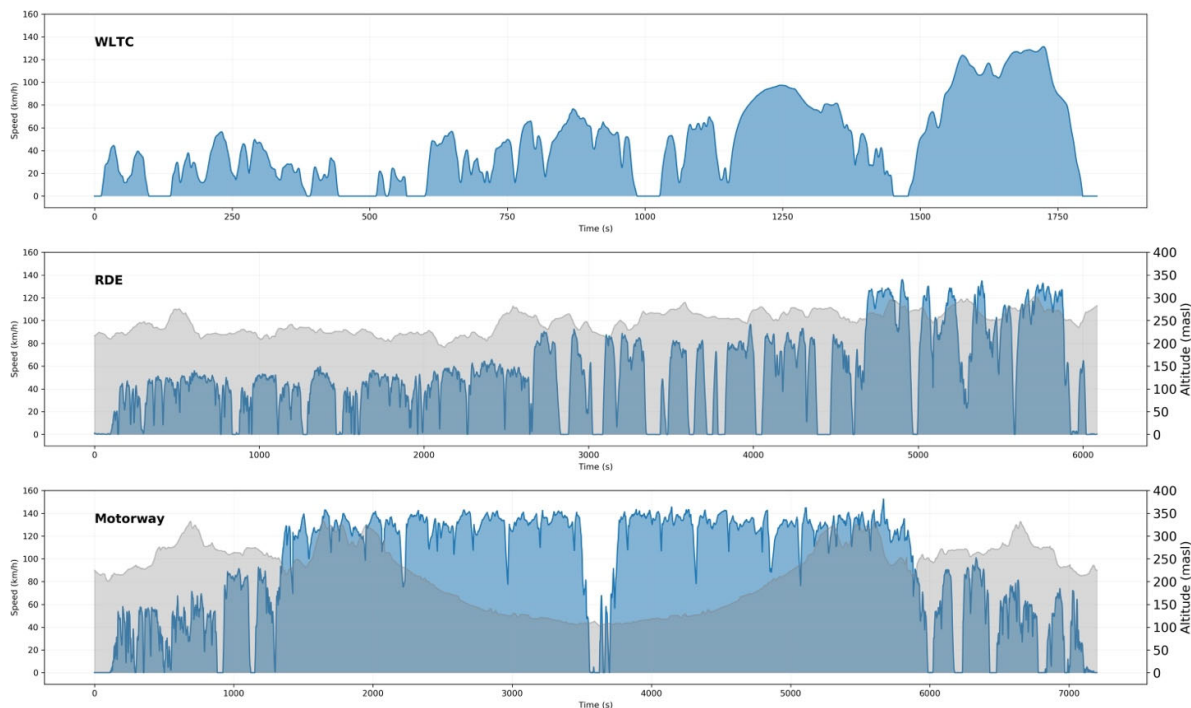


Figure S1 – Speed profiles for laboratory cycles. Examples of speed and altitude profiles for on-road routes

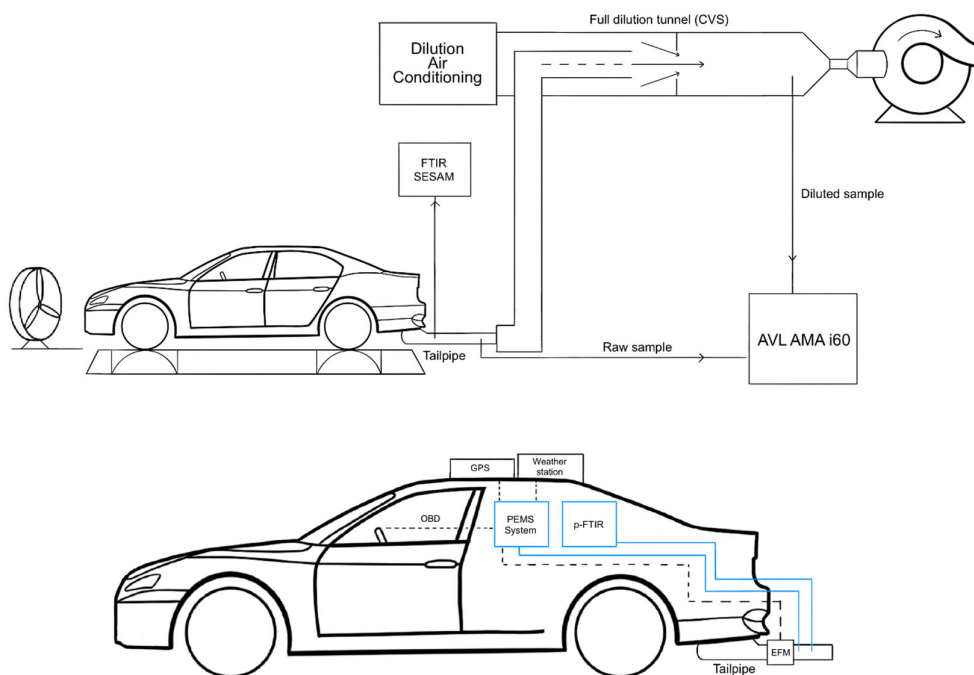


Figure S2 – Experimental set-up used during the tests performed at VELA 8 laboratory (top) and on-road (bottom)

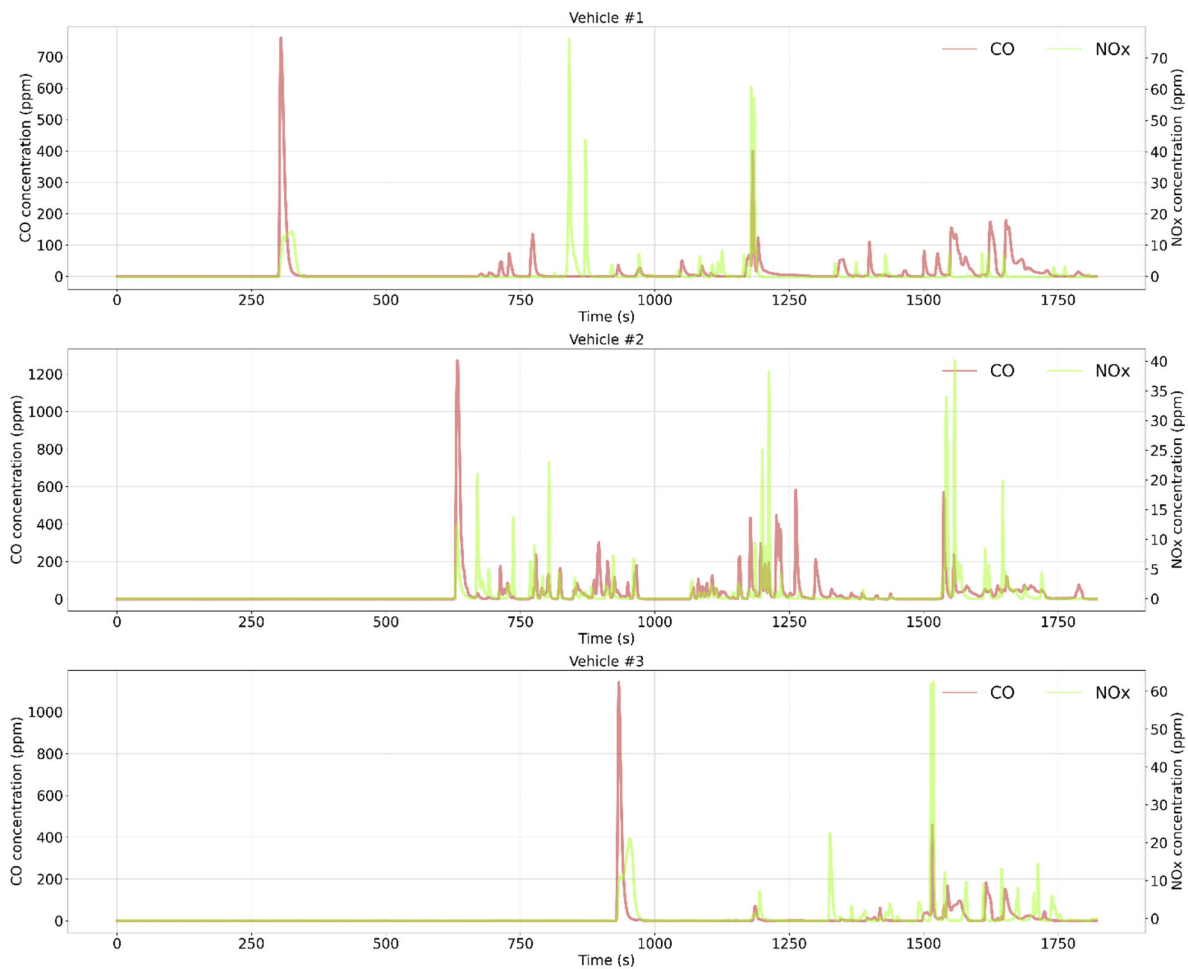


Figure S3 – Modal emissions on CD3 WLTC tests. CD3 indicates the third cycle in the charge depleting sequence (for all vehicles this was the cycle in which the ICE ignited for the first time), started with a battery initial State of Charge (SOC) equal to 100%. All tests were performed in the default user selectable mode.

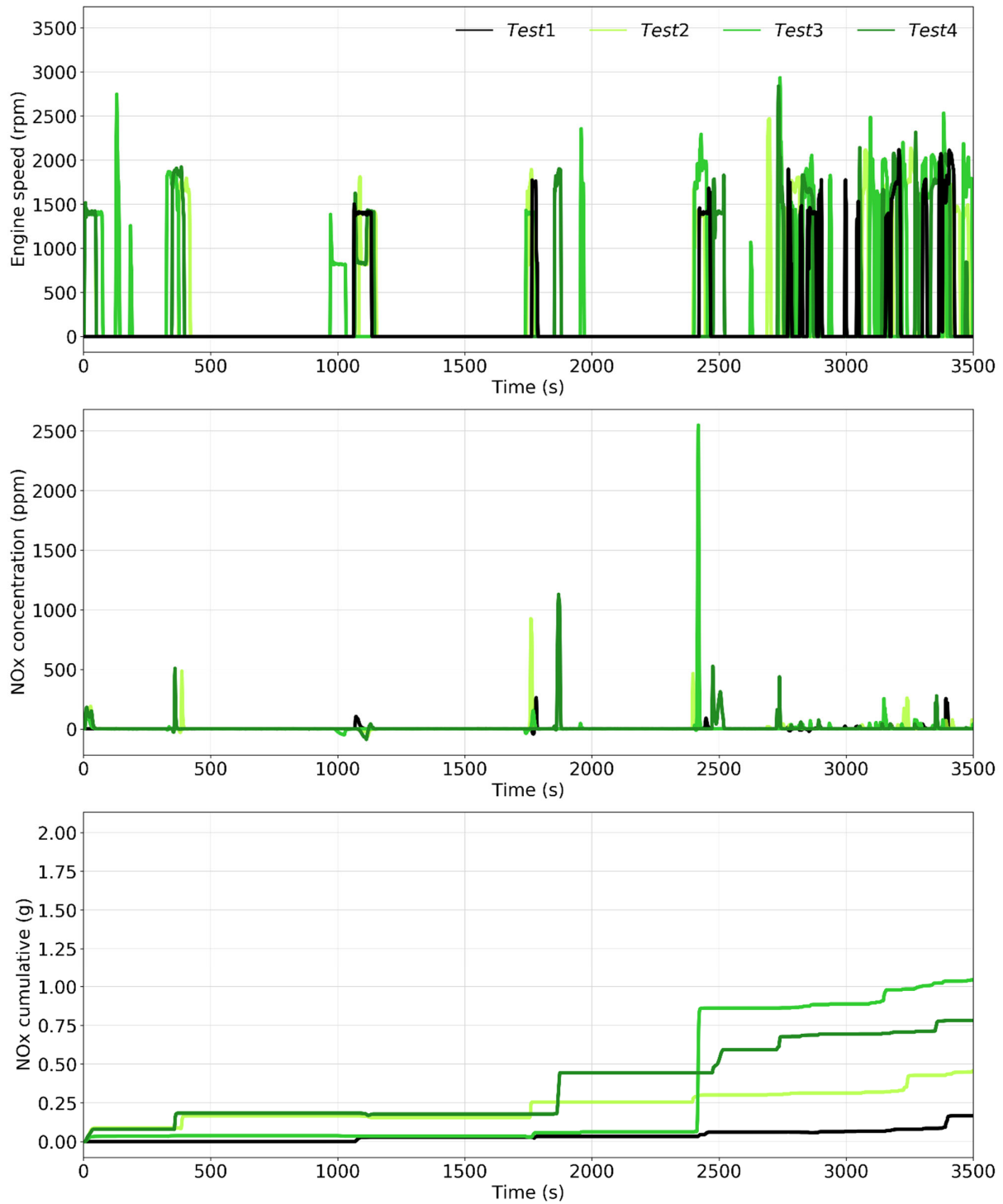


Figure S4 – Modal NOx emissions on the urban part of RDE compliant tests for vehicle #1. Tests were performed with a battery initial State of Charge (SOC) equal to 100%. All tests were performed in the default user selectable mode.

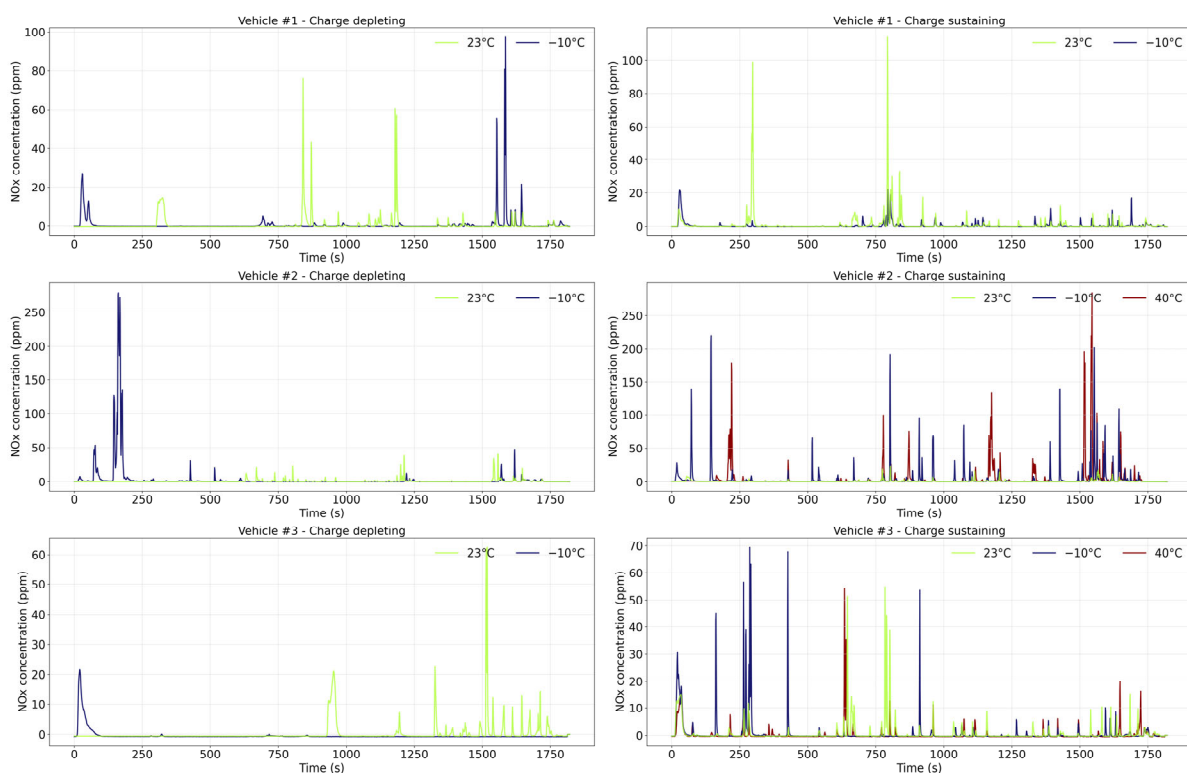


Figure S5 – Modal emissions on CD WLTC tests as a function of temperature. CD indicates the cycle in the charge depleting sequence, started with a battery initial State of Charge (SOC) equal to 100%, in which the internal combustion engine ignited for the first time (different depending on the test temperature but the same for all vehicles); CS indicates the charge sustaining cycle performed after the battery depleting sequence, i.e., starting with the minimum SOC. All tests were performed in the default user selectable mode.

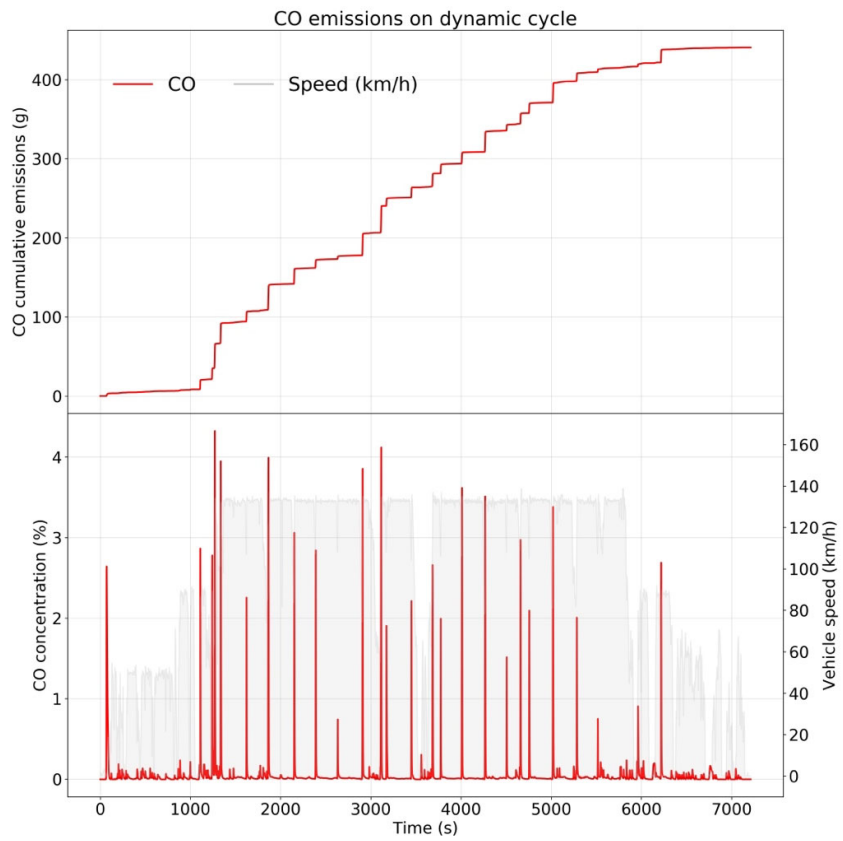
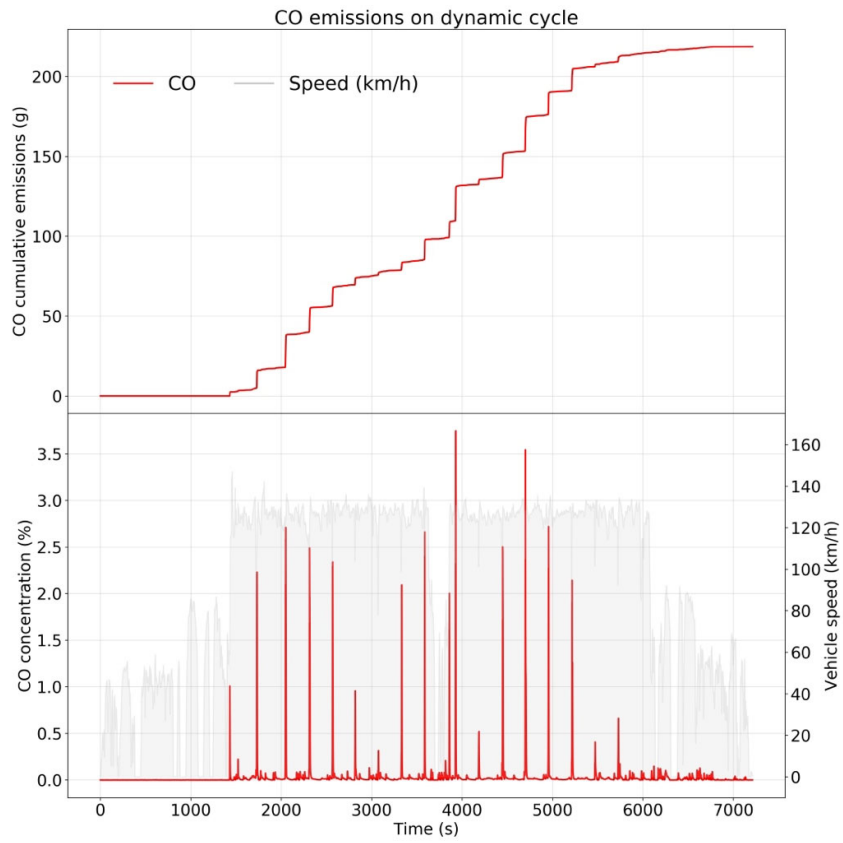


Figure S6 – CO on a dynamic motorway test on-road for the vehicle #1 (top figure) and vehicle #3 (bottom figure). The tests were performed with a depleted HV battery (minimum SOC) equal to the minimum. Upper panels in the figure report cumulated emissions of CO (red line). Lower panels reports instantaneous tailpipe concentrations of of CO (red line, measured with conventional PEMS) as well as the speed profile of the cycle (grey).

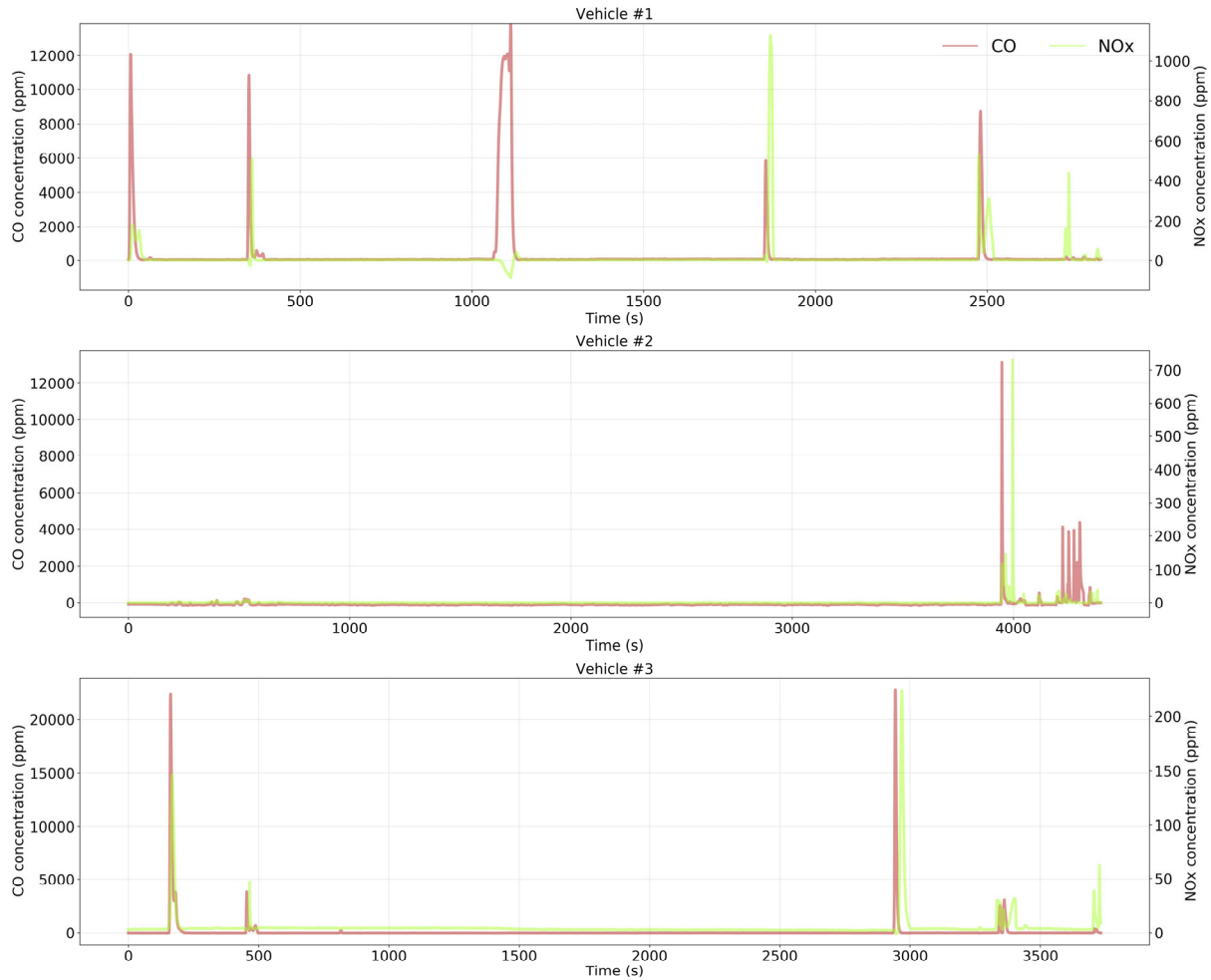


Figure S7 – CO and NOx modal emissions on RDE compliant CD100 test during the first cumulative 300 s of internal combustion engine operation, not necessarily consecutive. CD100 indicate charge depleting operation with battery initial State of Charge (SOC) equal to 100. All tests were performed in “hybrid” mode of operation.