Effects of four prototype gasoline particle filters (GPFs) on nanoparticle and genotoxic PAH emissions of a gasoline direct injection (GDI) vehicle

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Supporting information contents

Experimental

Table S1. Characteristics of the vehicle tested

	VOLVO V60 T4F	PEUGEOT 4008 1.6HDi STT
Number and arrangement of cylinder	4 / in line	4 / in line
Displacement (cm^3)	1596	1560
Power (Nm)	240 at 1600 rpm	84 at 3600 rpm
Injection type	DI	DI
Curb weight (kg)	1554	1462
Gross vehicle weight (kg)	2110	2060
Exhaust	Euro-5a	Euro-5b
First registration	27.01.2012	12.04.2013

Detailed description of the driving cycles and sampling

Each cycle consist of 4 phases (Fig. S1 and Table S1). For reporting PN data, for each phase (low, medium, high and extra high) we integrate the value and obtain a value in #/km for each phase. Then, a mean value for each phase is obtained from the different tests performed (normally driving cycles are repeated 3 or 4 times). A mean value of the whole cWLTC or hWLTC is given by summing the values obtained in each phase multiplied by the driving distance and dividing this sum by the total driving distance. This is the way of calculating the single emission values given in Fig. 2 and Table S2. However, PAHs are collected during one whole driving cycle and for all the phases together. We have not collected exhaust for this analysis in each phase. Therefore, the values given for PAH and nitro-PAH emissions correspond to a single test performed, without further repetitions.

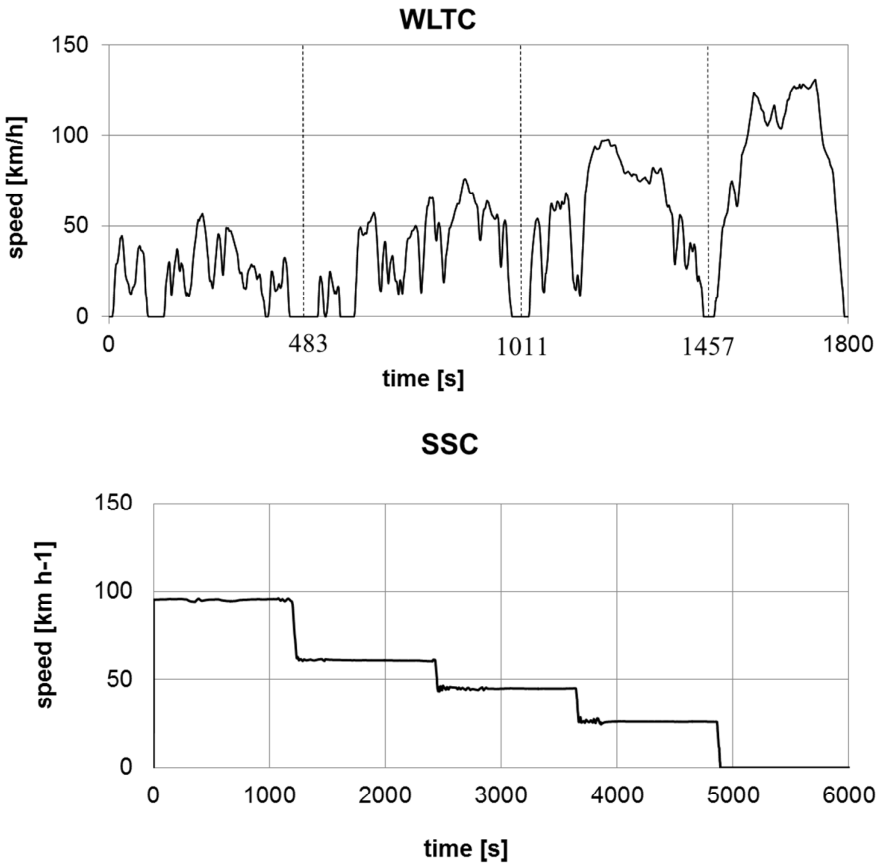

Fig S1. Driving cycles tested, WLTC above and SSC below.

Table S2. Characteristics data of the WLTC.

Phase	**Duration**	**Distance**	**V=0**		**V max**	**V mean w/o stop**	**V mean with stops**	**Max a+**	**Max a-**
	S	m	s	%	km/h	km/h	km/h	m/s^2	m/s^2
Low	589	3095	156	26.5	56.5	25.7	18.9	1.47	-1.47
Medium	433	4756	48	11.1	76.6	44.5	39.5	1.57	-1.49
High	455	7158	31	6.8	97.4	60.8	56.6	1.58	-1.49
Extra high	323	8254	7	2.2	131.3	94	92	1.03	-1.21

Results

Table S3. Emission factors of regulated pollutants for all vehicles[1].

Vehicle	PN (#/km)	THC (ng/km)	NOx (mg/km)	CO (ng/km)	CO_2 (g/km)	FC (L/100 km)
GDI-R (Euro-5,reference)						
cWLTC	$2.90 \times 10^{12} \pm 9.40 \times 10^{11}$	32 ± 2.0	23 ± 4.5	438 ± 86	187 ± 3.4	8.0 ± 0.1
hWLTC	$2.93 \times 10^{12} \pm 7.60 \times 10^{11}$	14 ± 1.3	18 ± 5.5	361 ± 89	182 ± 2.4	7.8 ± 0.1
SSC	$2.02 \times 10^{12} \pm 3.80 \times 10^{11}$	0.6 ± 0.6	0.1 ± 0.1	27 ± 24	87 ± 48.1	3.7 ± 2.1
GPF-1 (non-coated)						
cWLTC	$1.10 \times 10^{11} \pm 8.00 \times 10^{09}$	24 ± 0.1	17 ± 0.3	202 ± 18	172 ± 0.9	7.4 ± 0.0
hWLTC	$1.59 \times 10^{11} \pm 6.80 \times 10^{09}$	2.0 ± 0.1	8.4 ± 0.3	125 ± 14	170 ± 0.8	7.2 ± 0.0
SSC	$3.40 \times 10^{09} \pm 3.30 \times 10^{09}$	0.02 ± 0.1	3.0 ± 0.5	40 ± 4	134 ± 1.1	5.8 ± 0.6
GPF-2 (catalytic coating)						
cWLTC	$5.03 \times 10^{11} \pm 3.40 \times 10^{10}$	25 ± 1.7	20 ± 4.8	483 ± 52	181 ± 1.6	7.8 ± 0.1
hWLTC	$2.60 \times 10^{11} \pm 8.50 \times 10^{09}$	6.3 ± 0.9	14 ± 1.4	414 ± 25	177 ± 1.1	7.6 ± 0.01
SSC	$3.90 \times 10^{10} \pm 3.80 \times 10^{10}$	9.4 ± 0.05	4.1 ± 3.3	58 ± 9.4	136 ± 2.2	5.8 ± 0.1
GPF-3 (catalytic coating)						
cWLTC	$1.12 \times 10^{12} \pm 1.10 \times 10^{11}$	27 ±1.9	15 ± 4.4	180 ± 27	187 ± 1.8	8.0 ± 0.1
hWLTC	$6.80 \times 10^{11} \pm 4.34 \times 10^{10}$	8.2 ± 0.4	9.2 ± 6.4	117 ± 3.4	182 ± 1.5	7.8 ± 0.1
SSC	$1.90 \times 10^{11} \pm 3.41 \times 10^{10}$	1.1 ± 0.5	0.2 ± 0.1	43 ± 27	138 ± 0.9	5.9 ± 0.3
GPF-4 (non-coated)						
cWLTC	$9.70 \times 10^{11} \pm 4.40 \times 10^{10}$	30 ± 0.6	21 ± 4.2	730 ± 333	183 ± 2.1	7.9 ± 0.1
hWLTC	$6.30 \times 10^{11} \pm 3.10 \times 10^{10}$	12 ± 0.4	16 ± 2.6	666 ± 219	179 ± 2.5	7.7 ± 0.1
SSC	$2.00 \times 10^{11} \pm 1.98 \times 10^{10}$	0.4 ± 0.3	1.9 ± 0.1	60 ± 2.5	135 ± 0.6	5.8 ± 0.01

Table S2 (continuation). Emission factors of regulated pollutants for all vehicles[2].

[1] Mean values (± std) of 4 measurements during one run of the test cycle are reported for each vehicle. PN: particle number; THC: total hydrocarbons; NOx: nitrogen oxides reported as NO_2; CO: carbon monoxide; FC: Fuel consumption.

Vehicle	PN (#/km)	THC (ng/km)	NOx (mg/km)	CO (ng/km)	CO_2 (g/km)	FC (L/100 km)
GPF Mean (n=4)						
cWLTC	$6.77 \times 10^{11} \pm 2.60 \times 10^{11}$	27 ± 2.0	18 ± 3.1	399 ± 225	181 ± 2.5	7.8 ± 0.1
hWLTC	$3.97 \times 10^{11} \pm 2.70 \times 10^{11}$	7.1 ± 3.1	12 ± 3.0	330 ± 227	176 ± 5.4	7.6 ± 0.2
SSC	$1.08 \times 10^{11} \pm 8.08 \times 10^{10}$	0.4 ± 0.4	2.2 ± 1.1	50 ± 9.0	136 ± 1.4	5.8 ± 0.1
GDI Mean (n=7)						
cWLTC	$2.51 \times 10^{12} \pm 1.75 \times 10^{12}$	57 ± 28	53 ± 59	1400 ± 1420	174 ± 28	8.0 ± 1.0
hWLTC	$1.95 \times 10^{12} \pm 1.63 \times 10^{12}$	13 ± 7.2	49 ± 62	1080 ± 1270	174 ± 28	63 ± 67
SSC	$6.60 \times 10^{12} \pm 1.38 \times 10^{13}$	11 ± 11	97 ± 230	292 ± 590	132 ± 24	6.0 ± 1.0
DPF (Euro-5, bench mark)						
cWLTC	$3.95 \times 10^{10} \pm 2.59 \times 10^{10}$	4.7 ± 1.3	641 ± 63.0	70 ± 11.9	151 ± 5.3	5.8 ± 0.19
hWLTC	$2.81 \times 10^{09} \pm 6.04 \times 10^{09}$	1.4 ± 1.2	640 ± 46.5	24 ± 6.6	145 ± 3.6	5.5 ± 0.1
SSC	$1.70 \times 10^{08} \pm 1.30 \times 10^{08}$	5.7 ± 3.0	290 ± 8.8	28 ± 2.7	110 ± 1.0	4.3 ± 0.05

[2] Mean values (± std) of 4 measurements during one run of the test cycle are reported for each vehicle. PN: particle number; THC: total hydrocarbons; NOx: nitrogen oxides reported as NO_2; CO: carbon monoxide; FC: Fuel consumption.

Table S4. Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the cWLTC. Levels found in dilution air are reported as detection limits (italics).

	GDI-R	GPF-1	GPF-2	GPF-3	GPF-4	GDI Mean (n=7)	DPF
Naphthalene	47770	14070	50270	69240	79670	194800 ± 158000	5700
2-methylnaphthalene	17010	2470	7610	4930	11230	22500 ± 16800	1500
1-methylnaphthalene	9630	1660	5200	3370	6980	14300 ± 8480	900
2,6-dimethylnaphthalene	4390	290	800	360	1960	2000 ± 1490	260
1,6-dimethylnaphthalene	2200	190	400	220	1120	2104 ± 2310	310
1,2-dimethylnaphthalene	1140	30.0	250.0	70.0	350	630 ± 540	120
Acenaphthylene	9990	1620	4070.0	1470.0	4390	15790 ± 26300	3.7
Acenaphthene	570	310	170	190.0	370.0	3640 ± 6950	100
Fluorene	2470	560	740	470.0	1140.0	2340 ± 2600	270
Phenanthrene	10820	4380	2830	9490	4970	16650 ± 17800	3020
Anthracene	1830	190	440	760	510	1640 ± 1360	370
3-methylphenanthrene	1900	130	130	1370	410	760 ± 470	930
2-methylphenanthrene	1980	160	120	1820	440	870 ± 570	990
9-methylphenanthrene	710	100	52.4	650	190	350 ± 203	460
1-methylphenanthrene	1240	*70.0*	86.3	860	330	400 ± 250	470
1,7-dimethylphenanthrene	350	70.0	53.6	860	150	1280 ± 2720	150
2-methylanthracene	1950.0	*21.8*	89.6	620	310	480 ± 270	250

Table S4 (continuation). Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the cWLTC. Levels found in dilution air are reported as detection limits (italics).

	GDI-R	GPF-1	GPF-2	GPF-3	GPF-4	GDI Mean (n=7)	DPF
Retene	*15.3*	*16.6*	*20.0*	91	190	230 ± 150	78
Fluoranthene	2580	1290	380	18770	730	2030 ± 1460	4760
3-methylfluoranthene	57.4	*0.8*	17.7	210.0	36.3	35 ± 20	*0.9*
1-methylfluoranthene	85.0	0.0	11.6	120.0	19.9	25 ± 20	5.3
Pyrene	4020	6510	1330	10580	880	3240 ± 4420	3760
4-methylpyrene	220	17.3	13.4	135.2	30.7	61 ± 30	30
1-methylpyrene	140	10.6	10.4	72.5	25.6	32 ± 15	11
Benzo(a)anthracene	290	*1.1*	41.0	56.7	76.4	122 ± 90	6.7
Chrysene	420	36.8	74.1	78.9	140	186 ± 120	12.4
3-methylchrysene	43.1	13.8	20.8	*0.8*	10.0	60 ± 50	0.1
6-methylchrysene	*0.0*	0.0	5.0	*0.2*	0.0	8.9 ± 10	8
Benzo(b)fluoranthene	250	39.7	140	52.6	120	170 ± 140	8
Benzo(k)fluoranthene	52.2	*2.1*	2	14.8	20.8	60 ± 40	*1.3*
Benzo(a)pyrene	210	21.6	34.3	24.4	100	210 ± 260	5.5
Indeno(1,2,3-cd)pyrene	*8.4*	*10.1*	12.7	*11.9*	*11.3*	110 ± 130	*4.5*
Dibenz(ah)anthracene	*13.1*	*28.5*	*28.9*	*33.7*	*32.0*	25 ± 30	*9.1*
Benzo(ghi)perylene	190	84.2	170.0	*10.2*	63.2	377 ± 680	12

Table S5. Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the hWLTC. Levels found in dilution air are reported as detection limits (italics).

	GDI-1	GPF-1	GPF-2	GPF-3	GPF-4	GDI Mean (n=7)	DPF
Naphthalene	120	13650	13610	3040	10090	63300 ± 71600	1000
2-methylnaphthalene	1530	1730	4140	240	3700	10200 ± 9300	500
1-methylnaphthalene	1070	700	2120	170	1770	5400 ± 5360	300
2,6-dimethylnaphthalene	910	240	920	*9.0*	930	1680 ± 2040	42
1,6-dimethylnaphthalene	500	180	520	15.3	550	1430 ± 1530	46
1,2-dimethylnaphthalene	260	*30.0*	170	*3.4*	160	470 ± 580	16
Acenaphthylene	1620	590	1420.0	150.0	1390	5030 ± 5170	*0.6*
Acenaphthene	100	340	310	58.9	110.0	850 ± 1470	13
Fluorene	970	520	860	210.0	920.0	1400 ± 870	60
Phenanthrene	6450	4090	4470	4580	4480	13710 ± 9350	2700
Anthracene	540	230.0	340	390	450	1390 ± 990	210
3-methylphenanthrene	770	*90.0*	310	650	440	710 ± 780	160
2-methylphenanthrene	800	*110.0*	390	760	560	850 ± 580	150
9-methylphenanthrene	280	*26.8*	130	370	340	420 ± 280	54
1-methylphenanthrene	440	*52.0*	140	400	340	470 ± 340	61
1,7-dimethylphenanthrene	160	*21.3*	130	190	240	870 ± 1490	14
2-methylanthracene	470.0	*26.0*	120	190	160	390 ± 270	*2.6*

Table S5 (continuation). Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the hWLTC. Levels found in dilution air are reported as detection limits (italics).

	GDI-R	GPF-1	GPF-2	GPF-3	GPF-4	GDI Mean (n=7)	DPF
Retene	31.9	*16.1*	*20.0*	210	290	200 ± 210	1.1
Fluoranthene	1170	510	1260	840	2710	2480 ± 2780	300
3-methylfluoranthene	30.2	*1.2*	18.7	10.3	12.3	32 ± 40	*0.9*
1-methylfluoranthene	41.5	5.0	19.7	17.3	19.1	16 ± 20	*0.2*
Pyrene	1620	420	1160	940	14880	5680 ± 1030	*290*
4-methylpyrene	100	*1.1*	27.0	40.5	100.0	100 ± 100	9.8
1-methylpyrene	54.2	*1.1*	17.4	34.1	61.6	40 ± 40	3.9
Benzo(a)anthracene	87.5	*1.1*	18.3	24.0	51.8	70 ± 70	5.7
Chrysene	140.0	15.0	51.1	58.3	230	170 ± 170	6.4
3-methylchrysene	19.5	3.2	21.5	5.8	170.0	60 ± 80	*0.4*
6-methylchrysene	0.0	*0.2*	5.3	*0.2*	30.0	17 ± 20	9.6
Benzo(b)fluoranthene	86.4	*2.7*	27.7	18.3	580	180 ± 310	24
Benzo(k)fluoranthene	8.3	*2.1*	*2.1*	6.1	43.0	45 ± 40	*1.2*
Benzo(a)pyrene	190	*2.1*	*1.1*	42.0	360	259 ± 540	10
Indeno(1,2,3-cd)pyrene	5.8	*9.8*	*9.9*	*11.6*	*600*	134 ± 250	*4.2*
Dibenz(ah)anthracene	14.3	*27.6*	*27.9*	*32.8*	*31.0*	68 ± 90	*8.4*
Benzo(ghi)perylene	52.1	8.3	*8.4*	43.5	2420	729 ± 1530	*6.6*

Table S6. Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the SSC. Levels found in dilution air are reported as detection limits (italics). SSC values in GPF-2 are not reported.

	GDI-R	GPF-1	GPF-3	GPF-4	GDI Mean	DPF
Naphthalene	630	800	*56.1*	370	21100 ± 19700	*100*
2-methylnaphthalene	320	20.7	*23.2*	58.2	2400 ± 2570	*100*
1-methylnaphthalene	130	12.5	*14.0*	13.6	1300 ± 1520	*43*
2,6-dimethylnaphthalene	50	10.8	*12.1*	11.8	200 ± 260	*14*
1,6-dimethylnaphthalene	0	7.1	*7.9*	7.7	277 ± 310	*16*
1,2-dimethylnaphthalene	10	*4.1*	0.0	0.0	130 ± 190	*4.6*
Acenaphthylene	260	13.8	10.0	110	1040 ± 1600	*1.1*
Acenaphthene	*0.0*	12.5	*4.2*	0.0	280 ± 370	*6.5*
Fluorene	80	9.9	*11.0*	44.2	200 ± 270	*21*
Phenanthrene	300	110	130	120	2380 ± 2690	*170*
Anthracene	150	6.6	50.0	48.7	380 ± 330	*19*
3-methylphenanthrene	91	10.4	*11.6*	11.3	130 ± 130	*13*
2-methylphenanthrene	76	12.9	*14.4*	14.0	140 ± 150	*14*
9-methylphenanthrene	0	6.3	*7.0*	6.9	70 ± 80	*7.3*
1-methylphenanthrene	47	6.9	*7.7*	7.5	80 ± 80	*6.4*
1,7-dimethylphenanthrene	*2.7*	*2.9*	10.0	0.0	170 ± 280	*3.7*
2-methylanthracene	140	*3.9*	*4.4*	12.1	80 ± 60	*4.8*

Table S6 (cont.). Emission factors (ng/km) for detected PAHs and alkyl-PAHs in the reference vehicle without filter (GDI-R), with filters (GPF-1-4) and in the diesel vehicle with DPF (DPF) in the SSC. Levels found in dilution air are reported as detection limits (italics). SSC values in GPF-2 are not reported.

	GDI-R	GPF-1	GPF-3	GPF-4	GDI Mean	DPF
Retene	*4.0*	11.0	*12.4*	12.0	30 ± 10	*10*
Fluoranthene	12.4	29.6	100	32.2	250 ± 210	*62*
3-methylfluoranthene	9.0	*0.6*	0.0	0.0	3.5 ± 4.0	*1.6*
1-methylfluoranthene	10.7	*1.6*	0.0	0.0	1.2 ± 1	*0.3*
Pyrene	260	18.1	1500	130	340 ± 170	*430*
4-methylpyrene	20.0	0.8	9.3	10.0	8.1 ± 8.0	*5.2*
1-methylpyrene	10.6	0.4	7.4	0.0	2.6 ± 3.0	*0.3*
Benzo(a)anthracene	29.4	0.8	*0.9*	0.0	4.3 ± 5.1	*1.1*
Chrysene	40.5	1.5	*4.8*	0.0	5.3 ± 5.1	*2.4*
3-methylchrysene	0.1	0.5	*0.5*	0.0	-	*0.7*
6-methylchrysene	*0.0*	0.1	*0.2*	0.0	0.4 ± 0.2	*4.4*
Benzo(b)fluoranthene	*1.2*	1.9	*2.1*	0.0	4.9 ± 3.8	*11*
Benzo(k)fluoranthene	*0.5*	1.4	*1.6*	0.0	1.6 ± 2.0	*2.2*
Benzo(a)pyrene	*1.3*	1.5	33.8	0.0	3.6 ± 4.3	*3*
Indeno(1,2,3-cd)pyrene	*0.9*	6.7	*7.5*	*7.3*	6.1 ± 5.2	*7.8*
Dibenz(ah)anthracene	*3.6*	19.0	*21.2*	*20.6*	27 ± 54	*16*
Benzo(ghi)perylene	*1.3*	5.7	*6.4*	10.0	23 ± 27	*99*

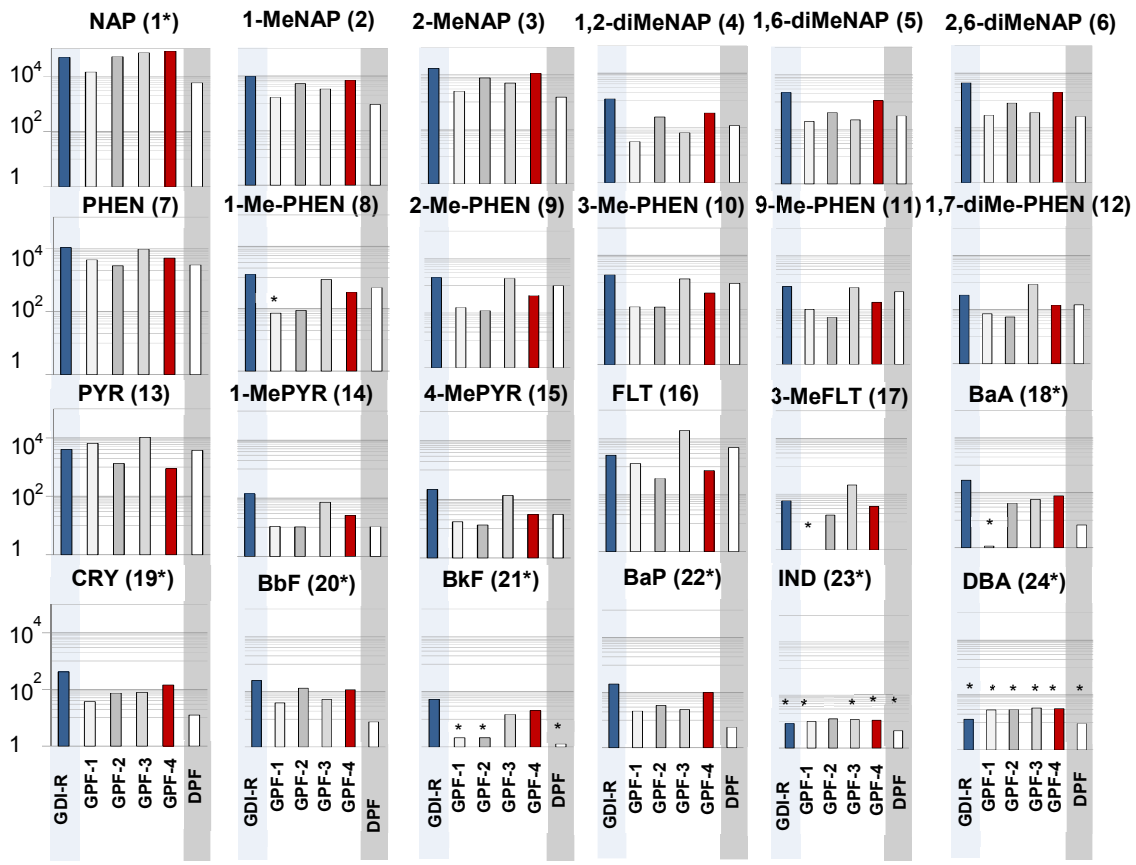

Figure S2. Effects of filters on selected PAH and alkyl-PAH emissions during the cold driving cycle (cWLTC). Values are reported as emission factors in ng/km The genotoxic compounds NAP (1), BaA (18), CRY (19),BbF (20), BkF (21), BaP (22), IND (23) and DBA(24) are labelled (*). PYR (13) and FLT (16) are precursors of respective genotoxic alkyl-PAHs. The reference vehicle without filter (GDI-1 Ref) is highlighted in red and the Diesel vehicle with DPF (D-DPF) in grey. The asterisk on the bar means detection limit values

Table S7. Toxicity equivalency factors (TEFs) and IARC classification of the carcinogenic potential.

Compound	TEFs	Reference	IARC Class
Naphthalene	0.001	1	2B
1-Methylnaphthalene	0.0025	2	
2-Methylnaphthalene	0.001	1	
Acenaphthylene	0.001	1	3
Acenaphthene	0.001	1	3
Fluorene	0.001	1	3
Phenanthrene	0.001	1	3
Anthracene	0.01	1	3
Fluoranthene	0.001	1	3
Pyrene	0.001	1	3
Benzo(a)anthracene	0.1	1	2B
Chrysene	0.01	1	2B
Benzo(k)fluoranthene	0.1	1	2B
Benzo(b)fluoranthene	0.1	1	2B
Benzo(a)pyrene	1	1	1
Indeno(1,2,3,-cd)pyrene	0.1	1	2B
Dibenzo(ah)anthracene *	1	1	2A
Benzo(ghi)perylene	0.01	1	3

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