Experience from new particle test equipment @ Bosch Karlsruhe: Mass-Bill, PCRF with large particles and test results

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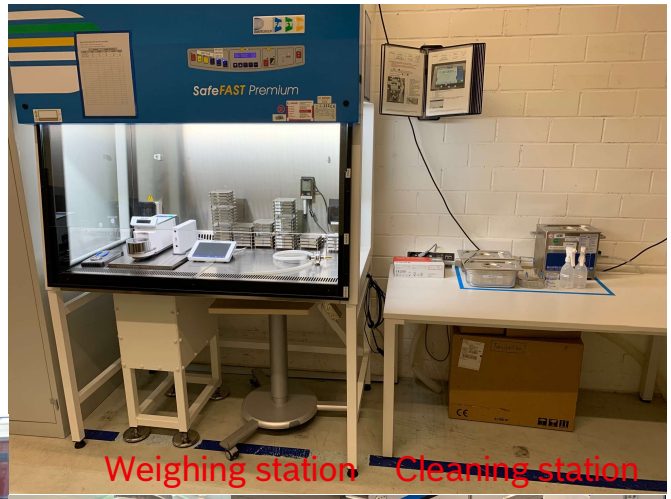
BOSCH

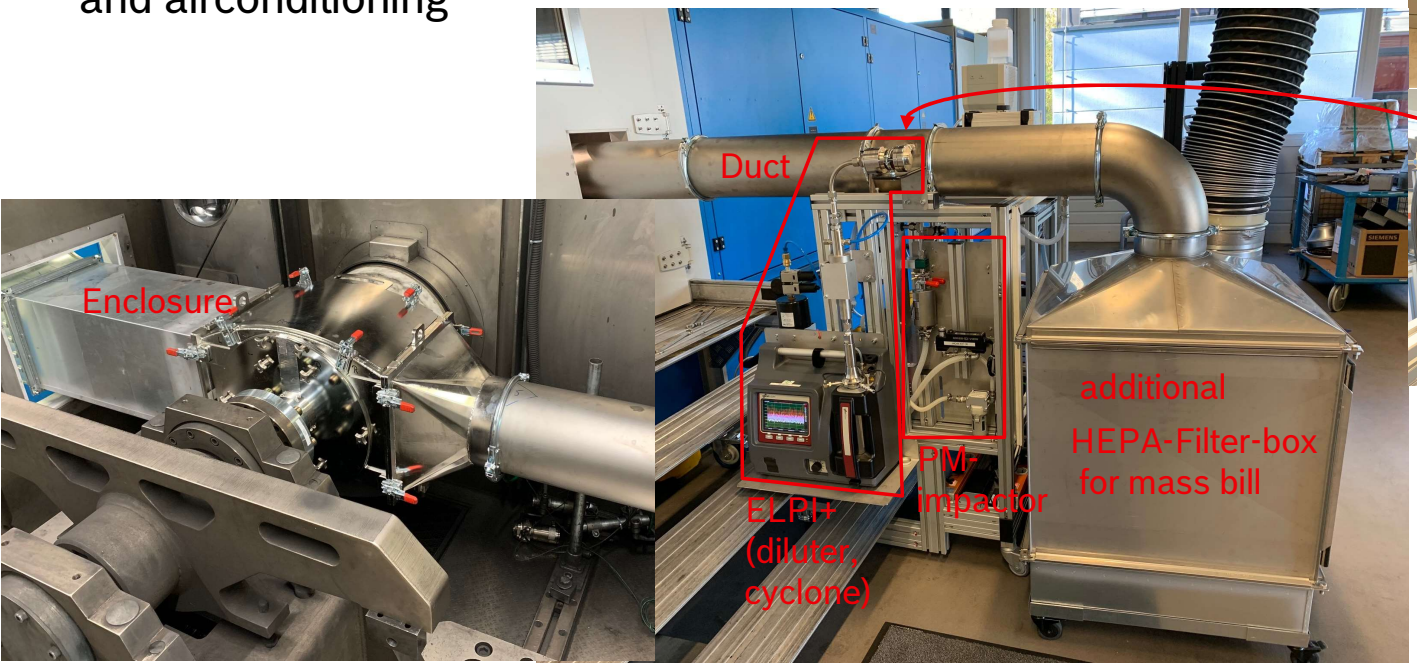
PMP-Brake PE test
Agenda

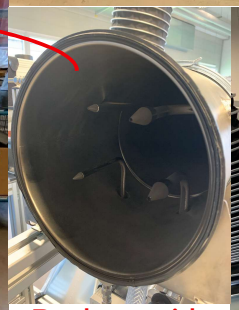
- Overall setup
- Deviations from PMP requirements
- Mass bill
- Loss-factors dependent on particle size
- Ford-Focus test according to ILS II
- Repeatability and Mass-Bill
- PN, PM and particle size distribution
- Conclusions

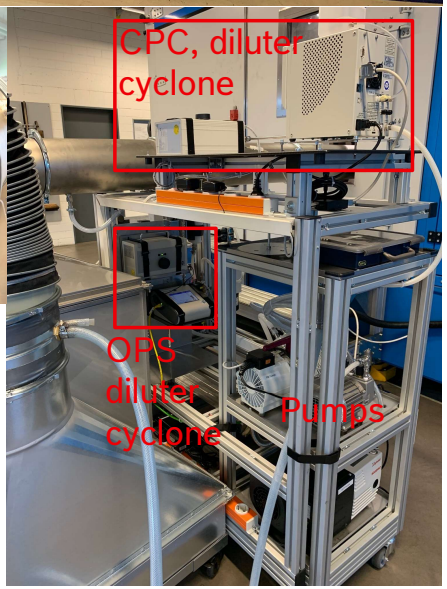
PMP-Brake PE test
Overall setup

- Enclosure, 200 mm duct, probes with isokinetic nozzles, ELPI+, PM-impactor, CPC and OPS, HEPA filtered air
- Weighing & cleaning station w. laminar flow box, 7-digit scale and airconditioning





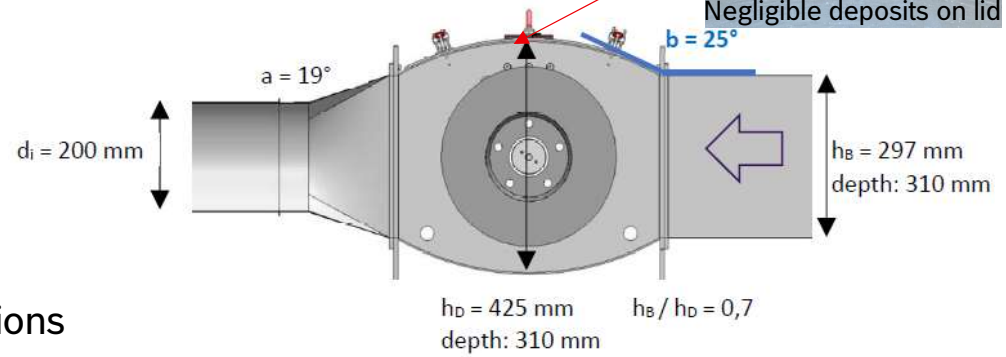




PMP-Brake PE test
Deviations from actual PMP requirements: Enclosure

- Enclosure setup unsymmetric:
  - Large rectangular inlet, round d = 200 mm outlet
  - Curvature with larger radius than circular shape
    => tangential to outlet cone
  - Size covers > 95 % of passenger car brake applications
  - Max 7” discs
    distance of caliper to lid: 10 mm
    deposits on lid: < 4 mg => negligible
- Airflow homogeneity validated
  - highest, medium, lowest airflow
  - C-plane according to largest and smallest disc diameter

  => according to actual requirements
  -16,4 ... +15 % << ± 35 %



Largest disc

450mm	406-411m³/h	1,35	
1,3	1,18	1,26	m/s
-3,86	-12,74	-6,82	Δ mean / %
1,5	1,46	1,32	m/s
10,93	7,97	-2,38	Δ mean / %
1,44	1,46	1,25	m/s
6,49	7,97	-7,56	Δ mean / %

450mm	1184-1207m³/h	3,60	
3,46	3,05	3,26	m/s
-3,80	-15,20	-9,36	Δ mean / %
4,08	3,86	3,51	m/s
13,44	7,32	-2,41	Δ mean / %
3,85	3,85	3,45	m/s
7,04	7,04	-4,08	Δ mean / %

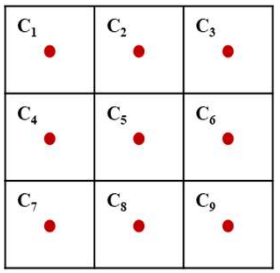
450mm	2422-2404m³/h	6,47	
6,15	5,41	5,93	m/s
-4,95	-16,38	-8,35	Δ mean / %
7,16	6,86	6,44	m/s
10,66	6,03	-0,46	Δ mean / %
6,74	7,2	6,34	m/s
4,17	11,28	-2,01	Δ mean / %

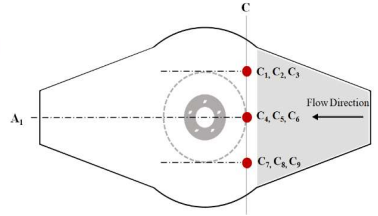
Smallest disc

320mm		1,27	
1,25	1,08	1,12	m/s
-1,57	-14,96	-11,81	Δ mean / %
1,46	1,41	1,16	m/s
14,96	11,02	-8,66	Δ mean / %
1,38	1,42	1,15	m/s
8,66	11,81	-9,45	Δ mean / %

320mm		3,31	
3,14	2,83	3,11	m/s
-5,10	-14,47	-6,01	Δ mean / %
3,75	3,69	2,99	m/s
13,33	11,52	-9,64	Δ mean / %
3,59	3,61	3,07	m/s
8,50	9,10	-7,22	Δ mean / %

320mm		6,18	
5,94	5,47	6,23	m/s
-3,90	-11,50	0,79	Δ mean / %
6,85	6,66	5,71	m/s
10,82	7,75	-7,62	Δ mean / %
6,6	6,44	5,73	m/s
6,78	4,19	-7,30	Δ mean / %





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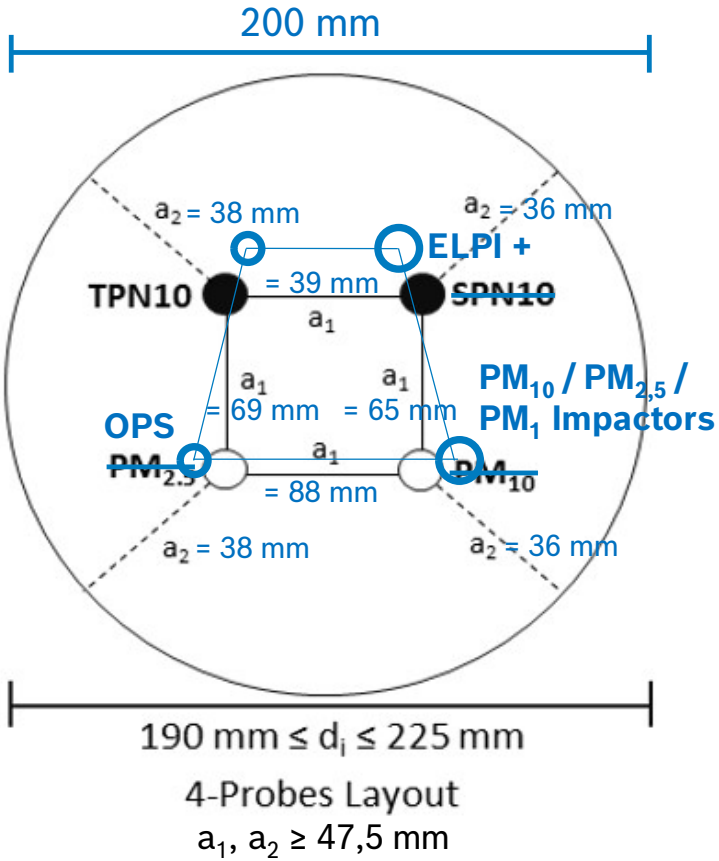
PMP-Brake PE test
Deviations from actual PMP requirements: probes

- design deviates from actual PMP equidistance requirement
  - Min distance requirement between probes: 47,5 mm
    distances between probes between 39 and 88 mm
  - Min distance requirement from tunnel wall: 47,5 mm
    distances from tunnel wall 36 or 38 mm
    Probe centers equidistant from wall: 42 mm

- Inner diameter of PM-probe is 10 mm
  - larger than largest isokinetic nozzle diameter (7 mm)

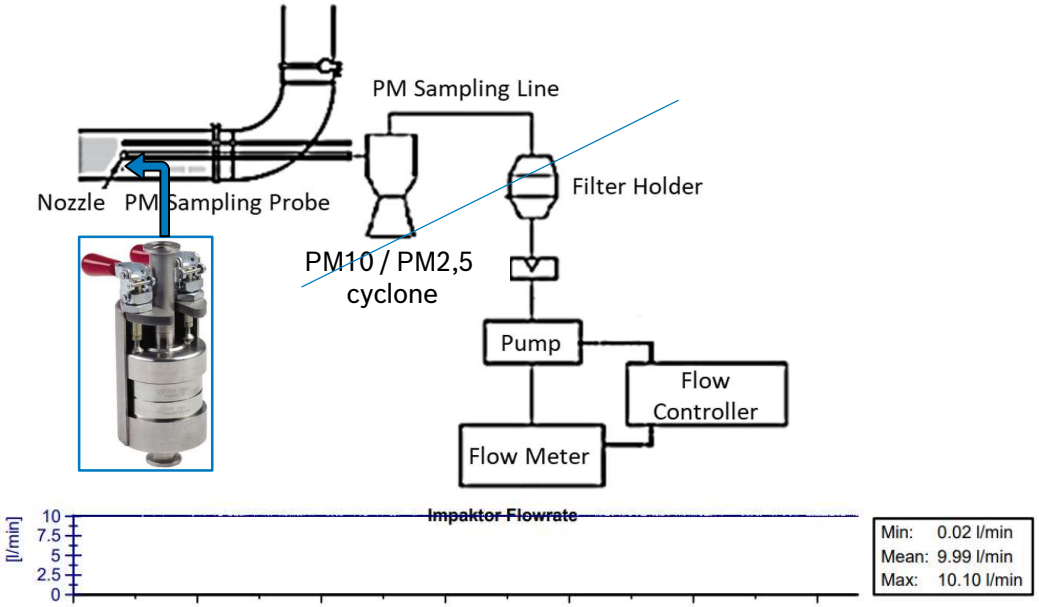


4-Probes Layout

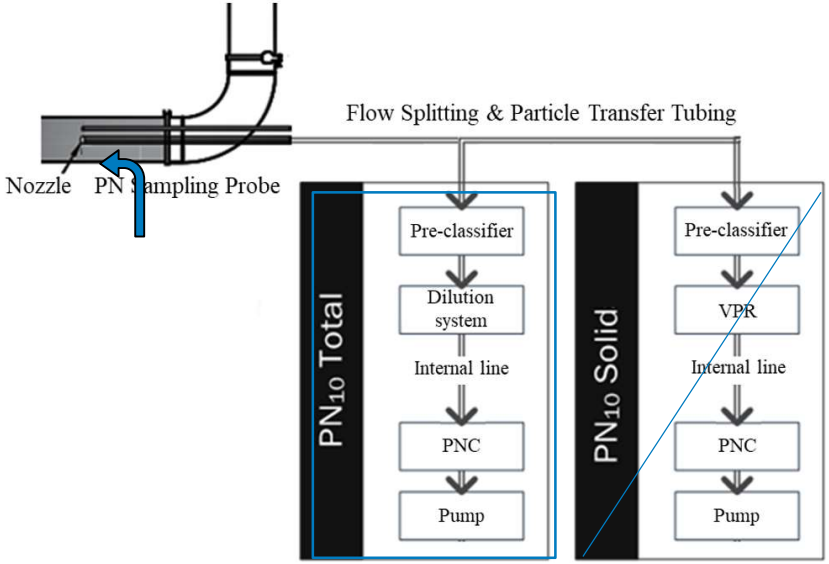
a_1, a_2 ≥ 47,5 mm

PMP-Brake PE test
Deviations: PM and PN measurement modules

- One Impactor instead of 2 PM test lines
  - Flow regulator
  - Online flow monitoring



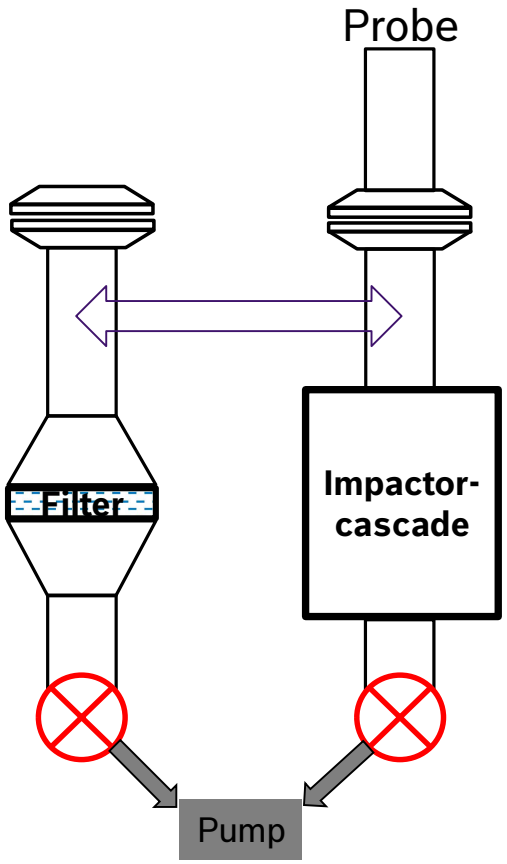
- Only TPN compliant with PMP requirements
  - Capillary diluter with straight alignment
  - Online PCRF monitoring
  - 10 nm CPC

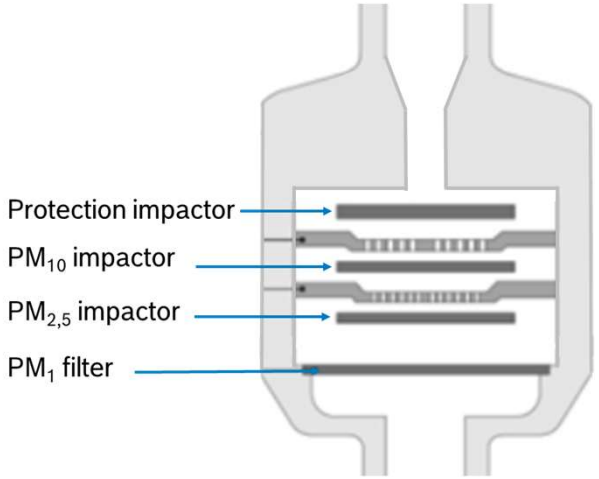


PMP-Brake PE test

All mass collected during T-check, bedding and WLTP-test

- During T-check and Bedding a PMP-compliant filter is installed at the probe to collect all mass before WLTP-test.
- The Impactor cascade is installed during WLTP-test.
  - protection from larger than PM10 particles
  - All particles collected as PM1 filter is installed equal to PMP-requirements
  - No overloading, load << 1 mg
    Greased Al-foils
    => bouncing minimized
- Complete mass-bill with comparison to weight loss of friction couple possible!

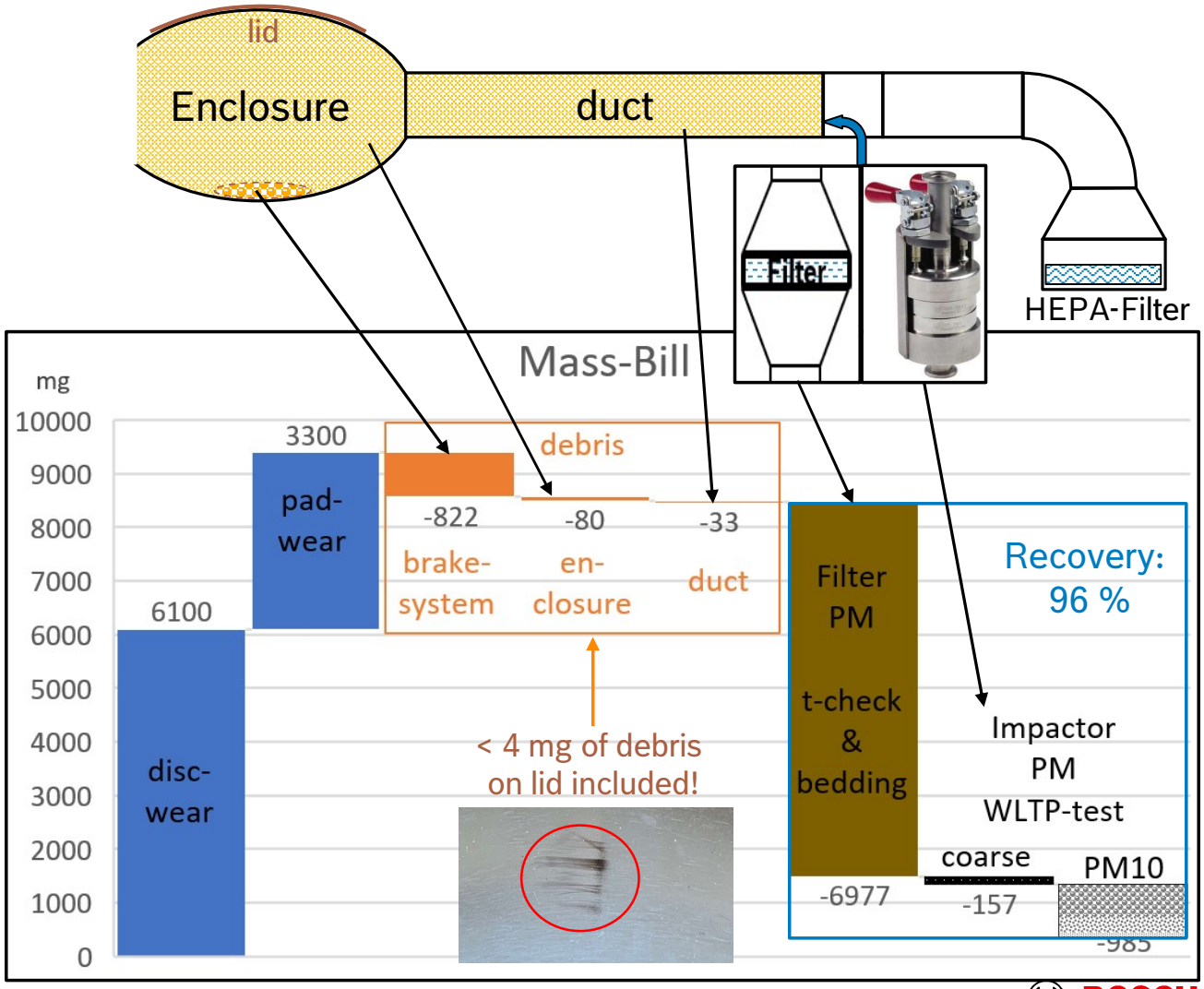




PMP-Brake PE test
Mass-bill

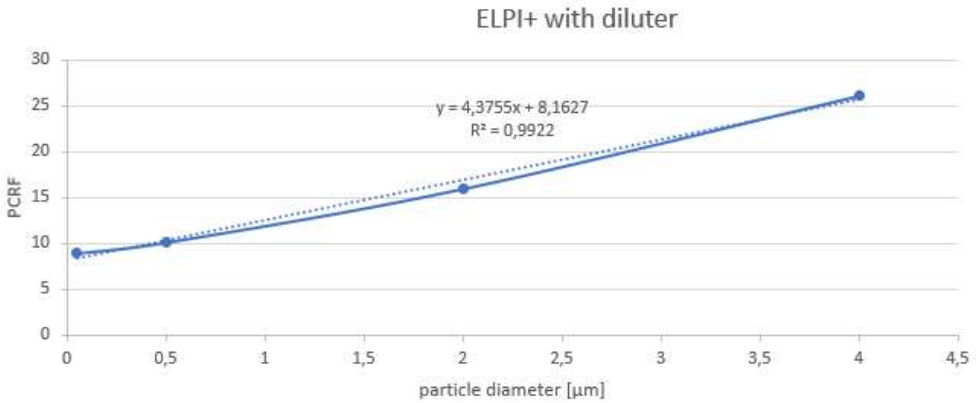
- So far recovery rate
  50 - 97 %
  - Example with 96 % recovery
  - *Large particles passing under probe in some applications?*

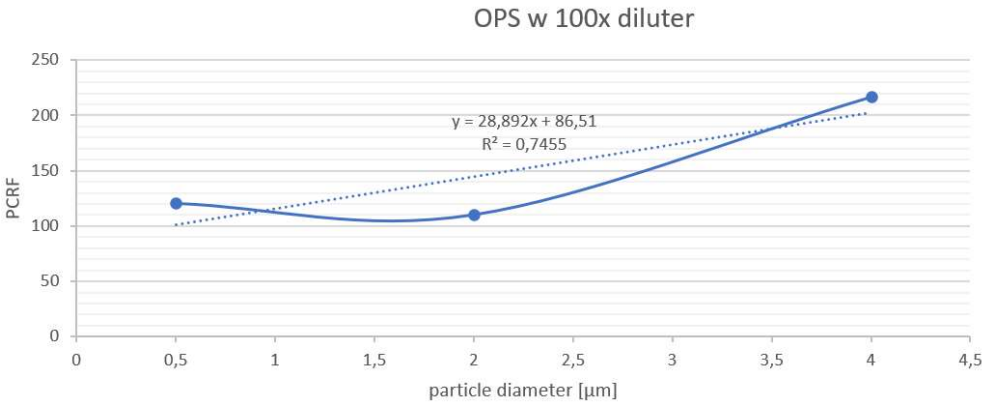
- Recovery check with HEPA-filter in duct not mature yet
  - *moisture effects !?*

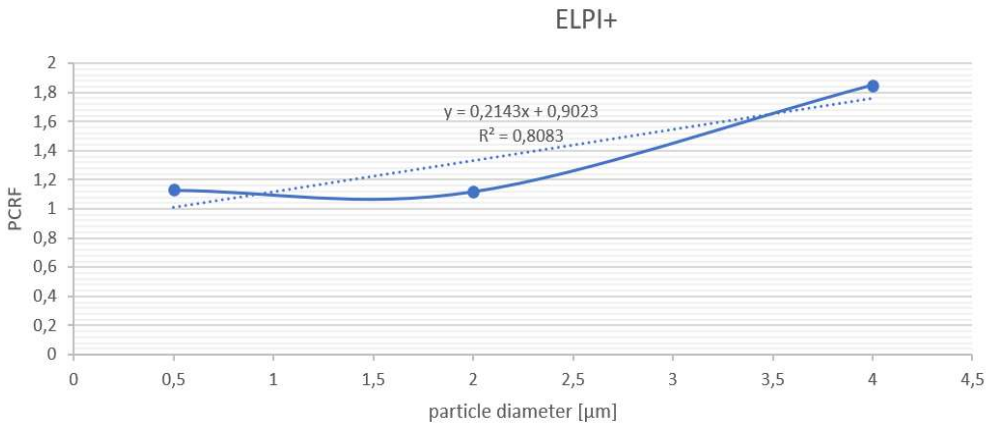


PMP-Brake PE test
PCRF ELPI+ / OPS

- Low particle loss up to 2 µm
- Higher particle losses for 4 µm particles
- In case ELPI+ is combined with an ejection diluter with ca. 6x dilution factor the PCRF increases with larger particles
- Same diluter for OPS and for CPC
  => PCRF equal for 0,5 to 2,5 µm



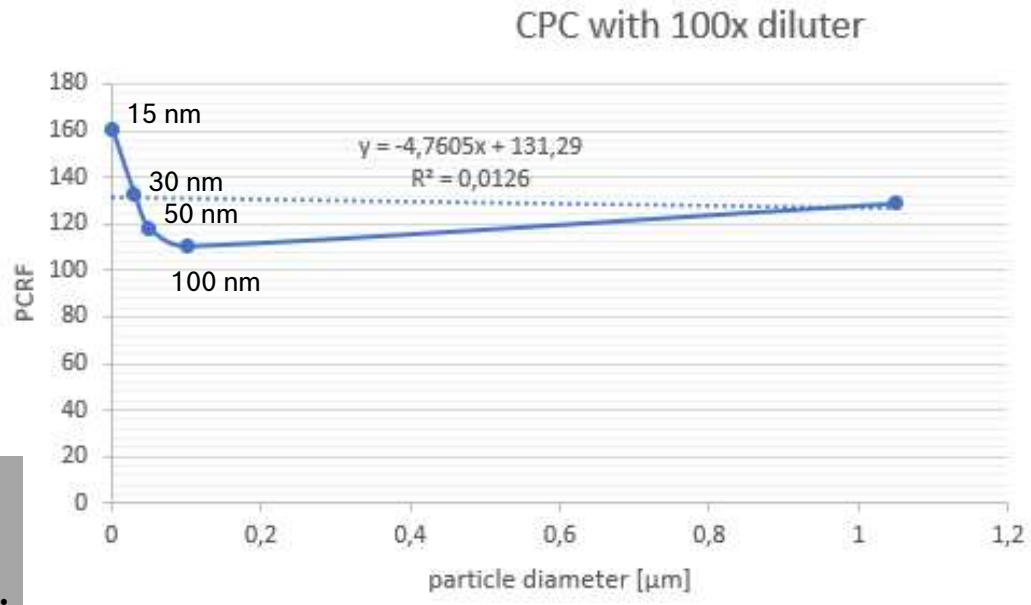




PCRF = Particle Concentration Reduction Factor

PMP-Brake PE test
PCRF – CPC: according to PMP & 1 µm

- Capillary diluter with 100 x dilution factor used
- As particles are larger than 100 nm, PCRF was determined also using 1 µm Polystyrene particles
- Larger particles are not lost in significant amounts in our test setup.
- The CPC test line consists of
  - 90° bent probe, Cyclon
  - Straight oriented:
    short tube, capillary diluter, short tube, CPC
- CPC detection limits: 10 nm – ca. 2,5 µm without size information

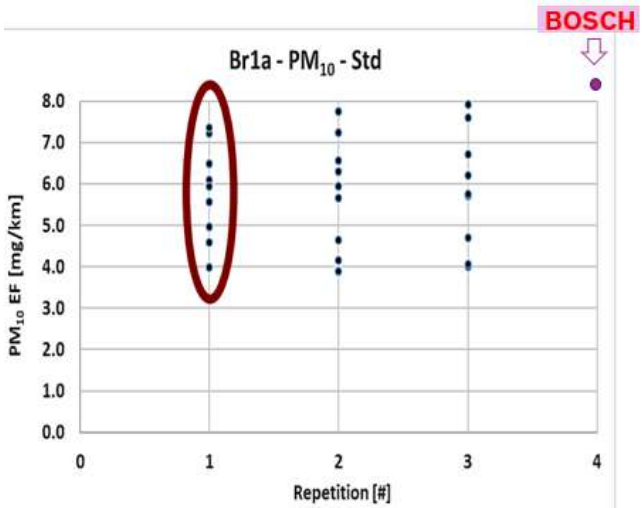


Recommendation to include larger particles of up to 2 µm in PCRF determination in case PN shall be measured to comply legal limits in future.

PCRF = Particle Concentration Reduction Factor

PMP-Brake PE test
Ford-Focus WLTP-test according to ILS II -trials

- Pads and discs in Bosch comparison test:
  same part numbers as for ILS but different batches



	unit	**PMP ILS** Ford-Focus	**Bosch** Ford Focus
inertia		**100%**	**100%**
PMP requirements		**07/2020**	**07/2020 = ILS**
Disc		OES	OES
pads		OES (Ferodo)	OES (Ferodo)
PM10	[mg/km]	**4 - 8**	**8,6**
PM2,5	[mg/km]	**1- 4**	**3,6**
PM2,5 / PM10 ratio	[%]	*< 57,3 !*	41,9
Mass loss (pads & disc in t-check, bedding, cycle)	[mg]	nn	17030
Mass loss w/o deposits (pads, caliper, enclos., duct)	[mg]	nn	14711
Mass collected in test cycle PM10 and coarse	[mg]	nn	1905
Mass collected in Bedding	[mg]	nn	9816
total mass collected	[mg]	nn	11721
recovery rate in PM-measurement	[%]	nn	68,8
PN	[#/km]	**0,9 - 4,6 x 10^9**	**3,0 x 10^9**
Background	[#/cm^3]	< 20 (requirement)	< 10

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PMP-Brake PE test
Repeatability and Recovery Rate

	Bosch AA pads & discs	unit	Test 1	Test 2	Test 3	Av	Std
PN	PN / test	#	1,51E+12	5,46E+11	7,07E+11	9,22E+11	5,18E+11
PM	PM10	mg/km	5,13	5,14	4,81	5,03	0,19
	PM2,5	mg/km	2,09	2,04	1,91	2,01	0,09
	PM1	mg/km	0,71	0,67	0,53	0,64	0,09
	PM2,5 / PM10 ratio	%	40,7	39,7	39,7		
Mass-Bill	WLTP-cycle PM >10	mg	123,0	157,0	158,4	146,13	20,05
	WLTP-cycle PM10	mg	1108,8	1143,2	1081,1	1111,03	31,11
	Bedding PM	mg	6976,8	7709,5	6969,2	7218,50	425,24
	total test PM	mg	8085,6	8852,7	8050,3	8329,53	453,42
	fr.couple weight loss	mg	9400	10250	9640	9763,33	438,22
	debris on Br.-Sys.	mg	821,90	917,26	759,70	832,95	79,36
	debris Enclosure	mg	79,60	38,53	100,30	72,81	31,44
	debris duct	mg	33,20	140,33	135,70	103,08	60,56
	Fr.-couple weight loss w/o debris Br.-sys, encl, duct	mg	8465	9154	8644	8754	357
	Recovery rate of PM vs weight loss	%	96	97	93		

- Application comparable to Ford Focus with close to equal mass and inertia
- Test conditions according to PMP 2023 requirements

PMP-Brake PE test
PN and particle size

- PN of CPC, ELPI+ and OPS are in the same order of magnitude
- PN>2,5 of OPS and ELPI+ align well
  but different distribution
  => more investigation required
- PN deviation of CPC and ELPI+ is as expected

Particle Number

CPC110

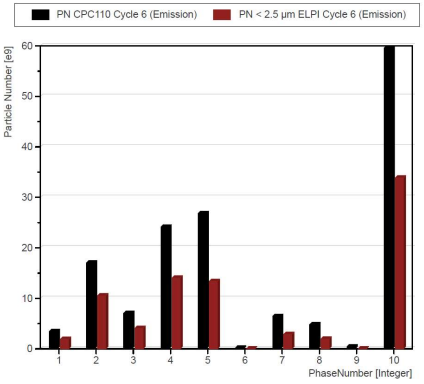
Particle number per test:	1.501E+11 #
Particle number per km:	7.808E+08 #/km

OPS

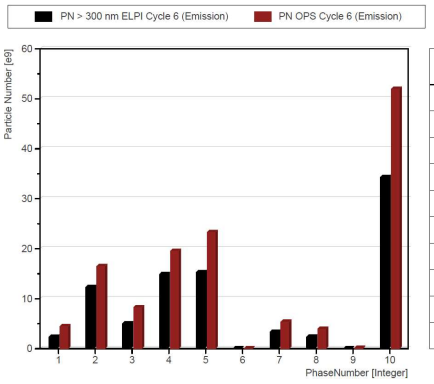
Particle number per test:	1.333E+11 #
Particle number per km:	6.936E+08 #/km

ELPI

Particle number per test:	8.997E+10 #
Particle number per km:	4.681E+08 #/km

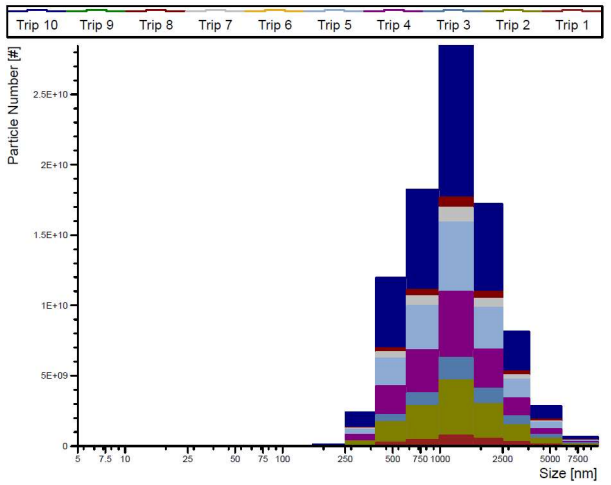


Trip Integer	CPC e9	ELPI e9
1	3.47	1.95
2	17.05	10.57
3	7.09	4.11
4	24.16	14.06
5	26.84	13.39
6	0.200	0
7	6.45	2.91
8	4.84	1.98
9	0.449	0
10	59.60	33.90



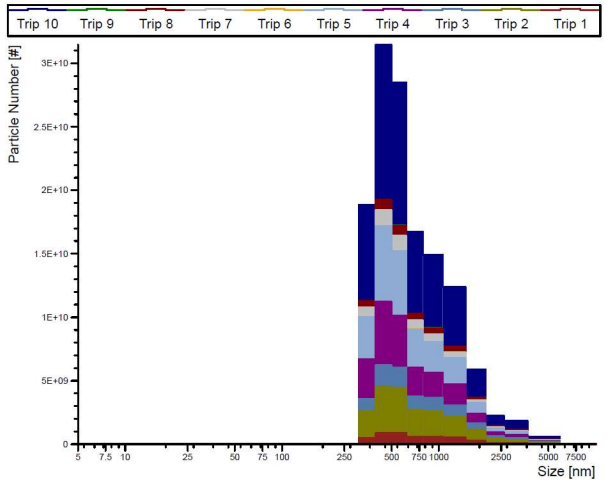
Trip Integer	ELPI e9	OPS e9
1	2.37	4.49
2	12.31	16.48
3	5.04	8.25
4	14.87	19.53
5	15.28	23.29
6	0	2.11E-03
7	3.33	5.37
8	2.38	3.95
9	2.51E-04	0.147
10	34.30	51.95

ELPI Particle Size Distribution (Number)



Size nm	Total Particles #
16 - 30	0
30 - 54	0
54 - 94	0
94 - 150	0
150 - 250	1.16E+08
250 - 380	2.41E+09
380 - 600	1.20E+10
600 - 940	1.82E+10
940 - 1620	2.84E+10
1620 - 2460	1.72E+10
2460 - 3630	8.13E+09
3630 - 5340	2.85E+09
5340 - 10000	6.56E+08

OPS Particle Size Distribution (Number)



Size nm	Total Particles #
300 - 400	1.89E+10
400 - 500	3.15E+10
500 - 600	2.85E+10
600 - 800	1.67E+10
800 - 1000	1.49E+10
1000 - 1500	1.24E+10
1500 - 2000	5.89E+09
2000 - 2500	2.25E+09
2500 - 3500	1.84E+09
3500 - 5500	5.85E+08
5500 - 10000	2.75E+07

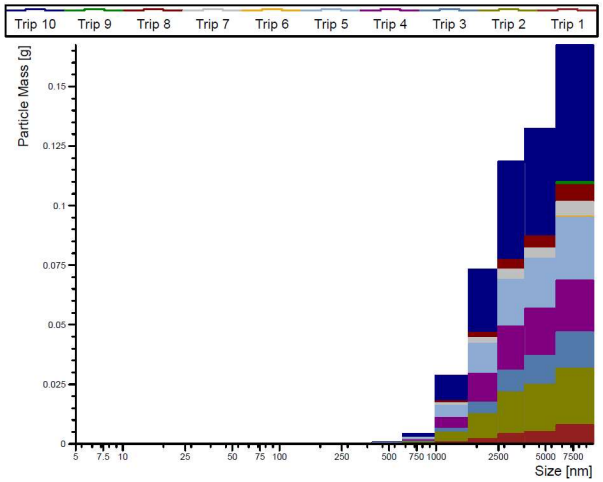
PMP-Brake PE test
PM and distribution

- Weighed PM and calculated PM from ELPI+ align quite well
- PM from OPS deviates.
  Actual density setting: 1 g/cm^3
  => *adjust density to e.g. 3 g/cm^3 ?*

Particle Mass

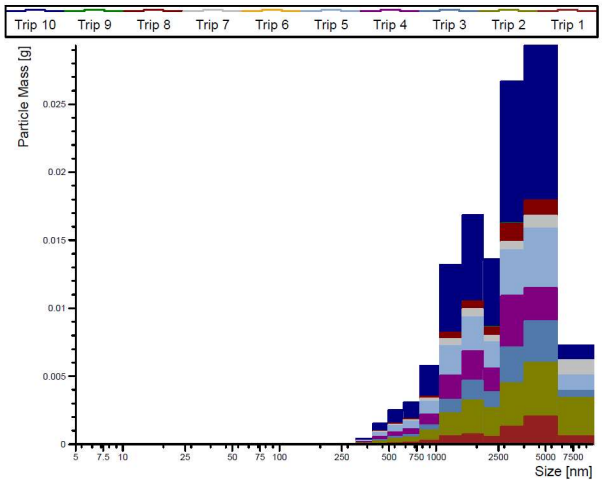
GenericPM	
Converted PM per test:(PM 2.5 / PM 10)	0.18 / 0.46 g
Converted PM per km:(PM 2.5 / PM 10)	0.95 / 2.38 mg/km
OPS	
Converted PM per test:(PM 2.5 / PM 10)	0.06 / 0.12 g
Converted PM per km:(PM 2.5 / PM 10)	0.30 / 0.62 mg/km
ELPI	
Converted PM per test:(PM 2.5 / PM 10)	0.11 / 0.48 g
Converted PM per km:(PM 2.5 / PM 10)	0.55 / 2.52 mg/km

ELPI Particle Size Distribution (Mass)



Size nm	Total Particles g
16 - 30	-1.02E-06
30 - 54	1.47E-06
54 - 94	2.17E-07
94 - 150	-6.55E-06
150 - 250	1.29E-05
250 - 380	8.92E-06
380 - 600	6.25E-04
600 - 940	4.29E-03
940 - 1620	0.0286
1620 - 2460	0.0731
2460 - 3630	0.118
3630 - 5340	0.132
5340 - 10000	0.167

OPS Particle Size Distribution (Mass)



Size nm	Total Particles g
300 - 400	4.14E-04
400 - 500	1.53E-03
500 - 600	2.50E-03
600 - 800	3.07E-03
800 - 1000	5.76E-03
1000 - 1500	0.0132
1500 - 2000	0.0169
2000 - 2500	0.0136
2500 - 3500	0.0267
3500 - 5500	0.0293
5500 - 10000	7.26E-03

PMP-Brake PE test
Conclusions

- PN as well as PM is in the range of the labs participating in ILS II and considered valid.
  However the PM10 is slightly higher compared to the highest numbers measured by the other labs.
  - bouncing can be exclude due to low load on >PM10 impactor and use of greased Al foils
  - consistent mass bills
  => we consider the PM measurements valid.
  We recommend to consider Impactor measurements in future PMP requirements with detailed definition how to use. Advantage of mass bill and validation.
- Large particle fraction – mostly dominant - is between 0,3 and 2 µm.
  => *we recommend PCRF factor determination for particles ≥ 1 µm additionally if PN limits are defined in EURO7 in future.*
- We consider the actual design rules for the enclosure too strict and the design too large.
  Large enclosure designs lead to higher dilution and may increase deviations by error propagation.
  - *unsymmetric designs should be accepted with e.g. rectangular inlets*
  - *flow homogeneity and maximum angles should be more dominant than dimensional requirements*