28.ETH-Nanoparticle Conference Zürich, June 2025

BENEFIT / COST

of Retrofitting Gasoline Vehicles with Particle Filters

Andreas C.R. Mayer

Diesel Particle Filters

the interdisciplinary VERT Research Network

1994 developped for tunneling NEAT
2000 some hundrets DPF in tunnel
2002-10 Swiss Construction 25'000

2011 EU adopts for Diesel, 2017 Petrol
2018 China, 2020 India
today > 300 Millionen worldwide

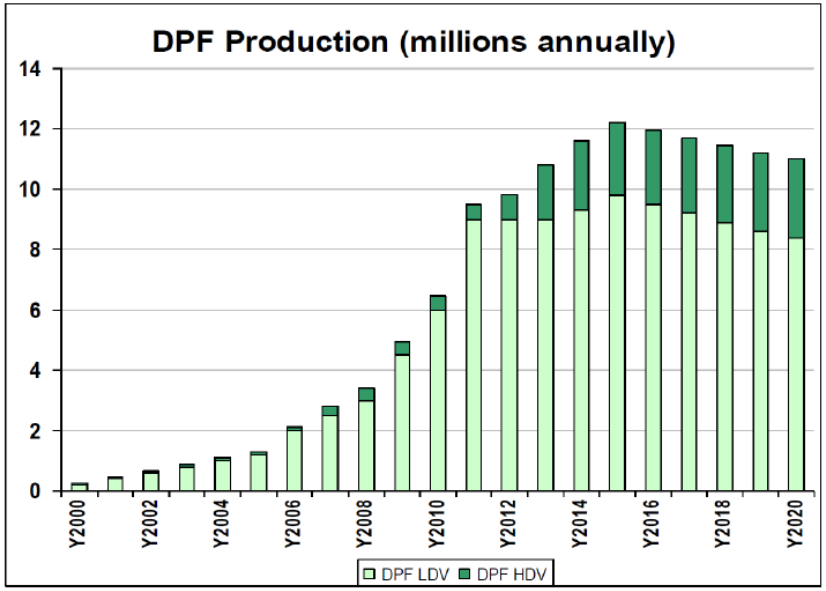
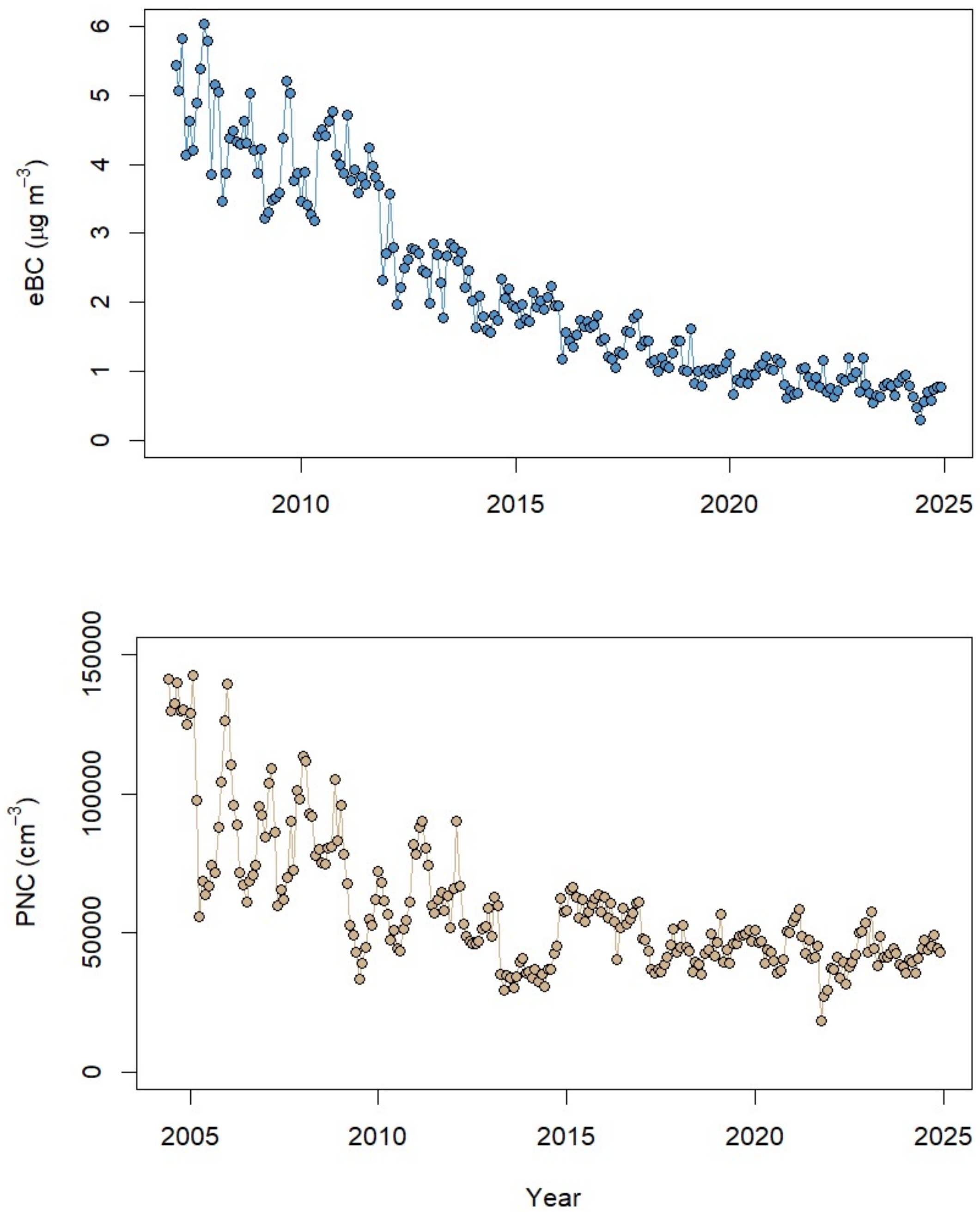


Fig. 6 DPF-Production annually for LDV and HDV – USA and Europe

10 Million premature death annually due to combusion particles **= 10 x Covid**

Thanks to Particle Filters > 2 Mio premature death less annually

UFP-Reduction at Härkingen motorway crossing reflects DPF & GPF



Source: Chr.Hüglin, EMPA

Benefit/Cost of DPF Implementation for Diesel Engines

B/C = 2.9 Switzerland 2003 for Retrofit of Constr.Machines

B/C = 13 US-EPA 2010 to justify «Diesel Emiss. Reduct. Act»

B/C = 24 EU-TSAP Report (Them. Strategy on Air Poll.) 2011

B/C = 33 IFEU-Study 2009 für DPF bei Baumaschinen

B/C = 30 US-EPA 2019 as Result of DERA

But what about Petrol Engines ?

Petrol Engines may emit as many PN as Diesels but less PM

We believe that the risk is given by each single particle so by the number and not by the individual nor the commulative mass

But classic Epidemiology believes in cummulative mass PM

This is our Dilemma

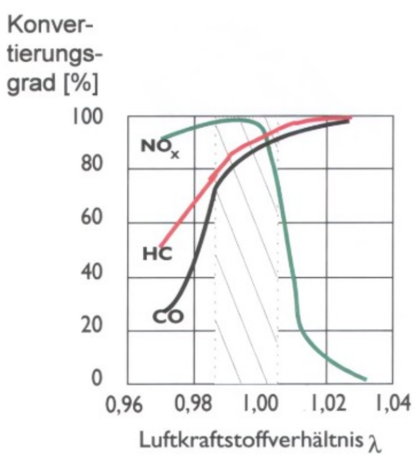
Population Diesel versus Petrol

15 % Diesel 85% Petrol

In total 1’500 million cars

Breakthrough with TWC for Gases
Particles not even mentioned in US-CAA

Carl. D. Keith (links) und John J. Mooney anlässlich der Verleihung der National Medal of Technology and Innovation (2003)



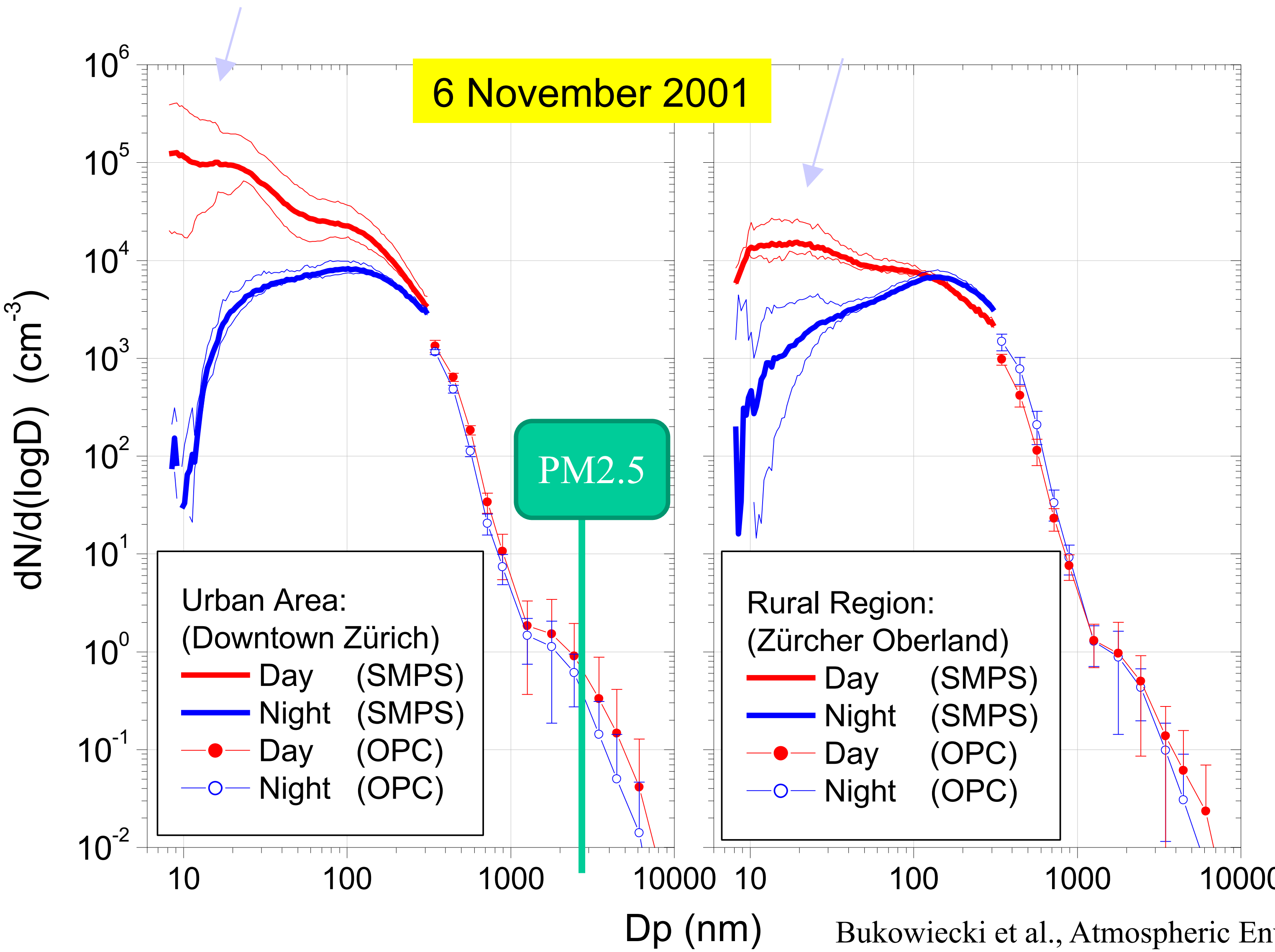
- 1978 John J.Mooney at Engelhard NJ co-invented the Tree-Way Catalyst
- only possible since Bosch had just invented the Lamba-Sensor and Volvo hat developed an electronic controlled injection petrol engine
- A groundbreaking development – now state of the art, but could only be introduced with lead-free fuel
- **Emission of UFP was not even discussed by the inventors and the TWC was open for UFP to pass**

Foto tomada el 20 de abril de 2006 a las 8:30 a.m. (smog fotoquímico)

All Megacities have the same pollution problem due to petrol traffic related particles

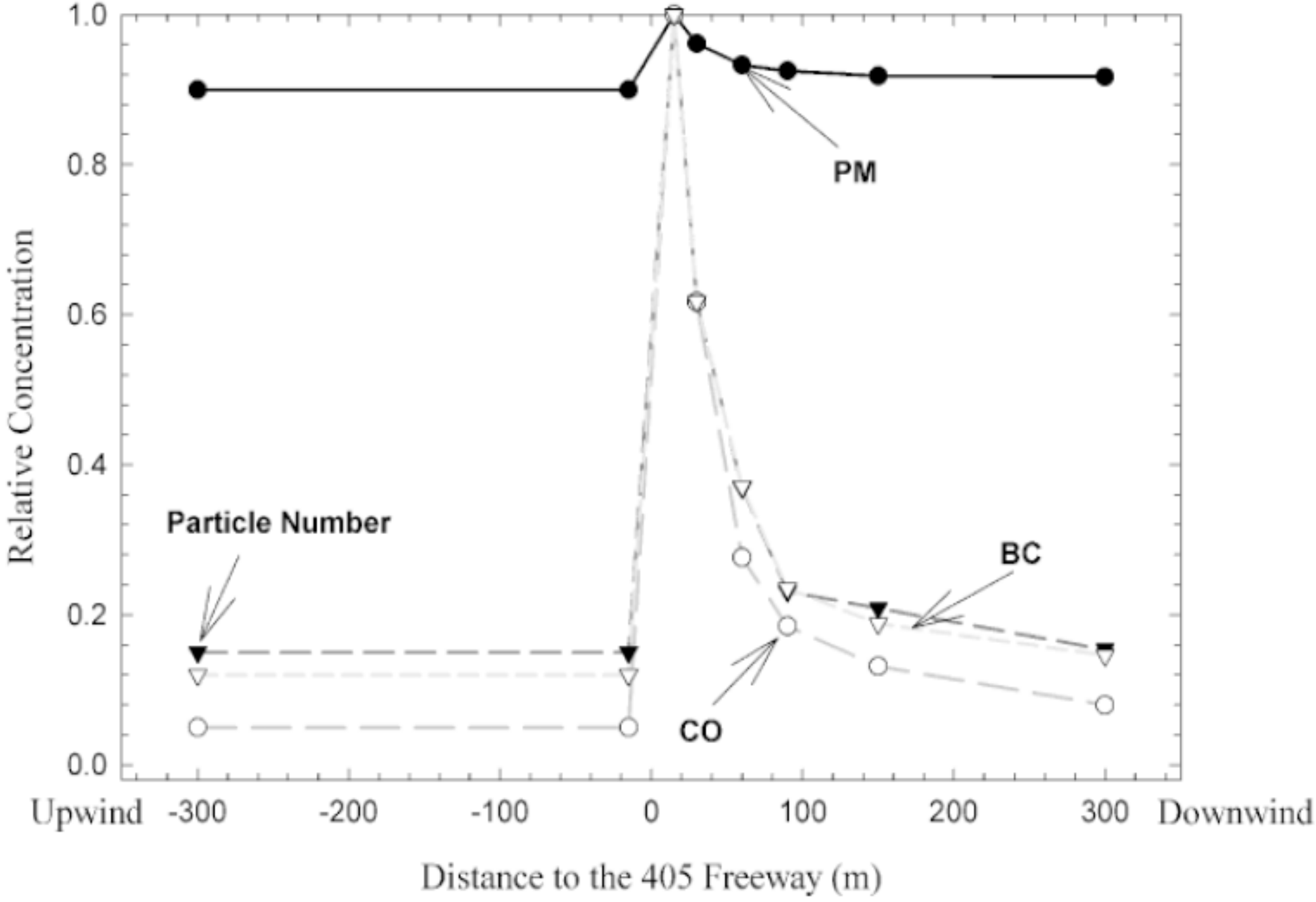
They believe to have a PM2.5 problem, but the particles are < 60 nm

Aerosol Number/Size – Distribution
City (Zürich) and Coutry (Zürcher Oberland)



Bukowiecki et al., Atmospheric Environment, 2002

PN reflects the traffic effect, not PM2.5



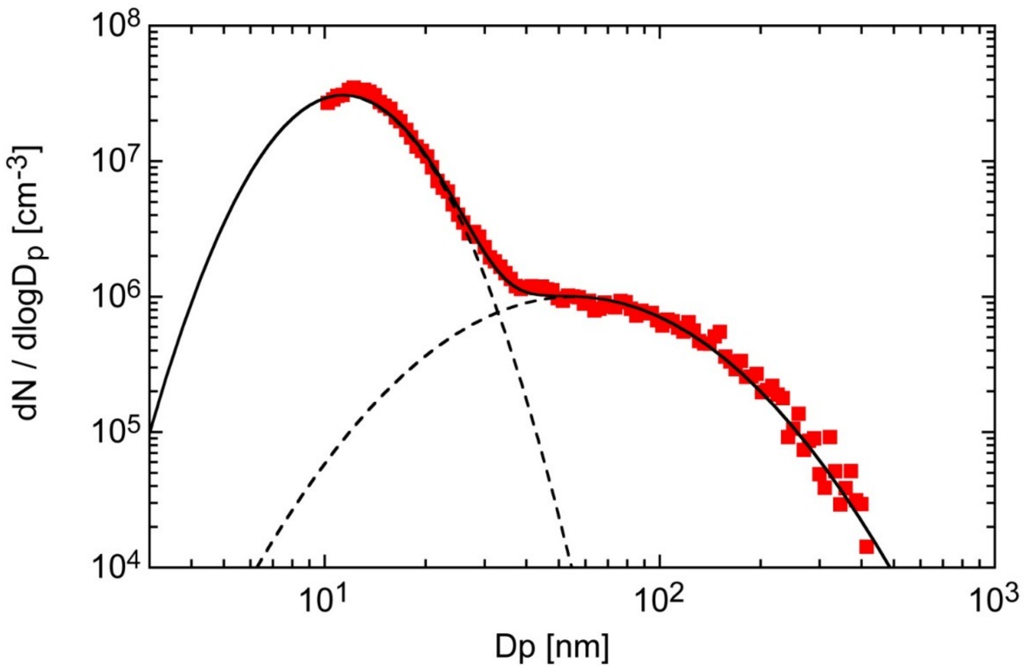
Source: Hinds, ETH-NPC 2010

Particle Emission of ICE

Diesel

Russpeak: 80 nm; 10^6

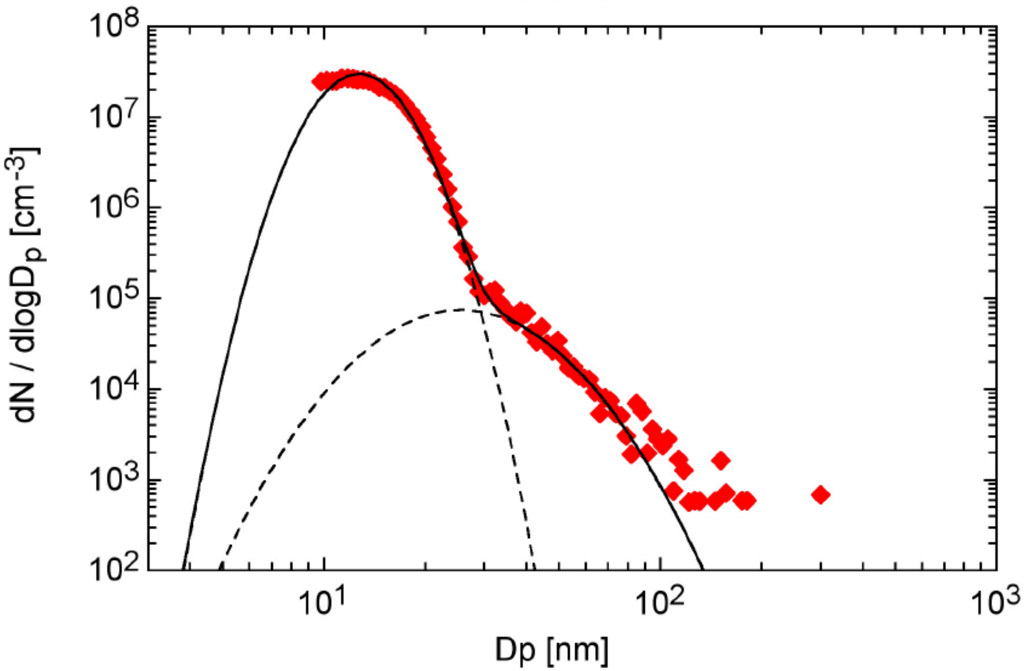
Aschepeak: 10 nm; 10^7

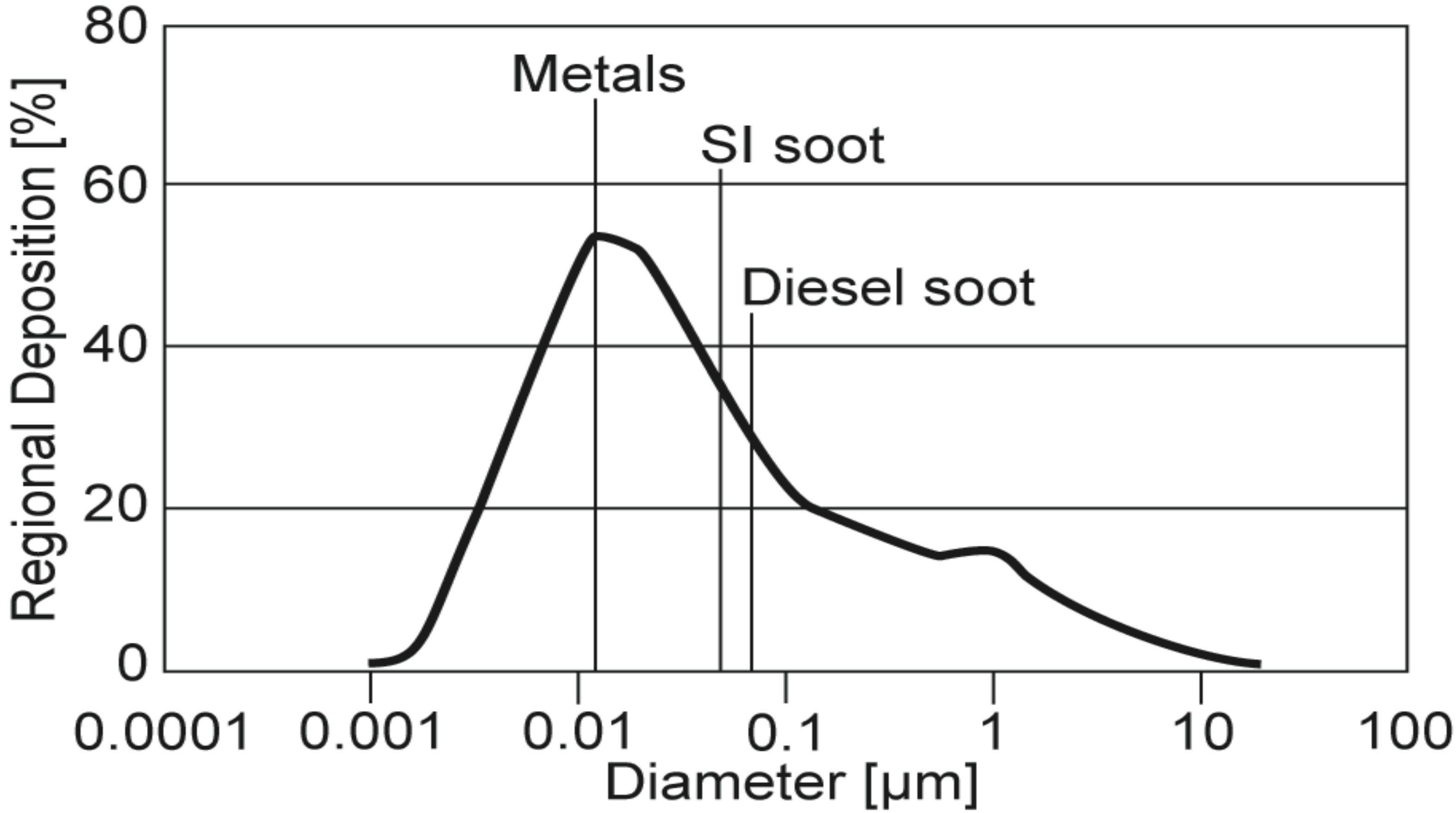


Petrol

Russpeak: 40 nm; 10^5

Aschepeak: 10 nm; 10^7

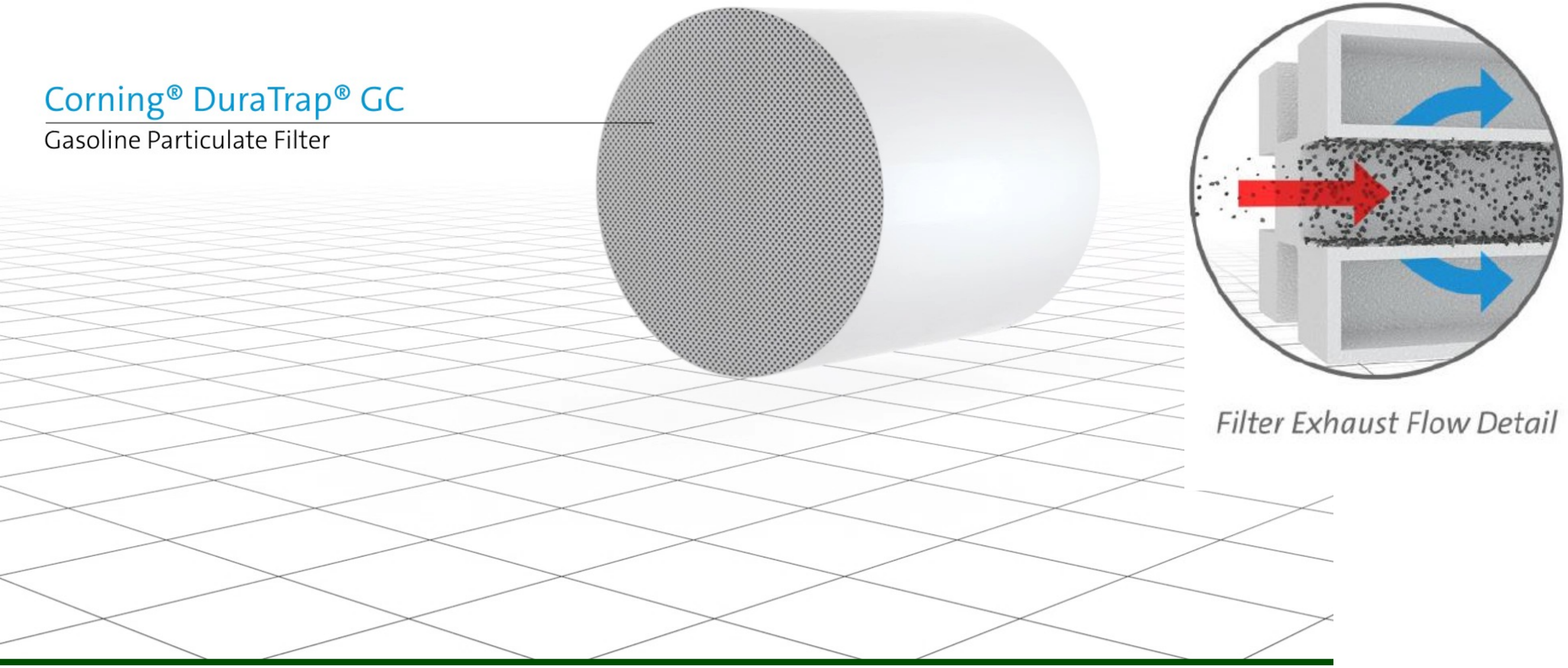




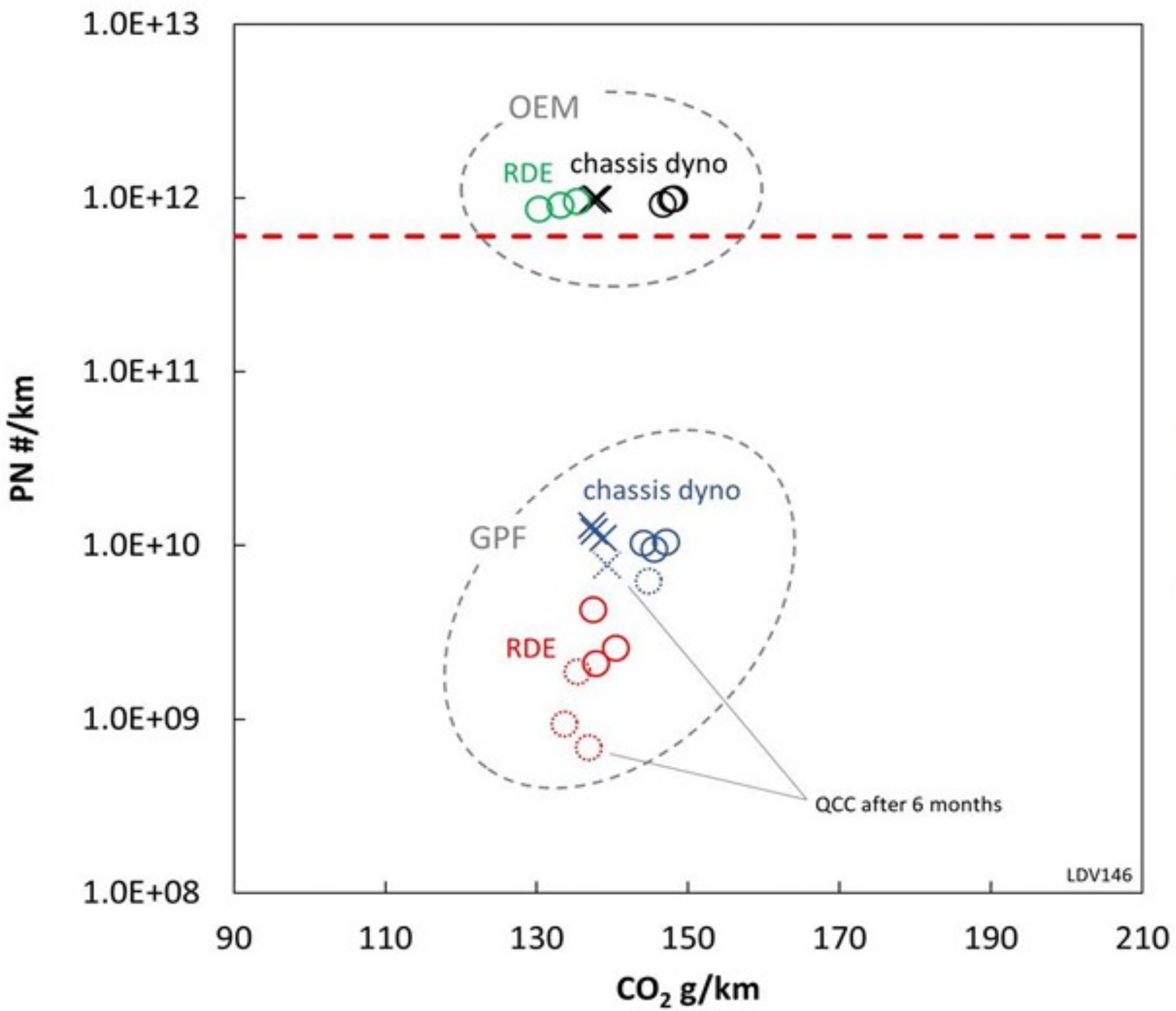
Deposition of UFP in the alveolar region

the Lung is an open door for ultrafine particles

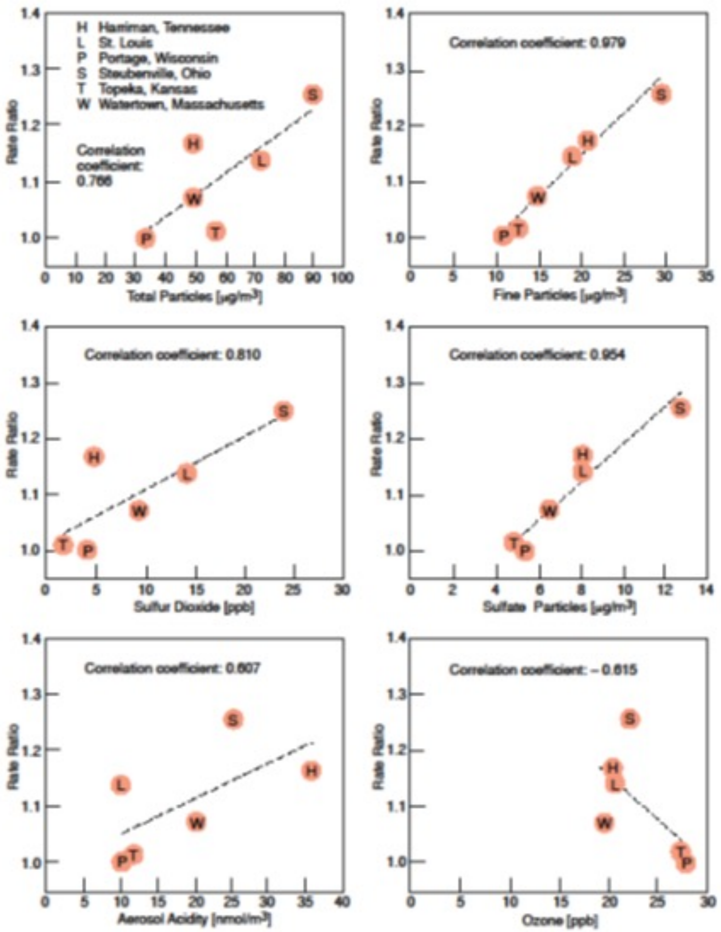
Ceramic Wall Flow Filter

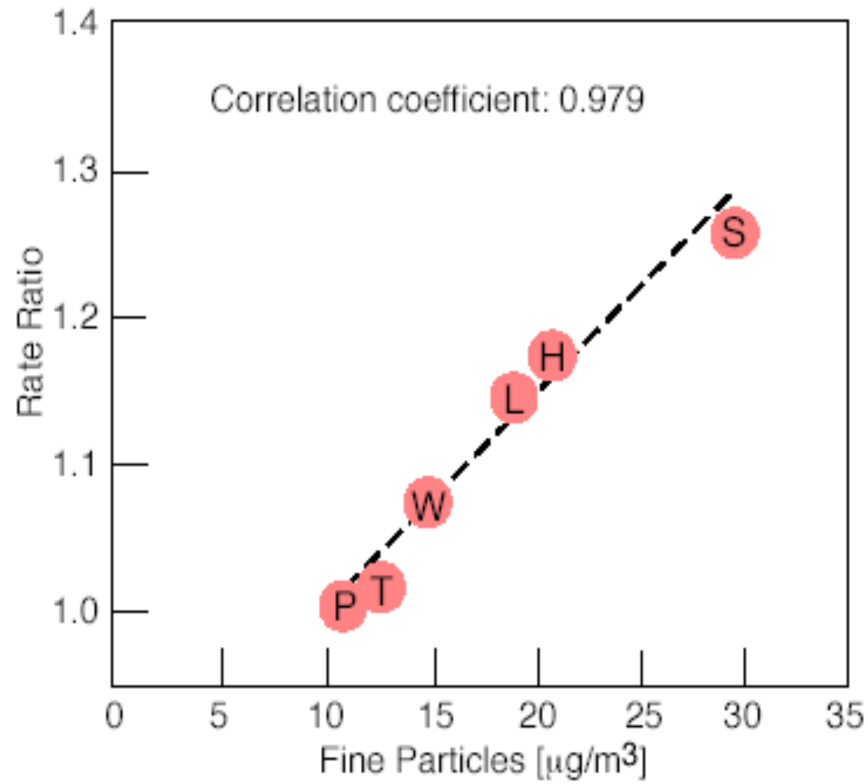


Newest Generation GPF by Corning



Quantification of Health Impact of PM





6-Cities-Study USA 1978-93
15‘000 cases

Source: Dockery NEJM 1993

H Harriman, Tennessee
L St. Louis
P Portage, Wisconsin
S Steubenville, Ohio
T Topeka, Kansas
W Watertown, Massachusetts

The classic Dose-Effect Factor with PM 2.5

But what is PM 2.5 ?

10 millions of premature deaths due to traffic

WHO region	Year	Population ($\times 10^6$)	Mortality attributable to air pollution (deaths $\times 10^3$)						
			$PM_{2.5}$					O_3	Total
			ALRI < 5 yr	IHD ≥ 30 yr	CEV ≥ 30 yr	COPD ≥ 30 yr	LC ≥ 30 yr	COPD ≥ 30 yr	
Africa	2010	809	90	55	77	11	2	2	237
	2050	1,807	158	185	262	38	5	12	660
Am		930	0	44	8	4	7	5	68
		91	0	75	15	7	11	11	119
Ea		02	56	115	86	12	5	12	286
		21	66	321	246	37	13	40	723
Eu		67	1	239	95	13	27	6	381
		86	1	307	156	18	37	11	530
So		62	64	327	250	124	15	82	862
	2050	2,332	104	865	807	419	48	227	2,470
Western Pacific	2010	1,812	19	299	794	209	107	35	1,463
	2050	1,861	16	413	1,120	309	155	57	2,070
World	2010	6,783	230	1,079	1,311	374	161	142	3,297
	2050	9,098	346	2,166	2,604	828	270	358	6,572

Lelieveld, Mainz 2018

GEOS-Chem spatial grid resolution[a]	Region[b]		Total deaths >14 years old, in thousands	Population-weighted annual mean $PM_{2.5}$ concentration, µg m^{-3}			Mean attributable fraction of deaths, % (95% CI)[d]	Deaths attributable to fossil-fuel related $PM_{2.5}$, in thousands (95% CI)[c]	GEMM function deaths attributable to fossil-fuel related $PM_{2.5}$, in thousands (95% CI)[e]
				$PM_{2.5}$ from all emission sources	$PM_{2.5}$ without fossil fuel	Estimated $PM_{2.5}$ from fossil fuel, %			
		Central America	1,148	10.06	3.03	7.03 (69.9)	8.2 (4.5-11.6)	94 (52-133)	80 (62-98)
			2,705	11.81	2.15	9.66 (81.8)	13.1 (7.8-18.1)	355 (212-490)	305 (233-375)
			250	12.01	1.76	10.25 (85.4)	13.6 (8.0-18.7)	34 (20-47)	28 (22-35)
			2,389	8.66	3.02	5.65 (65.2)	7.8 (4.5-11.0)	187 (107-263)	159 (121-195)
			8,626	19.22	4.68	14.54 (75.7)	16.8 (10.4-22.6)	1,447 (896-1,952)	1,033 (798-1,254)
Fine	Asia	Eastern Asia	25,468	51.72	8.68	43.05 (83.2)	30.7 (-189.1-52.9)	7,821 (-48,150-13,478)	4,945 (3,943-5,826)
Coarse		Western Asia & the Middle East	1,456	26.95	20.73	6.22 (23.1)	6.5 (3.0-9.9)	95 (44-144)	54 (43-65)
Fine	Africa		5,274	32.98	28.98	4.00 (12.1)	3.7 (-4.5-8.7)	194 (-237-457)	102 (81-121)
Coarse	Australia & Oceania		189	4.17	2.19	1.98 (47.4)	3.2 (1.6-4.8)	6.0 (2.9-9.0)	6.4 (4.8-7.9)
	Global		47,506	38.01	11.14	26.87 (70.7)	21.5 (-99.0-35.7)	10,235 (-47,054-16,972)	6,713 (5,308-7,976)

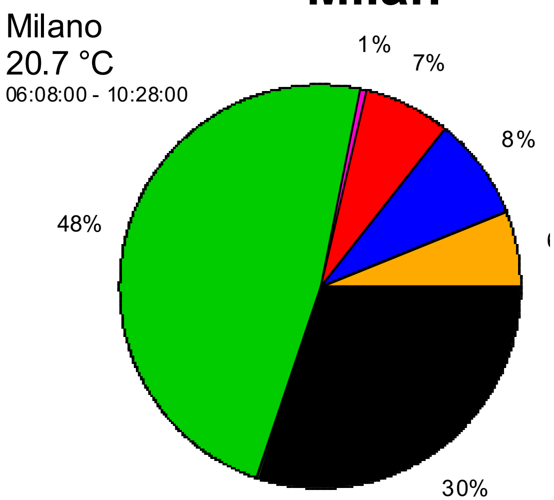
Schwartz, Harvard 2023

What is PM2.5 - Mass [mg/m3] of what ?

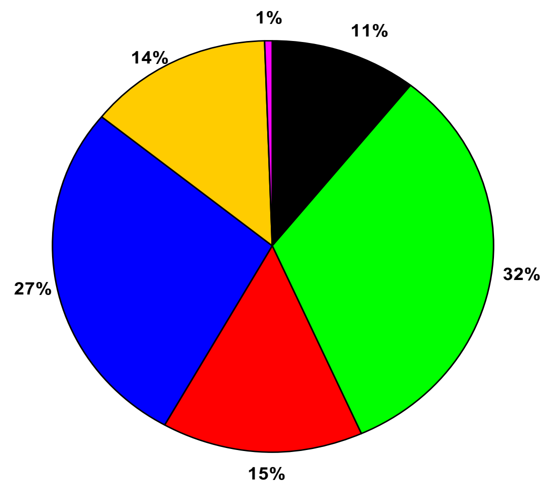
mix of unspecified substances – which is the toxic one ?

what represents the engine emission ?

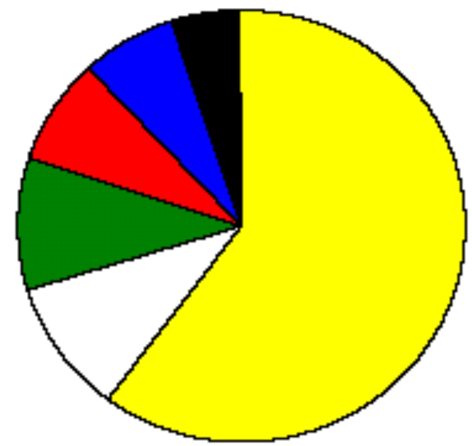
Milan



Zuerich



Hawai (?)



PM2.5 [µg/m³] **identical Mass**

But these 3 situations can definitely not represent same air pollution = toxicity

Black Carbon
Organic mass
Nitrate
Sulfate
Ammonium
Chloride

Which is the Toxic Substance within PM2.5 ?

Health Effect Equivalence Analysis HEQ, a tool to answer this question. Simplified Example:

Toxicity -Parameters	Sulfates Nitrates	Mineral Dust	Solid Nano-Particles
invasive (mobility) penetrate membranes ?	✯ 1	✪ < 0.1	✯ 1
Insoluble Solids ?	✪ 0.01	✯ 1	✯ 1
persistant collected and stored ?	✪ 0.01	✯ 1	✯ 1
carcinogen mutagene, genotoxic ?	✪ 0.01	✪ 0.01	✯ 1

HEQ The Health Effect Equivalent Model
PM2.5 Substance Classes

- **Carbon**:
  - EC (fine, coarse)
  - OM / OC (overlap with pPAH)
  - pPAH
- **Inorganics**:
  - NH4+
  - NO3-
  - SO4-
- **Metals and Metaloxides** :
  - transition metals (all; overlap with individual metal oxides)
  - FeO
  - MgO
  - CaO
  - precious metals (all; maybe individual: Pt, Pd, Rh)
- **Minerals**:
  - mineral dust (silicates, incl. Al, Mg, ...

Source: M.Kasper, ETH-NPC 2007

Toxicity Contributors

along the way of the particle entering the organisme

process	parameters	quantify
Location of aerosol deposition	Diffusion	**Size,** Hygroscopicity
Contact with body surface	Solubility in water… ... in Mucus, Surfactants?	**solubility** Lipophility
Translocation	Cell membrane penetration; Phagocytosis	**Size**
Interaction	Overall Toxixity Bioavailability Cytotoxicity Mutagenicity Carcinogenicity	**MAK (Threshold)** ? ? ? ?
Excretion	Biopersistence	Decay Time

multiply

HEQ Index Value

Source: M.Kasper, ETH-NPC 2007

HEQ Health Effect Equivalent
based on physico-chemical parameters

PM10-HEQ Influence Factors *Example*

PM10-Compounds	EC < 500 nm	EC > 500 nm	Metals Minerals > 500 nm	Metals <100 nm	Sea Salt	OM	Benz(a) Pyren	Ammonia	Nitrate	Sulfate	Water
Mass %	15	2	10	2	15	20	0.01	10	10	10	6
Solubility	1	1	1	1	0.001	0.2	1	0.01	0.01	0.1	0.0001
Mobility	1	0.1	0.1	1	1	1	1	1	1	1	1
Toxicity	1	0.1	0.1	10	0.01	0.1	50	0.1	0.1	0.1	0.001
HEQ -Index	1	0.01	0.01	10	0.00001	0.02	50	0.001	0.001	0.01	0.000001
PM10-HEQ	15	0.02	0.1	20	0.00015	0.4	0.5	0.01	0.01	0.1	0.000006

Quantification Elements

and Conclusions for the Urban Environment

- **Toxicity of Air Pollution (PM2.5) is dominated by traffic related Nano-Particles**
- **VERT-Filtration of all engines (plus furnaces) eliminates all particles thus eliminates Toxicity of Air Pollution**
- **Mortality due to traffic related air pollution nearly eliminated by implementation of DPF and GPF**

Financial Elements

- **To avoid one premature death is a monetized Benefit for the Society of 1M€**
  (Sommer 1996, Künzli 2001, WHO, EU, IMO > 1M€)
  10 M deaths - worldwide anual financial burden of 10^{13} € (twice BIP of G.)
- **To avoid one kg of PM 2.5 is for Swiss conditions a monetized Benefit for the society of 500 €**
  (EU-Studies NEEDS and IMPACT 2008)

→ if this kg PM2.5 contains 10% Diesel Particles by mass the Benefit of avoiding 1 kg Diesel Particles is 5000 €

→ If this kg PM2.5 contains 5% Petrol Particles by mass the Benefit of avoiding 1 kg Petrol Particles is > 10000

This mirrors the assumption that the health risk of UFP is the same per particle and not per cummulative particle mass

Top-Down Benefit/Cost Model for GPF

in a highly polluted city with only gasoline vehicles

- One billion cars kill 10 million persons annually
  on average 100 cars kill one person every year
- Health cost of one death is 1 M€ (WHO)
- one car causes health cost of 10 k€ per year
- one filter avoids health cost of 10 k€ per year
- over 5 years life the Benefit of one filter is 50 k€
- Cost of GPF retrofit is 1 k€

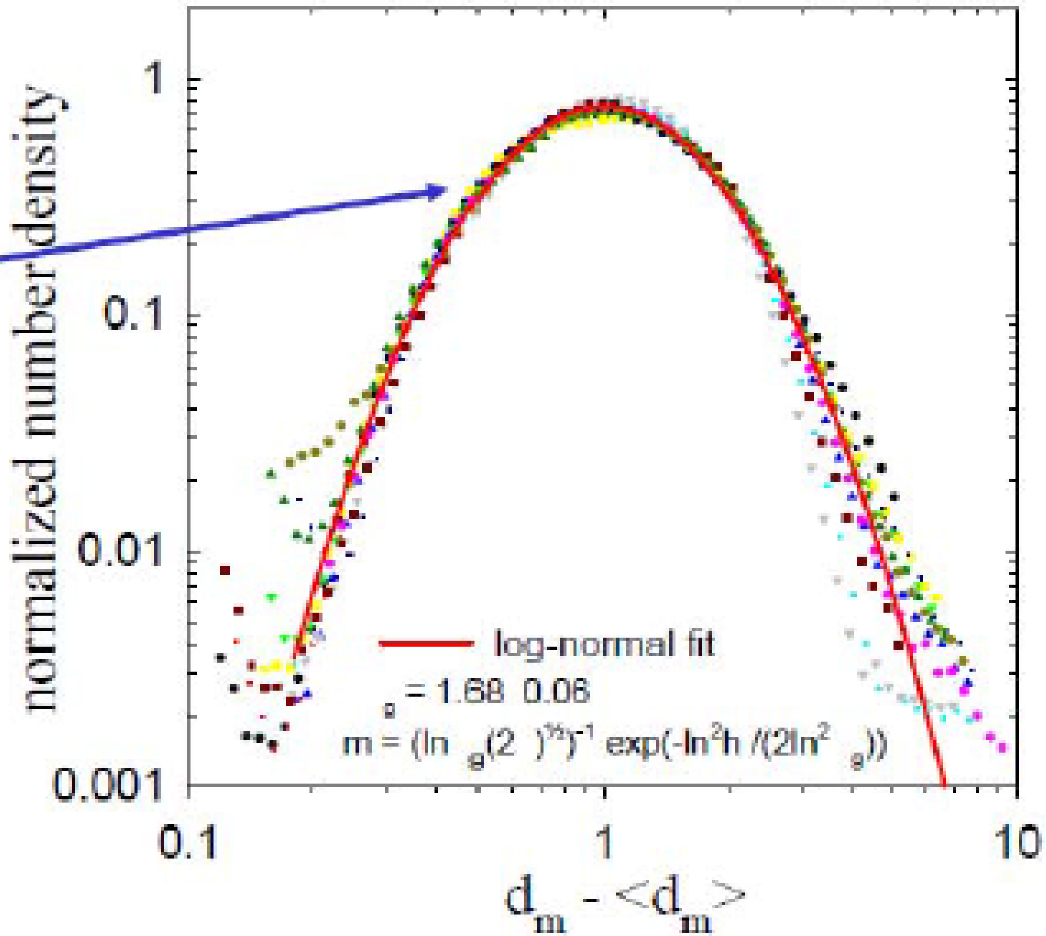
Benefit / Cost = 50 :1

Bottom-Up Model based on Particle Number

following the Maricq-Algorithm,

respecting size statistics, fractal dimension and density

- PMP method removes nuclei particles
- Remaining solid particles follow lognormal distribution with 2 free parameters
  - Number
  - Mean diameter
- Mean diameter between ~40 – 80 nm
- To fulfill number standard of 5×10^{11} #/km → PM mass must be < 1 mg/km



$$\text{Mass} = N\ \pi/6\ \rho_0\ d_0^{(3-df)}\ \mu_g^{df}\ \exp(df^2\ (\ln\sigma_g)^2/2)$$

Bottom-up Model based on PN

In-use petrol vehicles: 10^6-10^8 Partikel pro cc

(corresponds to 10^{12} – 10^{14} #/km during WLTP)

Mass per particle 1 Femtogramm 10^{-15} g

Mass per cc: 10^{-7}g = 10^{-4} mg per cc

Mass per m^3 = mass per km: 100 mg (with 7l/100 km)

Mass per year 2000 g

Mass per life 10 kg

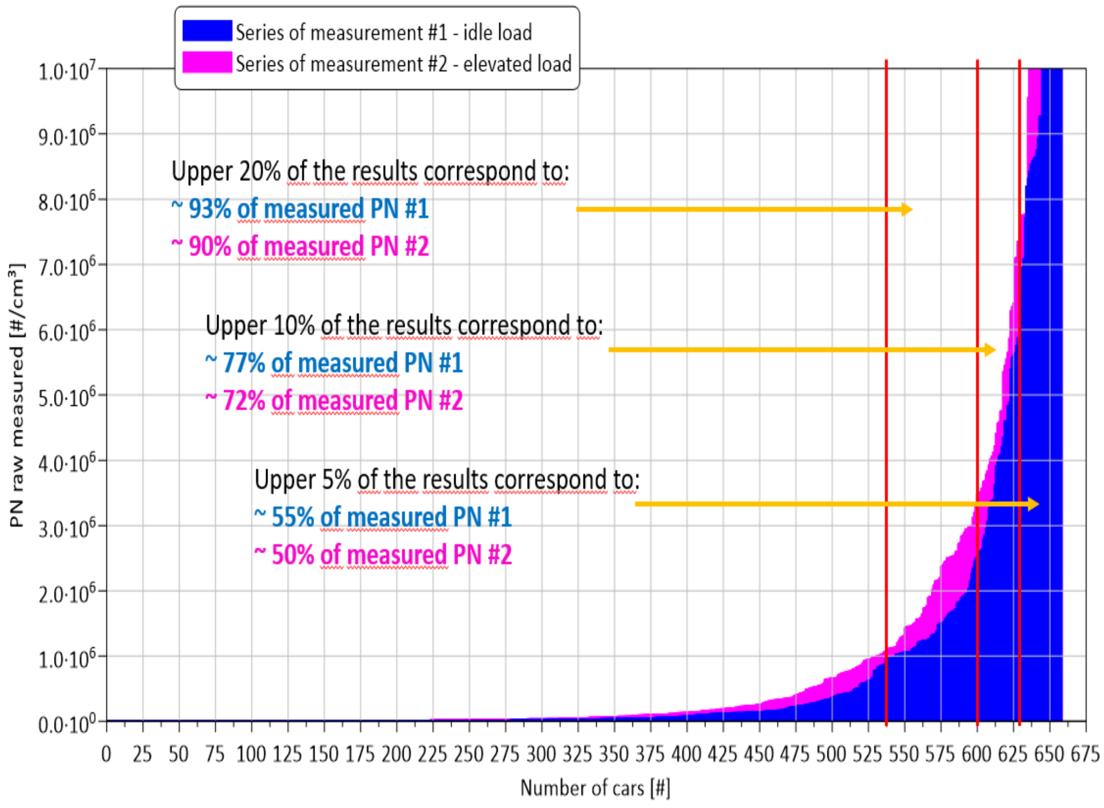
Health cost 10'000 Fr per kg petrol soot

Benefit / Cost for a car with 10^8 P/cc: 100:1

for emissions of average car 10^7 P/cc →B/C = 10:1

for emissions of clean cars 10^6 P/cc →B/C

Do we need to retrofit all vehicles? maybe only 10%, the DirtyTail



In this case the benefit / cost will raise to > 100:1

Conclusion

Benefit/Cost: 50:1 in the overall view

Benefit/Cost: 10:1 to 100:1 depending on emissions and model

Following the DirtyTail Paradigm and retrofit only high emitters: B/C > 100:1

And on Top Global Warming Mitigation in Polar Regions and on Glaciers

VERT-Team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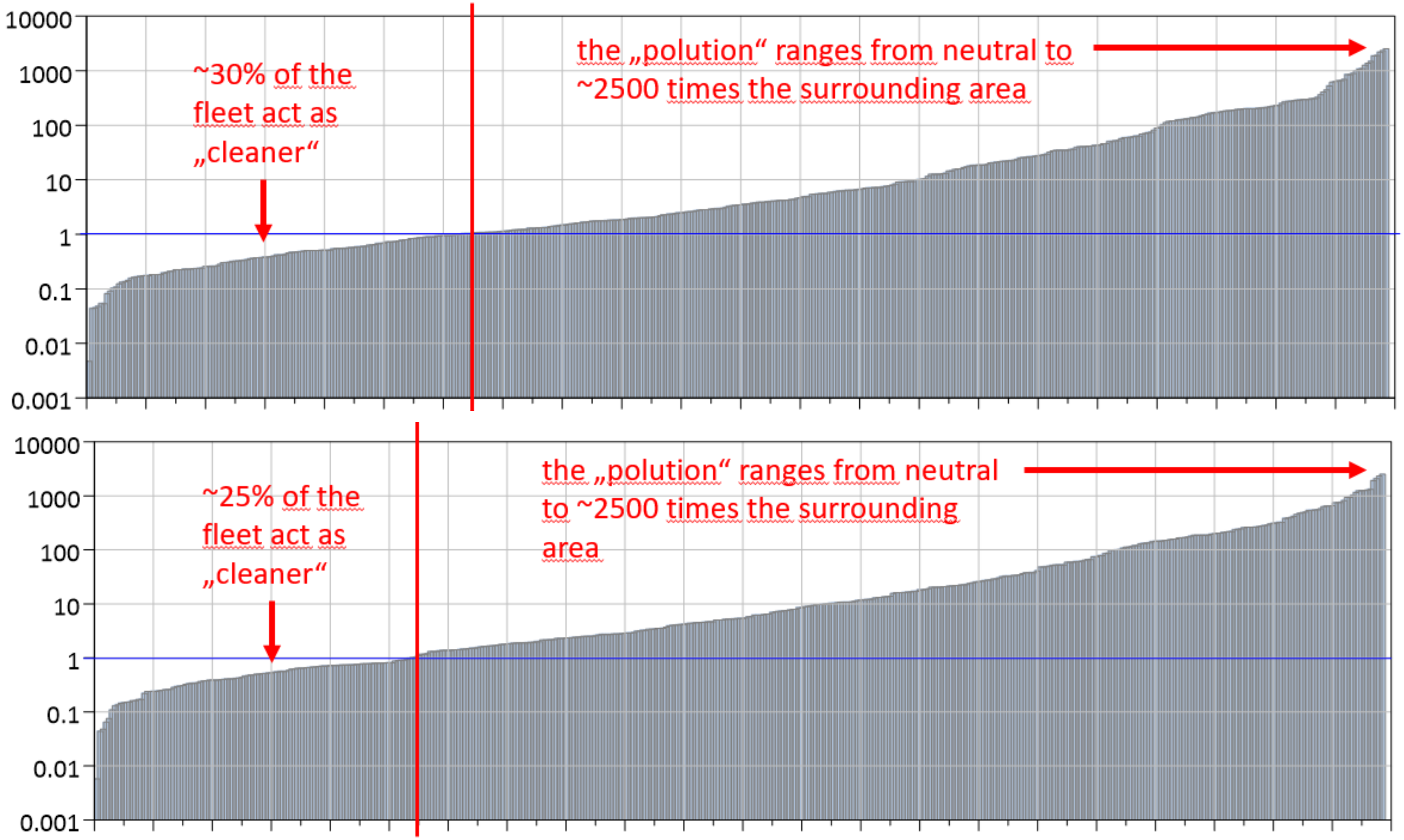
Matter Engineering AG
M. Kasper
& sein Team
P. Gehr
Die Biologen in Fribourg
A. Mayer

Particle Emissions of the Swiss Petrol Fleet

at 2000 rpm, idle; upper graph: no load;
lower graph with some load by air conditioning



Overall Mobility and Consequences

Last week we counted 1480 million cars ww (plus 83 M HDV and 4 M Buses)
Every Second 3 more, 100 M per year more
Overall E-Mobility is only 3.3 % of this fleet

→We will have to deal with combustion engine emissions for many more years

We demonstrated the health Risk by Gasoline Particles also in large Projects in China and Mexico

No Diesel Cars in Beijing

20.12.2012 **90-120.000 PN/cm³**
particle size 40-50 nm
PM2.5>300→1200µg/m³

18.12.2013 **200.000-500.000 P/cm³**
particle size 40-50 nm
PM2.5<50µg/m³

Apparent disconnect between PN number concentrations and PM concentrations in highly polluted atmospheres
(Haze = SOA on nanoparticle condensation cores)

These cities have no Diesel LDV fleet
Emission is high because of Petrol Engine emission

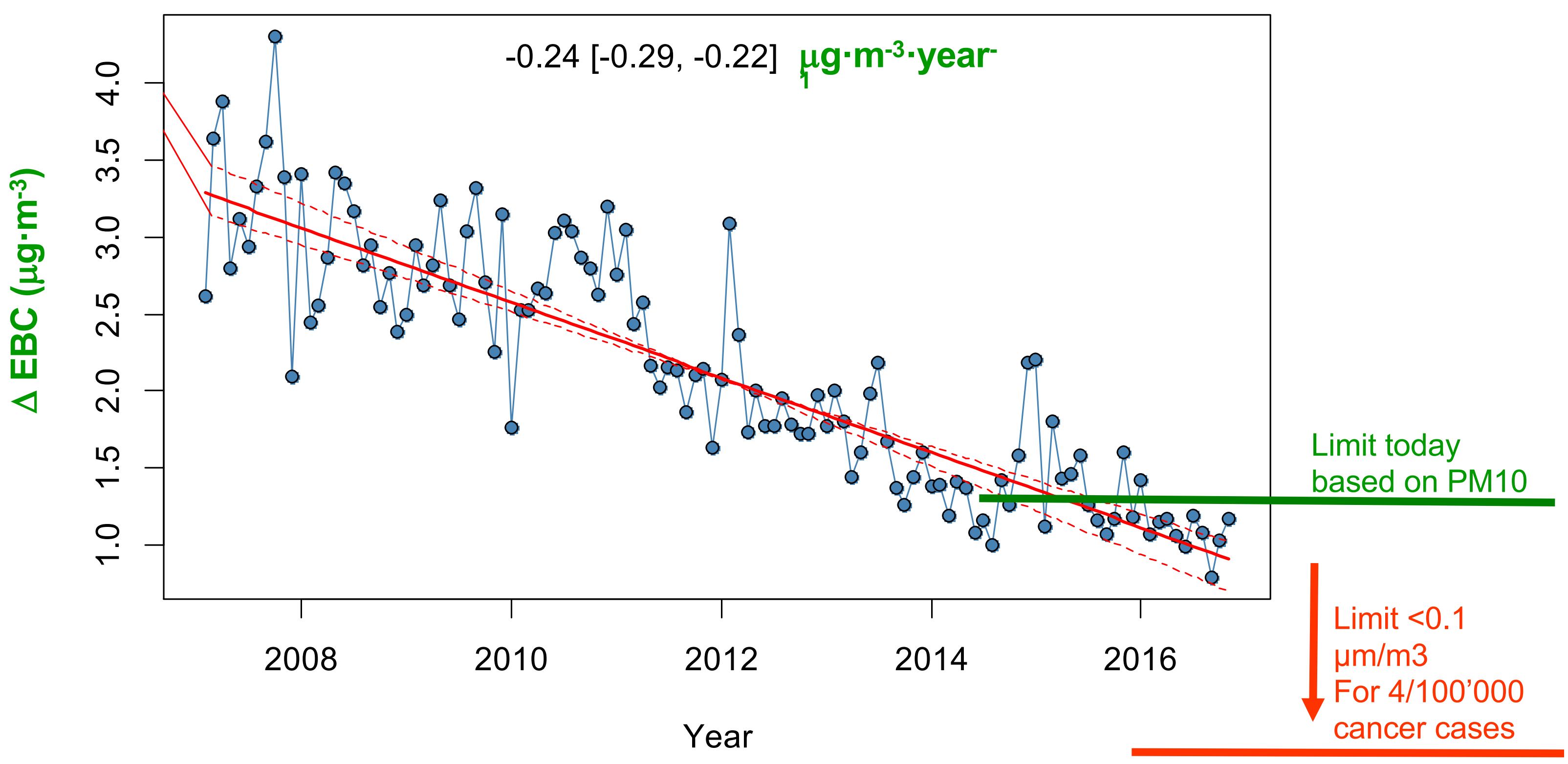
Foto tomada el 20 de abril de 2006 a las 8:30 a.m. (smog fotoquímico)

All Megacities have the same pollution problem due to growing size and traffic
VERT is everywhere active to transfer Best Available Tehnology for Health and Global Warming Mitigation

Pictures from VERT retrofit pojects

and the Result:
Cleaning the Air by DPF in Switzerland

Monitoring BC at the motorway crossing Härkingen



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Classic Epidemiology does not accept this model

VERT Filtration of all ICE eliminates all particles
so we claim
that the toxicity of the breathing air is eliminated

but PM2.5 mass is only reduced
by 5% (gasoline) to 10% (diesel)
so classic Epidemiology claims only 5-10%
health effect elimination

and this is the Dilemma

which needs new approaches