Luzern 14.Juni 2012

Benefit/Cost-Analysis when using Emission Control Devices for IC Engines

Andreas C.R.Mayer

In other words

are „Health Benefits“ and „Emission Control Devises“ like DPF and SCR different categories – **uncomparable**

or can they be **linked by money** –
using their monetary value as overall denominator ?

FOR THE OWNER, DPF/GPF has no direct commercial advantage ***„nothing but a Cost Factor“***

- Purchase price
- Installation cost
- Some maintenance involved
- Backpressure reduces fuel economy
- Warranty for the engine may be refused
- Additional safety and dependebility aspects ?

FOR GLOBAL SURVIVAL

the contribution to limit global warming might be the (a) decisive factor

If filters can contribute to lower global warming by eliminating Black Carbon Particles

→ what is the co-benefit for the global society and how does this translate into a monetary value?

THE REGULATOR: WHO 2012 and Environmental Law in Switzerland, EU: EURO-6, USA CAA 201 etc

- **Diesel Particle Emission is carcinogenic**
- **has no "no-effect" level**
- **Must therfore be minimized**
- **Best Available Technology BAT required**

But the law requires also ....

THE LAW requires in addition that the measures chosen must be

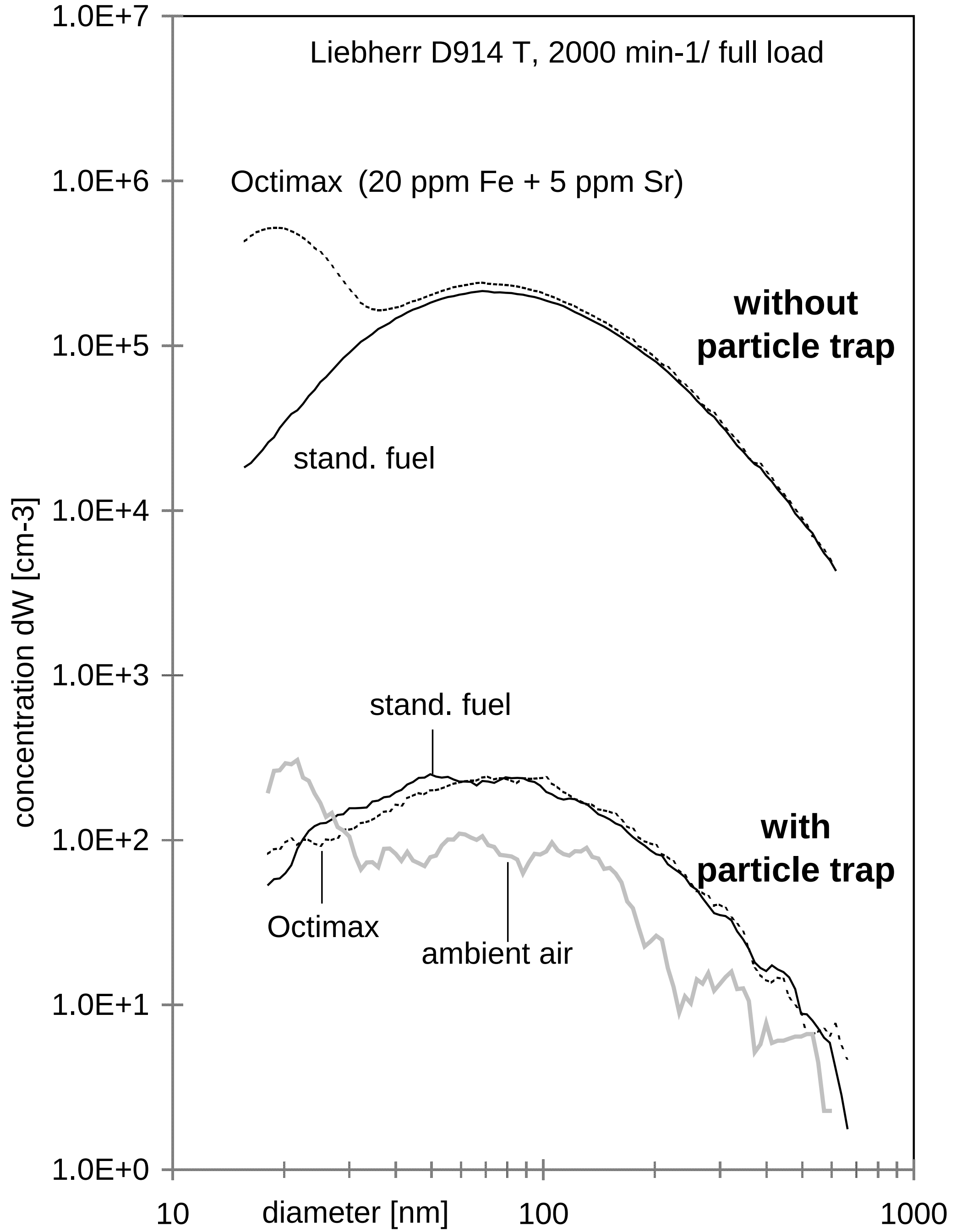
- **technically feasible** (technisch möglich)
- **operationally reliable** (betrieblich möglich)
- **cost must be in a reasonable relationship to benefit** (wirtschaftlich tragbar)

This is, what we intent to investigate here:

Extruded Cordierit and Silikonkarbid typical ceramics for honeycomb filters

Particle Elimination

with CORNING-Filter and FBC



Benefit / Cost

For the Society Benefits must be quantified in Monetary Terms and compared to Cost in order to decide whether a Measure is economic and therefore justified or not

Benefit / Cost – Factor

[€] / [€]

a dimensionless factor → comparing apples to apples

FOR THE SOCIETY Soot reduction includes two Categories of Benefits

- Public Health
- Global Warming

How to convert Public Health Effects into Monetary Terms ?

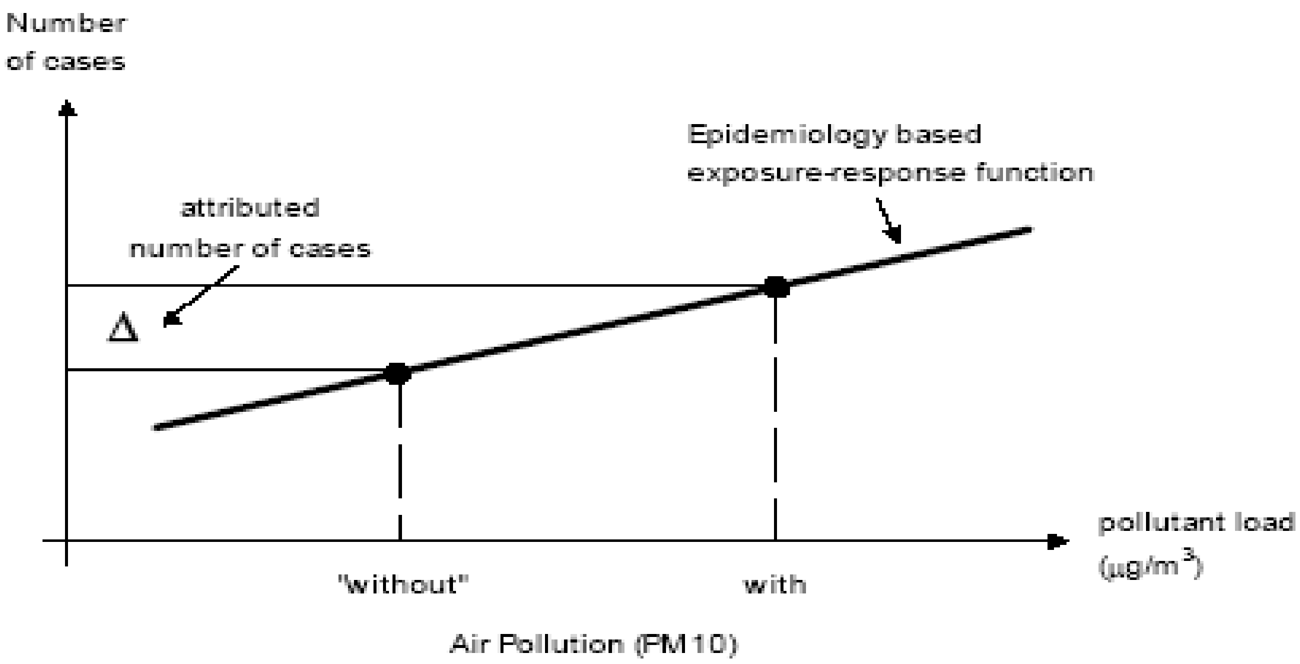
WHO and many National Health Institutions have investigated the multitude of so-called “external cost elements” like hospital cost, medication, lost working time, lateral cost, tax loss etc. in function of ambient air pollution and established dose-effect relationships.

They have statistically linked these cost to ambient air pollution to individual pollution parameters like Ozon, CO or PM10 and evaluated the integrated monetary effects on population living in megacities, cities or countryside.

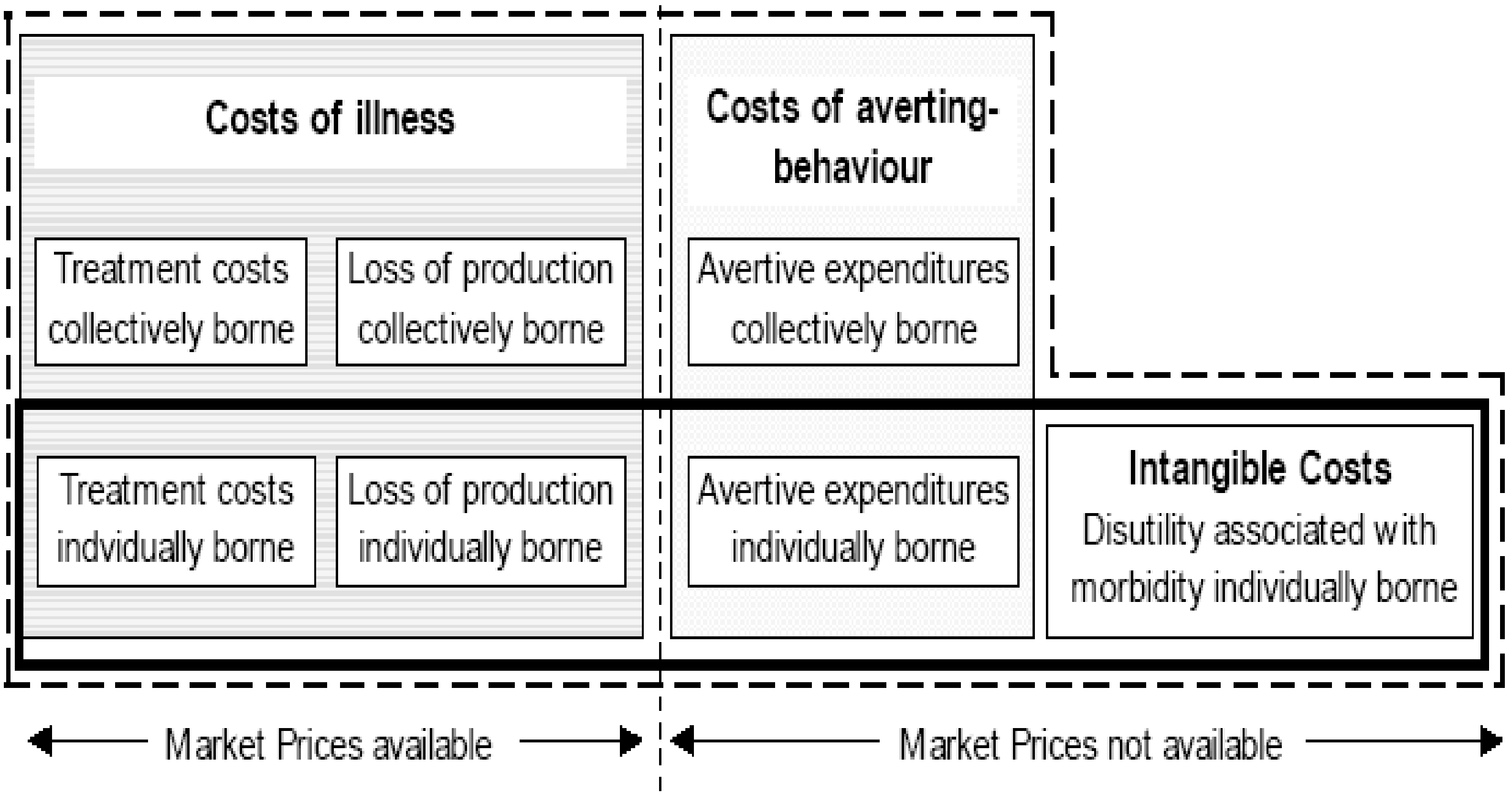
Epidemiologic Model for Health Cost „Dose/Effect Proportionality“

„Dose“ is PM10 – Concentration

„Effect“ can be Cancer Cases etc



Health Cost Elements



Results do vary depending on countries and whether metropolitan areas or non-urban polulations are investigated:

The IMPACT cost factors (2008) as well as the cost factors from NEEDS (2008) cover health costs, building and material damages as well as crop losses. See Table on following slide:

Table 1 Air pollution cost factors in EUR/ton of pollutant (€$_{2008}$ values)

Pollutant	$PM_{2.5}$ (exhaust)			PM_{10} (non-exhaust)			NO_x	NMVOC	SO_2
Region type	Metropolitan	Urban	Non-urban	Metropolitan	Urban	Non-urban			
Source	HEATCO	*UBA/ HEATCO	HEATCO	*UBA/ HEATCO	*UBA/ HEATCO	*UBA/ HEATCO	NEEDS	NEEDS	NEEDS
Country									
Austria	482,200	155,900	80,700	192,900	62,400	32,300	13'600	1'600	10'000
Belgium	483,400	156,000	104,400	193,400	62,400	41,700	8'700	2'600	10'900
Bulgaria	70,500	22,700	18,100	28,200	9,100	7,200	7'100	400	6'200
Czech Republic	355,400	114,500	88,200	142,200	45,800	35,300	10'600	1'100	9'500
Denmark	436,400	140,700	51,300	174,500	56,300	20,500	5'300	1'200	5'700
Estonia	261,700	85,000	44,200	104,700	34,000	17,700	2'800	600	4'500
Finland	432,600	139,400	36,100	173,000	55,800	14,400	2'600	600	3'500
France	438,600	141,200	87,700	175,500	56,500	35,100	10'500	1'400	9'900
Germany	430,300	138,800	83,900	172,100	55,500	33,600	12'700	1'400	10'900
Greece	338,600	109,100	47,700	135,400	43,600	19,100	2'700	600	5'800
Hungary	288,900	93,000	74,100	115,600	37,200	29,600	12'400	1'000	9'100
Ireland	537,200	173,400	56,200	214,900	69,300	22,500	4'400	1'100	5'400
Italy	397,400	128,400	72,300	159,000	51,400	28,900	9'500	1'100	8'700
Latvia	245,300	78,900	45,600	98,100	31,500	18,200	4'000	700	5'000
Lithuania	266,300	86,500	53,300	106,500	34,600	21,300	5'600	800	5'700
Luxembourg	877,100	282,400	125,000	350,800	112,900	50,000	12'700	2'400	10'300

Switzerland	498,700	160,500	82,400
Poland	248,900	79,900	74,700

Value chosen for CH:

460 CHF/kg PM10

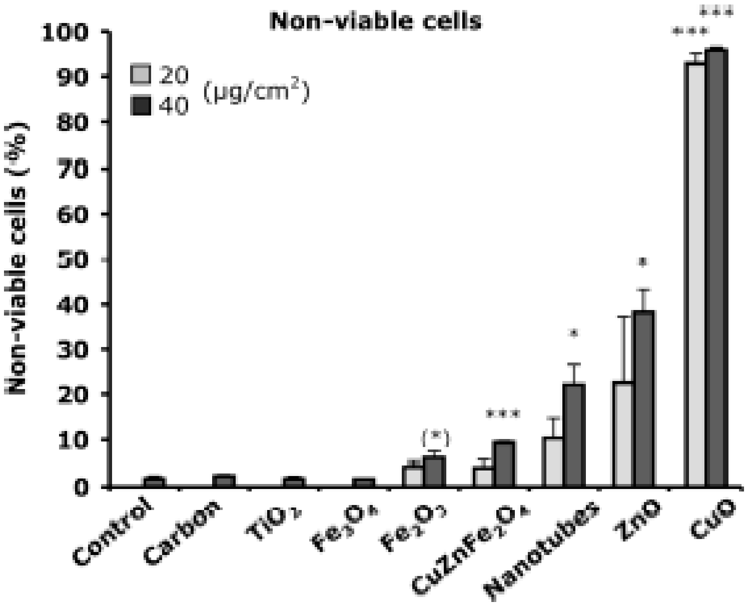
But is PM10 the right dose metric ?

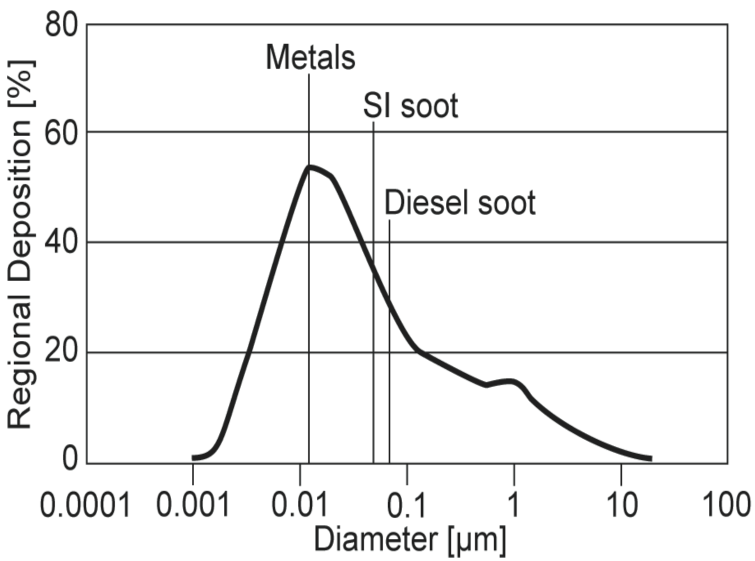
What makes Particles toxic ?

Cytotoxicity

Substances in soot particles have very different toxicity

Karlsson, Chem, Res.Tox 1998



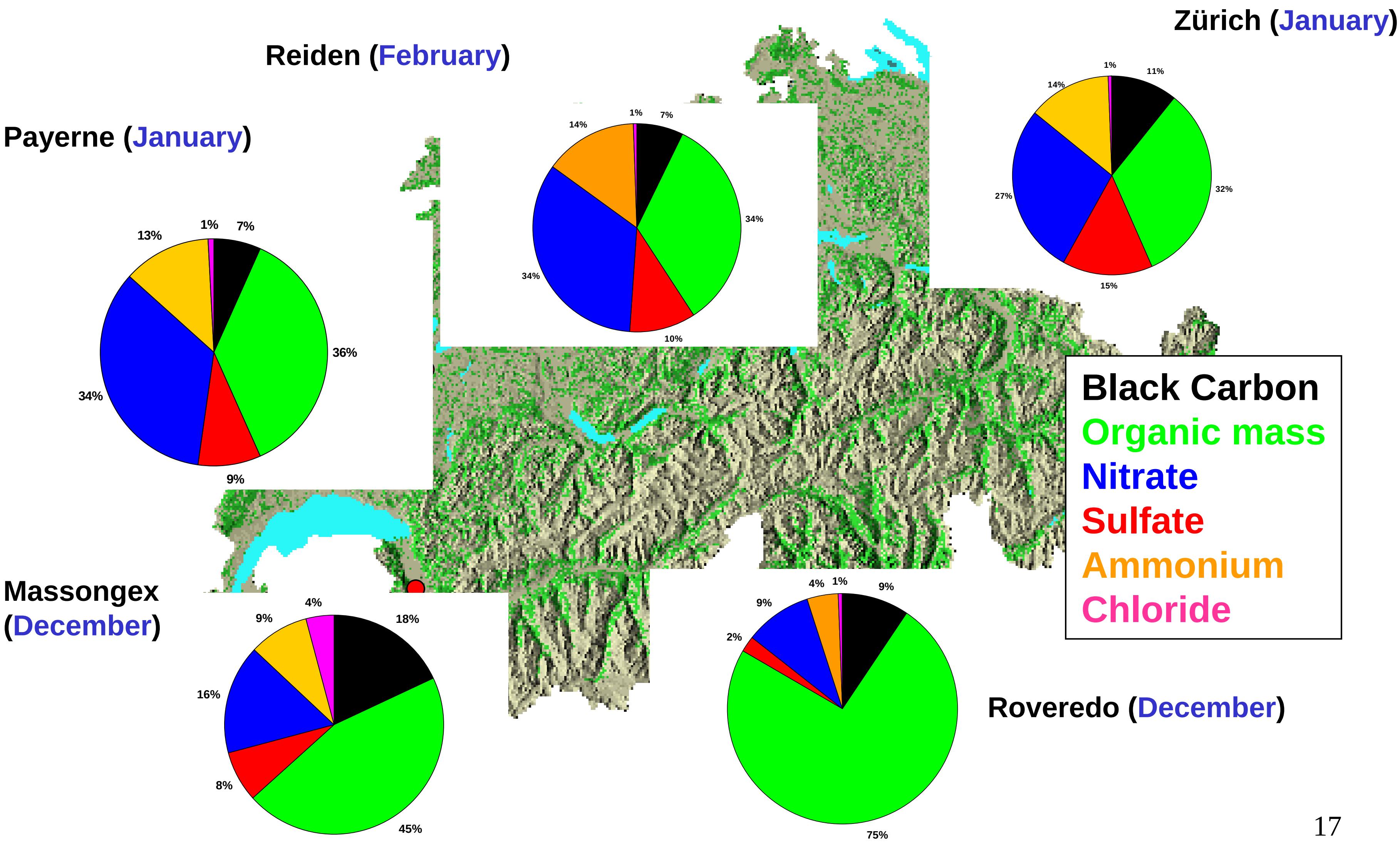


Lung Deposition

Size is decisive for system intrusion

Average CH-Compositions in Winter

PM10 ist very different from PM-Engine or BC-Soot



Health Effect and Cost due to Traffic PM

- California[1]
  - 12'000 premature deaths yearly
  - 190'000 children respiratory case
  - 1'200'000 lost workdays
  - total air poll.impacts $130 bill.pa (08)
- EU 27:
  - 260'000 premature death (to compare to 39'000 fatal traffic accidents
  - 8.6 months from the life of every person
  - Cost due traffic pollution: 380 Mia pa (1996)
- Switzerland:
  - 3300 death (onroad+offroad)
  - External health cost from epidemiology: 460 CHF/kg PM10 →1200-2400 CHF/kg BC

    → for this study 1'200 €/kg Engine Soot

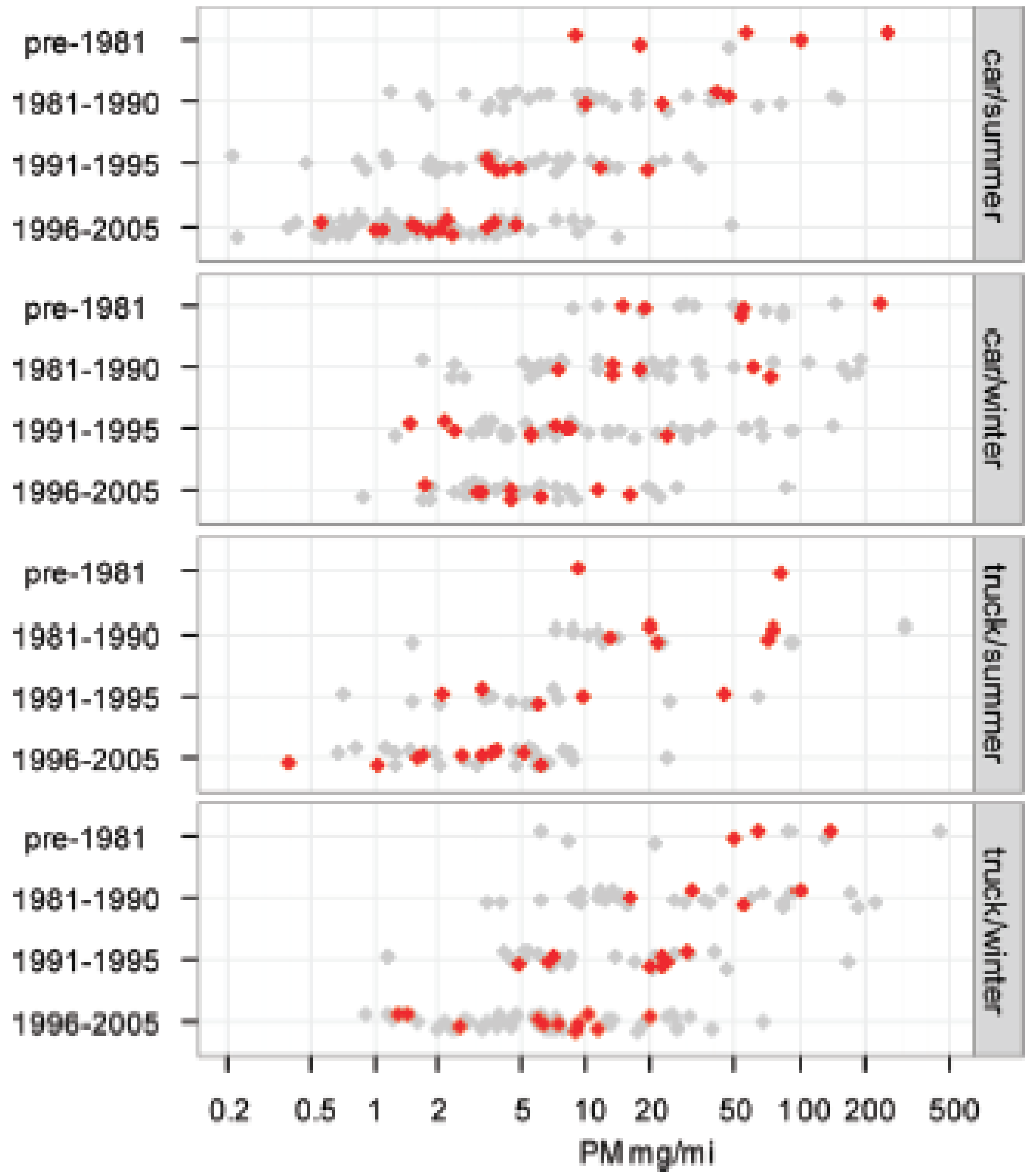
Sources:
1 CARB Climate Change Scoping Plan, December 2008 by A.Schwarzenegger et al.
2 CARB press release 09/17/08
3 WHO: PM: How it harms health

Diesel: Health Benefit for two typical retrofit DPF-Applications: *HDV+FFF versus LDV+FFF*

	HDV+FFF	**LDV+FFF**
PM-Emission (Euro III / 3)	0.1 g/kWh	0.05 g/km
Mileage	1000 hrs/yr	10'000 km/yr
Average Performance [kW]	100	10
PM Emission [kg/year]	10	0.5
Overall vehicle life [year]	15	10
Emission [kg/vehicle life]	150	5
Filter type	wall flow	wall flow
Filter efficiency [%]	99.9	99.9
Health Cost [€/kg Soot]	1’200	1’200.-
Total prevented soot [kg/life]	150	5
Health Benefit [€]	**180’000**	**6’000.-**

Gasoline
PM-Emission In-Use Gasoline Vehicles

US-EPA
Kansas, Feb 2012
99 vehicles
metal oxide content 17-35 %



3 Petrol Engines tested with GPF

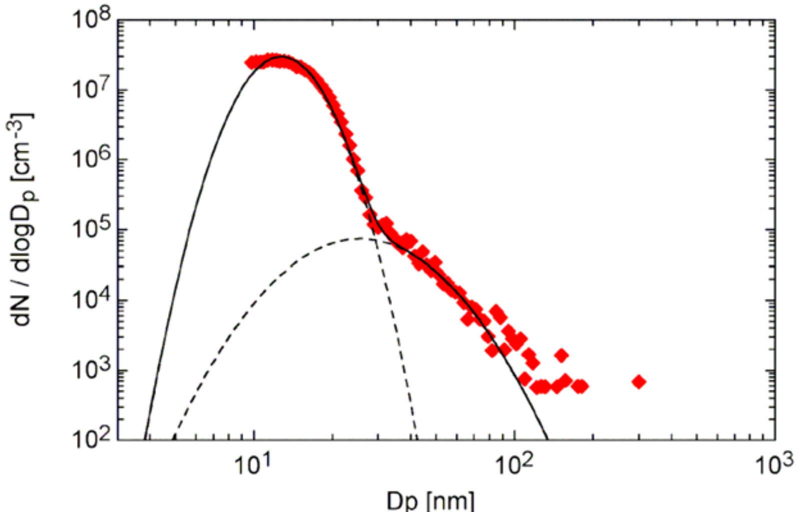
Fahrzeug	Aprilia Leonardo 125	Audi A3 2.0 TFSI	Renault 18 TX
Baujahr	2004	2007	1985
Motor	Viertaktmotor, Wassergekühlt	Viertaktmotor, Wassergekühlt	Viertaktmotor, Wassergekühlt
Hubraum	125 ccm	1984 ccm	2164 ccm
Zylinder	1	4	4
Gemischaufbereitung	Vergaser	Direkteinspritzung	Saugrohreinspritzung
Kraftstoff	Benzin bleifrei	Benzin bleifrei	Benzin bleifrei

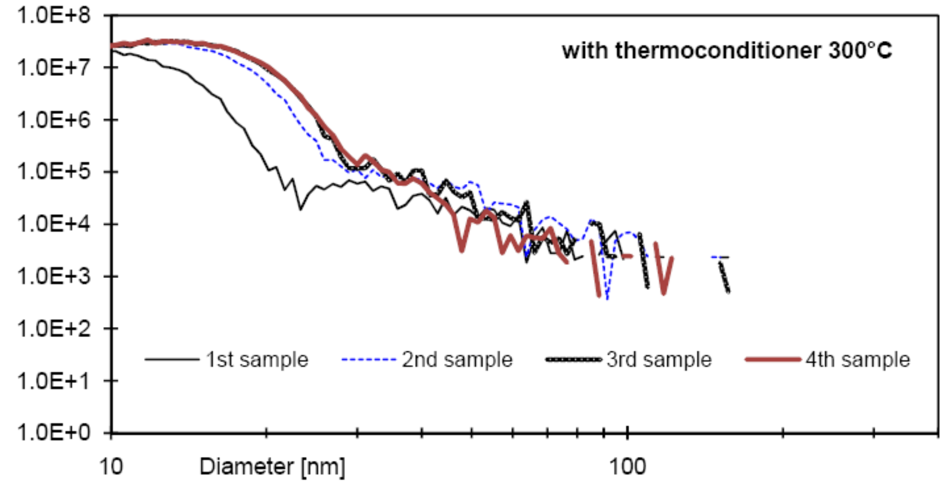
21

Honda 450 Motorbike (10‘000 km)

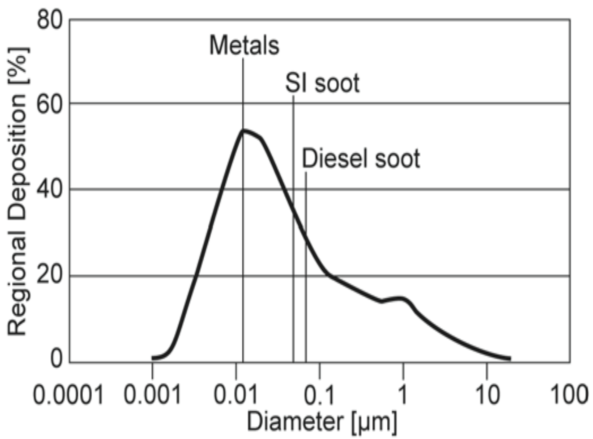
Size Distribution at Idle (upper) and 50 km/h (lower)

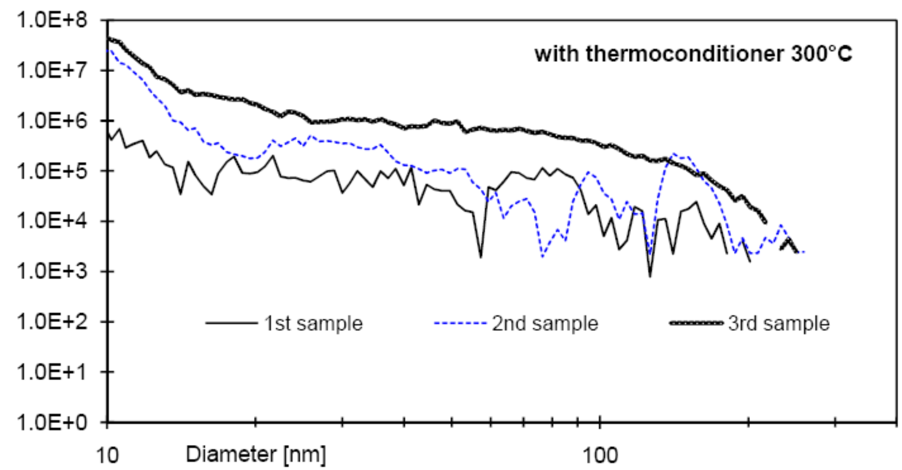
as many Particles as Diesel but smaller





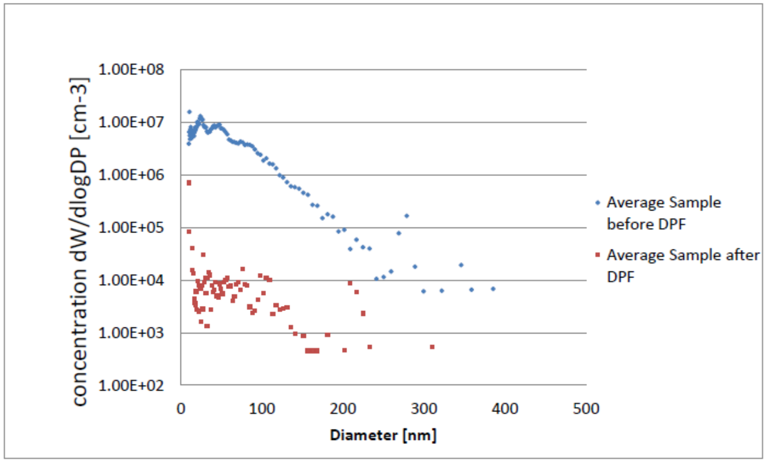
P/cm³

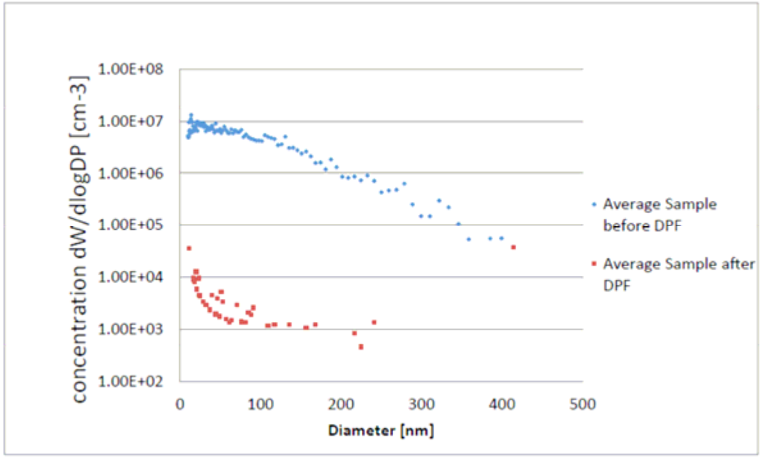


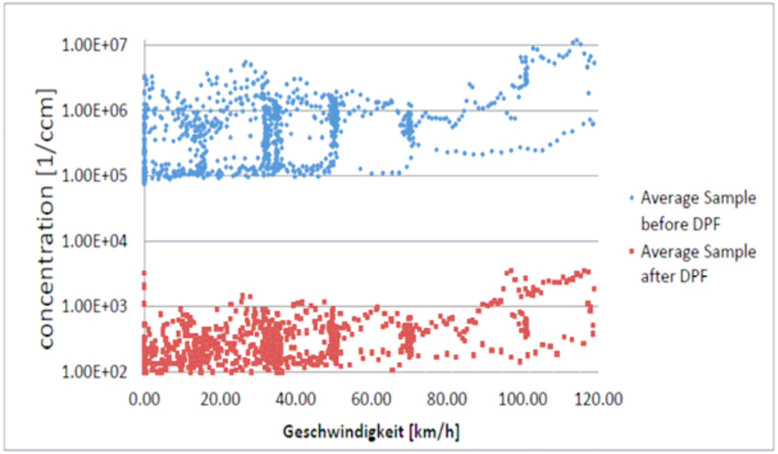


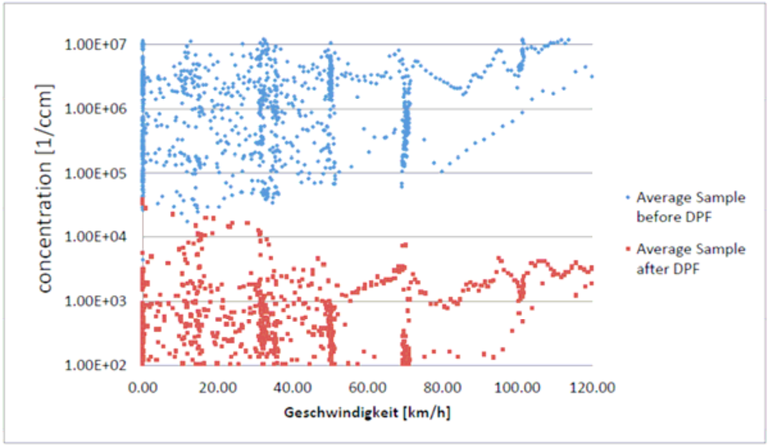
PN-Emission Petrol and GPF-Effects

Renault 18 PI (left) and Audi A3 DI (right) with GPF (red) and without GPF (blue)







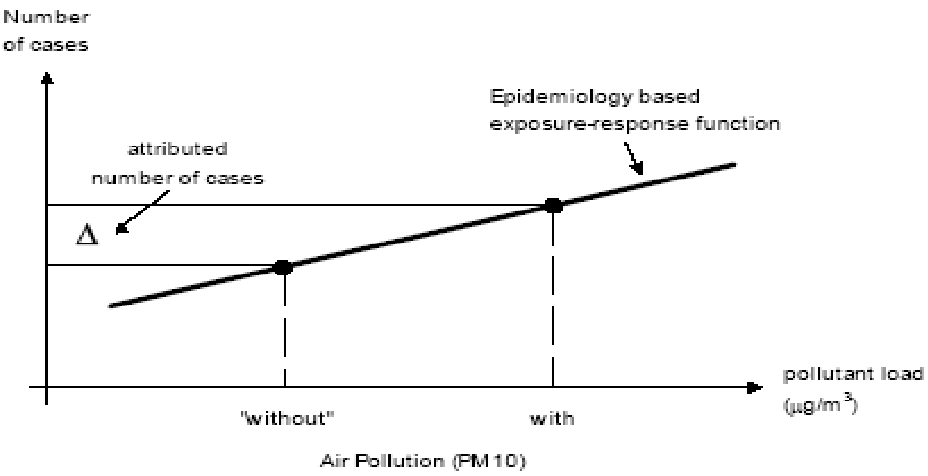


Health Benefit of Diesel LDV versus Gasoline based on soot particle mass PM

	Diesel+FFF	Gasoline+FFF
PM-Emission (Euro 3 or in use)	100 mg/km	10 mg/km
Mileage per anno	10'000 km pa	10'000 km pa
Average Performance [kW]	10	10
PM Emission [kg/year]	1.0	0.1
Overall vehicle life [year]	10	10
Emission [kg/vehicle life]	10	1
Filter type	wall flow	wall flow
Filter efficiency [%]	99.9	99.9
Health Cost [€/kg soot]	1’200	1’200
Total prevented soot [kg/life]	5	1.0
Health Benefit [€]	**12’000**	**1’200**

Epidemiology is traditionally Mass PM10-based

What about Particle Number to Health Effect Correlation ?

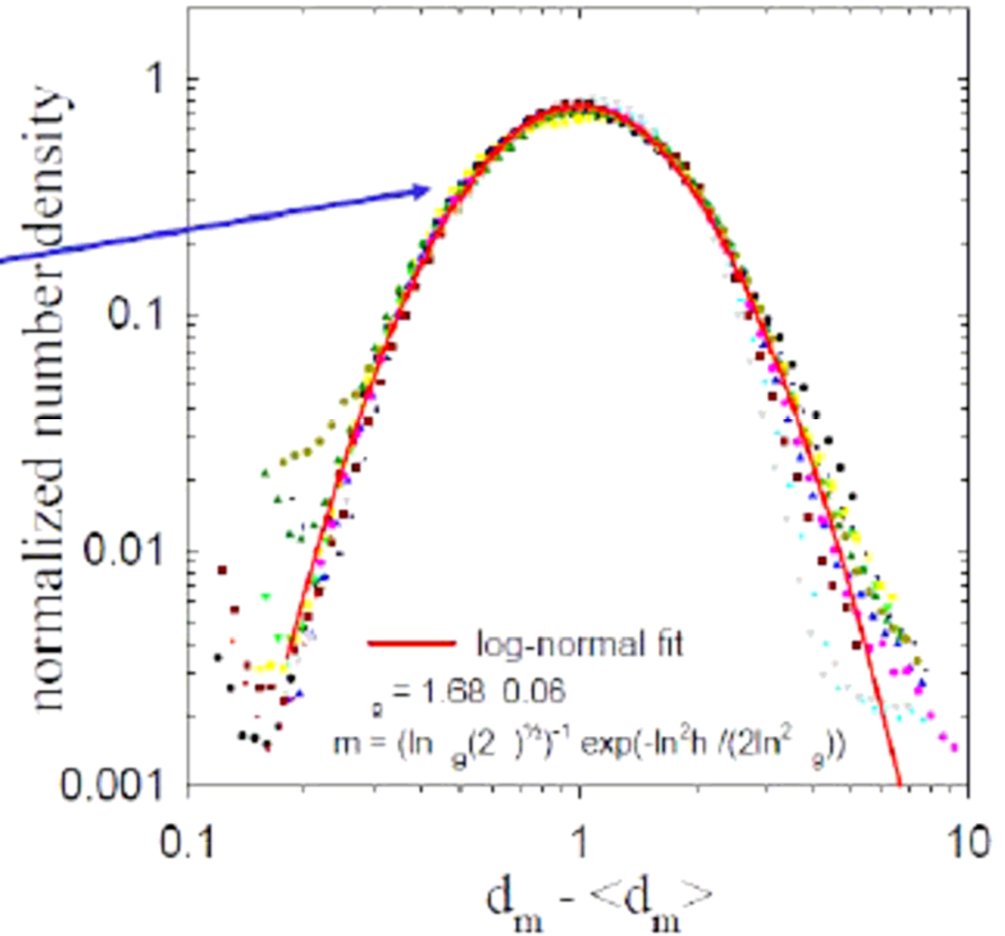


- Erfurt 1990-2010: increase by 7000 P/cc doubles mortality on a level of ca 15‘000 P/cc
- Beijing 2005-2008: increase by 8000 P/cc doubles mortality on a level of ca 50‘000 P/cc
- Size and substance are more important than mass

Calculate Number PN from Mass PM

Source M.Maricq, HEI 2009

- 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



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

Health Benefit of Diesel versus Gasoline based on Particle Number PN

	Diesel+FFF	Gasoline+FFF
PN-Emission	0.1g → 10^{14} P/km	0.01g→10^{14} P/km
Mileage per year	10'000 km pa	10'000 km pa
Particle size	100 nm	50 nm
PM Emission [P/year]	10^{18}	10^{18}
Overall vehicle life [year]	10	10
Emission [P/vehicle life]	10^{19}	10^{19}
Filter type	wall flow	wall flow
Filter efficiency [%]	99.9	99.9
Health Cost [€/kg = /10^{18} P]	1'200	1'600
Total prevented soot [kg/life]	10^{19}@100 nm	10^{19} @ 50 nm
Health Benefit [€]	**12'000**	**16'000**

Simplified:
mass of a 100 nm cube with unit density is 1 Femtogramm = 10^{-15} g

Health Benefit / Cost

- HD Diesel E3 Retrofit FFF: 180'000 / 8000 = 22.5
- HD-Diesel E5 OEM FFF: 36'000 / 4000 = 9
- LD Diesel E3 OEM FFF: 12'000 / 500 = 24

- LD Petrol with PM = 10 mg/km OEM:
  based on PM 1'200 / 100 = 12
  based on PN 16'000/ 100 = 160

Cost of HD DPF Retrofit : 8000.- DPF OEM: 4000.-

Cost of LDV DPF: 500.-

Cost fo LDV GPF: 100.-

FOR THE SOCIETY Soot reduction includes two Categories of Benefits

- Public Health
- Global Warming

Jacobson 2002

360,000-840,000 : 1

Is the atmospheric warming effect

by 1 kg of BC particles compared to 1 kg of CO2

120,000-280,000:1 for BC+OC to that of CO2

→ However different residence times must be respected: 20 years for CO2 and 1-2 month for BC which brings equivalence to about 1:2000

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

January and June 2009
M.Walsh

Table 1. Global Warming Potentials (GWP) drawn from the IPCC 4th Assessment Report

	GWP20	GWP100	GWP500
Black carbon	**1600**	**460**	**140**
Methane	72	25	7.6
Nitrous oxide	289	298	153
Sulfur oxides	-140	-40	-12
Organic carbon	-240	-69	-21
Carbon dioxide	1	1	1

Note: The methodology used for black carbon was also used for organic carbon and sulfur oxides. Values for black carbon, organic carbon and sulfur oxides were not published by the IPCC and are not official estimates.

Comparison of global warming by CO_2 and Back Carbon (BC) emissions of a Euro III HD vehicle engine (rough estimate)

	CO_2	BC	Warming effect CO_2 : BC
Relative absorption per unit mass	1	600'000	1 : 600'000
Residence time in atmosphere	20 years (1000 weeks)	4 weeks	250 : 1
Emitted mass (Euro III HD vehicle)	800 g/kWh 10 % reduction	0.100 g/kWh 100% reduction	800 : 1
Total warming effect			1 : 3

Result: Global warming reduction by DPF on a EURO III-engine is 3 x more efficient than a 10 % reduction of CO_2 of the same engine

Which €-Benefit associates the Society with Global Warming Reduction ?

Value of CO_2

- Trading CO_2 -Emissions (myclimate, atmosfair) costs 37-185 CHF per ton CO_2
- CO_2 –Tax today is 24-45 CHF per ton CO_2

→ Let's say: Value of CO_2–Reduction is 50 € per ton

BC / CO_2-GWP-Equivalent **(BC = ultrafine black carbon particles)**

- GWP of BC is 1'600 x higher than GWP of CO_2 for the same mass (kg)

→ Resulting Value of 1 kg BC-Reduction is 80 € (80'000 €/ton)

GW-Benefit [€] for the Society
2 typical Retrofit Applications

	HDV+FFF	LDV+PFF
PM-Emission (Euro III / 3)	0.1 g/kWh	0.05 g/km
Mileage	1000 hrs/y	10'000 km/y
Average Performance [kW]	100	10
PM Emission [kg/year]	10	0.5
Overall vehicle life [year]	15	10
Emission [kg/vehicle life]	150	5
Filter type	wall flow	partial flow
Filter efficiency [%]	99.9	20
BC GW benefit [€/kg soot]	80	80
Total prevented soot [kg/life]	150	1.0
Global Warming Benefit [EUR]	**12’000**	**80**

Summary

Overall Monetary Assessment of PM-Emission-Reduction by BAT Particle Filters has a double benefit for the Society reducing health risk and global warming.

*Benefit for the Society is **> 10 x higher** than actual Filter Cost*

Conclusion 1

Schweizer Bundesrat 2002:

„die Einführung des Partikelfilters ist eine volkswirtschaftliche Notwendigkeit“