SAE-NA Aftertreatment for Diesel Engines-28.June 2016 Reggio Emilia

Emission Reduction

Emission Stability

A.Mayer

Orders of Magnitude reached for Public Health by Emission Conrol Technology

but at same time running into high risk for Emission Stability due to serious flaws in Legislation for Implementation and Enforcement

In contrast to the ever repeated statements of engine industry the emission reduction potential of IC engines is very limited

Petrol engines are high emitters and were only cleaned by the 3WC – John J.Mooney 1970 – still they emit high PN and the 3WC let PN pass – GPF is needed

Diesel engines need DPF to «eliminate» PM/PN-emissions from fuel, lubrication oil and wear.

Diesel Engines also need oxidation catalysis DOC to eliminate PAH, Nitro PAH and other highly toxic substances

Diesel engines need DeNOx to reduce NO2 and NO → SCR+

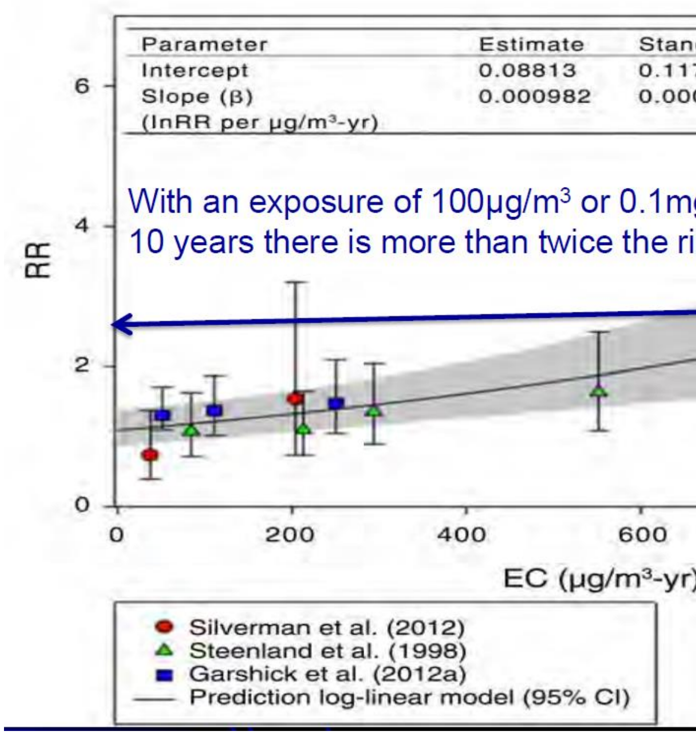
Health Impact Speculation ?

the newest numbers

by WHO 2012, Max Planck and Harvard 2015

ALRI: acute lower respiratory illness
IHD: ischaemic heart desease
CEV: cerebrovascular desease
COPD: obstructive pulmonary desease
LC: : lung cancer

10’000 killed per day - 20’000 by 2050



A more recent review by the IOM suggests that the risk is drastically higher for 45 year exposure period!!

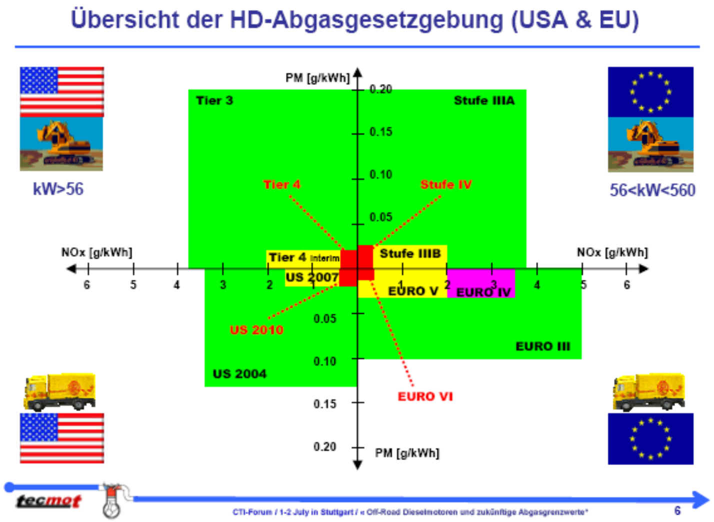
Mortality attributable to air pollution (deaths $\times 10^3$)
Mortality attributable to air pollution (deaths $\times 10^3$)

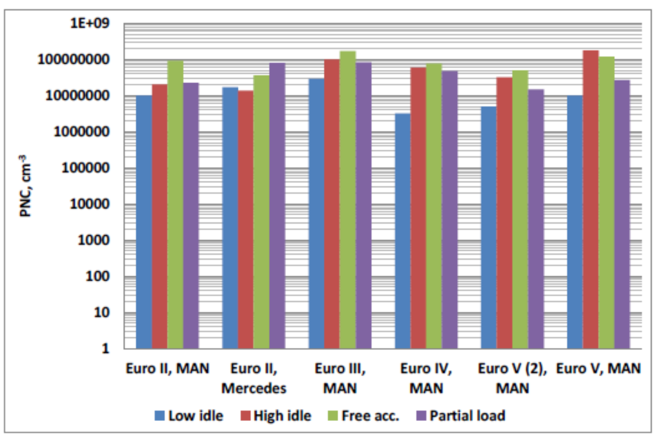
WHO region	Year	Population ($\times 10^6$)	$PM_{2.5}$					O_3	Total
			ALRI < 5 yr	IHD ≥ 30 yr	CEV ≥ 30 yr	COPD ≥ 30 yr	LC ≥ 30 yr	COPD ≥ 30 yr	
Africa	2010	809	90	55	77	11	2	2	237
	2050	1,807	158	185	262	38	5	12	660
Americas	2010	930	0	44	8	4	7	5	68
	2050	1,191	0	75	15	7	11	11	119
Eastern Mediterranean	2010	602	56	115	86	12	5	12	286
	2050	1,021	66	321	246	37	13	40	723
Europe	2010	867	1	239	95	13	27	6	381
	2050	886	1	307	156	18	37	11	530
Southeast Asia	2010	1,762	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

PN

NOx

What has been reached so far without Emission Control -Technology is disappointing





PM has been reduced but PN was not changed, particles are smaller

→ **more toxicity**

NOx has been reduced but NO_2 increased

→ **more toxicity**

Modern Diesel Drivetrains are Different

Classic Diesel Engines until Euro 5/V generate and control emissions by combustion. Trade-off NOx/PM and/or NOx/Be was needed to reach the limits. Emission deterioration by aging, wear was very limited (20-50%); the **Diesel was known to be very stable** with respect to emission and fuel consumption

For new Diesel Engine Systems **Combustion and Emission Control are decoupled.** The engine is optimized for power and economy; Emission reduction takes place by catalytic emission control DPF, DOC, SCR etc.

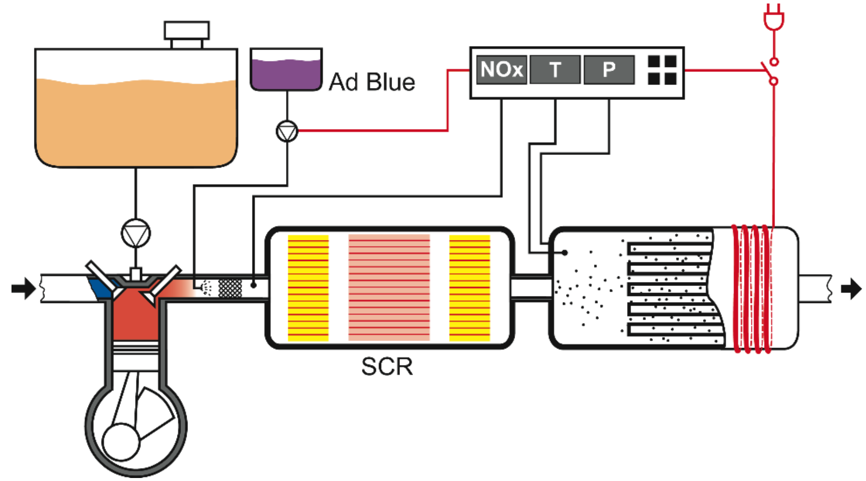
Emission Control by DPF, DOC, SCR **reduce raw emission by 2-3 orders of magnitude and we have now 100 millions vehicles on the road**. But these systems are more sensitive to aging, poisoning, manipulation, failures → **increase emission 100-fold and more**.

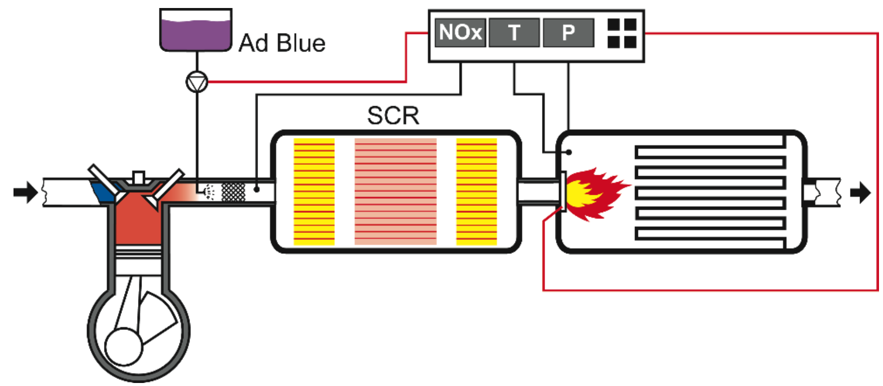
Raw Emission is increased in favour of power and fuel economy relying on the EC-capabilities. Should raw emission be controlled ?

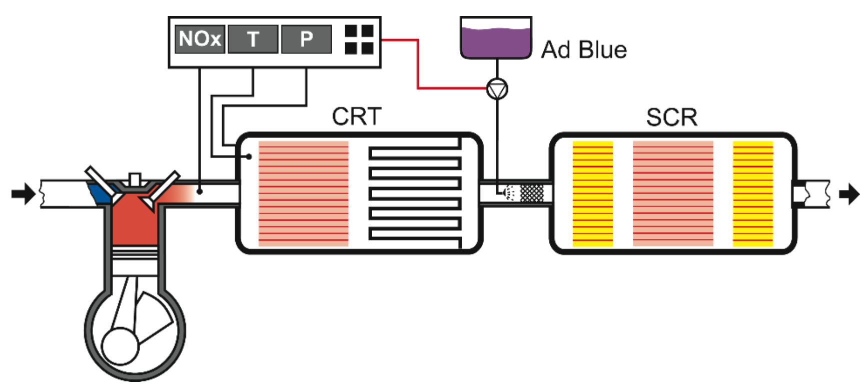
Emission Control by aftertreatment is indispensable

- very efficient > 99%
- but no plug and play
- depend on operation profile
- risk of wear, aging and poisoning, pollution
- risk of tampering and manipulation
- potential of intentional deterioration by defeat div.

→ ***Control is required***







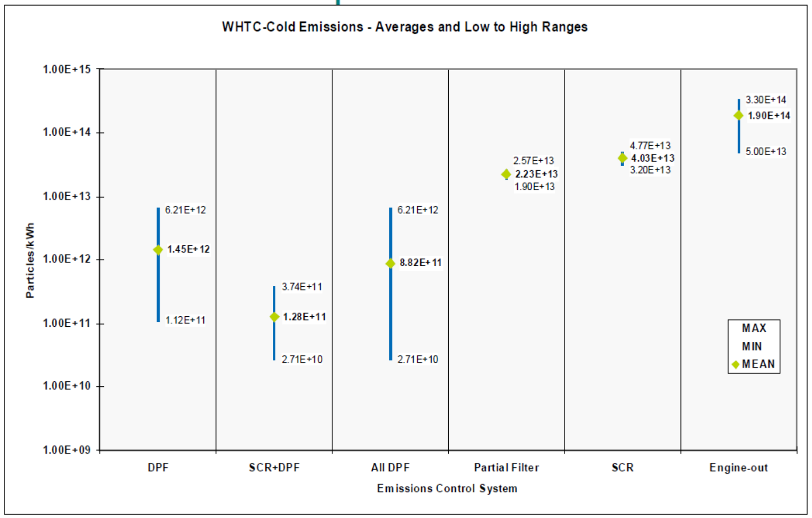
Potential of Particle Filters for CI and SI

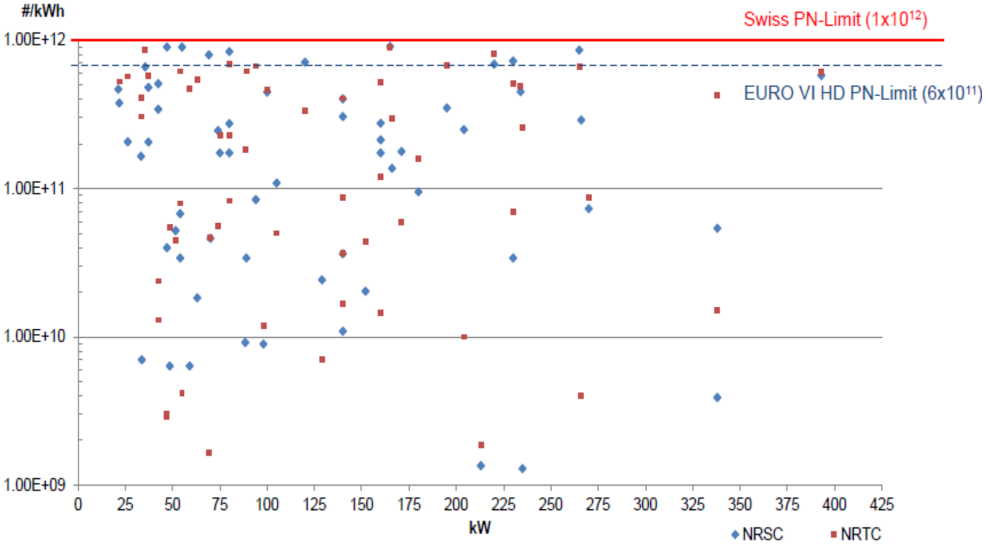
are not aging, cannot be manipulated
can be combined with catalysis

PN-Test results

Particle number spread – cold WHTC

Department for Transport





EU–Comission (Parkin) 2007/9

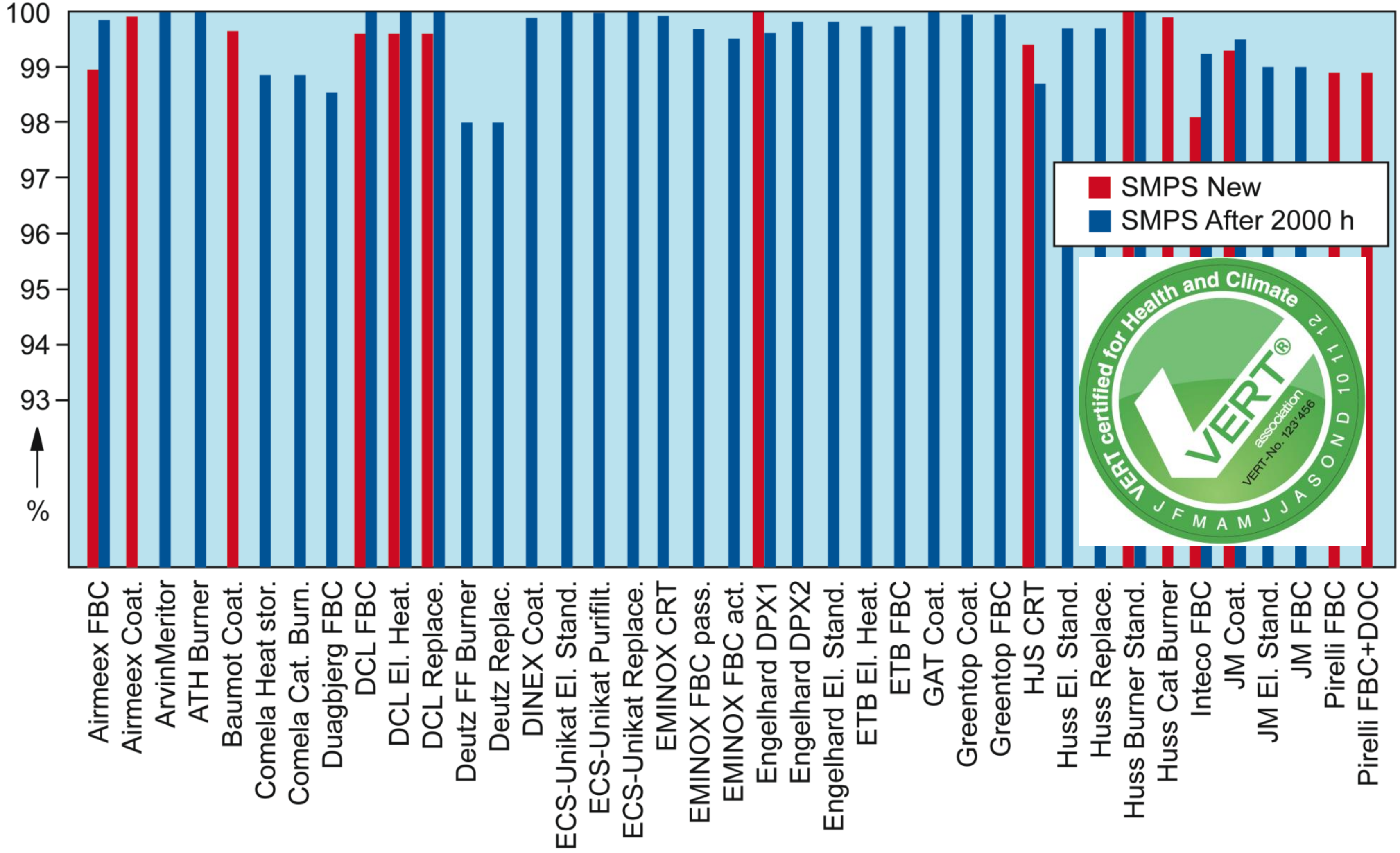
2-3 Orders of Magnitude

Swiss-Experience 2014 (**4-5 Orders**)

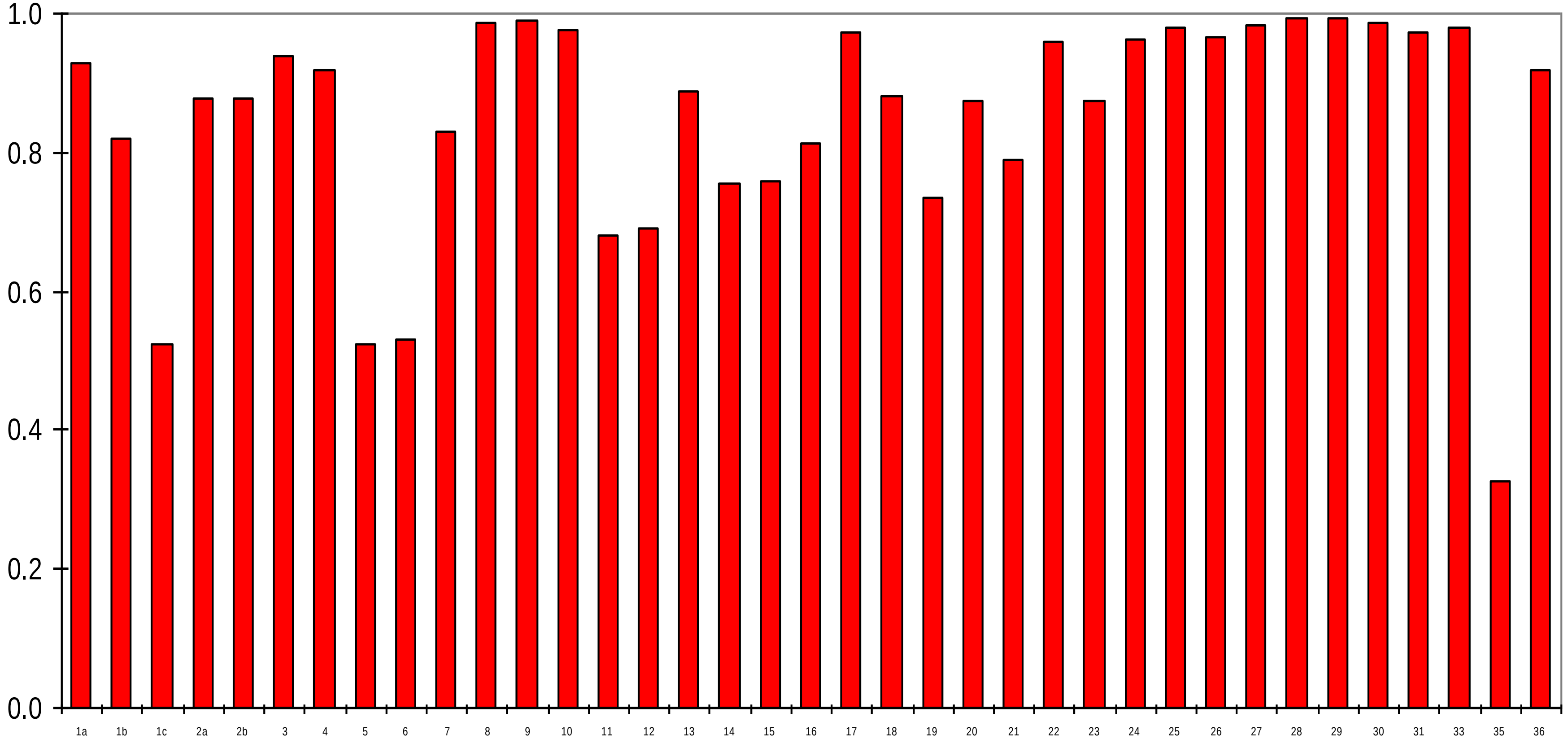
Filtration of all solid and semivolatiles. Soot, metal oxides and of all condensed HC. Filtration by PN must be controlled in function of size

Filtration - 65 DPF VERT tested

25 % > 99.8 % within size range 20-300 nm



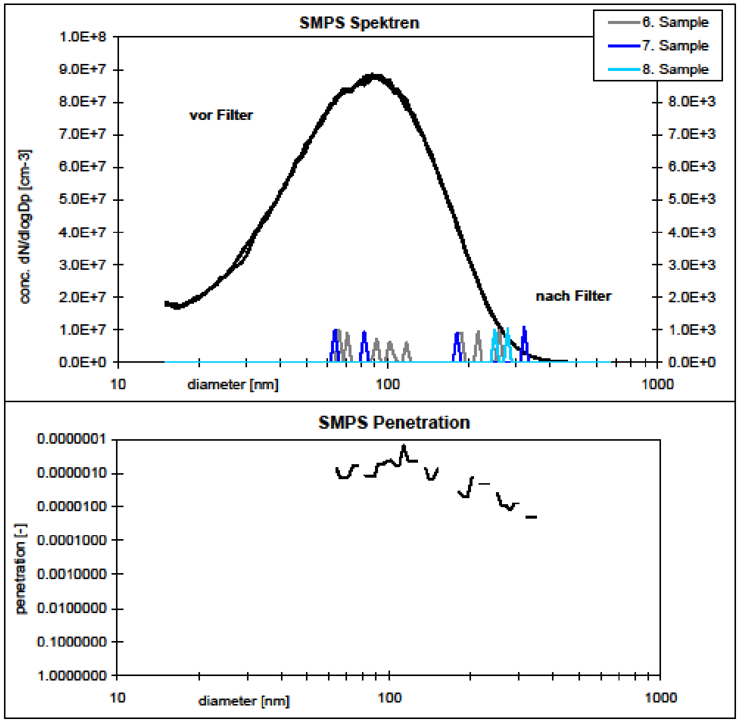
PAH are very effectively reduced in most filter systems



Filters can be excellent on SI and GDI

Matter Engineering AG
Nanoparticle Measurement

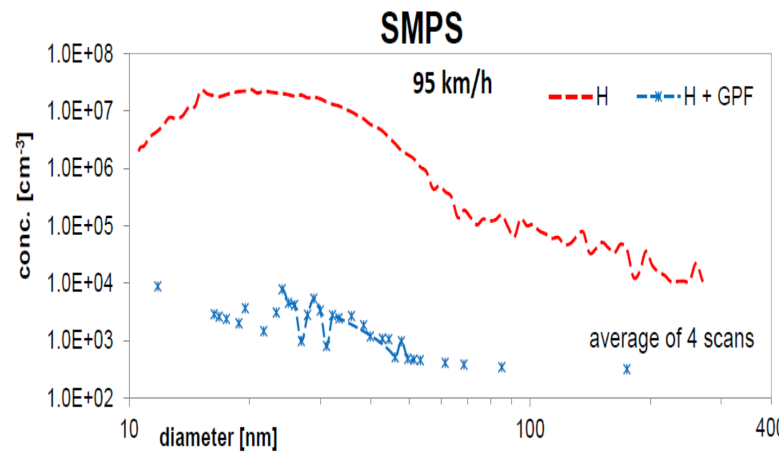
DPF Test an REXS Russgenerator
Filter: FAP/Peugeot, nach 100'000km Betrieb
Messung mit SMPS

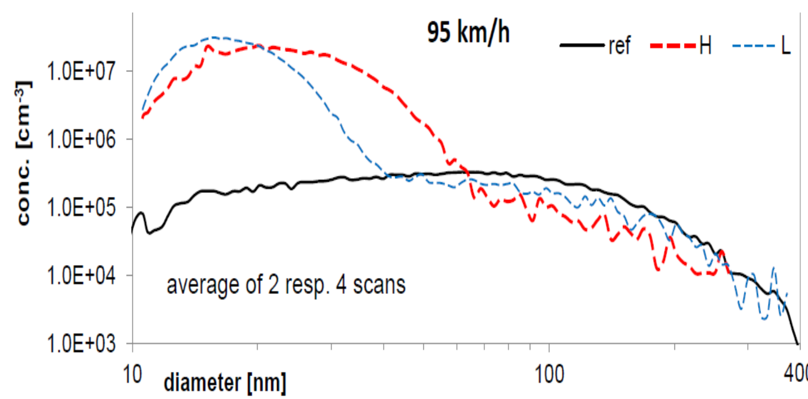


Total Konzentrationen:			vor Filter	nach Filter	Penetration [-]	Abscheidung [%]
SMPS	Konzentration	[1/cm3]	6.49E+07	4.62E+01	0.000001	99.99993

Messung 070411 Peugeot Meyer

Anhang 1





But by far not all fulfill this promise and lubrication oils should be controlled as well

And the Risks of DPF Application

- Filters can store and release
- Particles can penetrate in critical size range
- Filtration can breakedown during regeneration
- Filter can generate toxic secondary emissions
- Filters can desorb toxic volatiles

→ Legislation does not take care of this

→ Filter for vehicle engines must be certified to avoid these risks - a simple overall PN-limit is not enough

Potential of NOx-Reduction

- **SCR can reduce NOx by > 98%**
  (Genset HUG ETH 1996: 99.8 %) – **2 orders of magnitude –**
  at NH_3 slip limit – much more than combustion measures;
  whithout any negative effect on power or fuel economy -
  if exhaust temperature is above 230 °C

What can we do in addition below 230°C ?

- EGR with cleaned gas
- Water mixed into intake air
- TC-cooling to very low temperatures
- Engine tuning to low Nox
- Cool combustion
- Variable Emission Strategies

and the Risks of DeNOx by SCR

Engine manufacturers use this high DeNOx capability and tune the engine to much higher raw NOx-Emissions

→ NOx increase: TNO: 2-3 times,

→ Fuel comsumption → reduction 6-8% with Euro V

DeNOx-technology is easy to manipulate by electronic emission strategies and tampering

If the SCR fails by aging, poisoning, lack of Adblue etc. or by intentional tampering → NOx jumps up to raw emission levels higher than ever. And very strong formation of secondary toxics like NH_3, NO_2, N_2O can not be excluded.

→ **These systems require control on several levels – self control by manufacturers is not sufficient**

Potential of the Oxidation Catalyst DOC

- DOC converts gaseous HC, CO by 99%
- DOC also converts engine out NO to NO_2 by >70% which is Middle East, Inida, Sothmore toxic (10-100 times) but

  - needed for the DPF regeneration and

  - needed for the fast SRC-reaction
- DOC also converts SO2→ SO3 which is also toxic but with ULSF no longer a problem in developed countries, however in most megacities in China, Asia and Latin America

and the Risks of DOC

If the DOC gets aged, poisened, contaminated, dismantled, destroyed or the coating is at a lower limit for cost reasons

- HC and CO increase (moderately)
- The DPF regeneration fails
- The SCR function fails – NOx goes sky-high

Summary so far

- The Potential of Emission Control by Aftertreatment is a revolution, several orders of magnitude reduction of toxic air contaminant TAC – a must for public health
- But the introduction of this technology provides new technical challenges (which we all know from our retrofit experience)
- **And requires a different approach of legisation and control on all levels**

Basic Flaws or even
Conceptional Mistakes of Legislation

Potential of Emission Control
by Aftertreatment
Is it correctly implemented?
and is Emission Stability enforced?

Friedrich Hölderlin: Der Staat kann nur fordern, was er auch durchsetzen kann

Mistake 1

The legal and monetary value of engine emissions - TAC - is not defined

- **Safety and Health** must be on the **same legal level** as it is with occupational health at the working place
- The health related **Monetary Value** of emitted substances must be defined and taxed

  → 450 $/kg PM10, PM10 contains 20 % soot,

  → the monetary value of 1 kg soot is > 2’000 $

and **secondary emissions** as well as **grey emissions** must be included

Mistake 2
Responsibility is not defined

- **Polluter pays principle**
- In **Industry** the operator of an emission source is responsable and has to bear all cost
- In **Automotive** the manufacturer feels responsible only to fulfill emission limits of a new vehicle within defined operation conditions (→ *temperature window*)
- The driver does not feel any responsibility at all

→ **Must be changed like safety risks**: the driver is responsible for toxic emissions and if this increases he must be alerted by a big red lamp and if he not reacts the car goes on ***limp home*** **and** ***no re-start***

Mistake 3

Different Metrics

for tailpipe and street canyon

- Example NO_2

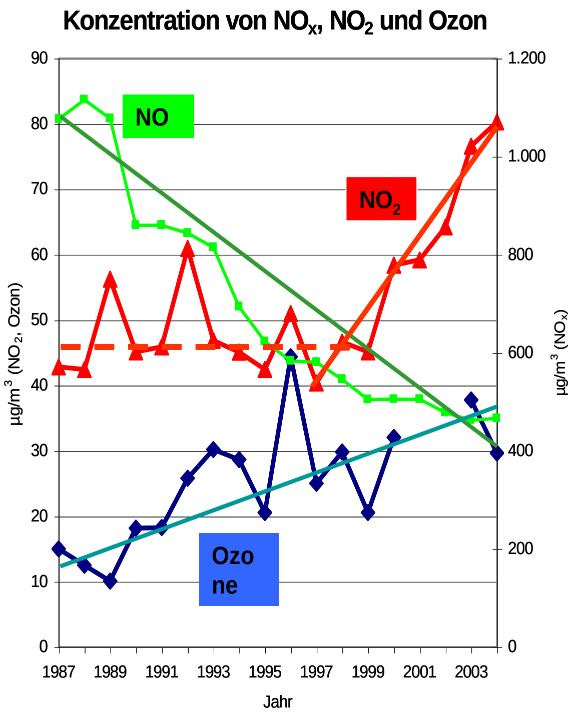
Cities complain high NO_2

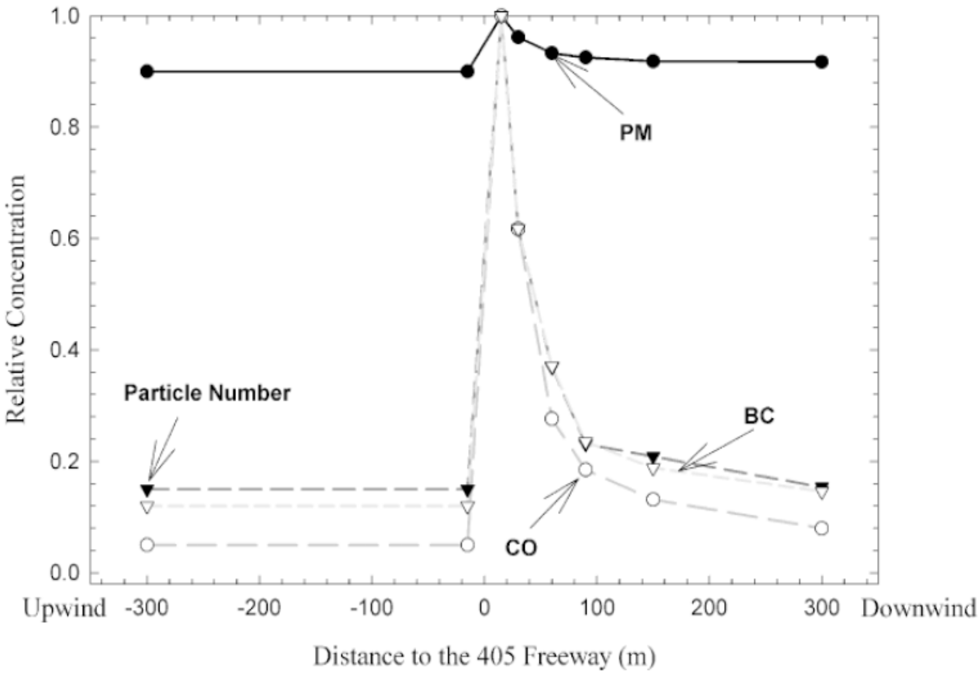
But NO_2 at tailpipe not limited

Example PM/PN

Road Proximity: high PN-Emission

but PN is not limited





Mistake 4

Independent Control by Autorities is delegated to OBD

A. OBD: Functionality and Safety
B. Homologation of New Engines
C. In Use Compliance and Manufacturing Conformity
D. Need 100% Periodic Control of in-use Fleet

cannot be manipulated like A, B, C

Control for public health must be independent (Montesquieu: la séparation des pouvoirs 1748 - base of our civilization) and cannot be replaced by OBD – ***see Dieselgate scandal***

and we have
the Tools available

developed for

Emission Control of Retrofit

2000 Swiss Ordinance for Field Control of gaseous emissions of Diesel engines

OFMET
EAM
UFMET

Eidgenössisches Amt für Messwesen
Office fédéral de métrologie
Ufficio federale di metrologia
Swiss Federal Office of Metrology

Richtlinie
über Abgasmessgeräte für Baumaschinen

vom 17. März 2000

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1 Gegenstand

1.1 Dieser Richtlinie unterliegen Abgasmessgeräte (Geräte), welche zur Kontrolle der Abgasemission von Baumaschinen gemäss Luftreinhalteverordnung vom 16. Dezember 1985 [1)], Anhang 2, Ziffer 88 dienen.

1.2 Die Richtlinie regelt die Anforderungen an die Bauart, das Vorgehen bei der Bauartprüfung, das Vorgehen bei den Kontrollen der im Betrieb befindlichen Geräte und die Zuständigkeiten.

1.3 Voraussetzungen für den Einsatz eines Geräts gemäss Ziffer 1.1 sind die Übereinstimmung mit der geprüften Bauart und die bestandenen Erst- und Nachkontrollen.

2012/14 New Swiss Ordinance for Field Control based on solid PN counting instruments

Ordinance of the FDJP
on Exhaust Gas Analysers
(VAMV)

Amendment of 22nd august 2012

The Federal Department of Justice and Police
hereby decrees:

B Measurement requirements

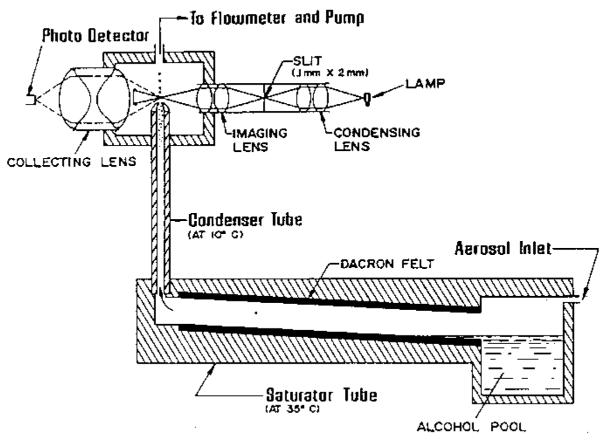
1 Measurement range

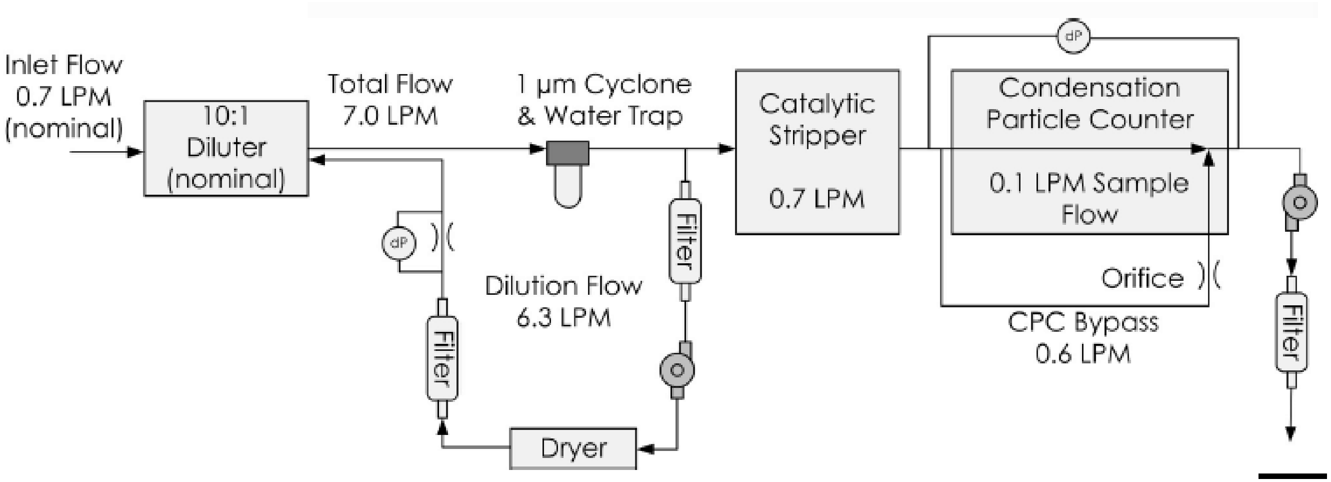
1.1 The measurement range for the nanoparticle number concentration is at least between 5×10^4 cm^{-3} and 5×10^6 cm^{-3}.

1.2 In case of measured values outside the measurement range, the measuring instrument must indicate whether the measured value lies below or above the measurement range. If no categorisation is possible, then no value should be displayed.

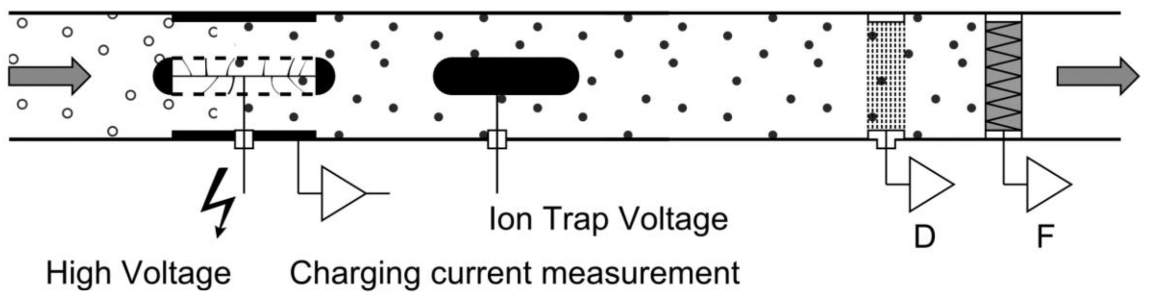
1.3 The particle number concentration of each measurement must be indicated at the ambient conditions.

Condensation Nucleus Counter – by TSI NPET



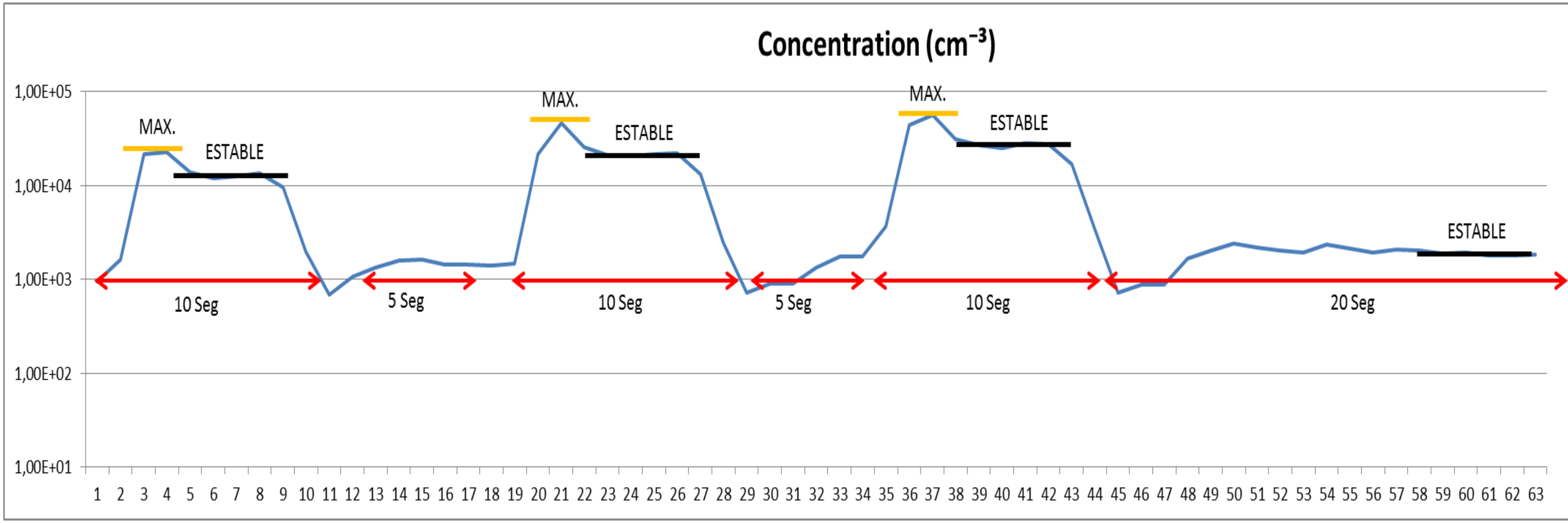


Diffusion Charging by Matter/TESTO NanoMet3 and PEPA



Measurement Roadside

Opacity and PN at exhaust exit
during free acceleration, high idle and low idle
2015 - 400 vehicles

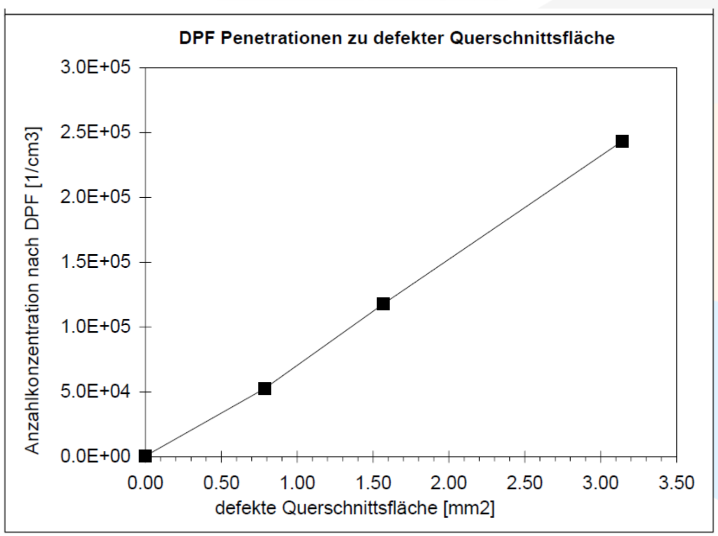


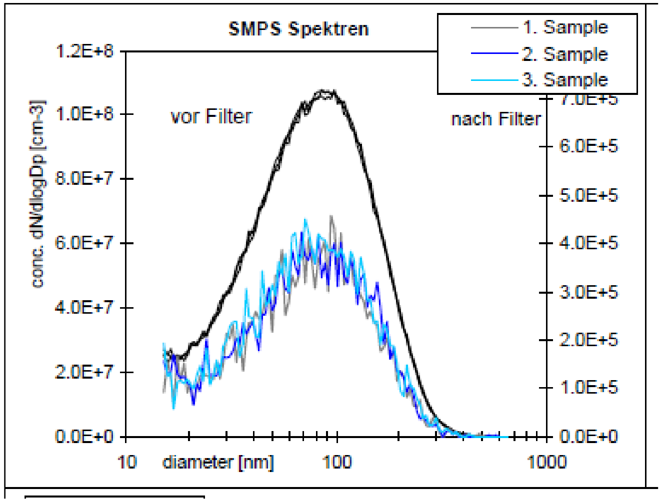
Filtration Efficiencies measured by PN Buses of Transiantiago city bus fleet after 4-6 years of operation

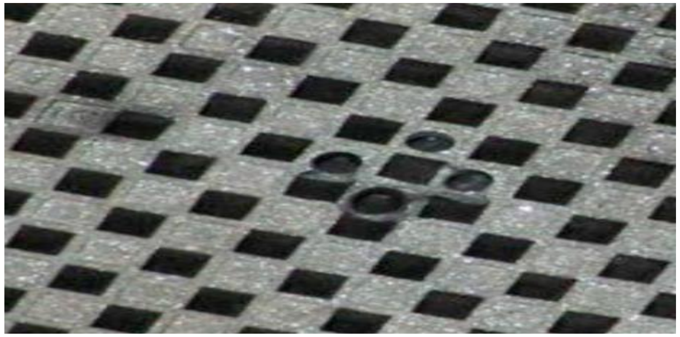
Modelo	Empresa	medicion 1	medicion 2	medicion 3	promedio fi	RESULTADO	RESULTADO	Prom. Max RPM
B7R	REDBUS	1,23E+06	1,61E+06	1,46E+06	1,33E+06	fallo	39,82%	
B7R	REDBUS	2,68E+06	2,55E+06	2,37E+06	2,21E+06	fallo		
LO915	REDBUS	7,52E+01	6,99E+01	5,60E+01	1,00E+03	paso	99,88%	1,00E+03
LO915	REDBUS	1,63E+06	1,55E+06	1,59E+06	8,20E+05	fallo		
O500U	REDBUS	8,67E+05	8,91E+05	9,10E+05	1,13E+06	fallo	73,02%	1,06E+06
O500U	REDBUS	4,51E+06	4,56E+06	4,36E+06	4,17E+06	fallo		
O500U	VULE	6,74E+04	6,62E+04	7,52E+04	7,49E+04	paso	98,04%	1,00E+03
O500U	VULE	3,94E+06	3,86E+06	3,72E+06	3,83E+06	fallo		
O500U	VULE	1,25E+04	1,22E+04	1,37E+04	1,46E+04	paso	99,29%	1,15E+05
O500U	VULE	2,31E+06	2,26E+06	2,25E+06	2,05E+06	fallo		
O500U	VULE	2,50E+03	3,19E+03	3,48E+03	4,55E+03	paso	99,83%	1,18E+05
O500U	VULE	2,58E+06	2,54E+06	2,39E+06	2,61E+06	fallo		
O500UA	METROPOLITANA	1,03E+05	1,08E+05	1,01E+05	1,07E+05	paso	97,52%	2,76E+03
O500UA	METROPOLITANA	3,91E+06	4,25E+06	4,25E+06	4,31E+06	fallo		
O500U	METROPOLITANA	5,73E+03	6,08E+03	5,71E+03	5,80E+03	paso	99,86%	4,40E+04
O500U	METROPOLITANA	4,30E+06	4,23E+06	4,32E+06	4,19E+06	fallo		
O500U	METROPOLITANA	6,28E+03	5,96E+03	6,28E+03	7,28E+03	paso	99,85%	4,40E+04
O500U	METROPOLITANA	4,97E+06	5,14E+06	5,06E+06	5,00E+06	fallo		

Detect Small Failures

(M.Kasper ETH-NPC 2008)







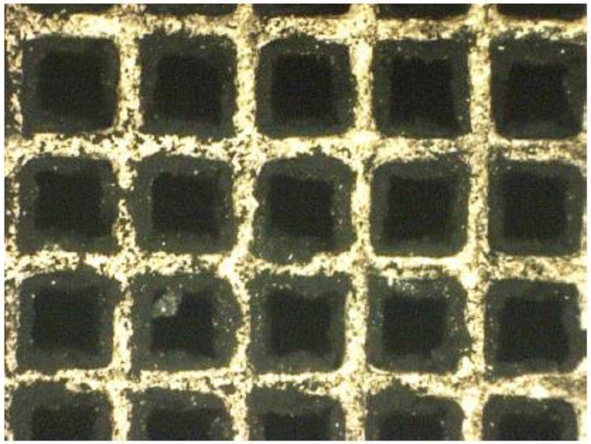
Can we also check Catalysts in-use

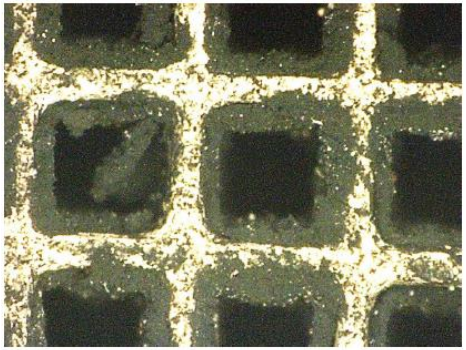
DOC
SCR
?

Yes, we can

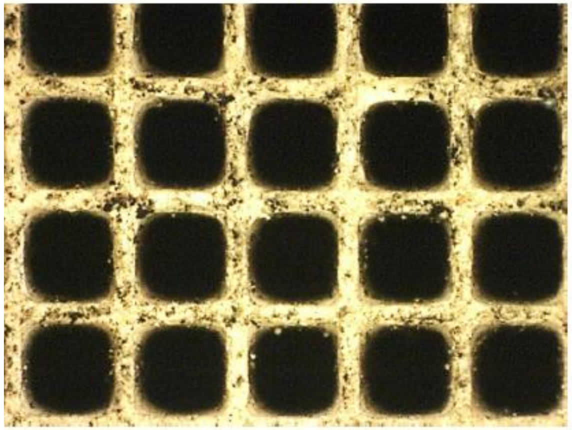
DOC might be covered by soot
or poisoned or destroyed or aged
or just not adequately coated

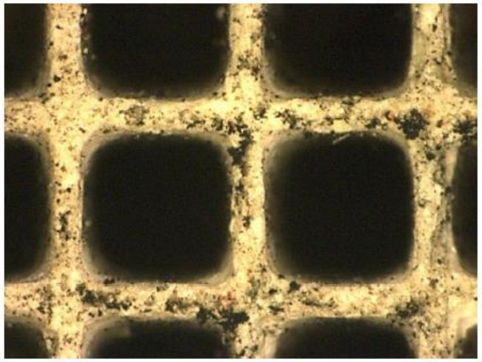
Inlet





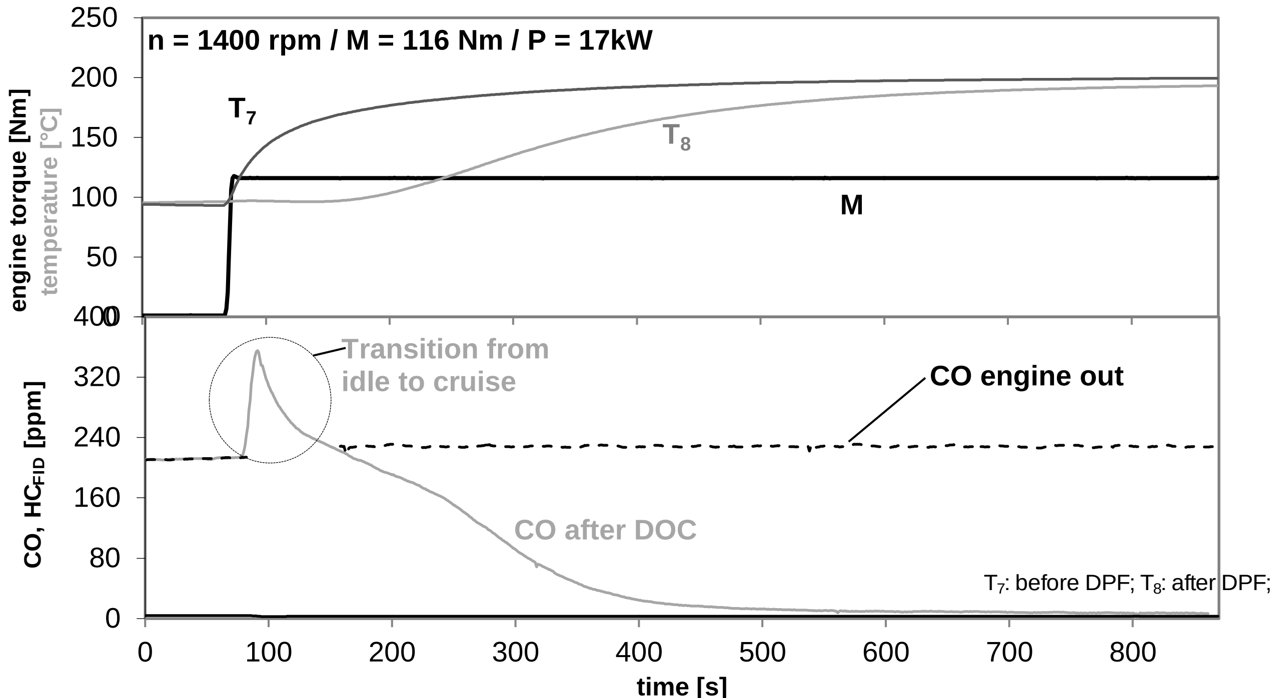
Outlet

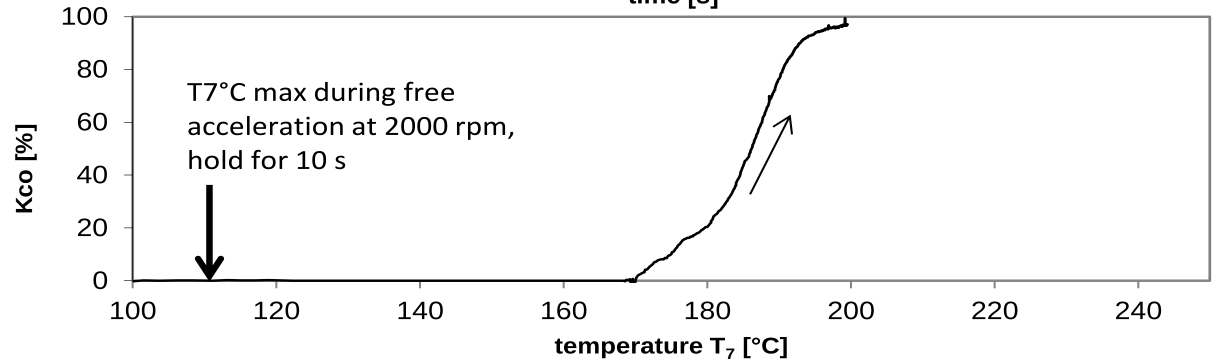




DOC Light off test during Load Step

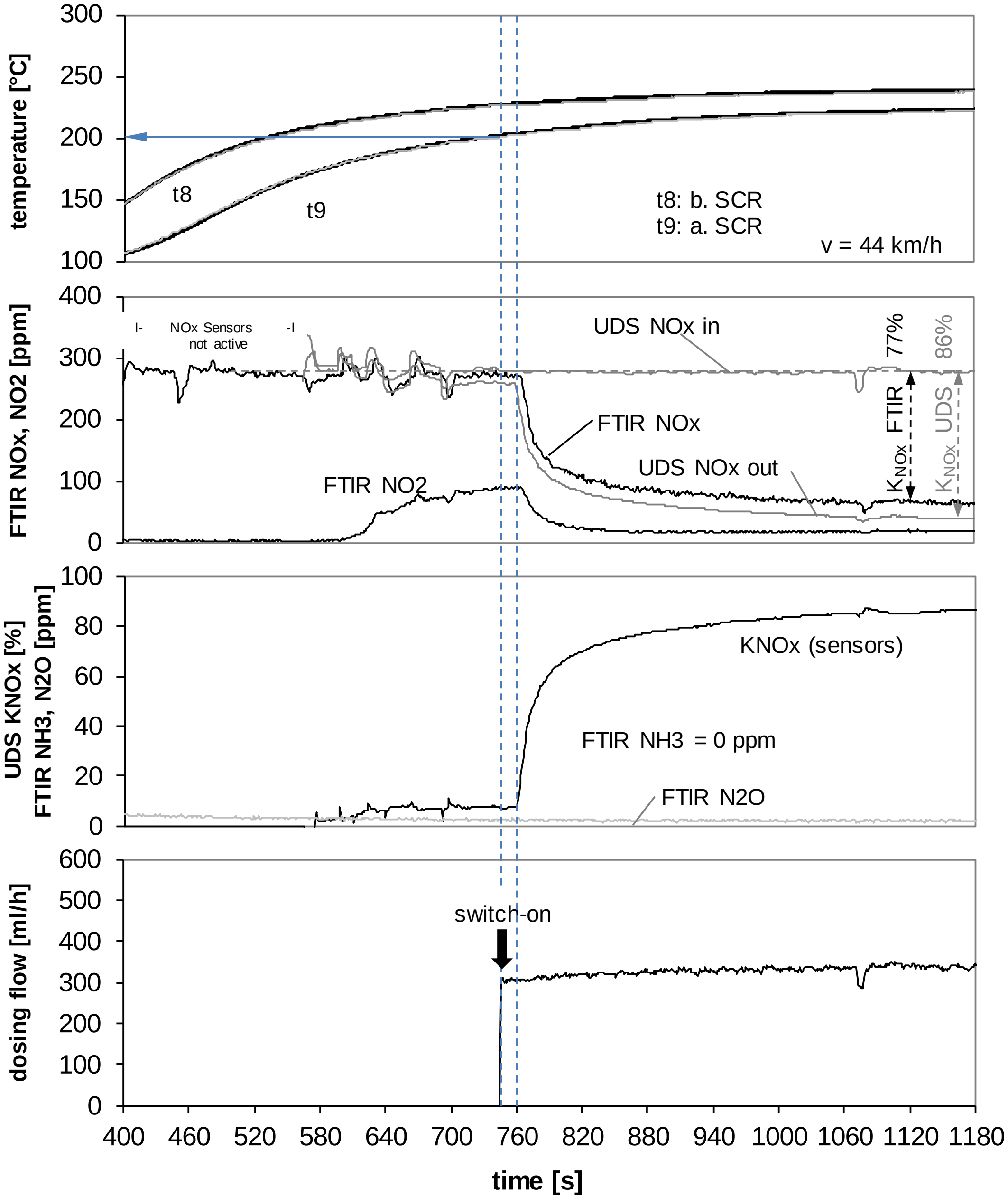
needs chassis dyno or torque converter stall - 20 sec





SCR Load Step

permits diagnosis of catalysis and dosing strategy flaws



Summary

very efficient and cost effective

100% periodic control in-use is feasable

- **PN-Test at low idle for DPF**
- **Load-Step 100°C auf 300°C at average RPM**

  - CO-Conversion > 80% → DOC OK

  - NOx-Conversion > 70% + NH3 < 20 ppm → SCR OK

This Test ist much more than just Pass/Fail

It supplies quantiative diagnostic information for the functionality of each emission control component and the engine as well and permits preventive repair and maintenance.

Condition is that OBD permits the test → Legislation

Aftertreatment masks the Engine

→ tailpipe control alone might be misleading

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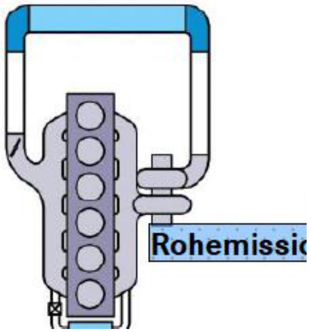
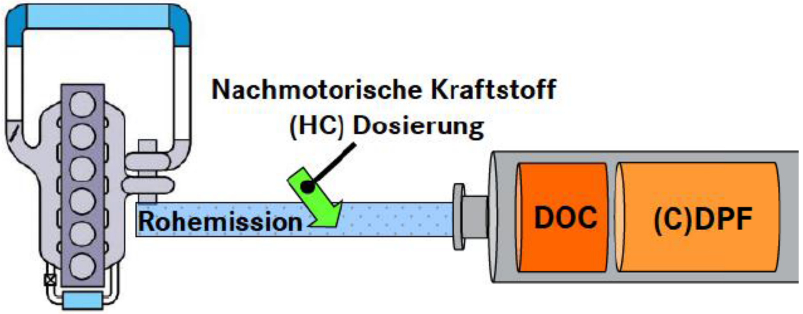


Old Engine: Raw Emission permits Engine-Diagnosis by noise, smoke, smell, colour
Free acceleration revealed all problems

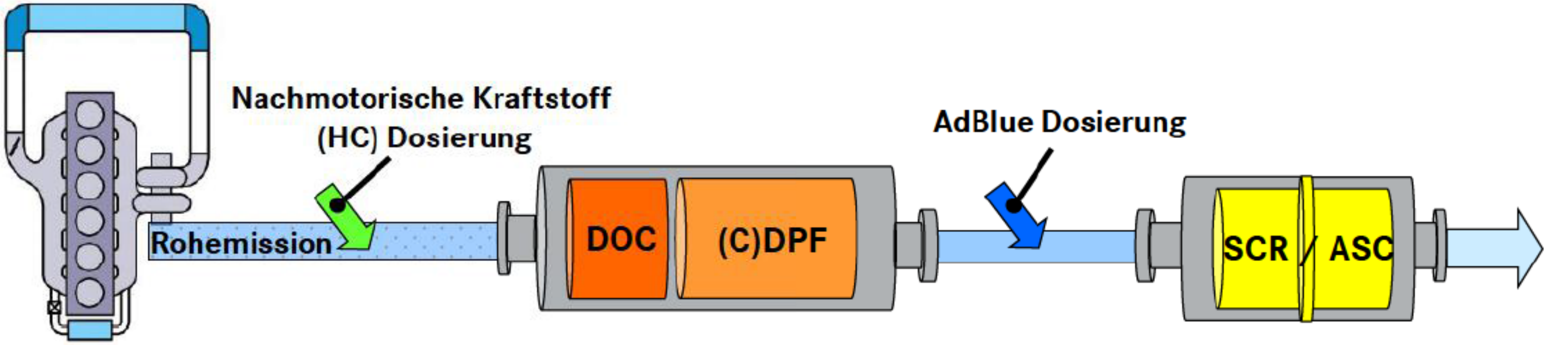


DPF and DOC mask smell and smoke, change noise and colour
→engine diagnosis impossible

→ Engine-Out control important for Engine protection and preventive maintenance

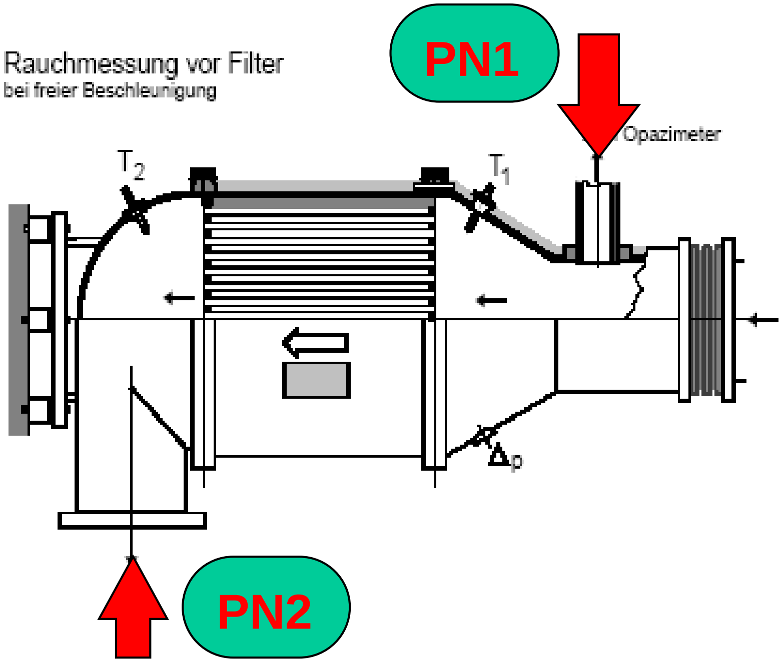
Technical Motivation for Independent Periodic Control of PN and Gas-Emissions

- Detection of Failures **of each component**
- Quantification of Failures
- Preventive Maintenance



Measurement PN upstream and downstream of DPF for filter efficiency

The filter masks the engine. Measurement upstream and downstream is needed to get information about engine raw emission and filter efficiency



PN1 before the filter determines the emission status of the engine itself, eventual failures, leakages, deterioration,aging

PN2/PN1 determines la stability of the filtration very accurately