The Dirty Tail of Vehicle Fleets & the Fastest Route to Clean Urban Air - the Horizon Europe AeroSolfd Project

The AeroSolfd Initiative for DPM Reduction

Dr. Lauretta Rubino

VERT Association

MDEC MINING VEHICLE POWERTRAIN CONFERENCE

October 21-24, Sudbury Ontario, Canada

AGENDA

- VERT
- Introduction & Motivation
- The HORIZON AeroSolfd Project
  - GPF retrofit of Petrol engines
  - NPTI testing campaign
- Results so far
- Summary

*NPTI = New Periodic Technical Inspection

What is VERT?

- **VERT is a Non-Profit International Association** of **filter, catalyst manufacturers, instrument, engine manufacturers, universities and research associates**, founded in 1993 in Switzerland
- **VERT stands for Verification of Emission Reduction Technologies** & it is a Particle Filter Testing, Certification & Quality Control System, a Trade Mark for Particle Filters of **Best Available Technology (BAT)**
- **The VERT® Association, originated during the NEAT New Transalpine Railways Program**, which was one of the biggest tunneling projects in Europe at the time
- **Since then, VERT® has developed some of the most important particle filter testing procedures,** supported various international partners with **retrofit programs** and retrofit consulting and **established a worldwide scientific network of manufacturers** of **components, systems, engines, vehicles and PN measurement devices** as well as environmental, medical and technical research facilities **specialized in the field of "air quality" and nanoparticle emissions control**
- **VERT organizes international conferences** every year (i.e. the **VERT Forum**) and the **ETH Nanoparticle Conference in Zurich**
- **VERT has over 35 members** including universities and research centres as associate partners

VERT and the Diesel Particle Filter

Research, Implementation and Quality Control the interdisciplinary VERT Research Network

- 1994 developed for tunneling NEAT
- 2000 some hundred DPF in tunneling
- 2002-10 Swiss Construction 25‘000
- 2011 EU for Diesel, 2017 for Petrol DI
- 2018 China, 2020 India

Today > 200 Milion worldwide

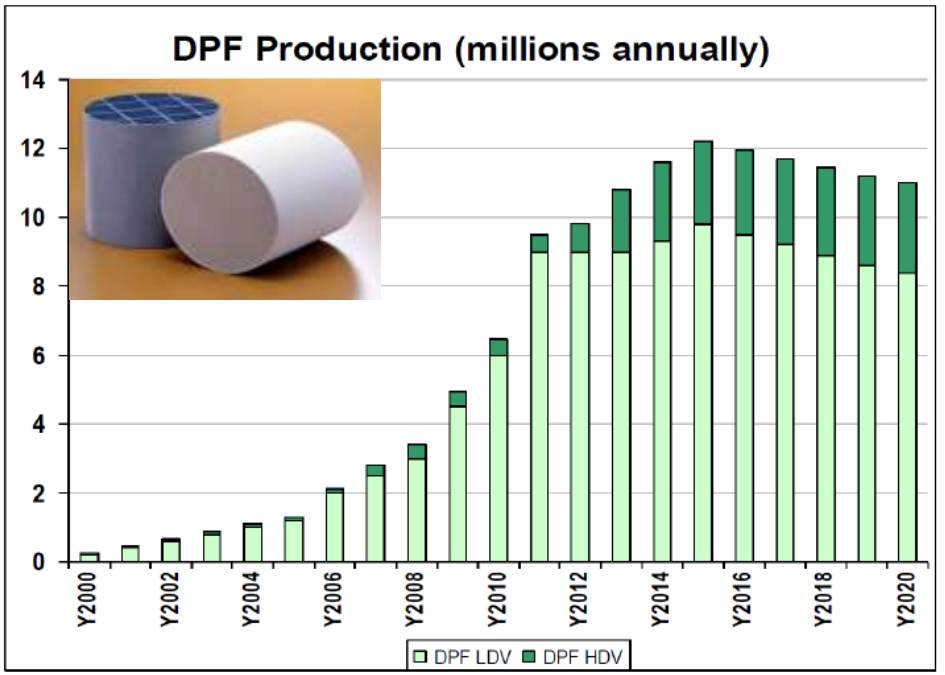


Fig. 6 DPF-Production annually for LDV and HDV – USA and Europe

Thanks to Particle Filters > > 3.5 Milion premature death less

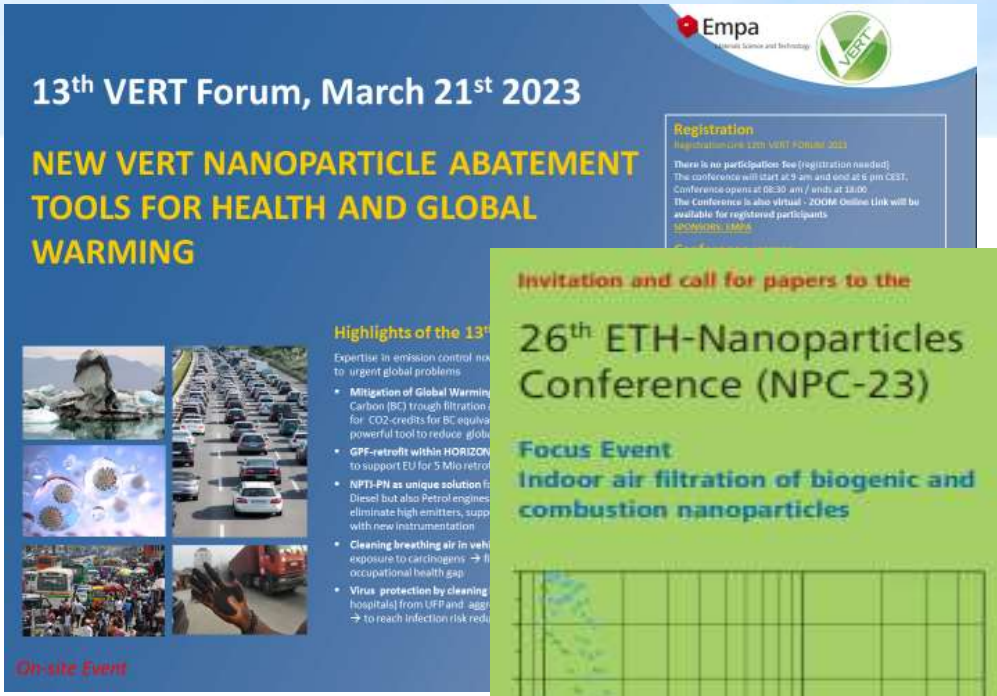
VERT scientific network

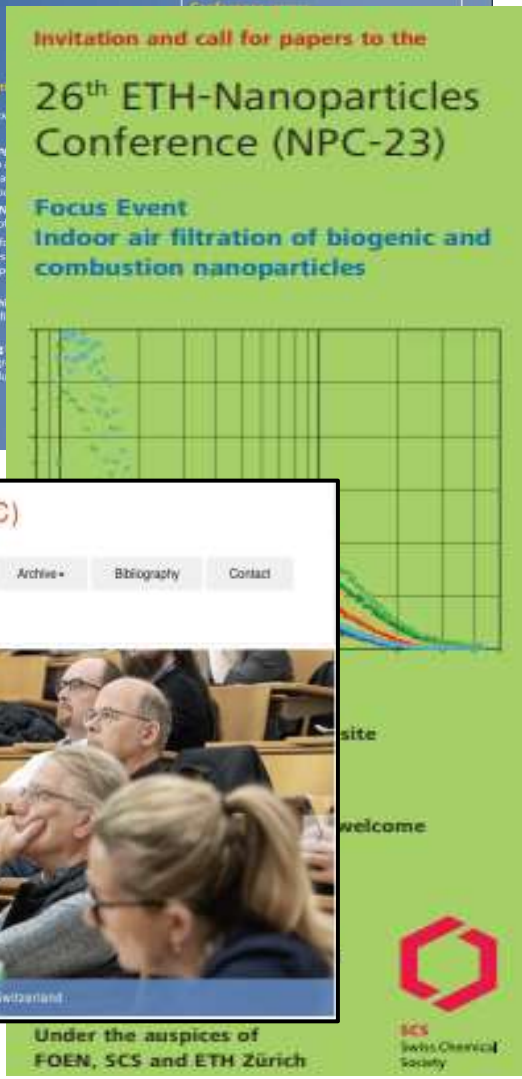
- **1997 first international ETH-NPC workshop - 40 participants**
- Today ETH-NPC is the annual event of UFP experts from science to technology
- **VERT Forum every year:**

- 14th VERT Forum on 22nd March 2024
- **15th VERT FORUM on 20 March 2025**

!! Save the date!! Location TBC

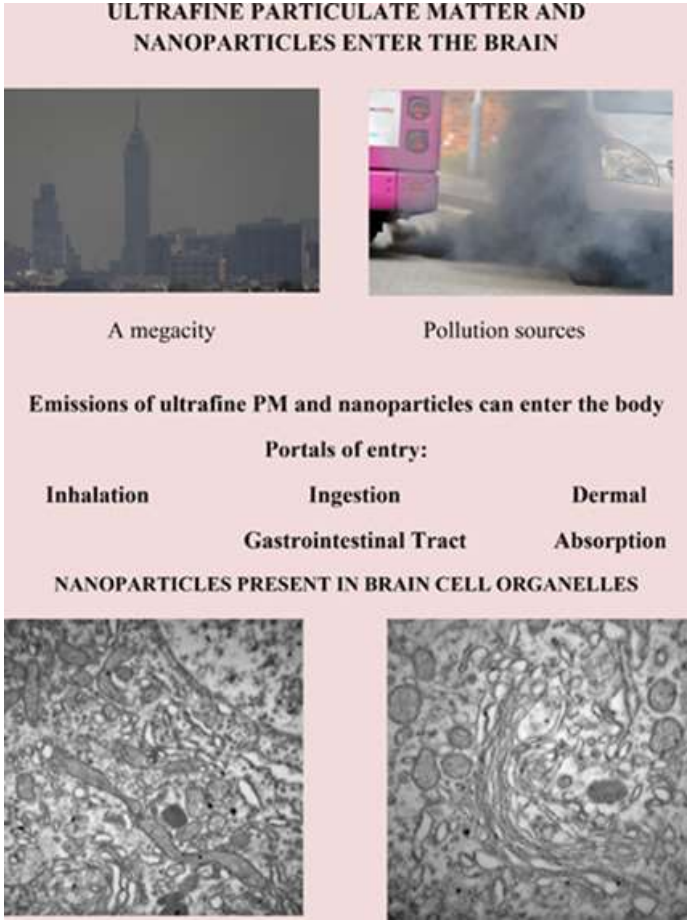
- www.vert-dpf.eu/



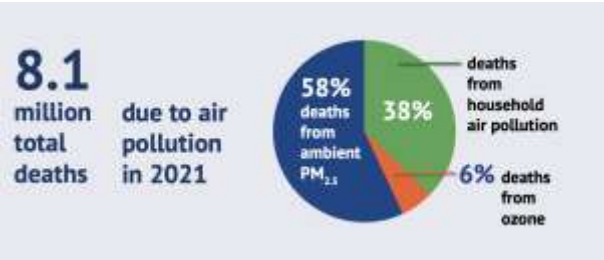


INTRODUCTION

- **Sub-50 nm particles** originating from traffic emissions **pose high risks to human health** due to their high lung deposition efficiency & potentially harmful chemical composition
- **Road Transport is the major contributors** & above all in urban areas with LEZ & Zero Emissions Zone (ZEZ) increasing in Europe
- **Several studies have shown that not only Diesel but also Petrol** engines are of concern as they emit **high PN** and **in smaller sizes** compared to Diesel and **high PAHs**
- **So far only GDI PN emissions are regulated** in Europe, **No PFI** and no PN emissions legislation in USA



Environ. Sci. Technol. 2022, 56, 11, 6847−6856



*Source New State of Global Air Report 2024

*Source Dr. LRubino et Al. - SAE Paper 2023-24-0114

PN Emissions from ICE

Diesel

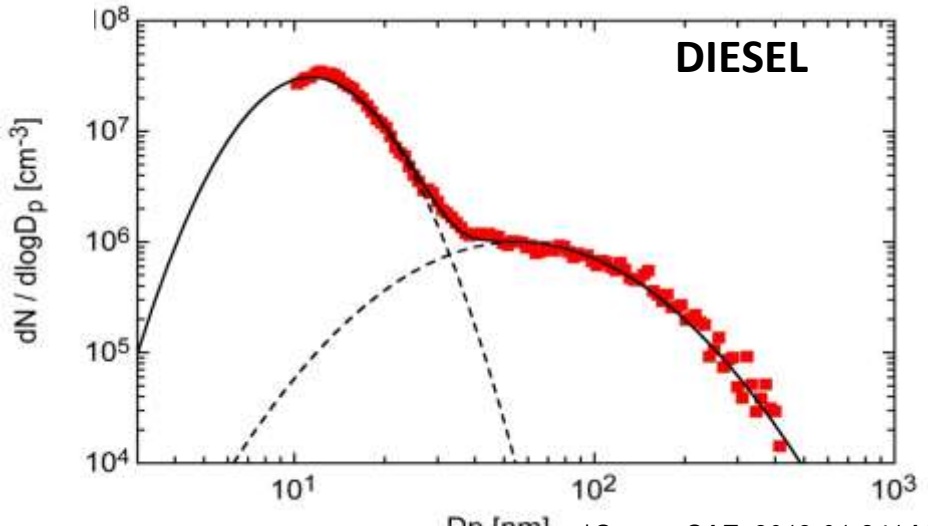
Soot peak: **~80 nm**; 10^6 -10^7

Ash peak: 10 nm;

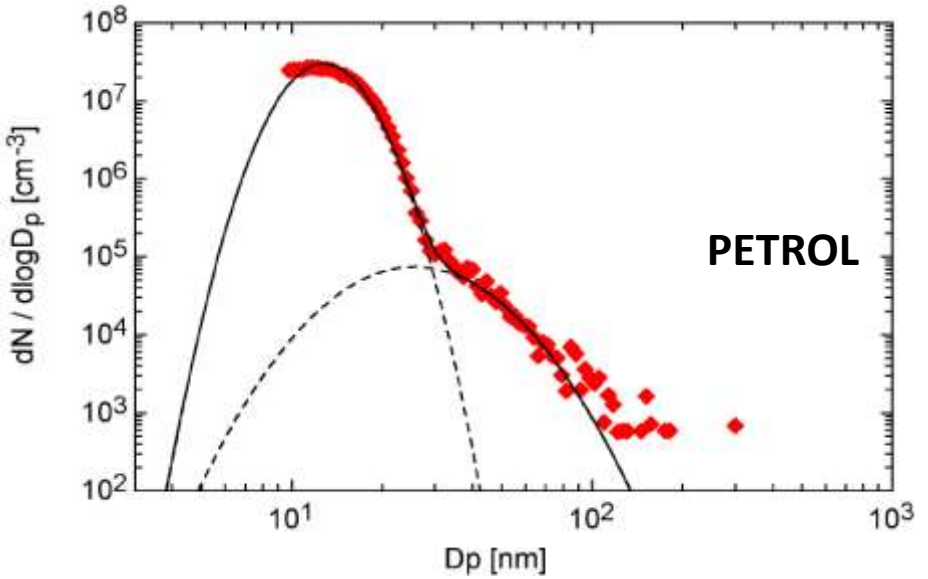
Petrol

Soot peak: **~40 nm**; 10^5-10^8

Ash peak: 10 nm;

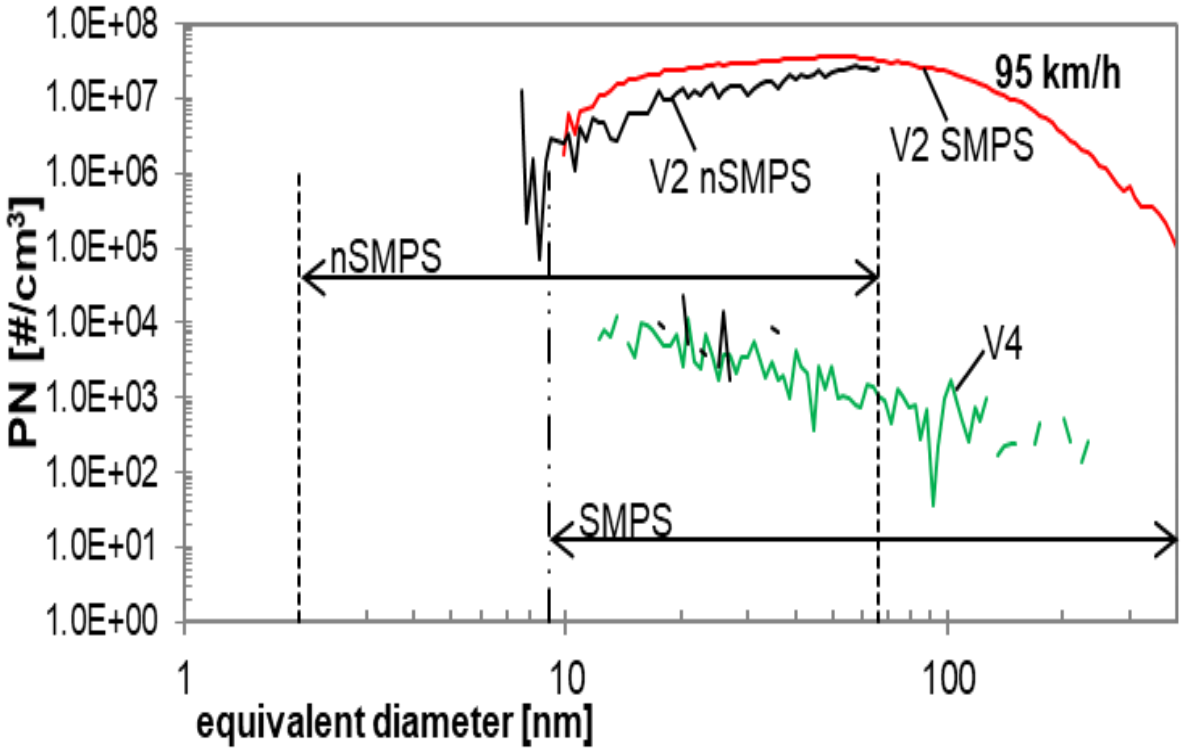


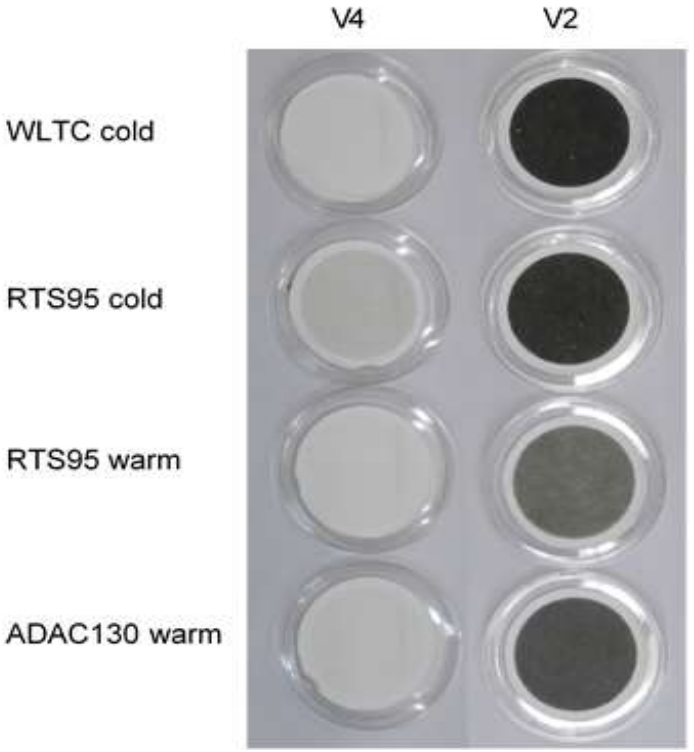
*Source SAE 2012-01-841 Mayer et al



*Source Dr. LRubino et Al.- SAE Paper 2023-24-0114

PFI engines may be even dirtier



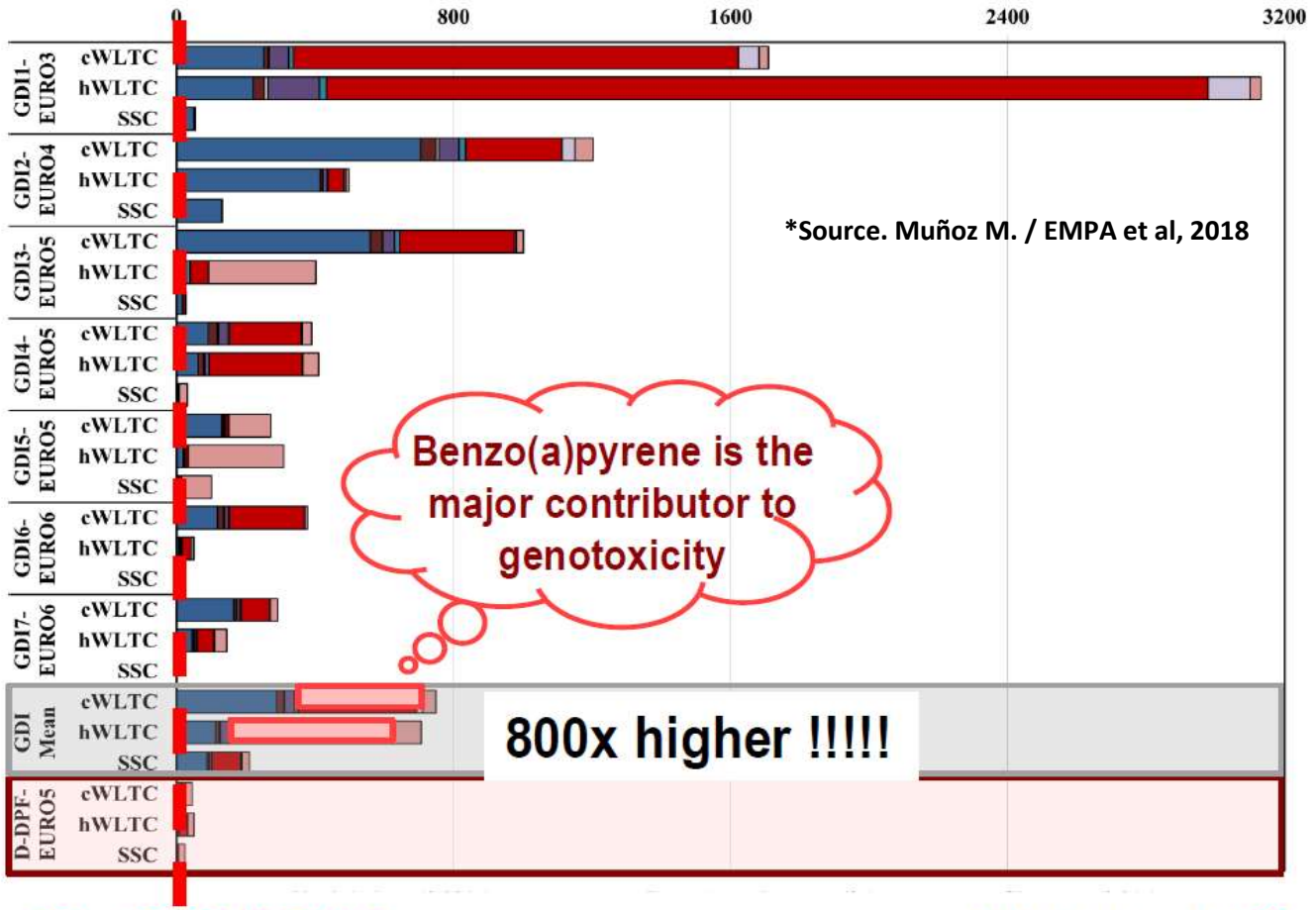


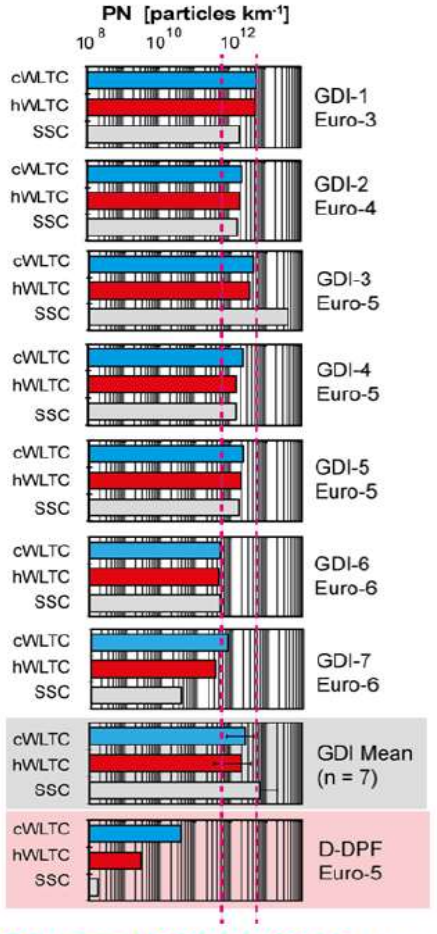
V2 vehicle

*Source SAE 2018-01-0363

- **PFI engines do not have to comply with EU-PN limit values**, i.e. they do not have particulate filters

DI Petrol Engine – High PAH Emissions

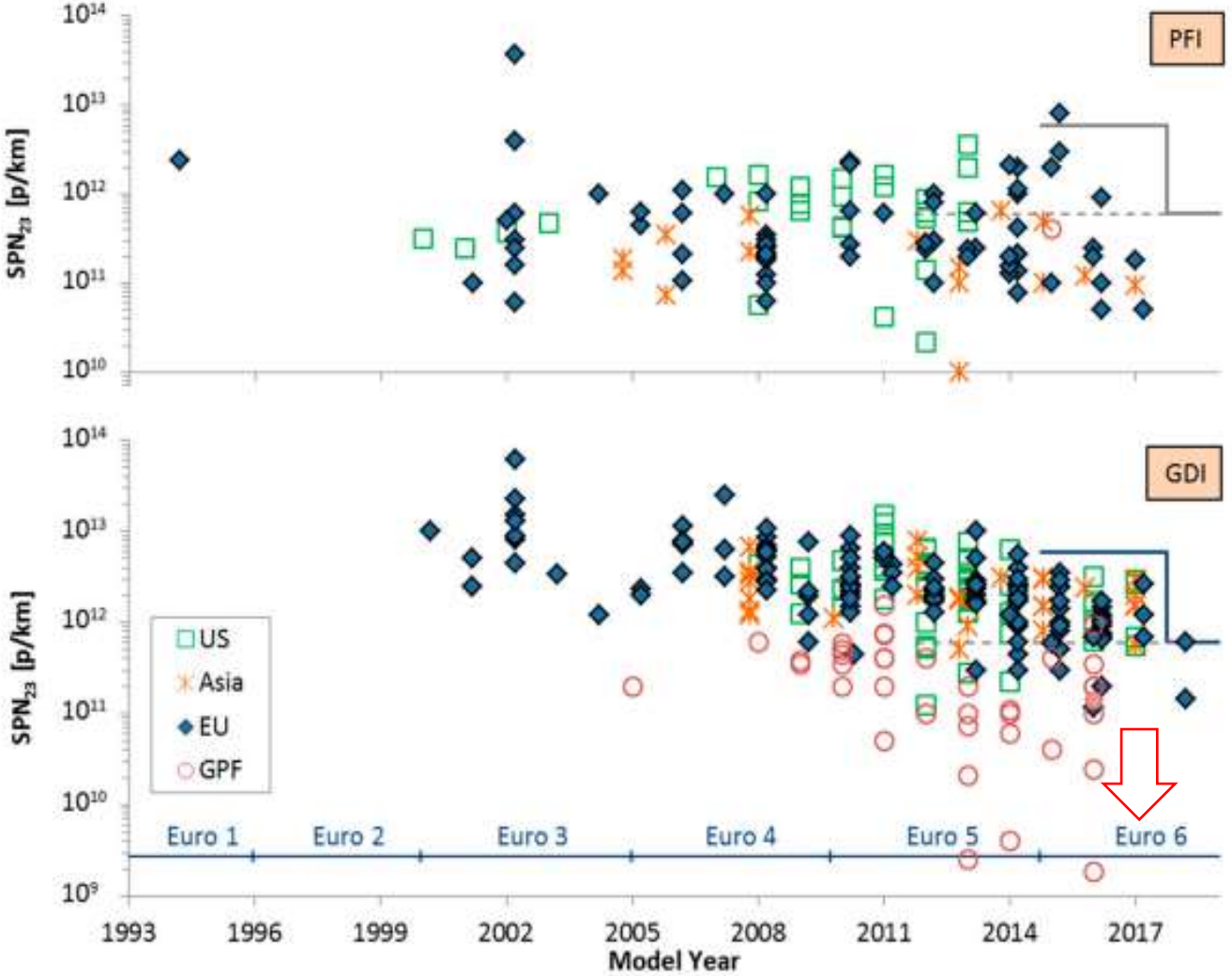




EU - air limit value:
1 ng/m³ benzo(a)pyrene (2014/107/EC Directive)

GDI fleet emits 64-, 700- and 39000-fold higher PN emissions than the Euro-5 diesel vehicle

GDI vs PFI



*Source: Catalysts 2019, 9, 586; doi:10.3390/catal9070586

- **Emissions levels from PFI** vehicles can exceed those from GDI vehicles
- **Low ambient temperature** conditions further increase the emissions
- **Assuming that PFIs still have an important market share**, they should be included in the next regulatory step

No EU PN Regulation for PFI yet

WHAT IS AEROSOLFD?

AeroSolfd
filtration devices

The name AeroSolfd stands for: Fast track **to cleaner, healthier urban Aerosols market ready Solutions** for:
(1) tailpipe
(2) brake systems
(3) (semi-)closed environments of retrofit Filtration Devices

- **EU CO-FUNDED HORIZON Europe INNOVATION ACTION**
- Grant agreement ID: 101056661 - Topic: HORIZON-CL5-2021-D5-01-15
- „**Development and demonstration** of cost affordable and adaptable **retrofit solutions for tailpipe and brake polluting emissions**“
- Duration: 2022/05 – 2025/04 (36 months)
- EU contribution: € 5.00 million - Total cost: € 8.22 million
- Coordinator: MANN+HUMMEL
- **Swiss Fundings (SERI) to VERT** for over 2.20 million CHF

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

APPROACH & TEAM

AeroSolfd
filtration devices

Development → Demonstration → Exploitation

- Specifications, design and integration
- Testing, process validation

- Onsite measurements
- Assessment

- Demo Sites
- Infrastructure

- Sustainability aspects

- Business plan
- IPR Strategy

16 Partners

8 Countries

Coordinator:
Mann + Hummel

Dissemination and Public Awareness

+ all Partners

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

AEROSOLFD APPROACH

AeroSolfd
filtration devices

(1) **Develop and demonstrate cost-efficient tailpipe retrofit filters for Petrol engines, both GDI and PFI**. **The Gasoline Particle Filter (GPF)** retrofit replaces the underfloor silencer to reduce particle number (PN)-emissions **with PN filtration efficiency above 95%** in the existing **high mileage urban fleets currently driving without any filter technology** (Euro 6c and earlier)

(2) **An existing passive brake dust particle filter (BDPF) concept developed by MANN+HUMMEL for passenger vehicles will be modified for bus and commercial vehicle brake applications**. Eco-friendly circular design approaches will be used. This solution is specially designed for long-lived public road transport assets like buses

(3) **An optimized version of a stationary air filter will be developed by MANN+HUMMEL for railway, metro companies or operators.** By combining the latest technologies and simulation tools for smart applications, **the exposure level will be lowered and as a result, the air gets cleaner**

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

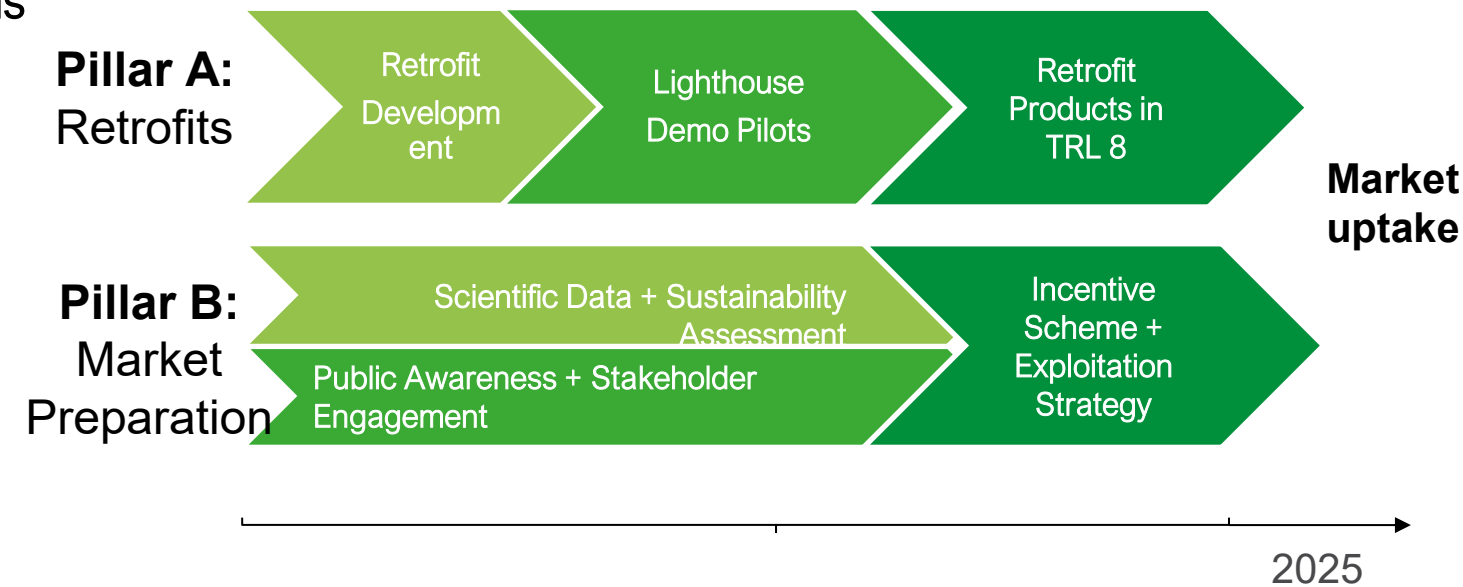
© 2022-2025 AeroSolfd Consortium Partners

FOCUS: RETROFIT WITH GASOLINE PARTICLE FILTERS (GPF)

AeroSolfd
filtration devices

- AeroSolfd Solutions:

Reducing tailpipe emissions



VERT Partners (WP1 & WP5)

HJS, TÜV Sud, G-technology, University of Applied Sciences Biel (BFH), CPK, Technion, Israel Institute of Technology, TCS (CH)

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

AeroSolfd - The Project Targets

AeroSolfd
filtration devices

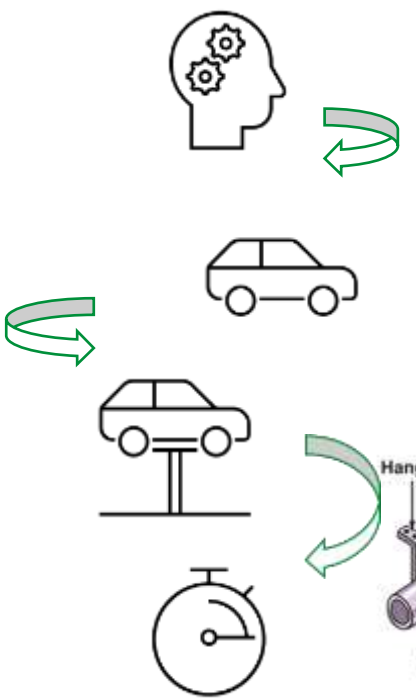
- Adapt and demonstrate an affordable **high efficient gasoline particle filter (GPF)**
- Capable of reducing **95% of the exhaust particles**
- **Cost efficient solution** (circa € 700 - 1.000) depending on engine size and power rating
- **Fast track to market** by using an already proven technology in high volume production
- **Measure PN and secondary emissions** (i.e. PAH, Nitro-PAH, NH3, N2O) to evaluate the impact of the retrofit filter
- **NPTI testing campaign of 1000 gasoline vehicles** (DI, PFI)
- **Exploitation plan for retrofitting 5 million vehicles with GPF** by 2035

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

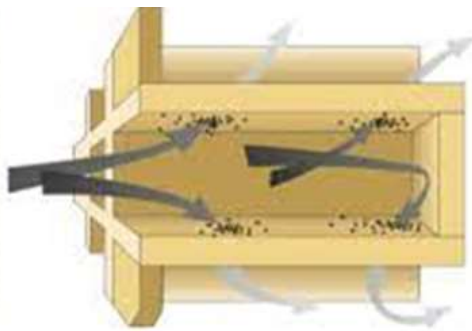
© 2022-2025 AeroSolfd Consortium Partners

Overview



Exhaust System

GPF



Corning 200/8 GC2.0

GPF serial production / GC2.0 APT2

Co-funded by the European Union

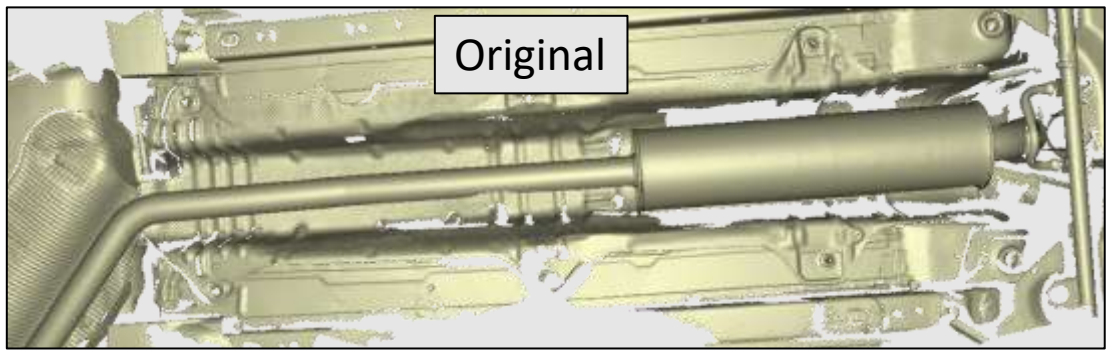
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

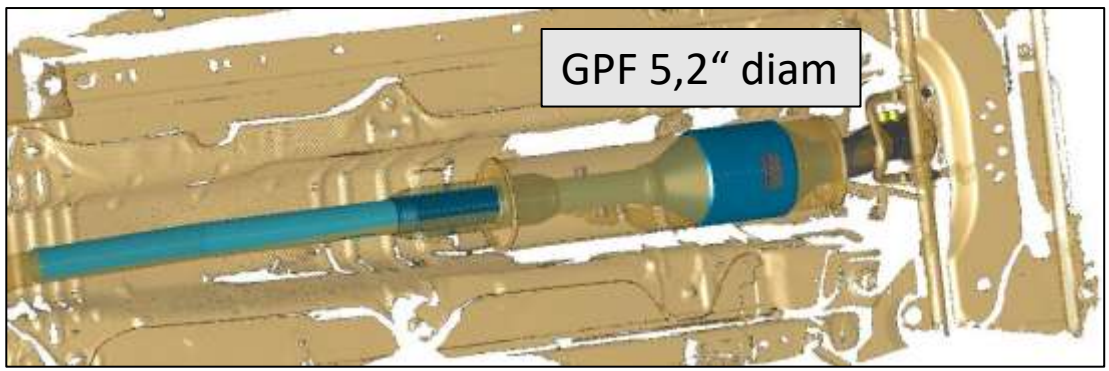
© 2022-2025 AeroSolfd Consortium Partners

4 Engine Families – GPF Retrofit

AeroSolfd
filtration devices

HJS Tailpipe GPF retrofit (example)





Peugeot 3008, DI ,1,6L

VW Golf

DI, 1,4L

FIAT, 500X

PFI, 1,6L

OPEL Corsa

PFI , 1,2L

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

AeroSolfd - Preliminary Results

AeroSolfd filtration devices

	V1 (DI)		V2 (DI)		V3 (PFI)		V4 (PFI)		
	GPF	OEM	GPF	OEM	GPF	OEM	GPF	OEM	
WLTC1	1.2E+10	9.9E+11	2.9E+10	1.9E+12	1.3E+10	1.9E+11	2.5E+10	3.3E+11	p/km
WLTC2	1.1E+10	9.7E+11	8.0E+09	2.1E+12	3.0E+09	1.4E+11	2.0E+10	4.9E+11	p/km
WLTC3	1.3E+10	9.9E+11	1.8E+10	1.8E+12	3.0E+09	1.6E+11	2.8E+10	5.0E+11	p/km
WLTC av.	**1.2E+10**	**9.8E+11**	**1.8E+10**	**1.9E+12**	**6.3E+09**	**1.6E+11**	**2.4E+10**	**4.4E+11**	**p/km**
$FE_{(WLTC)}$		**98.8**		**99.0**		**96.1**		**94.5**	**%**
Ratio		82		104		26		18	-

OEM: Original Equipment Manufacturer / GPF: Gasoline Particle Filter
Ratio: emissions in #/km without GPF divided by emissions in #/km with retrofited GPF

V1.. VW Golf
V2.. Peugeot 3008
V3.. Fiat 500X
V4.. Opel Corsa E

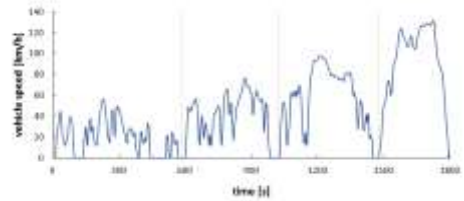
	V1 (DI)		V2 (DI)		V3 (PFI)		V4 (PFI)		
	GPF	OEM	GPF	OEM	GPF	OEM	GPF	OEM	
RDE1	4.2E+09	8.6E+11	5.9E+09	1.3E+12	1.6E+09	1.1E+11	2.7E+09	3.0E+11	p/km
RDE2	2.6E+09	9.5E+11	4.6E+09	1.2E+12	1.4E+09	9.3E+10	3.5E+09	2.7E+11	p/km
RDE3	2.1E+09	9.0E+11	2.2E+09	1.9E+12	1.2E+09	5.0E+10	2.5E+09	2.1E+11	p/km
RDE av.	**3.0E+09**	**9.0E+11**	**4.2E+09**	**1.5E+12**	**1.4E+09**	**8.3E+10**	**2.9E+09**	**2.6E+11**	**p/km**
$FE_{(RDE)}$		**99.7**		**99.7**		**98.3**		**98.9**	**%**
Ratio		305		345		60		90	-

OEM: Original Equipment Manufacturer / GPF: Gasoline Particle Filter
Ratio: emissions in #/km without GPF divided by emissions in #/km with retrofited GPF

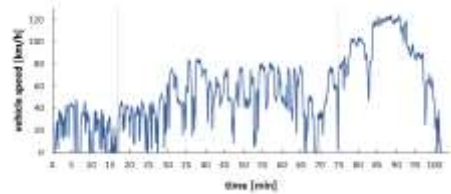
V1.. VW Golf
V2.. Peugeot 3008
V3.. Fiat 500X
V4.. Opel Corsa E

BFH University of Applied Science

GPF Filtration efficiency > **94,5% over 3WLTC**



GPF Filtration efficiency > **99% over 3 RDE**



Co-funded by the European Union

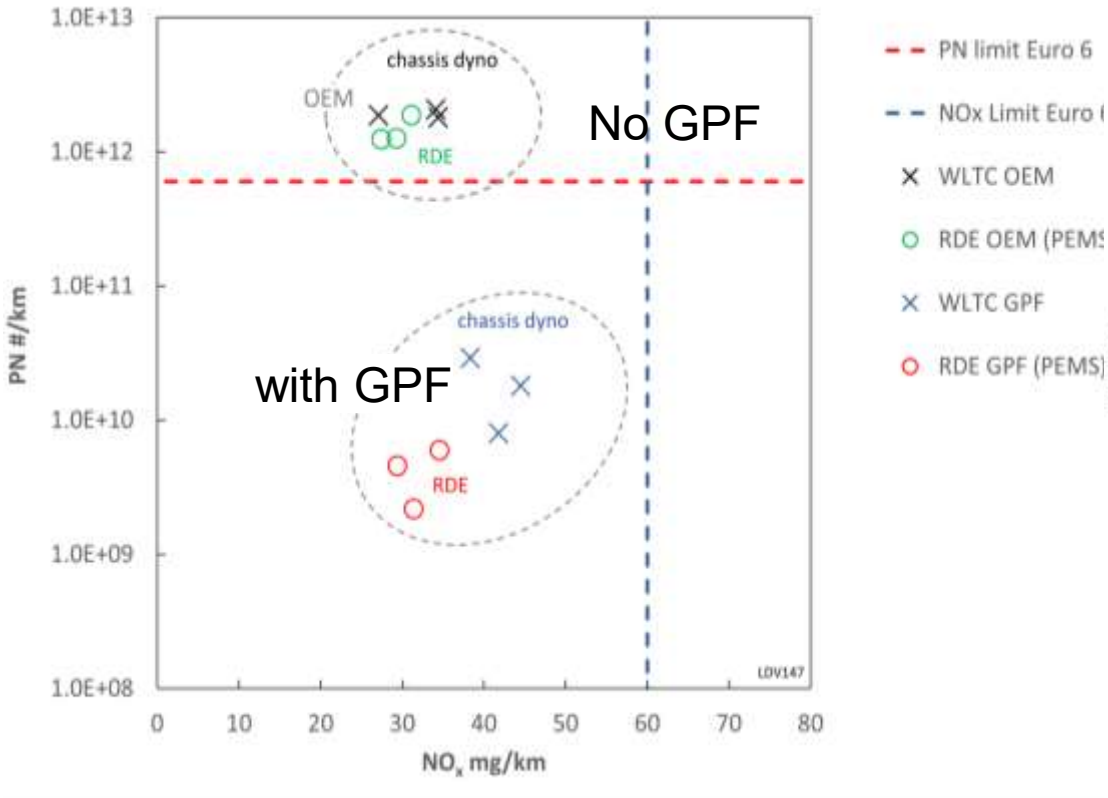
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

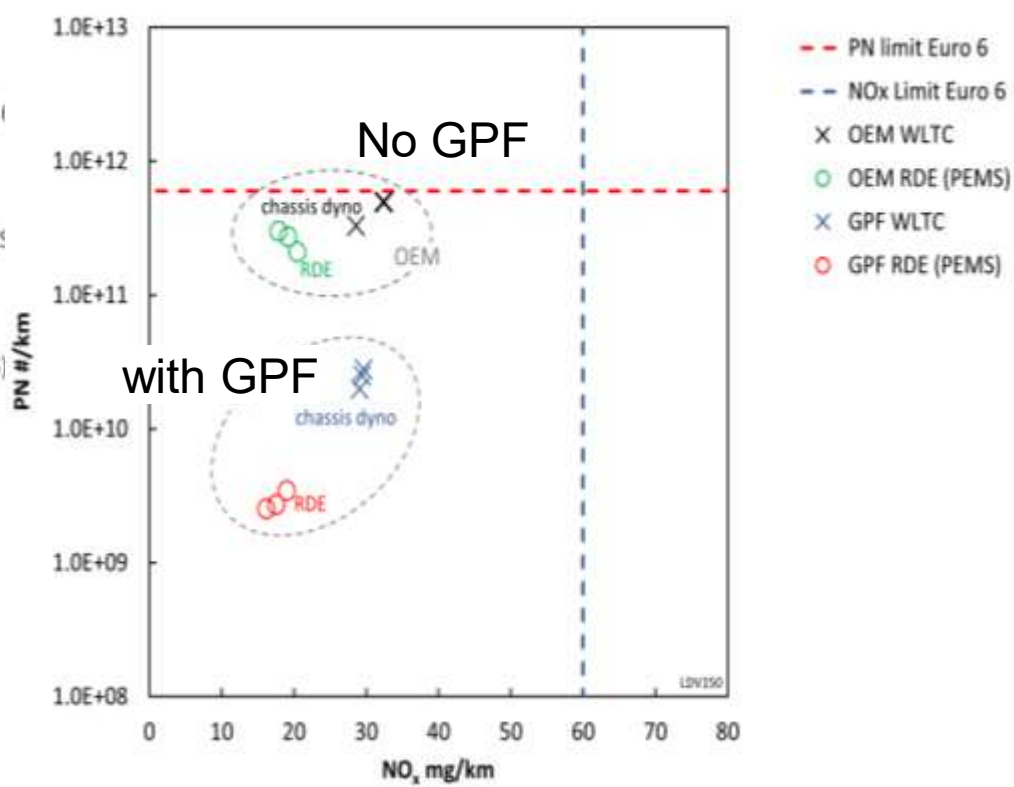
AeroSolfd - Preliminary Results

AeroSolfd
filtration devices

Pegeout 3008 - DI 1,6 L
PN vs. NO_x



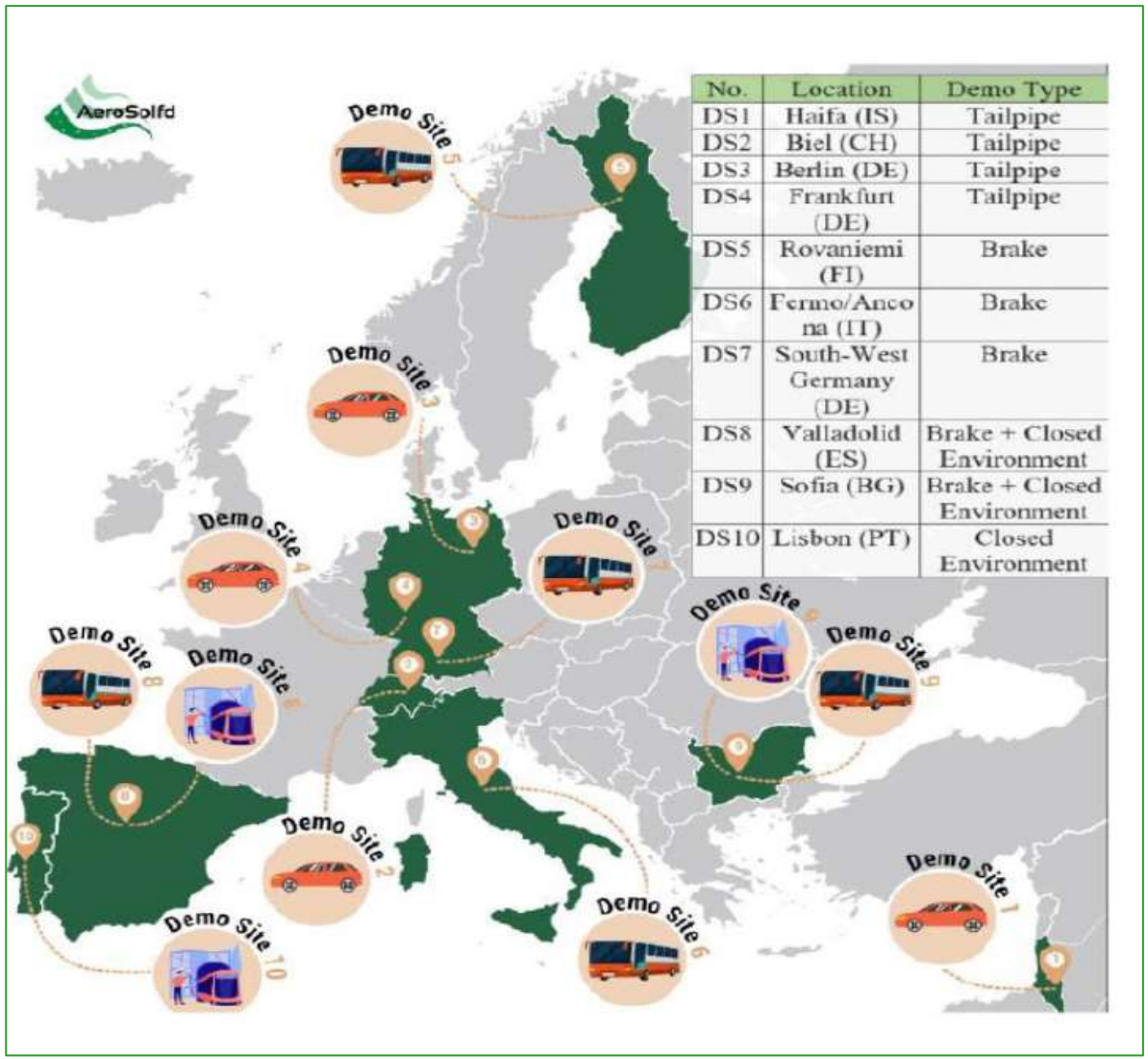
Opel Corsa – PFI 1,2 L
PN vs. NO_x



Co-funded by
the European Union

© 2022-2025 AeroSolfd Consortium Partners

Demonstration sites (VERT)



No.	Location	Demo Type
DS1	Haifa (IS)	Tailpipe
DS2	Biel (CH)	Tailpipe
DS3	Berlin (DE)	Tailpipe
DS4	Frankfurt (DE)	Tailpipe
DS5	Rovaniemi (FI)	Brake
DS6	Fermo/Ancona (IT)	Brake
DS7	South-West Germany (DE)	Brake
DS8	Valladolid (ES)	Brake + Closed Environment
DS9	Sofia (BG)	Brake + Closed Environment
DS10	Lisbon (PT)	Closed Environment

- Tot 50 vehicles with GPF Retrofit
  - one fleet in Germany
  - one fleet in Switzerland
  - one in Israel and Denmark
- operating 6-8 months, PN, PEMS & NPTI measurements

Co-funded by the European Union

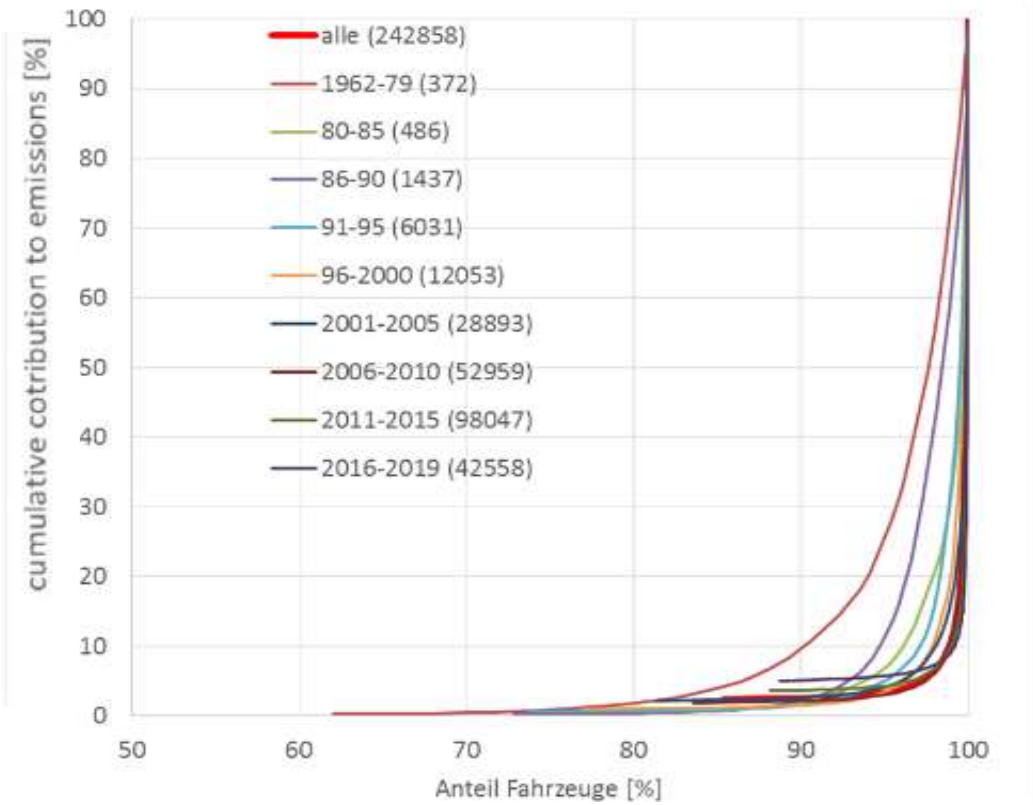
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

VERT & NPTI

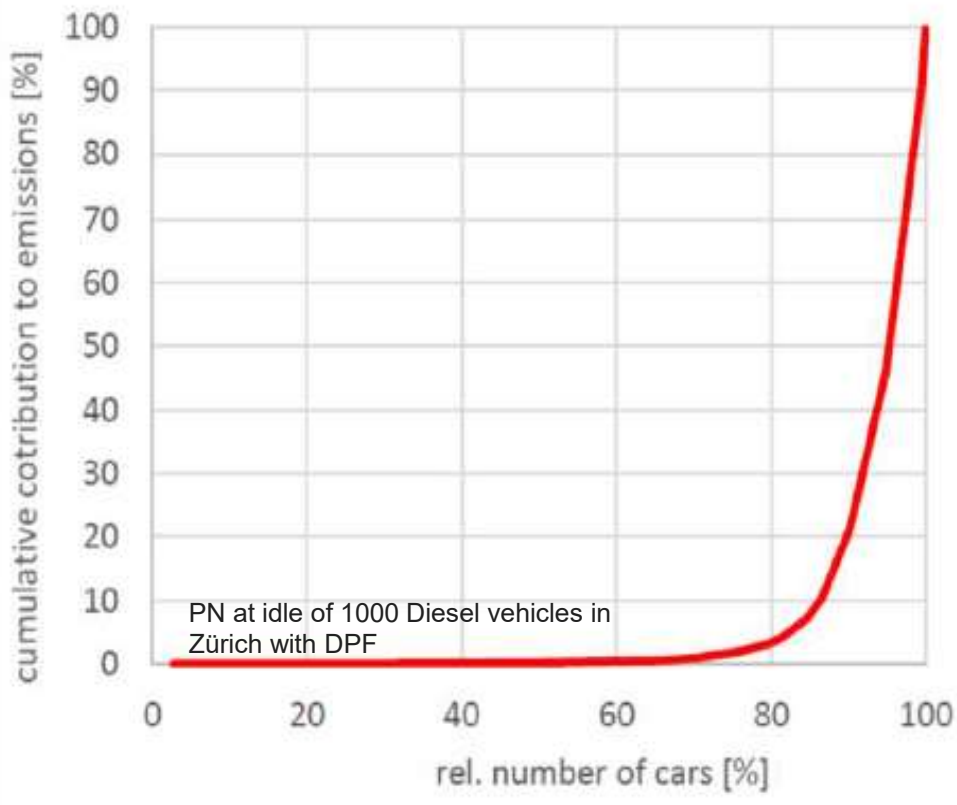
- **VERT has been very active on "New Periodic Technical Inspection" (NPTI)** since 2016, **establishing a new test method** within the international VERT-NPTI working group (2016-19) **now implemented in several European countries for testing of DPF-equipped Diesel vehicles**, and collaborating with different policymakers, environmental authorities, type approval authorities, equipment manufacturers and PTI service providers **as well as conducting different case studies**
- **In particular, VERT carried out** with the local authority SEDEMA **a PTI case study with 400,000 in-use gasoline vehicles in Mexico City** (2018); All PTI stations were equipped with roller dynamometers, so that a simplified test could be carried out that reflected the emission behaviour in urban traffic (Dominguez C. / GESPA 2018, JRC No.CTEX2020D380212-101)
- **PTI measurements in Mexico showed that 2-3% of the vehicles are responsible for over 90% of the particulate emissions of the all fleet.** For some generations of vehicles, the effect was even greater and **can dominate the pollution of urban air**
- **The problem is not only in Mexico City, but in many urban areas.** The analysis of 1000 **Diesel vehicles in Zurich showed that 8% of the vehicles** are responsible for **over 90% of the total emissions**

2-8% of the vehicles may produce > 90 % of the overall emission of the fleet



The «dirty tail» phenomenon with Petrol Engines
PN-Emission of 400'000 cars in Mexico City (VERT+Sedema, 2018)

* Source= Dominguez C. / GESPA; 2018; JRC No. CTEX2020D380212-101



The «dirty tail» phenomenon with Diesels <u>with particle filters</u>
Cumulative contribution of High Emitters to Zürich fleet emissions
(Gloor, VERT Forum 2018)

High Emissions because of Petrol Engines

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

*Source Dr. LRubino et Al. - SAE Paper 2023-24-0114

The "dirty tail" of every vehicle fleet

- **If these "high emitters" could be found and repaired or eliminated, particulate emissions would be reduced to 1/3 in a very inexpensive and quick action.** There is no other, more cost-effective method to reduce particulate emissions in a city so massively in such a short time
- **The causes for this phenomenon of "high emitters" are different and mostly stochastic in nature**:
  - Statistical error distributions in materials
  - Tolerance outliers, unexpected operating conditions
  - Non-standard fuels and lubricating oils
  - Overloading, lack of maintenance
  - Use of cheap spare parts
  - Manipulation, mostly for cost reasons
  - engine, turbo and aftertreatment (i.e. DOC/TWC/ SCR / DPF/GPF) malfunctions
  - ….

The "dirty tail" of every vehicle fleet

Just a few examples, which deserve **more research to understand the technical reasons of the "dirty tail"** in details:

- **Injection problems** ⇒ **PN**
- **Turbocharger problem** ⇒ **PN**
- **Valve leakage** ⇒ **PN**
- **Altitude compensation problem** ⇒ **PN**
- **Fuel problems / Lube Oil quality** ⇒ **PN**
- **EGR-Problems** ⇒ **PN**
- **DPF/ GPF-Problem** ⇒ **PN**
- **Piston, liner or ring wear** ⇒ **PN**
- **DOC and SCR-problems** ⇒ **PN**

Why choose PN?

PN is the best flagship metric for air pollution because:

- **it dominates the health risk in urban air**
- **It is the most sensitive criterion**, easy to control, monitor and quantify
- **it best characterizes the main contributor of the internal combustion engine (both Diesel & Petrol)**

➢ **The target is to use this tool for all vehicles and also to find out which technical measures can be recommended to mitigate the "high emitters"**

➢ **Preliminary data over 800 gasoline vehicles** from a **NPTI testing campaign of 1000 gasoline**, including GDI with no GPF, PFI and GPF-equipped vehicles, within the **Horizon Europe AeroSolfd project** are presented. Further testing and data analysis is ongoing

➢ **These preliminary data show a "dirty-tail phenomena"** that **needs attention and mitigation measures**

NPTI Testing Campaign – 1000 Gasoline Vehicles

AeroSolfd filtration devices

Test procedure

- Measurement 1 (high idle) **without load**
  - Engine speed between 2000 – 3000 U/min
  - 15 s stabilization, 15 s measurement
  - Record mean value
- Measurement 2 (high idle) **with load**
  - A/C (air conditioning) max + rear window heating
- Engine speed between 2000 – 3000 U/min
  - 15 s stabilization, 15 s measurement
  - Record mean value

Measurements carried out by TCS in Switzerland
In collaboration with AVLdiTest & BFH

Measurement Equipment

- **AVL DiTEST Standalone Counter**

- Based on advanced diffusion charging principle
- With heated measurement probe
- With water trap
- 23 nm cut-off

Co-funded by the European Union

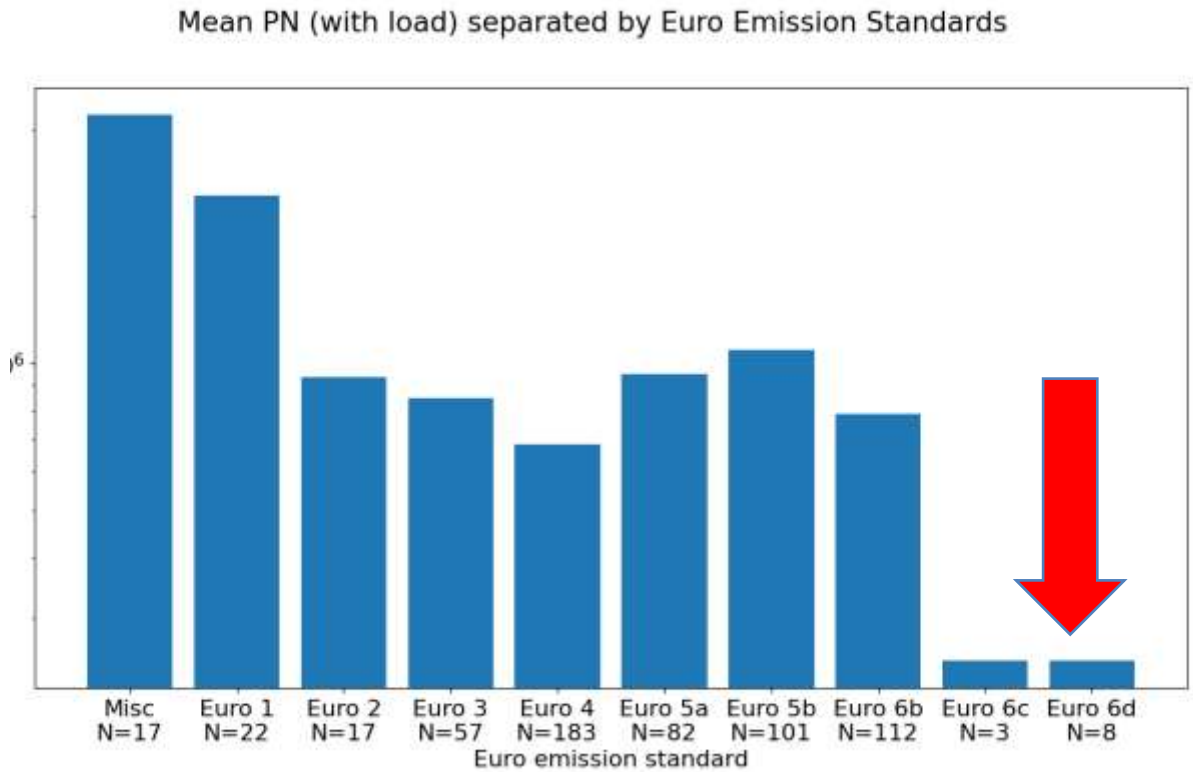
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

NPTI Testing Campaign – 1000 Gasoline Vehicles

AeroSolfd
filtration devices

- **Fleet tested:** Different **in-use gasoline vehicles**, including GDI, PFI and GPF-equipped vehicles



Euro 6d vehicles have significantly lower PN emissions (vehicles with GPF)

Co-funded by the European Union

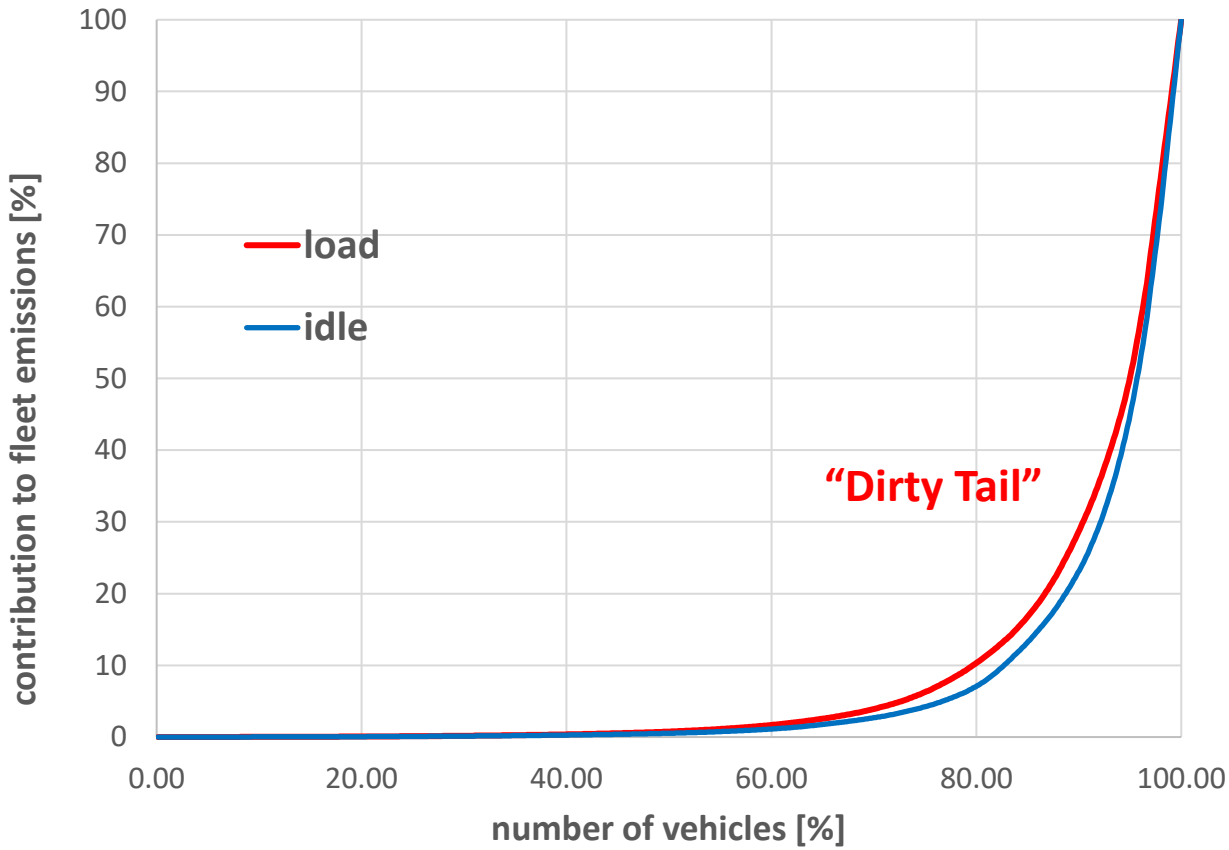
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

NPTI Testing Campaign – 1000 Gasoline Vehicles

AeroSolfd
filtration devices

- **Over 800 gasoline vehicles tested** so far for PN emissions
- Data analysis show good repetability
- **„Dirty Tail phenomena**“ observed



Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

© 2022-2025 AeroSolfd Consortium Partners

SUMMARY

- **The HORIZON AeroSolfd project, with GPF-retrofit** of gasoline vehicles **aims to a widespread introduction of GPF to reduce nanoparticle emissions** from high mileage vehicles, and will also serve as a platform to **continue research on PN & secondary emissions** from both **DI and PFI engines**
- **VERT, with its members partners,** HJS, CPK, BFH and CORNING, delivers a TRL 8 GPF-retrofit system for future market applications. **The GPF-retrofit system shows filtration efficiency over 99%** on standard cycles and on road.
- **The New NPTI Investigation of 1000 gasoline vehicles** including DI, PFI and GPF-equipped vehicles **within the AeroSolfd project is an important contribution** to analyse and identify **the root-cause of "high emitters"** and **the "dirty tail" phenomena** of gasoline vehicle fleets in urban areas
- **The "dirty tail" phenomena observed** in the in-use gasoline fleet (over 800 vehicles so far) **needs attention and mitigation measures –** Further testing and data analysis ongoing
- **The very likely "still presence" of gasoline vehicles until 2035** & beyond justifies **the need of GPF retrofit & mitigation measures for the "dirty-tail phenomena"** of vehicle fleets as **fast and cost-effective solution** to cleaner mobility
- **Clean Air & Clean Mobility cannot be a privilege but a right for All**

Acknowledgement

aerosolfd-project.eu

AeroSolfd filtration devices

Co-authors – VERT Association

Dr. A. Mayer

Prof. J. Czerwinski

Mr. T. Lutz

Mr. L. C. Larsen




https://www.vert-dpf.eu/

Special Thanks to the Swiss Federal Agencies FOEN, FEDRO and SERI for the financial support with, Horizon AeroSolfd and last but not least to **All the 16 AeroSolfd partners**

Disclaimer

AeroSolfd is co-funded by the European Union. " Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them."

© 2022-2025 AeroSolfd Consortium Partners

THANK YOU FOR YOUR ATTENTION!

aerosolfd-project.eu

https://www.vert-dpf.eu/

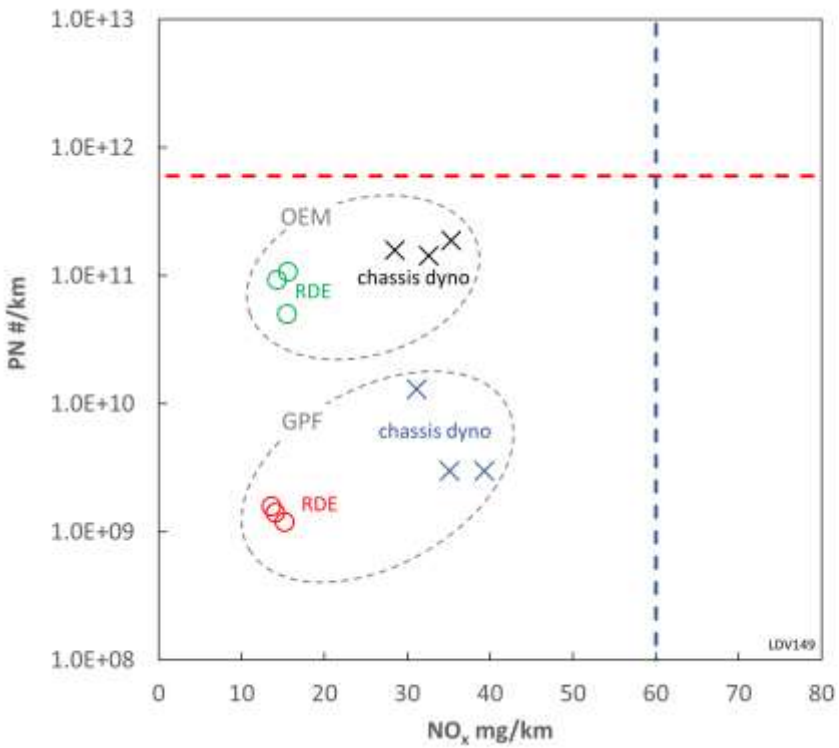
Questions?

Lauretta.Rubino@vert-dpf.eu

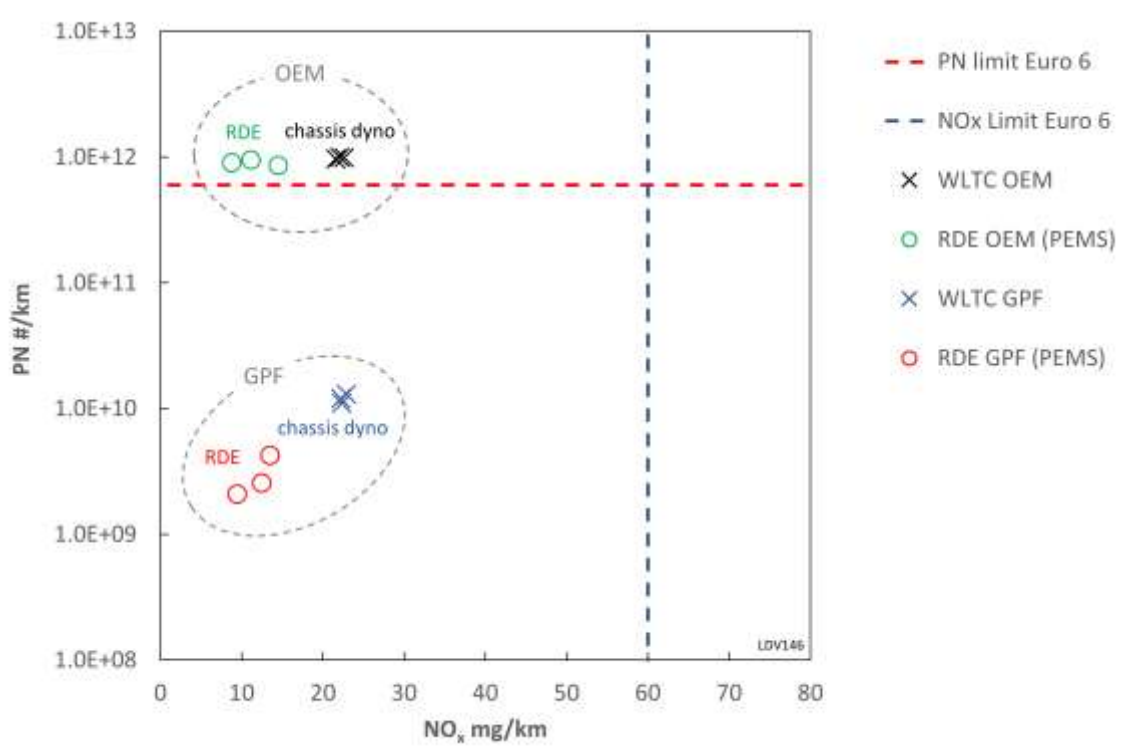
AeroSolfd - Preliminary Results

AeroSolfd
filtration devices

FIAT 500X – PFI, 1,6 L
PN vs. NO_x



VW Golf – DI, 1,4 L
PN vs. NO_x



Co-funded by
the European Union

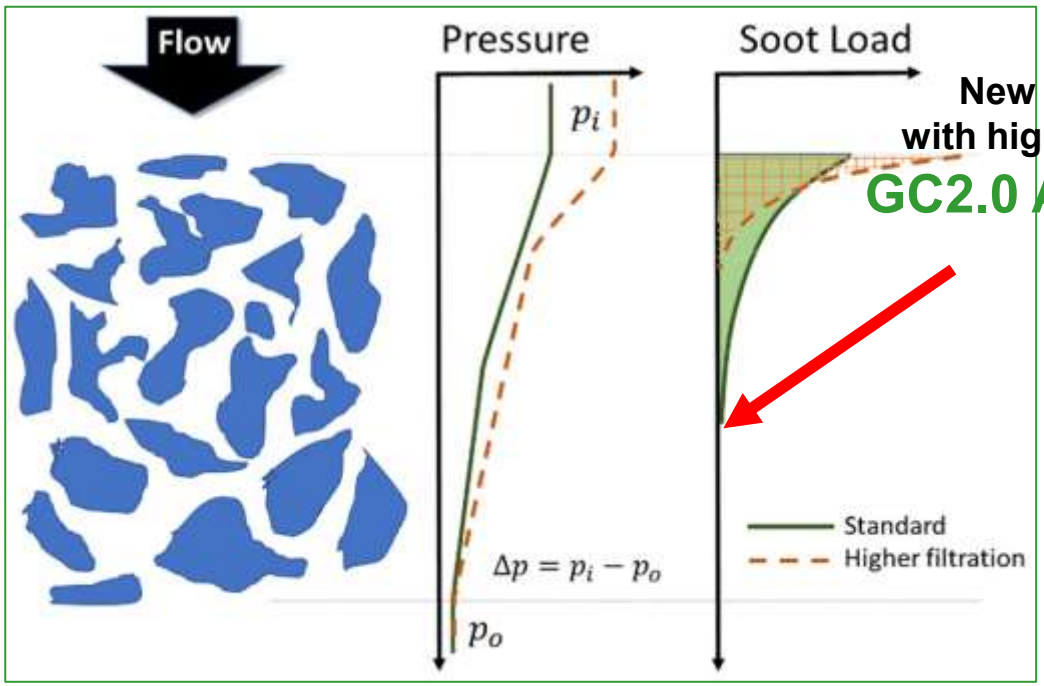
© 2022-2025 AeroSolfd Consortium Partners

INTRODUCTION

- **Homologation, Conformity of Production (COP), In Service Conformity (ISC) and Surveillance Monitoring** take care of systematic deteriorating effects of emissions given by the applied technology and established production quality
- **In view of the steadily tightening limits** of exhaust gas legislation, which now also includes a PN limit value for all new DI petrol engines in the EU, it is to be expected that **the vast majority of vehicles will comply with the limit values, or even be below them**
- **However, periodic technical inspections (PTI),** which are carefully carried out in many countries, and occasional roadside inspections by remote sensing or plume chasing, **show that a proportion of vehicles exceed the limits by a large margin - How can this be explained?**
- **What about wear, random failures, maintenance negligence and intentional manipulation**, which might have much stronger influence **on urban air quality** than built-in and well controlled systematic deteriorations?
- **This risk of deterioration in vehicle fleets has become even larger with the introduction of emission control elements like DPF, DOC and SCR since these technologies are expensive to replace and temptation for manipulation is increasing**

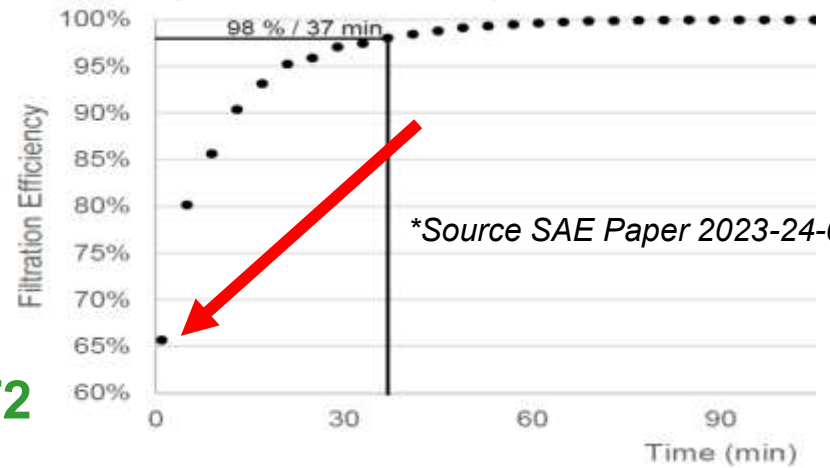
But these filters have low performance if not soot-loaded and… with petrol engines they remain clean

AeroSolfd
filtration devices

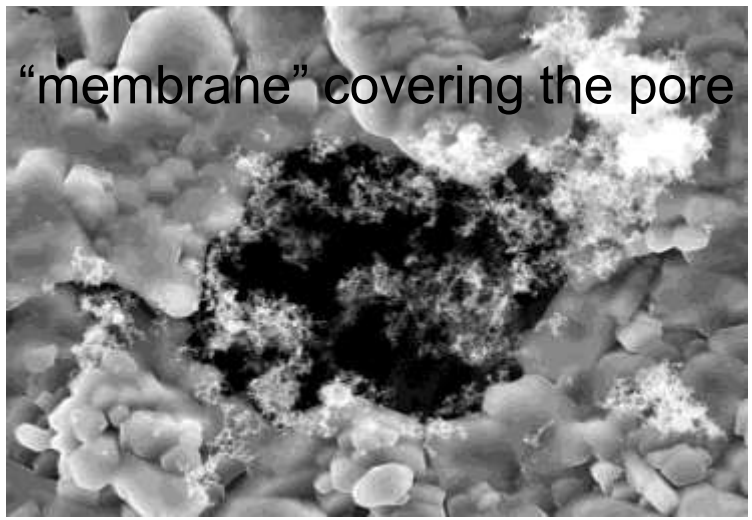


New GPF with high FE

GC2.0 APT2



*Source SAE Paper 2023-24-0114



Schematic representation of flow, pressure and soot collection (filtration) across a porous wall. Solid and dashed line represent two kinds of microstructure with standard and higher filtration efficiency (Boger, T.. et al., "Next Generation Gasoline Particulate Filters for Uncatalyzed Applications and Lowest Particulate Emissions," SAE Int. J. Adv. & Curr. Prac. in Mobility 3(5):2452-2461,2021, https://doi.org/10.4271/2021-01-0584.)

*Source: Payne S. /Uni. of Cambridge; Study of diesel particulate bridging behavior with SEM; ETH-NPC 2012

Co-funded by the European Union

© 2022-2025 AeroSolfd Consortium Partners