AVL POWERTRAIN ENGINEERING TECHDAY #4

Gasoline Particle Filter Development and Calibration

AVL List GmbH

Public

AVL EXPERIENCE ON GPF SYSTEM DEVELOPMENT

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2013	2014	2015	2016	2017

AVL GPF R&D project (permanently ongoing)

Collaboration with several GPF suppliers, coaters…

GPF system physical behavior identification and modeling (ash / soot loading, thermal model, regeneration…)

GPF system detailed requirements for SW functions → AVL GPF SW Development → AVL GPF SW for SOP

GPF system calibration methodology

GPF system development process

Several GPF Predevelopment customer programs

6 GPF Production calibration programs in Graz, 12 Worldwide

Our offer

Deep know how on GPF physical behavior (soot loading, active/passive regeneration…)

GPF SW architecture

GPF Calibration methodology

GPF System development process

GASOLINE PARTICLE FILTER

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PARTICULATE EMISSIONS OPTIMIZATION - OVERVIEW

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Status before recent Emission Compliance Issues:

- **Significant improvements of PN, but still on risk level for safe EU6d / RDE compliance for downsized /heavy vehicles or unsolved coking issues**
  ➔ GPF to be considered

EU- Consequences of Emission Compliance Issue:

- **Enhanced RDE requirements ➔ RDE Package 3**
- **Public pressure on emission compliance under all operating conditions even with Gasoline**

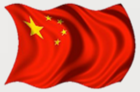
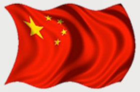
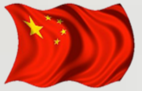
China – Release of stringent Ch6 incl. RDE for air quality reasons, PN is more critical due to fuel quality, driving style and lifetime aspects

➔ Introduction of GPF in an extremely wide range

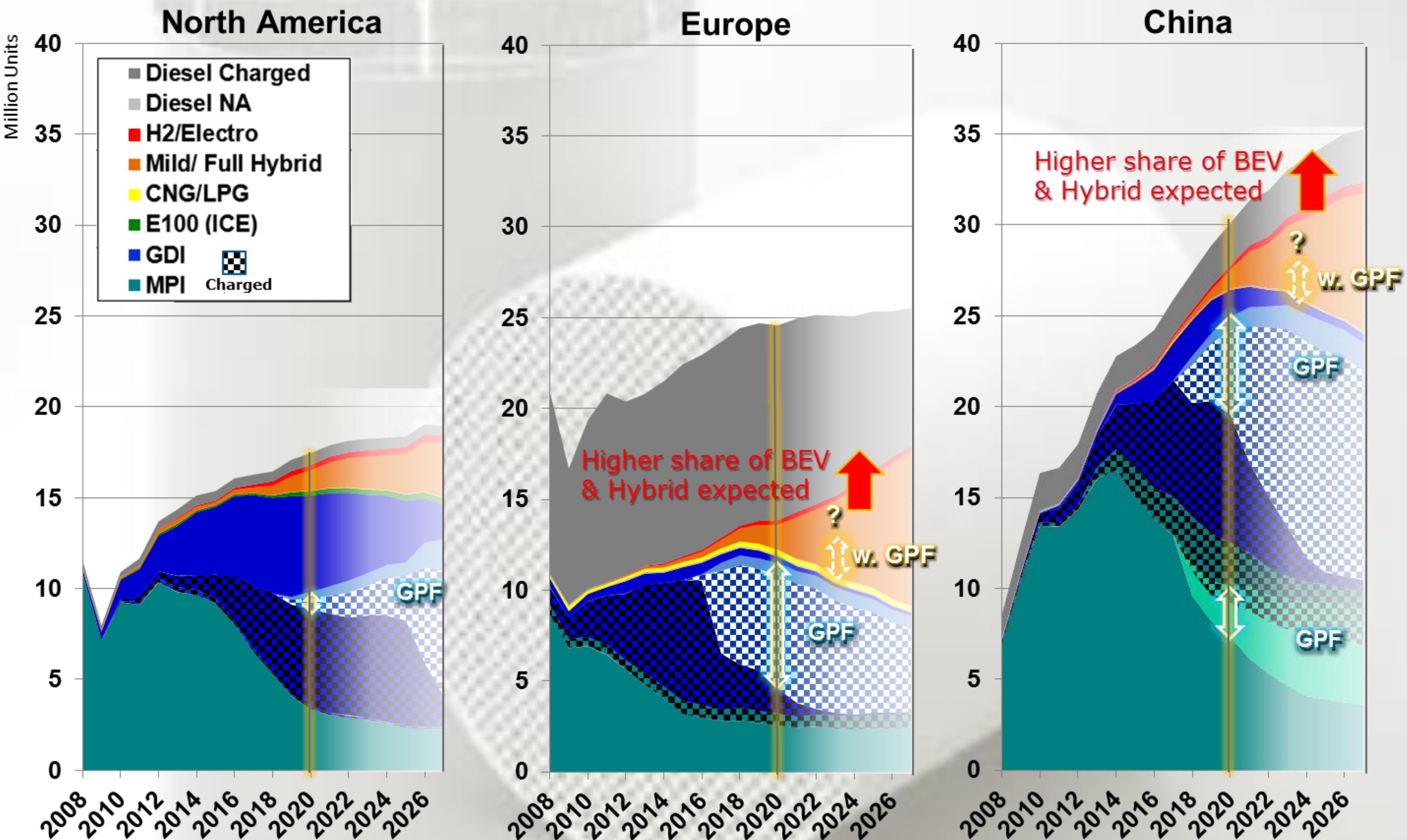
➔ Even with GPF combustion optimization for best EO-PN/PM is mandatory due to RDE Package 3 and generally to minimize GPF drawbacks

GASOLINE PARTICLE FILTER
OVERVIEW GPF – NEED FOR GPF

A GPF is usually taken into consideration for the following reasons:

- **Need to fulfill the particulate emissions on a robust basis** under consideration of the RDE requirements which comprise the entire engine load / speed map especially including high load dynamic operation **when Engine hardware/ Calibration upgrade is not possible or vehicle configuration is too extreme.**
- **Maximized robustness for critical power-to-weight vehicle ratios (i.e. heavy vehicle with a high efficient, downsized engine)**
  ➔ Up to moderate RDE load conditions mostly CO_2 neutral
- **Maximized robustness for real life fuel qualities and oil-born particulates** 
- **Maximized robustness in view of for the target market available HW SW solutions (e.g. injector coking / ballistic injection realization)** 
- **Possible "forced" GPF introduction** either for political / social reasons or due to legal requirements (e.g. by reduction of particle size cut-off threshold from currently 23 nm down to 10 nm) 
- **Aggressive driving with significant component protection shares also pushes MPI vehicles above PN limits**
  The EU could react with PN Limit for MPI/PFI vehicles 
  ➔ CHINA 6 draft includes this already 

ESTIMATION OF GPF INTRODUCTION



Source: Base Data: IHS Q4 2015, GPF: AVL June 2016

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GASOLINE PARTICLE FILTER
EAS CONFIGURATIONS FOR EU/ US / CH

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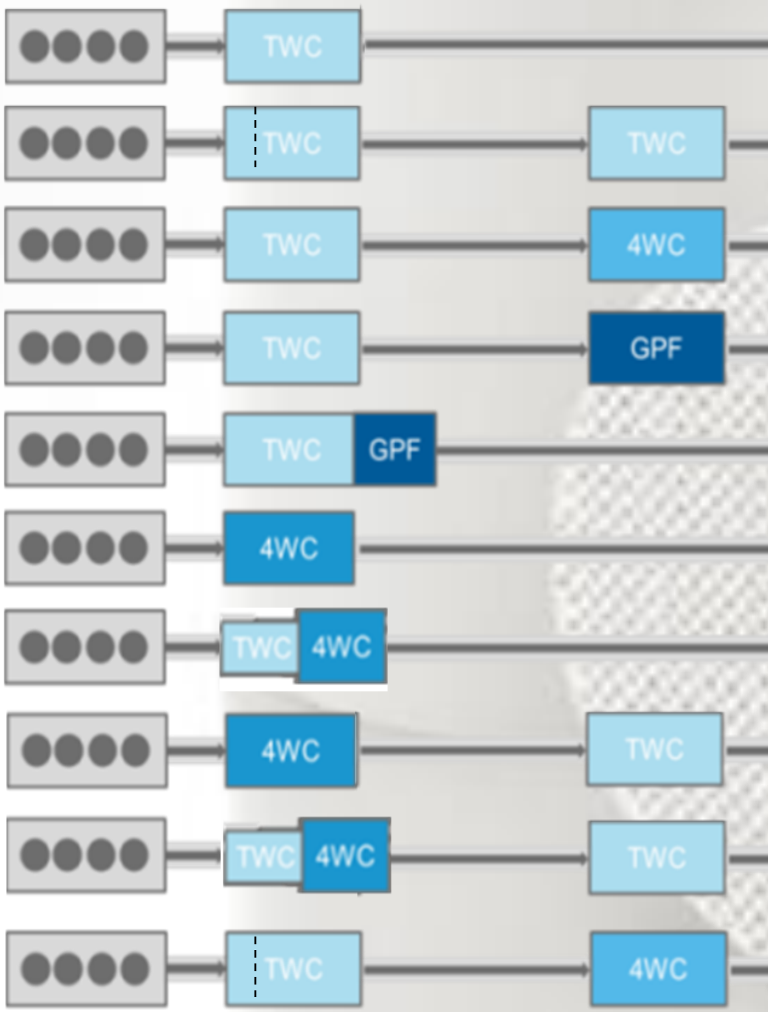


Eu4, Eu5, Eu6b, EU6c Low EO PN / LEV, ULEV

EU6d-temp w Low EO PN, ULEV, SULEV(staged pref.)

Eu6d with Lam=1 & Act. Reg./ LEV, (ULEV, SULEV), Ch6a/b

Eu6d with Lam=1 & Act. Reg., Ch6a

Eu6d with Lam=1 & Act. Reg., Ch6a

Eu6d w. very large Volume/Capacity and Lam=1, Ch6a

Eu6d w. large 4WC Volume/Capacity and Lam=1, Ch6a

Eu6d w. large 4WC Volume and with Lam=1, (ULEV), Ch6a

Eu6d 2020+ with Lam=1, (SULEV), Ch6a/b

Eu6d 2020+ with Lam=1, (SULEV), Ch6a/b

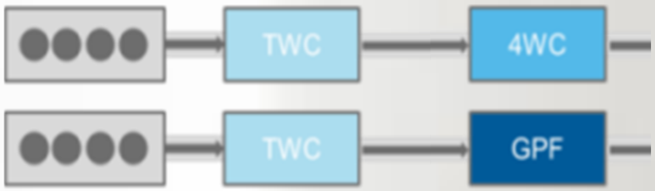
GASOLINE PARTICLE FILTER OVERVIEW GPF – PACKAGING

- **GPF close coupled (CC)**

- ➔ Passive Regeneration benefits due to higher temperature level
- ➔ Fuel-Cutoff phases leading to Regeneration can be as function of soot load critical, component protection needed (Motoring ctrl)
- ➔ High-load backpressure critical for power targets,
- ➔ 4WC GPF state of the art sample maturity as TWC replacement at RDE conditions proofed
- ➔ 2-brick solution after CCC prevents GPF ageing
- ➔ Coated GPFs show significant backpressure response on low (real life) soot quantities, important HW selection criterion
- ➔ Coated GPFs in CC position show potential for continuous Regeneration at Lambda=1 operation

GASOLINE PARTICLE FILTER
OVERVIEW GPF – PACKAGING

- **GPF underfloor (UF)**



➔ Regeneration temperature hardly reached if too far in UF position, esp. at short trip winter conditions

➔ Risk for uncontrolled burnoff significantly reduced, significant soot loading possible w/o immediate need for regeneration

➔ Remaining solution if packaging CC is critical

➔ Integration by partial replacement of muffler recommended (NVH positively influenced by GPF)

➔ High-load backpressure less critical but significant

- **What differentiates the GPF solutions?**

Very Engine/ Vehicle concept specific engineering solutions depending on:

- Target market / Engine lifecycle & technology level (EO PN Performance)
  ➔ Resulting GPF filtration efficiency demand
- Packaging possibilities & Integration potential
- Low cost approaches / High specific power requirements

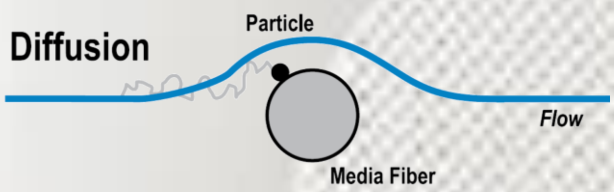
GASOLINE PARTICLE FILTER TRAPPING MECHANISMS

Collection efficiency:

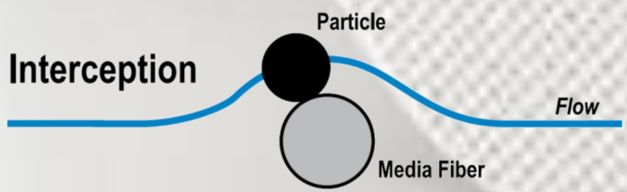
$$\eta = \eta_D + \eta_R + \eta_I$$

Diffusion   Interception   Inertial Impaction

Diffusion: Due to the Brownian motion the particles are made to deviate from the flow line and move towards the filter material where they are collected (small particles).

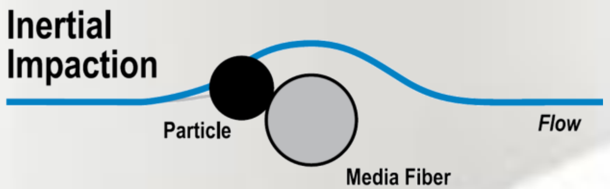


Interception: Interception is described as particles moving along a flow line and getting into contact with the filter material thus they are collected.

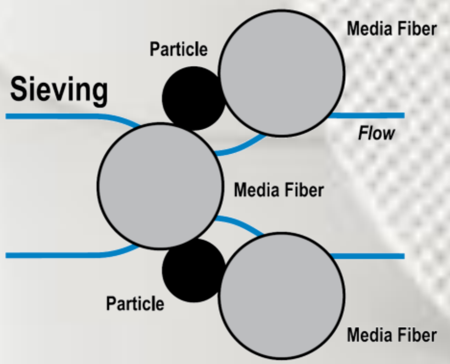


GASOLINE PARTICLE FILTER TRAPPING MECHANISMS

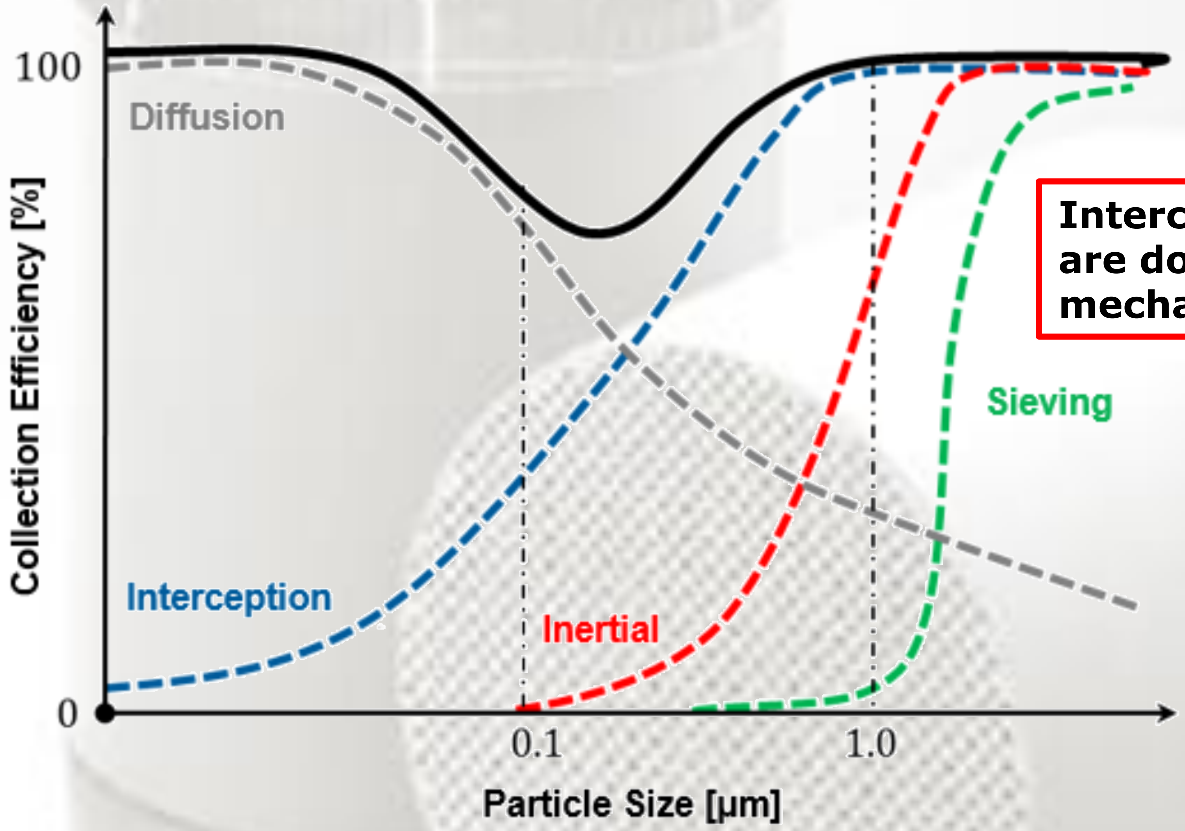
Inertial impaction: Due to rapid change in flow angle the particles deviate from the flow line and collide with the filter material and stick to the surface



Sieving: Sieving, the most common mechanism in filtration, occurs when the particle is too large to fit between the fiber spaces



GASOLINE PARTICLE FILTER TRAPPING MECHANISMS



Interception and Diffusion are dominating trapping mechanism for particles

Source: Hinds, 1999

Note:

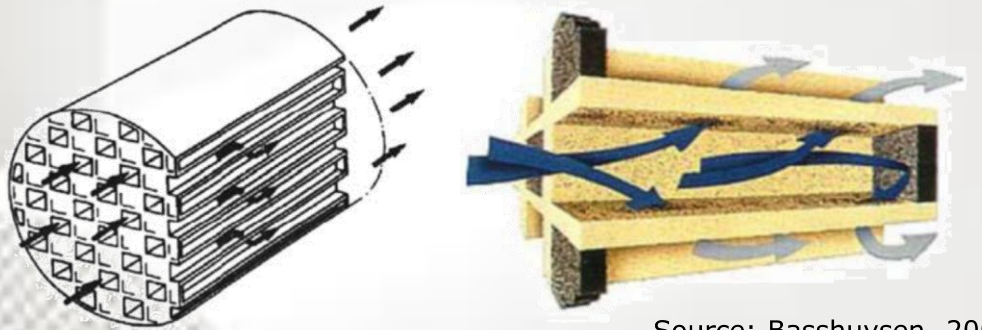
- minimum of the filtration efficiency for particles with an intermediate size
- two or more collection mechanism operate simultaneously but none of them is dominant.
- lowest for particles with a diameter of about 150 nm.
- dependent on the operating conditions as e.g. filter surface area, exhaust mass flow rate, differential pressure,...

GASOLINE PARTICLE FILTER PROPERTIES

Filtration efficiency is dependend on:

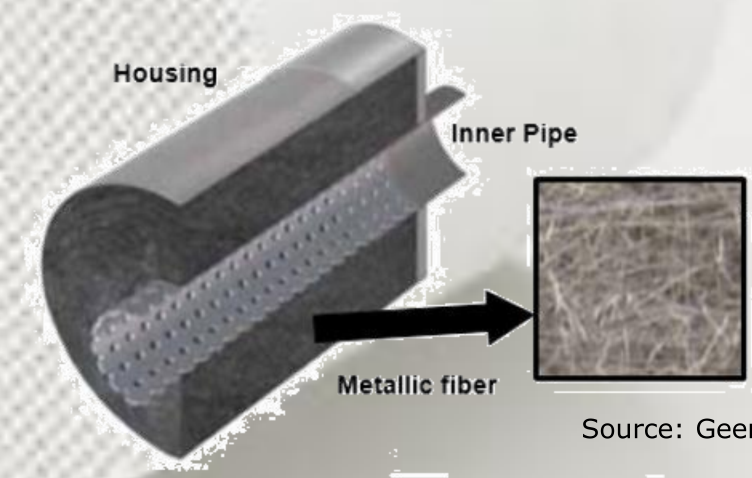
- pore diameter
- wall thickness
- cell density
- filter volumetric capacity

Wall flow filter



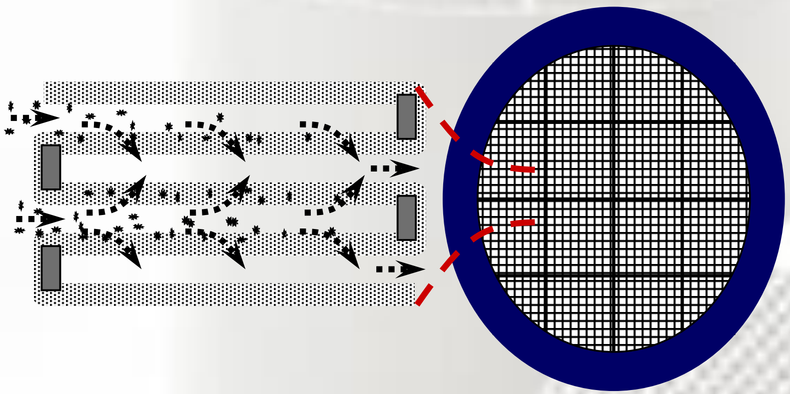
Source: Basshuysen, 2007

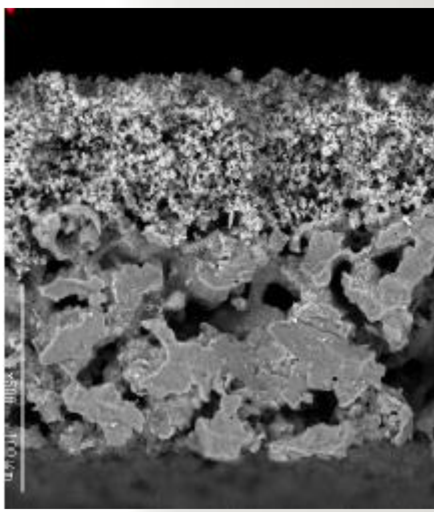
Flow through filter



Source: Geerinck, 2013

WALL-FLOW FILTER

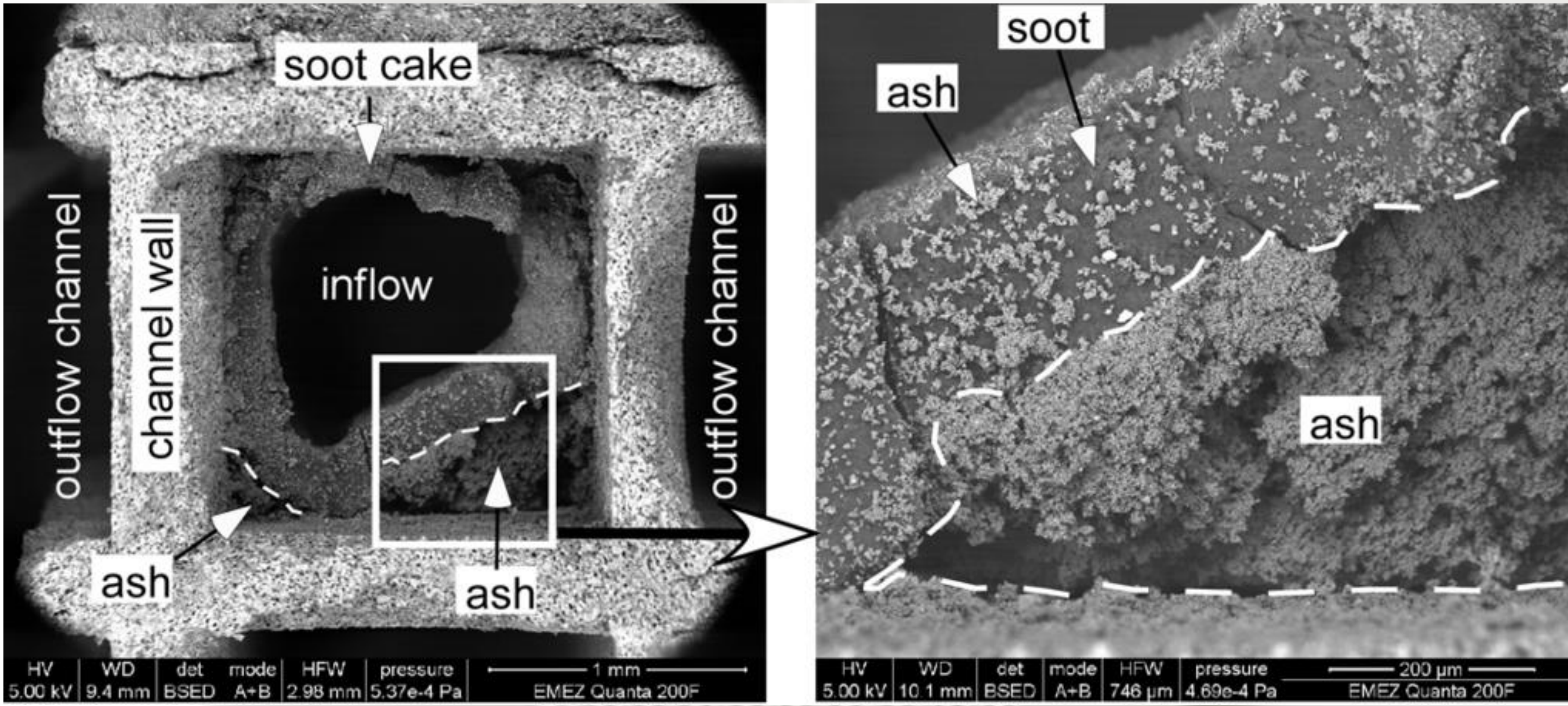




Source: NGK

- Wall-flow filters are most common filter technology in combustion engines.
- The porous wall has a particle reduction efficiency mainly depending on pore size distribution.
- Particles are accumulated in the filter pores (“deep bed filtration“ with 50-90% filtration efficiency) and secondly build a soot cake on top of the filter wall. The soot cake is a highly efficient particle filter (99% efficiency), **however gasoline engines emit rarely enough soot to build a permanent / effective soot cake**
- With oxidation the soot and associated hydrocarbon fraction of the filtered particles are converted to gaseous CO_2 and water.
- The ash fraction cannot be transferred into gaseous components. It is accumulated over lifetime and therefore influences filter sizing and maintenance intervals.

WALL FLOW FILTER WITH SOOT AND ASH LAYER



Source: Dimopoulos P. 2010, Swiss Competence Center for Energy and Mobility (CCEM)

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GASOLINE PARTICLE FILTER WORKPACKAGES

GPF WORKPACKAGES

- Layout and Specification
- ECU GPF Functionality Development
- GPF Development on Testbed
- GPF Development in Vehicle
- Durability Testing

GASOLINE PARTICLE FILTER WORKPACKAGES

GPF WORKPACKAGES	RELATED SUBWORKPACKAGES

Layout and Specification

ECU GPF Functionality Development

GPF Development on Testbed

GPF Development in Vehicle

Durability Testing

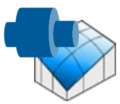
GPF concept definition
Sensor concept def. incl. OBD concept

- **Update on latest legal requirements on target markets**
- **EAS model set-up in CruiseM / "Model for Concept"**
- **EAS concept investigations**
    - CC/UF/4WC,…
    - Simulation of different filter materials, properties, dimensions
    - Packaging study
- **Elaboration of a sensor concept to meet OBD and operational requirements**
    - Absolute or Differential Pressure Sensor
    - Temperature Sensor
    - Alternative Solution
- **Supplier nomination**
- **ECU check in view of available functionalities**
- **EAS specification in co-operation with the nominated supplier**
- **CFD simulation of brick inflow**
- **EAS sub-system design & development**
- **EAS component procurement (core samples)**
- **Initial testing on Syn-Gas test rig (core samples)**

GASOLINE PARTICLE FILTER WORKPACKAGES

GPF WORKPACKAGES

Layout and Specification



ECU GPF Functionality Development

GPF Development on Testbed

GPF Development in Vehicle

Durability Testing

RELATED SUBWORKPACKAGES

ECU GPF Functionality Development based on sensor concept

Loading and Regeneration Model Functionality development based on available GPF instrumentation

- **Loading:**
  - Pressure / Diff. Pressure based estimation **and/or**
  - Soot Engine Map + Dynamic events + Cold start warmup based est. for Temp. sensor setups
- **Regeneration:**
  - Passive Regeneration modeling
    - Modeling of soot regenerated (passive)
    - Deactivated / shortened fuel-cut and reinstatement in case of to high soot load for component protection
  - Active Support of Passive Reg. (GPF Heating)
    - For controlled burnoff of high soot load
    - In Winter cond. / extreme UF positions
  - Active Regeneration w. $\lambda>1$
    - >4000km interval to be not continuous
    - Model reset function required

  Topics to be considered
  Thermal modeling; Balance Point / Equilibrium; Surface / Deep bed filtration; Coated / Uncoated GPF - TWC before?

- **OBD Functionality development**
- **Ash deposit modeling**

GASOLINE PARTICLE FILTER WORKPACKAGES

GPF WORKPACKAGES

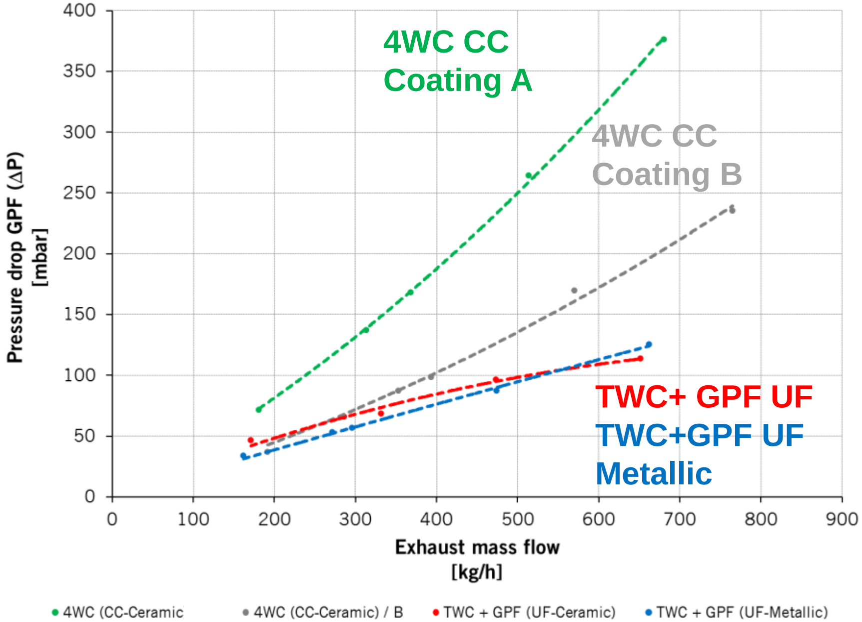
- Layout and Specification
- ECU GPF Functionality Development
- GPF Development on Testbed
- GPF Development in Vehicle
- Durability Testing

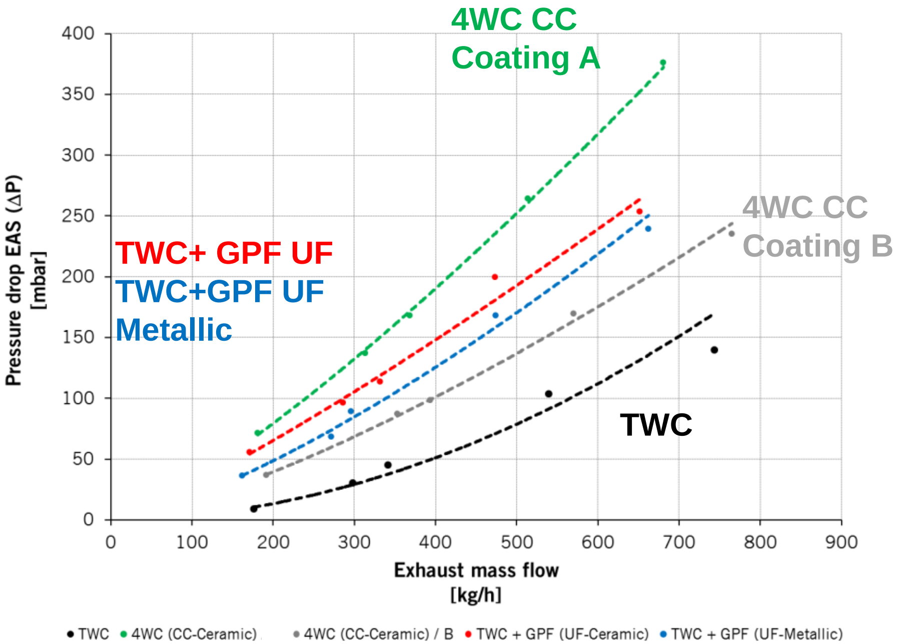
GASOLINE PARTICLE FILTER WORKPACKAGES

GPF WORKPACKAGES	RELATED SUBWORKPACKAGES
Layout and Specification	ECU functionality validation GPF stationary
ECU GPF Functionality Development	Determination of GPF pressure drop **Δp** & filtration efficiency **η** as function of soot load / MF
GPF Development on Testbed	Regeneration Testing Active/Passive Regeneration modeling
GPF Development in Vehicle	Determination of critical GPF loading
Durability Testing	GPF model verification stationary
	Base Calibration Update with GPF
	GPF aging / ash verification
	Base Calibration verification with final HW

GASOLINE PARTICLE FILTER
BACKPRESSURE EMPTY FILTER CONCEPTS

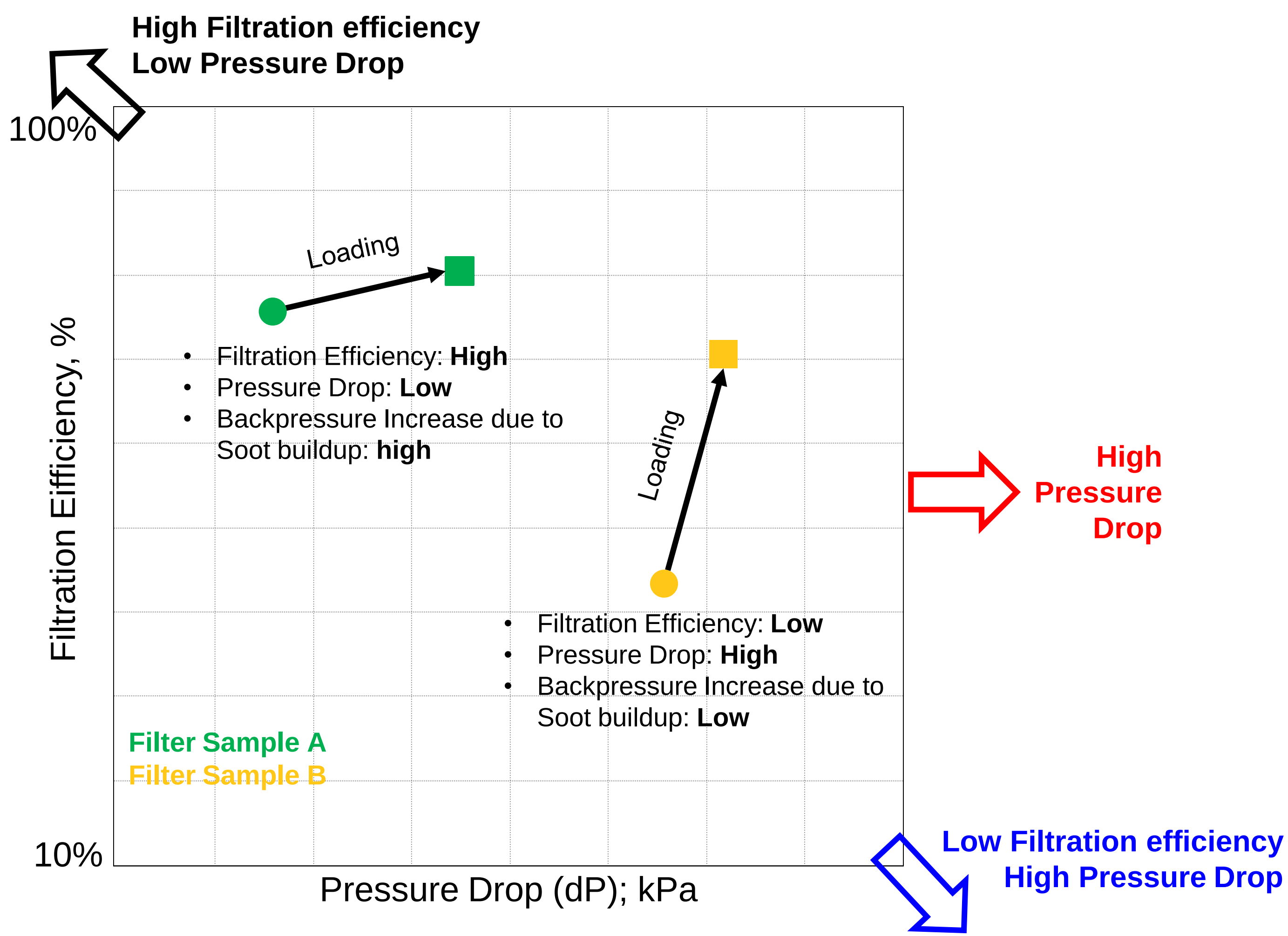
4WC CC Coating A ⬌ 4WC CC Coating B ⬌ TWC+ GPF UF ⬌ TWC+GPF UF Metallic





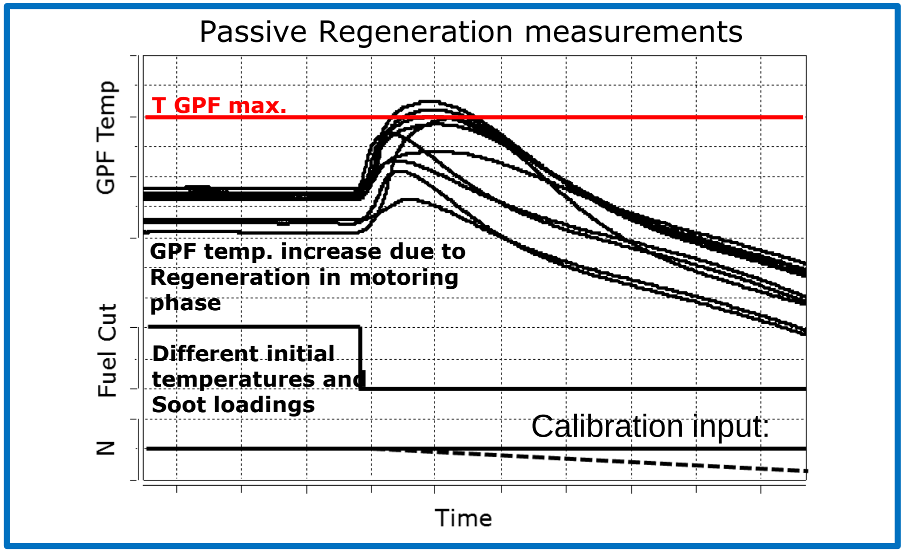
GASOLINE PARTICLE FILTER FILTR. EFFICIENCY AND ΔP OVER SOOT LOADING

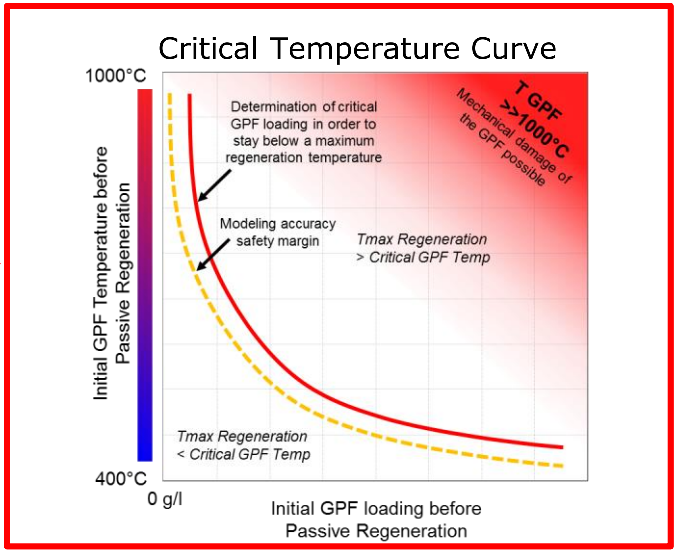
Evaluation of a GPFs Characteristics in terms of Filtration Efficiency and Pressure Drop



GASOLINE PARTICLE FILTER
GPF REGENERATION – CRITICAL TEMPERATURE

Critical filter loading in terms of maximum regeneration temperature during passive filter regeneration





Calibration Input:

O2 Model
Soot burn model

Calibration Input:

OPF Coordinator,
Component protection

GASOLINE PARTICLE FILTER WORKPACKAGES

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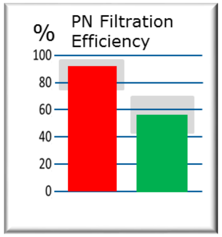
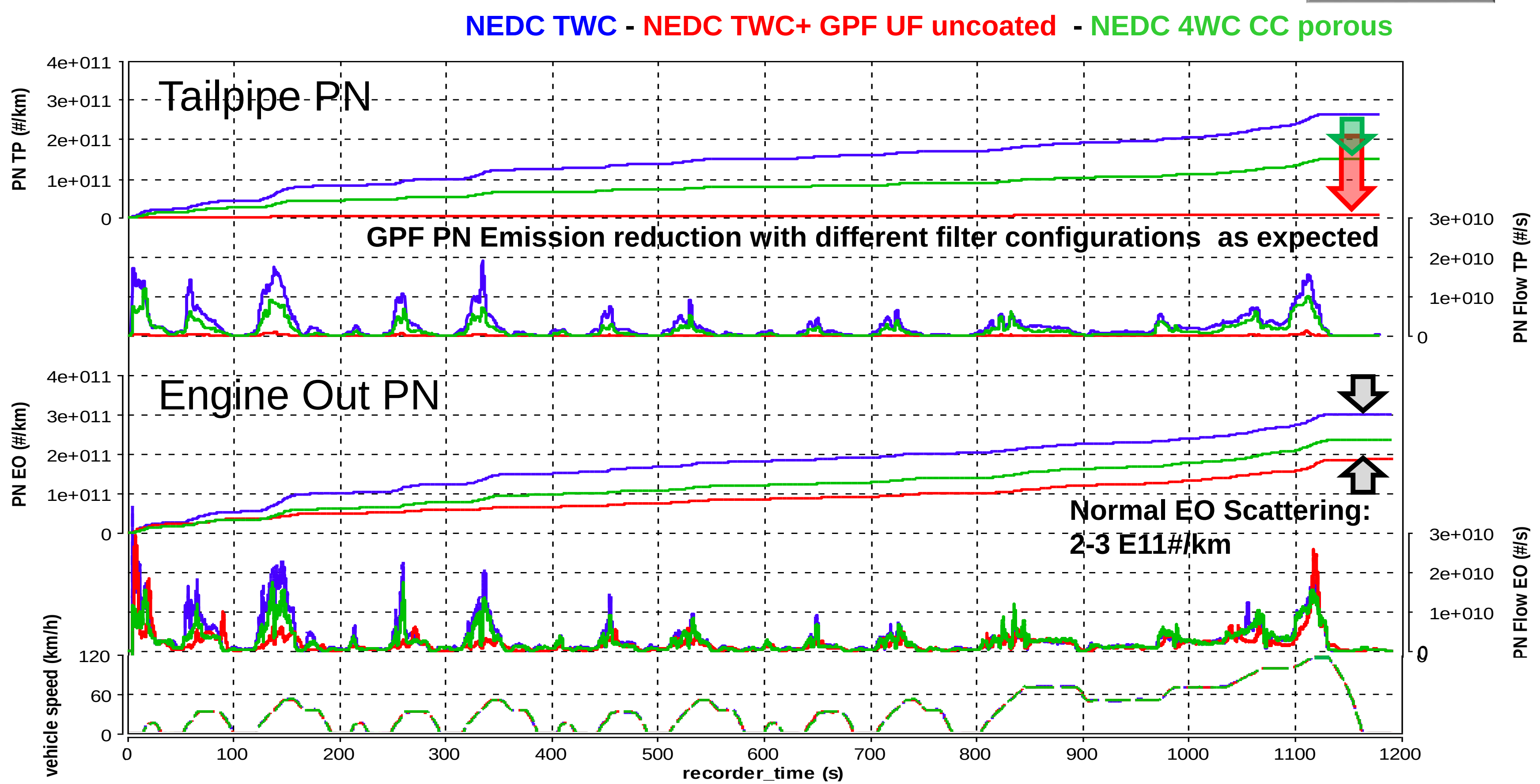
GPF WORKPACKAGES	RELATED SUBWORKPACKAGES
Layout and Specification	ECU functionality validation GPF dynamic
ECU GPF Functionality Development	Loading and Regeneration Model calibration
GPF Development on Testbed	Regeneration strategy Active/Passive
GPF Development in Vehicle	Worst case testing / RDE validation
Durability Testing	OBD calibration
	Ash loading model calibration

GASOLINE PARTICLE FILTER
VEHICLE TESTING

NEDC Results with and w/o GPF on EU6c calibrated gasoline vehicle

GPF testing on low 50% EU6c Engine Out NEDC PN Emission Level for representative future concept evaluation.





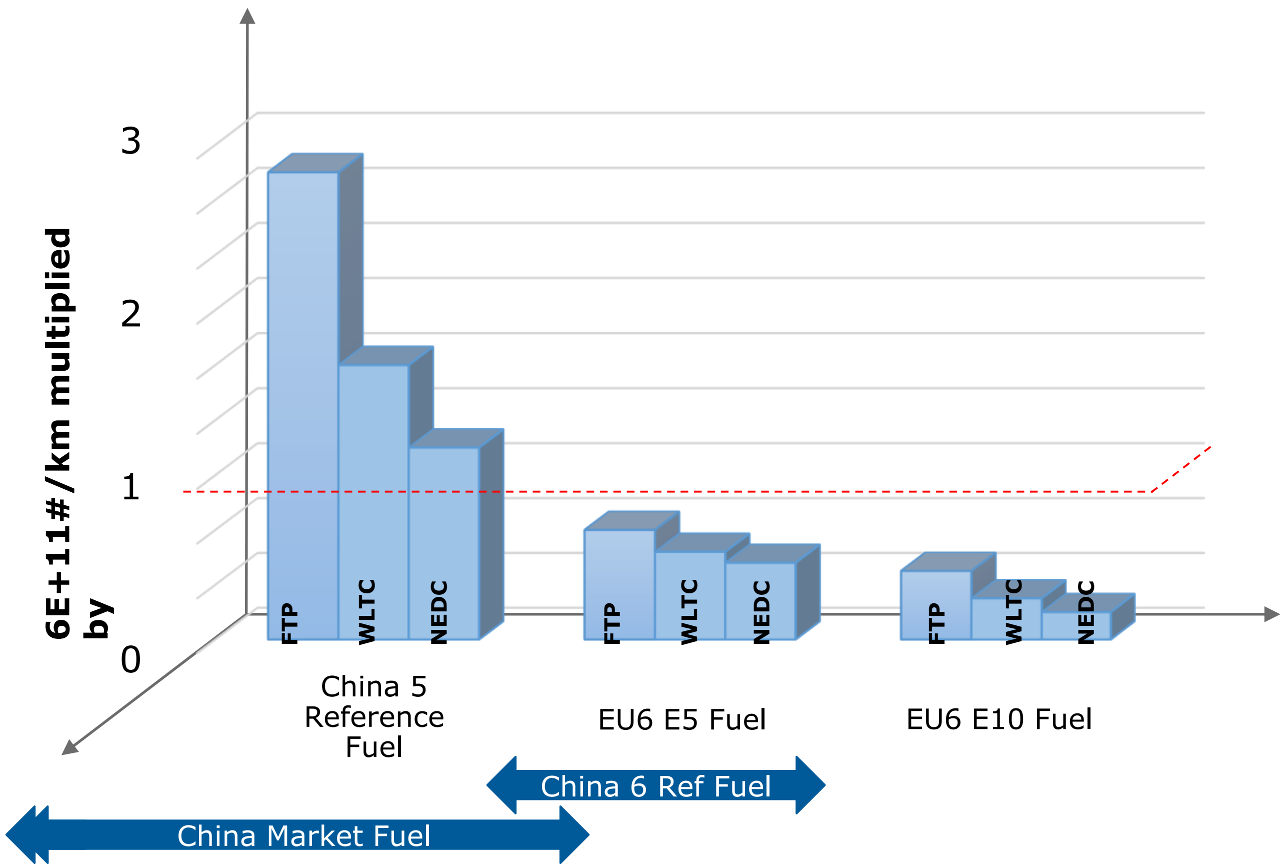
RDE CHALLENGES: FUEL INFLUENCE ON GASOLINE PARTICLE NUMBER

Fuel Influence on RDE-Particulate Raw Emissions Engine Out @ Standard cycles 23°C

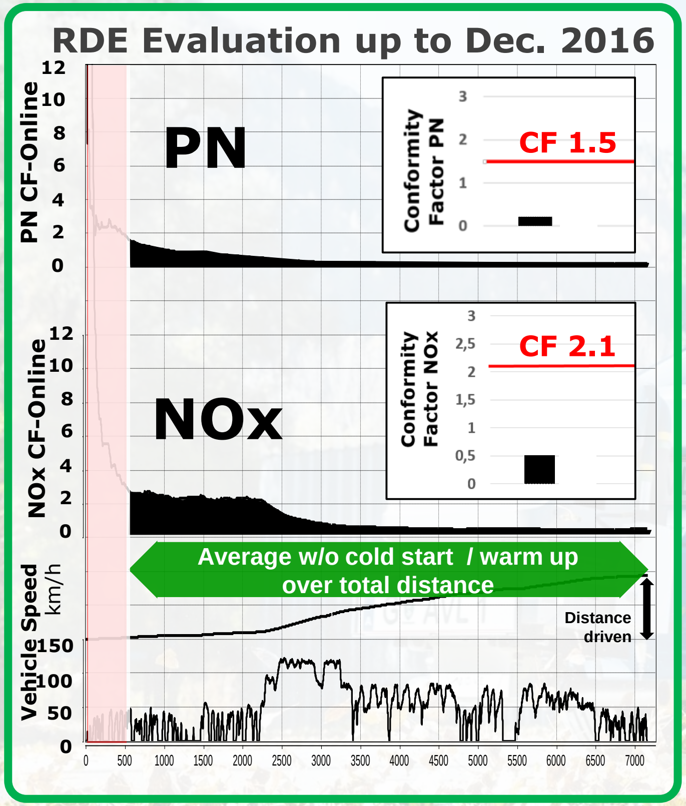
Possible Worst Case PN Scattering in the Field

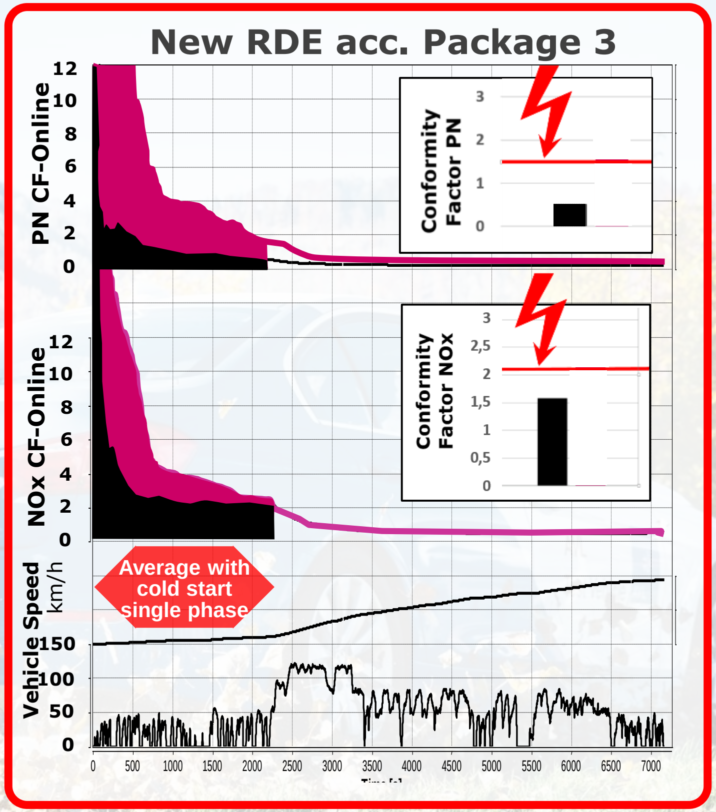
EU: Factor 2 (to 5)

CH: Factor up to 10 and more



RDE PACKAGE 3:
CF 1,5 FOR COLD URBAN CONDITIONS





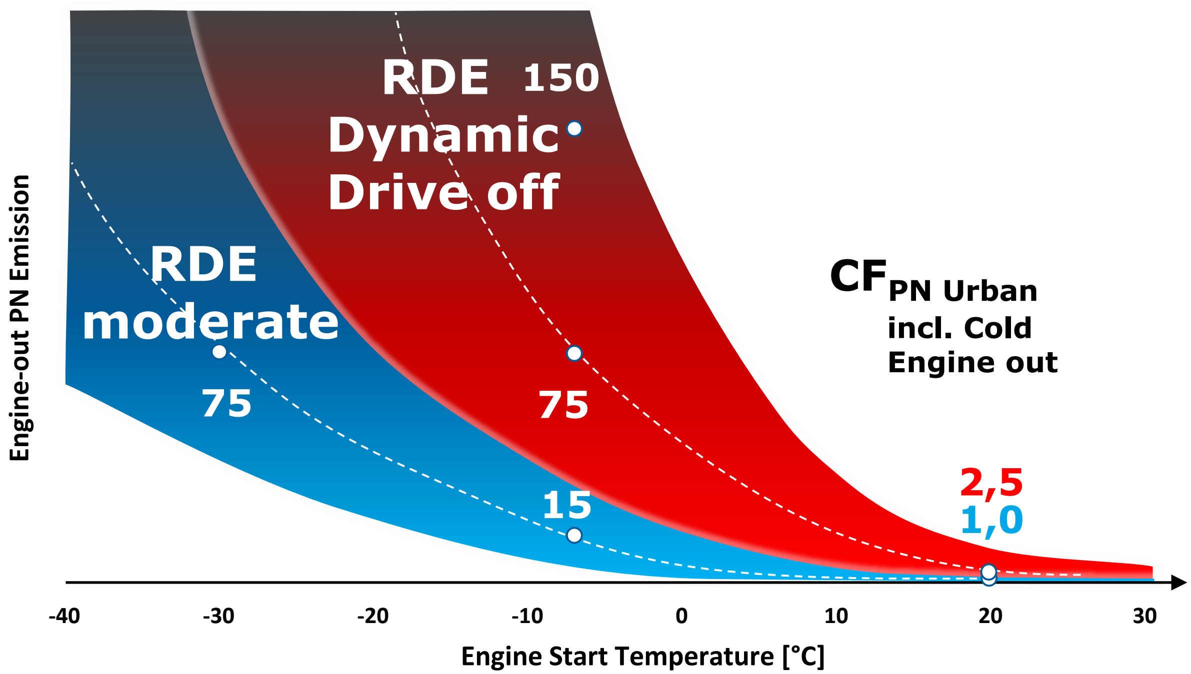
TGDI
Lifetime aged 4-way cat
20° Start

Driving Style:
- moderate
- dynamic drive off

Significant aggravation of RDE compliance by RDE Package 3

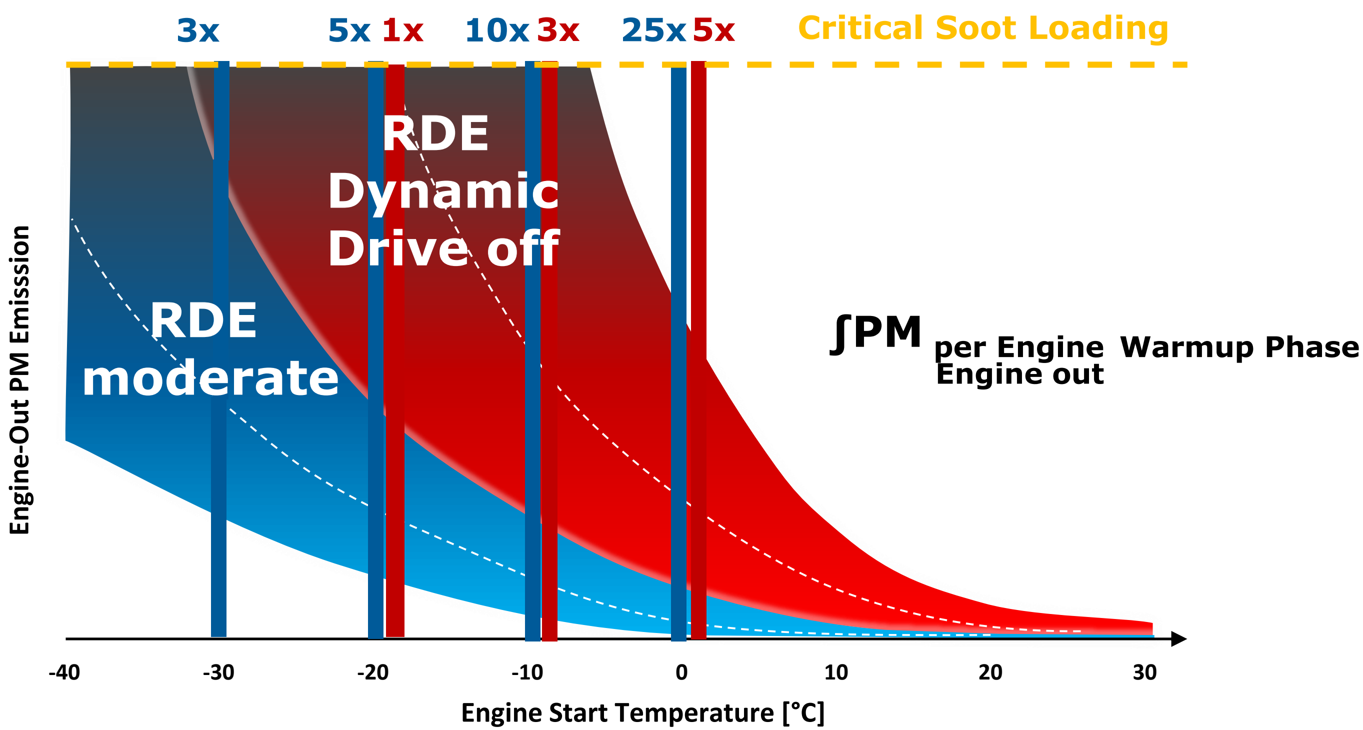
GDI PARTICLE EMISSIONS AT TEMPERATURES < 20°C WITH EU6C CALIBRATION

Engine Out PN Potential per Real World Driving Warmup Phase



GDI PARTICLE EMISSIONS AT TEMPERATURES < 20°C WITH EU6C CALIBRATION

Soot Loading Potential of GPF per Real World Driving Engine Warmup Phase



- **Driving style has a huge influence in soot accumulation at cold temperatures.**

GDI PARTICLE EMISSIONS AT TEMPERATURES < 20°C WITH EU6C CALIBRATION

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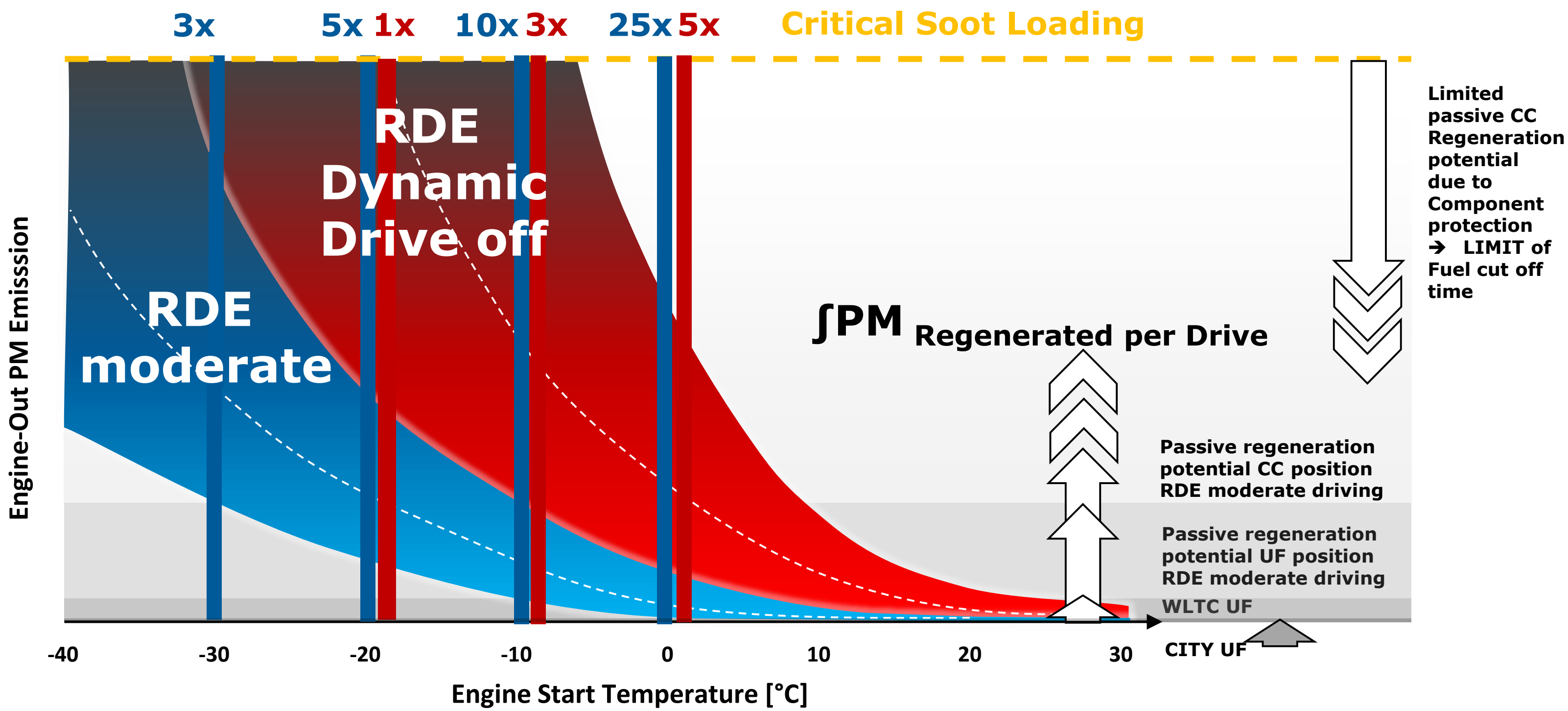
Soot Loading Potential of GPF per Real World Driving Engine Warmup Phase



- Driving style has a huge influence in soot accumulation at cold temperatures, dominated by drive-off emissions (not Start, CH…)
- GPFs in UF position have lower soot burning potential then GPF in CC position due to colder temperatures.
- No regeneration potential in city winter driving for UF GPF → too low temperatures and too short fuel cut off phases

Active Regeneration will be necessary for GPFs to avoid too high loading in winter city operation

GASOLINE PARTICLE FILTER REGENERATION

- Regeneration conditions >550°C and presence of Oxygen need to be fulfilled
- In emission cycle operation and standard RDE operation passive regeneration will be most likely be sufficient for CC position, especially for coated filters
- „Worst Case" conditions like e.g. „Doctor Cycle-Winter" will most likely require active backup measures at all configurations
- Underfloor Filter configurations with large distance to the engine will require active measures also in normal operation
- The oxygen content of 21 % in fuel cut off is (at sufficiently high GPF temperature level >>500°C before fuel cut off) leading to very effective soot oxidation potential in comparison to permanent lean operation where the available oxygen content is limited by engine roughness (alternatively external devices that provide oxygen to the GPF could be used as well)
- At fuel cut-off phases in cases of critical filter soot loading risk of thermal destruction while regeneration (as function of temperature level before drop to idle), further risks at Scavenging / Misfire cases
- Repeatedly triggered active regeneration with lean Lambda is a way to surely avoid excessive filter soot loading, however, the NOx cross-sensitivity and the interaction with driveability and base calibration is remarkable.
- Alternatively a simple GPF Heating with torque reserve / Lambda split operation can support using the real world frequency of fuel cut off events more effectively, however, the regeneration potential is limited dependent on EAS system configuration

GASOLINE PARTICLE FILTER
GPF TEMPERATURE LEVELS IN DRIVING CYCLES

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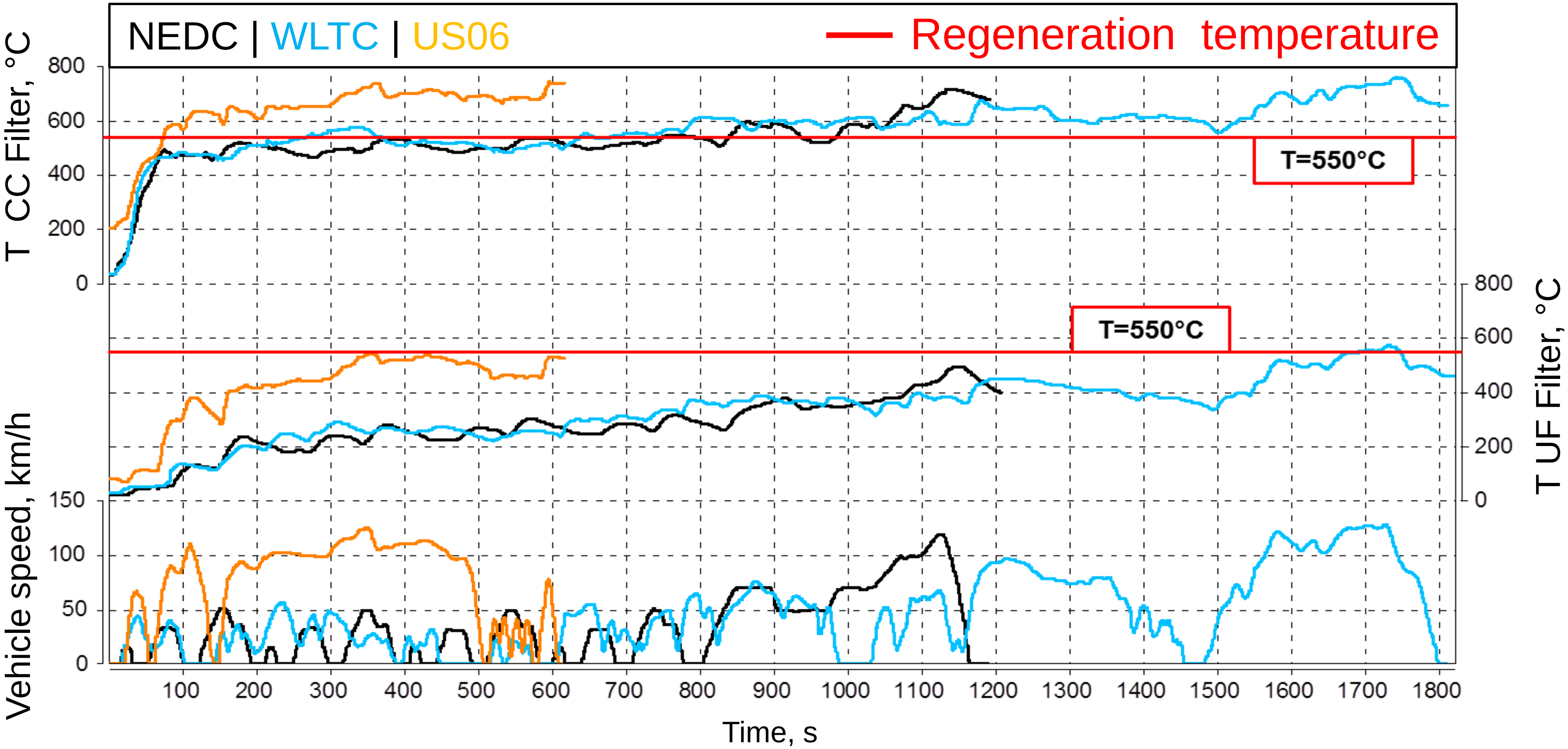
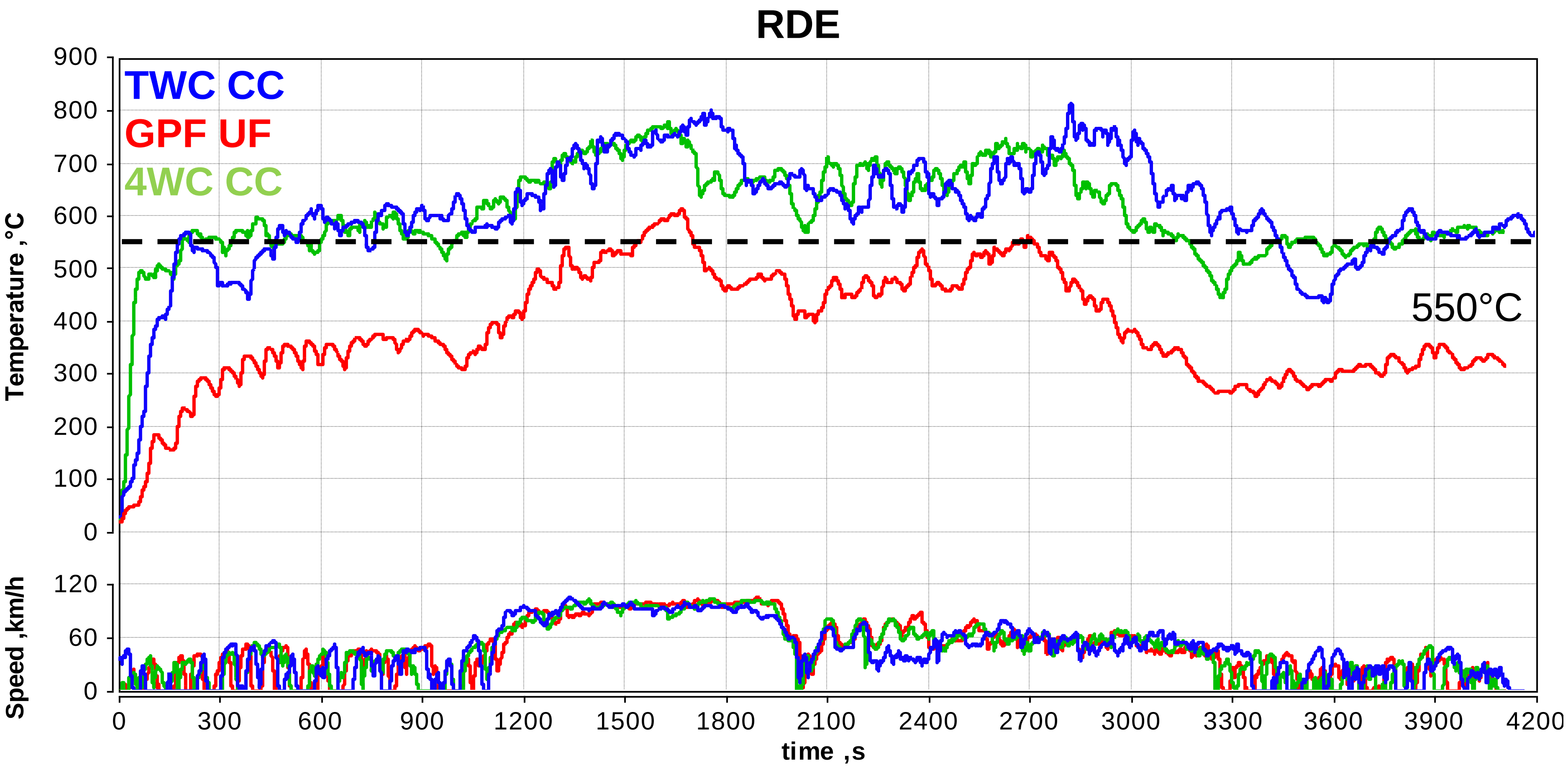
- Regeneration conditions >550°C at different GPF positions for NEDC, WLTC and US06



- CC GPF: temperature condition fulfilled in all cycles
- UF GPF: NEDC and US06 temperature condition not fulfilled; WLTC for short time in the high-speed part of the cycle

GASOLINE PARTICLE FILTER
GPF TEMPERATURE LEVELS FOR RDE

- Regeneration conditions >550°C inside GPF at different GPF positions.



- With all different filter concepts it is possible to reach the required temperature for regeneration → UF GPF at high loads on the highway

GASOLINE PARTICLE FILTER REGENERATION

Standard Regeneration Strategies

- Passive Regeneration in fuel cut events
- Active support of passive regeneration by GPF heating
  (+ Natural occurrence of fuel cut events)
  - GPF heating by applying torque reserve without injection mode change
  - GPF heating with change to "catalyst heating like" stratified modes

  Managed by regeneration manager dep. on customer driving profile either moderately "on occurrence if convenient, e.g. while motorway driving" ➔ Low CO_2 or
  For worst case winter city drivers and high soot loads with high frequency even at low speed driving conditions / stops ➔ Significant CO_2 investment

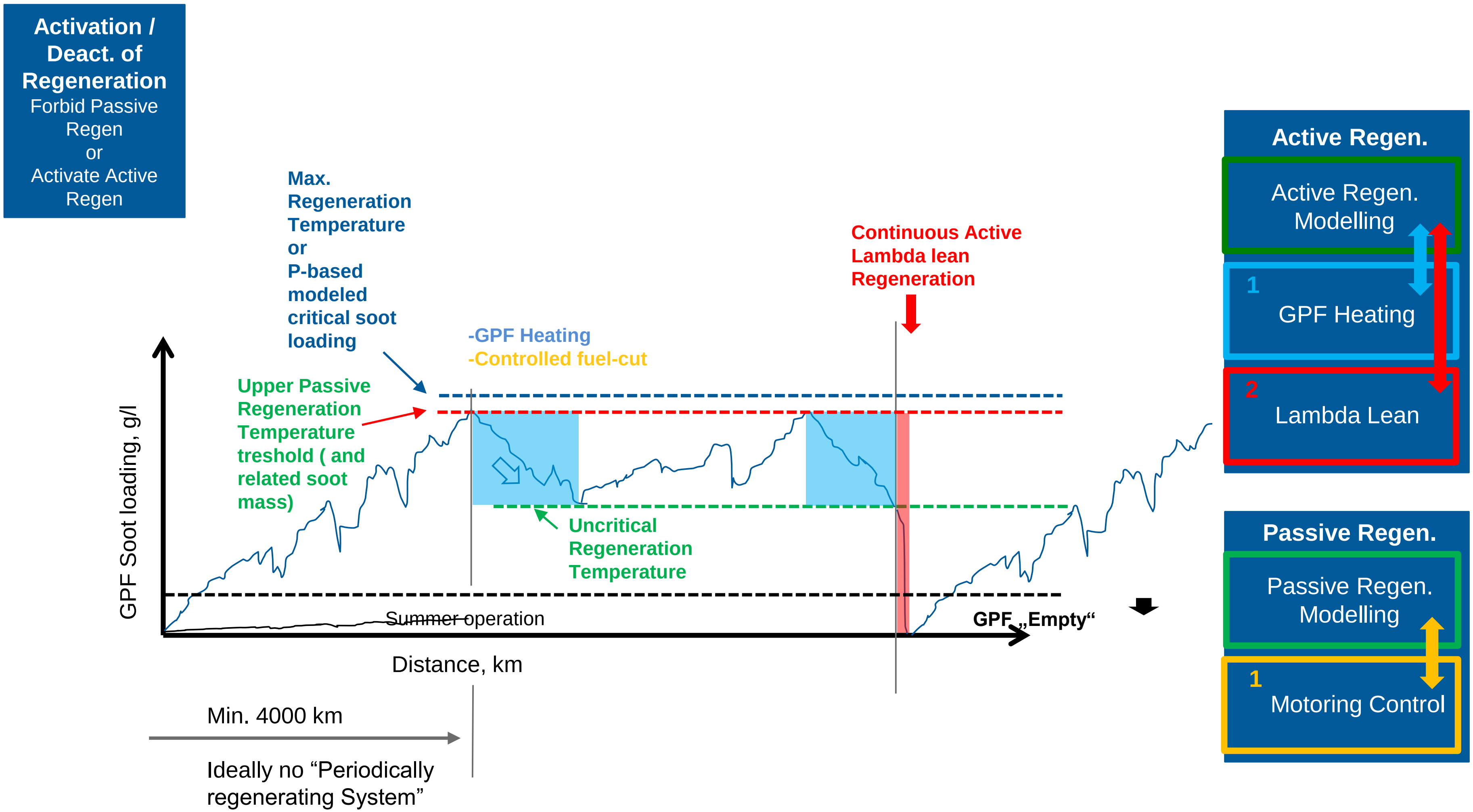
Extended Regeneration Strategies

- Active Regeneration by lean lambda operation (low oxid. rates ➔ long duration, NOx!)
  - Distance triggered "keep clean" ➔ KI Factor risk!
  - Soot loading triggered if required when fuel cutoff frequency too low and temperatures for lean lambda regen achievable

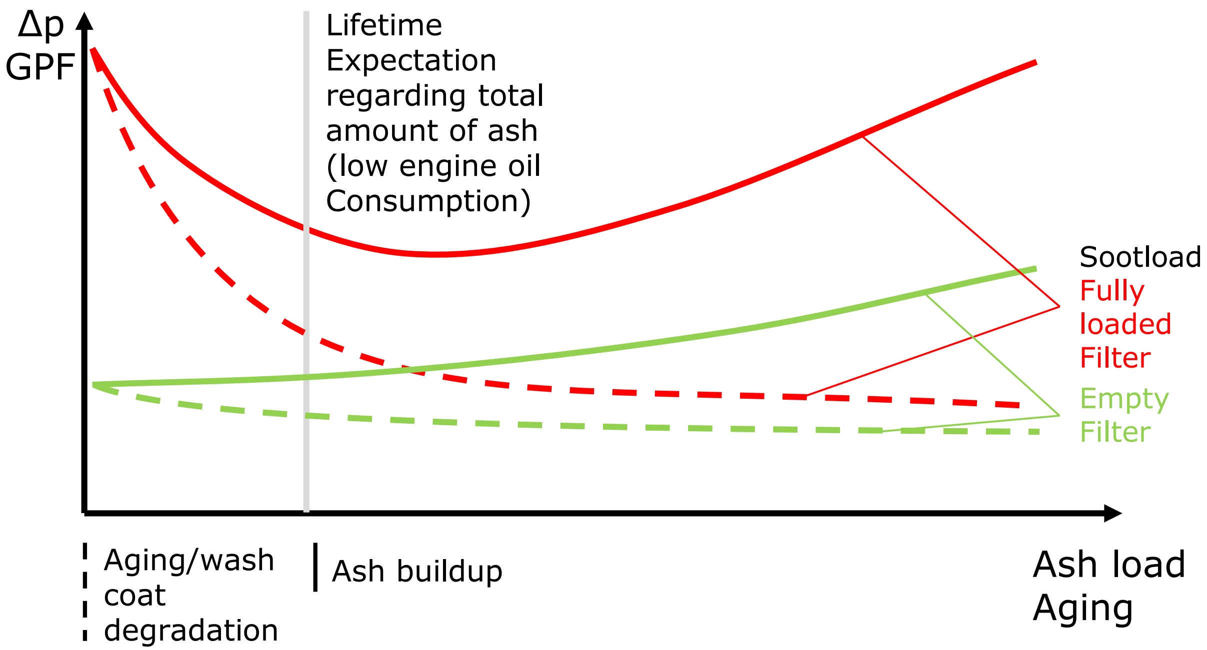
Worst Case Backup Strategies

- Workshop Regeneration with activated Dashboard message at (standing) / <u>driving</u> vehicle
  - Aggressive GPF Heating strategy followed by lean operation
- Dashboard Message "Send Customer (to Motorway) /out of rural area for > X minutes"
- ~~Self triggered "Workshop like" Regeneration at the customer with activated Dashboard message at standing /driving vehicle ➔ Cancelled for customer acceptance reasons~~

GASOLINE PARTICLE FILTER REGENERATION STRATEGIES I



GASOLINE PARTICLE FILTER
PRESSURE DROP OVER ASH LOAD AND AGING



- Aging / Wash coat degradation: The pressure drop response on soot loading of a coated GPF (empty filter) is usually remarkably decreasing with component aging / washcoat degradation (no ash)
- Ash: For a fully soot loaded filter pressure drop is decreasing first and then again increasing with ash load. The pressure drop of an empty filter is increasing with ash loading
- A positive delta P offset (rather small) at empty filter would be adapted by the ash model

GASOLINE PARTICLE FILTER ASH ACCUMULATION

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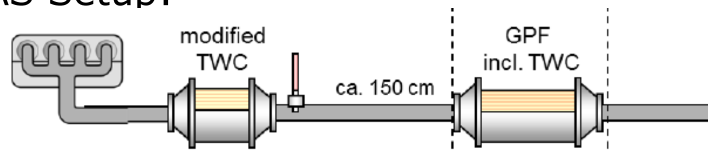
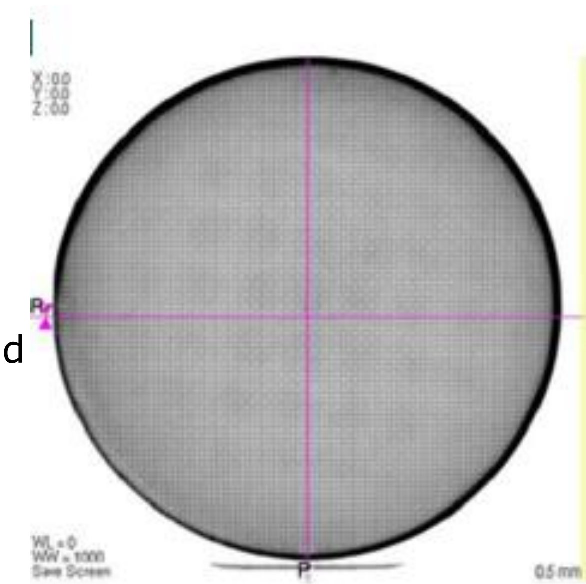
Vehicle: 1.8l λ=1 TGDI - 160000 km - ash accumulation

- EAS Setup:

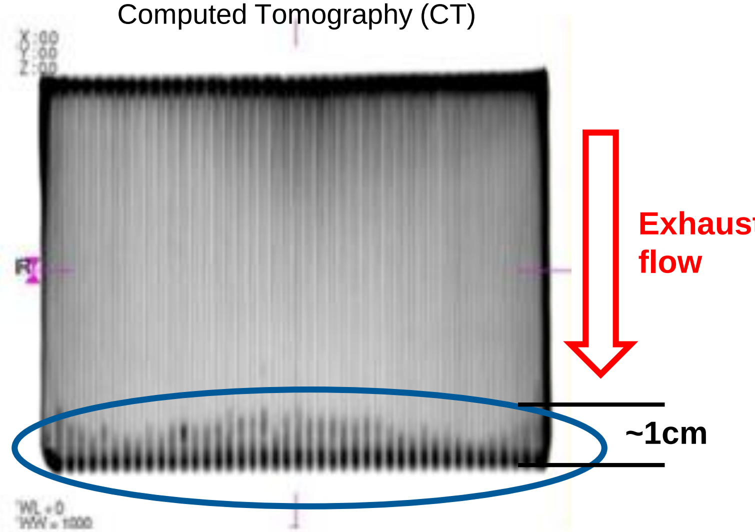


- No significant increase in CO_2 Emission in NEDC and minor influence in WLTC
- The CO_2 increase due to backpressure increase of an aged filter is low and hardly detectable
- Main source of ash: Burned oil
- Less ash accumulation than in a diesel engine

Ash deposit after 160000 km	
Calculated ash mass based on oil consumption (total 4.7liter)	18.6g
Real ash mass including additional abrasives from other powertrain or EAS components	22g



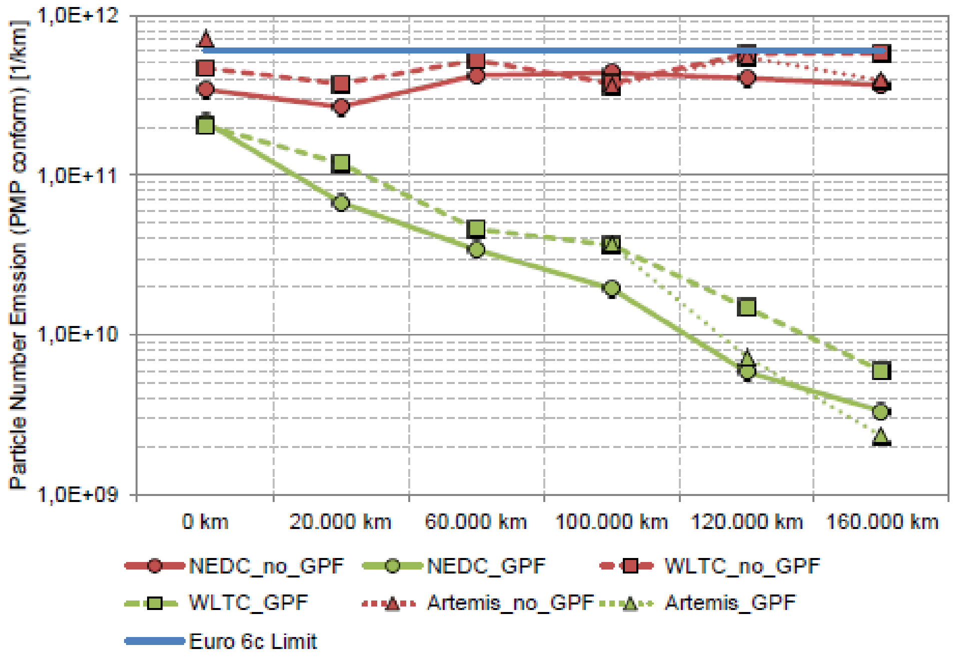
Computed Tomography (CT)



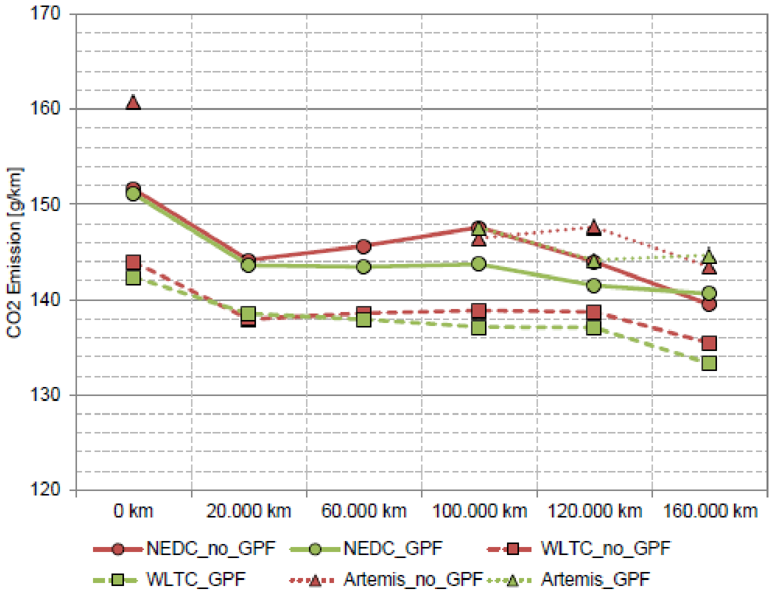
Source:
23rd Aachen Colloquium Automobile and Engine Technology 2014,
Novel GPF Concepts with Integrated Catalyst for Low Backpressure and Low CO2 Emissions,
NGK EUROPE GmbH

GASOLINE PARTICLE FILTER
ASH ACCUMULATION

Decrease of PN Tailpipe Emission by ash accumulation
(Increase of Filtration efficiency by ash layer buildup from oil ash on the filter wall)



Influence on CO2 Emission
(NEDC, WLTC and Artemis)



Source:
23rd Aachen Colloquium Automobile and Engine Technology 2014,
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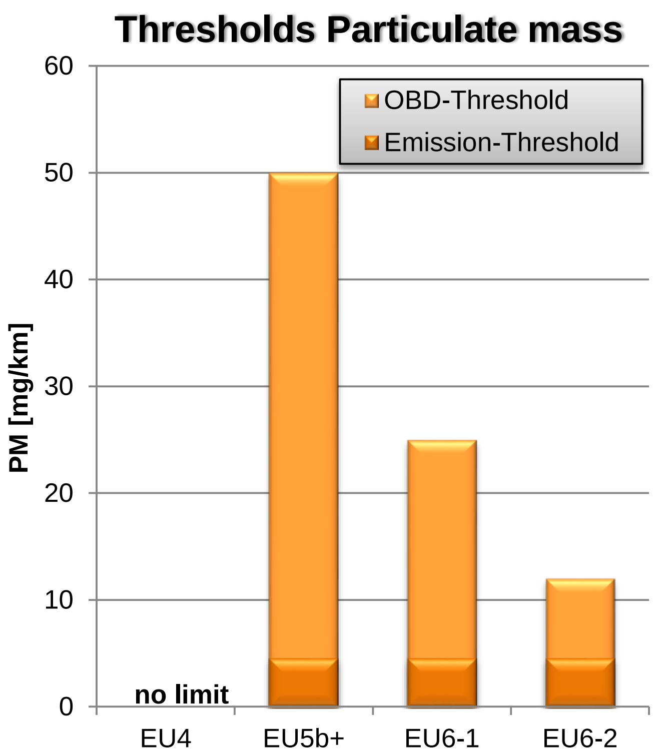
GASOLINE PARTICLE FILTER MONITORING
OBD LEGAL REQUIREMENTS

Legal Emission and OBD limits:

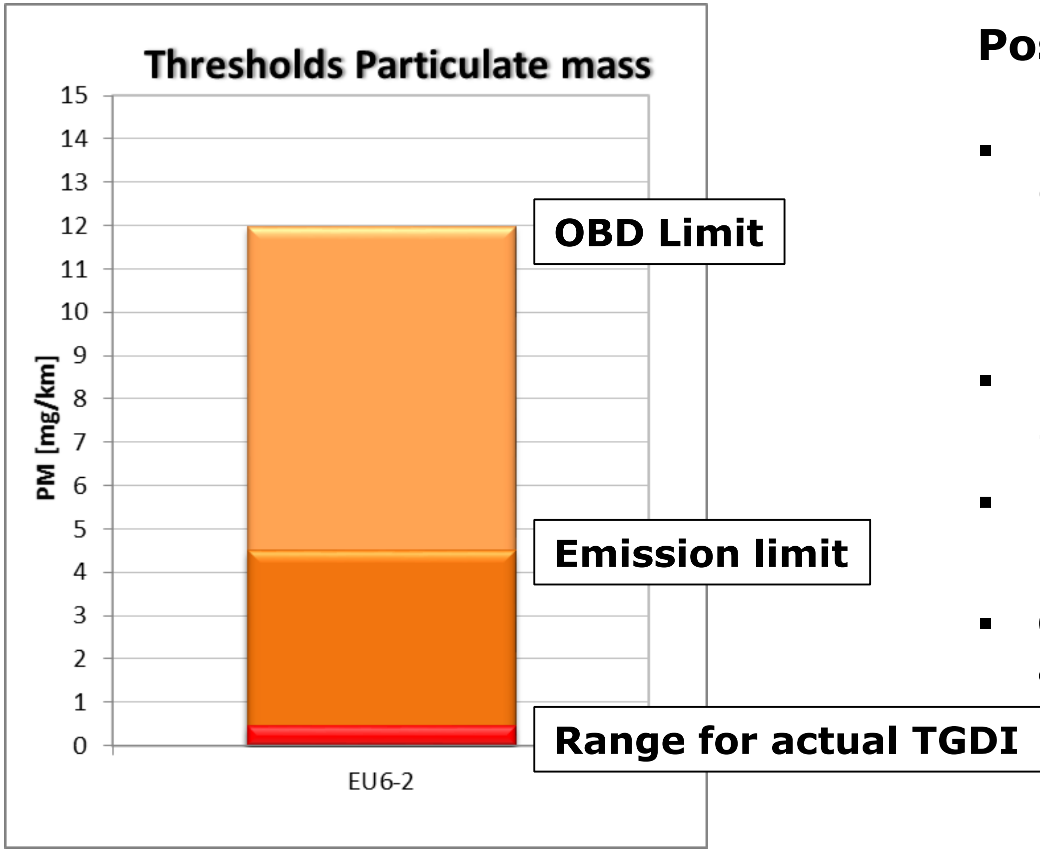
	Introduction Type approval	**Introduction** New registration	**PM limit** (mg/km)	**OBD limit** (mg/km)	**OBD threshold factor**
EU5b+	Sept. 2011	Jan. 2014	4.5	50	11.1
EU6-1	Sept. 2014	Sept. 2015	4.5	25	5.6
EU6-2	Sept. 2017	Sept. 2018	4.5	12	2.7



Up to 2020:

- Currently no OBD Limit for PN yet but in planning, values not defined yet

GASOLINE PARTICLE FILTER MONITORING REALIZATION



Possible Approach 2017+:

- Low PM emissions
  (5-10% of PM Emission target)

- PM emission relevant errors needs 25x deterioration for OBD relevance
- HC, CO, NOx deteriorates usually faster → OBD because of gaseous emissions
- GPF black/white monitoring in any case required

GASOLINE PARTICLE FILTER MONITORING

- **Differential-pressure based monitoring**
  - Besides monitoring; soot loading estimation and / or engine protection against over-loaded GPF can be realized, especially recommended for Chinese /RdW applications
  - Continuous Monitoring capability and low calibration effort for total failure monitoring
  - Calibration effort to monitor a partly damaged GPF can be high
- **Absolute pressure based monitoring**
  - Lower sensor cost
  - Reduced monitoring capability compared to differential pressure based monitoring for comparable calibration effort but feasible for Gasoline requirements
- **Temperature-based monitoring**
  - Low sensor cost
  - Limited to total failure detection and critical at low flows
- **(OSC based monitoring)**
  - No additional cost
  - Requires a coated GPF to be utilized
- **(PM-Sensor based monitoring)**
  - Resistive classic sensor not feasible for gasoline, as EO-PM is too low to build up soot layer,
  - Electric charge based sensor layouts may be also a solution gasoline (GPF)
  - Higher cost than differential-pressure sensor
  - Higher calibration effort than differential pressure based monitoring concept
  - Significant number of sensor diagnostic functions need to be implemented and calibrated (very demanding effort in order to comply with US legislation)

GASOLINE PARTICLE FILTER WORKPACKAGES

AVL

GPF WORKPACKAGES	RELATED SUBWORKPACKAGES
Layout and Specification	
ECU GPF Functionality Development	
GPF Development on Testbed	
GPF Development in Vehicle	
Durability Testing	Set-up of a GPF related Load Matrix
	Definition of a testing program based on Load Matrix methodology
	Monitoring of test results & update of LM
	Durability testing on test bed: thermal cracks and ash loading
	Durability testing in the vehicle incl. PEMS testing

Table of Contents

AVL RECOMMENDATIONS ON A GPF SENSORCONCEPT

- GPF solutions without sensors or regeneration seem cost-wise on the first glance an attractive solution but the risk in the field remains high and is not recommended.
- Series production demands of worst case conditions regarding critical soot loading can not be sufficiently covered, backpressure response can not be monitored and may get critical regarding Power loss / Durability. (esp. in winter conditions, with bad fuel qualities and over lifetime + ash/oil-born particles).
- AVL Recommendation is to use a p-based sensor in combination with a proper EO-PM model.
- Generally Sensor application and GPF Regeneration strategies for underfloor filters are strongly recommended to cover series production fleet risks (as mentioned above)
- Close coupled GPF Setups do anyway always require sensor application and related Functional/Calibration solutions as overcritical passive regeneration in fuel cut-off may happen at high CC temperatures already at low soot loads. A p-based sensor concept (+ EO model) is preferred, additional production intend temperature sensors also helpful (Exh. Temp. Model accuracy), but not dynamic enough to cover regen risks completely (backup only), still for OBD demands in some setups necessary.

THANK YOU

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