Fundamental Study of GPF Performance on Soot and Ash Accumulation over Artemis Urban and Motorway cycles. Comparison of Engine Bench Results with GPF Durability Study on Road

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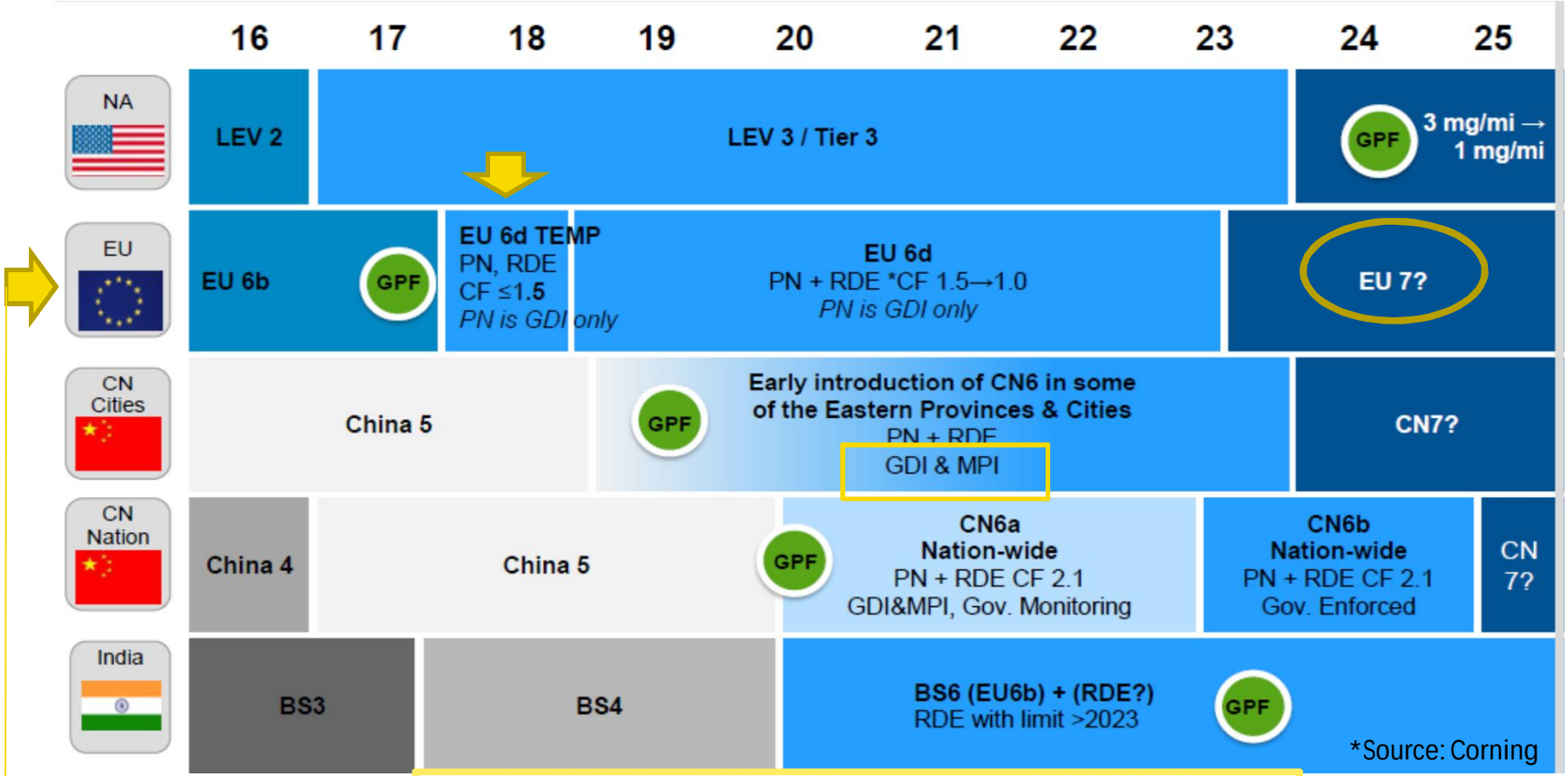
OUTLINE

- Introduction
- Objectives
- Experimental facilities & test procedure
- Results
  - Artemis Cycles
  - Vehicle Durability Study on Road
- Summary

INTRODUCTION - LEGISLATION ROADMAP



Emission limit for particle number emissions $6x10^{11}$#/km

- GDI only

Real world driving emissions (RDE) defined

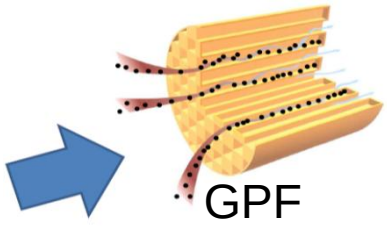
- Compliance factor (CF) for PN is CF = 1+x
  - With x=0.5 starting 09/2017 (new TA) and 09/2018 (all new)
  - Measurement uncertainty „x“ to be reviewed regularly, assuming it to be reduced over time
- Cold start will be included in RDE (initial phase of RDE trip)

MOTIVATION

- **Increasing health concerns and tight PN emissions regulations** affect Gasoline Direct Injection (GDI) engines in addition to Diesel
- **Recent literatures highlight the health concerns** related to PN from GDI engines and in particular PAH emissions from GDI; they can pass through a TWC but can be finally trapped in the GPF (M. Muñoz, Empa 21st ETH Conference on Combustion Generated Nanoparticles, June 2017)
- **The introduction of Real Driving Emissions (RDE) including "cold start" and** the Particle Number (PN) limit for GDI vehicles has accelerated the development of Gasoline Particle Filters (GPF)
- **GPFs are expected to appear on mass-market production vehicles from 2017 onwards**
- **Even if some learnings from DPFs** can be transferred to GPF, the particulate composition, the PM to PN ratio, the exhaust temperature as well as the gas composition of gasoline engines are significant different to diesel engines

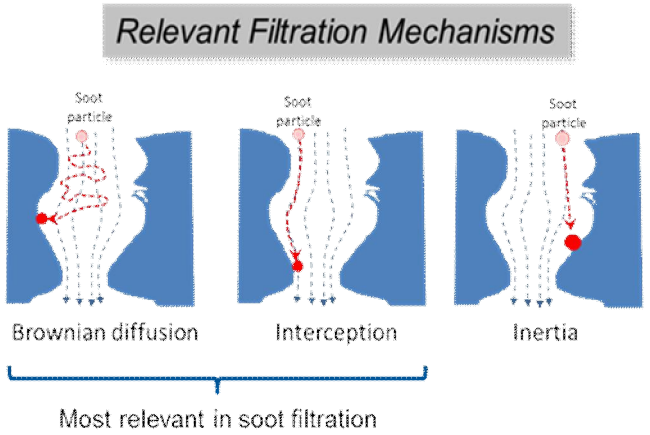
OBJECTIVES

- **Investigation of soot and ash accumulation on an uncoated GPF by conducting a fundamental investigation on engine bench and vehicle** using the same engine type (OPEL1,6 liter turbo GDI)
- **The effect of different cycles (Artemis Urban and Artemis Motorway),** the effect of ageing up to 20k km, the effect of engine ageing and oil consumption are reported
- **In parallel, a durability study on an "average customer cycle" on road up to 200k km** was conducted by using two identical vehicles (Zafira Tourer) equipped with the same GDI engine and same GPF type
- **A comparison of the engine and vehicle study of the GPF performance** on the well-known Artemis cycles versus the "real world driving" case is presented



INTRODUCTION - GPF

	PM	Engine out Gas T (deg. C)	O2 Conc.
GDI	LOW PN (1-10x10E+12 #/Km) PM (2-10 mg/Km)	HIGH (up to 700 deg. C)	LOW (0-20%)
Diesel	HIGH PN 10-100x10E+12 #/Km PM (10-50 mg/Km)	LOW (Max 400 deg. C)	HIGH (10-20%)

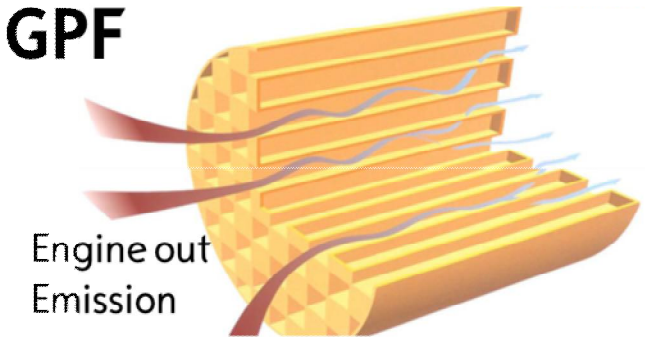


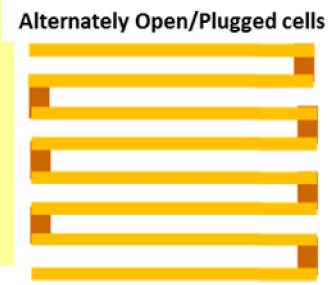
- Fast soot accumulation (Diesel) vs. Slow soot accumulation (Gasoline)
- Higher impact on back pressure (Gasoline)
- Since gasoline engines exhibits very dynamic exhaust heating & cooling - Thermal Shock Resistance is critical for GPF

Cordierite best option material so far for GPF

✓ Superior thermal shock performance (low CTE*)
✓ Better light off performance
✓ Isostatic strength & weight similar to substrate

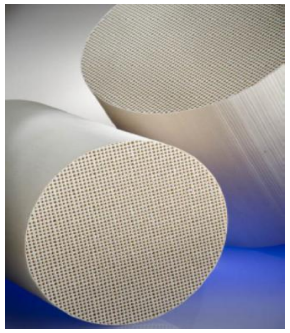
*CTE= Coefficient of Thermal Expansion





Ø **GPF filtration is dominated by the filter material vs. the soot cake in case of a DPF**

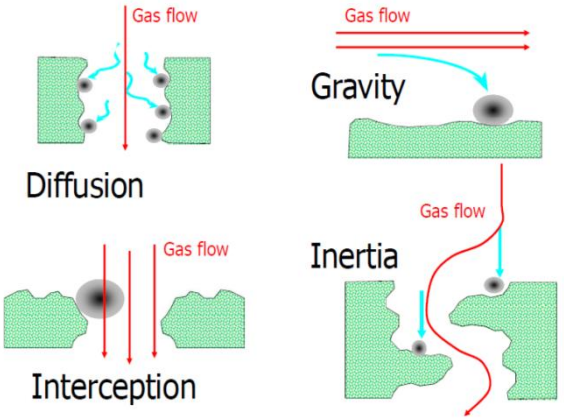
GPF Filtration & Backpressure

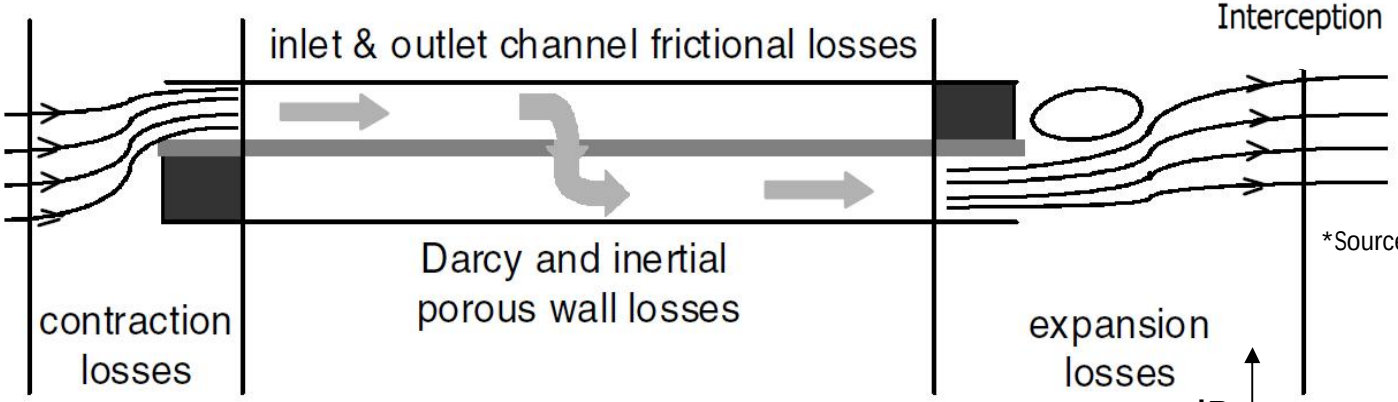


Backpressure drivers:

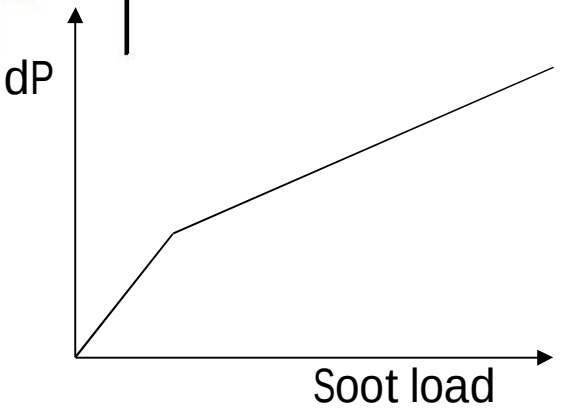
Ø Deep bed filtration

Ø Soot cake





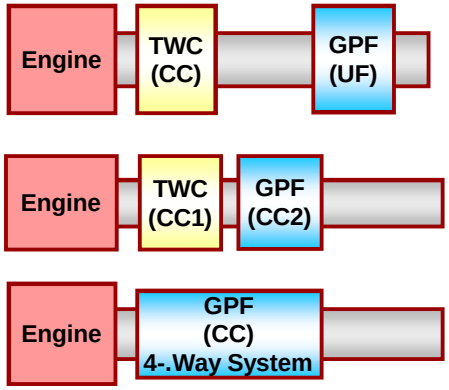
*Source: SAE 2001-01-0909



Ø Flow contraction when entering the filter channel
Ø Friction within channel
Ø Flow trough soot cake
Ø Flow trough (soot loaded) filter wall
Ø Expansion losses when leaving the channel

GPF REQUIREMENTS

System Architectures



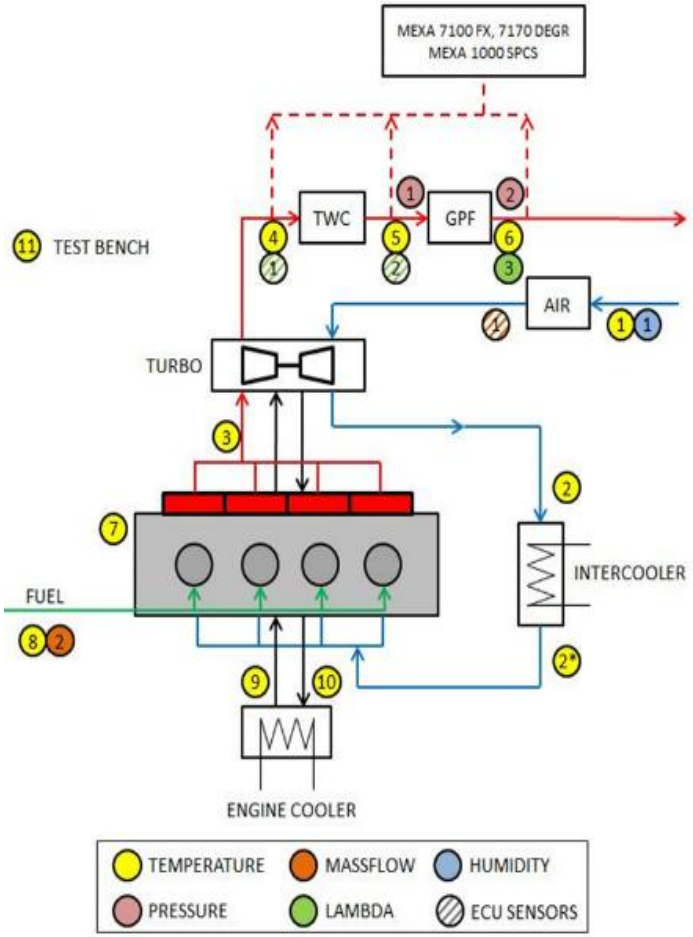
- CC / UF
- Coated / Uncoated

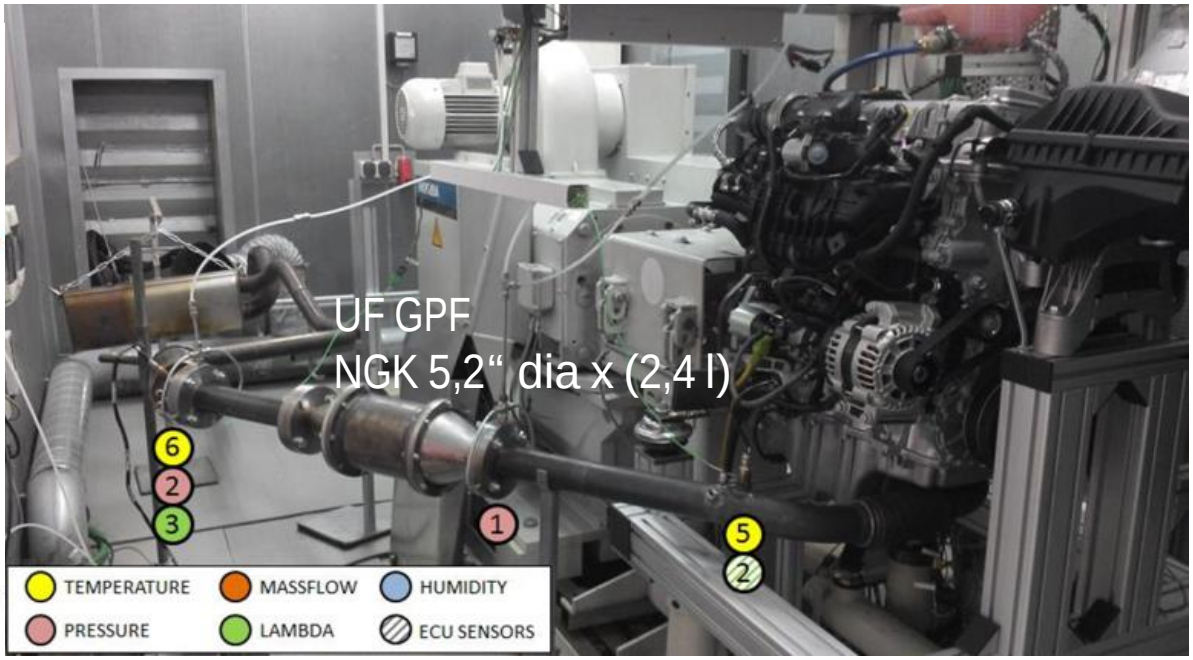
GPF

Requirements

- Particle reduction
  - Meet Euro 6d limits
  - Meet filtration & Backpressure requirements
- Durability
  - >160k km lifetime
  - Thermal & Physical
- Soot regeneration
  - Optimise passive regen
  - Lean combustion (stratified)
- Backpressure
  - Minimise impact on powertrain
- TWC activity
  - Promote regeneration
  - Substitute existing TWC volume (coated GPF)

EXPERIMENTAL SET-UP: ENGINE DYNO





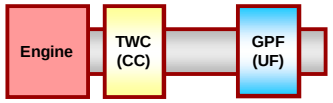
Source: SAE 2017-24-0127

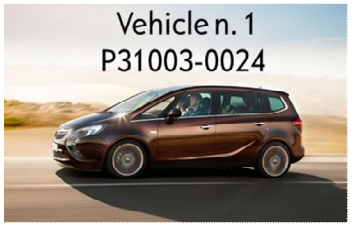
Specification	GDI Opel Engine
Displacement	1,598 cm3
Valves/cylinder	4 & 4
Air charging system	Turbo charger
Max Power hp	170 hp/6000 rpm
Max Power kW	125 Nm /1,650-3200 rpm w/o overboost
Max Power Nm	280 Nm/1,650-3200 rpm with overboost
Bore/Stroke	79 mm/81,5 mm
Compression ratio	10.5:1
Dimensions	L:638 mm W: 564 mm H: 701 mm

- Cycles: Artemis Urban & Motorway up to 20k km
- Fuel Super RON 95; Oil Dexos 1 (SAE Class 5W-30)

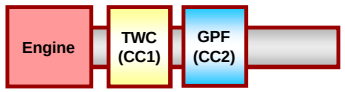
Experimental set up: 2 identical vehicles with GDI 1,6 liter - UF vs CC GPF

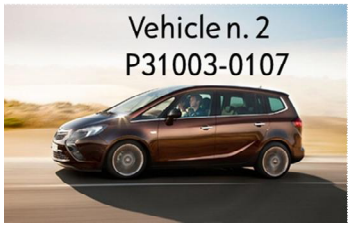
Evaluated Exhaust Layout 1:



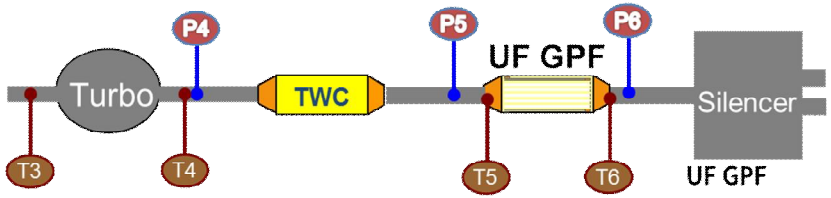


Evaluated Exhaust Layout 2:

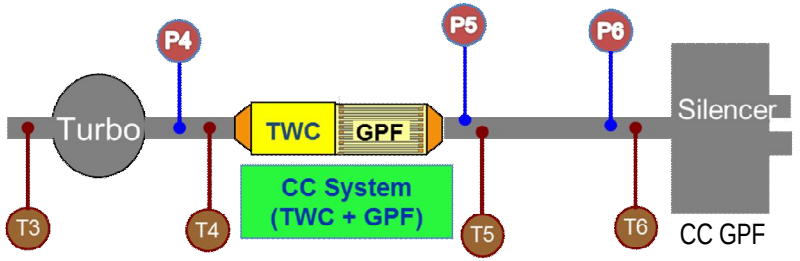


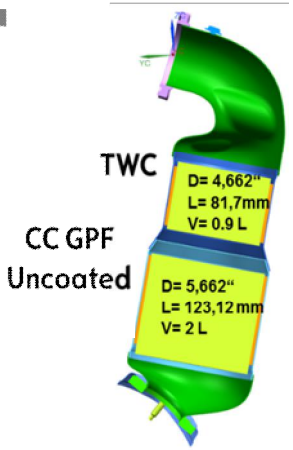


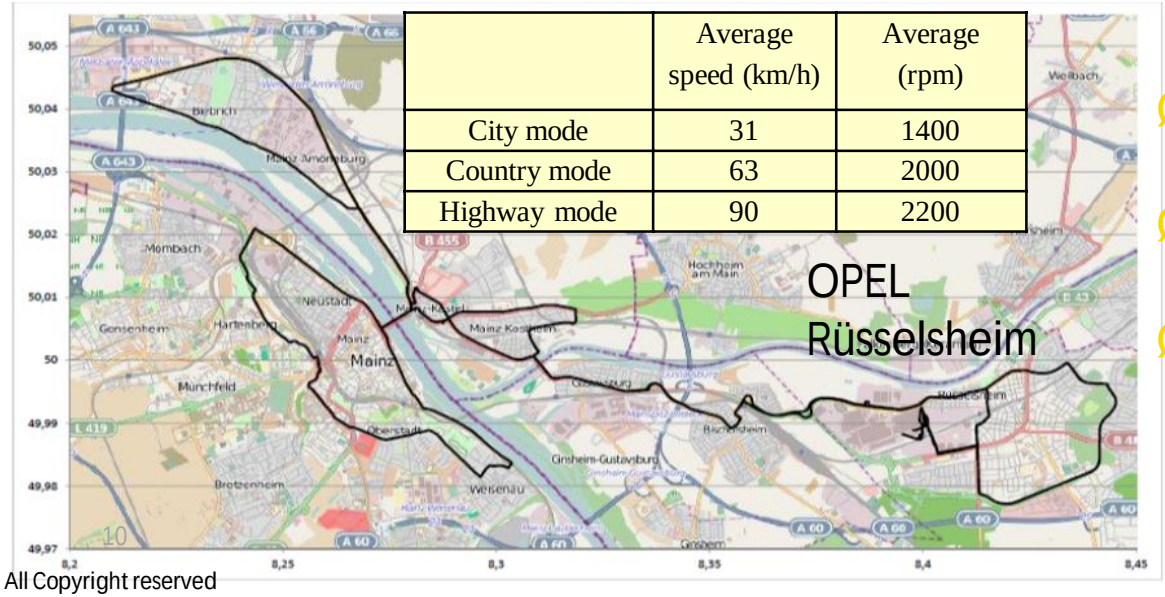
**Source: SAE 2017-24-0127*



Experimental Lay out



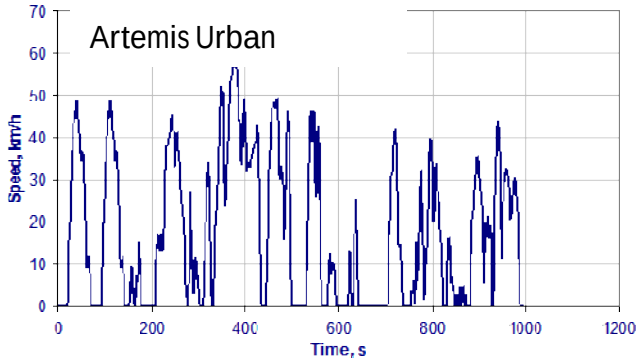


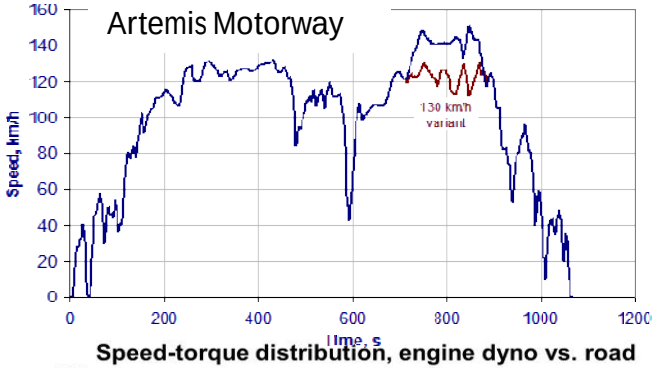


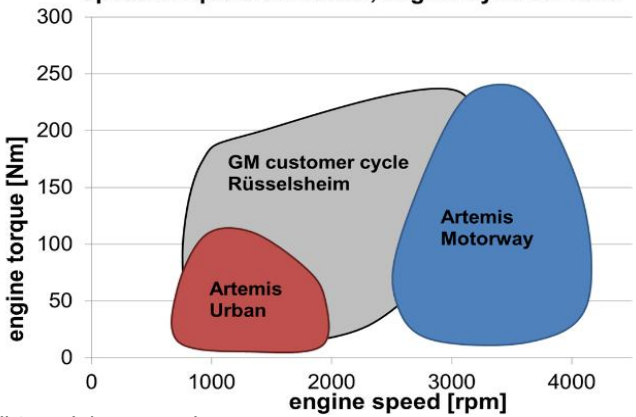
	Average speed (km/h)	Average (rpm)
City mode	31	1400
Country mode	63	2000
Highway mode	90	2200

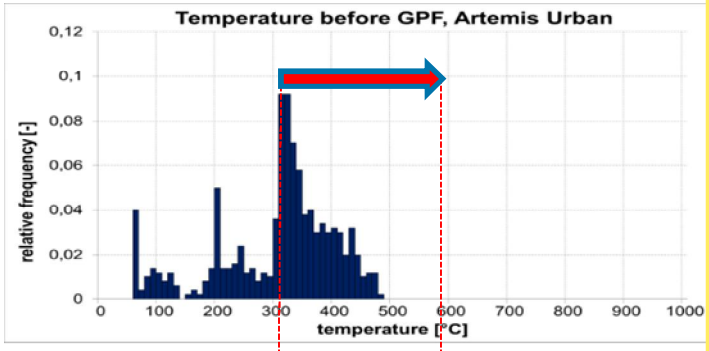
- Ø Gaseous & PN measurements over WLTC every 20k km
- Ø GPF weighing and CT scan every 20k km
- Ø Fuel Super RON 95 - Dexos 1 Oil (SAE Class 5W-30)

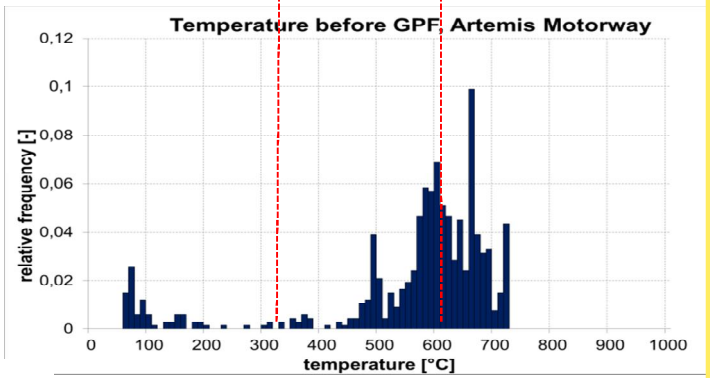
CYCLES CHARACTERISTICS

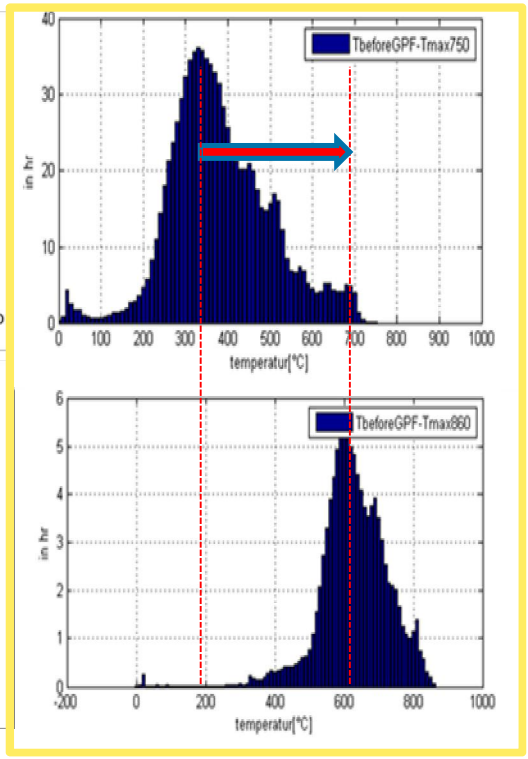








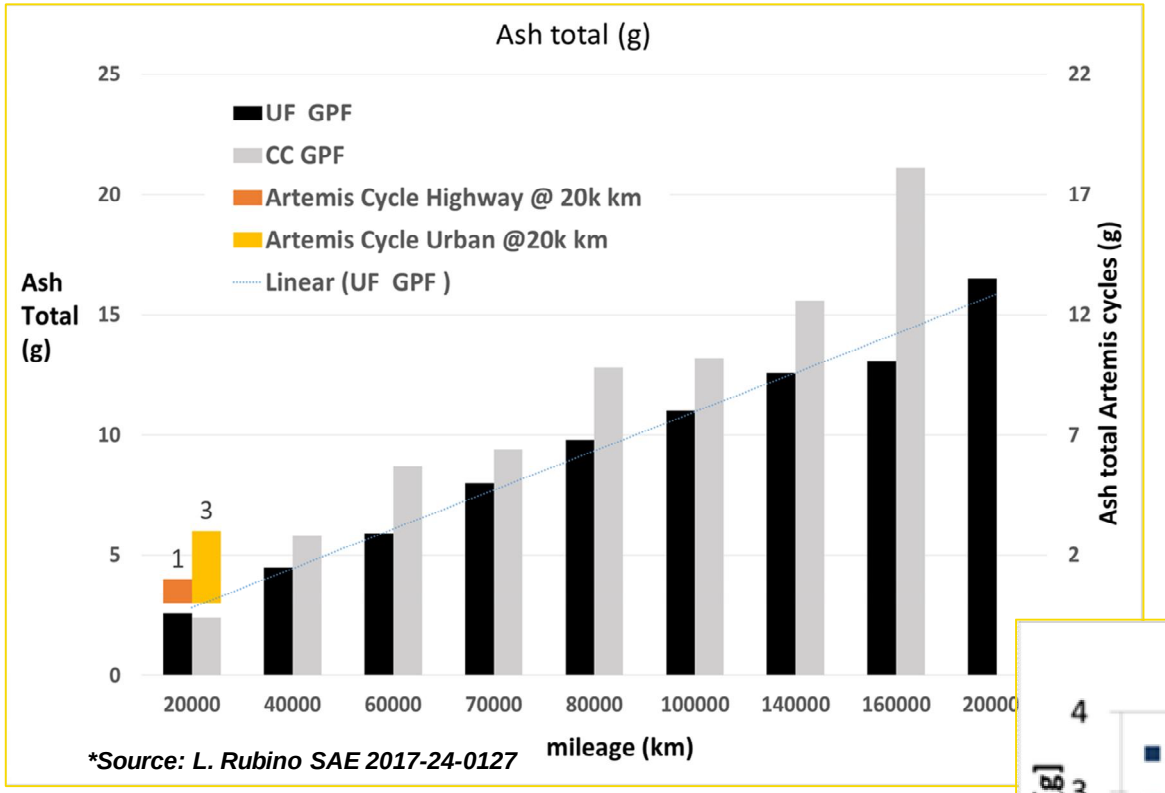




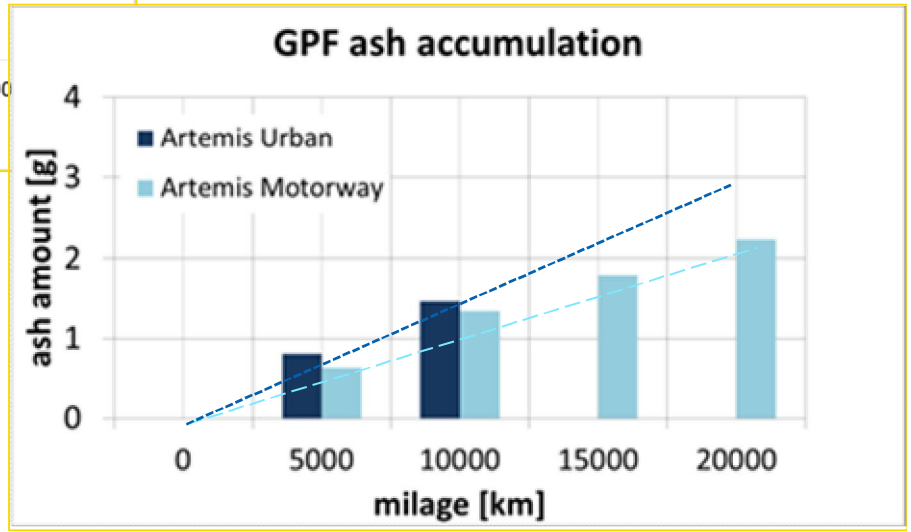
Source: SAE 2017-24-0127

Ø Good correlation between the „average customer cycle“ on road and the Artemis cycles (Urban vs Motorway)

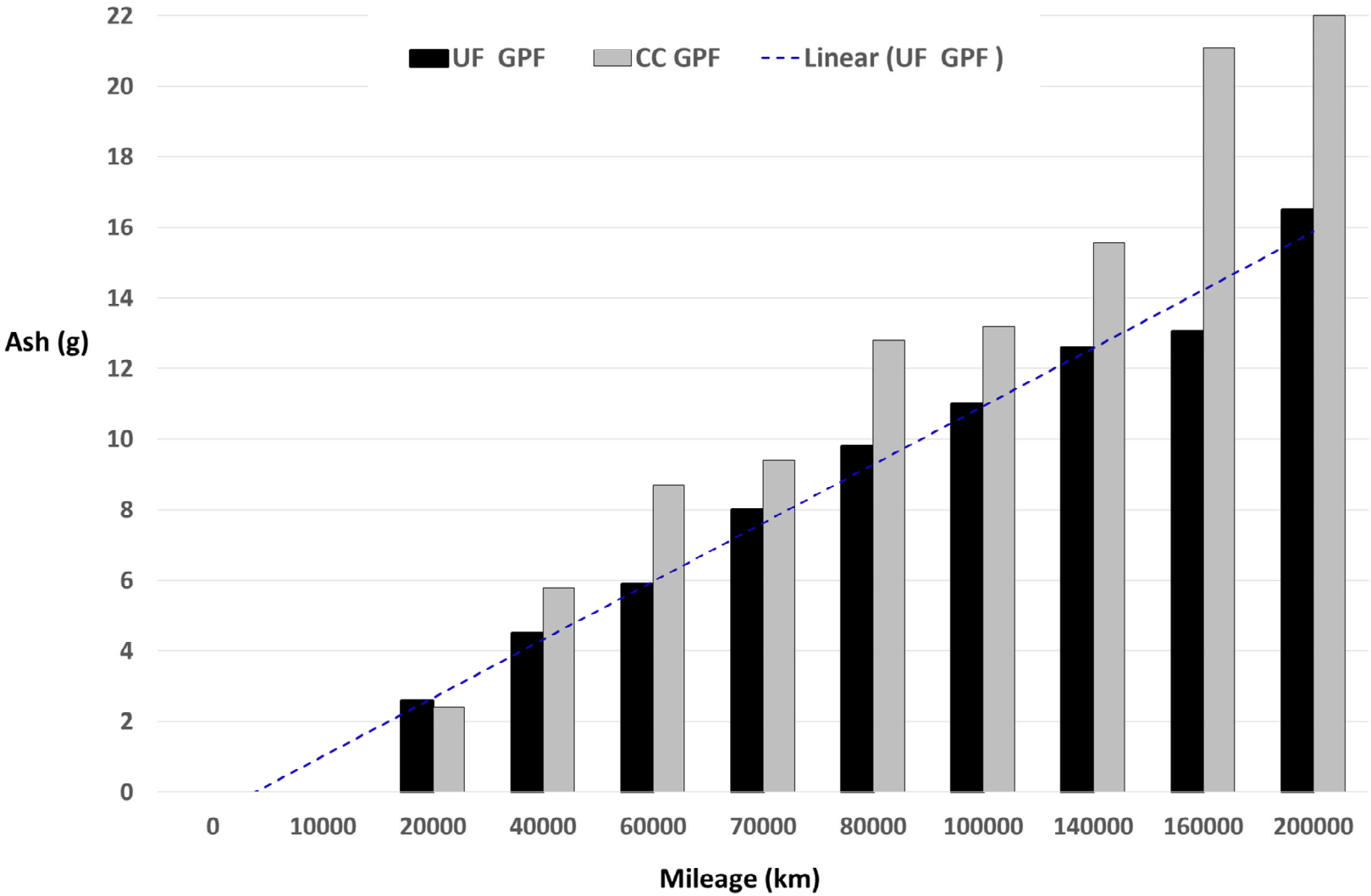
EXPERIMENTAL RESULTS: ASH ACCUMULATION - ARTEMIS CYCLES



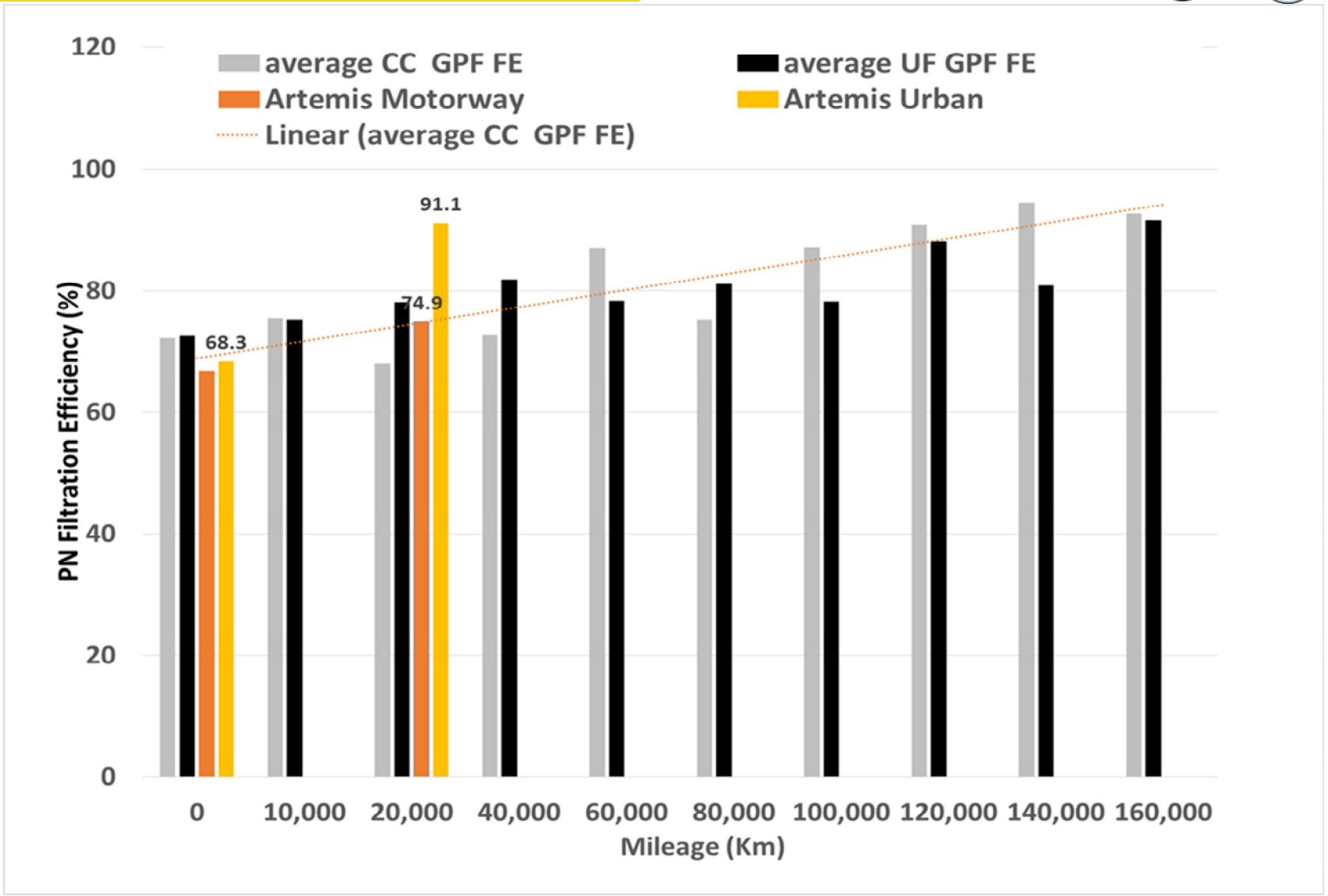
*Source: L. Rubino SAE 2017-24-0127



EXPERIMENTAL RESULTS: ASH ACCUMULATION - VEHICLES ON ROAD

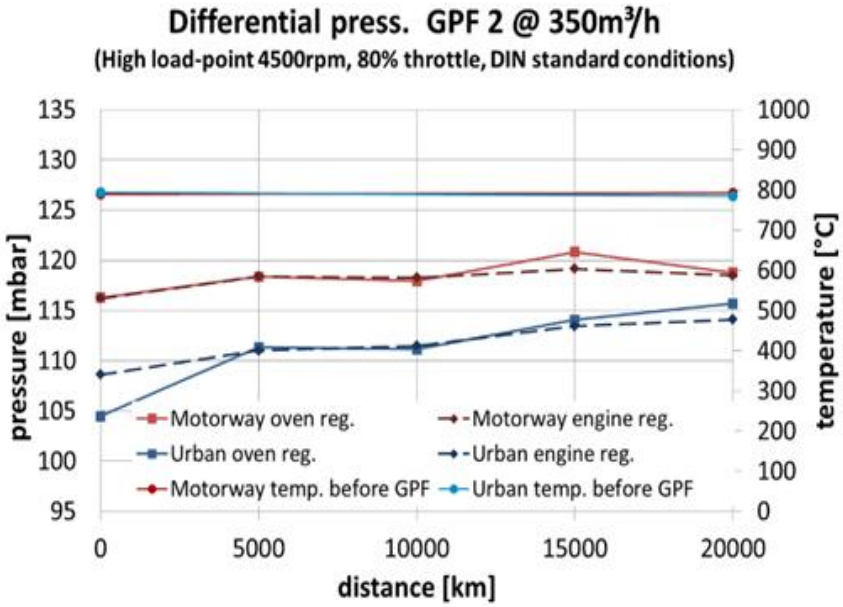


EXPERIMENTAL RESULTS: FILTRATION EFFICIENCY (%) over WLTC

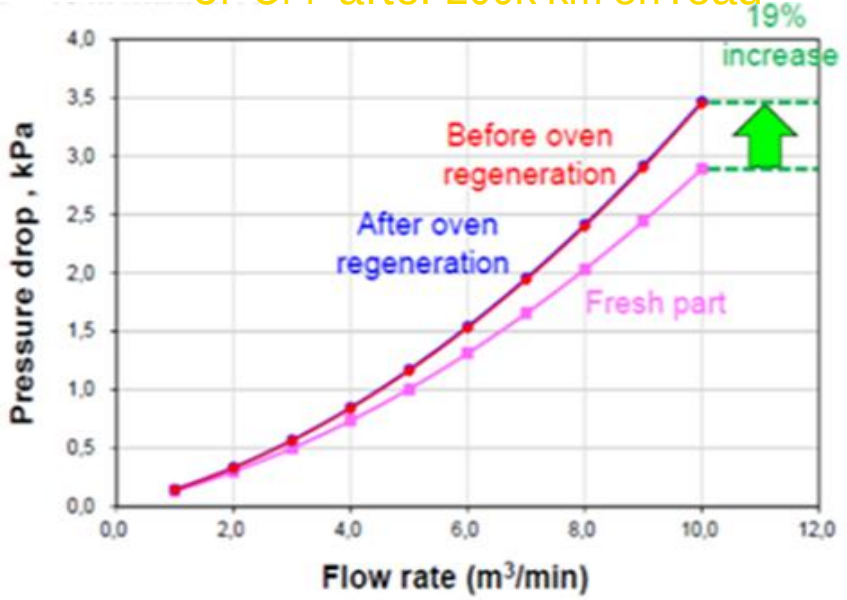


EXPERIMENTAL RESULTS: BACKPRESSURE (BP)

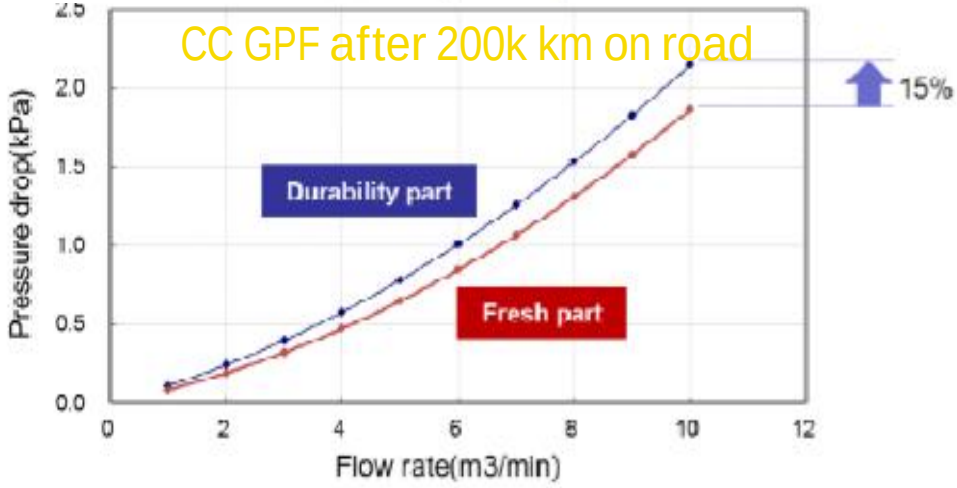
ARTEMIS Cycles



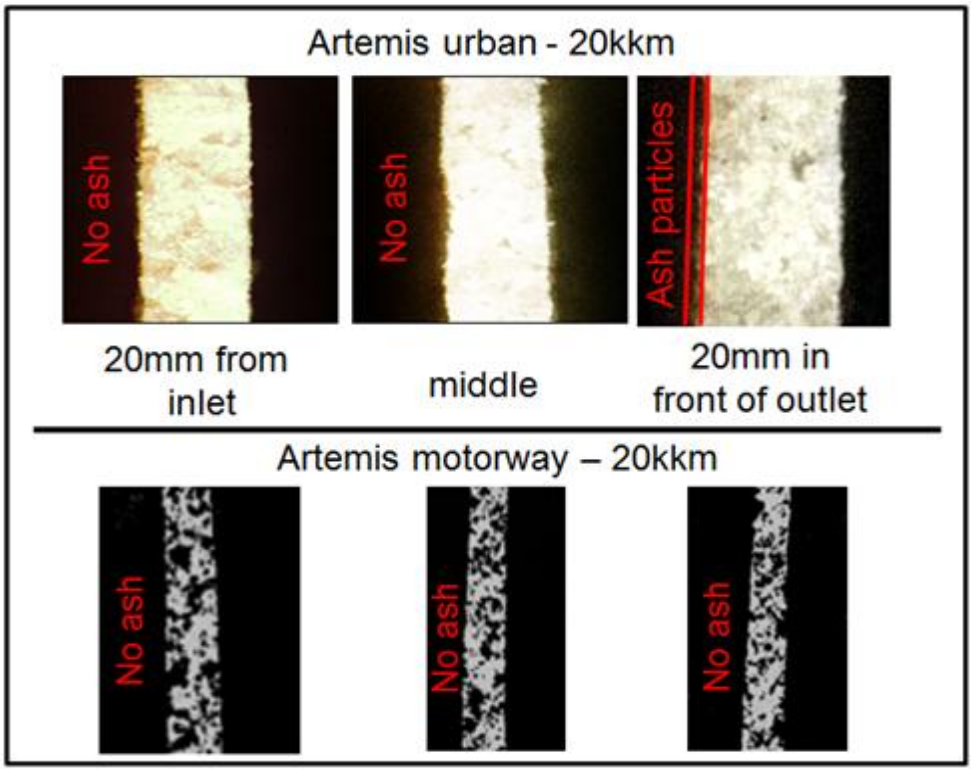
UF GPF after 200k km on road



CC GPF after 200k km on road



EXPERIMENTAL RESULTS: ASH DISTRIBUTION & COMPOSITION

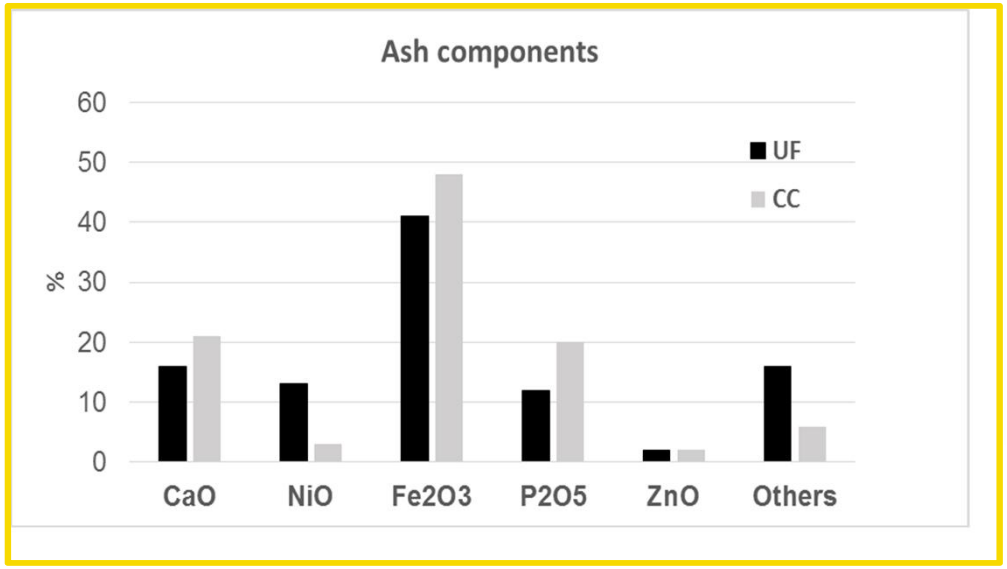


*Axial direction (20mm from inlet, middle of GPF, 20mm in front of GPF outlet)

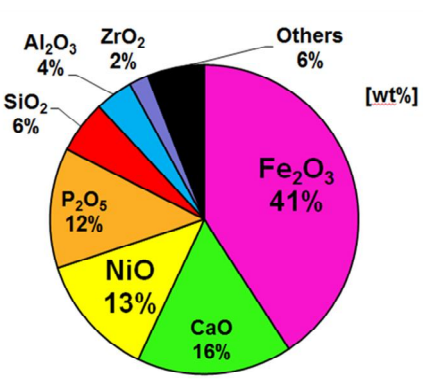
*CT= Computed tomography

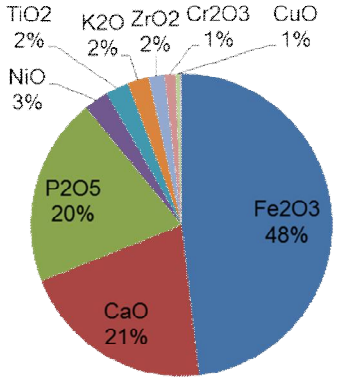
- **Over 20k km, ~1g total ash was accumulated on the GPF over the Artemis Motorway and ~ 3g over the Artemis Urban**. This matches well with the vehicles “on road” (~ 2.5g ash after 20k km).
- **Over 200k km on road the ash did not penetrate into the filter walls**. The maximum ash plug height is ~2.5 mm at the peripheral center
- **The ash plugs are assumed** to follow a half-elliptical distribution. Outlet plug ash layer weight is ~10g and this is ~ 40% of the total ash accumulated in the GPF

EXPERIMENTAL RESULTS: ASH DISTRIBUTION & COMPOSITION



XRF analysis after ~200k km



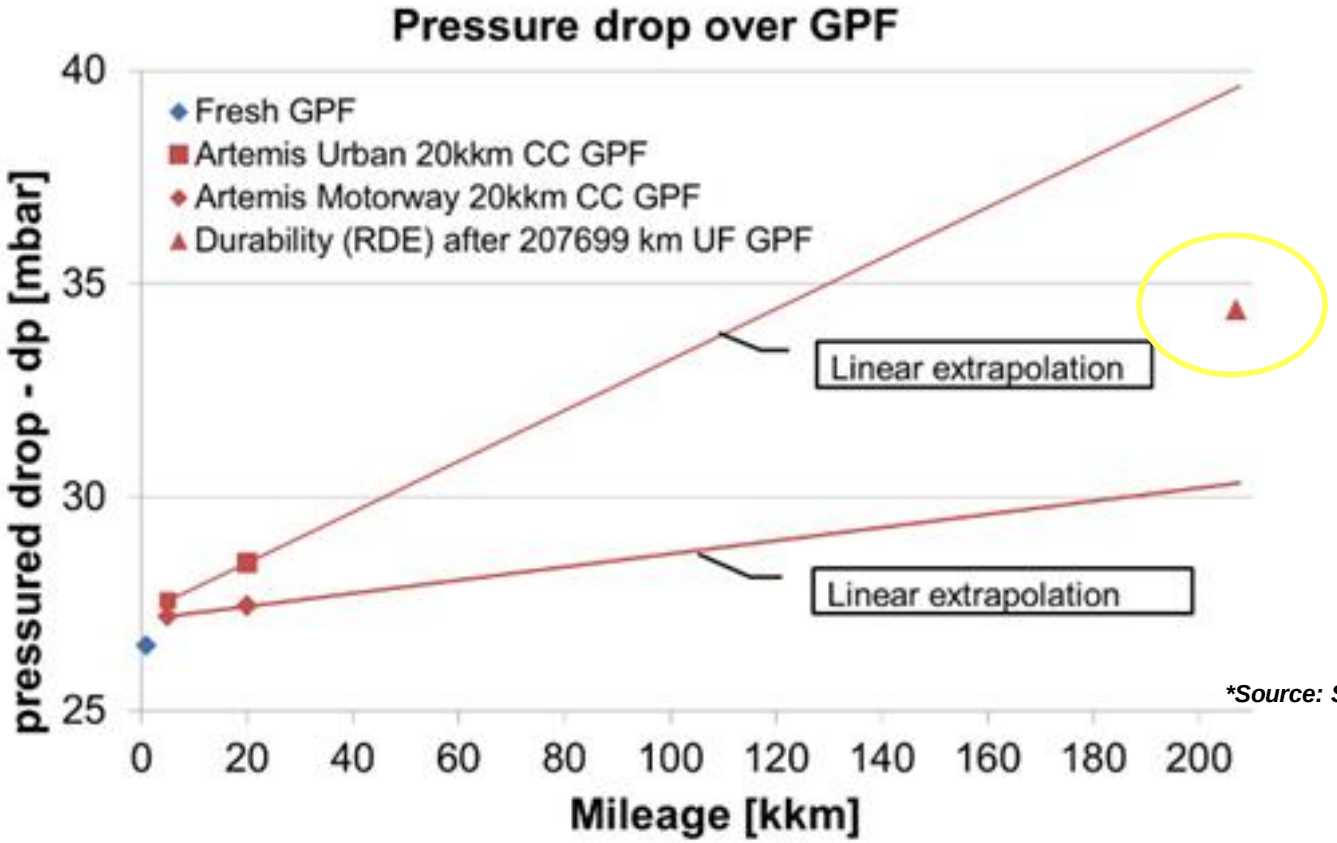


UF GPF **CC GPF**

*X-ray fluorescence (XRF)

- **After 200k km on road** XRF ash analysis showed similar ash composition for both UF and CC GPF
- **Iron oxides are the main components** (probably wear of the engine/exhaust system) of both types of ash for the UF GPF and CC GPF. Calcium and Phosphorus are second and third major components of the ash
- **GPF ash is mainly located in front of the rear plugs of the GPF.** Further analysis of the ash content of the Artemis Urban GPF is ongoing
- **The ash in the CC GPF is shaped as an "ash ring"** around the center of the GPF at the outlet side

COMPARING ENGINE & VEHICLE RESULTS - BACKPRESSURE



*Source: SAE 2017-24-0127

Ø **By applying the Artemis Urban cycle for 20k km** on the engine bench, ash accumulation as well as backpressure increase can be reasonably extrapolated to give an upper limit for 160k km vehicle operation for an “average customer cycle” on road

SUMMARY (I)

- **This study investigated soot and ash accumulation on GPF** by conducting a fundamental investigation on Artemis Urban and Motorway cycles using an uncoated NGK GPF in UF location of a 1.6 litre turbo GDI OPEL engine on a dynamic engine bench
- **In parallel, a durability study on an "average customer cycle" on road up to 200k** km was conducted by using two identical vehicles (Zafira Tourer), equipped with same GDI engine type and NGK GPF type
- **Ash correlated well to oil consumption**, with relatively higher oil consumption over the Artemis Urban cycle ~0.02 l/1000km compared to the Artemis Motorway ~0.012 l/1000km
- **Over 20k km, ~ 1g total ash was accumulated** on the GPF over the Artemis Motorway and ~3g over the Artemis Urban; this matches well with the vehicles "on road" measurements
- **The "average customer cycle" on road** with an in-between engine, torque and speed distribution did show also an in-between oil consumption and ash accumulation behavior with a tendency to be closer to the Artemis Urban cycle
- **PN GPF filtration efficiency (FE) increased with mileage** and was dependent on the „driving mode"; over the WLTC, FE of ~70% (clean filter) to ~75% (after 20k km Artemis Motorway cycle) and up to 91% over the Artemis Urban
- **A similar trend in FE was observed also for the vehicles** study with FE up to ~ 92% for both UF and CC GPF after 160k km

SUMMARY (II)

- **Post mortem analysis (PMA)** of the GPF after 20k km Artemis Urban cycle showed a very thin ash layer on the filter walls; very low ash collected during Artemis Motorway
- **PMA of the UF GPF after 200k km vehicle operation** on road showed a homogeneous ash distribution along the inlet channel of the whole length (inlet to outlet). **The ash did not penetrate into the filter walls for both UF and CC case**; ash plugs were also found and estimated to be ~40% of the total ash accumulated in the GPF
- **The ash for the CC GPF case** was shaped as an “ash ring” around the center of the GPF at the outlet side
- **Iron-oxides are the main components** of ash accumulated on the UF and CC GPF. Calcium and Phosphorus are second and third major components of the ash
- **Backpressure (BP) increased** ~19% after 200k km for the UF GPF vehicle case and ~15% for the CC GPF case (cold flow bench measurements)
- **By applying the Artemis Urban cycle for 20k km on the engine bench**, the measured data for ash accumulation as well as BP increase can be reasonably extrapolated to give an upper limit for 160k km vehicle operation for an “average customer cycle” on road
- **Further work & data analysis is ongoing** to better understand the relationship between oil consumption and ash accumulation

ACKNOWLEDGMENTS

- The collaboration of colleagues at Opel for helping with vehicle testing and data analysis is highly acknowledged
- The support from NGK in particular Dominic Thier, Torsten Schumann, the University of Applied Science Darmstadt, Stefan Güttler and prof. Gerald Russ and Evonik Dr. Bartels is highly appreciated and acknowledged

- *Rubino, L., et al.,* ***SAE Technical Paper 2017-24-0127****, 2017, doi:10.4271/2017-24-0127*
- *Rubino, L., et al. ,* ***21st ETH-Conference on Combustion Generated Nanoparticles****, Zurich, 19th – 22nd June, 2017*

THANKS

QUESTIONS?

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