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Particle number emissions from a Euro 6d-temp GDI under extreme European temperature and driving conditions

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Agenda

- Motivation
- Test vehicle, fuel and PN equipment
- Test Matrix and Drive cycles
- PN emissions results
- CLOVE: PN data from Euro 6d diesels and limit proposals
- Summary

Motivation

- GPF technology is becoming more prevalent and PN emissions are comfortably below the $6x10^{11}$ #/km limits under certification conditions (WLTC and RDE)
- Real world operation at or beyond the current RDE boundary conditions were of interest with regard to potential Euro 7 developments
- Key challenges were anticipated to be demanding urban, highly dynamic high speed, high payload plus very low and high ambient temperature operation
- There is currently minimal published information regarding PN emissions of GPF-equipped vehicles under extreme operation
- The research primarily aimed to determine the impact of extreme temperatures and driving conditions on tailpipe PN from a Euro 6d temp GDI with TWC + GPF, and to put emissions in context of those observed from current filter-equipped diesel vehicles

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Test vehicle and PN measurement equipment

- Euro 6d-temp-EVAP-ISC
- 8-speed auto
- Gasoline direct injection
- 1998cm^3, 135kW
- cc-TWC + uf-GPF (uncoated)
- Odometer: ~24150km SoT
- Eu pump–grade E10 fuel
- As-received lubricant

	Euro 6 limit	Type approval
THC (mg/km)	500	15.3
NMHC (mg/km)	[-]	11.9
NOx (mg/km)	60	19.4
PM (mg/km)	4.5	0.15
PN (#/km)	$6x10^{11}$	$4.66x10^{10}$

PN Measurements: SPN10 and SPN23

ET-equipped AVL APC with 23nm and 10nm CPCs (Both 10nm and 23nm corrected via mean PCRF at 30, 50, 100nm)

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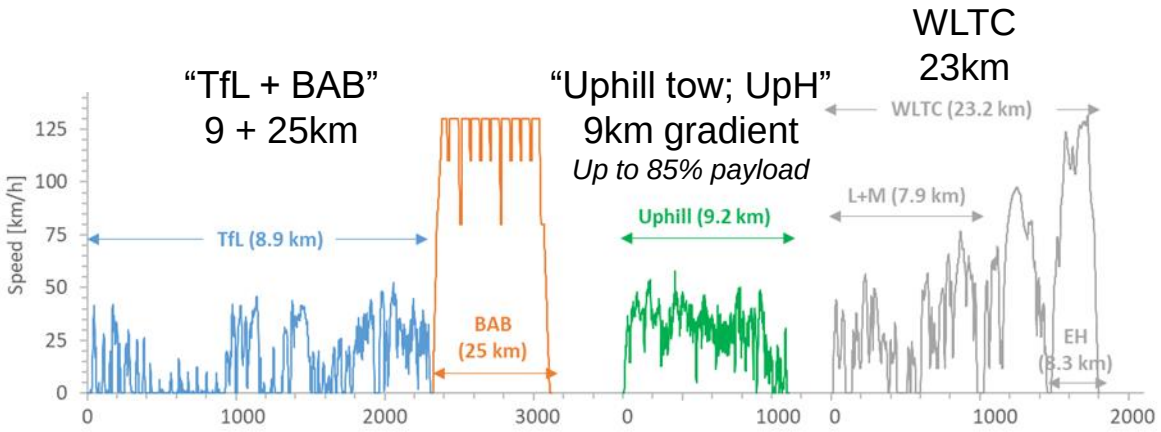
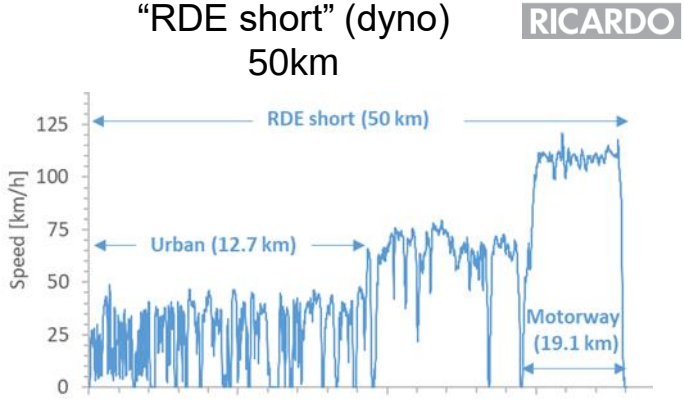
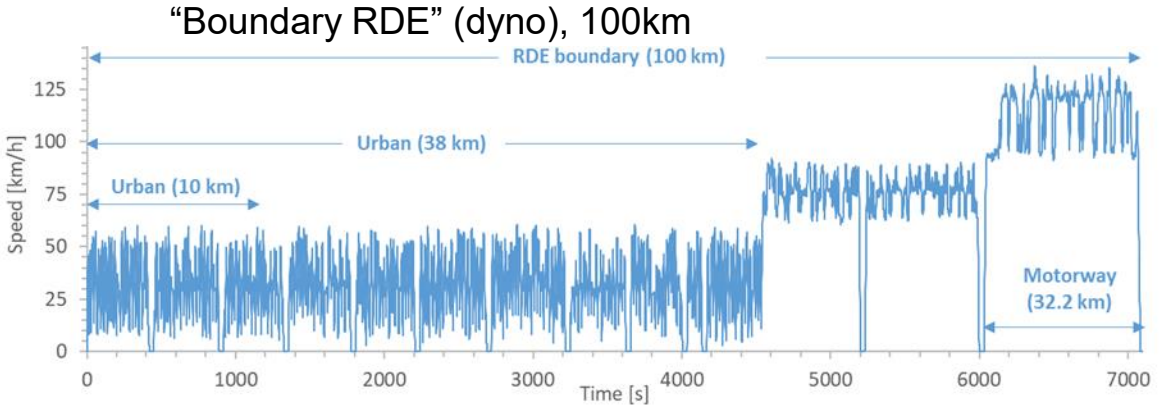
7 different drive cycles: covering moderate and severe operation

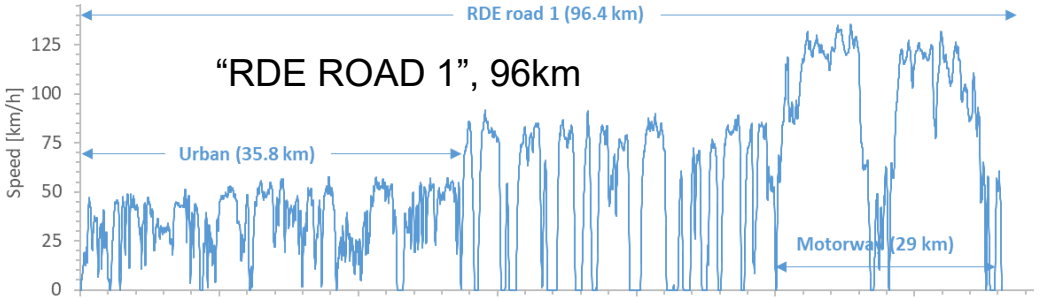


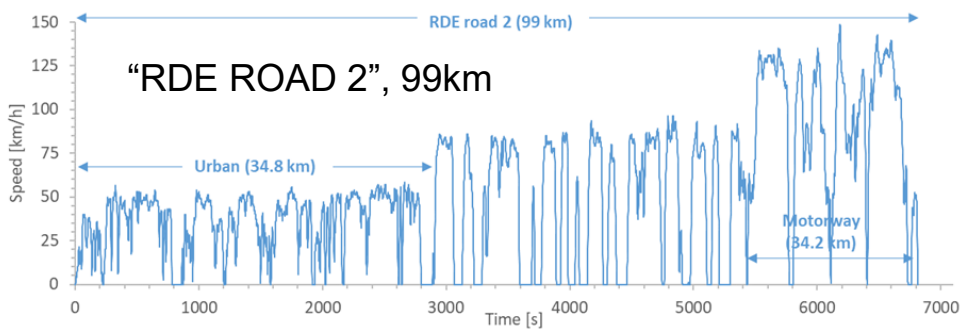




A range of test temperatures

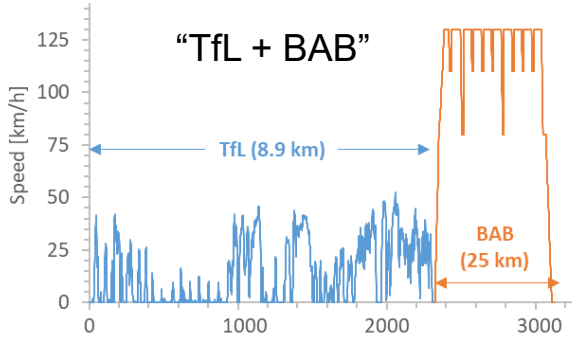
	-30°	-10°	-7°	5°	17-20°	23°	50°
Road RDE 1,2					1, 1		
WLTC						2	
TfL + BAB	1	1	1	1		1	1
RDE Short	1	1		1		1	1
Uphill tow		1	1				
RDE Boundary		1					

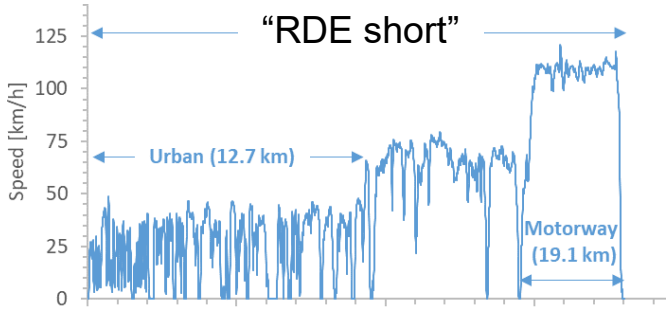




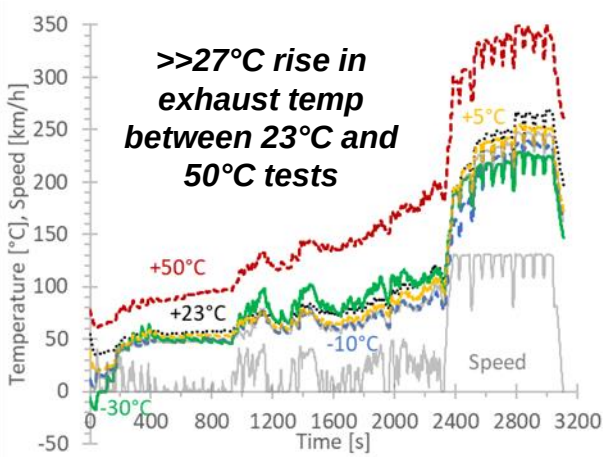
A range of challenging drive cycles were used to determine the impact on PN for both SPN10 and SPN23

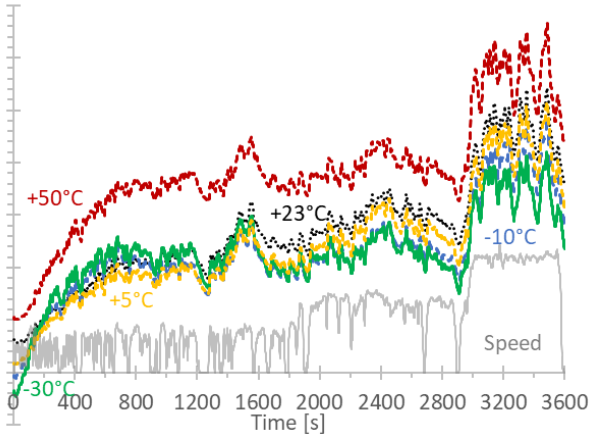
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 7	Day 8
Place	Road	Lab	Lab	Lab	Lab	Lab	Lab	Lab	Lab
Temp.	17 - 20°C	23°C	23°C	-10°C	-30°C	-10°C	5°C	50°C	-7°C
Morning	RDE road 1	WLTC	TfL+BAB	TfL+BAB	TfL+BAB	Uphill tow	TfL+BAB	TfL+BAB	TfL+BAB
Evening	RDE road 2	WLTC	RDE short	RDE short	RDE short	RDE boundary	RDE short	RDE short	Uphill tow 85%





Urban characterized by consistently very low tailpipe temperatures throughout





Motorway characterized by high tailpipe temperatures throughout

- The thermocouple was housed at the **tailpipe of the exhaust, so** does not indicate the GPF temperature

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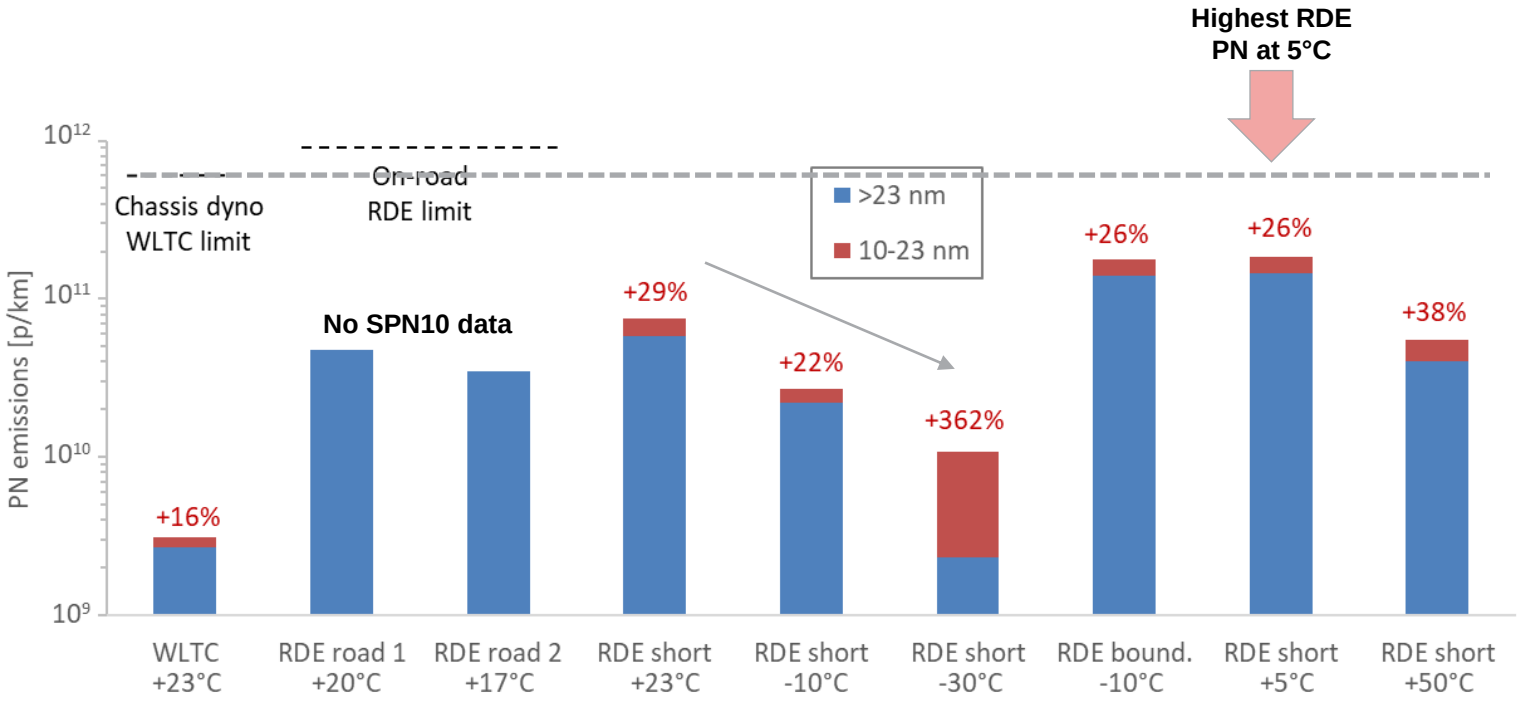
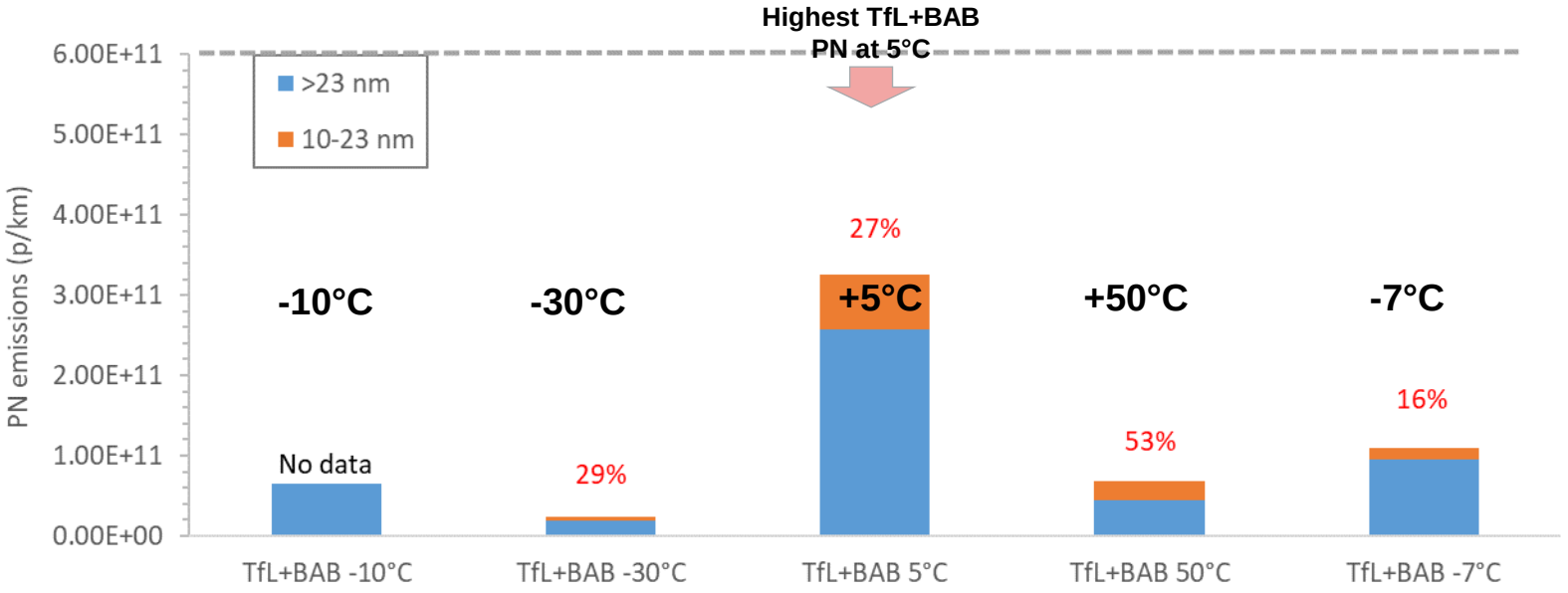
RDE cycles in test order, indicates SPN10 & SPN23 emissions well below 6x10^{11}#/km



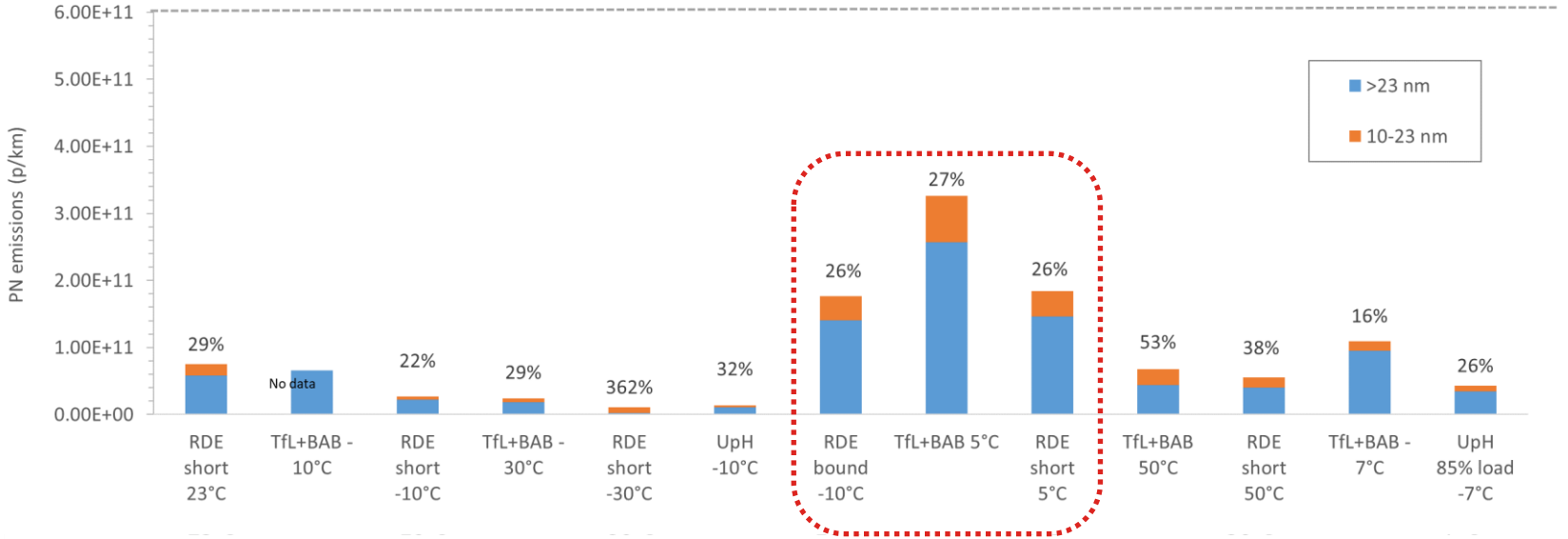
- GPF is effectively controlling SPN23 to <20% of the Euro 6 limit value across a range of real world drive cycles and climatic conditions
- PN10 levels are also well below the limit value
- **RDE short -30°C** shows a very high proportion 10-23nm PM, but related to the lowest (<10^{10} #/km) emissions of SPN23; RDE short 5°C shows highest emissions

TfL+BAB PN23 results all below 6x10^{11}#/km

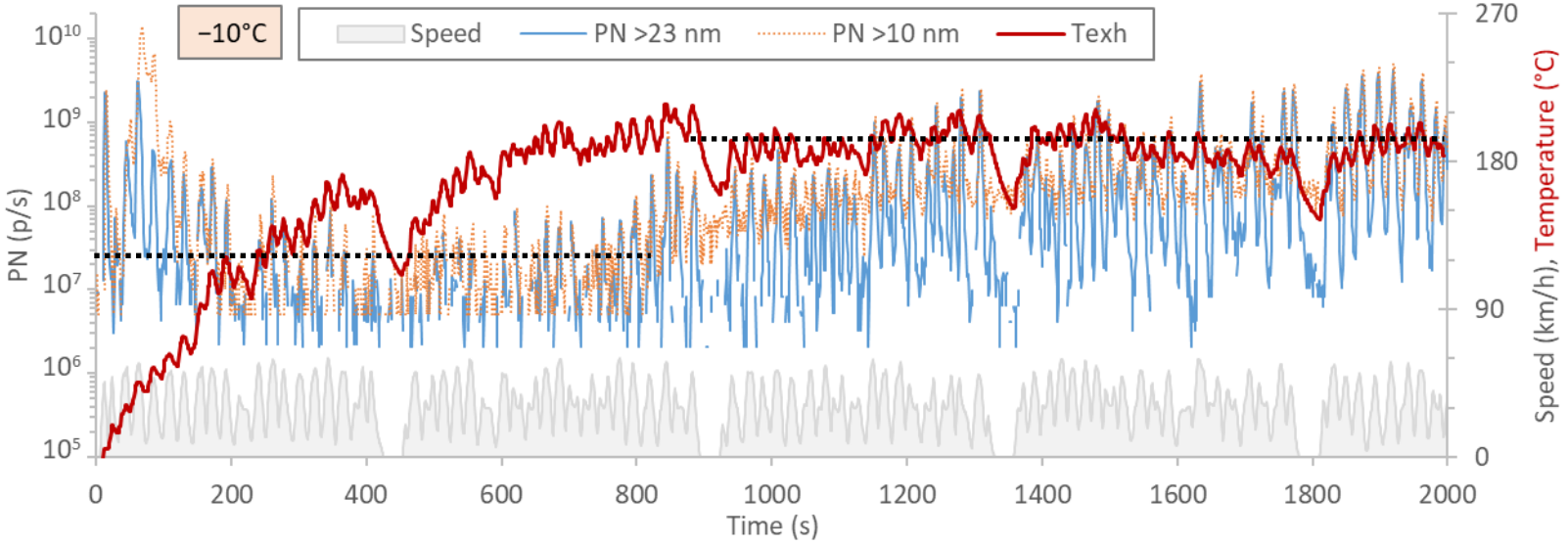


- 10-23nm levels typically add ≤ 50% to SPN23 levels
- 5°C tests substantially higher PN than other temps. Why?

- In test order TfL+BAB 5°C and then RDE short 5°C follow long duration, highly dynamic -10°C RDE boundary test

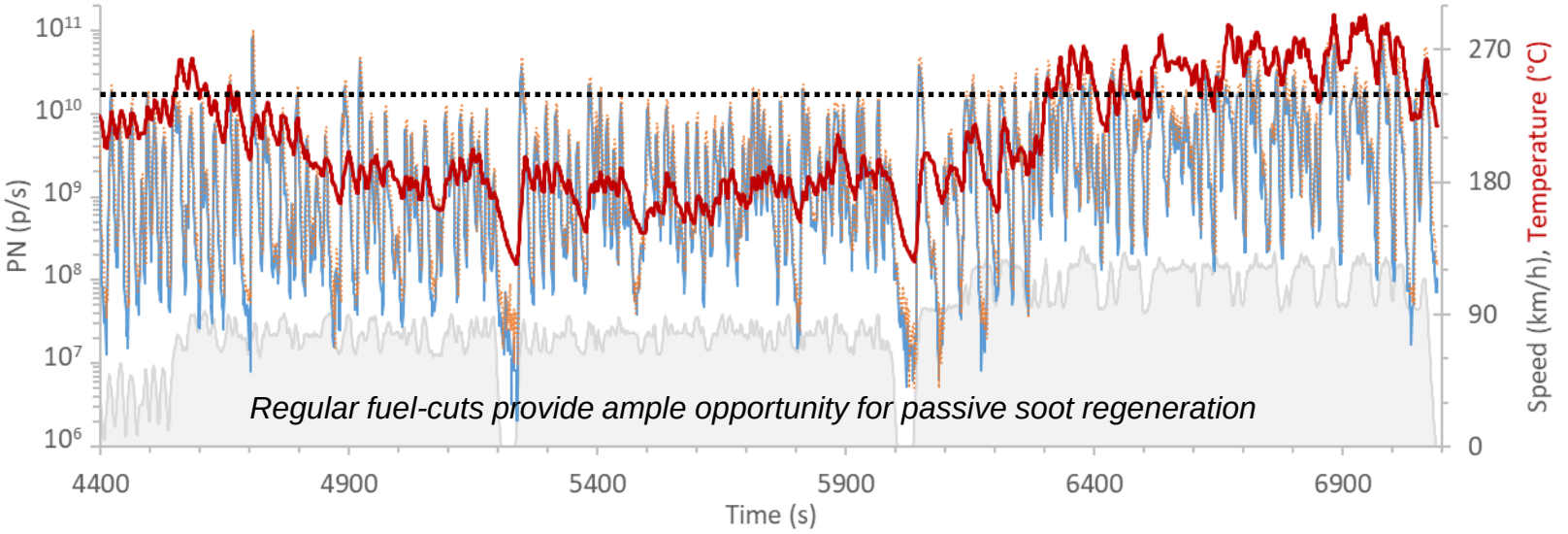


RDE boundary cycle shows increasing PN emissions related to rising, and consistently elevated, exhaust temps



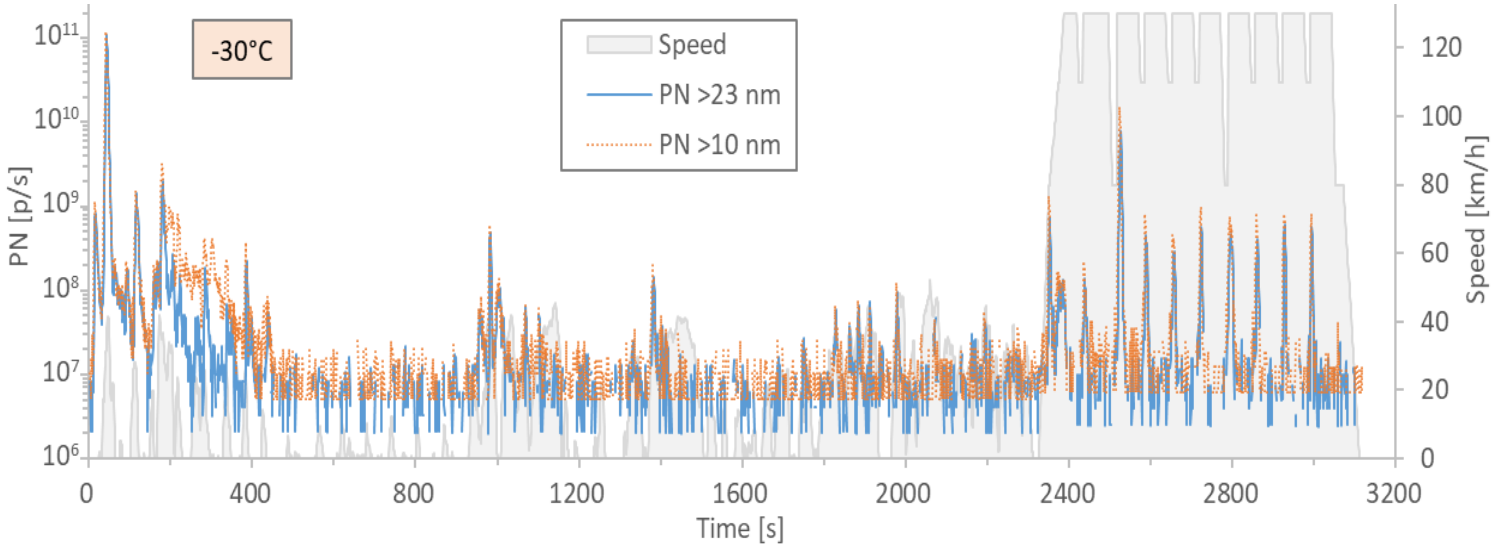
- Excepting cold start, PN levels run at just above 10^7/s for the first ~800s then peaking ~50x higher after ~30 mins of the cycle

- By the end of the cycle, PN peaks exceed 10^{10}/s, likely a combination of higher engine-out PN emissions and elimination of soot from GPF reducing filtration efficiency

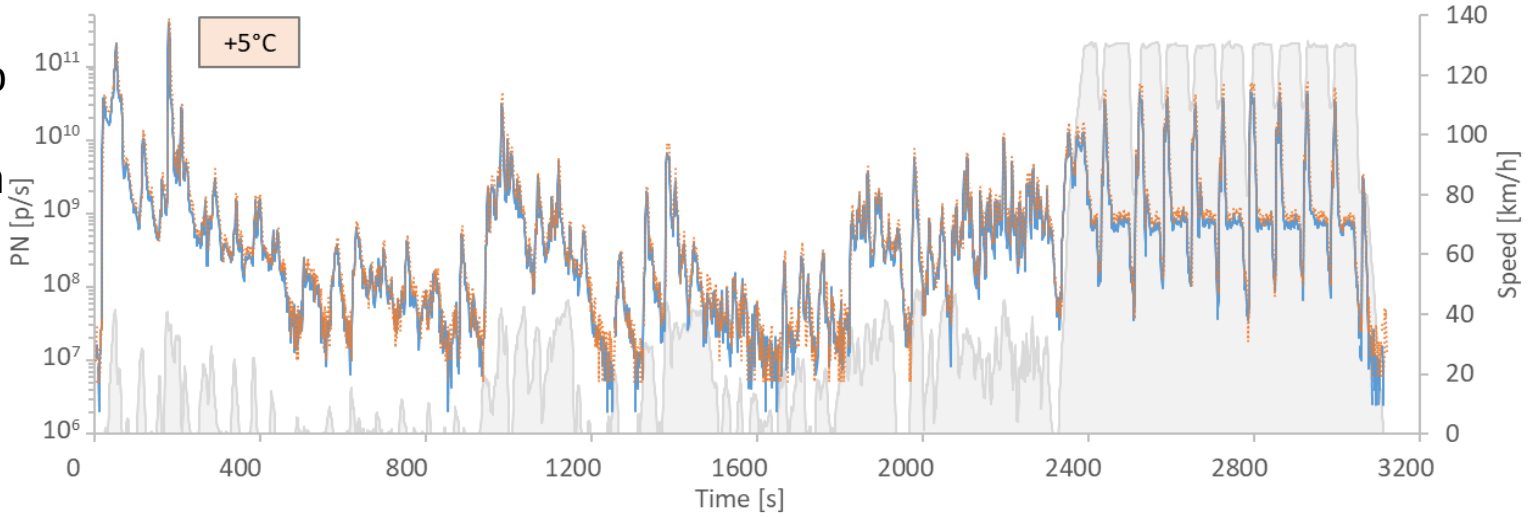


TfL+BAB at 5°C shows substantially elevated PN under both cold and hot start compared to -30°C test

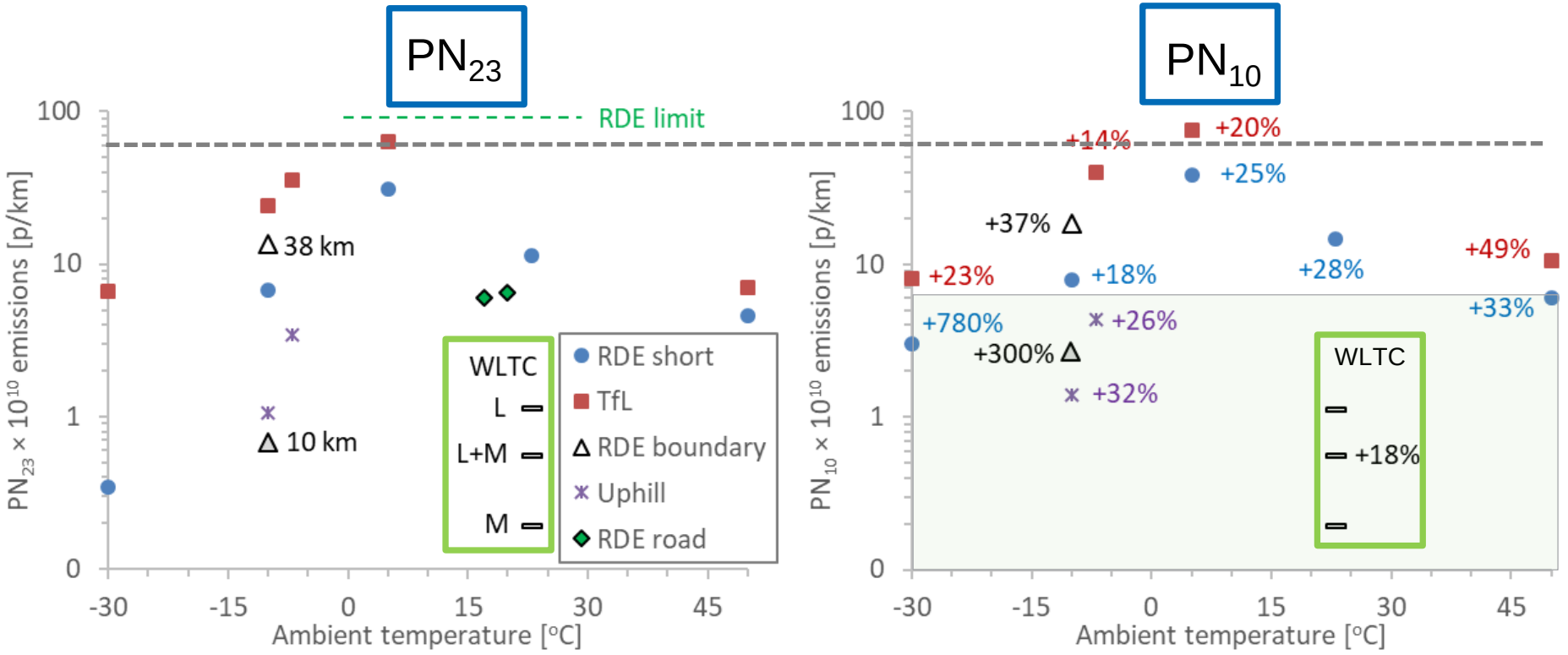
- **-30°C**
- Test starts with some soot loading and high engine-out soot accumulates on GPF
  - Low PN even in (short) BAB



- **5°C**
- Test starts with no soot loading and soot accumulation is minimal
  - High PN throughout

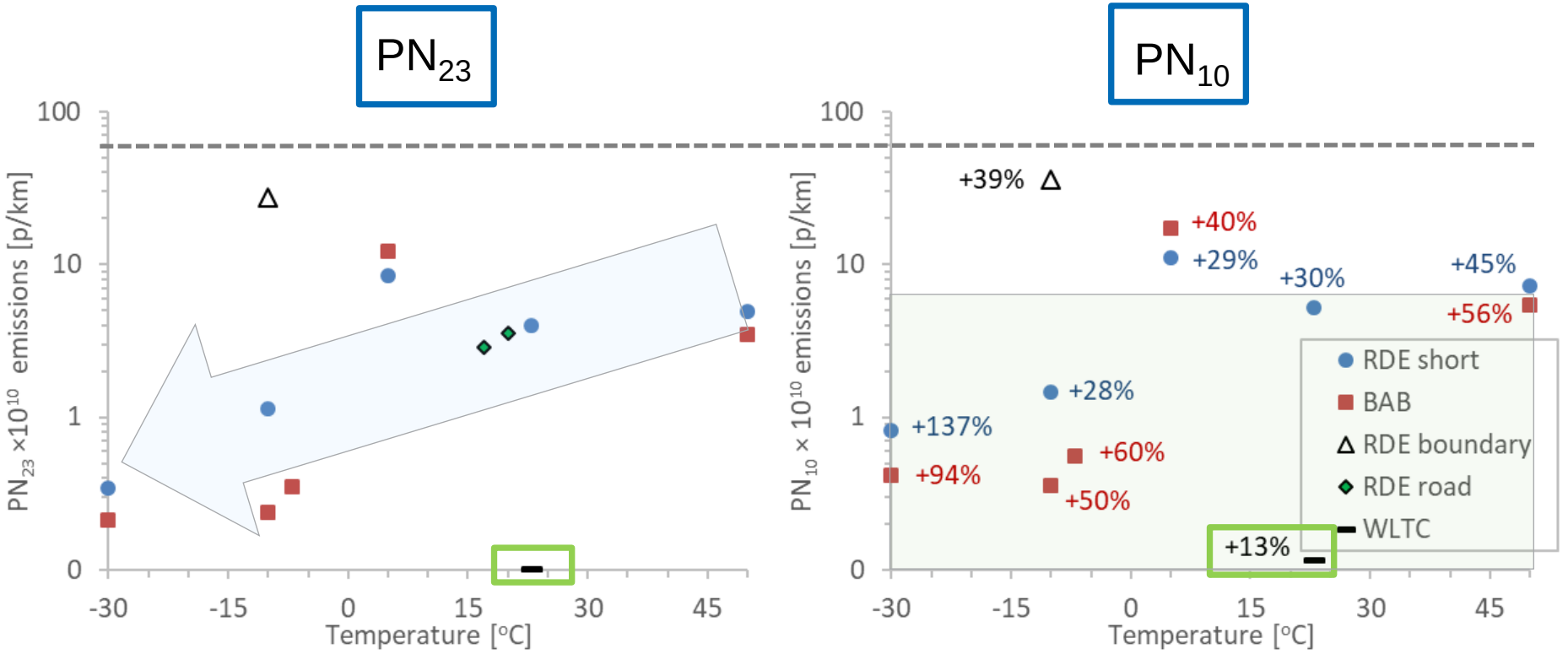


Severe urban TFL results show higher PN emissions compared to other urban cycles but still remain below the RDE PN_{23} limit



- PN_{10} chart shows the increase in PN compared to PN_{23} in % terms
  - Up to 49% increase at PN_{10} for TFL compared to PN_{23}
  - Large percentage increases can be seen in PN10 from other cycles, but only when emissions approach 10^{10} #/km

Motorway BAB results show generally lower PN emissions compared to other cycles, but all are below the RDE PN_{23} limit



- PN_{10} chart shows the increase in PN compared to PN_{23} in % terms
  - Up to 56% increase at PN_{10} for TFL compared to PN_{23} (at >6x10^{10}#/km), some higher percentages below
  - Trend of reducing SPN23/10 emissions from motorway cycles at lower ambient temperatures

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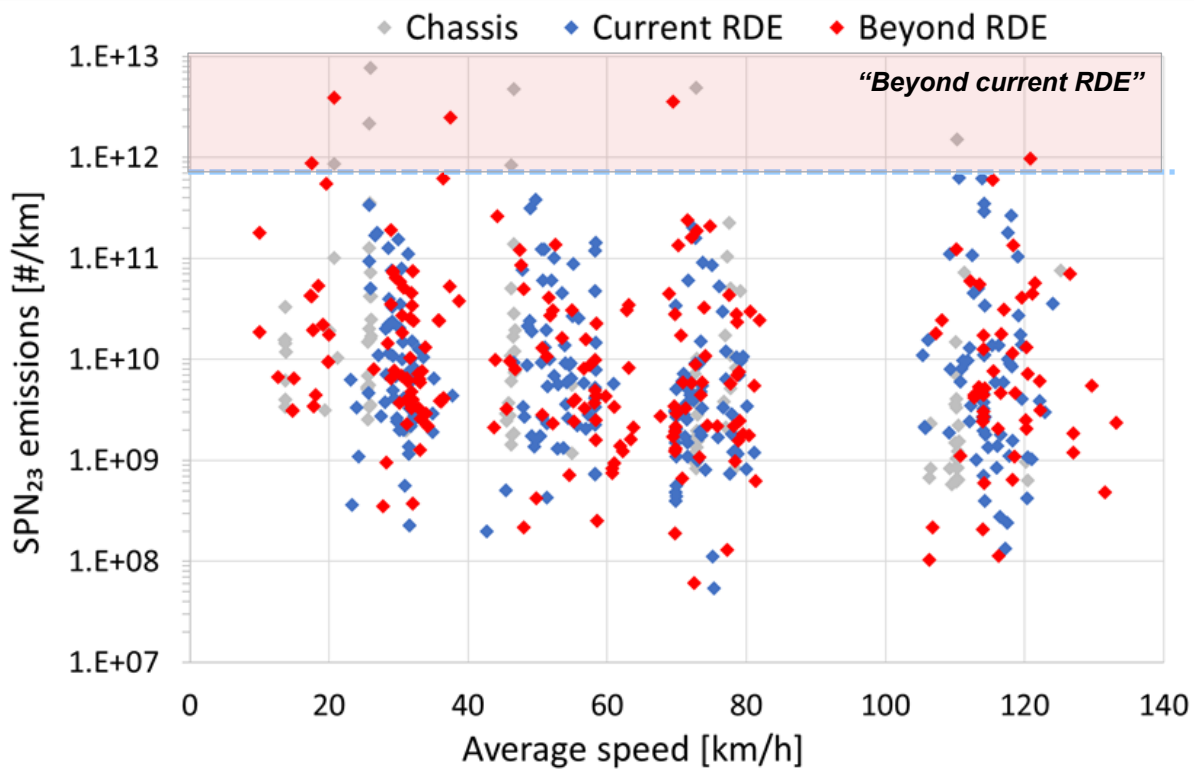
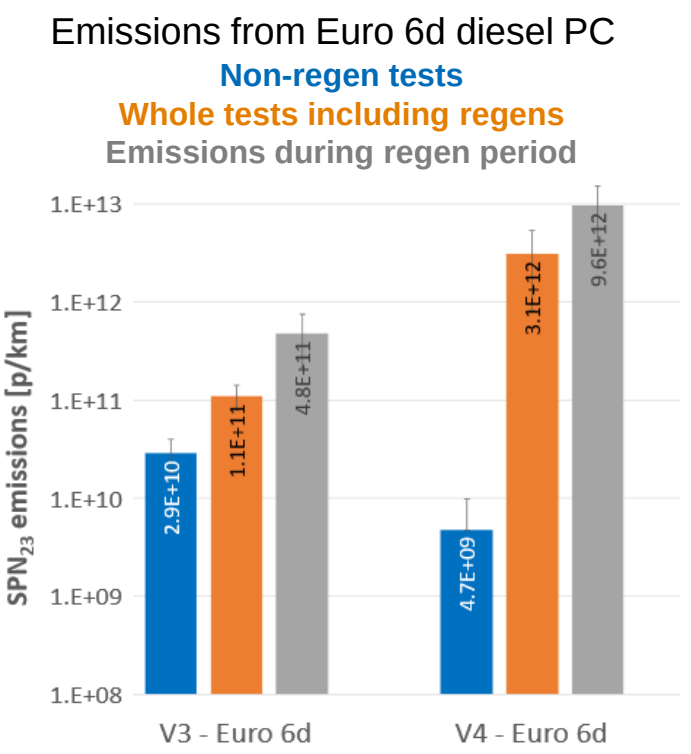
Late Euro 6 diesel PN Emissions





- Non-regenerating PN23 emissions can be below 10^8#/km
- Emissions on tests including DPF regeneration can be > 100x higher than tests without regen, and emissions during DPF regeneration period in isolation can be further 10x higher
- Today these excess emissions are not covered by regulation
- Filtration efficiency of "clean" filters (during and after regen) still an issue in diesel vehicles

Data from the CLOVE database

CLOVE proposals for future PM and PN limits

- CLOVE has submitted proposals to the European Commission for future PM and PN limits
  - These will be considered by the Commission, along with inputs from stakeholders, before final Euro 7 outputs are published (due end of 2021)

	Euro 6	Clove Proposal
PM (mg/km)	4.5	2.0
PN (#/km)	SPN23: $6x10^{11}$	*SPN10: $1x10^{11}$

* Regen included / Some allowances for extreme conditions / very short trips are anticipated

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- Gasoline particle number (PN) emissions were below the Euro 6 PN limit under all driving conditions, confirming the effectiveness of the GPF
- Emissions close to the limit were measured during the two 5°C cycles following the dynamic RDE test
- It was assumed that the GPF passively regenerated during the dynamic RDE cycle. The emissions were then elevated during the subsequent cycles due to the decreased filtration efficiency, highlighting the importance of the vehicle pre-conditioning and showing that soot load can play a part in gasoline PN control
- There was also some evidence that very low temperature operation increased GPF soot loading and had a favorable impact on filtration efficiency
- Relatively elevated emissions were measured during cold start, and cycles including harder accelerations
- At higher emissions levels the sub-23 nm fraction was around 14%-60% depending on the cycle and ambient temperature
- Higher percentages of <23nm PN were measured during the first minutes of cold start and low ambient temperatures, but the absolute emissions levels from these cycle types were at least two orders of magnitude below the current PN limit

Thanks for your attention!

Any questions?

- More information on this study can be found at the following open-access link: https://www.mdpi.com/2073-4344/11/5/607