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Particulate emissions from hybrid electric vehicles using advanced biofuels

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Particulate Matter Filtration Flows in Automotive and Marine Applications

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1. Introduction

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- Despite significant reductions of harmful air pollutant emissions over the past three decades in the EU, around 300 000 deaths per year (compared to up to 1 million per year back in the early 1990s) and a significant number of non-communicable diseases are still attributed to air pollution (and especially related to particulate matter, nitrogen dioxide and ozone).

- The good news is that clean air policies work, and have delivered a significant reduction in the adverse impacts of air pollution during the past three decades.

- In December 2019, in the **European Green Deal**, the European Commission committed to further improve air quality and to aligning EU air quality standards more closely with the recommendations of the World Health Organization (WHO), which were most recently revised in September 2021 and are subject to periodic scientific review, typically every 10 years.

- As a result, the EU sets up the **Zero Pollution Action Plan,** with a vision for 2050 to reduce air (as well as water and soil) pollution to levels no longer considered harmful to health and natural ecosystems, and complemented by 2030 targets to reduce by more than 55% the health impacts (premature deaths) of air pollution, and by 25% the EU ecosystems where air pollution threatens biodiversity. The Commission also announced in the European Green Deal that it would strengthen air quality monitoring, modelling and planning.

Are air quality legislation and policies effective in the control air pollutions in the EU?

The EU looked at the three policy options for 3 scenarios compared to the WHO guidelines.
Policy I-1 aligns with WHO completely. I-2 and I-3 partially aligned.

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Table 2 – Assumption for EU air quality standards for different policy options

	Current EU standards	Current WHO guidelines	Policy option I-1 (2030) *	Policy option I-2 (2030) *	Policy option I-3 (2030) *
$PM_{2.5}$ (annual) [µg/m³]	**25 / 20**	**5**	**5**	**10**	**15**
$PM_{2.5}$ (daily) [µg/m³]	-	(99%) **15**	(99%) **15**	(95%) **25**	(95%) **37.5**
PM_{10} (annual) [µg/m³]	**40**	**15**	**15**	**20**	**30**
PM_{10} (daily) [µg/m³]	(35 days) **50**	(99%) **45**	(99%) **45**	(95%) **45**	(90%) **50**
NO_2 (annual) [µg/m³]	**40**	**10**	**10**	**20**	**30**
NO_2 (daily) [µg/m³]	-	(99%) **25**	(99%) **25**	(95%) **50**	(90%) **50**
NO_2 (hourly) [µg/m³]	(18 hours) **200**	(99.98%) **200**	(99.98%) **200**	(99.98%) **200**	(99.98%) **200**
O_3 (peak-season) [µg/m³]	-	**60**	**60**	**70**	**100**
O_3 (8-hour mean) [µg/m³]	(25 days) **120**	(99%) **100**	(99%) **100**	(95%) **120**	(95%) **120**
SO_2 (annual) [µg/m³]	**20**	**-**	**20**	**20**	**20**
SO_2 (daily) [µg/m³]	(3 days) **125**	(99%) **40**	(99%) **40**	(95%) **50**	(95%) **50**
SO_2 (hourly) [µg/m³]	(24 hours) **350**	-	(99.98%) **350**	(99.98%) **350**	(99.98%) **350**
CO (daily) [mg/m³]	-	(99%) **4**	(99%) **4**	(95%) **4**	(95%) **7**
CO (8-hour) [mg/m³]	**10**	**10**	**10**	**10**	**10**

(European Commission Brussels, 26.10.2022 COM(2022) 545 final)

Benefits of different air quality policies

Table 3 – Direct benefits of policy options, relative to the baseline – per year in million Euro (2015)

			2030				2050		
Policy Option / Scenario			**($PM_{2.5}$ at 20 µg/m^3)**	**I-3 ($PM_{2.5}$ at 15 µg/m^3)**	**I-2 ($PM_{2.5}$ at 10 µg/m^3)**	**I-1 ($PM_{2.5}$ at 5 µg/m^3)**	**I-3a ($PM_{2.5}$ at 15 µg/m^3)**	**I-2a ($PM_{2.5}$ at 10 µg/m^3)**	**I-1a ($PM_{2.5}$ at 5 µg/m^3)**
Human health benefits	Mortality (VOLY)		9 505	25 182	32 394	34 734	2 897	16 287	16 935
	Mortality (VSL)		33 486	85 697	110 517	118 764	11 097	63 194	65 804
	Morbidity		2 343	6 141	7 992	8 610	529	3 121	3 310
Environmental benefits	Material		29	181	196	204	12	156	160
	Crops		67	188	254	276	44	259	258
	Forests	Low	69	222	287	316	52	292	293
		High	69	222	287	316	127	712	716
	Ecosystems	Low	101	448	706	863	83	790	931
		High	302	1 345	2 117	2 588	250	2 370	2 794
TOTAL gross benefits	Low (based on VOLY)		12 114	32 362	41 829	45 003	3 617	20 905	21 887
	High (based on VSL)		36 296	93 774	121 363	130 758	12 059	69 812	73 042

[1] VOLY (value of a life year) represents an estimate of damage costs based on the potential years of life lost, which takes into account the age at which deaths occur (i.e. higher weighting for younger people).

[2] VSL (value of statistical life) represents an estimate of damage costs based on how much people are willing to pay for a reduction in their risk of dying from adverse health conditions.

(European Commission Brussels, 26.10.2022 COM(2022) 545 final)

Transport emissions

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Road transport is a major contributor to air pollution, in particular in cities. Although air pollution from transport has decreased in the past few years following the introduction of Real Driving Emissions (RDE) tests and due to the shift to electric vehicles and the use of other clean technologies, too many people are still exposed to excessive air pollution.

- 96% of people in EU towns and cities were exposed to centration's of fine particles above WHO guidelines in 2020.
- Expose to $PM_{2.5}$ caused the premature death of at least 238,000 people in the EU

(https://www.europarl.europa.eu/topics/en/article/20230822STO04226/air-pollution-what-are-the-effects-and-eu-actions-to-reduce-it, accessed 13/12/2024)

Transport emissions

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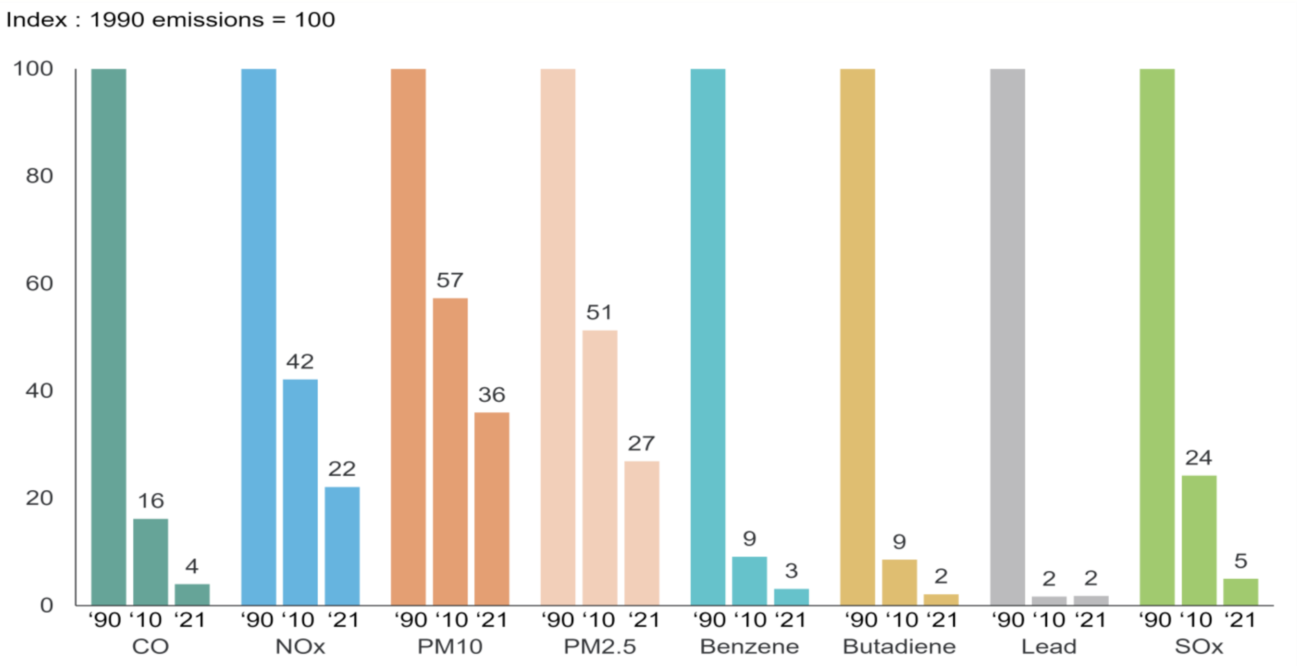
In 2021, transport contributed a substantial portion of air pollutants to the UK's domestic total:

- 32% of nitrogen oxides
- 14% of PM2.5 emissions
- 12% of PM10 emissions

(https://www.gov.uk/government/statistics/transport-and-environment-statistics-2023/transport-and-environment-statistics-2023)

Emissions from transport in 2021, compared to their levels in 2010 and 1990.



NOx have reduced 88%, $PM_{2.5}$ has reduced 73%.

2. EU vehicle exhaust emission standards

EU emission standards for positive ignition (gasoline) passenger cars

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Stage	Date	CO	HC	HC+NOx	NOx	PM	PN[a]
		g/km					*#/km*
Positive Ignition (Gasoline)							
Euro 1	1992.07	2.72	-	0.97	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	
Euro 3	2000.01	2.30	0.20	-	0.15	-	
Euro 4	2005.01	1.0	0.10	-	0.08	-	
Euro 5	2009.09	1.0	0.10	-	0.06	0.005	-
Euro 6	2014.09	1.0	0.10	-	0.06	0.005	6.0×10^{11} [b]
Euro 7	2026.11.29	1.0	0.10	-	0.06	0.0045	6.0×10^{11}

Only apply to GDI engines

a. Euro 5-6: particles > 23 nm; Euro 7: particles > 10 nm
b. DI (direct injection) engines only

https://dieselnet.com/standards/eu/ld.php#stds

EU emission standards for compression ignition (diesel) passenger cars

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Stage	Date	CO	HC	HC+NOx	NOx	PM	PN[a]
		g/km					#/km
Compression Ignition (Diesel)							
Euro 1	1992.07	2.72	-	0.97	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09	0.50	-	0.23	0.18	0.005	-
Euro 5b	2011.09	0.50	-	0.23	0.18	0.005	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005	6.0×10^{11}
Euro 7	2026.11.29	0.50	-	0.17	0.08	0.0045	6.0×10^{11}

a. Euro 5-6: particles > 23 nm (PN23); Euro 7: particles > 10) nm (PN10)

https://dieselnet.com/standards/eu/ld.php#stds

- Same limits and test condition for PN for passenger cars.
- PN and PM will apply not only DI-PI but also all PI vehicles, i.e. including PFI vehicles.

New in Euro 7 emission standard

What's new in the Euro 7 regulation?

For all cars, vans, trucks and buses

- Limits for emissions from brakes
- Rules on microplastic pollution from tyres
- Vehicles need to comply with emissions rules for longer period
- More effective emissions tests
- Digital monitoring of compliance
- Better market surveillance tests

For internal combustion engine vehicles

- Fuel- and technology-neutral emission limits
- Regulating additional pollutants
- On-road tests with broader range of driving conditions

For electric and plugin hybrid vehicles

- Battery durability requirements

https://single-market-economy.ec.europa.eu/system/files/2022-11/Euro%207%20factsheet.pdf

New in Euro 7 emission standard

What will be the impact of the Euro 7 rules?

The new rules will apply to both cars and vans but also heavier vehicles, such as lorries and buses. They remain relevant even with the 100% target for zero emission cars and vans in 2035, as more than 20% of cars and vans and more than 50% of the heavier vehicles on our streets are expected to emit pollutants from the tailpipe up to 2050. Moreover, the new rules on emissions from brakes, tyres and for batteries durability will be relevant for electric vehicles as well.

Lower emissions by 2035 compared to Euro6/VI

Reduction of NOx emissions

- **35%** from cars and vans
- **56%** from buses and lorries

Reduction of particles from the tailpipe

- **13%** from cars and vans
- **39%** from buses and lorries

Reduction of particles from the brakes

- **27%** from the brakes of a car and vans

Low impact on consumers

These emission reductions are expected to be achieved with existing technologies. A moderate impact on the costs of cars - between €90 and €150 - and on the cost of buses and lorries - around €2600 - is expected.

Big benefit for health and environment

For each euro spent on technologies for Euro 7, more than 5 euros are saved on health and environment.

https://single-market-economy.ec.europa.eu/system/files/2022-11/Euro%207%20factsheet.pdf

3. Real Driving Emissions (RDE) from hybrid vehicles using advanced biofuels -

3.1 Background of the project

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In the UK, at the end of June 2024, 40.3% of all vehicles were diesel ICE vehicles, and 0.3% were diesel hybrids.

At the end of 2023, around 80% of all licensed vehicles in the UK were more than 3 years old.

Compatible low-carbon alternatives are needed to replace the diesel used across the transport sector.

Air quality also needs to improve globally, so alternative fuels should produce lower air pollutant emissions than existing fuels.

Advanced biofuels produced from non-food cellulosic and lignocellulosic feedstocks are mandated to be used in the transport sector as part of the EU Renewable Energy Directive (RED II & RED III).

One such production process could be acid catalysed alcoholysis of lignocellulosic biomass.

3.2 Vehicles and Portable Emissions Measurement System (PEMS)

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- A Horiba OBS-ONE portable emissions measurement system (PEMS) was installed with a gas analyser unit (NOx, NO_2, CO, CO_2) and a particle number (PN)(23-1000nm) unit.
- A C-tube was used on the C300h and a B-tube was used on the Yaris.
- Gasmet Fourier Transform Infrared (FTIR), sampling from a sampling probe at the tailpipe.
- Temperature logging across the exhaust using k-type thermocouples.
- Electronic Control Unit (ECU) parameters were logged using the OBD (on-board diagnostics) port using an Influx Rebel LT logger in the C300h and a HEM Logger in the Prius.

Mercedes C300h with OBS-ONE and C-tube installed

Toyota Prius with OBS-ONE PEMS installed

3.3 RDE driving route

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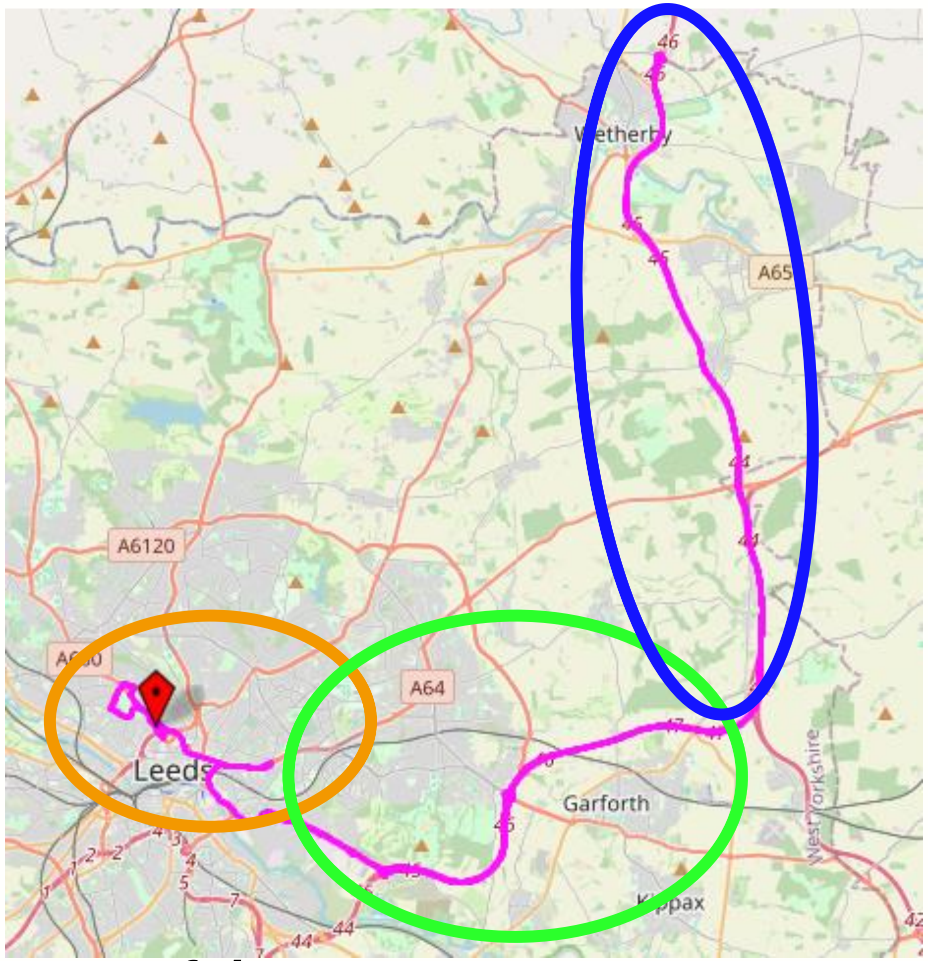
- A RDE (real driving emissions) route around Leeds was designed and developed to comply with the RDE requirements.
- Total journey length: 97.2 km.

Urban Section Ratio (%)	Rural Section Ratio (%)	Motorway Section Ratio (%)
32.7 – 34.2	32.3 – 33.3	32.5 – 35.0%

- 3 cold start RDE tests were conducted with each fuel to allow for any difference between test runs, such as congestion and ambient conditions.
- Data was processed using RDE package 3 for CO_2 moving average window and package 4 for other emissions.
- All data is normalised relative to the diesel tests.



Map of the RDE test route

3.4 Results

Transient Particle Number (PN) and NOx emissions for diesel in a RDE test

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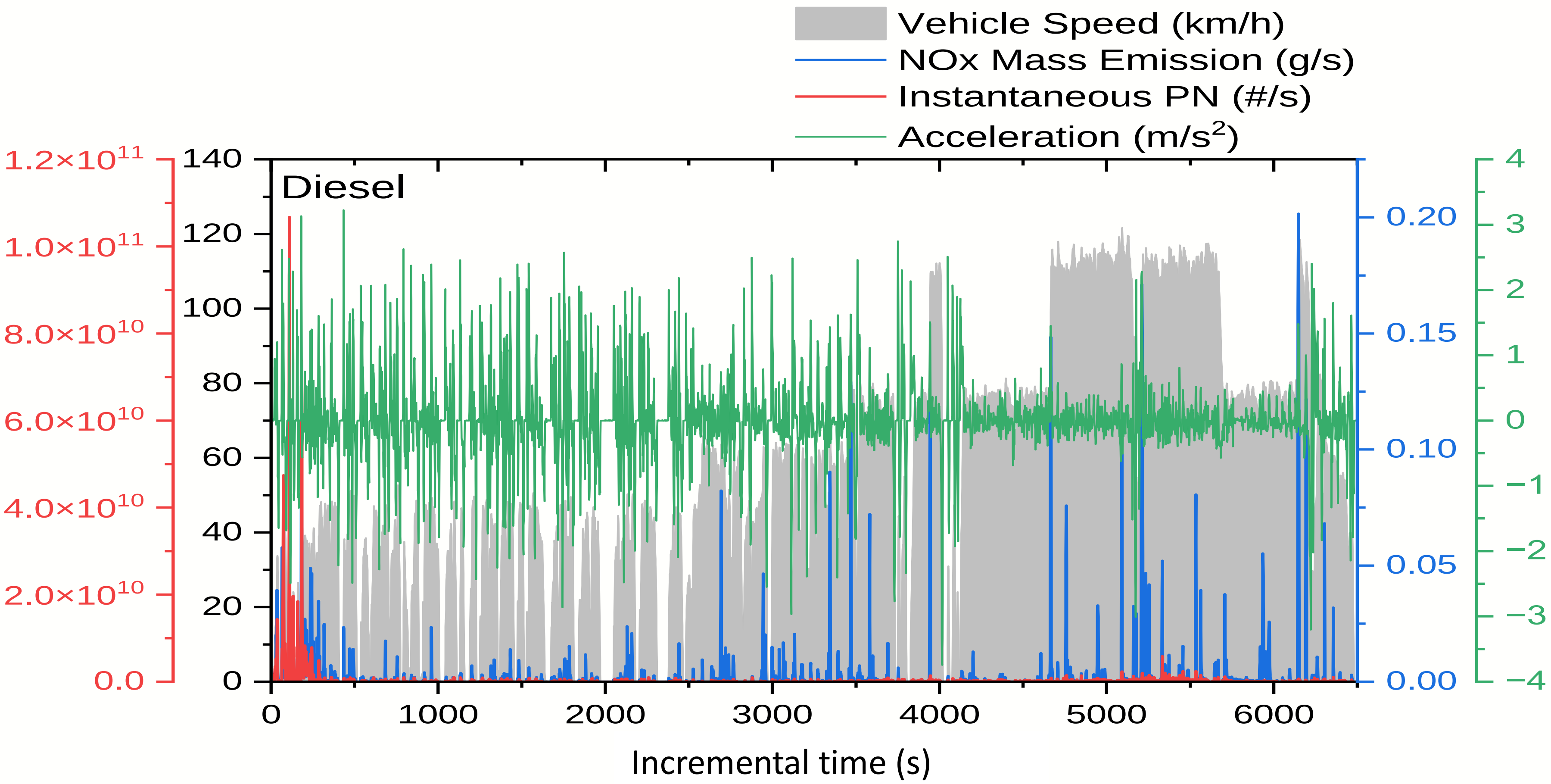
- PN emission peaks mainly occurred during cold start

- NOx emission spikes occurred at high power and acceleration events.



PN and NOx Transient Emissions Vs Vehicle speed and accelerations for diesel

Transient Particle Number (PN) and NOx emissions for a biofuel blend in a RDE test

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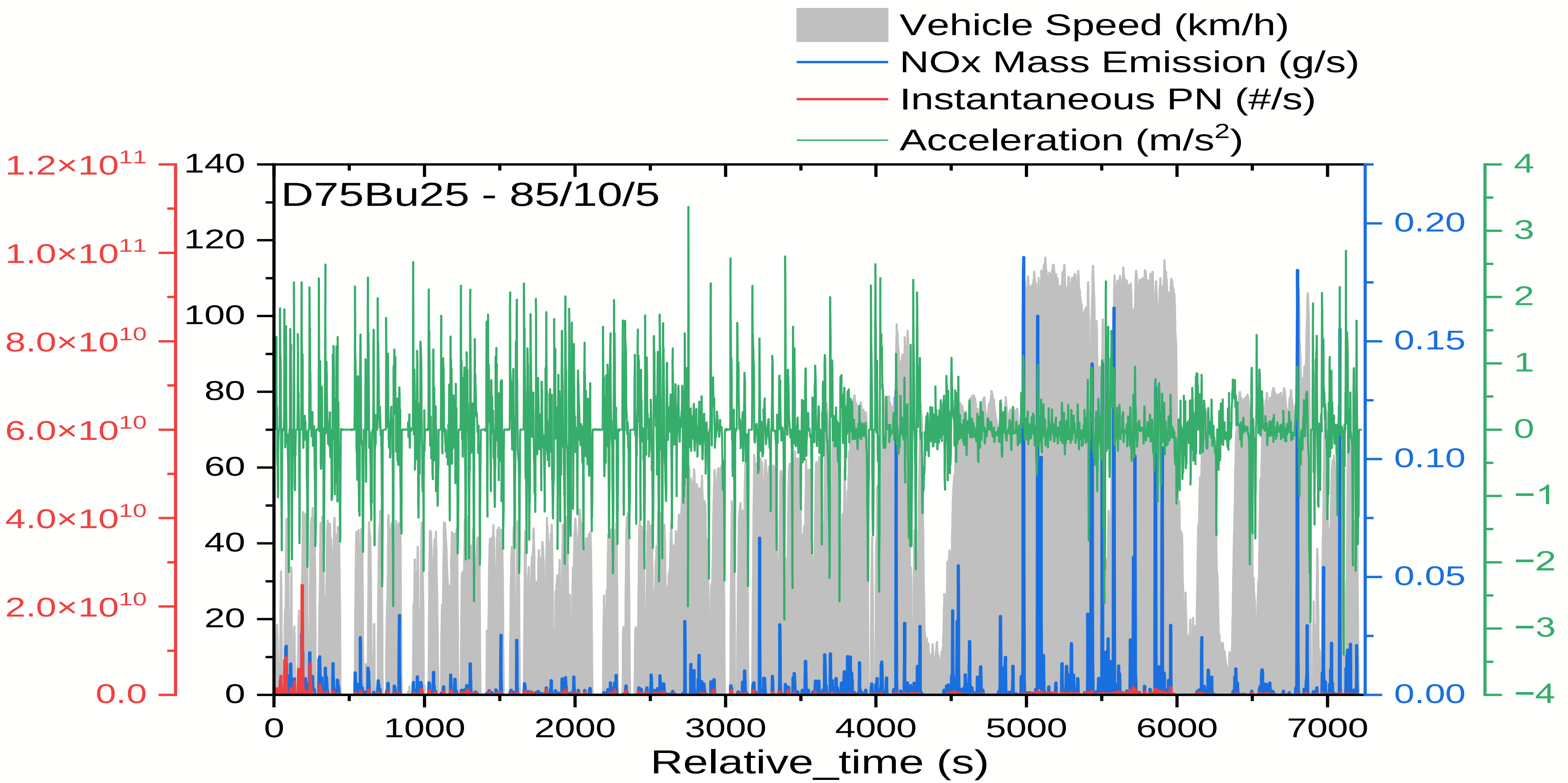
- PN emission peaks during cold start are much lower than that of diesel.
- NOx emission spikes are greater than diesel.



PN and NOx Transient Emissions Vs Vehicle speed and accelerations for a biofuel blend

Transient and cumulative PN emissions for three diesel RDE tests

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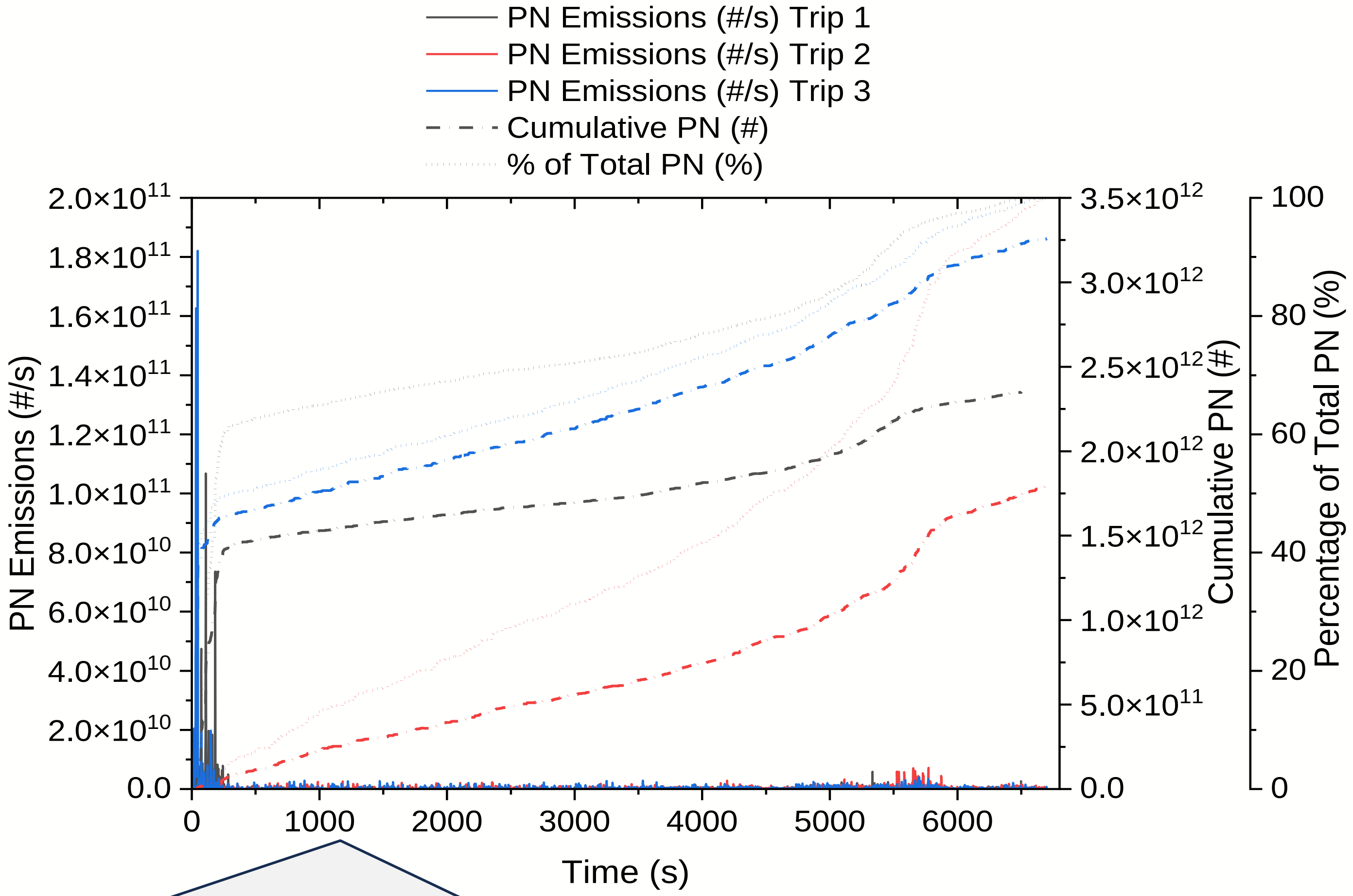
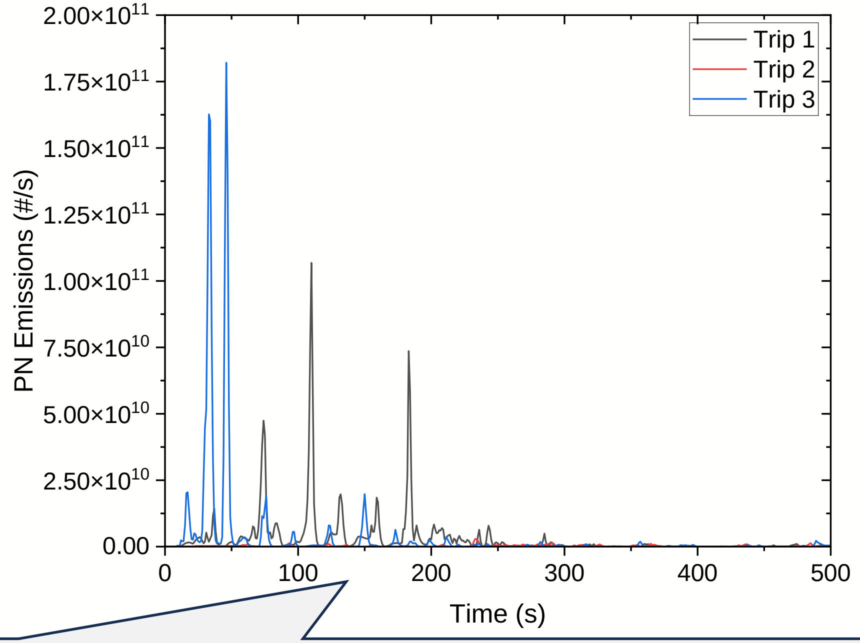


Transient and cumulative PN emissions for three diesel RDE tests

- PN emissions from the cold start phase, particularly the 1st 200 seconds, could reach 60% of the total trip PN but may have exceptions (e.g. trip 2, red line where no cold start peak was observed).
- The trip total PN can vary significantly between trips (doubled between trips 2 and 3).



Transient PN emissions during the 1st 500 s for three diesel RDE tests

Transient and cumulative PN emissions for biofuel blend (Bu25) RDE tests

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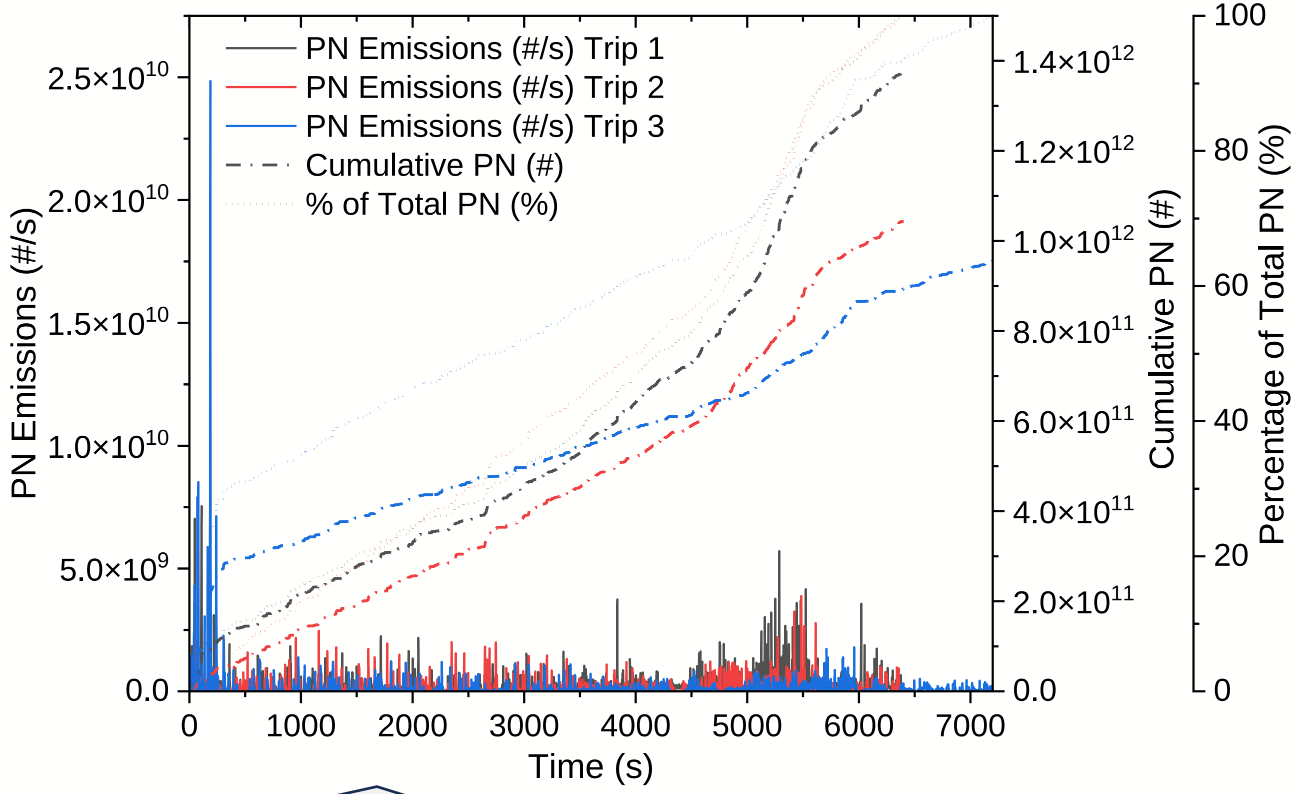
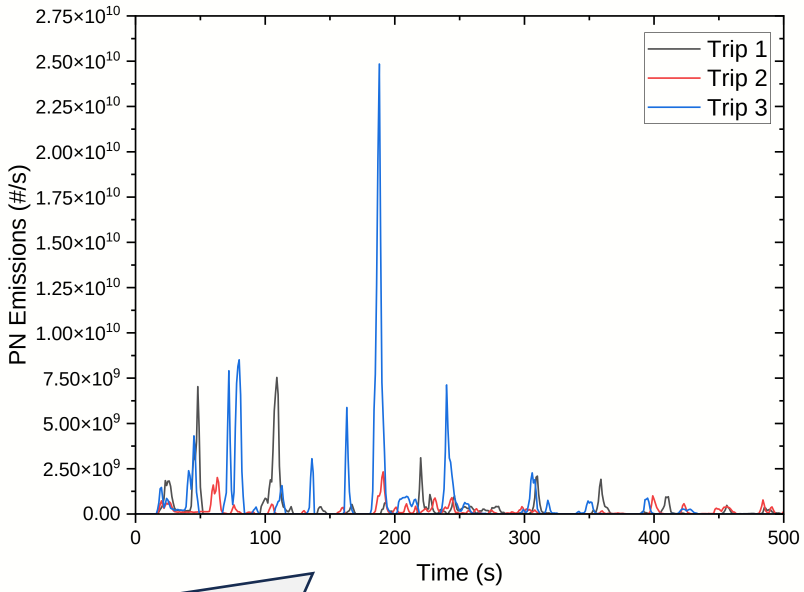


Transient and cumulative PN emissions for biofuel blend (Bu25) RDE tests

- With a biofuel blend, PN emissions from the cold start phase had much a lower peak (30% of the total for trip 3) and no obvious peaks for trips 1 and 2, which could be due to lower engine PN emissions from the biofuel blend.
- PN peaks could happen at the later stage of the trips (Motorway part) due to harsh accelerations.



Transient PN emissions during the 1st 500 s for Bu25 RDE tests

Influence of the biofuel blends on PN Emission Factors, EF(PN)

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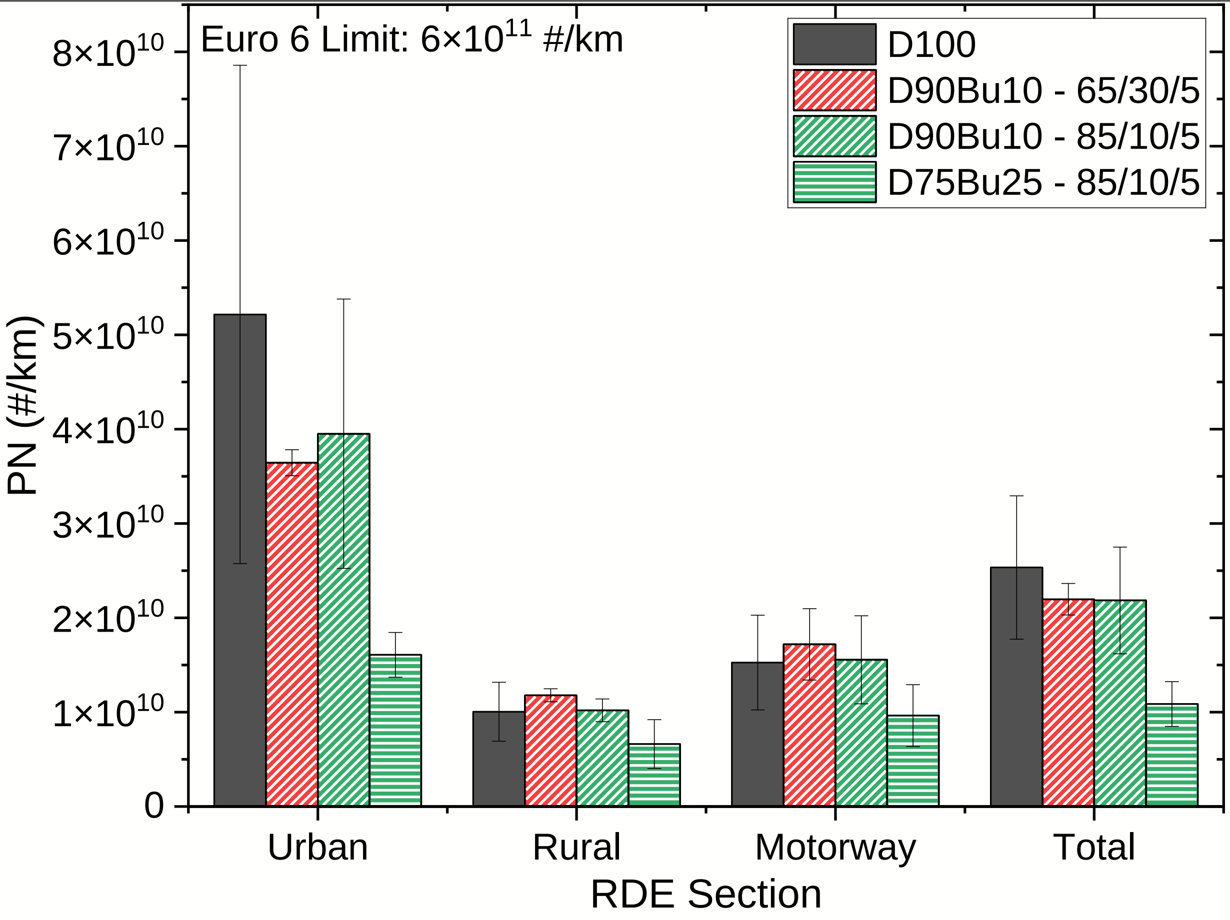
- PN emissions were well below the Euro 6 limit with all fuels.
- The Bu10 blends increased PN relative to D100.
- The Bu25 blend reduced the PN emissions, even with the DPF. The reductions in the urban phase and total emission factor were statistically significant.
- In the diesel generator set (genset), every blend tested had reductions >50% in total PN and reductions in the elemental carbon content of the captured $PM_{2.5}$ of 20% - 50% at maximum load.



PN emission factor, EF(PN), from RDE tests using different fuels from diesel HEV C300h

PN Emission Factors from biofuel blends normalized to diesel

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- PN emissions were well below the Euro 6 limit with all fuels.
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- The Bu25 blend reduced the PN emissions, even with the DPF. The reductions in the urban phase and total emission factor were statistically significant.
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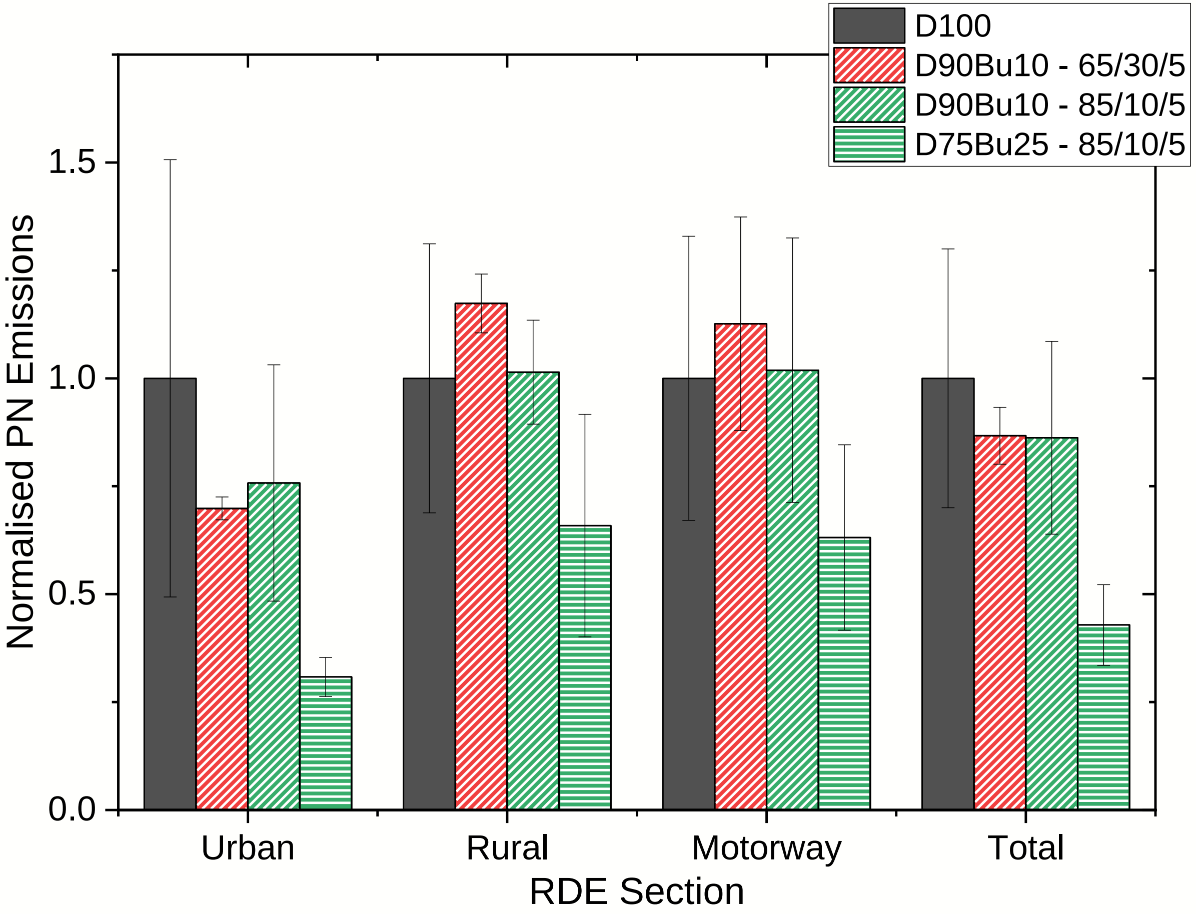
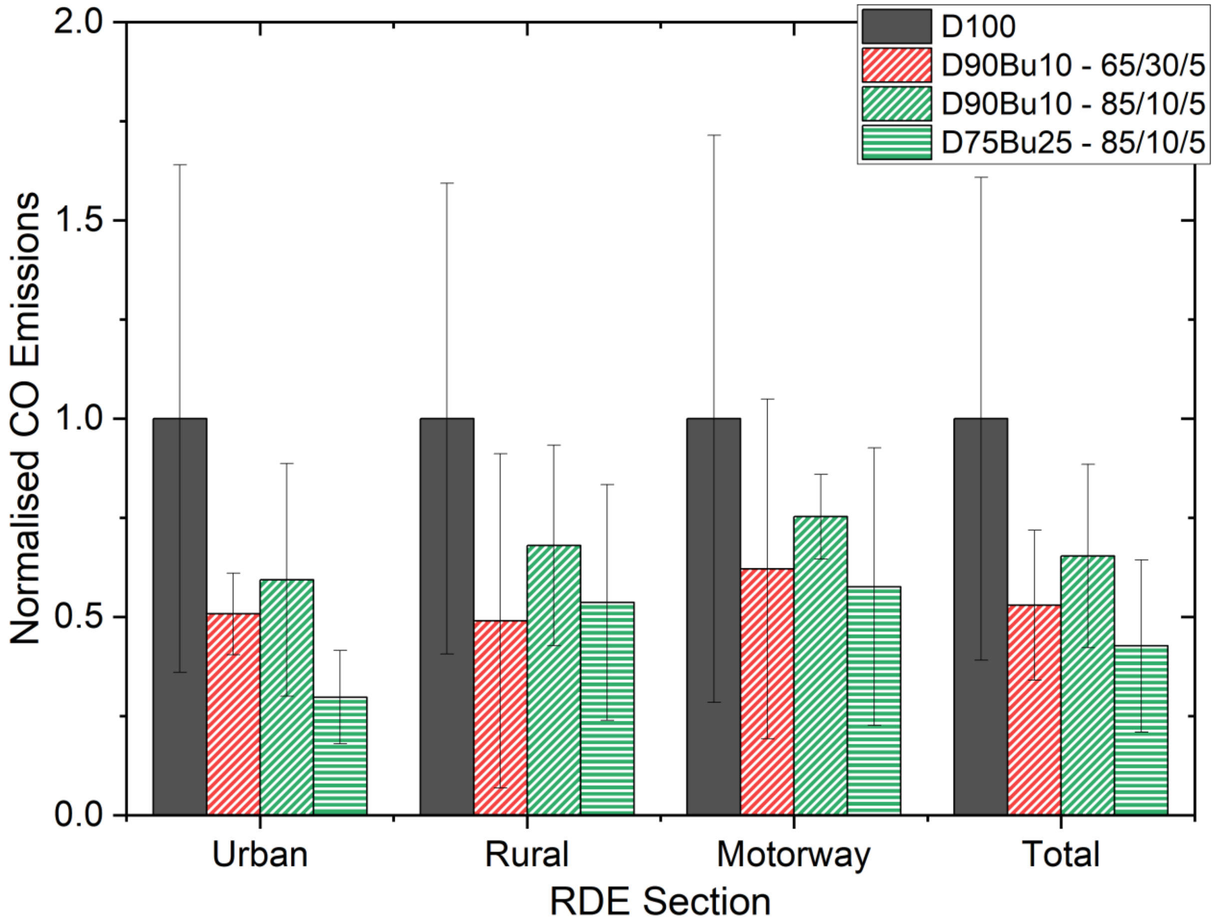


PN emission factor, EF(PN), from C300h Normalised Relative to Diesel

Influence of the biofuel blends on CO emissions

- There is an overall trend of reductions in CO emissions with increasing biofuel and *n*BL fractions.
- However, the reductions were less significant statistically due to large variabilities in CO emissions from D100, reflecting uncertainty of RDE (more repeats are needed).
- Oxygen content in the biofuel components helped oxidation of hydrocarbons, leading to lower CO emissions.



CO emission factor, EF(CO), from C300h Normalised Relative to Diesel

Influence of the biofuel blends on NO_X emissions

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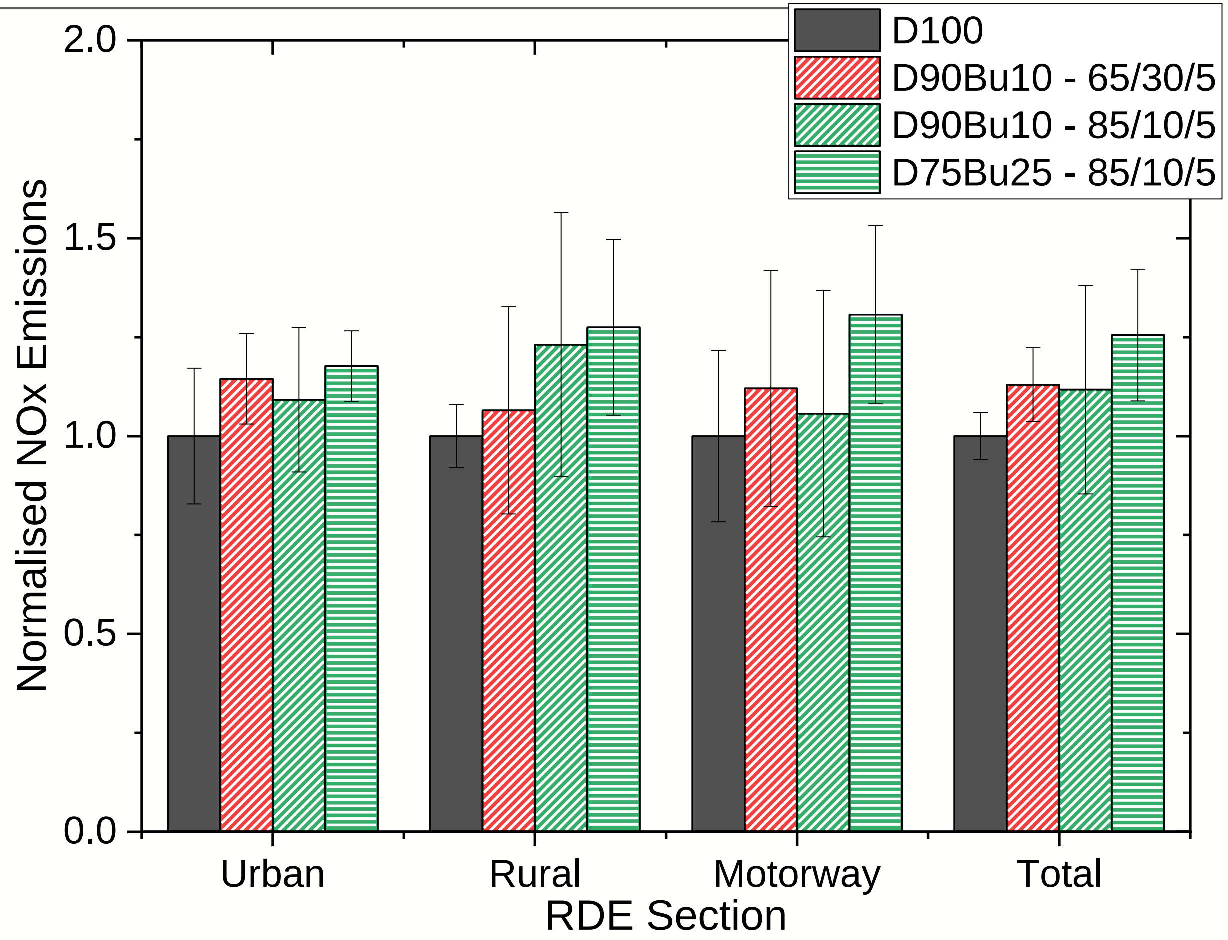
- Increased tailpipe NO_X emissions from biofuel blends were observed.
- The increases in the rural, motorway, and total emissions factor for the Bu25 blend were statistically significant.
- Engine-out NO_X emissions increased with the increasing biofuel and *n*BL fractions.
- It is likely that the engine-out NO_X concentration from the Bu25 blend was too high for the SCR to have the same level of reduction compared to D100.



NO_X emission factor, EF(Nox), from C300h Normalised Relative to Diesel

Influence of the biofuel blends on NO_X removal efficiency

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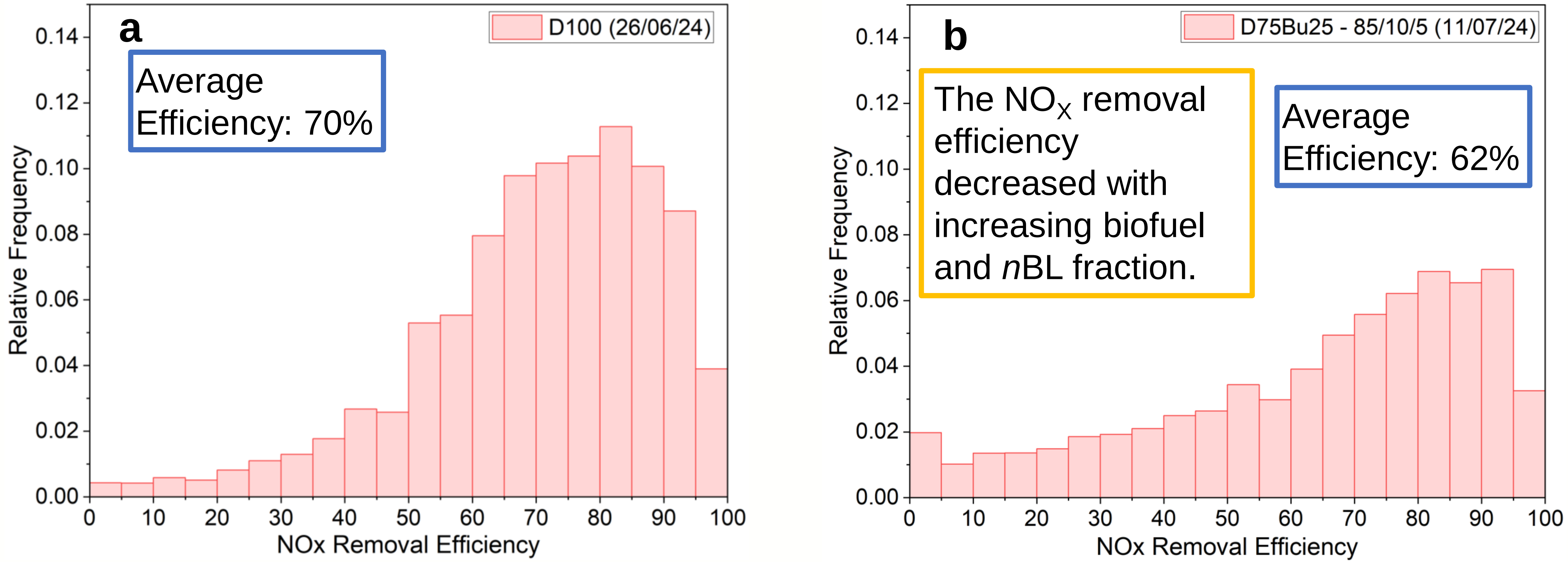

Relative frequency distributions of NO_X removal efficiency during an RDE for a – D100 and b – D75Bu25 – 85/10/5.

PN size distribution during cold start vs warm start for SI hybrid electric vehicle

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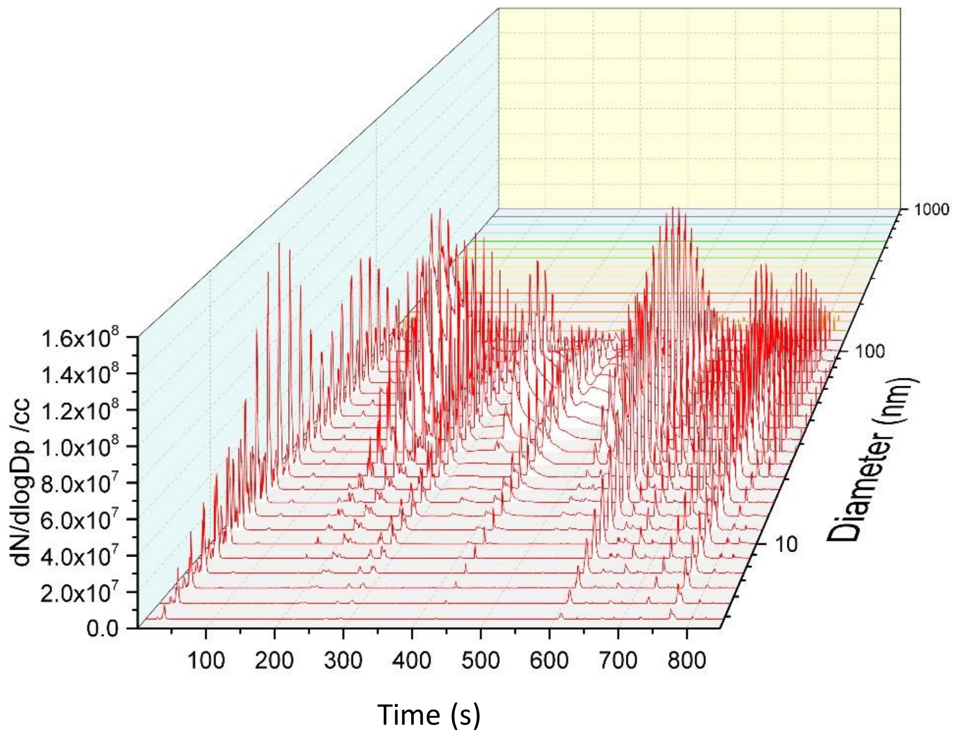
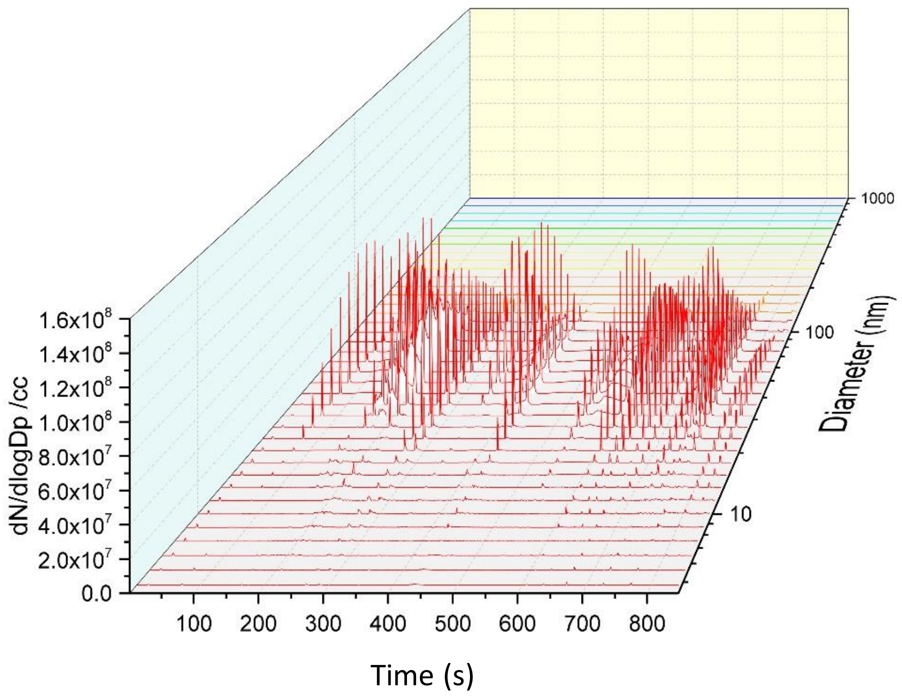
The SI HEV was tested on a chassis dynamometer using the WLTC test cycle. A DMS500 particle size analyser was used to measure particle number size distribution.

The PN distributions were peaked between 40-80nm, with the tail-off from the peaks not going above 200nm diameters for either test. We see a second peak at smaller diameters on initial cold start engine start.



Cold Start WLTC test



Warm Start WLTC test

PN Size Distribution During Cold Start vs Warm Start for SI hybrid electric vehicle

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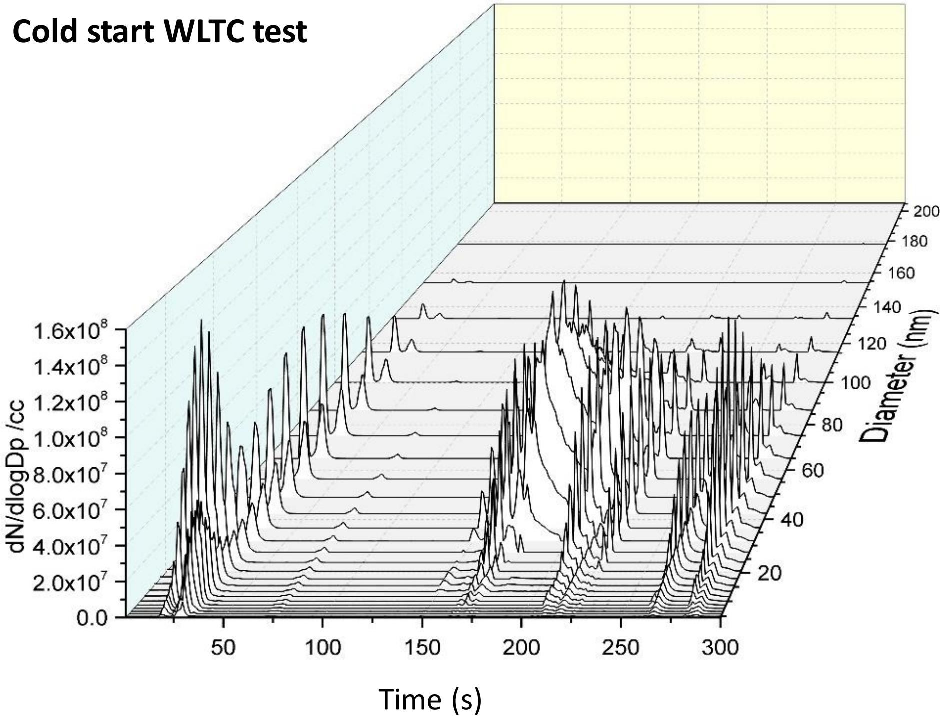
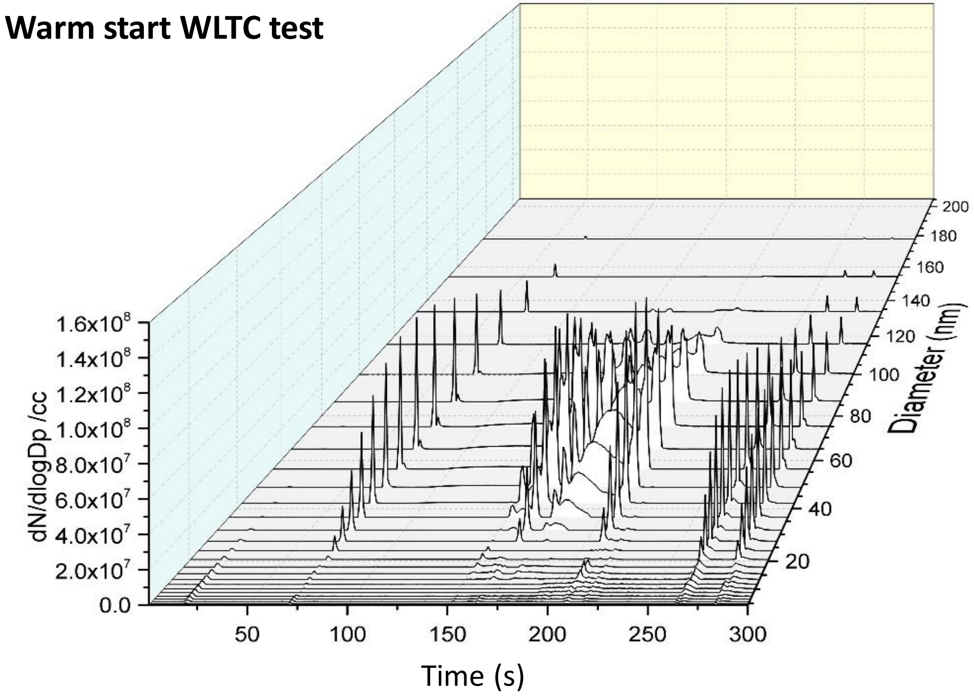
We see a bimodal or multimodal distribution in the initial cold start engine-on event (nucleation mode peaking around 20nm D_p), not in subsequent starts or any warm start test starts. The PN seen in later engine starts only peaks at the larger diameter.

- ➢ Indicates the initial spike is likely a result of bad air/fuel mixing caused by poor vaporisation of fuel in cold combustion chamber leading to fuel enrichment and PN increases
- ➢ This never occurs to the same degree once the engine heats up - HEVs ***aren't*** releasing the more damaging nucleation mode particles on each engine restart.

Cold start WLTC test



Warm start WLTC test



4. Conclusions

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- PN emission peaks mainly occurred during cold start, which could reach 60% of the trip total PN (diesel).
- Biofuel blend can effectively reduce cold start PN spikes due to reduced engine out PN emissions. The share of cold start PN could be reduced to 30% or lower of the trip total PN.
- There were some small PN spikes after the engine was hot which is linked with harsh accelerations.
- PN emission factors for all the fuels, including diesel, were well below the Euro 6 and 7 emission standards ($6x10^{11}$ #/km) .
- Biofuel blend reduced urban phase PN emissions (CO emissions too) significantly but there were some minor increases in NOx emissions.
- It is likely that the engine-out NO_X concentrations from the Bu25 blend were too high for the SCR to have the same level of reduction compared to D100.
- PN size distribution data show that particle emission peaks from a SI HEV were between 40-80nm, tail-off from the peaks not greater than 200nm diameters.

5. Future work

Co-optimisation of deNOx catalytic converters and fuels (2024-2026)(STFC)

Aim:
To develop co-optimised low temperature deNOx catalyst (LowCat) based exhaust aftertreatment systems with various fuels including low and zero carbon fuels, and widen the applications of LowCat to cover off-road and marine propulsions.

Objectives:

a) Market research into future fuel strategies for engines and emissions

b) Investigation of impacts of current and low/zero carbon fuels on the performance of LowCat based exhaust aftertreatment systems.

c) Optimisation of configuration of LowCat based exhaust aftertreatment systems.

d) Establish a low/zero carbon fuels and emission testing and innovation centre.

e) Develop a design tool for LowCat based exhaust aftertreatment systems.

6. Acknowledgement

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- UKRI EPSRC for funding the research through grant EP/T033088/1
- Horiba UK for their support and loan of the OBS-ONE during the testing programme
- Kevin Tully for his support, training, and providing the OBS-ONE
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- Horiba MIRA for conducting the WLTC on the C300h
- SusLABB Project Group