PN Concentration and Size Distribution Measurements from CNG and Diesel HGVs

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Introduction

- Compressed Natural Gas (CNG) engines are used worldwide as an alternative to diesel engines in the heavy-duty sector.
- CNG vehicles are often reported to emit less PN than diesel engines [1] due to lower soot particle formation levels during methane combustion.
- However, the PN emissions from modern CNG vehicles are often higher than diesel counterparts the action of the diesel particulate filter [2].
- PN size distribution (PNSD) studies (e.g. [3]) indicate more small particles emitted from CNG vehicles, due to lube oil burn [4] and catalytic action [5].
- Until Euro VI regs, CNG engines had no PN limit. From Euro VI, CNG vehicles have $6x10^{11}$ #/km limit on solid particles >23 nm diameter [6].

[1] Kontses, A., Triantafyllopoulos, G., Ntziachristos, L., Samaras, Z., 2020. Particle number (PN) emissions from gasoline, diesel, LPG, CNG and hybrid-electric light-duty vehicles under real-world driving conditions. Atmospheric Environment 222, 117126. https://doi.org/10.1016/j.atmosenv.2019.117126.
[2] Giechaskiel, B., 2018. Solid Particle Number Emission Factors of Euro VI Heavy-Duty Vehicles on the Road and in the Laboratory. International Journal of Environmental Research and Public Health 15, 304. https://doi.org/10.3390/ijerph15020304.
[3] Lähde, T., Giechaskiel, B., 2021. Particle Number Emissions of Gasoline, Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG) Fueled Vehicles at Different Ambient Temperatures. Atmosphere 12, 893. https://doi.org/10.3390/atmos12070893.
[4] Lähde, T., Giechaskiel, B., Martini, G., Howard, K., Jones, J., Ubhi, S., 2022. Effect of lubricating oil characteristics on solid particle number and CO2 emissions of a Euro 6 light-duty compressed natural gas fuelled vehicle. Fuel 324, 124763. https://doi.org/10.1016/j.fuel.2022.124763.
[5] Lehtoranta, K., Murtonen, T., Vesala, H., Koponen, P., Alanen, J., Simonen, P., et al., 2017. Natural Gas Engine Emission Reduction by Catalysts. Emiss. Control Sci. Technol. 3, 142–152. https://doi.org/10.1007/s40825-016-0057-8.
[6] European Commission. Commission Regulation (EU) No 133/2014 of 31 January 2014. Off. J. Eur. Union 2014, L47, 1–57.

Test Program Vehicles and Fuels

- PN, PNSD and gaseous pollutant emissions were investigated on a CNG truck and a Diesel truck at Transportes Iceberg in Colombia.

	CNG Truck	Diesel Truck
Vehicle	Shacman X5000	Shacman X5000
Model Year	2023	2023
Emissions Standard	Euro 6	Euro 6
Fuel Type	CNG	Diesel
Engine	Cummins X15N: 500 hp, 14.5 L turbo charged engine	Cummins ISZ: 460 hp, 13 L turbo charged engine
Aftertreatment	Catalytic converter only (no particulate filter)	EGR, DPF and SCR
OBD/ECU?	OBDII connector was available, but did not power/connect to the ECU reader - *Mass emissions could not be calculated*	OBDII connector was available, but did not power/connect to the ECU reader - *Mass emissions could not be calculated*

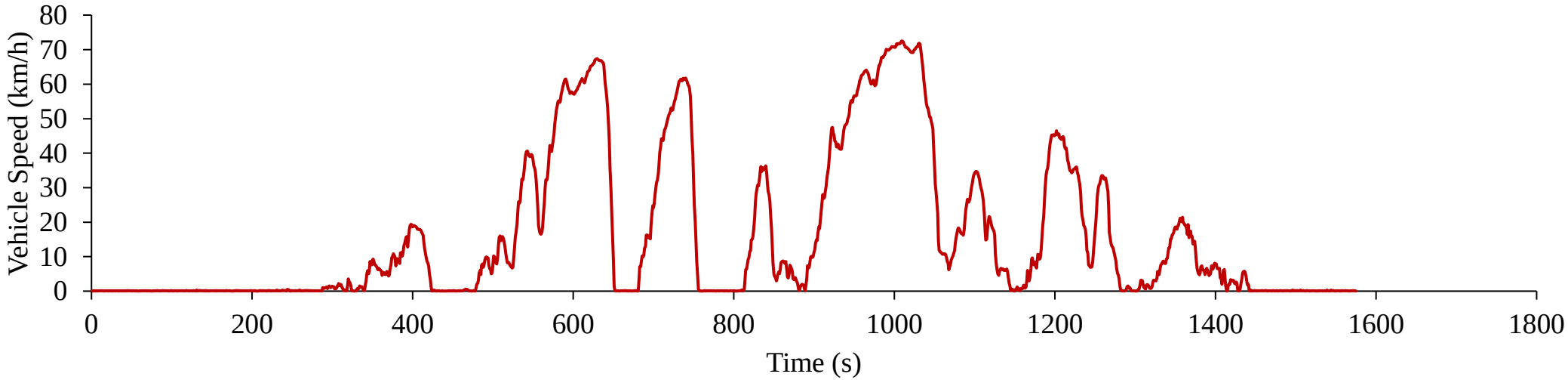
Test Cycles

- Each vehicle performed three test types: Idle, High Idle and Drive
  - Idle & High Idle:

Pre-conditioning	Idle	High Idle	Idle
30 min idle warmup	1 min @ low idle	30 s @ 2500 rpm	1 min @ low idle

  - Drive: On-road drive test of varying dynamic properties, from cold start.

Example Speed Profile for On-road Drive



Equipment used – 3DATX parSYNC FLEX-PNC iPEMS

- Pollutants measured:
  - PN (23 nm cutoff, VPR ~ SPN23),
  - CO, CO_2, HC, O_2, NO & NO_2.
- ECU reader: Vehicle speed, engine speed, mass air flow, throttle position, lambda, fuel rate, absolute throttle position, air intake temperature *(not present)*.

- GPS and ambient monitor: Amb Temp (degC), Amb Pressure (hPa, kPa), Amb Rel Humidity (%), Amb Abs Humidity (g/m3, %), Amb H_20 Density (g/kg), Epoch, Latitude (deg), Longitude (deg), Altitude (m), Speed (km/h), Heading (deg), Fixtype, SIV.

	Non-Dispersive Infrared Spectrometer (NDIR)			Individual Electro-Chemical Cells			Diffusion Charger
	CO_2	CO	HC	O_2	NO	NO_2	PN
Measurement Range	0-20%	0-15%	0-4000 ppm	0-100%	0-5000 ppm	0-300 ppm	5000-5x10^6 #/cm3
T_{90} Response Time	< 3.5 s	< 3.5 s	< 3.5 s	< 6 s	< 5 s	< 35 s	< 10 s
Accuracy	±0.3% abs ±3% rel	±0.02% abs ±3% rel	±8 ppm abs ±3% rel	±0.1% abs ±2% rel	±15 ppm abs ±2% rel	±5 ppm abs ±2% rel	±25,000 #/cm3 abs ±25% rel
Repeatability	±0.1% abs ±2% rel	±0.02% abs ±2% rel	±6 ppm abs 2% rel	±0.1% abs 2% rel	5 ppm 2% of signal	5 ppm 2% of signal	Counting efficiency 23 nm ± 5%: 20-60% 50 nm ± 5%: 60-130% 80 nm ± 5%: 70-130%

Equipment used – Dekati ELPI+

- Measurement principle: unipolar charging of particles followed by aerodynamic size classification in cascade impactor via electrical measurement.
- Size distributed particle number (dN and dN/dlogDp) from 6 nm – 10 µm particle aerodynamic diameter.
- Dekati E-Diluter Pro device was used with dilution factor of 50, and removal of volatiles (no 23nm cutoff).

Source: https://dekati.com/products/elpi/

Data Processing

- Mean concentrations and standard deviations calculated for idle and high idle (no mass data calculated as no exhaust flow rate info from ECU).
- VSP analysis was conducted on the drive test:

$$VSP = v\left[1.1a + 9.81\left(\frac{r}{100}\right) + 0.132\right] + 0.000302v^3$$

Where: v is velocity (m/s); a is acceleration (m/s^2); r is road grade (%) ≈ 0.

The 1 Hz concentration data was analysed in VSP bins:

Braking (acceleration <0 m/s2)	**Idle (speed -1 – 1 mph)**	**VSP (kW/ tonne) / Speed (mph)**	**VSP <0**	**VSP 0 - 3**	**VSP 3 - 6**	**VSP 6 - 9**	**VSP 9 - 12**	**VSP >12**	**VSP 12 - 18**	**VSP 18 - 24**	**VSP 24 - 30**	**VSP >30**
Bin 0	Bin 1	**Speed 0-25**	Bin 11	Bin 12	Bin 13	Bin 14	Bin 15	Bin 16				
		Speed 25-50	Bin 21	Bin 22	Bin 23	Bin 24	Bin 25		Bin 27	Bin 28	Bin 29	Bin 30

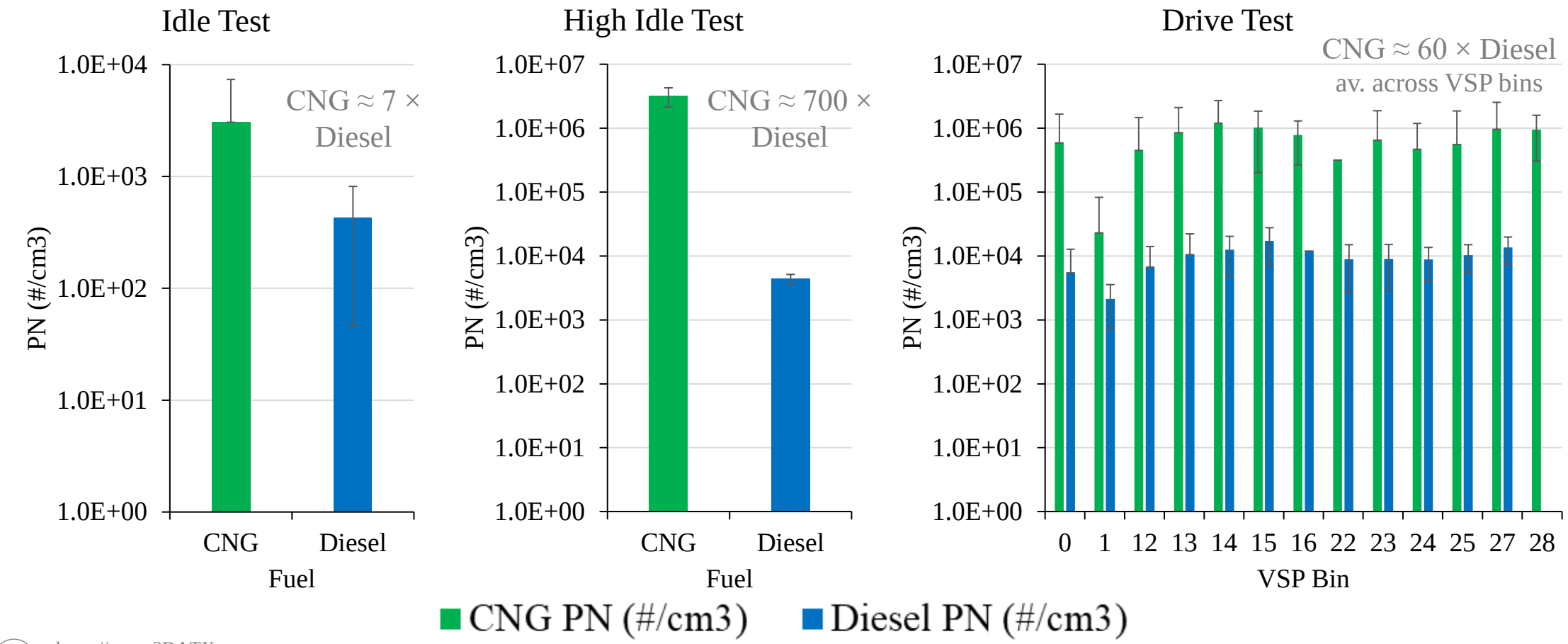
Mean concentration and standard deviation were calculated for each Bin.

Results

Particle Number (SPN23) Results

Data from parSYNC FLEX-PNC

CNG truck had significantly greater PN emission concentrations than the Diesel truck. Error bars are standard deviations of the 1 Hz data.

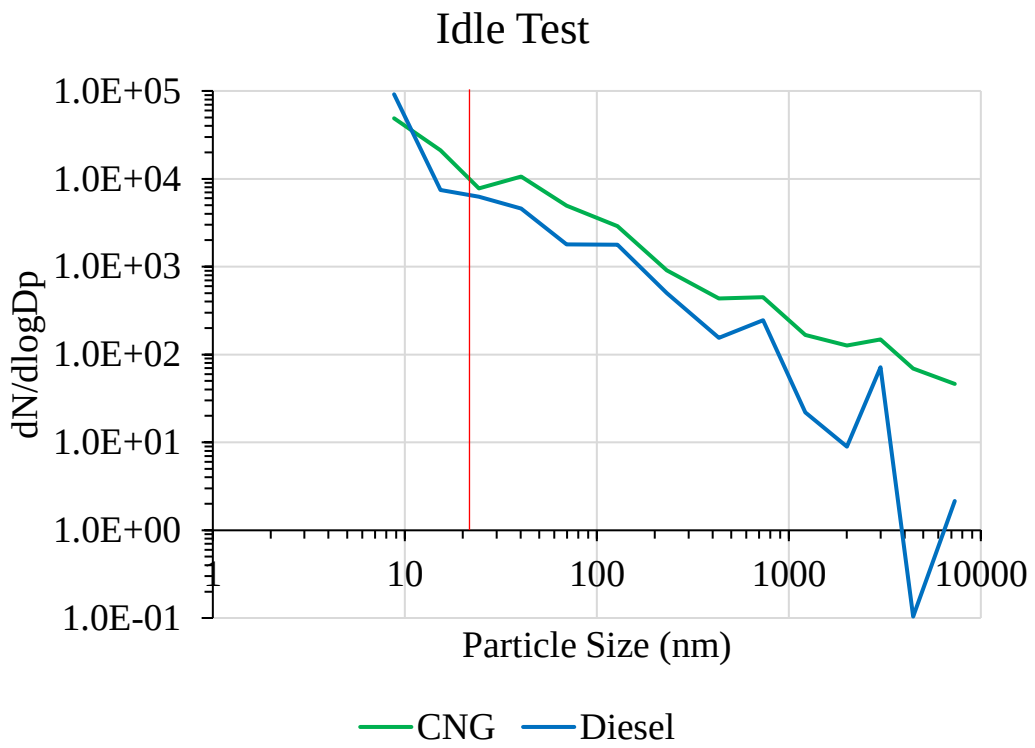


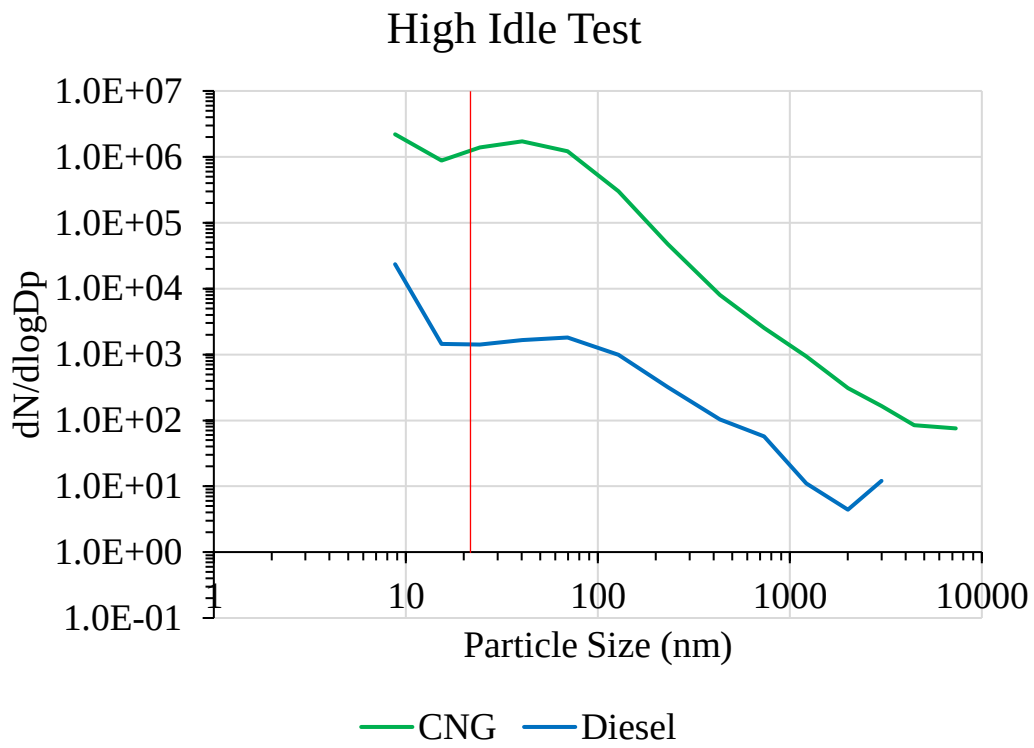
Particle Number Size Distribution (PNSD)

Data from ELPI+

The sub-23nm fractions of total solid PN:

- Idle test was approximately 88% for the CNG and 93% for the diesel,
- High Idle test was approximately 55% for the CNG and 82% for the diesel.





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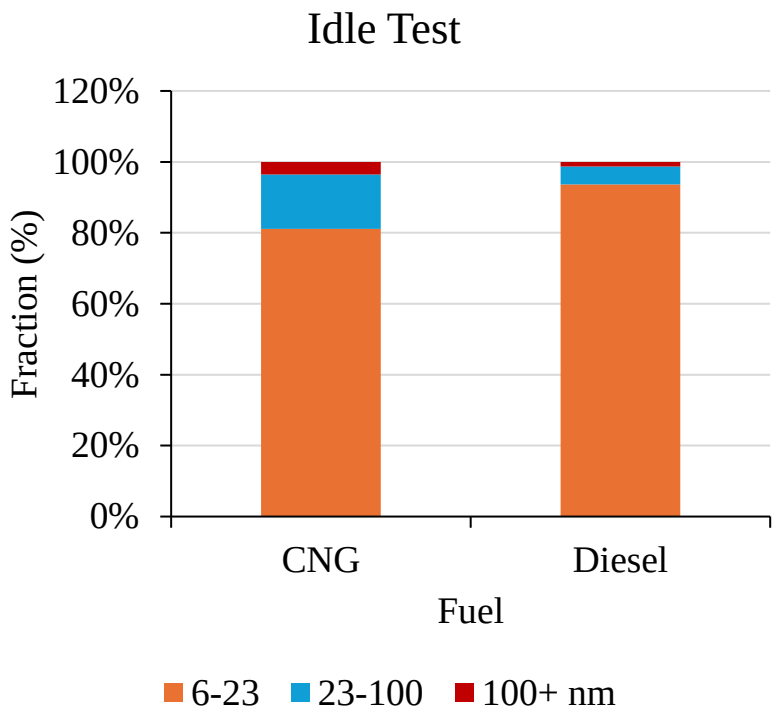
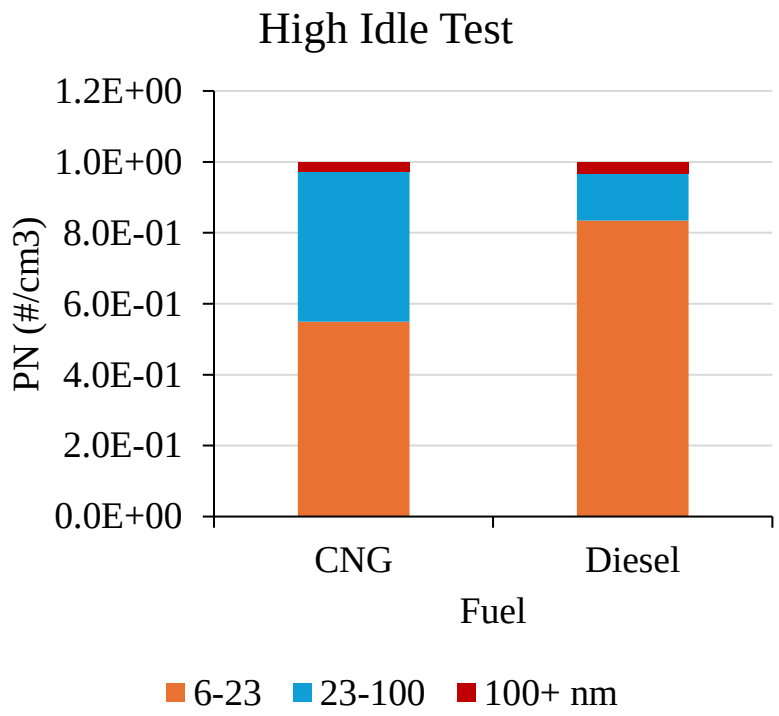


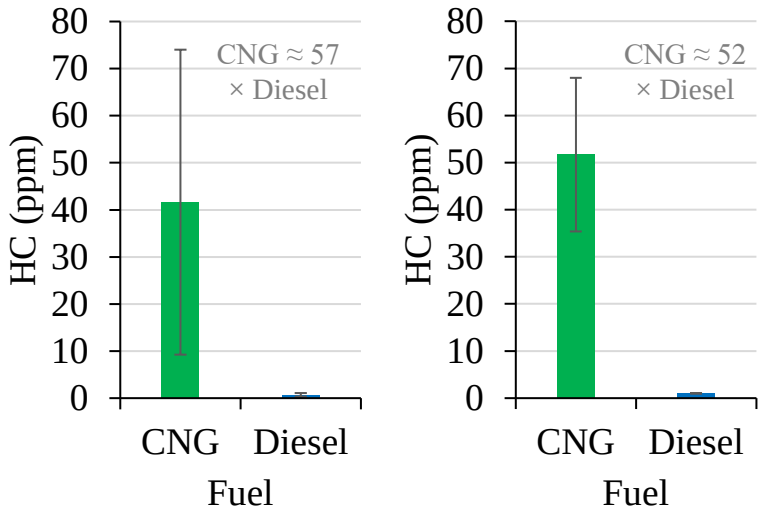


Other atmospheric PM precursors: HC, CO and NOx

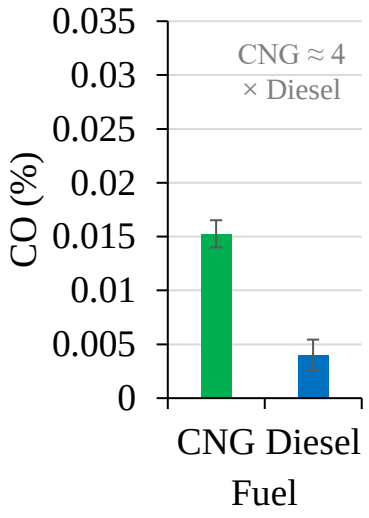
Data from parSYNC FLEX-PNC

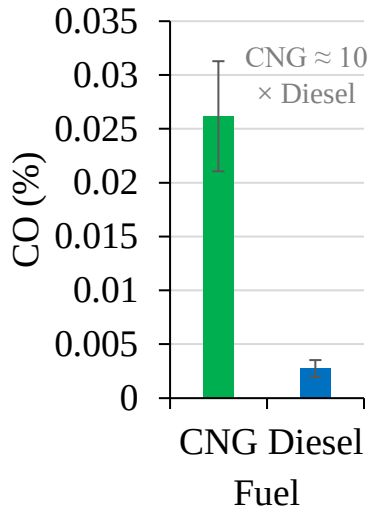
Concentrations of HC, CO and NOx were higher from CNG than diesel for idle and high idle tests. Error bars are standard deviations of 1Hz data.

HC



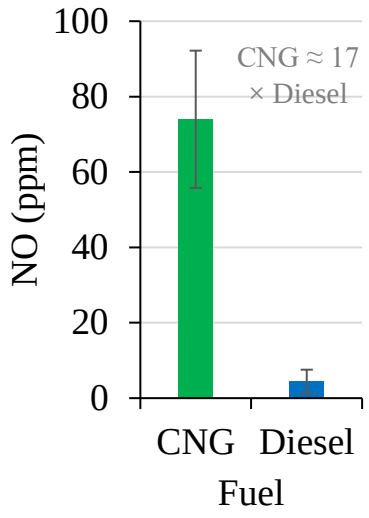
CO

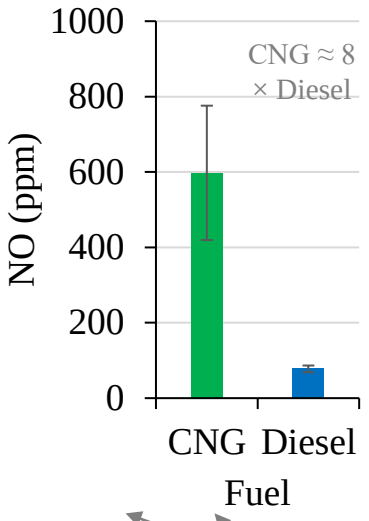




NO

(Majority of NOx was NO)





Note axis scales

HC and CO was also higher from CNG than Diesel on Drive test, but NOx had mixed results (CNG was higher at lower VSP, and diesel higher at higher VSP).

Conclusions

- SPN23 concentrations from CNG were higher than Diesel for all test types:
  - Idle test – 1 order of magnitude,
  - High Idle test – 3 orders of magnitude,
  - Drive test – 2 orders of magnitude.
- Sub-23nm fraction for both CNG and Diesel was substantial,
  - Slightly higher for Diesel than CNG, but with much lower concentrations.
- Combination of high PN with high sub-23nm fraction – important to include CNG in a sub-23nm PN (e.g. PN_{10}) type approval procedure.
- Concentrations of HC, CO and NOx were also greater from the tests (only exception: NOx Drive test had mixed results).
- Note: Pollutant mass emissions do not necessarily correlate with emission concentration. This is especially at low loads, where SI and CI engines exhaust flows are typically different (CNG can have lower mass flow).

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Thank You for Listening. Any Questions?

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