POZNAN UNIVERSITY OF TECHNOLOGY

Particle Number Concentration and Size Distribution in the Cabin of a Light Aircraft during Real-World Flight Operations

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EPPG AIRPORT KAKOLEWO SCIENCE • AVIATION • ENERGY

INTRODUCTION

Airborne particulate matter (PN), particularly ultrafine particles below 100 nm, may penetrate the cabin of light aircraft during real-world flight operations through ventilation systems, air leakages, and engine-related emissions. Due to the limited cabin volume and close proximity between occupants and emission sources, pilots and passengers may be exposed to elevated particle number concentrations during taxiing, take-off, climb, and low-altitude operations. Chronic exposure to ultrafine particles is associated with adverse respiratory, cardiovascular, and neurological effects, while short-term exposure may contribute to fatigue, reduced cognitive performance, and impaired situational awareness. In aviation environments, these risks are particularly important because pilots operate in conditions requiring sustained concentration, rapid decision-making, and high levels of psychophysical performance. Despite growing interest in aircraft emissions and outdoor air quality near airports, limited attention has been given to the penetration, distribution, and size characteristics of particles inside the cabins of light aircraft during actual flight missions. Therefore, the present study investigates the particle number concentration and particle size distribution within a light aircraft cabin under real operational conditions, with the aim of improving understanding of occupational exposure and potential health risks in general aviation.

METHODOLOGY

Airport and Test Platform

Cessna 172S - Lycoming IO-360-L2A (134 kW) - Avgas 100LL

EPPG Airport Kakolewo

Instrumentation

Instrument	Measured parameter	Notes
TSI EEPS 3090 (Dilution ratio 100:1)	dN/dlogD$_p$ 5.6–560 nm · 32 size channels	ground-based measurements
Optical Particle Sizer 3330	dN/dlogD$_p$ 0.3-10 µm · 16 size channels	in-flight experimental campaign
NanoScan SMPS Nanoparticle Sizer 3910	dN/dlogD$_p$ 10-420 nm · 13 size channels	in-flight experimental campaign
Garmin G1000 EIS (1 Hz · factory calibrated)	Engine rotational speed, Cylinder Head Temperature, Exhaust Gas Temperature, Oil Temperature and Oil Pressure Fuel Flow Rate	in-flight experimental campaign/ground-based measurements

Measurement protocol and Data processing

Ground-based measurements were conducted to evaluate the influence of engine operating conditions on particulate emissions under controlled stationary conditions. The measurement campaign included eight stabilised engine speed setpoints ranging from 1000 to 2400 rpm with an increment of 200 rpm, while particle number concentrations were recorded at a frequency of 1 Hz using the EEPS 3090 system and engine operating parameters were collected via the Garmin G1000 EIS. At each operating point, the throttle position was stabilised for 90 s to ensure repeatable and steady-state measurement conditions. The in-flight measurement campaign, including its methodology, operating conditions, and selected flight parameters, is presented in the table below. **The measurements were preceded by a 5-minute particle concentration measurement inside the aircraft cabin before engine start-up. Two flights were performed: one with the air vents closed and the other with the air vents open.**

In-flight experimental campaign

	Parking	Taxing	Takeoff & Climb	Level Flight	Turn 30° Left	Turn 30° Right	Turn 45° Left	Turn 45° Right	Climb	Descent	Landing
Duation [min]	5 min	7 min	2 min	10 min	5 min	5 min	4 min	4 min	4 min	4 min	5 min
Engine Speed [rpm]	1000	1100	2400	2150	2200	2200	2200	2200	2400	1900	2000
Altitude [ft]	200	200	200-2000	2000	2000	2000	2000	2000	2 000->4000	4000->2000	2000->200

Raw EEPS 3090A data (32 channels, 5.6–560 nm) were corrected for dilution (×100). Mean PSD spectra were computed over stable measurement windows at each of the 8 engine speed setpoints (1000–2400 rpm), with transient periods excluded. EEPS spectra were interpolated onto the NanoScan 3910 grid (13 channels, 11.5–365.2 nm) using **Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) in $\log_{10}$–$\log_{10}$ space.**

The engine-attributed cabin signal was isolated by subtracting a pre-engine-start cabin reference measurement:

$$\Delta N(D_p) = N_{cabin}(D_p) - N_{background}(D_p)$$

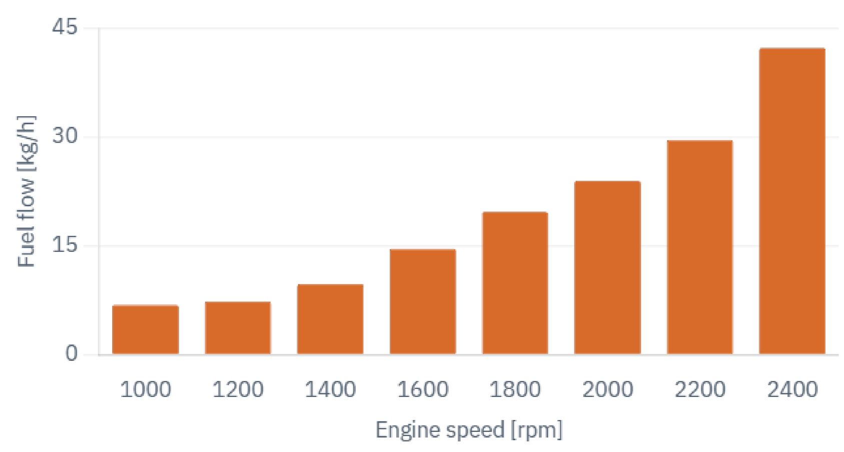
The penetration factor η was calculated for each particle diameter across the valid overlap range (15.4–205.4 nm):

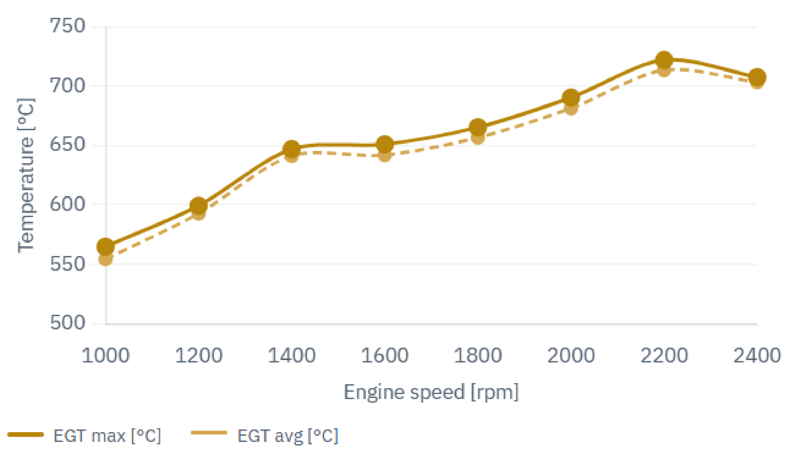
$$\eta(D_p) = \frac{\Delta N_{cabin}(D_p)}{\bar{N}_{exhaust,interp}(D_p, RPM)}$$

RESULTS GROUND-BASED MEASUREMENTS

Engine Performance

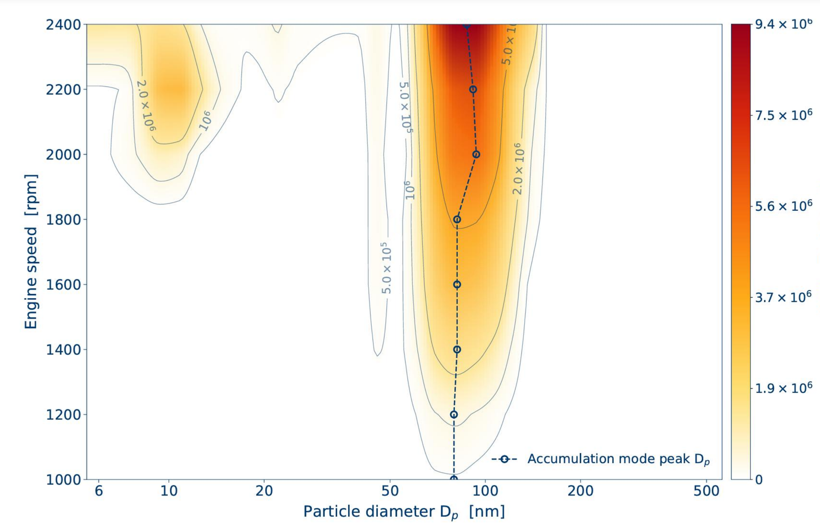
The charts illustrate the relationship between fuel flow and exhaust gas temperature across different engine speeds. As the rotational speed increases, fuel consumption rises steadily, reflecting the growing power demand. Simultaneously, the exhaust gas temperature (EGT) increases, reaching its peak at the highest speeds. These results demonstrate typical engine behavior under load.

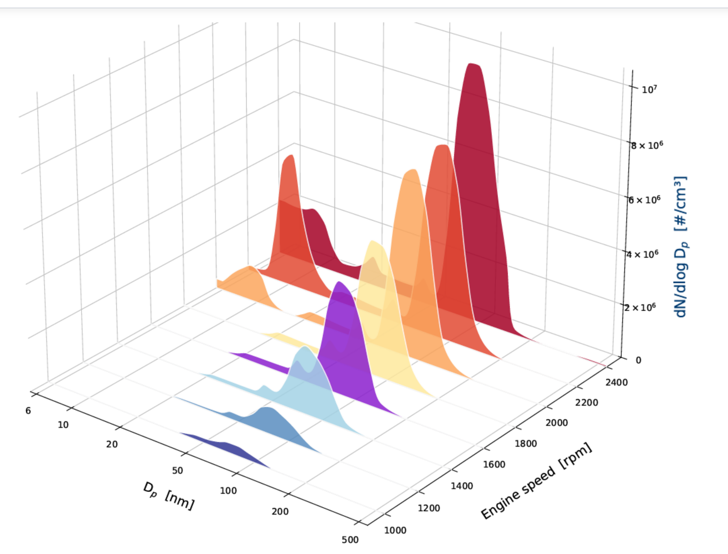




Particles Concentration and Size Distribution

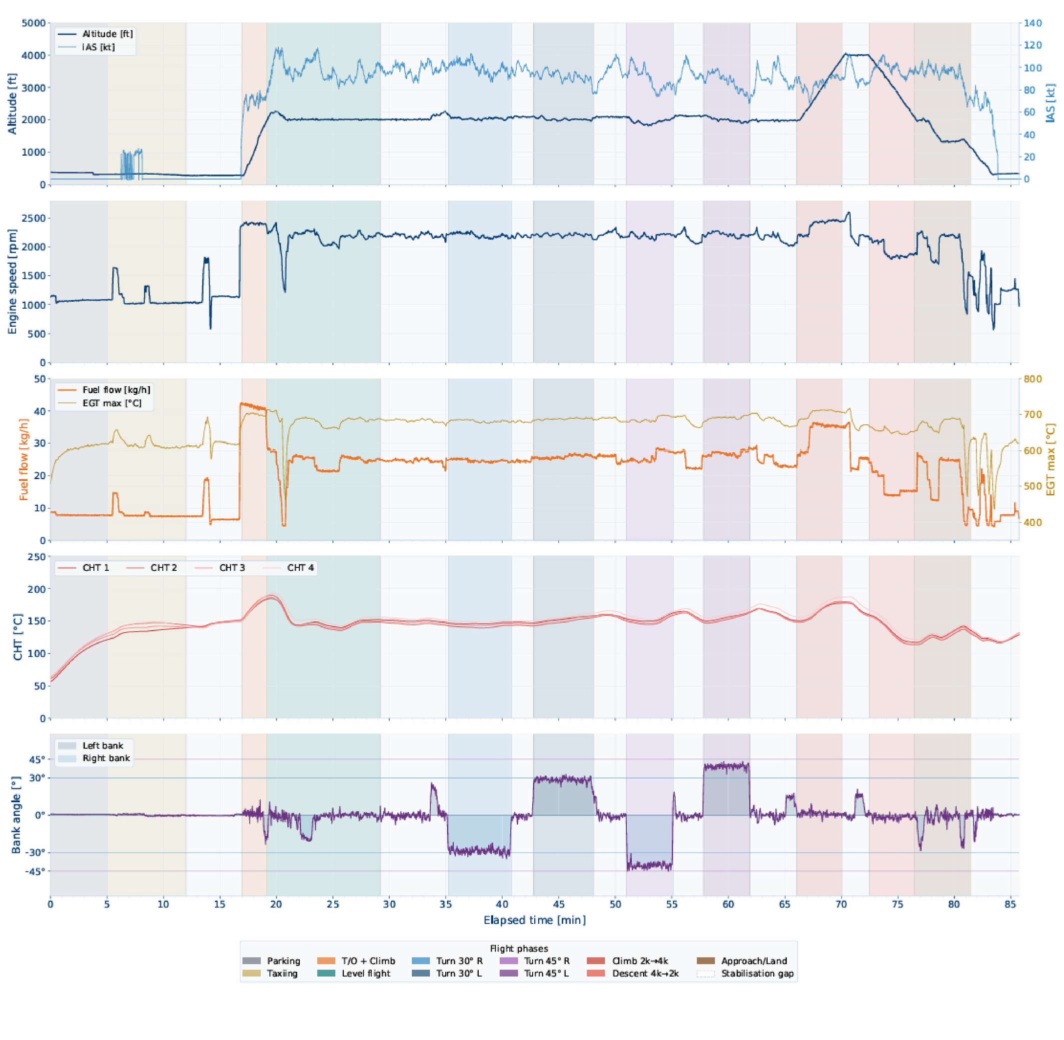
The presented plots illustrate how particle number concentration varies with engine speed and particle diameter. The contour map shows regions of high particle concentration, with the accumulation mode peaking near 80 nm as engine speed increases. The 3D surface plot provides a complementary perspective, highlighting distinct peaks corresponding to different operating conditions.



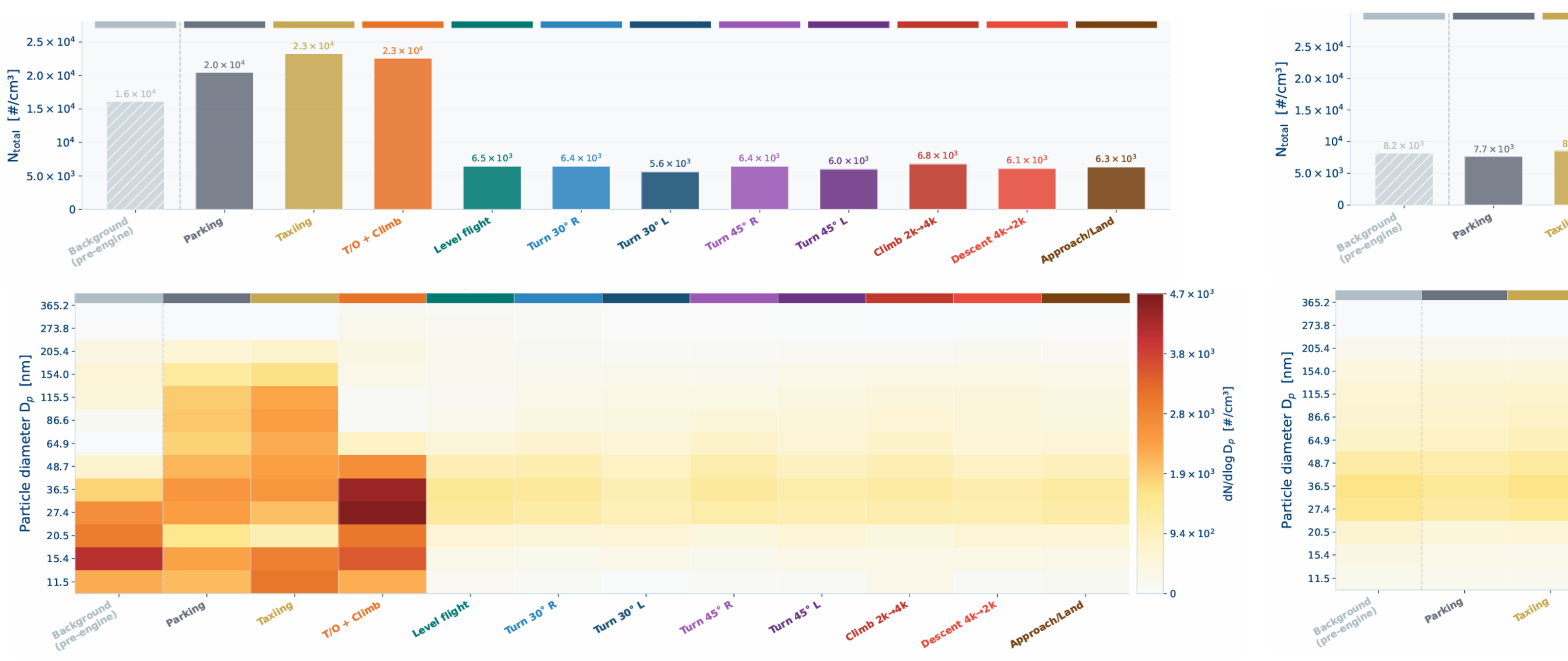


RESULTS IN-FLIGHT EXPERIMENTAL CAMPAIGN

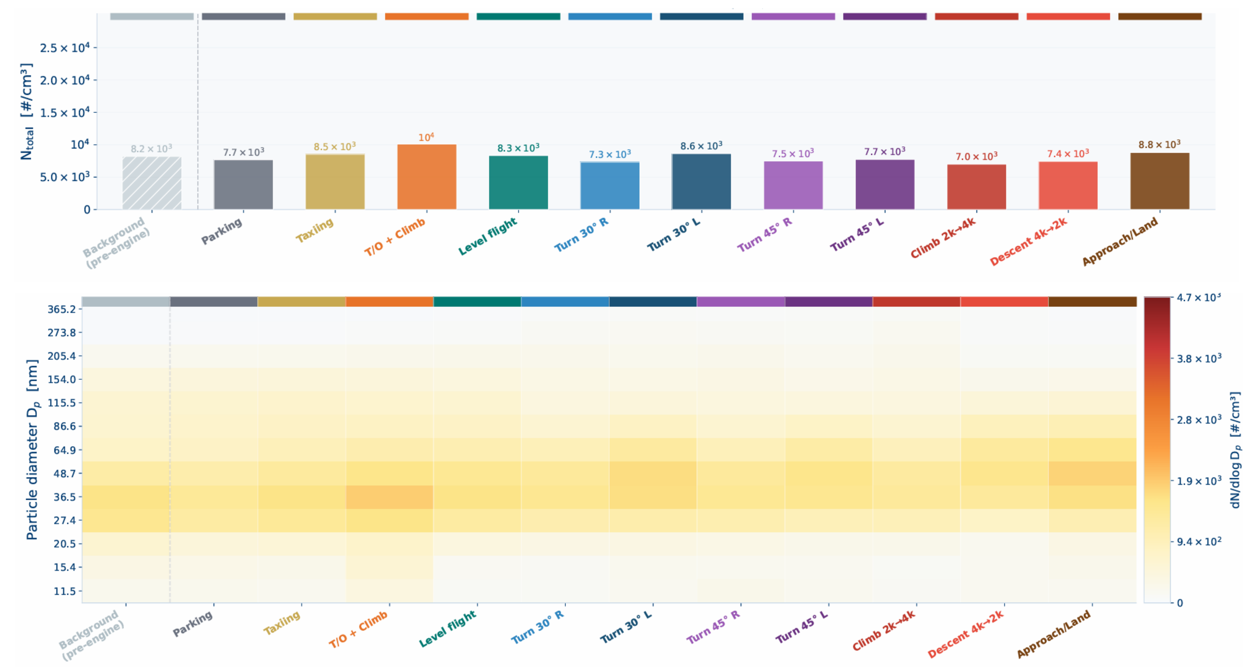
Flight Parameters Analysis



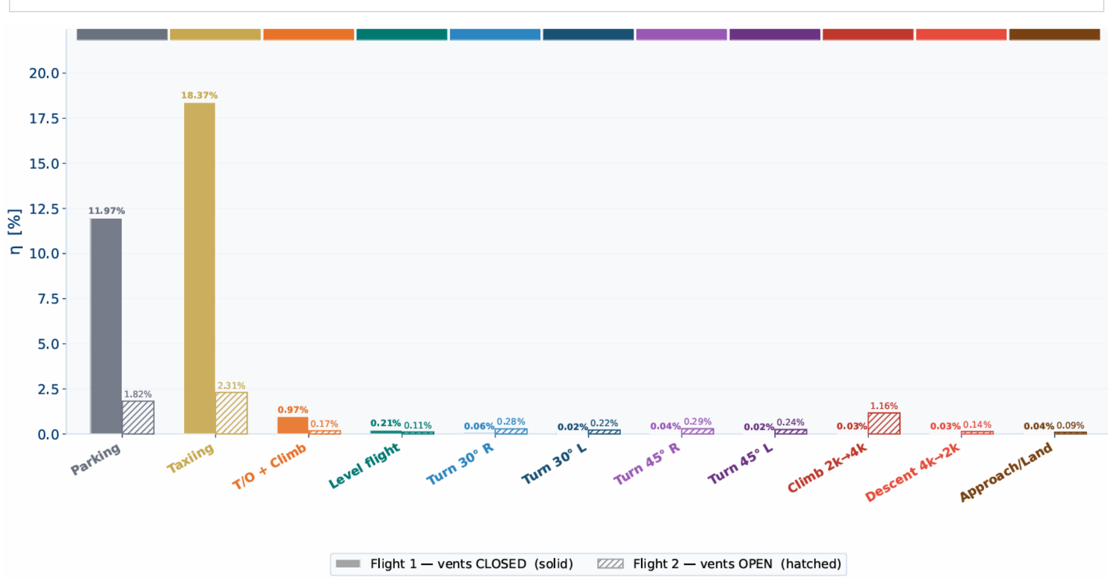
Particle Number Concentration and Size Distribution – Air Vents Closed



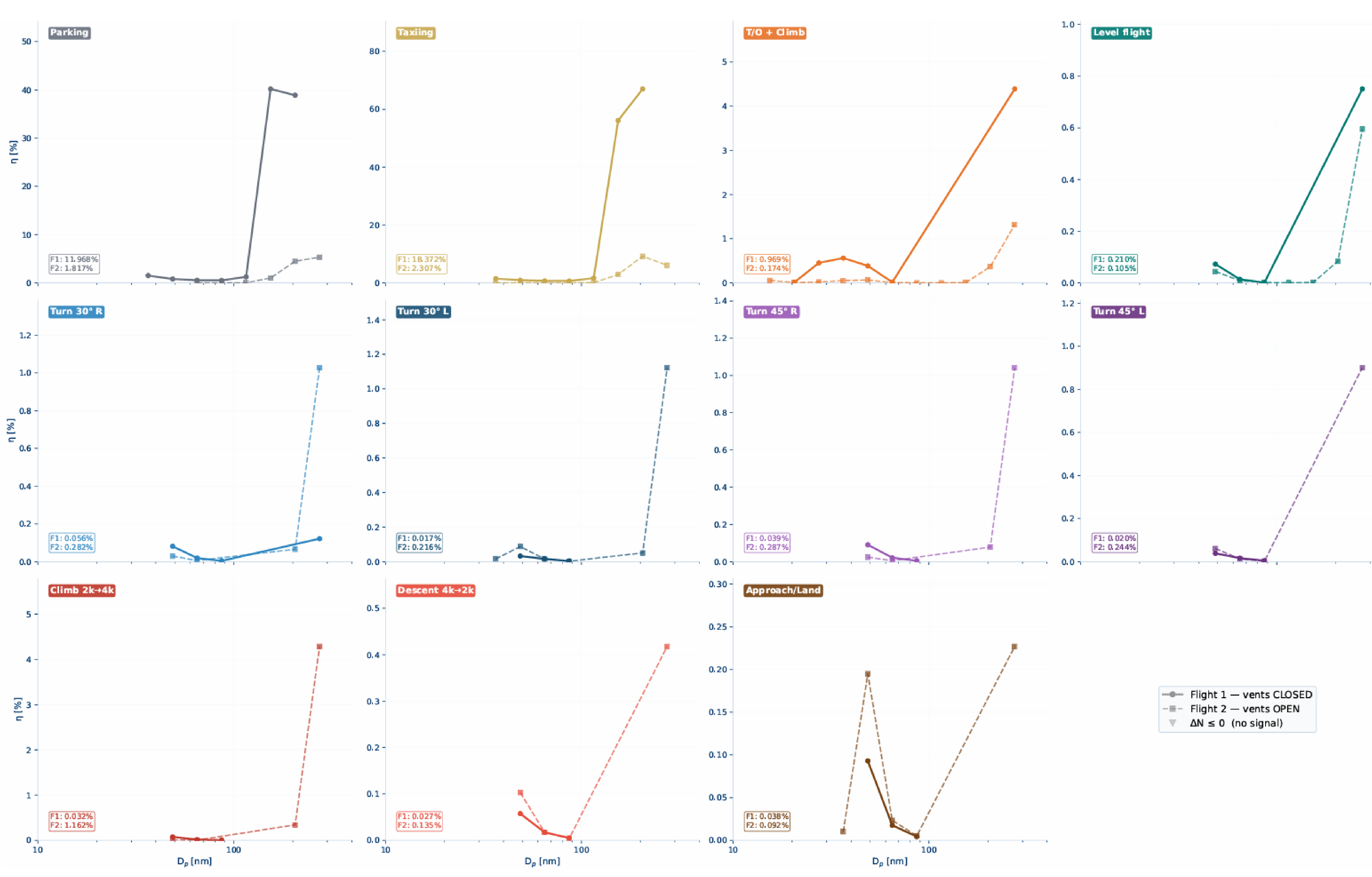
Particle Number Concentration and Size Distribution – Air Vents Open



Penetration Factor η(phase) – Mean



Penetration Factor η(D_p) per Flight Phase



CONCLUSIONS

- **Ground operations** represent the highest cabin PM exposure phase. With vents closed, the penetration factor η reached **11.97% (parking) and 18.37% (taxiing)**, confirming substantial exhaust recirculation into the cabin at low engine speeds. Opening all four vents reduced ground-phase η by a factor of 6–7, providing effective dilution of engine-sourced particles.
- **Airborne phases** showed a dramatic reduction in cabin particle concentration - from 20,000 #/cm³ on the ground to 6,000 #/cm³ in all flight phases, falling **below the pre-engine background level**, consistent with lower ambient aerosol loading at 2,000 ft above the urban boundary layer.
- **Vent configuration reverses its effect in flight.** Open vents increased η during airborne manoeuvres by factors of 5–37 relative to closed vents, with the strongest effect during the 2,000→4,000 ft climb (η ratio F2/F1 = **36.7**). This is attributed to aerodynamic ingestion of propeller wake and engine exhaust through side vents during high-power climb.
- **Bank angle manoeuvres** (30° and 45°) showed no statistically significant difference in cabin particle concentration, suggesting that flight attitude has a negligible independent effect on penetration at cruise power settings.
- **Engine PSD** exhibited a bimodal structure above 2,200 rpm, with an accumulation mode at 80–93 nm and an emerging nucleation mode below 15 nm. The accumulation mode peak diameter shifted progressively from 80 nm (1,000 rpm) to 93 nm (2,400 rpm).
- **Practical implication:** Pilots of piston-engine GA aircraft should keep cabin vents **open during ground operations** to dilute engine-sourced particles, and **closed or partially open with caution during climb**, where open vents significantly increase cabin PM exposure due to aerodynamic ingestion of propeller wake and exhaust gases.

See the research in action - scan to watch the flight

TSI NanoScan · EEPS 3090 · Garmin G1000 · Cessna 172S SP-UTD

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