# Implications of the New PM Emission Standard for Jet Engines

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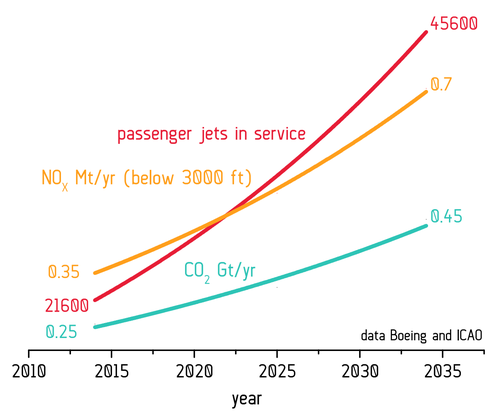
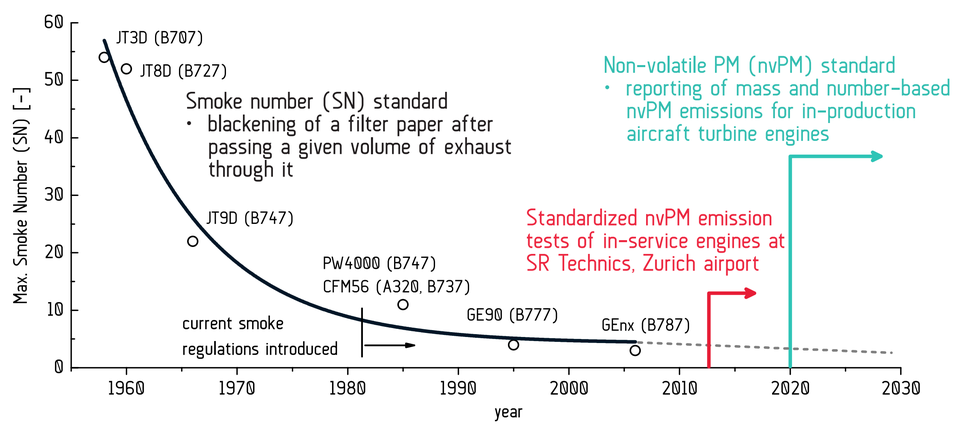
## Background

### Projected aviation growth and emissions




### Soot emission standards – from (in)visibile smoke to nanoparticle counting




### Methods for estimating aviation nvPM emissions

| Method | mass | number | fuel sensitivity |
|---|---|---|---|
| First order approximation (FOA) from SN – Wayson et al. [1] | estimate | cannot resolve | |
| Alternative correlation with SN – Peck et al. [2] | | | |
| Formation-oxidation (FOX) model – Stettler et al. [3] | | | |
| This study – estimation from certification-quality nvPM data | measurement data | | |

## Objectives

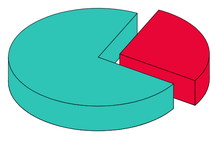
- calculate nvPM number and mass emissions below 3000 ft (landing-take-off cycle, LTO)
- calculate emission indices (amount of pollutant / kg fuel burned) at cruise altitude
- calculate nvPM emissions per passenger and km as a function of flight duration and distance
- compare aircraft and vehicle nvPM emissions

## Scope

### The aircraft

Boeing 737 Next Generation
engines: 2x CFM56-7B
capacity: 160 passsengers (series 800)
No. of passengers at 80% occupancy: 130
shortest scheduled flight: ~35 min
longest scheduled flight: ~7 h 20 min


~27% of all passenger jets are 737NG (~6000 aircraft)

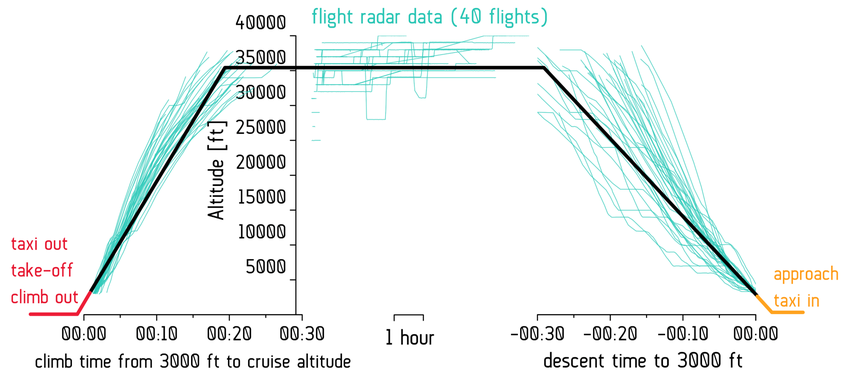


### The flight (> 3000 ft altitude)

Climb to cruise altitude
- vertical speed 1750 ft/min
- duration 18.3 min
- indicated air speed 250 knots below 10000 ft and 280 knots above

Cruise
- altitude 35000 ft
- duration 5 min to 6 h 30 min
- Mach 0.785

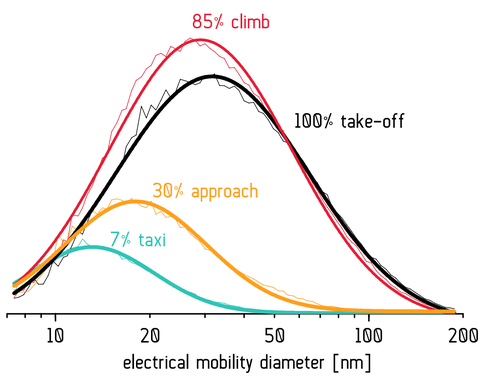
Descent
- vertical speed 1100 ft/min
- duration 29 min
- indicated air speed 250 knots below 10000 ft and 280 knots above



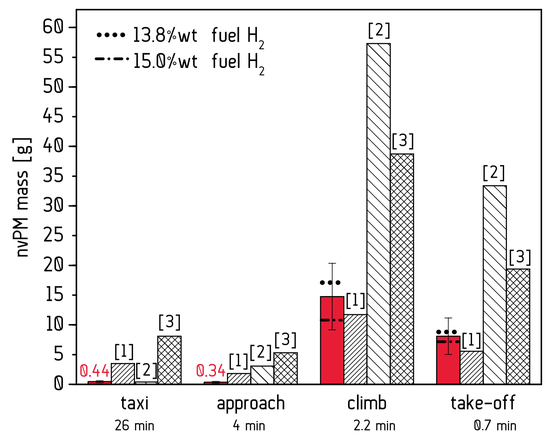

## Results

### Landing-take-off cycle emissions (< 3000 ft)

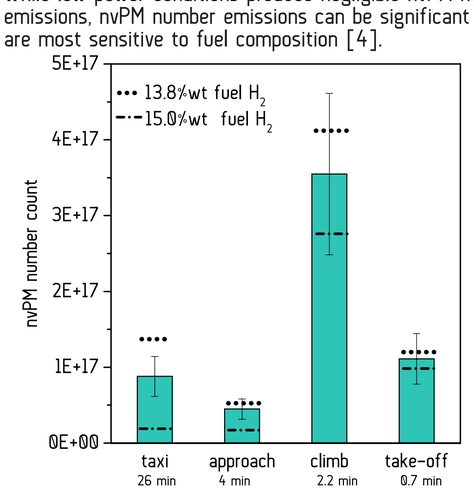
Particle size distributions at the engine exit plane strongly depend on engine power.



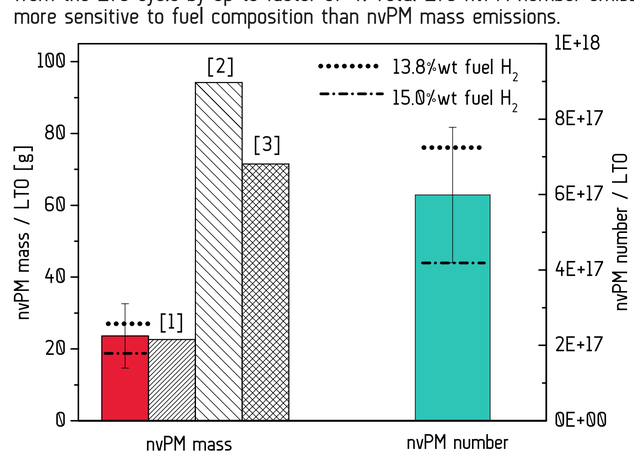

NvPM mass emissions are up to factor of 20 lower than predicted by the methods based on SN correlation and combustion models.




While low power conditions produce negligible nvPM mass emissions, nvPM number emissions can be significant and are most sensitive to fuel composition [4].

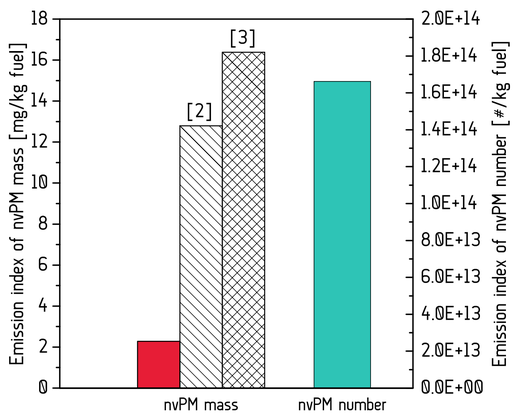



Except for FOA [1], previous methods overestimate the nvPM mass emissions from the LTO cycle by up to factor of 4. Total LTO nvPM number emissions are more sensitive to fuel composition than nvPM mass emissions.

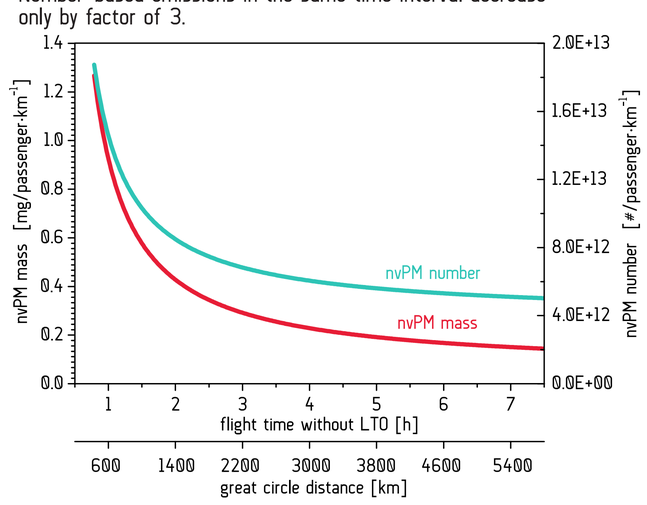



### Flight emissions (> 3000 ft)

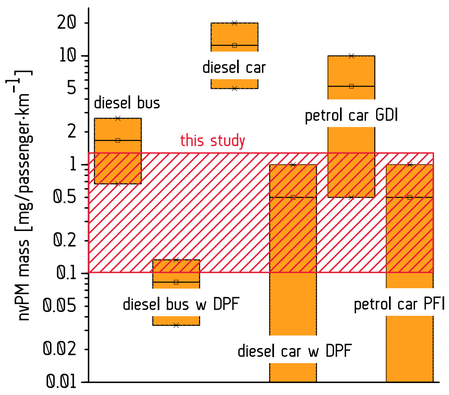
In comparison with the methods based on SN correlation and combustion models, emission index of nvPM mass at cruise altitude is up to factor of 8 lower.



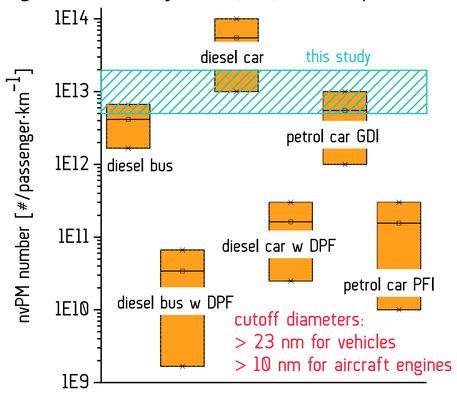

Mass-based emissions per passanger and km decrease by up to factor of 6 with flight time (1 hour flight v. 7 hours). Number-based emissions in the same time interval decrease only by factor of 3.



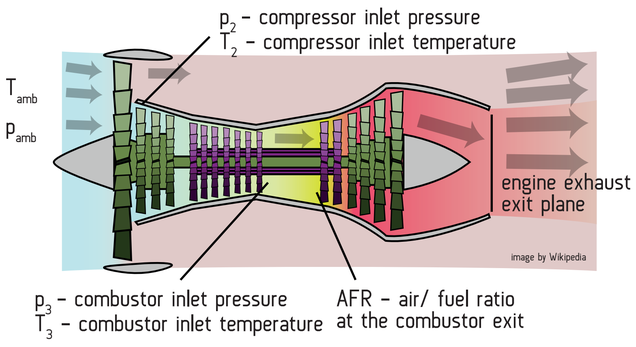

Comparison with vehicle emissions [5]:
- car occupancy: 2
- bus occupancy: 30
- plane occupancy: 130




Mass-based nvPM emissions compare to diesel vehicles with a particle filter (DPF) and a port fuel injection (PFI) petrol car. Number-based nvPM emissions compare to diesel and gasoline direct injection (GDI) without particle filters.




## Methods




measurement data
(2 engines, 5 test runs)

- nvPM mass concentrations
- nvPM number concentrations
- $CO_2$, CO, HC concentrations
- engine performance data

Correction for particle losses in the sampling system

- sampling system geometry
- system temperatures and flow rates
- particle size distribution properties
- particle effective density

Averaged exit plane mass- and number-based emission indices (EIs) as a function of sea level static thrust ($F_{00}$) and $T_3$

LTO emissions

- time in mode $f(F_{00})$
- fuel burn in mode $f(F_{00})$

flight emissions

flight conditions as a function of altitude

- $p_{amb}$, $T_{amb}$
- speed of sound
- true air speed
- Mach number

engine performance as a function of altitude

- $T_2$, $p_2$
- fuel burn
- $p_3$, $T_3$
- AFR

correction of EIs at reference ground conditions to flight conditions

- EI mass correction factor
  $f = (AFR_{ref}/AFR)^{2.5}(p_3/p_{3,ref})^{1.35}$ [6]
- assumption: EI number / EI mass = const $f(T_3)$
  (geometric mean diameter = const $f(T_3)$)

## References

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## Funding

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## Test cell and engineering services

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