AIRCRAFT ENGINES

ASSESSMENT OF AIRCRAFT ENGINES PARTICLES EMISSION IN CRUISE

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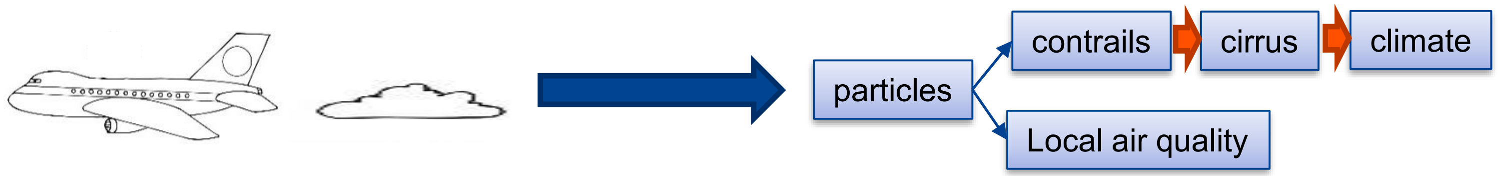
Introduction



Need in inventories for assessing aviation impact on climate and air quality, to estimate non volatile Particulate Matter (nvPM) cruise emissions

> Inventories performed for instance in European projects (QUANTIFY, REACT4C…), or in CAEP frame (ICAO)
> Coarse assumptions are often used, as for ex. using a constant value for all aircrafts

Objectives

> To estimate cruise nvPM emissions : **mass and number**
> Propose a methodology to derive an optimal best practice

The analysis which is presented considers

> Different existing modelling strategies from literature and used in inventories
> Existing experimental results, including from French Mermose project

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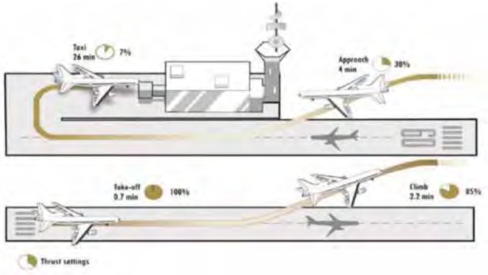
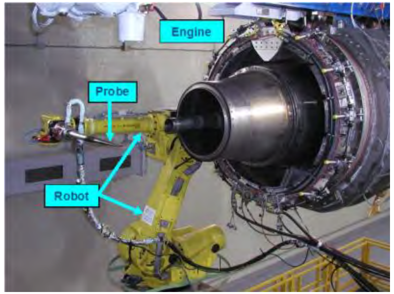
What do we have?

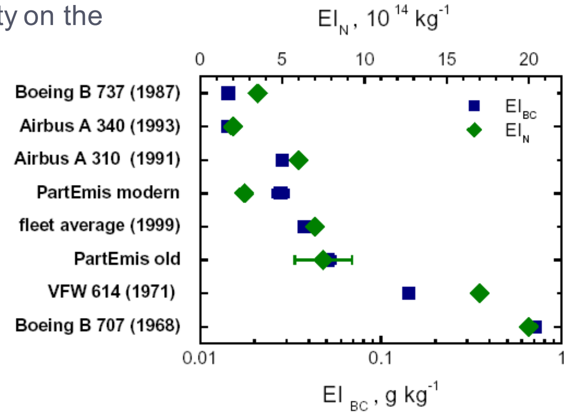
- **For all engines**
  - > **Smoke Number** at Mach and altitude = 0 for 4 operating points ➔ necessary to certify a turbo engine
  - > In the near term, thanks to new regulation, direct **nvPM** measurements are being gathered

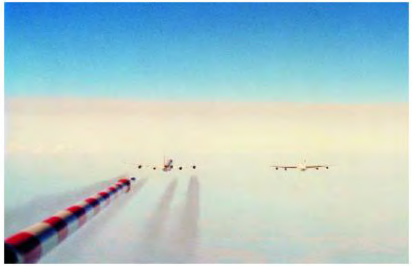




- **For some engines**
  - > In flight measurements (method? ➔ Strong uncertainty on the values)

Aircraft	Engine	Certif. Year	BPR	OPR	F00 (kN)
B737-300	**CFM56-3B1**	1983	5.1	22.4	89.4
A340-300	**CFM56-5C4**	1991	6.6	31.1	151.2
A310-300	**CF6-80C2A2**	1985	5.1	28	233.4
ATTAS	**M45H MK501**	1971	3.0	16.5	32.4
B707-307C	**JT3D-3B**	1974	1.4	13.6	80.1





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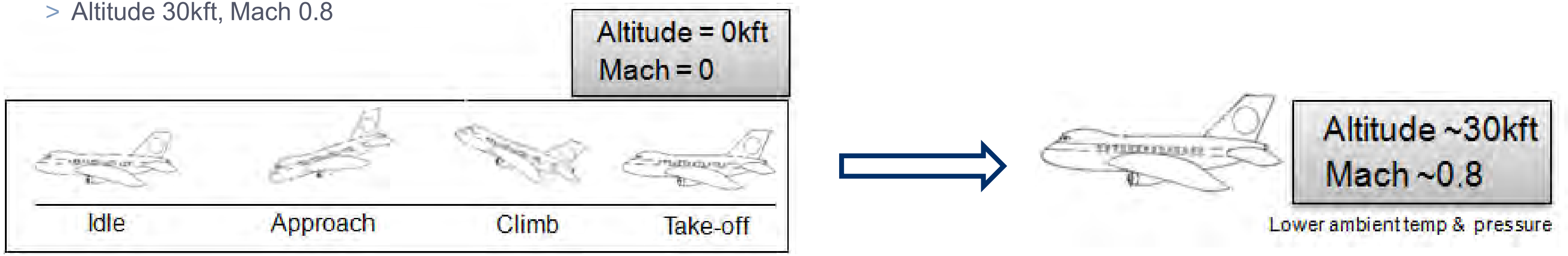
What do we need?

- **Cruise nvPM emissions**
  - nvPM, not SN
  - Altitude 30kft, Mach 0.8



Options

- In flight measurements ➔ expensive, very difficult
- **Develop a method to transpose ground measurements to flight estimation**

Necessary to have:

- The cruise conditions inside the combustor
- A transposition method

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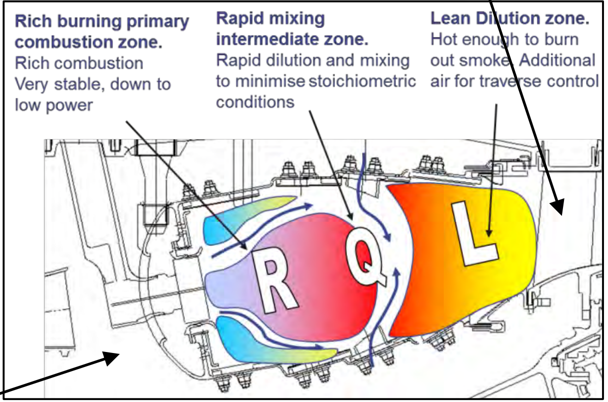
Combustor technologies

C(nvPM): mass or number concentration
EI(nvPM): mass or number per kg of fuel

Conventional combustor – Rich-Quench-Lean (RQL)

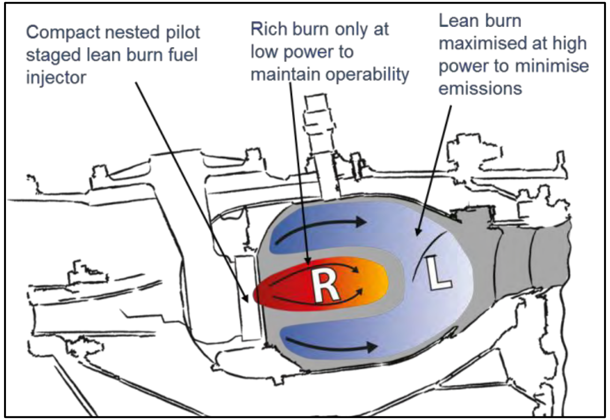
- A rich diffusion flame in the primary zone recirculation
- Provides a high level of resistance to flame out (combustor lean overall)
- Produce soot particles (in the rich zone)
- Controlled introduction of air down the length of the combustor dilutes the mixture and enables most of the soot produced in the rich zone at high power to be consumed
- Vast majority of combustors in the fleet

Conditions inside the combustor: T3, P3, FAR3



Staged combustion – Lean

- Two fuel injection zones : pilot and main
- Added degree of freedom for control of the combustion processes
- At low power, pilot fuel injection
- Higher up the, fuel is introduced to the main fuel injectors
- The combustor behaviour can be controlled to give lower emissions without compromising operability requirements
- Only two certificated engines: GENx (GE) and LEAP (CFM)



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C = Concentration nvPM
EI = Emission Index
SLS = Sea Level Static
cr = Cruise

Existing Methods to predict cruise nvPM

DLR methodology

Model developed in the early 2000, several publications (Döpelheuer 1998, Petzold et al., 1999) ➔ inspired the following approaches

Step A – SN(sls) ➔ C(sls) : Use LTO SN and engine thrust (F or %F00) to determine soot mass concentration and combustor inlet temperature (T3) at sea level static (SLS) condition

> In the original DLR methodology, the C(sls) vs SN(sls) function was based on measurements from the 1970-90s. However, other more recent C(sls) vs SN(sls) functions can now be used as well; for instance, the FOA3 (Wayson et al., 2009)

Step B – C(sls) ➔ C(cr) :

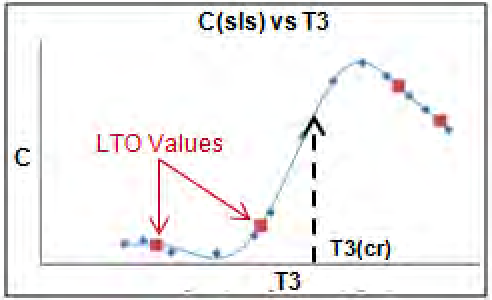
DLR correction (1998)

$$C_{BC} = C_{BC,ref}\left(\frac{\phi}{\phi_{ref}}\right)^{2.5}\left(\frac{P_3}{P_{3,ref}}\right)^{1.35}\left(\frac{e^{-20,000/T_{fl}}}{e^{-20,000/T_{fl,ref}}}\right)$$

- Find the reference ground concentration C(sls)ref defined by T3(sls) = T3(cr) - but P3(sls)≠ P3(cr) for ex
- Calculate in-flight C(cr) by using the transposition equation and relevant thermodynamic data of the operating condition of interest: i.e., equivalence ratio (φ), combustor inlet pressure (p3) and flame temperature (Tfl)

Step C – C(cr)➔ EI(cr) : Convert the estimated in-flight C(cr) into total soot mass, and calculate the soot mass emission index (EIm) using air and fuel mass flow data

> Note: the transposition C/EI can be done at every step



- Some steps are missing : determination of T3/P3 inside the combustor, interpolation
- No widely accepted SN/EI/C correlation available at the time
- Nothing for number

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Existing Methods

Identifying the necessary steps

SN = Smoke number
C = Concentration nvPM
EI = Emission Index
SLS = Sea Level Static
cr = Cruise

N	Step
0	SN(sls)➔ C/EI(sls)
1	T3/P3(cr)
2	Def ref pt.
3	Interpolation
4	C(sls)➔C(cr)
5	➔nvPMnum

N°	Step	Clarification	Existing models		Level of Confidence/Accuracy	Recommendations
0	Ground nvPM data pre-treatment	nvPM mass concentration correlated to Smoke Number	M1 = Champagne [1971]; M2 = Hurley [1993]; M3 = Whyte [1982]; M4 = Döpelheuer [2001], M1/2/3 combination; M5 = Peck et al. [2013]; M6 = Wayson et al. [2009] = FOA3 SN/C(BC) correlation; M7 = Stettler et al. [2013] = variant to FOA3 SN/C(BC) correlation; M8: CAEP-10 correlation database	😐	SN - nvPM mass correlation could be improved with on-going PMTG work; available correlation for the particle number is weak in principle	Use the new PMTG mass correlation; strengthen work and focus as well on particle number correlation
		nvPM mass & number concentration direct measurement (in particular nvPM standard certification values)	N/A	😐	Number of compliant engine nvPM measurements until today is still small and not sufficiently representative for engine "fleet"; however, work in progress	Exploit future validated results
1	Determination of cruise condition in combustor	Estimation of relevant combustor parameters from flight conditions	* Derived from fuel flow (Wf) knowledge with a more or less simplified engine model: M1 = Döpelheuer [2001]; M2 = Stettler et al. [2013]; * F/F00 assumption: M3 = Peck et al. [2013]	😐	Some parameters, like cruise fuel flow, may not be derived easily without knowing the precise combustor technology; some recent approaches are not satisfactory when compared to engine performance model (Peck et al. [2013])	Need for consensus and consolidation on how key drivers such as T3, P3 and FAR might be estimated in cruise from fuel flow Wf, and up to what level of accuracy
2	Choice of ISA-SLS Reference Point	How the ground reference conditions are derived from cruise conditions	* Same combustor inlet temperature T3: M1 = Döpelheuer [2001]; M2 = Peck et al. [2013] * Max fuel flow (Wfmax) taken: M3 = Stettler et al. [2013]	☹	Very little material available today to assess the best parameter: for instance, T3, P3, FAR4 (or less-proprietary one, if any)	Run more rig tests (single/multi sector or full annular or core test) to perform sensitivity analysis in order to assess impact of key drivers and derive appropriate correction laws
3	Reference Point nvPM value	Attribution of an nvPM value (generally in terms of mass concentration) for the ground Reference Point	* Interpolated: M1 = Dopelheuer [2001]; M2 = Peck et al. [2013] * Directly estimated from combustor reference conditions: M3 = Stettler et al. [2013] = FOX model	😐 ☹	* With enough care on interpolation * Lack of validation of Stettler (FOX) method; very dependent a priori on technology	Prefer interpolation of ground nvPM data
4	Correction law on operating conditions	Need to correct the ground reference nvPM value to cruise conditions	Same formula on the mass concentration used in all methods: M1 = Döpelheuer [2001]	☹	Validation against a too small number of data and rather old technology	Consolidation based on rig tests
5	Derivation of nvPM number from nvPM mass	Currently, existing methodologies estimate first the cruise nvPM mass emission index (EIm) and then derive the number EI. This is thus an additional step if of interest	* Average particle mass assumed: M1 = Petzold [2001] ; M2 = Eyers et al. [2004] (depending here on altitude) * Assumed size distribution + particle density: Righi [2013] ; PMTG6-WP11	☹	Lack of validation; should the size distribution be the one just at the engine exit?	Consolidation need based on rigs tests in cruise conditions
	Calibration / Validation using cruise nvPM data	Not properly a step of a cruise nvPM methodology but a key concern. Cruise nvPM data might be obtained from chase aircraft measurements or cruise conditions test rig measurements	N/A	☹	Existing cruise conditions measurements not sufficient. Full methodologies validation based on a too small number of representative engines	Increase size of the cruise data bank

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Existing Methods

Peck et al – Stettler et al.

N	Step
0	SN(sls)→ C/EI(sls)
1	T3/P3(cr)
2	Def ref pt.
3	Interpolation
4	C(sls)→C(cr)
5	→nvPMnum

SN = Smoke number
C = Concentration nvPM
EI = Emission Index
SLS = Sea Level Static
cr = Cruise

The 2 methods basically follow the DLR methodology but fill the blanks

Peck et al.

- Step 0 –SN to EI : $EI_{BC,ref} = 14.8 \times SN_{ref}$
- Step 1 – **Hypothesis : Fcr = 65%F00 or fuel flow method needed**
- Step 2 – Ref point : T3(cr) = T3(sls) (same approach as DLR)
- Step 3 – Polynomial interpolation from the 4 LTO points
- Step 4 – Transposition to cruise (DLR correlation)

Stettler et al.

- Step 0 – The ground concentration: FOX method $C_{BC,ref} = \dot{m}_f \left(356\, e^{\left(-\frac{6390}{T_{fl}}\right)} - 608\, \mathrm{AFR}\, e^{\left(-\frac{19778}{T_{fl}}\right)}\right)$
- Step 1 – P3 & FAR assumed to vary linearly with Wf (**fuel flow) ;** T3 simply derived
- Step 2 – Ref point: NTO
- Step 3 – No interpolation (correlation)
- Step 4 – Transposition to cruise (DLR correlation)

Methodologies are applied to SAM146 engine

→ EInvPMm =1.6 mg/kg

→ EInvPMm =15.6 mg/kg

Which one is better?

Very strong impact of the methodology

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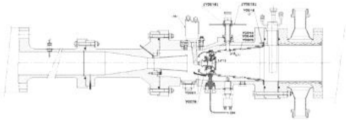
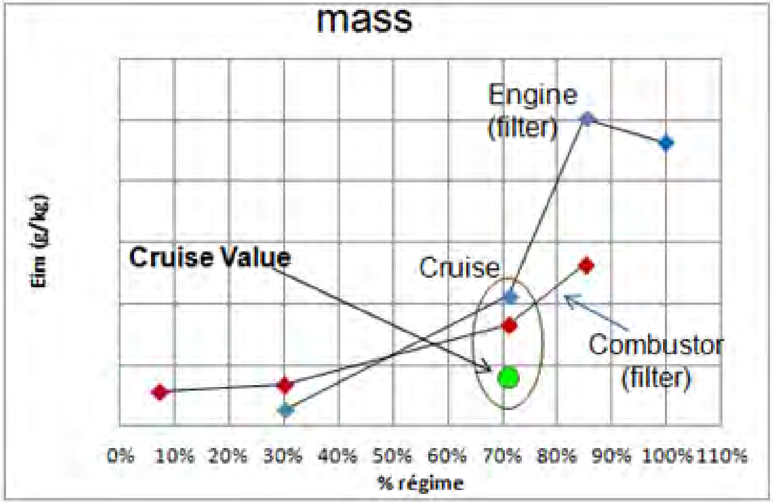
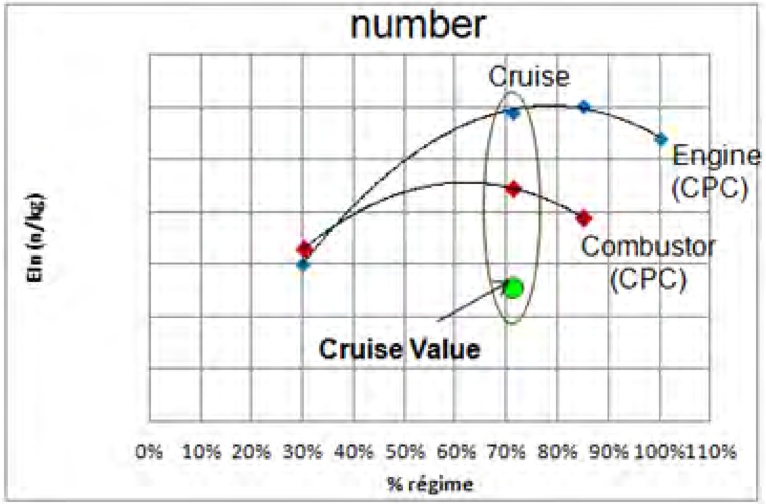
Cruise nvPM / SAM146 estimated cruise EIs



MERMOSE results

Joint analysis of results of MERMOSE campaigns on SaM146 engine and combustor permitted to extrapolate particles mass and number emissions indices (EIm & EIn) in cruise. This was a first attempt, and there are still strong uncertainties.





- 15.6mg/kg (Stettler's method) is much closer to the actual measurement
- Is Stettler method good? Are there compensating errors ? What about Peck's?

➔ Comparing only the finale value is <u>not sufficient</u>

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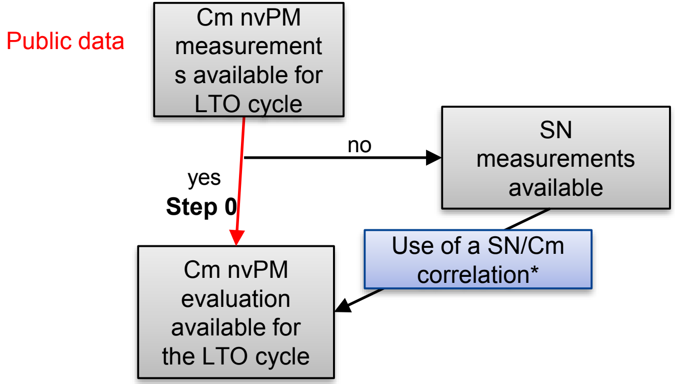
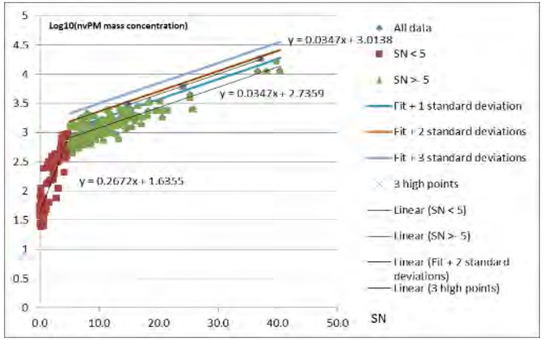
Workflow

for nvPM mass concentration





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EI = Emission Index
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cr = Cruise

N	Step
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1	T3/P3(cr)
2	Def ref pt.
3	Interpolation
4	C(sls)➔C(cr)
5	➔nvPMnum

Step 0: Available methods

- **SN/Cm correlations***
  - FOA3 ➔ Current recommended practice

$$C_{BC} = 0.0694 \times SN^{1.24}$$

  - CDb ➔ The nest fit line corresponds to the best knowledge available recently gathered in CAEP

$$Log_{10}(C(nvPM)) = 0.0347 \times SN + 2.7359 \quad [>5SN]$$

$$Log_{10}(C(nvPM)) = 0.02672 \times SN + 1.6355 \quad [<5SN]$$

  - SN/Cm correlations **may be further consolidated with manufacturers proprietary data**, in particular with engines currently tested to fill a CAEP database

- Alternative: no use of a correlation with SN, but direct calcultation (see FOX method developed by Stettler et al)

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Workflow

SN = Smoke number
Cm = nvPM mass Concentration
EI = Emission Index
SLS = Sea Level Static
cr = Cruise

N	Step
0	SN(sls)➔ C/EI(sls)
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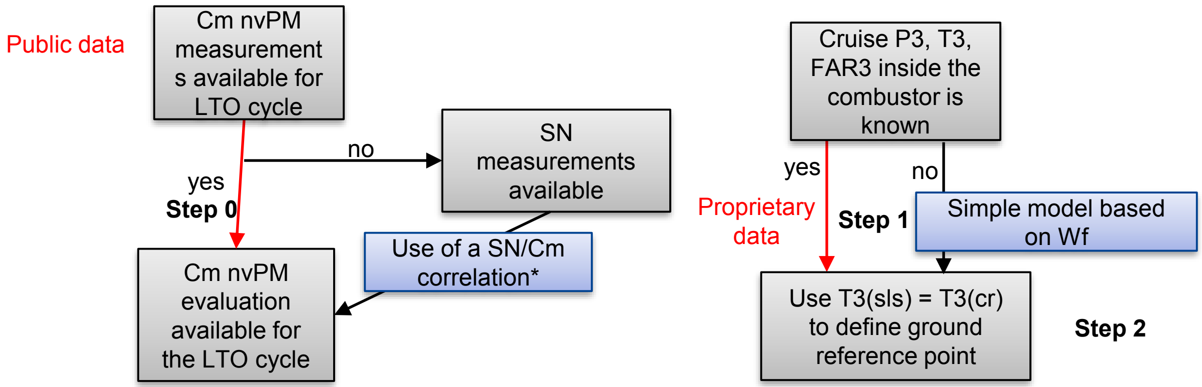
2	Def ref pt.
3	Interpolation
4	C(sls)➔C(cr)
5	➔nvPMnum



Step 1 – Reconstitution of the combustor characteristics P3,T3, FAR (cr)

- Stettler et al. and others if proposed
- **Engine manufacturers should test the methods and compare to actual proprietary data**

Step 2 – Choice of the referent point

- Without more data (test rigs sensitivity study): use T3(sls) = T3(cr) ; but not sure T3 is the most relevant parameter ?

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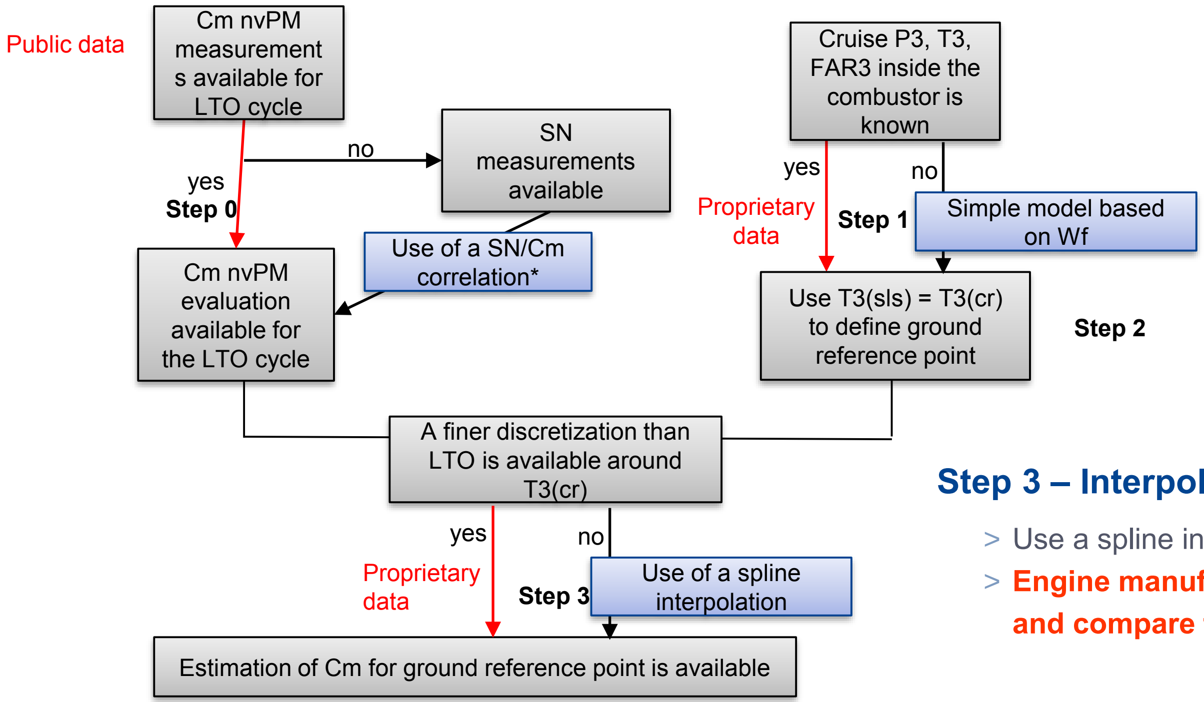

Step 3 – Interpolation

> Use a spline interpolation and/or other methods

> **Engine manufacturers should test the methods and compare to actual proprietary data**

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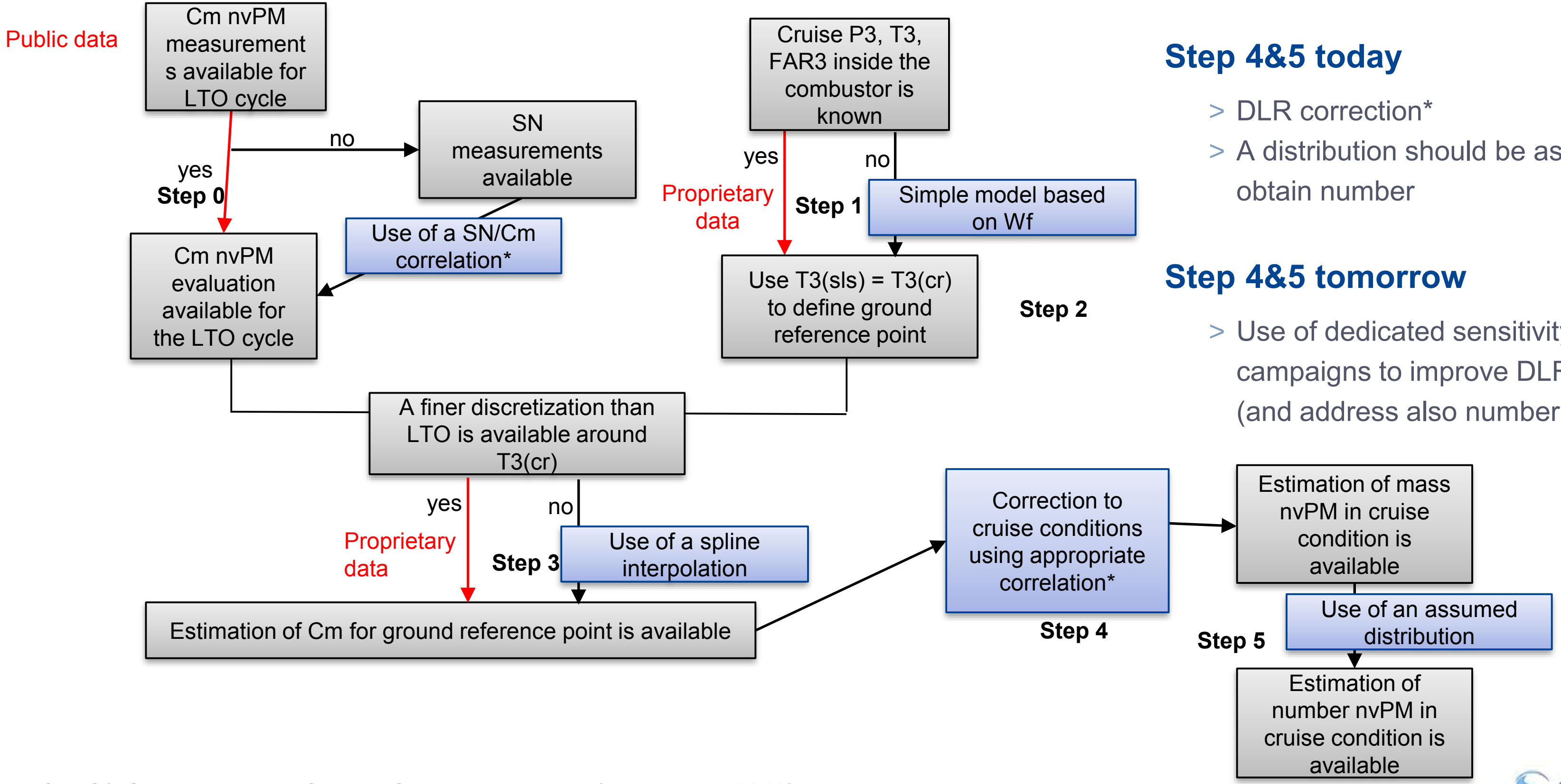

Step 4&5 today

> DLR correction*

> A distribution should be assumed to obtain number

Step 4&5 tomorrow

> Use of dedicated sensitivity test rig campaigns to improve DLR correction (and address also number)

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Conclusions

The review of existing cruise nvPM methods shows that adequate validation is limited (if not lacking) and that current cruise nvPM methodologies should be clearly improved for modellers purpose and usage.

They share the same backbone, which should be the structure for future studies, but quantitative estimation may vary greatly (e.g. 1 order of magnitude for SaM146)

- **A best practice for each step is proposed, but above all a validation procedure done by engine manufacturers using proprietary data, should be carried out, while keeping trace of uncertainties**

- **Keeping track of the technology (RQL/LEAN) is necessary** (=> effect on correction law?)

- **When performing studies requiring the knowledge of nvPM concentrations or EIs at engine exit in cruise, strong uncertainty on the assumed value should be considered (1 or 2 order)**

Nota: on which to focus the improvement modelling on cruise nvPM: mass/number? ; concentration/EI? And what about particles other than nvPM, in particular SOx type?

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