ICAO's work on NO_x emissions regulation

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The climate impact of aviation today generally stems from emissions of carbon dioxide (CO_2) and cloud formations like contrail-cirrus, while air quality impacts are mainly due to emissions of oxides of nitrogen (NO_x) and particulate matter (PM). NO_x regulations have been in place for decades and NO_x emissions continue to be a major engine design parameter. In summary, NO_x environmental impacts are as follows:

NO_x and climate: The net present-day radiative effect of aircraft NO_x emissions is estimated to be positive (i.e. a warming effect). However, this estimate does not account for the (highly uncertain) cooling from NO_x attributable to aerosols. Because of these indirect forcings and potential changes in background concentrations of ozone precursors, future net NO_x radiative forcing could vary from positive to negative. Since NO_x radiative forcing is currently estimated to be positive and the effects are relatively short-lived, stabilization of aircraft NO_x emissions may be a reasonable target with respect to climate effects.

NO_x and local air quality: Aviation emissions contribute to the degradation of air quality via increases in ground level concentrations of harmful pollutants like NO_2. Recent research has strengthened the understanding that aviation air quality impacts include both local-to-regional scale impacts due to near-surface (near airport) emissions as well as global scale impacts resulting from emissions during cruise. Some modelling studies[1] find that global aviation air quality impacts are principally due to cruise-altitude emissions of NO_x. Aircraft emissions during the LTO phase also have been shown to cause health impacts due to exposure to ultrafine particles (UFP), PM2.5, O_3 and NO_2 concentrations. In many countries, local air quality regulatory limits for NO_2 are therefore in force and tend to become more stringent over time. From a local air quality perspective, increasing aviation NO_x emissions around airports are of concern.

While more modern engines tend to emit less pollutants thanks to reduced fuel consumption and improved combustion technology, this is not generally the case for NO_x. Already during the CAEP/12 cycle, the CAEP Impacts and Science Group (ISG) and the Emissions Technical Working Group (WG3) identified increasing NO_x emissions for modern aircraft-engine combinations replacing older aircraft-engine combinations of similar capacity. Some inventories showed an increase in absolute NO_x emissions from aviation, which was even higher than the increase of absolute CO_2-emissions caused by growth of aviation. How was this possible?

The existing Landing and Take-off cycle (LTO) NO_x metric in ICAO environmental standards for engine certification has been originally designed to incorporate relevant physical parameters related to NO_x emissions, namely the fuel flow and a correlation to the overall pressure ratio (OPR) of the engine. The higher the OPR of an engine, the higher the thermodynamic efficiency, but the higher the combustion temperatures and the harder it gets to control NO_x. This is because, at these conditions, Nitrogen and Oxygen (the primary constituents of air) start to react with each other. In order to account for the physical dependence on OPR, NO_x regulatory limits have a positive slope as a function of OPR. The higher the OPR of an engine, the higher is the regulatory limit. As higher OPR is linked to higher combustion efficiency, there is an inherent trade-off between fuel burn and NO_x emissions. Therefore, the

1 Barrett et al. 2010; Eastham et al. 2024; Eastham and Barrett 2016; Lee et al. 2013; Quadros, Snellen, and Dedoussi 2020, Grobler et al. 2019 (details in References)

development of more fuel-efficient engines was leading to higher OPR, which in turn tended to produce higher NO_x emissions. There are exceptions, as engine manufacturers have been working very hard to optimize or even develop dedicated complex combustion systems to better control NO_x. In terms of changes in fleet composition, also a tendency towards using larger aircraft has been observed. With the exception of the most modern combustion technology, larger engines also tend to produce higher NO_x per unit of thrust.

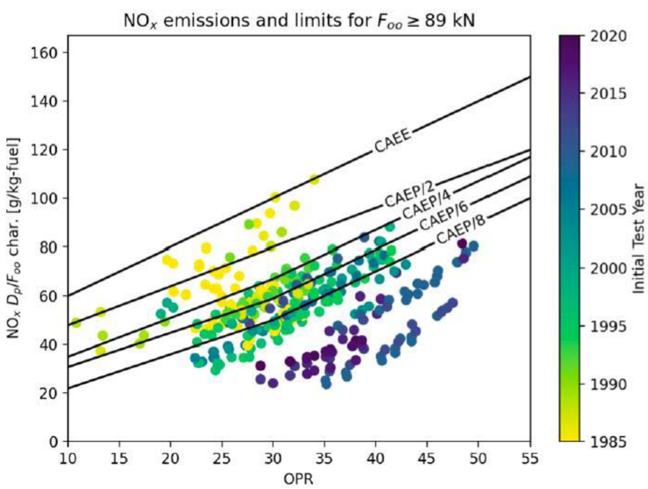

FIGURE 1: LTO NO_x metric values (mass of NO_x emitted during the LTO cycle over the engine rated thrust (Dp/Foo[2]), colored dots) in function of engine OPR. The black lines correspond to the regulatory limit lines for engines with rated thrust > 89 kN, with the original highest limit "CAEE" and the latest limit "CAEP/8" agreed in 2010. The color scale indicates the year of the emission certification test of the engines. (Source: ICAO Engine Emissions Databank[3])

The ICAO LTO NO_x Standard has not been updated since 2010 (CAEP/8). Taking the history and advancements in certified combustion system designs for latest generation engines into account, it became obvious that the standard needs an update. During the last three years, a number of alternative metrics and stringency approaches have been considered by WG3 with a view to correct for the observed trend of increasing NO_x emissions. For future work on NO_x regulation, it was determined in the CAEP/13 cycle that the current NO_x metric system (LTO NO_x normalized by rated thrust vs OPR) still has the best possibility for controlling NO_x and be backward compatible with existing regulations. WG3 found that the regulatory problem identified can be addressed by keeping the metric but updating the design and shape of the regulatory limit line. In February 2025, the CAEP/13 meeting recommended to start a NO_x LTO Stringency Standard Setting Process, pending Council approval, following three possible approaches or a combination of them:

a) Shift the CAEP/8 line (right or down) to achieve NO_x neutral improvement,
b) Change (decrease) the slope of the LTO NO_x per rated thrust (Dp/Foo) vs OPR line, and
c) Place a "cap" on the maximum Dp/Foo value (either a flat "cap" or a "cap curve" asymptoting to a maximum value)

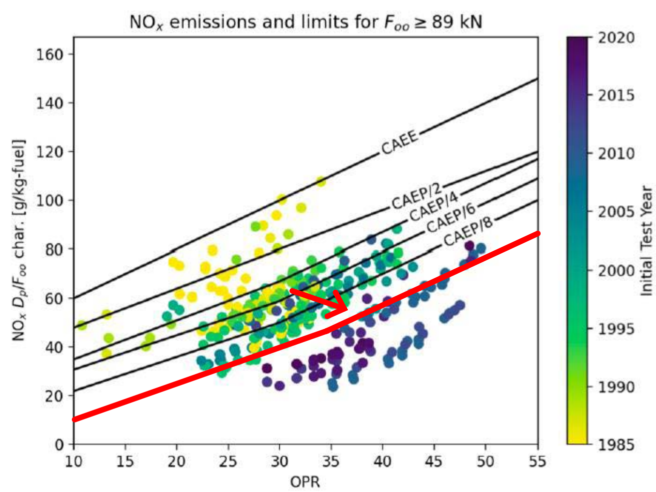

FIGURE 2: Illustration of the option for shifting the CAEP/8 line to the right, based on expected future increase in engine OPR, with a view to stabilize NO_x emissions in balance with high fuel efficiency.

Subject to Council approval, CAEP will undertake the analysis and develop proposals for an updated, more stringent LTO NO_x regulation. An updated standard will have to follow the CAEP principles, balancing environmental benefit with technological feasibility, economic viability, and the interdependency between environmental factors. Completion of an updated LTO NO_x stringency in ICAO Annex 16, Volume II is targeted for CAEP/14 (2028).

2 The mass, in grams (Dp), of any pollutant emitted during the reference landing and take-off (LTO) cycle, divided by the rated output (Foo) of the engine.

3 ICAO Aircraft Engine Emissions Databank: https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

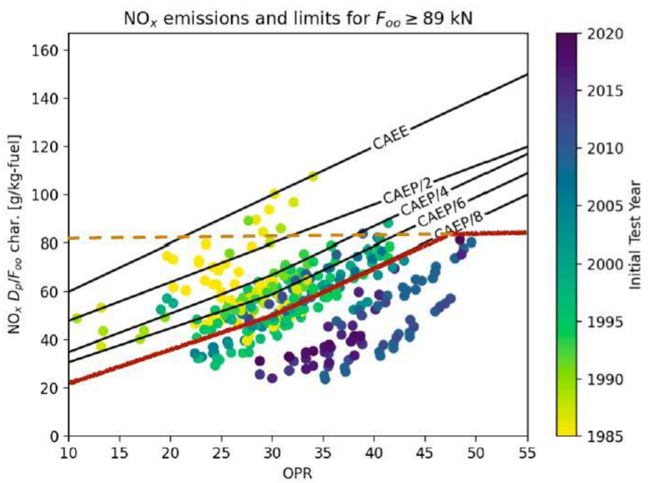

FIGURE 3: Example of putting a cap (red horizontal line) for a maximum NO_X Dp/Foo. The colored points correspond to certified values in the ICAO engine emissions database, with the color code indicating the year of the emission certification test.

Due to climate issues, cruise NO_X increased in importance. The traditional LTO NO_X metric has been designed with a view to control airport-related NO_X emissions and consequently to satisfy local air quality standards. This includes the choice of four reporting points, which are linked to taxi operations (7% Foo) on ground, full rated thrust take-off roll (100% Foo), a climb (85% Foo) and an approach mode (30% Foo), see Figure 4. With increasing scientific knowledge and awareness of impacts from cruise NO_X emissions, the question of how well the LTO regulation is able to control cruise emissions was coming more and more into focus. The cruise NO_X performance of an engine cannot be measured at ground conditions. In terms of combustor inlet temperature in cruise, a ground level thrust setting with the same inlet temperature will usually be somewhere in the middle between 30 and 85% thrust. But since engine combustion pressures, ambient temperature and the lack of forward movement of the engine in the static test do not correspond to cruise conditions, a ground level measurement does not relate to the emissions during cruise in a straightforward way and conversion calculations to altitude conditions are necessary.

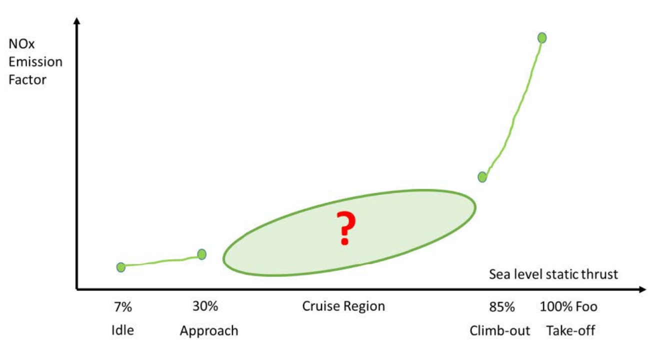

FIGURE 4: Illustration of certification NO_X emission factors measured at 7, 30, 85 and 100% sea level static thrust. The green circle depicts an area of cruise NO_X emission factors, which are currently interpolated between 30 and 85% points and corrected for altitude cruise flight conditions for NO_X emission inventories.

Historically, it has been accepted that controlling LTO NO_X would control cruise/climb NO_X to a high degree. The main reason for this is the heavy weighting of the 85% thrust point in the LTO metric. If this point is at a relatively low value, the slope of the interpolation between 30 and 85% will be lower. However, it was unclear whether interpolation assumptions would be good enough for most modern and future engine designs. In the CAEP/13 cycle, analysis was done considering new technology combustors (i.e. advanced rich burn and lean burn as currently certified), the several stages of the cruise phase (fuel flow and power varies between early, middle, and late cruise) as well as considering all phases of full flight except leaving out the LTO components. The analysis showed that the cruise/climb emissions can depend differently on the engine power points compared to the LTO emissions. As an example, two most modern engines could have similar values in the LTO NO_X metric, while they might have very different cruise NO_X performance.

In February 2025, the CAEP/13 meeting therefore decided, pending Council approval, that WG3 should continue to develop an additional engine-level cruise NO_X metric to complement the LTO NO_X metric and assess its ability to better control cruise NO_X emissions.

As mentioned above, the LTO metric lacks reporting of emission factors between 30 and 85% sea-level static thrust (Foo). However, this range is relevant for cruise NO_X estimations, as can be seen in Figure 4. The CAEP/13 meeting therefore agreed to investigate (pending Council approval) the feasibility and added value of a potential reporting point for EI NO_X at 57.5% Foo (the mid-point between 30 and 85%). The goal is to better characterize cruise emissions in the future while recognizing that the ground-based 57.5% Foo point does not correspond directly to cruise emissions. WG3 will collect and analyse emission indices NO_x data of modern gas turbine engines for combustor inlet temperature ranges relevant for cruise flight conditions. Depending on the outcome of such analysis, it will propose amendments to implement a respective reporting requirement into Annex 16, Volume II. This activity is strongly related to actions on aviation Non-CO_2 emissions and on nvPM reporting.

References

Barrett, Steven R. H., Rex E. Britter, and Ian A. Waitz. 2010. "Global Mortality Attributable to Aircraft Cruise Emissions." *Environmental Science & Technology* 44(19):7736–42. doi: 10.1021/es101325r.

Eastham, Sebastian D., Guillaume P. Chossière, Raymond L. Speth, Daniel J. Jacob, and Steven R. H. Barrett. 2024. "Global Impacts of Aviation on Air Quality Evaluated at High Resolution." *Atmospheric Chemistry and Physics* 24(4):2687–2703. doi: 10.5194/acp-24-2687-2024.

Eastham, Sebastian D., and Steven R. H. Barrett. 2016. "Aviation-Attributable Ozone as a Driver for Changes in Mortality Related to Air Quality and Skin Cancer." *Atmospheric Environment* 144:17–23. doi: 10.1016/j.atmosenv.2016.08.040.

Lee, H., S. C. Olsen, D. J. Wuebbles, and D. Youn. 2013. "Impacts of Aircraft Emissions on the Air Quality near the Ground." *Atmospheric Chemistry and Physics* 13(11):5505–22. doi: 10.5194/acp-13-5505-2013.

Quadros, Flávio D. A., Mirjam Snellen, and Irene C. Dedoussi. 2020. "Regional Sensitivities of Air Quality and Human Health Impacts to Aviation Emissions." *Environmental Research Letters* 15(10):105013. doi: 10.1088/1748-9326/abb2c5.

Grobler, Carla, Philip J. Wolfe, Kingshuk Dasadhikari, Irene C. Dedoussi, Florian Allroggen, Raymond L. Speth, Sebastian D. Eastham, Akshat Agarwal, Mark D. Staples, Jayant Sabnis, and Steven R. H. Barrett. 2019. "Marginal Climate and Air Quality Costs of Aviation Emissions." *Environmental Research Letters* 14(11):114031. doi: 10.1088/1748-9326/ab4942.