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Analysis of LTO Cycle Emissions as Results of Aircraft Operations in the Vicinity of Torino Caselle Airport

Edoardo Blanco[1,a] and Davide Ferretto[1,b] *

[1]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

[a]s347182@studenti.polito.it, [b]davide.ferretto@polito.it

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Abstract. This paper proposes a methodology based on the Boing Fuell Flow Method 2 (BFFM2) in order to assess non-CO2 emissions resulting from the analysis of real-life aircraft Landing and Take-Off (LTO) cycles. The method is validated exploiting, as case study, the operational procedures in the vicinity of Torino Caselle airport, in the north-west part of Italy. Notably, this study focuses on the analysis of the individual operational procedures, including Standard Instrument Departures (SIDs), Standard Terminal Arrivals (STARs) and Approaches, published by the Italian Air Navigation Service Provider (ENAV), in order to assess the expected level of emissions for nominal trajectories, potentially identifying those flight legs which can be more relevant in terms of impact on air quality. This may open up for suggestions about updates to the procedures themselves, according to a trade-off with actual flown distance (i.e. fuel consumption), also looking at the most congested trajectories.

Introduction

The mitigation of aviation's environmental impact is a key requirement to ensure the sustainable growth of the sector, in line with regulatory demands and the continuous increase in air traffic. Following the goals of the 2015 COP 21 Paris Agreement [1], the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [2], as part of the Long-Term Aspirational Goal (LTAG) [3] defined by the Committee on Aviation Environmental Protection (CAEP).

While CO2 reduction is critical in order to reduce global climate impact, the influence of non-CO2 emissions and, notably, Unburned Hydrocarbons (HC), Carbon Monoxide (CO) and Nitrogen Oxides (NOx) [4], directly affects air quality around airports. To quantify these pollutants, ICAO established an engines certification procedure based on standard operating points of the Landing and Take-Off (LTO) cycle [5], with results collected in a continuously updated database [6].

To extend such certification data beyond LTO conditions, Boeing introduced the Fuel Flow Method 2 (BFFM2) [7], which uses semi-empirical correlations to estimate continuous in-flight emissions. Compared to more detailed methods (such as P3T3 [8]), BFFM2 offers a simpler yet effective framework, which has been applied also to non-conventional configurations [9]. These approaches have since enabled preliminary assessments of local environmental impacts by combining traffic data with airport-specific characteristics and operational patterns [10, 11, 12].

This paper proposes a methodology based on the BFFM2 in order to assess non-CO2 emissions resulting from the analysis of real-life aircraft LTO cycles. The method is validated exploiting, as case study, the operational procedures in the vicinity of Torino Caselle airport, in the north-west part of Italy. Notably, this study focuses on the analysis of the operational scenario, including Standard Instrument Departures (SIDs), Standard Terminal Arrivals (STARs) and Approach procedures, published by the Italian Air Navigation Service Provider (ENAV) [13], in order to assess the expected level of emissions for nominal trajectories. The main goal is to provide a preliminary evidence of the impact of current operational procedures on air quality, which can be used as basis for a potential update of the trajectories, also considering a trade-off with actual flown distance (i.e. fuel consumption), especially looking at the most congested paths (according to open flight tracking data).

The paper is organized as follows: after this short introduction, a methodological section is presented, with the aim of describing the approach used for the collection of flight data and the implementation of the BFFM2. A section including the main results is then described, with focus on emissions computed for all SIDs and STARs/Approaches. Ultimately, a short summary collects the main outcomes of the work and paves the way for future research.

Methodology

The modeling approach adopted in this work relies on dedicated datasets assembled to characterize inbound and outbound traffic, engine performance, and mission profiles. These inputs were used to estimate non-CO2 emissions in the proximity of Torino Caselle International Airport (LIMF) through the implementation of BFFM2 method.

The structure of such database was divided in three main, branches (Fig. 1): a collection of all information related to standard departure and arrival procedures (SIDs/STARs) involving the airport and derived by official documentation released by ENAV [13]; a catalog of aircraft engines performance across specific regimes obtained from the ICAO Engine Data Bank [6]; a flight database obtained from the sampling of a time frame that could be considered unaffected by bias due to traffic seasonal peaks, thanks to open tracking services.

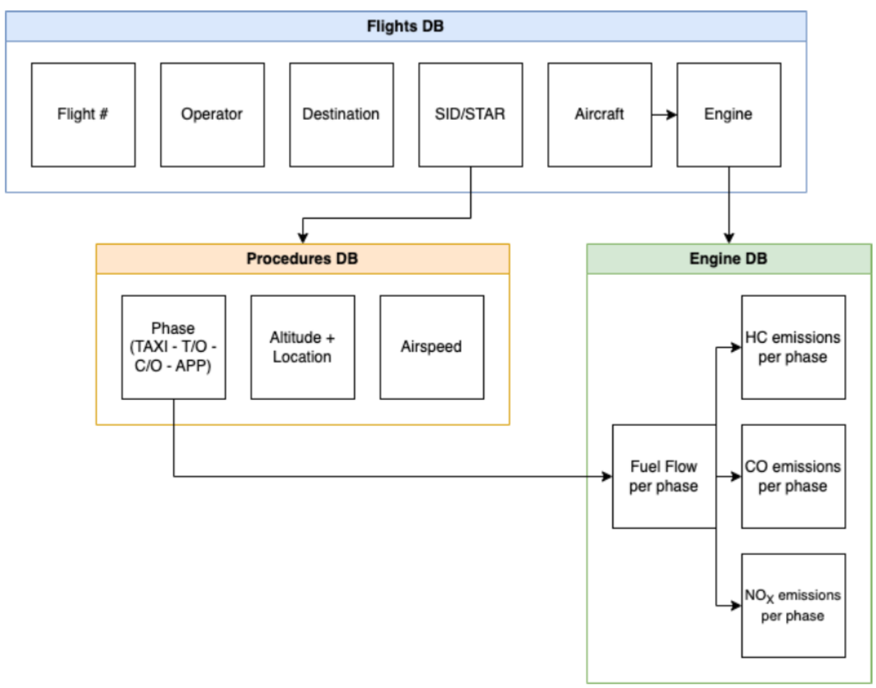

Figure 1: Datasets exploited and related links

Basic data specific to flights was collected exploiting the web based Flightradar24© service. The determination of aircraft model for each LTO cycle created an unambiguous link between the propulsive database, through the determination of the model, and number of installed engines. Furthermore, visual inspections of flight paths enabled the recognition of the actual procedures and consequent mission profiles followed. Samples presenting mismatches between actual tracks and official procedures were excluded from the study. In fact, differently from other works available in literature, such as [12], this paper does not exploit flight tracking service as unique

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source of data to build the reference trajectory, but only as verification mean to quantify the usage of the operational procedures. Undoubtedly, in order to start an informed decision making process for procedures update, aimed at improving air quality around the regions affected by air operations, it is important to refer, in the first place, to the official procedures representing the intended paths published by the Authority, rather than looking only at flown trajectories, which may be affected by episodic bias, as well as tracking errors.

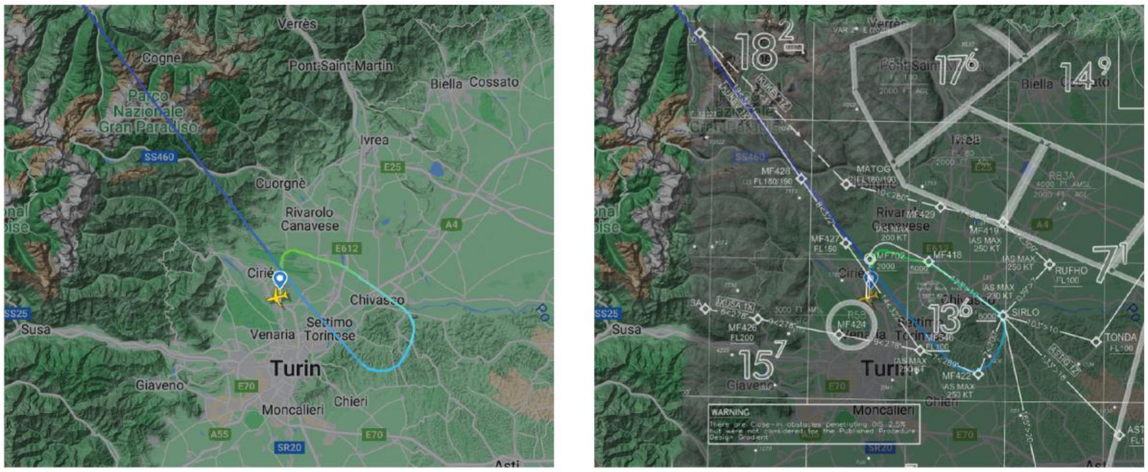

Figure 2: Example of valid trajectory (sources: FlightRadar24) and its adherence to official procedures [13]

The estimation of non-CO2 emissions was then carried out, as already mentioned, using the BFFM2 [7], a semi-empirical approach developed to extrapolate certification data to the entire operational envelope of the engine. The method establishes correlations between fuel flow rate and Emission Indices (EI), allowing the calculation of pollutant mass flows under arbitrary operating conditions. For each i-th pollutant, the emission index EI_i [g/kg_fuel], at a given operating point, is expressed as a function of the reference emission index at equivalent sea-level static conditions ($EI_{i,ref}$) (Eq. 1 to 3), associated, exploiting the data in the ICAO Databank [6], to the reference fuel flow rate $\dot{m}_{f,ref}$ (Eq. 4) computed by translating the actual rate $\dot{m}_f$ (in flight) to sea-level conditions as well.

$$EIHC = EIHC_{ref} \cdot \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \tag{1}$$

$$EICO = EICO_{ref} \cdot \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}} \tag{2}$$

$$EINO_x = EINO_{x_{ref}} \cdot \sqrt{\frac{\delta_{amb}^{1.02}}{\theta^{3.3}}} \cdot e^H \tag{3}$$

$$\dot{m}_{f,ref} = \frac{\dot{m}_f}{\delta_{amb}} \cdot \theta_{amb}^{3.8} \cdot e^{0.2 \cdot M} \cdot r \tag{4}$$

where δ_{amb} and θ_{amb} are ambient pressure and temperature ratios, M is the Mach number and H is a humidity correction factor. The reference flow rate is also multiplied by a coefficient r, which accounts for installation and bleed air extraction losses. Representative values of r for the different operating regimes are reported in Table 1.

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Table 1: Correction coefficients ***r*** *for fuel flow*

	Idle	Approach	Climb-Out	Take-Off
Throttle [%]	7	30	85	100
r [-]	1.100	1.020	1.013	1.010

The methodology was applied to Torino Caselle International Airport (LIMF), selected as a representative regional hub characterized by mixed short and medium-haul operations. A traffic sample was collected for a reference period between 8-14 March 2024, chosen to minimize seasonal biases and ensure a statistically representative dataset. The resulting dataset included 232 departures and arrivals, covering 14 different aircraft/engine combinations. For each mission profile, the BFFM2 model was applied to compute continuous emission indices and pollutant mass flows up to 10,000 ft, thus extending the conventional LTO cycle and enabling the assessment of local air quality impacts in the airport surroundings. The equations were implemented in a Python model, allowing the automated processing of flight data and the discrete estimation of emissions at specific waypoints along each trajectory.

Results

The model application yielded quantitative estimates of HC, CO and NOx emissions for the reference time frame. Results are presented in terms of average emission rates per flight and their spatial distribution with respect to airport surroundings, according to the SIDs (Fig. 3) and STARs (Fig. 4) respectively followed.

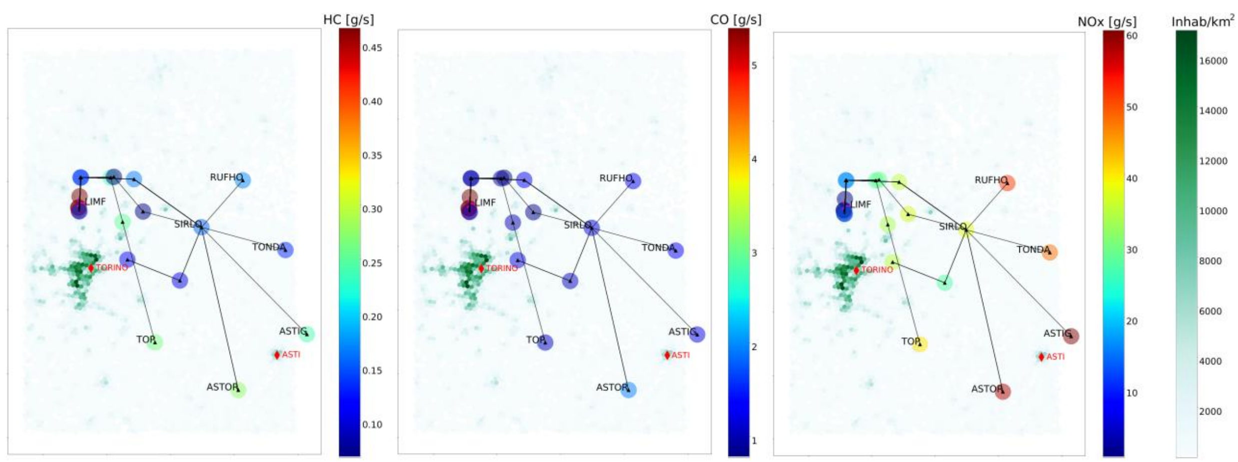

Figure 3: Visualization of emission rates according to SIDs (overlaid with population density)

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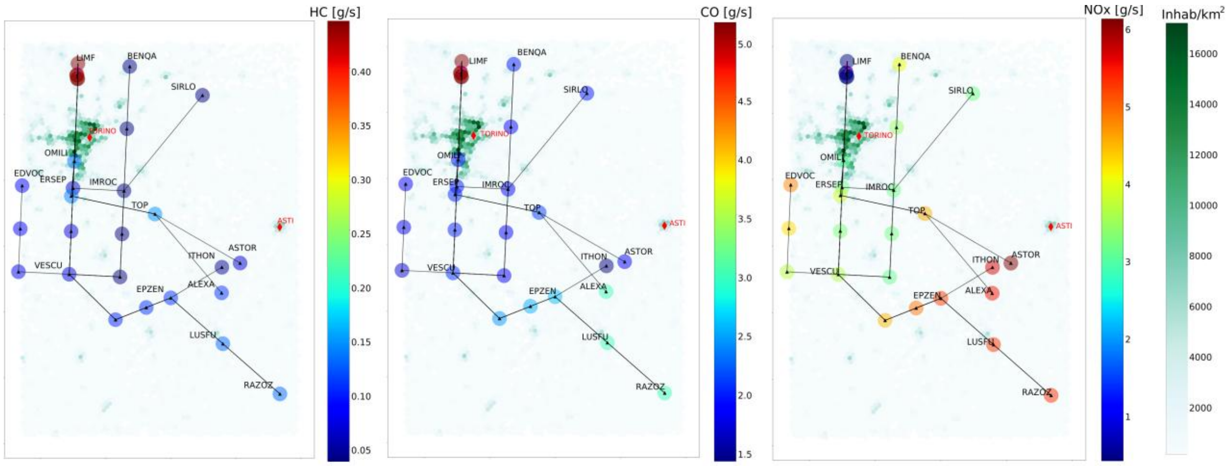

Figure 4: Visualization of emission rates according to STARs/Approaches (overlaid with population density)

Analysis of the emission profiles indicates that more than 50% of HC and CO emissions occur during ground operations (idle and taxi), with a marked reduction at take-off, where maximum thrust is applied. This confirms their nature as incomplete combustion products. In contrast, NOx production showed a strong dependence on altitude and engine thrust. Emission rates for NOx at take-off represented in fact approximately 15% of the peak values observed during climb-out segments around 10,000 ft, where temperatures and pressures combination in the combustor favour NOx formation. The spatial mapping of emission sources across procedures highlights that instantaneous peaks of NOx are concentrated along departure and initial arrival corridors, whereas HC and CO remain localized in the immediate airport vicinity. When overlaid with population density data, the results reveal that the areas most affected by pollutant emission sources are generally displaced from the most densely populated districts of Turin. This may be favourable from an exposure perspective, as the strongest sources are far from densely populated areas, even though a dispersion analysis is required to evaluate the true impact on ground, also according to meteorological data.

Summary

This work exploits the Boeing Fuel Flow Method 2 (BFFM2) in order to evaluate non-CO2 effects on local air quality referring to real world navigation and traffic data. The method is validated with reference to the Landing and Take-Off (LTO) cycles associated to operations in the vicinity of Torino Caselle International Airport (LIMF). In this case, results show that the positioning of emission sources along the trajectories is located far from densely populated areas, with the majority of HC and CO emitted on ground (on airport premises), while NOx have peaks at higher altitudes. The work confirms that this approach can be effectively adopted to potentially consider updates to operational procedures, in order to account for local air quality impact, even though dispersion analyses are needed, as future works, to better assess the distribution of pollutants with time, making benefit of meteorological data.

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