Integrating Eco-Efficient Flight Planning In Aircraft Conceptual Design: Minimal NO_x Routes For High-Speed Aircraft Using Hydrogen

Fabrizio Borgna[1], Valeria Borio[2], Roberta Fusaro[3], Nicole Viola[4] & Guido Saccone[5]

[1] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy)
[2] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy)
[3] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy)
[4] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy)
[5] Italian Aerospace Research Centre, Via Maiorise, 81043 Capua (Italy)

Abstract

The increasing global demand for faster air transport has recently redirected the aviation industry's focus to the field of high-speed aircraft. This trend has motivated notable interest within the scientific community in assessing the environmental impact of potential fleets of supersonic and hypersonic aircraft. These aircraft categories widely employ hydrogen as an eco-friendly fuel to minimize carbon emissions. However, high-speed aircraft utilizing hydrogen as fuel generate concerns regarding non-carbon emissions, particularly NO_x emissions. To accompany this transition towards a greener scenario of high-speed hydrogen-powered transport, it is necessary to develop new strategies to anticipate the estimation of NO_x emissions from this category of aircraft in the conceptual design phase. A more accurate estimation of these emissions allows for assessing their impact in terms of anthropogenic climate forcing and pollution. Furthermore, the integration of new emission estimation methodologies into the aircraft route optimization process allows for minimizing the aviation net positive contribution to global warming. To promote eco-strategic air traffic planning, the present paper proposes a specialized algorithm for high-speed hydrogen-fueled aircraft, leading to the formulation of a route characterized by minimal environmental impact regarding NO_x emissions.

Keywords: Eco-efficient flight planning; High-speed aircraft; Nitrogen oxide emissions; Hydrogen-fueled aviation; Conceptual design optimization.

1. Introduction

The contemporary landscape is marked by a return of air transport demand to pre-pandemic levels. This resurgence poses a challenge to the decarbonization objectives and climate change mitigation imperatives stipulated by international agreements [1]. Consequently, there is a growing and compelling need for systematic exploration and specialization in understanding global aviation emissions and their associated impact on anthropogenic climate forcing [2].
Global aviation activities contribute to climate change through an intricate array of processes that culminate in a net warming effect on the Earth's surface. CO_2 emission has historically been the focal point of attention, with the aviation sector contributing to 2.5% of global emissions [2]. Nevertheless, as emphasized in Lee et al.'s study, which seeks to assess the overall impact of aviation on global warming through Radiative Forcing (RF) evaluation, the total contribution of

aviation to climate change is significantly higher. Radiative forcing quantifies the disparity between incoming energy and the energy emitted back into space: an excess of absorbed energy over radiated energy results in atmospheric warming. According to the findings of Lee et al., aviation contributes approximately 3.5% to the total radiative forcing, signifying a 3.5% contribution to the warming phenomenon. Despite the predominant focus on CO_2, its contribution to this warming is less than half. A substantial majority, approximately 66%, is ascribed to non-CO_2 forcing, specifically water vapor and NO_x [3]. Furthermore, emissions containing nitrogen dioxide (NO_2) and nitrogen monoxide (NO) play a substantial role in altering the concentration of ozone (O_3), consequently amplifying the overall environmental implications [4]. This perspective, linked to the alteration of the composition of the ozone sphere due to emissions from aviation, becomes even more concerning when considering the recent expansion of this industry into supersonic and hypersonic flight. As for high-speed aircraft, the aviation industry has demonstrated a growing interest in adopting hydrogen as an ecological alternative to conventional fuels. Recent research studies have demonstrated that the utilization of Sustainable Aviation Fuel (SAF) and hydrogen, as alternatives to traditional kerosene, results in an estimated 50%-75% reduction in the environmental impact of the aviation industry. Furthermore, utilizing hydrogen as fuel results in the elimination of particulate and carbon dioxide CO_2 emissions, making it the optimal candidate for minimizing the carbon footprint within the sector [5]. However, due to significantly higher altitudes involved in supersonic and hypersonic flights compared to subsonic ones, non-CO_2 emissions take place in the stratosphere and exhibit longer atmospheric lifetimes compared to emissions from subsonic aircraft, which predominantly operate within the troposphere, causing concern within the scientific community regarding their impact on global warming. NO_x and H_2O emissions from these aircraft have effects on the distribution and concentration of stratospheric ozone. Such implications are critical, given that the ozone layer acts as a shield for the Earth's surface against biologically harmful ultraviolet radiation from the Sun and plays a fundamental role in the context of global warming. Furthermore, NO_x emissions during supersonic and hypersonic flight occur at altitudes that can lead to both ozone increase and decrease, contingent on flight conditions, adding to the complexity and environmental implications [6] [7] [8].

In the recent scenario of ecological transition in the high-speed air transport sector, it is appropriate to focus on NO_x emissions, investigating their spatiotemporal influencing factors, estimation methodologies, and strategies for reducing their environmental impact. In this regard, the present study aims to investigate eco-planning strategies to be integrated into the conceptual design of high-speed aircraft. To this end, three different reviews are reported concerning (i) strategies for the assessment of the environmental impact of NO_x emissions based on the spatial location of the emission point, (ii) route optimization methodologies for eco-strategic flight planning, and (iii) new methodologies for estimating NO_x emissions for high-speed hydrogen-fuelled aircraft suitable for conceptual design. Specifically, Section 2 provides a comprehensive literature review encompassing all projects that have aimed to quantify the global impact of aviation NO_x emissions as a function of the spatial coordinates of the emission point. Table 1 provides an overview of the selected publications for this discussion.

Table 1 - Global impact of aviation NO_x emissions, a Review.

Authors	Title	References
M. Niklaß et al.	Potential to reduce the climate impact of aviation by climate-restricted airspaces	[4]
A. Ingenito	Impact of hydrogen-fueled hypersonic airliners on the O_3 layer depletion	[6]
J. Zhang et al.	Stratospheric ozone and climate-forcing sensitivity to cruise altitudes for fleets of potential supersonic transport aircraft	[7]
J. Pletzer et al	The climate impact of hydrogen-powered hypersonic transport	[8]
F. Yin et al.	Predicting the climate impact of aviation for en-route emissions: the algorithmic climate change function submodel ACCF 1.0 of EMAC 2.53	[9]
M. O. Kohler et al.	Latitudinal variation of the effect of aviation NO_x emissions on atmospheric ozone and methane and related climate metrics	[10]
J. van Manen, V. Grewea	Algorithmic climate change functions for the use in eco-efficient flight planning	[11]
K. N. Tait et al.	Aircraft emissions, their plume-scale effects, and the spatiotemporal sensitivity of the atmospheric response: a review	[12]
D. Lee et al.	Lower NOx at higher altitudes - policies to reduce the climate impact of aviation NO_x emission	[13]
J. Zhang et al.	Potential impacts of supersonic aircraft emissions on ozone and resulting forcing on climate: An update on historical analysis	[14]

Once this phase of reviewing the state-of-the-art techniques for high-level estimation of the impact of NO_x emissions based on spatiotemporal parameters is concluded, Section 3 proceeds with an analysis of multi-objective route optimization strategies suitable for aircraft conceptual design. Table 2 summarizes the content reviewed during this phase of the study.

Table 2 - The route optimization problem.

Authors	**Title**	**References**
V. Kumar et al.	Airplane flight route optimization problem with multi-constraints	[15]
S. Hartjes et al.	Efficient trajectory parameterization for environmental optimization of departure flight paths using a genetic algorithm	[16]
V. Ho-Huu et al.	An optimization framework for route design and allocation of aircraft to multiple departure routes	[17]
M. P. Fanti et al	Flight path optimization for minimizing emissions and avoiding weather hazard	[18]
F. Vergnes et al.	Environmental impact optimisation of flight plans in a fixed and free route network	[19]

To extend the applicability of environmental impact mitigation strategies to the case of NO_x emissions produced by high-speed aircraft powered by non-traditional fuels, Section 4 investigates new mathematical tools for estimating NO_x emissions from these categories of aircraft. These new emission estimation methodologies have been recently developed specifically to address emissions from the conceptual design phase of the aircraft onwards. The strategy proposed in the reference studies reported in Table 3 involves modifying and adapting the classical formulations of emission estimation methods developed for subsonic aircraft powered by traditional fuels, the P3T3 and the BFFM2 [20], to the high-speed hydrogen-fuelled case study.

Table 3 - Novel emission index estimation methodologies.

Authors	**Title**	**References**
F. Borgna	Conceptual design methodology and tools for the estimation of emissions from SABRE engine in airbreathing mode	[21]
R. Fusaro et al.	NO_x emissions estimation methodology for air-breathing reusable access to space vehicle in conceptual design	[22]

R. Fusaro et al.	Analytical Formulations for Nitrogen Oxides Emissions Estimation of an Air Turbo-Rocket Engine Using Hydrogen	[23]
R. Fusaro et al.	Sustainable Supersonic Fuel Flow Method: An evolution of the Boeing Fuel Flow Method for Supersonic Aircraft Using Sustainable Aviation Fuels	[24]

Based on the gathered information on tools and methodologies, Section 5 presents a preliminary design phase algorithm formulated for the minimization of NO_x emissions utilizing an aircraft route optimization process. The presented strategy involves an initial data collection phase aimed at formulating an aerodynamic and logistical database specific to the examined high-speed aircraft. Furthermore, novel methodologies for estimating high-speed aircraft NO_x emissions during the conceptual design phase need to be employed. Using this data, it is possible to introduce Climate change Cost Functions CCF, whose constrained minimization enables the formulation of a route estimation characterized by the minimal environmental impact of NO_x emissions.

2. Spatial planning factors that influence NO_x emissions environmental impact

In the assessment of the environmental impact of NO_x emissions, it is crucial to attribute a spatial connotation to the emission estimates under consideration. Georeferencing emissions, indeed, facilitate the evaluation of their interaction with the surrounding environment under specific atmospheric conditions. This, in turn, enhances the reliability of assessing the effects of such interactions at a chemical-physical level. Furthermore, investigating the synergistic relationship between the three spatial coordinates expressed in terms of latitude, longitude, and altitude, in conjunction with the estimated emissions for a given engine, lays the groundwork for a preliminary examination of what are referred to as climate-optimized flight trajectories [9]. The close connection between the emission point location of NO_x and its subsequent impact has been studied since the early 2000s, as evidenced by the work of M. O. Kohler et al. In this study, the response to regional and latitudinal changes in aircraft NO_x emissions is evaluated using various climate metrics, including Radiative Forcing (RF), Global Warming Potential (GWP), and Global Temperature change Potential (GTP). During this study, chemical transport model experiments were executed, implementing regional perturbations in aircraft NO_x emissions. Initially, emission perturbations were uniformly distributed throughout the vertical extent of the atmosphere across four distinct geographical regions. Subsequently, targeted increases in NO_x were introduced at cruise altitude within discrete latitude bands. The results of this investigation reveal a notable regional sensitivity of ozone and methane levels to variations in NO_x emissions, particularly at cruise altitude. Overall, increases in emissions at lower latitudes tend to exert more pronounced impacts on the ozone (O_3) column and methane (CH_4) lifetimes compared to increases in emissions at higher latitudes [10]. As highlighted by the work of M. Niklaß et al., non-CO_2 emissions are highly influenced by chemical and meteorological background conditions. Moreover, because of their considerably shorter lifetimes compared to CO_2, the climate impact of non-CO_2 emissions is significantly affected by emission location (altitude, latitude, longitude) and time (time of the day and season). Considering these dependencies, the most effective mitigation strategies involve optimized flight trajectories that minimize both time and emissions climate impact, particularly in climate-sensitive regions. It is therefore conceivable to employ an operational and regulative approach to emission minimization that involves the identification of so-called Climate-Restricted Airspaces (CRA), similar to military exclusion zones. Based on these areas, a recalculation of the flight path for the affected aircraft can be conducted. These airspaces are defined based on 3-D climate change functions, which characterize the environmental impact resulting from aircraft emissions at specific locations [4]. To achieve this, 3D Climate Change Functions (CCF) have been computed, delineating the environmental impact resulting from a reference aircraft emission at a specific location. The CCF had been used to estimate the Average Temperature Response (ATR) resulting from aviation NO_x emissions. The study reveals a promising potential for emissions mitigation; however, it should be noted that the computational cost of climate change function simulations makes them impractical for real-time calculations and operational implementation. The same issue has been addressed by J. van Manen and V. Grewe in their work [11], demonstrating that a solution to this problem can be achieved by devising algorithmic approximations for the global climate impact. In their study, they develop algorithmic Climate Change Functions (aCCFs) through regression analysis, approximating changes in water vapor concentration from local aviation emissions, ozone changes from local NO_x emissions, and methane changes from local NO_x emissions based on instantaneous model weather data. The outcomes indicate that the meteorological conditions at the time of emission play a crucial role in determining the evolution of the emitted species, with the quality of the aCCF diminishing as the lifetime of the respective species increases [11]. This research confirms the feasibility of planning climate-optimized routes through the avoidance of climate-sensitive regions where non-CO_2 effects, such as strong contrail formation and ozone production, are particularly pronounced. Recent advancements arise in the study conducted by F. Yin et al., in which the submodel ACCF 1.0 of the global atmosphere-chemistry model EMAC is described. This submodel is deployed to assess the climate impact of aviation emissions along the flight corridor of the Northern Hemisphere, serving as an instantiation of the aCCF formulas. This submodel computes the climate impact of aviation emissions, encompassing both CO_2 emissions and non-CO_2 effects. The non-CO_2 effects include those induced by NO_x, such as NO_x-induced O_3, NO_x-induced CH_4, H_2O, and contrail cirrus. The results of this analysis enable the profiling of the magnitude of non-CO_2 effects, particularly NO_x, based on latitude, longitude, and altitude [9]. To enhance the current relevance of this study, consideration has been given to the work of Zhang et al., highlighting a paradigm shift in the aviation industry's focus toward supersonic and hypersonic flight. In Zhang et al. investigation, a series of sensitivity experiments on potential future cruise altitudes has been undertaken to evaluate the potential atmospheric response for a fleet of supersonic aircraft. This prospective fleet may induce both ozone increase and decrease, dependent upon altitude, primarily attributed to nitrogen oxide emissions. The alterations in Total Column Ozone (TCO) are altitude-dependent. Additionally, the study explores seasonal ozone loss, changes in ozone, and climate radiative forcing per unit of fuel burn, all correlated with the cruise altitude [14].

3. Aircraft route planning optimization in conceptual design

The second part of this study focused on the investigation of a constrained route optimization strategy compatible with the conceptual design phase when the designer has limited access to proprietary aircraft data. In this regard, four distinct approaches derived from the literature have been analysed and chosen as references. Kumar et al. propose a comprehensive overview of aircraft flight route optimization, addressing the complex aspects of the problem where optimization is subject to multiple constraints. The proposed algorithm, which utilizes MATLAB Optimization Toolbox, reduces the total time spent flying long-distance routes by optimizing trajectory in a three-dimensional wind environment constrained by various time-of-arrival requirements [15]. Despite the presented problem focusing on temporal optimization of the route, this study is noteworthy for its stochastic modelling of the considered environmental conditions and the utilization of the MATLAB function *fmincon* for solving the optimization problem. This function, designed for finding the minimum of a constrained nonlinear multivariable function, proves to be particularly suitable for the approach adopted in the current work. The second referenced study, authored by Ho-Huu et al., presents a two-step optimization framework developed for the design and selection of aircraft departure routes, coupled with the allocation of flights among these routes. The first step involves multi-objective trajectory optimization, used to compute and store a set of routes characterized by minimum fuel consumption and minimal noise. In the second step, the selection of routes from the pre-computed optimal set and the optimal allocation of flights to these routes are conducted simultaneously to minimize the cumulative noise. The noteworthy aspect of this work is the trajectory parameterization, implemented using the method presented by Hartjes and Visser [16]. This technique divides the trajectory into two components: a horizontal and a vertical profile. This approach allows for the separation of these two profiles, simplifying the optimization problem for spatial coordinates, including latitude, longitude, and altitude [17]. The publications cited so far provide guidelines in terms of methodology and tools to address the route optimization problem. However, the primary focus of these studies is to enhance aircraft performances, except for Ho-Huu's work, which addresses the theme of noise minimization. Regarding the strategic route planning problem aimed at minimizing pollutant emissions and their environmental impact, the study conducted by Fanti et al. can be used as a reference. This study introduces a methodology for determining aircraft's optimal path with the dual objectives of avoiding weather hazards and reducing CO_2 and NO_x emissions. In this dissertation, the aircraft movement is identified through a finite state automaton, which is a state vector whose components include its spatial coordinates, airspeed, and heading. The optimal transition state path is the outcome of a finite-horizon open-loop optimization problem that considers all the possible connections among the states that the aircraft can reach based on feasible manoeuvres. Through a Model Predictive Control (MPC) approach, it identifies the path characterized by the lowest estimated emissions using the Base of Aircraft DAta (BADA) [25] and ICAO models, alongside the Advanced Emission Model 3 (AEM3) [18]. Lastly, it is useful to reference the recent work conducted by Olive et al., which aligns with the framework of aircraft conceptual design. This paper describes and implements a pathfinding algorithm based on the definition of a heuristic technique, in contrast to previously mentioned strategies characterized by a stochastic approach. This algorithm represents an extension of the Dijkstra algorithm, commonly used for solving the shortest path problem. It allows the selection, through the study of a heuristic function, of a sequence of waypoints that minimizes the total flown distance, total burnt fuel, CO_2, and non-CO_2 emissions. This approach starts with the simplification of the aircraft dynamics equations and the introduction of geometric-spatial constraints derived from the analysis of Free Route Areas (FRA) and the ATS route Network (ARN) between departure and arrival airports. The selection of waypoints that form the optimal eco-route occurs through the optimization of the heuristic, coinciding with the minimization of the so-called Climate Change Cost Function (CCF), defined as follows:

$$CCF(t) = \sum_{i=1}^{n_{gas}} GWP_i * EI_i * \int_{t_0}^{t_f} ff(t)dt \tag{3.1}$$

where GWP_i is the CO_2-equivalent emission, EI_i is the emission index for the i-th gas and ff(t) is the fuel flow. As evident from the experimental results reported in the paper, this algorithm appears to be a viable deterministic solution for 3D flight plan optimization in both fixed route and free route networks [19].

4. Novel NO_x emissions estimation methods for high-speed aircraft powered by non-conventional fuel

For subsonic aircraft propelled by traditional fuel (kerosene), numerous methodologies are available in the literature for estimating emissions of pollutants and greenhouse gases. According to [20], five different categories of methods for estimating emissions can be identified: (i) correlation-based models, (ii) P3T3 methods, (iii) Fuel-Flow methods, (iv) simplified physics-based models, and (v) high-fidelity simulations. The correlation-based, P3T3, and FF methods are of interest for the present study and exhibit a similar approach for estimating the Emission Index (EI) of pollutants and greenhouse gases (GHG) produced by the engine under study. Focusing on NO_x emissions, correlation-based methods assess the $EINO_x$ of the engine using empirical or semi-empirical relationships derived from the analysis of correlations between NO_x emissions and primary or secondary propulsion-emission variables. The P3T3 and FF methods represent a specialization of correlation-based models with a much broader range of applicability. They require a limited amount of input data and calculate the $EINO_x$ at Flight Level (FL) based on the $EINO_x$ measured at Sea Level (SL), which must be adjusted to altitude conditions using both altitude and ground-level combustor operating conditions. Specifically, the P3T3 and FF methods provide generalized mathematical formulations for estimating $EINO_x$, valid for any subsonic aircraft powered by traditional fuels, and suitable for the conceptual design phase. To extend the applicability of these emission estimation methods to high-speed flights powered by non-conventional fuels, recent studies have proposed innovative strategies for updating the mathematical formulations and adapting the aforementioned methods. As detailed in [21], the proposed strategies involve modifying the classical formulations of the P3T3 and Fuel-Flow methods to tailor their applicability to the characteristics of next-generation aircraft case studies. Specifically, the new formulations of these methods are suited for estimating NO_x emissions from high-speed engines using sustainable aviation fuels. This adaptation and enhancement process from the original P3T3 and BFFM2 is achieved by introducing new parameters in the form of non-dimensional ratios between FL and SL conditions, coupled with the optimized updating of the coefficients in the original mathematical formulations. These new parameters are derived from correlation-based research that investigates the relationships between combustion-propulsive variables and the formation of NO_x in the engine. The selected parameters are considered particularly influential in shaping the emissions profile of the propulsive system under study. The parameters chosen for updating the original formulations of the methods may vary depending on the fuel used by the engine, its operation, and potentially the mission phase under consideration. The outlined strategy was employed in [21] [22] to evaluate the $EINO_x$ of the Synergetic Air Breathing Rocket Engine (SABRE), designed by Reaction Engine Limited to be hydrogen-fuelled and capable of reaching low Earth orbit (LEO). This study focused on the engine air-breathing mode, which extends from subsonic to hypersonic flight regimes. In this case, both the classical formulations of the P3T3 and BFFM2 methods were updated and adapted to the

case study, resulting in estimation errors of less than 10%. A similar approach of updating and adapting the classical emission estimation methods was proposed in [23] for the P3T3 method to evaluate the NO_x Emission Indices of the Air Turbo-Rocket Engine (ATR) Using Hydrogen. Likewise, the study on the Concorde engine [24] proposed an evolution of the Boeing Fuel Flow Method for Supersonic Aircraft Using Sustainable Aviation Fuels, with a special focus on biofuels and biofuel blends.
The original mathematical formulations of the classical P3T3 and BFFM2 methods for evaluating $EINO_x$ are reported below for informational purposes, respectively in Eq. 4.1 and Eq. 4.3.

$$EINO_{X\,FL} = EINO_{X\,SL}\left(\frac{p_{3FL}}{p_{3sL}}\right)^{n}\left(\frac{FAR_{FL}}{FAR_{SL}}\right)^{m}\exp\left(H\right) \tag{4.1}$$

$$H = 19 * (h_{SL} - h_{FL}) \tag{4.2}$$

$$EINO_{X\,FL} = EINO_{X\,SL}\left(\frac{\delta_{amb}^{i}}{\theta_{amb}^{j}}\right)^{k}\exp\left(H\right) \tag{4.3}$$

$$\theta_{amb} = T_{amb}[K]/288.15 \tag{4.4}$$

$$\delta_{amb} = p_{amb}[Pa]/101325 \tag{4.5}$$

The P3T3 method evaluates the $EINO_x$ under FL conditions by correcting the $EINO_x$ recorded under SL conditions using a correction factor that is a function of the inlet pressure to the combustion chamber (p_3), humidity factor H, and the Fuel to Air Ratio (FAR). All parameters are interpolated and expressed as a function of the inlet temperature of the combustion chamber (T_3). Conversely, concerning the BFFM2, the $EINO_x$ under SL conditions are interpolated and expressed as a function of the fuel flow (ff), and the correction factor is a function of the theta and delta ratios, respectively representing the temperature and pressure ratios between FL and standard SL conditions. The generalized formulation of the P3T3 method for evaluating $EINO_x$ under FL conditions for all subsonic aircraft powered by traditional fuels involves coefficients m and n set to 0 and 0.4. Similarly, coefficients i=1.02, j=3.3, and k=0.5 provide the generalized formulation of the BFFM2. The previously mentioned works propose new mathematical formulations that, while maintaining the form and parameters, modify the original ones to account for the effects of high speed and the type of fuel used. The derived new formulations introduce new parameters, such as the Mach number, and the Damköhler number, rather than new ratios of temperatures, pressures, or mass flow rates characteristic of the engine under study, along with optimized exponent coefficients to better fit emission profiles. All the cited research led to estimation relative errors of less than 10%, and even lower than 5% for the more comprehensive mathematical formulations derived from the original P3T3 and FF methods. Given the excellent results obtained in the context of the aircraft conceptual design, it is promising to consider the use of these new mathematical tools not only to estimate emissions before they occur but also to prevent emissions themselves by leveraging this preliminary quantitative estimation.

5. Development of Eco-Efficient Flight Planning Algorithm

The concluding segment of this study entails the development of a specialized flight planning algorithm for high-speed aircraft, drawing from the three literature reviews conducted earlier. This algorithm implements a route optimization process to minimize the aircraft NO_x emissions, providing as output the spatial coordinates of waypoints that constitute the best eco-route. Specifically, the chosen strategy is the minimization of the previously introduced CCF specialized for NO_x emissions, as this methodology proves to be the most compatible with the dataset available to the designer during the conceptual design phase. To achieve this, it is necessary to input into the algorithm an aerodynamic database and a logistical one, specific to the aircraft under examination. The aerodynamic database should encompass all the aerodynamic features essential for formulating a fuel flow model, such as the Base of Aircraft Data (BADA) model [25]: this model is designed to provide the fuel flow variable as a function of the flight speed. The fuel flow parameter, in addition to explicitly appearing in the CCF relationship, is also crucial for evaluating the NO_x emission index, which is also featured in the CCF relationship. Recent studies have indeed demonstrated that new formulations of the Boeing Fuel Flow Method 2 (BFFM2), originally applicable only to subsonic aircraft, can now estimate the NO_x emission index as a function of the fuel flow profile for high-speed aircraft as well, even in the case of aircraft powered by non-traditional fuels [21],[24]. In addition to the new mathematical formulations of the BFFM2 for estimating NO_x emissions in the context of high-speed flight and Sustainable Aviation Fuel, studies [21], [22], and [23] also present updated formulations of the P3T3 estimation method. Depending on the type of available input data, one method may be preferred over the other, and it is also possible to adapt the chosen formulation to new case studies to obtain a more precise estimate of emissions. On the other hand, the logistical database should include not only the pair of cities that the selected aircraft needs to connect but also information regarding the Free Route Areas (FRA) and the ATS route network (ARN) between departure and arrival airports. Based on these geometric-spatial constraints, it is possible to identify all possible sequences of waypoints within the area of interest. For this purpose, the introduction of an additional geometric tool, such as the Exploration Cone introduced in [19], may be considered to limit the number of nodes to be investigated as potential waypoints. Lastly, starting from the identified list of potential waypoints and the parameters derived from the aerodynamic database, it is possible to evaluate the CCF for each pair of nodes and select the next waypoint from the starting one such that the climate change cost function is minimized. Iterating this process of CCF evaluation for each segment connecting two waypoints from take-off to landing, it is possible to construct the minimum NO_x trajectory. The following diagram summarizes the workflow that the algorithm follows to identify, starting from the departure airport and then for all subsequent points until the arrival airport, the next waypoint of the minimum NO_x trajectory.

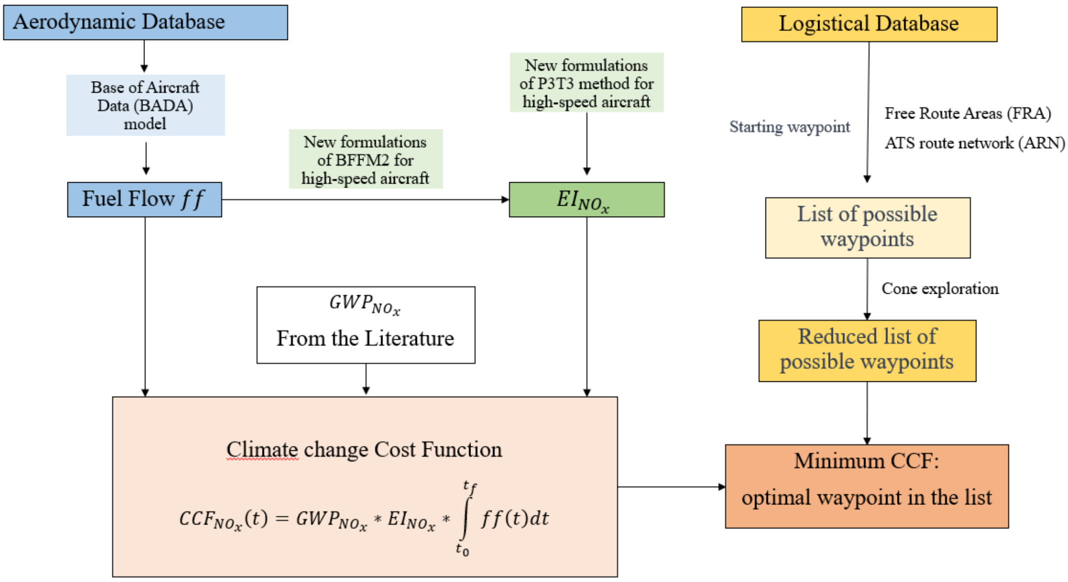

Figure 1 - Route optimization process to minimize aircraft NO_x emissions.

6. Conclusion and discussion

Upon a thorough analysis of the cited case studies, it is possible to present a comprehensive overview of the techniques for assessing the global effects of non-CO_2 emissions in the context of aviation, with a particular focus on NO_x emissions. Regarding NO_x emissions, this study discloses the significance of understanding their spatial resolution referring to the magnitude of their environmental impacts. Considering the contemporary interest of the aerospace industry in high-speed aviation, this study focuses on the impact of NO_x emissions from supersonic and hypersonic aircraft, highlighting the challenges associated with higher altitudes where these emissions occur. The purpose is to provide readers with insights into the potential of route modifications to optimize the minimization of these emission's climate impact. In this regard, a review of high-level methodologies for assessing the environmental impact of these emissions is initially presented. Subsequently, various case studies from the literature proposing multi-objective route optimization techniques for emission minimization are analysed. Considering that every emission reduction strategy and subsequent environmental impact mitigation of the mission relies on the most accurate estimation of the emissions under study, a brief overview regarding the state-of-the-art emission estimation methodologies is provided, particularly focusing on NO_x emissions from high-speed aircraft powered by sustainable aviation fuel. Indeed, the literature presents mathematical formulations for estimating the Emission Indices of pollutants and GHGs produced by this new generation of aircraft. These formulations represent an update of the classical formulations of the P3T3 and BFFM2 methods, traditionally used for estimating emissions from subsonic aircraft powered by kerosene. The strategy of updating the mathematical formulations of the classical methods based on the architectural and operational characteristics of the engine under examination is briefly summarized in Section 4 and detailed in the bibliography.

From these three state-of-the-art reviews, the information and tools required to formulate a NO_x emissions minimization strategy applicable in the conceptual design phase are obtained, and a preliminary algorithm is provided. In conclusion, this study aims to deliver to readers a general method applicable to high-speed aircraft, facilitating a preliminary route optimization study. This optimization extends beyond the traditional focus on cost or consumption minimization and delves into the domain of non-CO_2 emissions climate impact minimization. Such an outcome opens roadmaps for numerous future developments, particularly the specialization of this methodology for different aircraft categories utilizing various fuels and operating within distinct high Mach number regimes.

7. Contact Author Email Address

Fabrizio Borgna, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy), fabrizio.borgna@studenti.polito.it, +39 3273963849

Valeria Borio, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy), valeria.borio@polito.it

Roberta Fusaro, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy), roberta.fusaro@polito.it

Nicole Viola, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin (Italy), nicole.viola@polito.it

Guido Saccone, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua (Italy) g.saccone@cira.it

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