Aviation-induced nitrogen oxide emissions and their effect on the energy budget of the Earth-atmosphere system

Identification of climate optimized trajectories

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***Abstract*—The present paper contains statements about the influence of the aviation-induced nitrogen oxide emissions on the atmosphere and investigates the generation of climate optimized trajectories. First, it presents a general model approach which connects all needed single models for generating optimized trajectories concerning minimization of the nitrogen oxide induced climate impact. Second, it contains the calculation of emitted nitrogen oxides for different generated horizontal trajectories including variable flight distances and altitudes. Subsequently, qualitative statements about the generation of climate optimized trajectories in terms of nitrogen oxide emissions are derived. Furthermore, some potential strategies for reducing the climate impact of nitrogen oxides regarding operative regulatory measures are discussed.**

Keywords- nitrogen oxide emissions; climate optimized trajectories; trajectory assessment

I. INTRODUCTION

Air transport is assumed to be one of the key roles in international mobility. It provides the only worldwide transportation network [18]. It is the fastest and safest transport sector and the aviation industry is in constant growth. Since the crisis in 2009, the number of passengers in Germany has increased by 11%, in Europe by 9.3% and worldwide by 29% [1]. This is accompanied by an increase in global fuel consumption and aviation-induced emissions of pollutants. Therefore, air transport has a significant impact on climate change, which will also continue to grow. The aviation emissions: carbon dioxide (CO_2), nitrogen oxides (NO_x), water vapor (H_2O), sulfur dioxide (SO_2), carbon monoxide (CO), unburned hydrocarbons (UHC) and soot (C), change the natural composition of the atmosphere. Thus, the concentrations of the greenhouse gases CO_2, H_2O, ozone (O_3) and methane (CH_4) are altered and also the formation of contrail- cirrus is influenced. Consequently, aviation changes not only the natural composition of the atmosphere, but also the climate change [2].

In recent years, the environmental awareness grew especially in the industrialized countries. Securing the sustainability of the Earth and the protection of climate and environment is unquestionably a global challenge, which necessarily has to be faced by politics and economics. This ambitious goal is already one of the objectives of SESAR and NextGen. To meet this challenge the Institute of Logistics and Aviation at the Faculty of Transportation and Traffic Sciences at the Technical University of Dresden started the project MEFUL (Minimizing Flight Emissions while Sustaining Guaranteed Operational Safety as a Contribution to an Environmental Friendly Air Transport System), which is funded by German Federal Ministry of Economic and Energy (BMWI) and Lufthansa Cargo AG. The aim of the project is the implementation of an ecologically friendly and safe air transport system to ensure the sustainability of aviation as mode of transport. To realize this, not only a reduction of emissions but also a reduction in their influence on the radiation budget of the atmosphere is required.

In this paper, the nitrogen oxide emissions are focused, since their effects are associated with diverse and complex chemical processes in the atmosphere. On the one hand, they induce a short term increase in ozone production and on the other hand, a long-term reduction of methane and ozone concentration in the atmosphere. So, contrary processes are accomplished which are very difficult to measure and calculate. So far, there are different results in terms of the extent of the compensating effect.

The aim is to identify trajectories with minimal impact of nitrogen oxide emissions in the radiation budget of the atmosphere within the MEFUL-project.

This work is part of the research project MEFUL (Minimize emissions in the operational flight with guaranteed operational safety as contribution to an environmentally friendly air transport system), financed by the Federal Ministry for Economic Affairs and Energy Germany (BMWI).

II. CALCULATION OF THE NO_X EMISSIONS

A. *Aircraft Performance Model*

In order to calculate the NO_x emissions it is necessary to generate vertical trajectories. Therefore, the aircraft performance model COALA is used, which was developed at the Technical University Dresden, Institute of Logistics and Aviation within the MEFUL project. It generates vertical flight trajectories for the aircraft type Airbus A320 with the engine type CFM56-5A3 (2 times per 111.2 kN power rating).

It is based on the integration of a dynamic equation which results from the flight mechanics, including the decrease in the mass of the aircraft due the fuel flow. The temporal discretization is $dt = 1$ s. The model assumes a Continuous Climb of the aircraft with a maximum climb gradient up to an altitude of 10.000 ft which is defined as first climb phase. After reaching this level, the aircraft increases continuously with the maximum climb rate up to the optimal cruise altitude. This second climb phase is already used for a maximum increase of flight distance. The Take-Off is realized with 100% thrust and after 3 min the thrust is reduced to 85% with a reduction of one percent per second. For the descent, continuous descent operations are assumed. To calculate the maximum thrust at a certain level and the fuel flow the BADA (Base of Aircraft Data) of EUROCONTROL is used [3].

To calculate the nitrogen oxide emissions different vertical trajectories were generated by COALA. Therefore, different distances and cruise altitudes were taken into consideration. So, the distances include ranges of 2.000, 3.000, 4.000, 5.000 and 6.000 km. The altitudes contain 5.000, 6.000, 7.000, 8.000, 9.000, 10.000, 11.000, 12.000 and 13.000 m as well as optimal cruise altitude for the maximum specific range. In this calculation the optimal cruise altitude is about 11.7 km. For using a different altitude than the optimum cruise altitude, the fuel consumption increases. If this altitude is achieved on a flight, the altitude increases continuously due to the loss of weight because of the fuel consumption. This cruise method is defined as Maximum Range Cruise. It guarantees the lowest fuel consumption but means at the same time that the airspeed is relatively low and an extended flight time [4].

B. *Generated and calculated parameters*

The parameters listed in the following Table 1 are output by the flight performance model and were available for further calculations.

Furthermore, the calculation of other parameters on the basis of the output data of the flight performance model is needed (see Table 2). The calculation rules are explained for the additional parameters.

The total parameters $T_{t,0}$ and $p_{t,0}$ are calculated as follows

$$T_{t,0} = T_0 + c_0^2/2*c_p \quad (1)$$

$$p_{t,0} = p_0*(T_{t,0}/T_0)^{\kappa/\kappa-1} \quad (2)$$

with the isentropic constant κ=1,4 and specific heat capacity cp=1004,5 Nm/kgK. The reference plane 1 corresponds to reference plane 2, therefore applies

$$T_{t,0} = T_{t,1} \quad (3)$$

$$p_{t,0} = p_{t,1}. \quad (4)$$

Furthermore, for the calculation of emissions of nitrogen oxides by the Boeing Fuel Flow Method 2 the Mach number M and the local sonic speed *a* are needed [9]

$$M = c/a \quad (5)$$

$$a = (\kappa*R_i*T_0)^{-1/2} \ . \quad (6)$$

Here, *c* [m/s] describes the True Air Speed (TAS) and is generated by the COALA. To calculate the local sonic speed the isentropic constant κ and the specific gas constant R_i=287 Nm/(kg*K) are required [5].

TABLE I. OUTPUT PARAMETERS

Parameter	**Definition**	**Unit**
t	flight time	[s]
x	distance	[m]
y	altitude	[m]
v	true air speed	[m/s]
m_{Fuel}	fuel mass	[kg]
F	thrust	[N]
$\dot{m}$	Fuel Flow	[kg/s]
p_3	combustor inlet pressure	[Pa]
T_3	combustor inlet temperature	[K]
p_0	ambient pressure	[Pa]
T_0	ambient temperature	[K]

TABLE II. CALCULATED PARAMETERS

Parameter	**Definition**	**Unit**
$T_{t,1}$	total engine inlet temperature	[K]
$p_{t,1}$	total engine inlet pressure	[Pa]
M	mach number	[-]
a	local sonic speed	[m/s]

C. Calculation of nitrogen oxide emissions

There are various methods and models to calculate the emission index of nitrogen oxides (*EINOx*) which can be classified into the following categories: correlation models, fuel flow methods, simplified physics-based models and CFD (computational fluid dynamics) models [7].

Due to the complexity of the other methods as well as of the required extensive computer performance and data, correlation models are used for further calculations. These are described in the following section.

1.) Döpelheuer[8]

This method is one of the semi-empirical models and uses reference values measured at sea level published by the ICAO. Therefore, actual parameters are involved in the calculation, such as in this case, the actual fuel flow. This is related to the corresponding reference values on the ground.

For the determination of the reference values ($EINO_{x,ref}$) the emissions on the ground are measured for the four different thrust levels: 100% (Take Off), 85% (Climb Out), 30% (Approach) and 7% (Idle) for all common engine types. These are published in the ICAO emissions database.

The reference value for the fuel flow and emission indices are taken out of this database for the A320 CFM56-5A3 used in the aircraft performance model. See Table 3.

The emission indices can be calculated as follows.

$$\frac{EINO_x}{EINO_{x,ref}} = \left(\frac{p_3}{p_{3,ref}}\right)^{0,5} \left(\frac{T_{3,ref}}{T_3}\right)^{0,5} \left(\frac{T_{PZ,ref}}{T_{PZ}}\right)^{1,5} e^{38000\left(\frac{1}{T_{fl,ref}}-\frac{1}{T_{fl}}\right)} \quad (7)$$

To be able to apply formulas like these practically, it is necessary to make further modifications. The following formula is simplified by further approximations [8].

$$EINO_x = const. * p_3{}^a * e^{bT3} \quad (8)$$

Hereby, the problem is reduced to a formula that requires only the combustor inlet temperature T_3 and pressure p_3. But these data are the property of the engine manufacturers and are considered very sensitive.

TABLE III. OUTPUT ENGINE-SPECIFIC DATA FROM ICAO DATABASE

	T/O	C/O	APP	IDLE
EINOx [g/kg]	26,4	21,1	8,3	4,1
Fuel Flow [kg/s]	1,131	0,925	0,307	0,1044

Therefore, methods were considered, which do not require this data. So, there were applied further simplification with the correction factor for the temperature θt and pressure δt and these two relations [8]

$$T_{3,corr} = T_3/\theta_t \text{ with } \theta_t = T_{t,1}/288,15K, \quad (9)$$

$$p_{3,corr} = p_3/\delta_t \text{ with } \delta_t = p_{t,1}/101,3kPa. \quad (10)$$

Furthermore, another approximation is used, which avoids T_3 in the exponent. So applies

$$EINO_x = const. * p_3{}^a * T_3{}^b. \quad (11)$$

In order to get the emission indices on reference level ($EINO_x$) it is necessary to correct fuel flow by the following formula

$$w_{fuel,corr} = \frac{w_{fuel}}{\delta t\sqrt{\theta t}}. \quad (12)$$

With equations (9) and (10), the following simplified formula is used to calculate the emission indices

$$\frac{EINO_x}{EINO_{x,ref}} = \delta_t^a * \theta_t^b. \quad (13)$$

Assuming an International Standard Atmosphere (ISA) and sea level conditions δt and θt become unity: $\delta t = \theta t = 1$. In this case, the $EINO_x$ represents the reference value. The evaluation of (Equation 11) shows, that a=0,4 to a=0,5 for the pressure exponent and b=3 for the temperature exponent. Measurements yielded a=0,4 [8].

2.) Boing Fuel Flow Method 2[9]

The Boeing Fuel Flow Method 2 (BFM2) sets the exhausted emissions in relation to the fuel flow. This method is also recommended by the ICAO Committee on Aviation Environmental Protection (CAEP). Even here, reference is made to the ICAO emission databank to investigate the correlation ratio. There, the data for the fuel flow and the emission indices for the four power settings are retrieved. Though, these data do not contain installation effects, so initially the fuel flow values have to be corrected [6].

$$RW_{ff} = RW_{ff,u} * r \ , \quad (14)$$

where r denotes the correction factor, $RW_{ff,u}$ the fuel flow at reference conditions published by ICAO and RW_{ff} the corrected fuel flow at reference conditions considering installation effects. The correction factor r is established for the four different thrust settings, which are defined by the ICAO database (see Table 4).

TABLE IV. FUEL FLOW CORRECTION FACTOR R FROM ICAO DATABASE

	T/O	C/O	APP	IDLE
Thrust Setting [% F_{00}]	26,4	21,1	8,3	4,1
Correction factor r	1,010	1,013	1,02	1,100

The fuel flow data, which are output of the performance model, also need to be corrected. The corrected fuel flow is defined as fuel flow factor W_{ff}. W_f describes the actual fuel flow at altitude [9]

$$W_{ff} = \frac{W_f}{\delta}\theta^{3,8}exp(0,2M^2). \tag{15}$$

With this correction factor the emission indices can be calculated as follows [9]

$$EINO_x = EINO_{x,ref}\sqrt{\frac{\delta^{1,02}}{\theta^{3,3}}}\,e^H. \tag{16}$$

Here, H is the correction factor for the humidity and forms the difference between the specific humidity at ground level hum_{SL} and flight level hum_{FL} [kg/kg]. H [kg/kg] is an empirical factor which considers the specific humidity at a certain altitude [7] [10]

$$H = 19(hum_{SL} - hum_{FL}). \tag{17}$$

3.) DLR Fuel Flow Method

The fuel flow method of the German Aerospace Centre (DLR) possesses the same function as the BFM2. Here, the certified emission indices are correlated with the fuel flow which is corrected for flight conditions. The corrected fuel flow $\dot{m}_{fSL}$ is calculated using Equation 16

$$\dot{m}_{fSL} = \dot{m}_{fFL}\left(\frac{1}{\delta_t {\theta_t}^{0,5}}\right). \tag{18}$$

The parameters δt and θt as well as H have been already described. Thus, the emission indices $EINOx$ can be calculated as follows [7]

$$EINO_x = EINO_{x,ref}(\delta_t^{0,4}\theta_t^3)exp(H)\ . \tag{19}$$

III. OPTIMIZATION OF FLIGHT TRAJECTORIES

The effects of air traffic nitrogen oxide emissions on climate and radiation budget can be reduced by an eco-efficient planning of flight trajectories. In general, the contribution of aviation to climate change can be sustainably reduced by exploiting several optimization potentials simultaneously. To prevent a high air traffic contribution to global warming, technical, operational and regulatory approaches are conceivable [11] [12].

On the one hand, this can be implemented directly by reduction at source, such as by reducing the absolute emissions due to lower specific emissions. On the other hand, innovative technologies, a higher load factor, fuel-optimized flight trajectories, the use of alternative fuels, lower cruise speeds and a reduction in transport volume due to a decrease in transport demand are potential strategies. Also the impact of non-CO_2 emissions can be decimated by changing cruising altitudes and by considering eco-efficient flight trajectories [11].

All non-CO_2 emissions have a much shorter lifetime than CO_2 and are therefore highly dependent on chemical and meteorological ambient conditions [14]. Hence, the optimization of flight trajectories regarding the effects of NO_x emissions requires a cost function which depends on several parameters. The climate impact depends on the time of emission (daytime and season) and the location of emission, described by altitude h, latitude φ and longitude λ [12]. During cruise, NO_x are emitted in the upper troposphere and lower stratosphere (UTLS). In these altitudes, the pollutants have a much higher residence time than on the ground. The washout of nitrogen oxides and ozone occurs much more slowly and the ozone radiative forcing reaches its maximum. Accordingly, climate impact can be reduced by operational changes in the cruise altitude towards a lower flight level (FL) [12].

The design of eco-efficient flight trajectories can be implemented by a cost function which depends on location, altitude and time of emission and determines the climate impact of a unit emission for each space and time. The climate impact can be calculated by an integral over the total emissions of a flight trajectory. If this integral is minimized by varying the trajectory the climate impact reaches a minimum. This approach is similar to the determination of operational flight trajectories which includes the flight time, fuel consumption and operational costs as parameters. A minimization of climate impact is accompanied by an increase in operational costs [11].

A. Modelling approach for trajectory optimization

In order to optimize flight trajectories regarding the impact of nitrogen oxide emissions on climate change, the access to different data and models is absolutely necessary. First, data of all existing air links have to be extracted. These data includes the airport origins and destinations, aircraft types and engine types, departure times and reference trajectories based on minimal operational costs. These have to be implemented in a simulation environment of the air traffic flow. A number of 4D trajectories can be generated for any flight regarding origin and destination airport and possible restrictions on flight path.

These trajectories can be developed considering various cost functions and optimization intentions. The minimization of climate impact requires the optimization of a climate cost function. In addition, an emission model has to be implemented which determines the actual fuel consumption as well as the emitted amount of nitrogen oxides concerning the type of aircraft and engine. Further on, a model of the global atmosphere (Chemistry Transport Model), such as used by [15] and [17] is necessary which includes chemical, physical and meteorological characteristics and processes within the atmosphere. Also tropospheric and stratospheric properties as well as the interaction with oceans, continents and anthropogenic influences must be represented as detailed as possible.

Next, the definition of a globe-spanning grid is essential. This grid requires a low resolution to cover as many points all over the globe (e.g. 1°x1°, corresponds to 64.800 grid points uniformly distributed over the globe). The study "Aircraft routing with minimal climate impact: the REACT4C climate cost function modelling approach (V1.0)" already defined a grid for the North Atlantic. For each grid point various levels of altitudes has to be defined to cover the standard cruise altitude as well as altitudes up to 2.000 ft above and 6.000 ft below (based on [13]). Also a temporal division of the day is required to evaluate the climate impact depending on diurnal variations. In different sources there is a tripartite division which includes 6, 12 and 18 UTC [14]. An hourly division is recommendable for covering all individual influences such as the changing radiation, the intensity of solar radiation and the associated photo-chemical activity in the atmosphere. Table 5 shows the defined grid and its required characteristics.

Consequently, all designated part models have to be combined in one model: flight data, model for generating flight trajectories, emission model, model of the global atmosphere (CTM) and the grid model. The use of these models consequently determines trajectories and their climate impact, first based on minimal operational costs and subsequently based on minimal climate impact. This is accomplished by using a climate cost function which calculates alternative trajectories with less impact on climate based on trajectories with optimal operational and fuel consumption costs [14]. Therefore the grid is used, for calculating the impact of nitrogen oxide emissions on all grid points while using the climate cost function.

TABLE V. DEFINITION OF THE GRID

Dimension	Quantity	Unit	Values
Longitude	360	°O/°W	0-180
Latitude	180	°N/°S	0-90
Altitude	5	FL	standard cruise altitude; +2000 ft; - 2000, 4000, 6000 ft
Temporal Division	24	UTC	1-24

B. *Qualitative optimization strategies*

Due to the absence of an air traffic flow model and a chemistry transport model, general strategies for generating trajectories, which lead to a reduction of climate impact of nitrogen oxide emissions, were derived. These are summarized and discussed in the following.

1) Decrease of standard flight altitude

First, the possible reduction of climate impact and radiation impact by vertical variation of altitude is considered.

In general, fuel consumption decreases by increasing altitude but the amount of emitted nitrogen oxides increases. In case of a reduction of cruise altitude by 2000 ft a contrary development applies i.e. the fuel consumption increases and the nitrogen oxides concentration varies only slightly [15]. In case of further reduction of cruise altitude, an increase of nitrogen oxides applies. Nevertheless, the impact of an equal amount of nitrogen oxides on the radiation budget at standard cruising altitude (UTLS) is higher than at 2000 ft below the UTLS [15]. This is due to the decreasing NO_x background concentration and temperature with increasing altitude. In general, a low NO_x background concentration leads to a more effective ozone production. Thus, the ozone production increases with an increasing altitude and decreases with a decreasing altitude due to the induced extensive chemical reactions caused by the change in the nitrogen oxide concentration in the atmosphere. Additionally, the increasing life time of ozone precursors with increasing altitude, due to the slower washout, contributes to this effect. Furthermore, the reduction of methane is higher with a decreasing altitude caused by an increasing hydroxyl radical (OH) production which is directly influenced by NO_x emissions. With increasing flight level the OH concentration in the atmosphere increases in tropical latitudes and decreases in middle and polar latitudes. In total, the OH concentration increases, resulting in an extended CH_4 lifetime. Hence, radiative forcing for methane (RF_{CH4}) and ozone (RF_{O3}) increases with increasing cruise altitude by 2000 ft and this causes an increasing total radiative forcing of nitrogen oxides (RF_{NOx}). With a decreasing cruise altitude by 2000 ft the RF_{O3}, RF_{CH4} and RF_{NOx} decreases [15].

For the transatlantic region exact statements for altitudes with minimal climate impact were estimated by [2]. There are differences between Westbound and Eastbound flights caused by considering wind systems like Jet Stream. So, for westbound flights the climate impact is minimized at Flight level FL 310 (9448 m). In contrast, the altitude of minimal economic cost is at FL 380 (11582 m). This corresponds to a decrease of altitude by 7000 ft, i.e. 2134 m. For eastbound flights the altitude with minimal climate impact is at FL 320 (9753 m) and for minimal economic costs at FL 390 (11887 m). This means a reduction of standard cruise altitude by 2000 m reduces the impact of nitrogen oxide emissions on climate. Such detailed calculations have to be considered for all regions to derive measures for reducing radiative forcing and climate impact for each region on Earth.

2) Lateral trajectory optimization towards higher latitudes

The horizontal modification of flight paths, i.e. the variation of latitude and longitude, offers the potential for reducing the radiative forcing. Nitrogen oxide emissions in higher latitudes have longer lifetimes caused by a slower washout. Also the production of ozone is lower, because of the lower solar radiation and photochemical activity at higher latitudes. In addition, the changes caused by methane and primary mode ozone (PMO) are more effective. Therefore, the radiative forcing is often negative in higher latitudes. The warming RF_{O3} almost compensates the cooling RF_{CH4} and RF_{PMO}. Emissions at low latitudes are indeed leached more quickly resulting in a shorter lifetime but the ozone production increases. The lower the latitude or the closer to the equator, the efficiency of O_3 production per NO_x molecule and the lifetime of methane increases. Overall, the effect of increasing O_3 dominates which induces a positive rate of change for lower latitudes. This results in a higher warming potential. The same amount of emitted nitrogen oxides leads to a lower radiative forcing in higher latitudes and to a higher RF in lower latitudes. This establishes the strong latitudinal dependence [16].

Also, there is a strong dependence on the prevailing weather conditions and the longitude. The same amount of emitted nitrogen oxides at the same time, altitude and latitude but with a longitudinal difference of 30° over north atlantics induces completely different values for the radiative forcing. This is caused by air mass movements in different directions, e.g. one air parcel is transported to tropical regions and the other remains in the mid-latitudes. The total radiative forcing RF_{NOx} is seven times larger in low latitudes than in areas of 60-80° [16].

In order to reduce climate impact, exact measures for the transatlantic region have been researched. Thus, the climate impact of westbound flight will be reduced by shifting the centers of trajectories in South and West direction. For eastbound flights the opposite applies, so the centers have to be relocated towards east and north direction [2]. Also detailed studies need to be conducted for all remaining regions of the world to include all wind systems and to be able to make recommendations of this kind for all regions.

3) *Avoidance of oceanic air space*

Furthermore, there are differences in climate impact above oceans and continents. The efficiency of ozone production is significantly higher over oceans than over continental regions. In northern hemisphere this difference goes up to 34 %. This is caused by the lower concentration of nitrogen oxides in the atmosphere over oceans because there is less contamination of the atmosphere. As already explained, a lower background concentration of nitrogen oxides induces a higher efficiency of ozone production. So, the ozone production efficiency is higher over oceans than over continents. Consequently, avoiding oceanic areas during cruise, if there are alternative flight paths over continental regions, offers a potential to reduce the climate impact of nitrogen oxides [17].

All three measures offer a potential to reduce the nitrogen oxides climate impact and therefore also impact on radiation budget and climate change. But these strategies only describe qualitative approaches. For an exact quantification the access to diverse models and very high computing power is absolutely essential.

C. Assessment of NO_x calculations

The following section evaluates the determined amounts of nitrogen oxides for the applied emission models (Döpelheuer (DH), Boeing Fuel Flow Method 2 (BFM2), DLR Fuel Flow Method (DLR)) for all generated trajectories. From a variety of emission models these three were selected because the available data were sufficient. The emission models use different parameters for the calculations of the total emitted amount of nitrogen oxides. This indicates highly different distributions for the individual models and flight altitudes.

Fig. 1 represents the fuel consumption and the flight time for the ranges of 3.000 km and 4.000 km depending on the altitude. In general, flight time decreases continuously with increasing altitude from 5.000 m to 12.000 m. For an altitude of 13.000 m the flight time increases again because each engine operates most efficiently in terms of operating costs at a certain altitude. Generally, engines are not designed for efficient operating in such low altitudes like 5.000 m or 6.000 m. Also, fuel consumption reaches a minimum at a cruise altitude of 12.000 m, suggesting, that costs for airlines reach their minimum regarding to operational costs.

Fig. 2 presents the profiles for the determined nitrogen oxides for all three models exemplary for a flight distance of 3.000 km and 4.000 km which show clearly the differences between the amounts depending on the applied correlation model. It can be assumed that formulas depending on the reference emission indices *EINOx* comes closes to reality.

Fig. 2 and even the distributions for two further considered flight distances (2.000 km and 5.000 km) show a Minimum of emitted nitrogen oxides at a cruise altitude of 9 km. Likewise, the Minimum has the same location for flight distance of 6.000 km for BFM2. For DLR and DH the minimum is located at 10 km. The maximum values are at an altitude of 13 km on all models and distances. The emitted amount for optimum altitude and maximum specific range is located between 11km and 12.000 km. In general, these emission models show a consistent position of minimum and maximum and general distribution of emission amounts. Thus, a recommendation for a cruise altitude of 9.000 m can be given which represents the least pollution of atmosphere and also on the environment in terms of emission quantity.

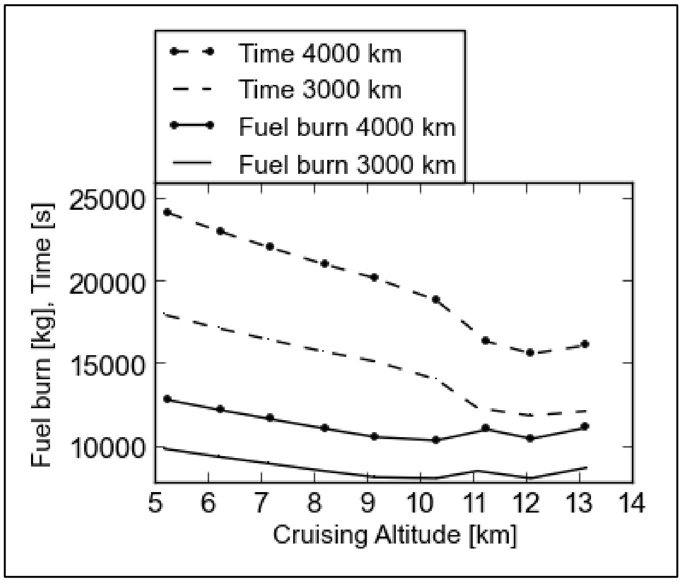

Figure 1. Fuel burn and flight time for flight distances 3.000 and 4.000 km depending on cruising altitude.

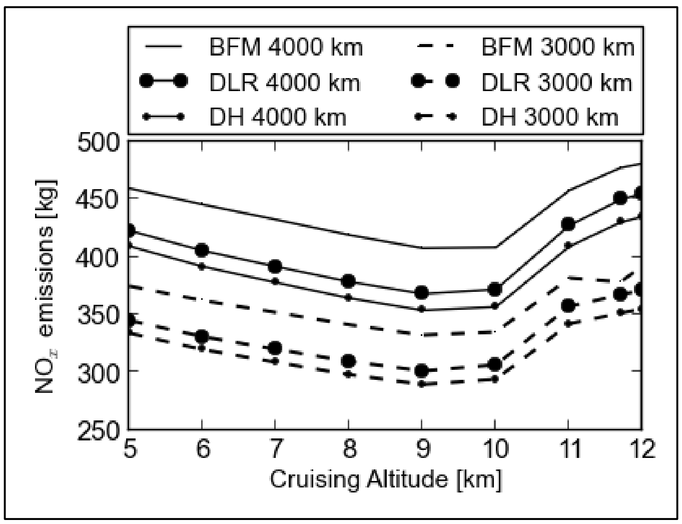

Figure 2. Emitted NOx for Boeing Fuel Flow Method 2 (BFM), DLR Fuel Flow Method and Döpelheuer (DH) for flight distances 3.000 and 4.000 km depending on cruising altitude.

Unfortunately, the impact on radiation budget cannot be quantified because of missing access to extensive climate models which are required for this purpose. Nevertheless, the stated recommendation can be supported qualitatively by [2], which gave also recommendations for flight altitudes with minimal impact on radiation budget and climate. They recommend a reduction of altitudes for westbound flights to FL 311 and for eastbound flights to FL 324 for transatlantic regions. This indicates a reduction of climate impact up to 100% compared to optimal operational costs. Transferring these altitudes to current ATM concept, so FL 310 (9.450 m) can be used as altitude for westbound and FL 320 (9.754 m) for eastbound flights which are assumed as altitudes with minimal climate impact. Consequently, flights with cruise altitudes between 9 km and 10 km not only reach a minimum in terms of emitted nitrogen oxides but also a minimum with respect to the climate impact.

IV. Conclusion and Outlook

In this study, possible approaches for reducing nitrogen oxides climate impact through changed trajectories were examined. Air traffic has a special contribution because it is the only emitter of pollutants in the upper troposphere and lower stratosphere. To know the exact impact on climate it is necessary to calculate the precise amount of emitted nitrogen oxides during a flight. Therefore, three emission models were considered which require knowledge of various engine parameters. For a more accurate calculation methods are required which includes more parameters for a better representation of reality. Not only a precise knowledge of the amount of emitted nitrogen oxides is necessary but also the processes in atmosphere and their specific characteristics and weather conditions, such as solar radiation and photochemical activity. Likewise, the influence of winds on the amount and distribution of nitrogen oxides in the atmosphere should be considered in a further study.

All in all, the horizontal and vertical variation of trajectories as operational approach to minimize the climate impact offers the potential in order to protect the environment and the climate sustainably. Furthermore, it will be probably more important in the future, to know not only the effect of a specific emission, such as nitrogen oxides, but also the interaction between all emitted pollutants. The reason is that optimization with respect to one species may in turn bring disadvantages for another. Furthermore, it should not be neglected that all airlines operate very close to fuel and operating costs optimum. So, a variation of trajectories regarding to minimal climate impact always implies an increase in cost. For this purpose the environmental awareness in aviation industry has to increase to implement new climate friendly flight operation strategies despite financial disadvantages.

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