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QUANTITATIVE EMISSIONS OF NO_X, CO AND CO_2 DURING AIRCRAFT OPERATIONS

Pawel Glowacki, Michal Kawalec
Institute of Aviation

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Abstract

Based on the available information and the authors self - assessments, this article presents the effects of turbine engine exhaust gases on the environment, both near to the aircraft whilst the engine is idle and during takeoff, climb, cruise and descent.
The paper summarizes the results and analysis of approximately 20,000 flights and 5 types of aircraft.
This paper also presents the emission calculation results of aircraft, providing an example of CO and NOx emission estimations based on 40 engine test-cell characteristics and the ICAO Aircraft Engine Emissions Databank. Engines whose parameters are outlined in this Databank are described as "ideal". The authors would like to draw the attention of aviation professionals to the fact that the amount of exhaust emissions from the turbine engines is so significant that they may adversely affect the ambient air near the aircraft.
Consequently the increased level of carbon monoxide (CO), unburned hydrocarbons (UHC) during engine start–up (whilst the engine is on idle) can be a threat to the health of the ramp staff.
Additionally, high emission levels of nitrogen oxides (NOx) during takeoff, climb, cruise and a descent are not indifferent to the environment around airport airspace as well as the troposphere. The study also provides calculated results of aircraft CO_2, CO and NOx effusion using fuel consumption data taken from aircraft Flight Data Recorders (FDRs) in the landing and takeoff cycle (LTO), as well as during the remaining flight phases. Engine deterioration and jet stream velocity were also studied as influencers of aircrafts increased fuel consumption.
LTO cycle and remaining aircraft phases considered in this paper contain actual values of aircraft fuel consumption and figures on the duration of airplane maneuvers.
Fig. 1 shows the difference between the fuel consumption of an "ideal" CFM56-3C-1 compared with overhauled engines, whilst Fig. 2 presents an example of emission estimations of overhauled CFM56-3C-1 engines installed on specific aircraft (same as on Fig. 1) when compared to "ideal". Polynominal of the third degree describes installed engine NOx emissions.

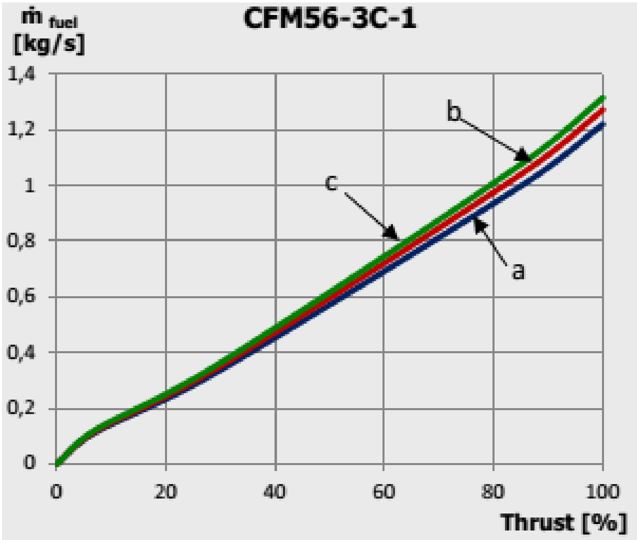

Fig. 1. Fuel consumption of: a-ICAO Aircraft Engine Emissions Databank engine; b, c- test-cell results of overhauled engines.

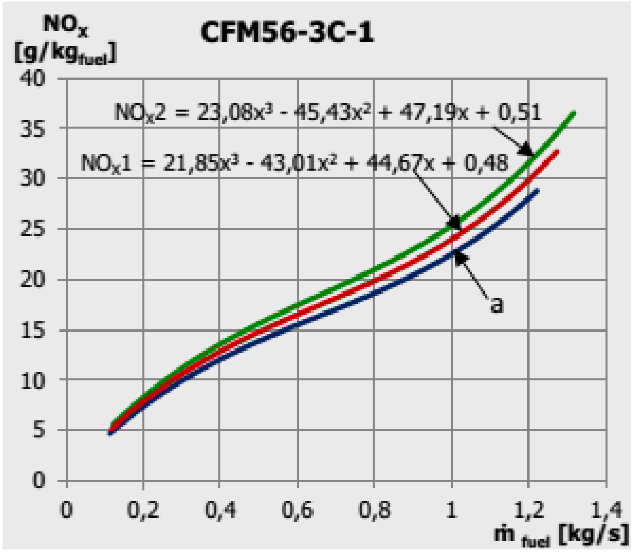

Fig. 2. Dependence of NOx emission from fuel consumption of the installed CFM56-3C-1 engines. Where "a" represents an "ideal" engine.

It is common knowledge that engines are deteriorating during exploitation and have different characteristics hence such factors have to be taken into consideration when calculating the emissions of each aircraft. Even if they are of the same type, the calculations have to be considered individually. Fig. 3 shows an increase of NOx emissions for specific aircraft when engine deterioration (from installation until now) is taken into account.

NOx emissions of aircraft (fig.3) have increased by 3.4% during the climb from 3,000 feet to cruise altitude; by 3.3% during cruise; and by 3.5% during descent from cruise altitude to 3,000 feet. CO emission shown on Fig. 3 is provided for reference.

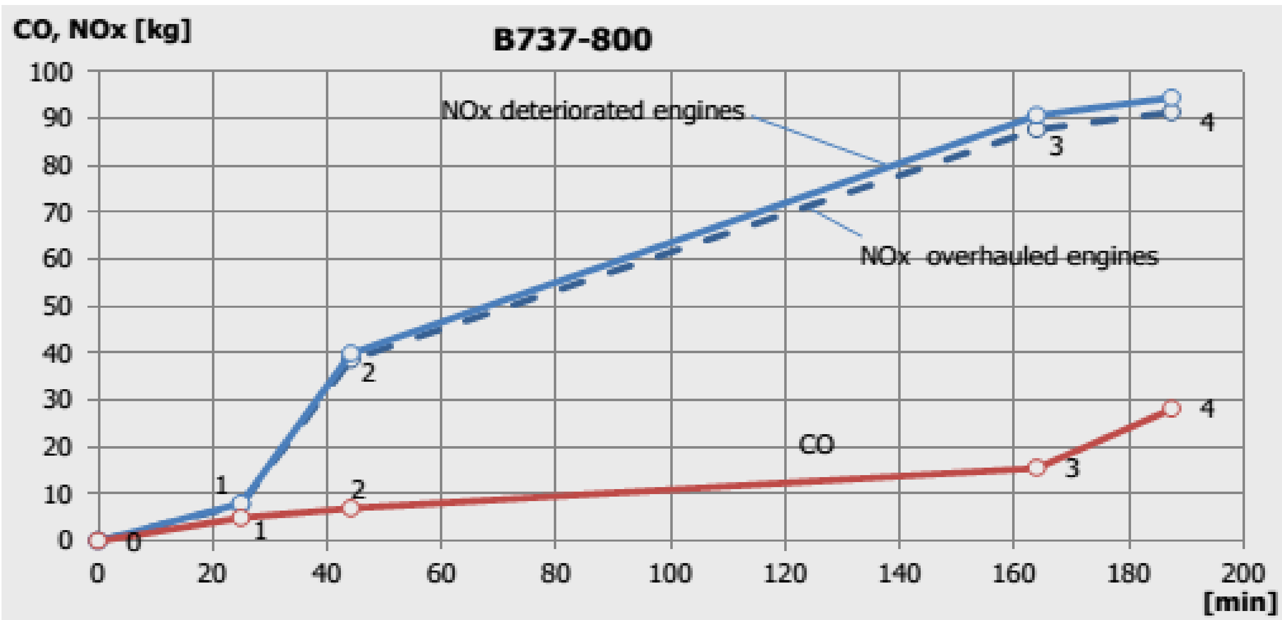

Fig. 3. *NOx emission during B737-800 flight while engine deterioration is taken into account. 0-1 Landing and takeoff cycle, 1-2 Climb from 3000 feet to the cruise altitude, 2-3 Cruise, 3-4 Descent to 3,000 feet.*

Jet stream phenomena in high altitudes have to be considered during flight planning. Routes where high speeds of jet streams have occurred have been analyzed. Aircraft ground speed, heading, Mach number, jet stream direction and speed are known as they were

registered by FDRs. Calculations performed showed that, for each 5 knots, (10 m/s) the jet stream axial component increases the 4 hour flight duration of the B737-400 by 9 minutes, with approx. 0,3 tons of burned fuel.

1 Introduction

Over the last sixty years, according to Bernard L. Koff, aviation turbine engines have evolved to become the most complex product in the world, exerting an amazingly positive impact on humanity [8].

Continuing the thoughts of eminent engine designers it is argued that modern turbo fan engines are state of the art product, demanding a broad spectrum of skills and talents in multiple fields of science from their builders. These are infinite in number and range from materials science through aerodynamics and thermodynamics to electronics, economics and ergonomics. Passenger and cargo aircraft power plants have unquestionably made our world much, much smaller.

During each aircraft takeoff its engine creates an air stream which is accelerated under fan pressure to more than 300 m/s. A side effect of this highly effective thrust, however, is turbulence and noise. The exhaust gas stream from the internal duct in particular is not only a major source of these issues, but is also a key driver behind the emissions of toxic gases and heat. Exhaust streams can reach speeds of 600 m/s and temperatures of more than 1000K (+ 750°C).

Turbofan engines of passenger and long-range cargo aircraft require big amount of air to ensure they proper performances. For example; an engine which powers B737 aircraft necessitates air amounts in the region of 370 kg/s.

In the combustion of fuel only 10% to 20% of total air mass which flows through the engine is used. It is still very large amount.

B747-400 planes are powered by four engines which, together, produce 720 kg/s of exhaust at takeoff. In addition to carbon dioxide (CO_2), water (H_2O), nitrogen (N_2) and oxygen (O_2) these exhausts contains toxic gases, including highly harmful nitrogen oxides (NO_x).

On 18-19 March 2015 a conference organized by the ICAO-"ICAO International Aviation and Environment Seminar" was held in Warsaw. Representatives of this UN institution presented their plans for projects related to the reduction of the negative impact of aviation on the environment.

The most important message was concerning a two percent reduction in fuel consumption (and thus reducing CO_2 emissions and toxic exhaust) in aviation by 2021, with a further 2% per year until 2050. This ambitious goal is to be achieved not only through the introduction of new technologies applied in the aircraft and propulsion systems manufacturing, but also inter alia through the introduction of special procedures for the management of air traffic control. The significant effect of exploitation by both pilots and maintenance staff on aircraft engines was also stressed. Appropriate maintenance actions taken at the right time can significantly improve the performance of an engine, consequently reducing fuel consumption and reducing the amount of unwanted emissions.

For example, the use of maneuvers such as continuous climbs/descents will shorten the duration of these phases of flight, thus reducing the fuel consumption of the aircraft. The procedure of the engine gas path wash reduces SFC by almost 0,5%.

Due to the aviation industry being constantly in the public eye, emissions produced by this mode of transport are particularly considered in details.

It has been estimated that the aviation industry's contribution towards the global contamination of earth's atmosphere is approximately 2-3%.

Conversely, the concentration of greenhouse gases and pollutants in airport areas and at high altitude is unusually high, which probably can has negative impact on ramp staff health and the greenhouse effect.

To improve the awareness of the quantity of CO_2 and carbon monoxide (CO), NO_x and unburned hydrocarbons (UHC) emissions in these spaces, therefore it appears. It is for airlines, airports, medical services, climatologists and for these which enjoying all the benefits of aviation.

The aim of this article is to provide an information about the quantitative emission of toxic gases in the airport airspace and at the high altitude during the cruise and proposed ways of reducing them.

Method of estimating the amount emitted by aircraft engines toxic gases contained in the exhaust and fuel consumption during all phases of the flight has been presented by authors of that paper during CEAS 2015 Conference [6]. Its introduction to the use by commercial aviation operators will allow:

- True calculation of fuel consumption, and thus charges for carbon dioxide emissions.
- Getting the right amount of any taxes on emissions at airports in the future.
- Precise determination of time to take certain preventive measures to improve the parameters (reduction in fuel consumption) of the engines, through favorable for the environment measurements to minimize the amount of harmful emissions, reduce operational costs of the aviation operator.

For the airports will enable:

- Accurate estimation of the aircraft engines exhaust pollutants in the airport vicinity, so will support airport authorities in the analysis of aircraft maneuvers different technics. This will help in the aircraft movement optimization so that its fuel consumption could be possibly the smallest.

As being engineers we have a duty to determine the amount of carbon dioxide emissions and pollutants contained in the exhaust gases of the aircraft engines, as well as the intensity of their spreading both in airports space and in the atmosphere.

Medical professionals and climate specialists should assess their impact on human health and climate change.

2 Aircraft engine emissions at the airport airspace

The International Civil Aviation Organization (ICAO) has published regulations for civil subsonic turbojet/turbofan engines with rated thrust levels above 26.7 kN for a defined landing-takeoff cycle (LTO) [11], which is based on an operational cycle around airports. Graphical presentation of this LTO cycle is shown on fig.4.

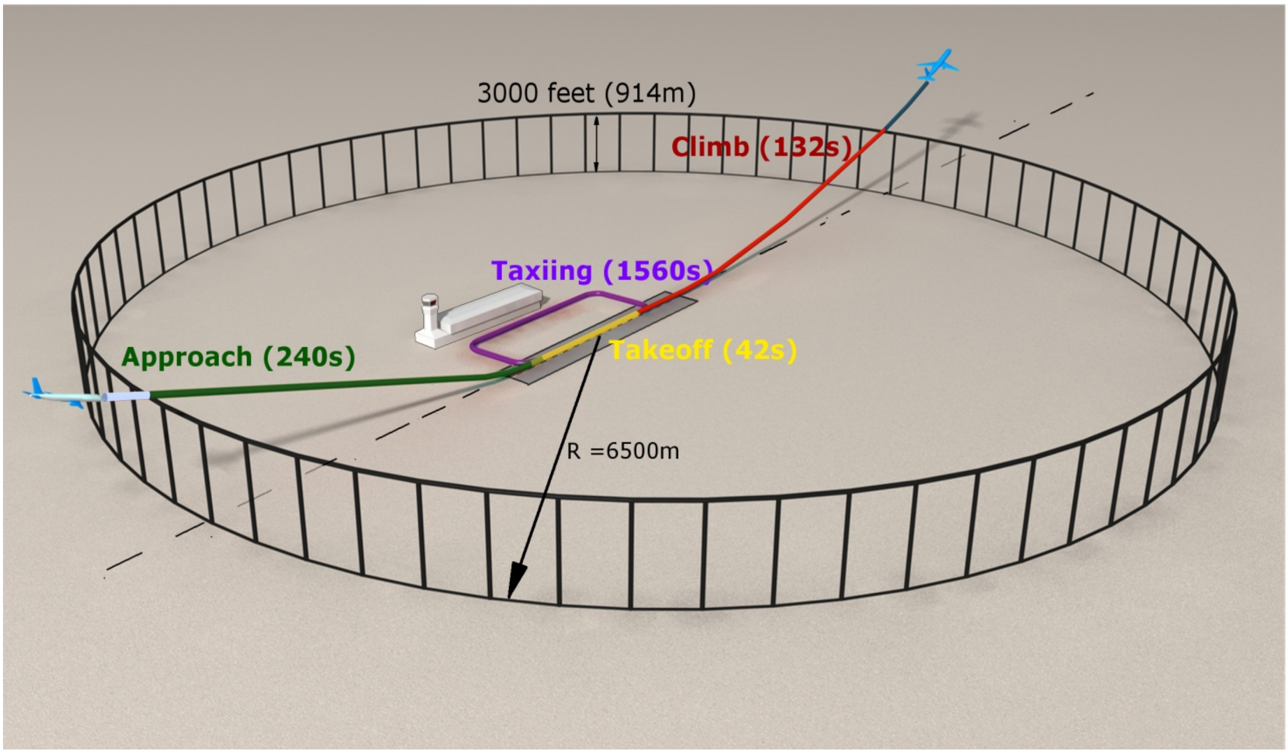

Fig. 4. Airport airspace affected by aircraft engine exhaust emissions in the LTO cycle defined in [11]

Such a defined landing and takeoff cycle gives us information that each aircraft of the same type has the same type of engines fitted, with same performances, at each airport in the world emits the same amount of the exhaust with its toxic components in the same time of the maneuver duration.

Unfortunately emissions amount according to the present regulation do not take into account the amount of fuel consumption and pollutants emissions of a particular aircraft equipped with certain engines.

The actual amount of the harmful emissions can be significantly different from once calculated in accordance with adopted (averaged) durations of the aircraft maneuvers and engine operating ranges throughout their duration.

Practice in aviation is more complicated than simplification, as is the case of the LTO cycle obligatory definition.

After the powerplant installation on the airframe the engine has different characteristics than that recorded at the test cell, its parameters differ from those measured in almost laboratory conditions.

Utilized by the operators engines, even of the same type and version have different characteristics - in many cases significantly different from the “test-cell” engine.

Moreover, in the exploitation of the characteristics, gradual deterioration takes place and the amount of fuel needed to provide the same thrust increases significantly compared to after the installation on the airframe of a new or overhauled engine.

During takeoff, pilots, depending on the takeoff mass of the aircraft, runway length and environment conditions, apply derate or thrust reduction modes. The aircraft’s takeoff maneuver could be performed with a thrust 20% less than the maximum takeoff thrust.

At the discretion of air traffic control, duration of the climb and approach can be different. In addition, the specifics of each airport are reasons for very different times allocated for taxiing, including stops to wait in line for further taxiing and takeoff.

Approximately 10000 of the LTO cycles at different airports flown by various aircraft types have been analyzed. Using methodology [6], calculations were performed. They were carried out in order to estimate the total amount of emissions in various airports.

Tab. 1 shows estimated quantitative emissions in the LTO cycle at a medium-sized European airport. Daily, 200 LTO cycles occur, flown by various types of aircraft.

It contains real emission of carbon dioxide and time duration of maneuvers (taken from FDR) compared with those resulting from the currently effective LTO cycle definition. Emissions of NO_x and CO were calculated according to the earlier mentioned methodology [6]. Differences between values are given in percent. Red colour denotes real values while blue colour indicates values calculated based on the currently in force LTO definition.

Tab.1

			EMISSION PER DAY						EMISSION PER YEAR		
Maneuver	**TIME [s]**		**CO_2 [t]**		**CO [t]**		**NOx [t]**		**CO_2 [t]**	**CO [t]**	**NOx[t]**
TAXING	**1054**	**68%**	**109,9**	**60%**	**1,34**	**56%**	**0,166**	**73%**	**40106**	**488**	**61**
	1560		**184,1**		**2,4**		**0,227**		**67201**	**875**	**83**
TAKEOFF	**45,2**	**108%**	**38,2**	**78%**	**0,01**	**175%**	**0,25**	**73%**	**13950**	**3,7**	**91,1**
	42		**48,8**		**0,006**		**0,342**		**17810**	**2,08**	**124,9**
CLIMB OUT	**85,6**	**65%**	**72,6**	**57%**	**0,012**	**67%**	**0,454**	**63%**	**26510**	**4,43**	**165,8**
	132		**126,8**		**0,018**		**0,721**		**46273**	**6,59**	**263,3**
APPROACH	**263**	**110%**	**68,52**	**87%**	**0,18**	**213%**	**0,198**	**92%**	**25014**	**64,82**	**72,45**
	240		**78,8**		**0,08**		**0,217**		**28767**	**30,44**	**79,1**
TOTAL	**1448**	**73%**	**289**	**66%**	**1,54**	**61%**	**1,07**	**71%**	**105580**	**561**	**390**
	1974		**438**		**2,50**		**1,51**		**160050**	**914**	**550**

Presented in tab. 1, the data shows how the duration of the various maneuvers and actual power setting of the engines influence quantitative emission sizes in the airport vicinity. Also, it can help in several analyses which may lead to the determination of the internal airport procedures concerning aircraft movement. For example, reduction of the approach duration by 10 seconds reduces emission of CO_2 in that airport by 950 tons per year, NO_x by 2,7 tons and CO by 2,45 tons. During taxiing, emission of CO is the largest due to the engines' low power setting (low combustion temperatures). Every 60 seconds of taxiing maneuvers, emission of carbon monoxide in that airport equals approx. 107 kg, so if taxiing could be reduced by 60 sec. emission of CO will be reduced by 38,5 tons per year. Based on tab.1, it can be concluded that in this particular airport, some projects should be done by ATC in order to reduce duration of approach maneuvers. Similar research can be performed in any airport worldwide. Knowledge of the toxic emission quantities makes modeling of its spreading in the airport easier as well as the assigning of their concentration levels in locations where ramp staff are staying.

Generally, significant reduction of toxic gas emissions in the airport can be achieved by towing the aircraft to the runway.

The results of the calculation presented in the tab. 1 indicate how big the difference is between the aircraft emissions at a particular airport and those adopted by the LTO, defined by currently obligatory rules. This mismatch is shown in percentages in this table.

The usefulness of such calculations for airlines is very important because knowledge of the duration of the aircraft maneuvers at the airport allows for negotiations with air traffic control for efficiency. Also, it should help during talks about the size of the fees for emissions, if imposed.

3 Aircraft engine emissions at cruise

Noteworthy is a minimum emission of toxic compounds of exhaust gases during the landing and takeoff cycle compared to the entire flight, but only the landing and take-off cycle is described by ICAO standards.

Important is the fact that the use of an on-board flight data recorder can accurately count all the emissions "produced" during the flight. The operator can therefore carry out any analysis for a particular route and aircraft, eg. fuel consumption per passenger, seat, etc. This is important for assessing the effectiveness of flights performed by the operator and the actual emission quantities for each flight.

For long haul destinations, "share" of the cruise part is almost 86% of the total flight duration, however, for European connections, it is only 65%. For example, the B767-300 (see fig. 5), at 10000 m altitude, leaves, approx. 475 kg of NO_x during a flight from Europe to the US (2 kg NO_x/passenger), while the B 737-800 (see fig. 6), at the same altitude, emits 45 kg of NO_x (0,28 kg NO_x/passenger). Also, both fig. 5 and fig. 6 show how NO_x emission is divided between flight phases. Segment 0-1 corresponds to the LTO cycle; 1-2, the climb from 3000 feet to cruise altitude; 2-3, the cruise; and 3-4, the decent to 3000 feet. Knowledge of quantitative aircraft NO_x emission at high altitudes is important for atmospheric scientists. If there are 1000 flights daily between Europe and the US, then aircraft NO_x emissions can be estimated at 500 tons, which gives 182 thousand tons a year. Indirect evidence of the impact of aviation on NO_x emission at high altitudes is a factor of its concentration in the northern hemisphere at 11000 m., which is 8,87 e-12 [kg/m^3/s] while in the southern, it is almost 0 [10]. In [10], it is also shown that the biggest NO_x concentration coincides with the aircraft routes.

It is also worth noting that the LTO cycle, the only phase of flight described by emission regulations, takes from 5% (long haul flight) to 15% (short flight) of total flight duration.

Reduction of nitrogen oxide emissions at high altitudes becomes very important for aircraft engine designers.

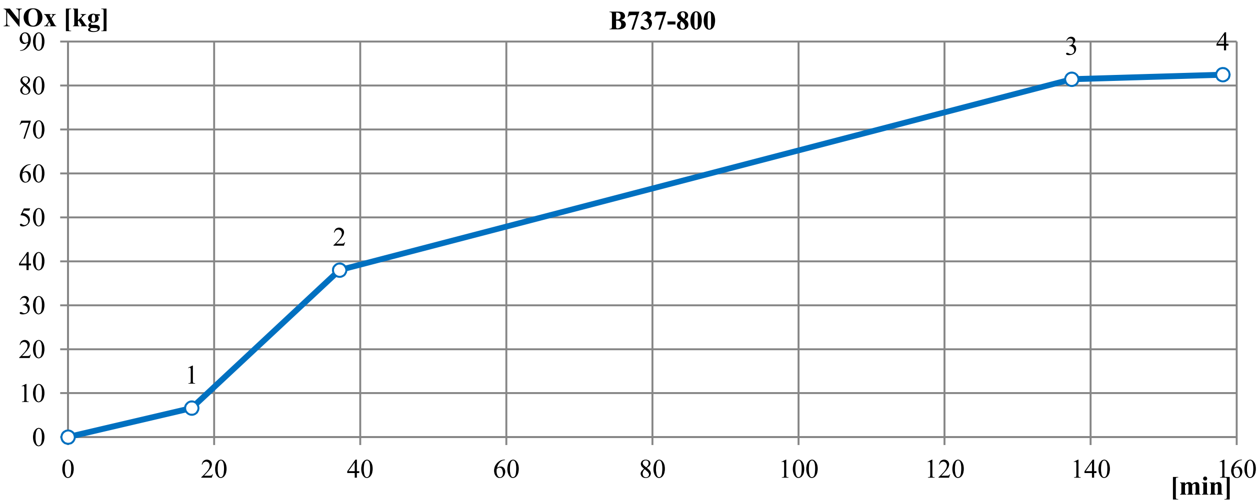

Fig. 5. NO_x emission during aircraft flight between European airports

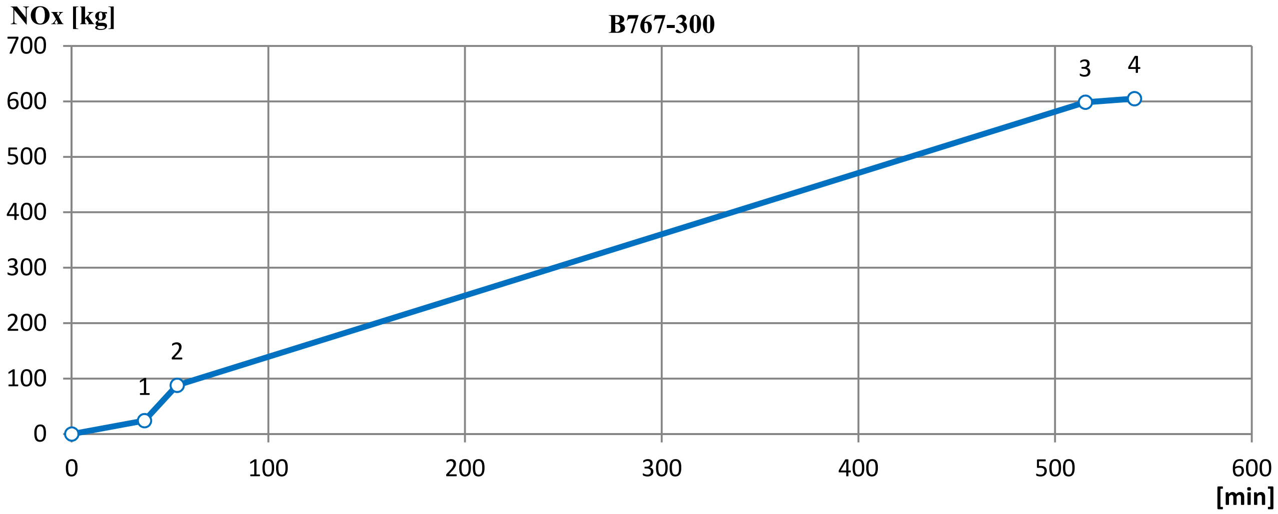

Fig. 6. NO_x emission during aircraft flight between Europe and US

For operators there is possibility of fuel burn reduction, thereby, emissions of such flight planning from the tail jet stream are the biggest.

Jet streams occurring at cruise altitudes have a significant impact on fuel consumption.

Fig. 7 and fig. 8 show the results of calculations for the flights of one type of aircraft with similar takeoff mass, on a certain route.

For the operator, important information is that for every 10 m/s of speed, the opposite axial component of the jet stream increases fuel consumption by about 300 kg, for approx. 4 hours of flight.

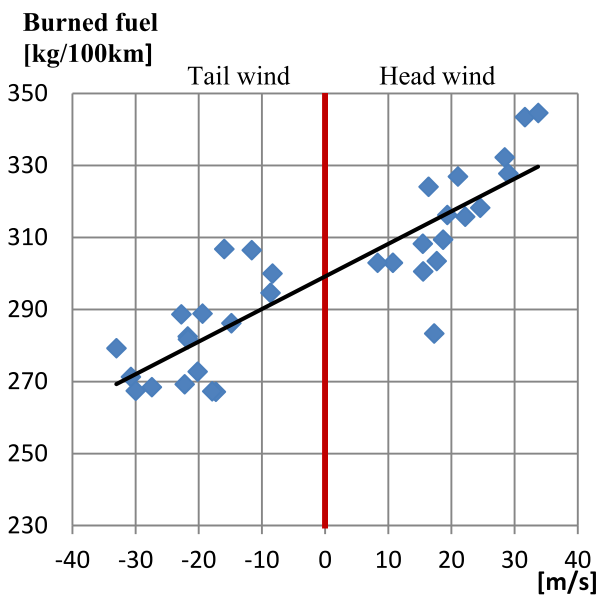

Fig. 7. Aircraft fuel consumption per 100 km depending on axial component of the jet stream

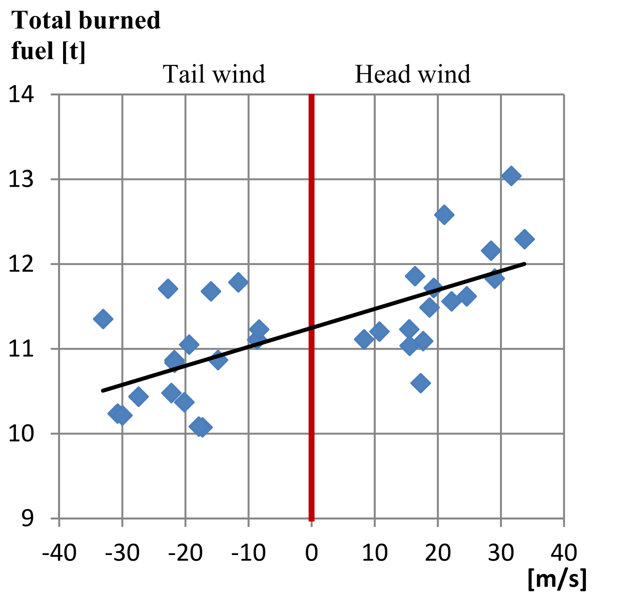

Fig. 8. Total aircraft fuel consumption on certain route depending on axial component of the jet stream

4 Conclusions

In order to reduce unwanted emissions and properly assume their quantity, concentration and spread projections have to be taken and tasks have to be considered by the aviation industry. Some of them were already indicated in this paper. It is believed that mentioned below are also worth consideration.

The aircraft should not be treated as a statistical unit. Emissions should be evaluated for each aircraft individually.

Combustor design should be "emission efficient" at aircraft engine cruise power settings.

Systematic fuel consumption increases by the aircraft, for the same conditions, are signals to the Operator's technical staff to take steps in order to improve the engine performances, such as: gas path wash, and even the decision to overhaul the engine.

It is necessary to analyze the effectiveness of various techniques of an aircraft's takeoff, climb, or approach.

The focus of further in-depth analysis should be to optimize the use of engine thrust derate procedures during take-off, so that the benefits were not limited by longer lasting climb associated with the higher fuel consumption.

As a consequence of the depth, flight analysis is improving the operating parameters of an aircraft and its power plants, which increases the flight safety.

Not without significance is its positive effects on the environment and a positive impact on aircraft operator economic performance.

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