Aviation – Environmental Threats.
Simplified methodology of NOx and CO emissions estimation.

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ABSTRACT

Based on the available information and authors self - assessments, this article presents turbine engine exhaust gases effect on the environment, especially near to the aircraft during their engines idle and takeoffs settings.

The authors would like to draw attention of the aviation professionals to the fact that amount of exhaust from the turbine engine is so significant that may adversely change the ambient air near to the aircraft. Consequently increased level of carbon monoxide (CO), unburned hydrocarbons (UHC) during engine start–up and idle can be a threat to the ramp staff health. Also high emission level of the nitrogen oxides (NO_x), during takeoff, climb, cruise and decent is not indifferent for the environment around airport space as well as ionosphere. The paper gives an example of CO and NO_x emission estimation based on ICAO Aircraft Engine Emissions Databank. Engines which parameters are given in this Data Bank authors called as “ideal”. Also provides calculation results of aircraft CO_2, CO and NO_x effusion using fuel consumption data taken from aircraft Flight Data Recorder (FDR) in the so–called landing and takeoff cycle (LTO) and during remaining flight phases of various aircraft types.

LTO cycle considered in this paper contains actual values of aircraft fuel consumption and duration of the airplane maneuvers.

Fig. 1 shows difference between fuel consumption of “ideal” CFM56-3C-1 and overhauled engines, when Fig. 2 presents emissions estimation for “ideal” engine.

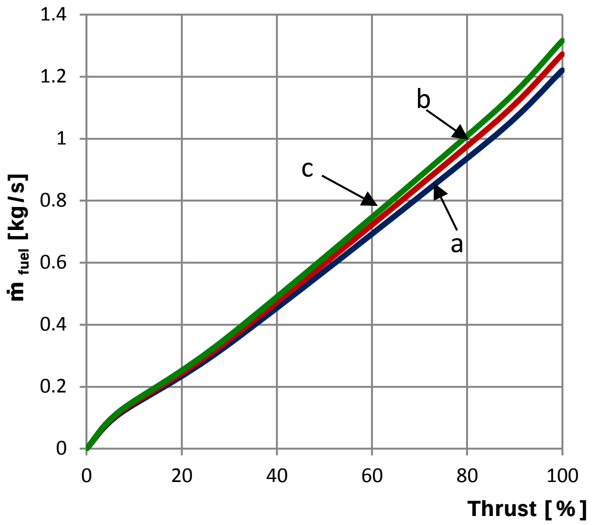


Figure 1: Fuel consumption of: a-ICAO Aircraft Engine Emissions Databank engine [8]; b, c- test-cell results of overhauled engines.

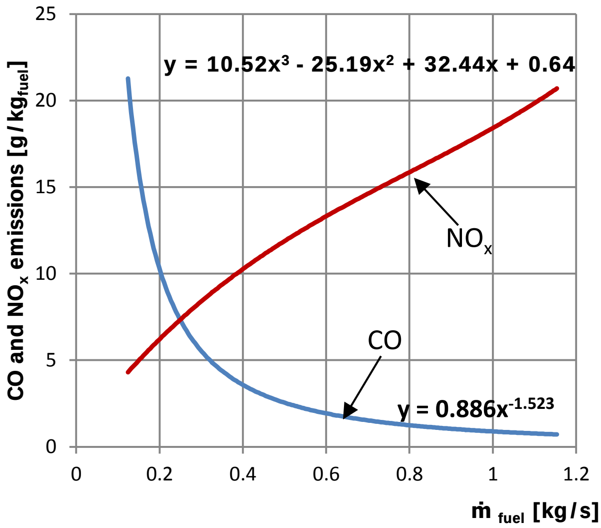


Figure 2:CO and NO_x emissions for ICAO Aircraft Engine Emissions Databank engine [8].

It is cliché that engines during exploitation are deteriorating and have different characteristics hence such factors has to be taken into consideration in emission calculations and each aircraft, even of the same type, has to be considered individually.

Figure 3 presents how emission of NO_x differs between overhauled and “ideal” CFM56-3C-1 engine. Approximate value of NO_x emission for repaired engines has been calculated using as a standard equations describing curves of “ideal” engine (Fig.2).Fig. 4 shows quantity of NO_x and CO emissions estimations for all flight phases of long haul aircraft.

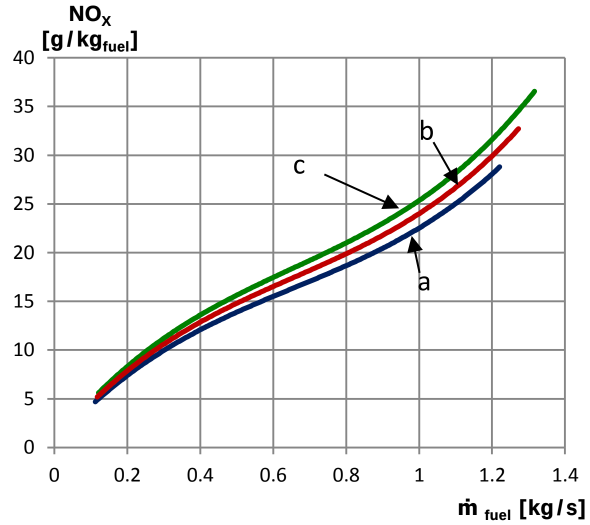


Figure 3: NO_x emission estimation of : a-ICAO Aircraft Engine Emissions Data Bank engine[8]; b, c- test-cell results of overhauled engines.

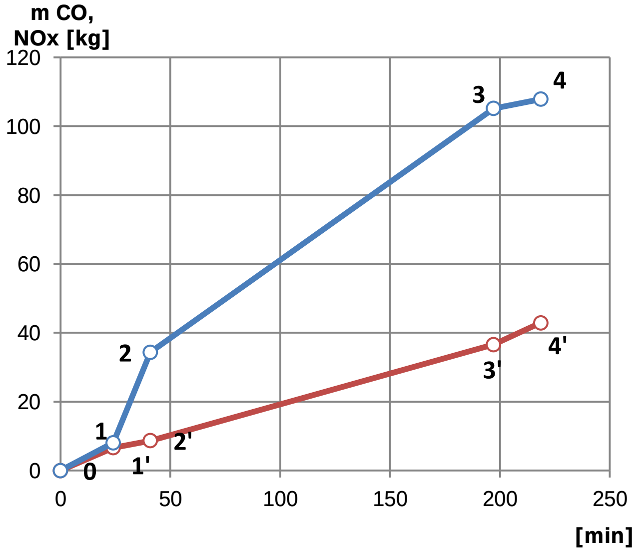


Figure 4: Emissions during flight of B737-400 on route from Europe to North Africa.

Aircraft flight phase:

0-1 i 0-1’ – LTO cycle (Landing and takeoff)

1-2 i 1’-2’ – Climb from 3000 feet to cruising altitude

2-3 i 2’-3’ – Cruise

3-4 i 3’-4’ - Descent to 3000 feet

For short and medium range flights “share” of cruise phase in total flight duration is smaller in favor of LTO cycle.

Calculated on the engine characteristics basis the mass flow rate of exhaust gases, and knowledge of the aircraft real LTO cycle duration allow to estimate the amount of CO_2, CO and UHC “left" at the airport space.

The final answer to questions about threats to the ramp staff can be obtained after a detailed study of the pollutants concentration distribution zones (a task for us - engineers) and determine the safe limits of these gases for human (a task for medical services).

High altitude emissions especially NO_x and CO_2, their influence on ionosphere requires more studies of climate experts. For now we are trying to estimate more precisely volume of pollutants.

1. Introduction

According to statistical data fossil liquid fuels “consumed” by modern aviation reach approx. 3% of total used by mankind. Seemingly, this is a negligible quantity, but the production and dispersion of the exhaust gases emitted into the atmosphere takes place in a particularly undesirable way, i.e. in one point (airport), during taxiing and aircraft takeoffs and landings. Engine exhaust are also spreading during flights at high altitudes (over 10,000 meters) with speed close to 1000 km/h. It has to be known that mass flow of the exhaust gases from one engine currently varies between 20 kg/s and 200 kg/s and air flow rate in turbofan engine exceeds 1300 kg/s. Air velocity in the inlet (Fig. 1) is around 200 m/s and 300 m/s behind fan, while engine exhaust speed is around 600 m/s at the temperature more than 1000 K. Boeing 747 during takeoff emits approx. 720 kg/s of the exhaust gases with its toxic content.

It is a cliché that exhaust gas from jet engines and exhaust gas plus air from turbofan engines have negative impact on the environment. Carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC) and particularly nitrogen oxides (NO_x) are not indifferent to humans and animals. Effect of NO_x on the ionosphere has not been fully explored yet (after all it is emitted during flights on high altitudes).

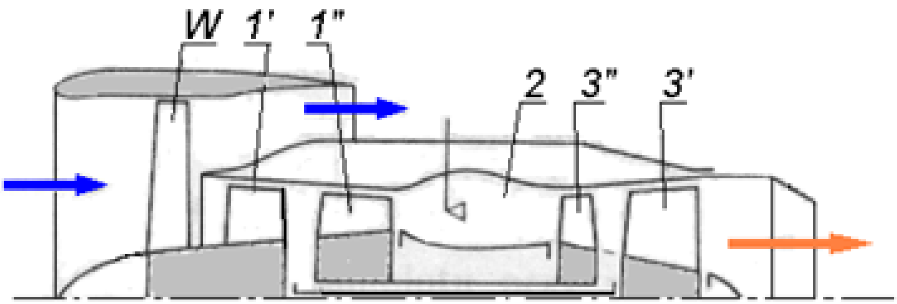


Figure1: Flow diagram of turbofan engine : 1’, 1”– compressors; 2 - combustion chamber; 3’, 3” - turbines ;W – fan

On 18-19 March 2015 conference organized by the ICAO-"ICAO International Aviation and Environment Seminar" was held in Warsaw.

Representatives of this UN Institution have presented their plans for the projects related to the reduction of the negative impact of aviation on the environment.

The most important message was an information about two percent reduction in fuel consumption (and thus reducing CO_2 emissions and toxic exhaust) for aviation by 2021, and then to the 2050 2% per year. 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.

For example, the use of so-called maneuvers, continuous climb and continuous descent will shorten the duration of these phases of flight, thus reducing the fuel consumption of the aircraft.

Around aviation, due to its significant visibility, especially emissions produced by this mean of transport, there is the atmosphere of exaggeration in the assessment of its impact on the environment.

The need to improve awareness of the quantity of CO_2 and CO, NO_x and UHC emissions, it therefore appears necessary. It is for both the aviation industry, and for these which enjoying all the benefits of aviation.

This material has to be considered as a voice in discussion about ways of the fuel consumption reduction by the aviation.

The aim of this paper is to provide and present the results of a simple method usage for estimating the amount emitted by aircraft engines toxic gases contained in the exhaust and fuel consumption during all phases of the flight. Its introduction to the use by commercial aviation operators will allow:

-Precise definition of fuel consumption during various flight phases, and thus charges for carbon dioxide emissions.

- Almost exact quantity of exhaust toxic emissions calculation results during all flight phases
-Getting the right amount of any taxes (if imposed) on emission sat airports.
-Reduction in fuel consumption
-Accurate determination of time to take certain preventive measures to improve the parameters of the engines so, through favorable for the environment to minimize the amount of harmful emissions, reduce operational costs of the aviation operator and improves flight safety.

In this paper examples are given for B737-400 with CFM56-3C-1, B767-300ER with CF6-80C2B6, B737-800 with CFM56-7B26 and ERJ 195 with CF34-10E engines.

2. Jet engine exhaust gases toxic compounds emission

During the movement of the aircraft in the airport using their own engines (working at close ranges to idle) there is the phenomenon of the fuel incomplete combustion hence exhaust from an aircraft gas turbine is composed of high amount of carbon monoxide (CO) and unburned hydrocarbons (UHC). Opposite, at the maximum thrust ranges due to high temperatures in the combustion zone significant amounts of undesirable, highly toxic nitrogen oxides NO_x are formed. Differentiation of these components composition is a result of the air-fuel mixture changes in combustion zone as a function of engine power setting in a different climatic and aircraft flight conditions.

For aircraft “users” useful is a practical knowledge how quantitative content of UHC, CO and NOx emissions depend on current engine thrust.

Figure 2 shows typical for modern jet engines used by passenger and cargo aviation exhaust emission characteristics. It is clear that the nature of toxic exhaust gases components formation is such that the concentration of CO and UHC are highest at low engine power conditions and diminish with an increase in power.

From the other hand NO_x formation is insignificant at low power settings and reaches maximum value at highest power condition.

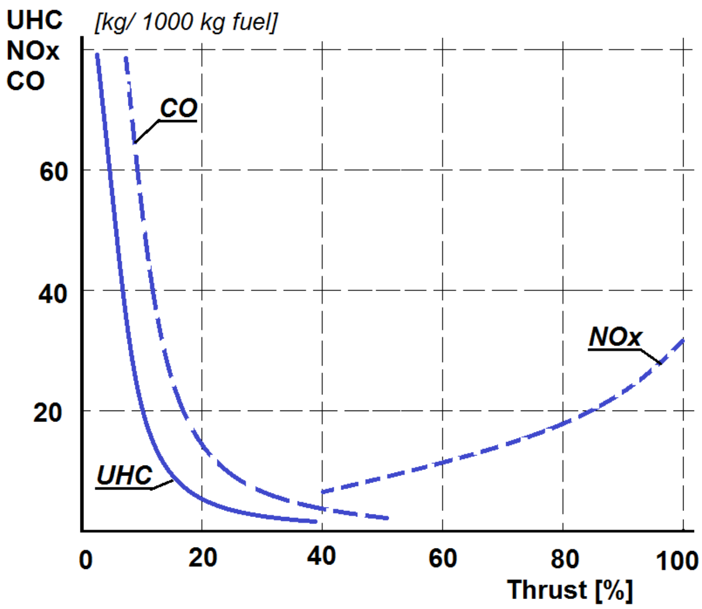


Figure2: Emission characteristics of gas turbine engine (based on [6]).

The parameters of the maximum power of the engine with high combustion temperatures diminish emission of UHC and CO, but unfortunately - favor the formation of nitrogen oxides NO_x - larger quantities the higher the temperature of combustion.

We can see here the contradiction in the engine concept: the higher the combustion temperature - the higher the efficiency of the engine and its performance, but greater toxicity of exhaust gases.

It is necessary to reconcile efforts of minimizing production and direct maintenance costs of the engine, and ecological requirements.

3. Existing rule of determining turbine aircraft engines the amount of emissions of toxic gases and carbon dioxide

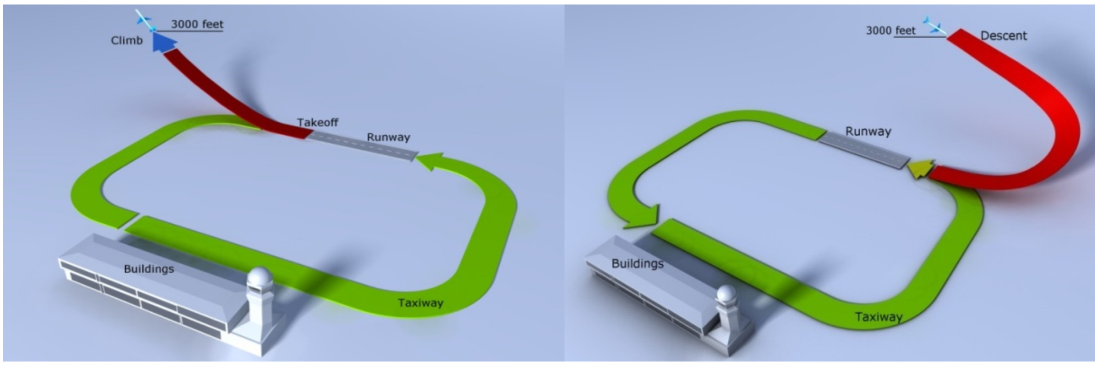
The current standards for emissions of carbon monoxide(CO), nitrogen oxides (NOx), unburned hydrocarbons(UHC) and smoke are defined by ICAO [7].

Engine manufacturers according to procedures developed by this organization for landing and takeoff cycle (LTO) perform the tests on their own test cell and reporting the results on a special document - "ICAO Aircraft Engine Emissions Databank"[8].

In this document values of the engine fuel consumption and emissions of CO, NO_x, UHC and smoke are given for a specific thrust settings and time of their duration.

These emissions values are compared with current standards. In this way, it is known what is the "reserve" to achieve the limit. The best engine of a given type is chosen to such tests, and can be specified as "ideal".

Figure 3 is a graphical representation of the LTO cycle defined by ICAO.



Flight phase	Engine thrust [%]	Duration time [min]
Take off	100	0,7
Climb to 3000 feet	85	2,2
Approach from 3000 feet	30	4,0
Taxiing	7	26,0

Figure 3: Landing and Take Off cycle – LTO as defined by ICAO[7]

It should be emphasized that in aviation there are no standards for carbon dioxide emission. The fuel consumption and emissions in the currently valid definition of the LTO cycle of the twin-engine aircraft considered in this paper have the values given in the following tables.

Table 1:B737-800 (2x CFM56-7B26)[8]

Maneuver	Duration [s]	Fuel consumption [kg]	CO emission [g]	NO_x emission [g]
Takeoff	42	103	21	2966
Climb	132	261	157	5872
Approach	240	162	259	1750
Taxiing	1560	353	6636	1659
Total	**1974**	**879**	**7073**	**12247**

Table 2:B737-400 (2x CFM56-3C-1)[8]

Maneuver	Duration [s]	Fuel consumption [kg]	CO emission [g]	NO_x emission [g]
Takeoff	42	97	87	2008
Climb	132	252	227	4486
Approach	240	161	499	1465
Taxiing	1560	387	10372	1664
Total	**1974**	**897**	**11185**	**9623**

Table 3:B767-300ER (2xCF6-80C2B6)[8]

Maneuver	Duration [s]	Fuel consumption [kg]	CO emission [g]	NO_x emission [g]
Takeoff	42	217	13	6192
Climb	132	553	22	12002
Approach	240	323	616	4042
Taxiing	1560	640	12082	3032
Total	**1974**	**1732**	**12733**	**25267**

Table 4:ERJ 195 (2xCF34-10E5)[8]

Maneuver	Duration [s]	Fuel consumption [kg]	CO emission [g]	NO_x emission [g]
Takeoff	42	67	29	777
Climb	132	174	66	2062
Approach	240	109	455	1862
Taxiing	1560	265	13101	5600
Total	**1974**	**615**	**13651**	**10302**

Above tables are showing that for such defined landing and takeoff cycle each aircraft of the same type with the same type of the engines fitted, 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.

On the basis of the data from ICAO's Aircraft Engine Emissions Databank for each engine type approximate performances can be determined and emissions depending on fuel consumption can be described by the equations (see figures below).

Figures 4, 5, 6 and 7 are showing the performances of an "ideal" engines determined on the basis of the test results given in the ICAO Aircraft Engine Emissions Databank[8].

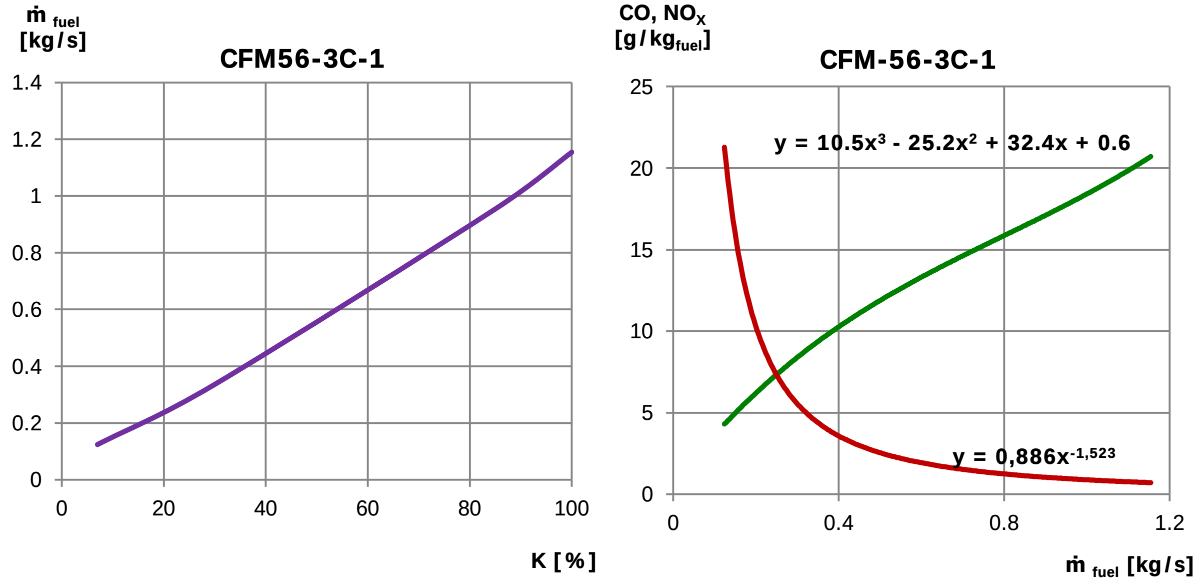


Figure 4:Fuel consumption and CO, NO_x emissions of the "ideal" CFM 56-3C-1 engine[8]

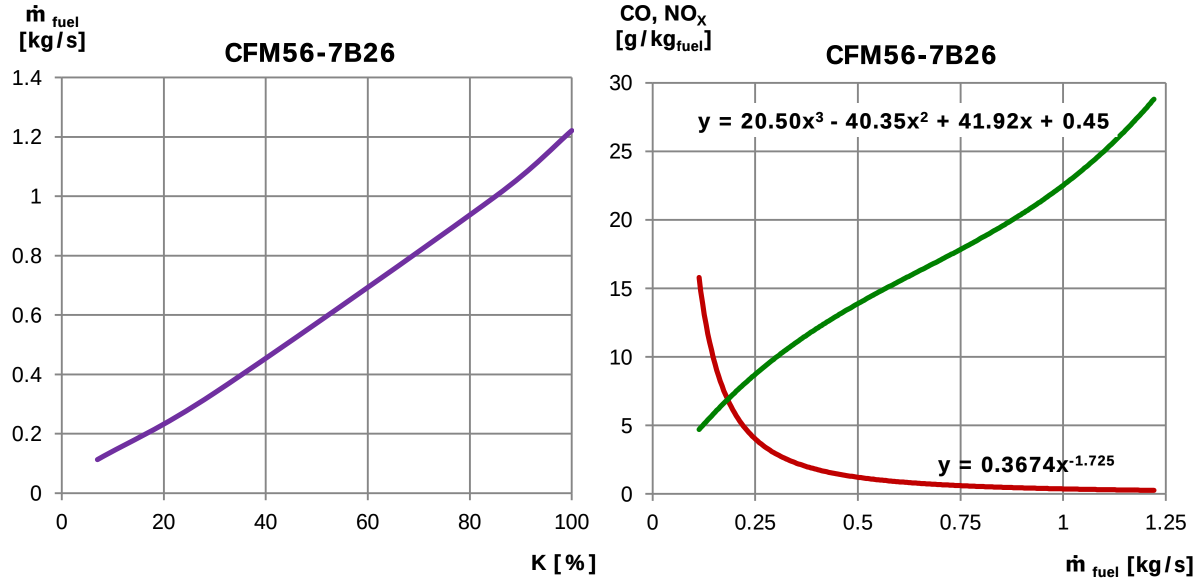


Figure 5: Fuel consumption and CO, NO_x emissions of the "ideal" CFM 56-7B26 engine[8]

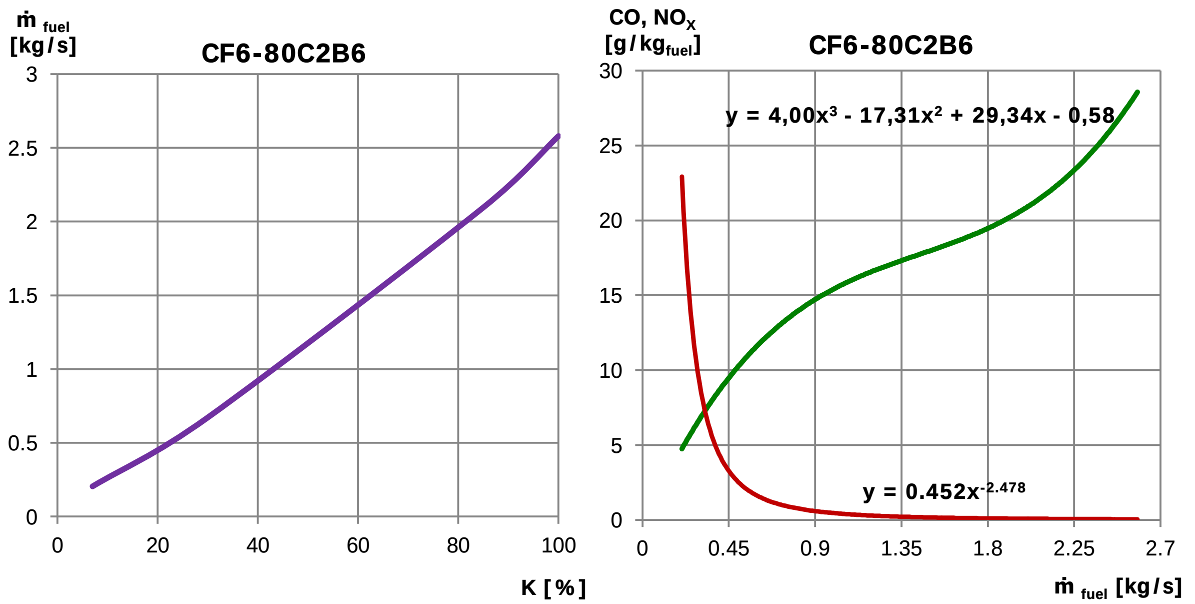


Figure 6: Fuel consumption and CO, NO_x emissions of the "ideal" CF6-80C2B6 engine[8]

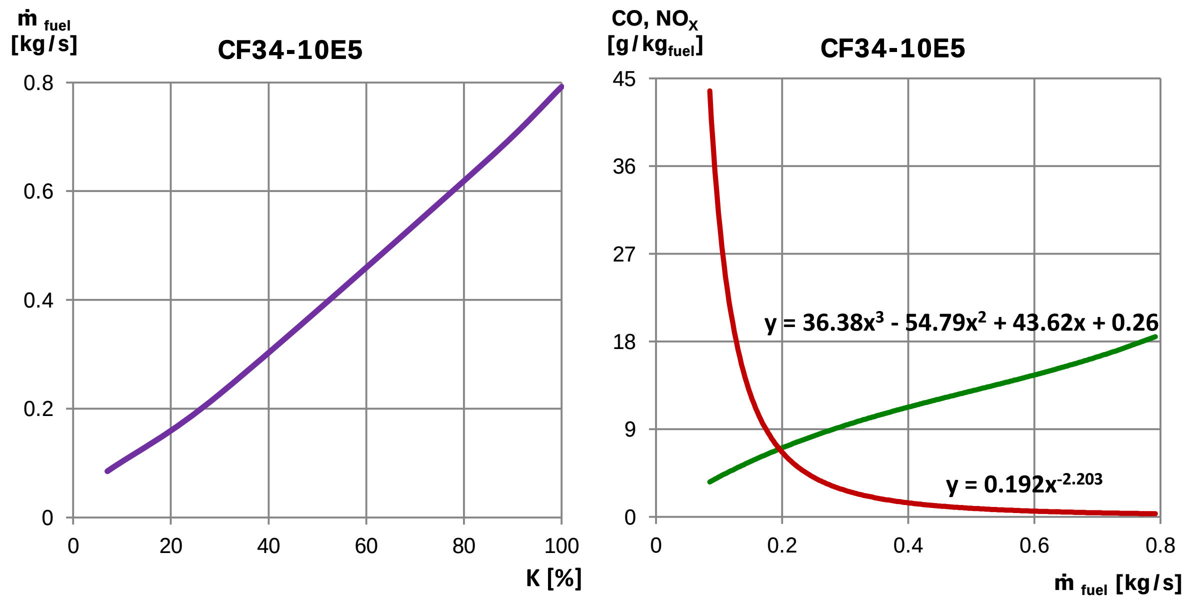


Figure 7: Fuel consumption and CO, NO_x emissions of the "ideal" CF34-10E engine[8]

4. The proposed methodology for turbine jet engines emissions estimation

Presented in Section 3 rules of emission calculations do not take into account the amount of fuel consumption and pollutants emission of a particular aircraft equipped with certain engines. In this way, during the operation of the aircraft it is impossible to asses quantitatively real toxic exhaust emissions.

The actual amount of harmful emissions can be significantly different from that 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 of the use parameters average values, as is the case of the LTO cycle obligatory definition.

After power plant 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 "ideal" engine.

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

EGT margin also is decreasing, which means that the temperature of the exhaust gases on max. power setting can approach the limit. Thus, NO_x emission increases.

Pilots during takeoff, depending on the takeoff mass of the aircraft, runway length and environment conditions apply derate or thrust reduction. It happens that the aircraft's takeoff maneuver is performed with a thrust smaller by over 20% compared to the maximum takeoff thrust.

At the discretion of the air traffic control profiles durations of the climb and approach can be different. In addition, the specificity of each airport is a reason for very different time allocated for taxiing, including stops to wait in line for further taxiing and takeoff.

For operators of both passenger and freight aircraft amount of toxic exhaust emissions, calculated according to landing and takeoff cycle can be particularly important because in the future fees for its "production" in the vicinity of airports can be imposed.

Similarly, the CO_2 emissions, both near the airport (LTO), and in other phases of flight.

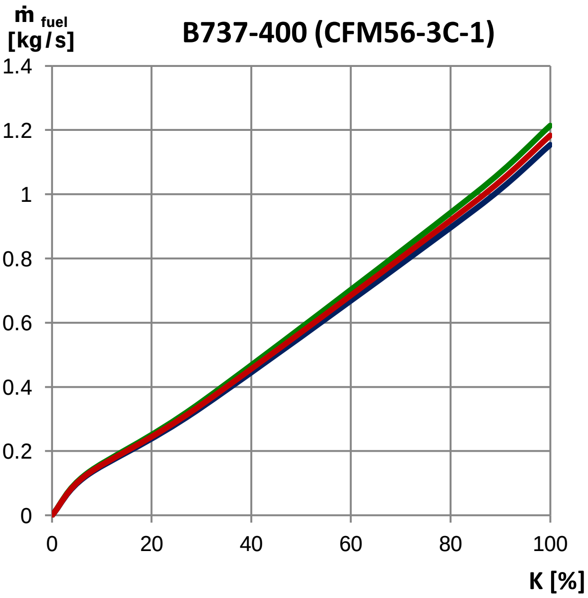
The methodology proposed in this paper is to use the recorded parameters from the on-board flight data recorder. The actual fuel consumption of the aircraft, the duration of each of its maneuvers and environmental conditions are taken into counting procedure.

Test-cell performances of the engines installed on the airframe are taken into account in the calculation of NO_x emissions.

Quantitative NO_x emission depending on the fuel consumption is calculated based on the "ideal" engine test data. Than for each of the engines installed on the aircraft, considering their test results, NO_x emission is determined and after adding both, the amount of aircraft emissions.

CO emission of the aircraft is calculated using the equation described by the exponential function for the "ideal" engine, because the difference between its performances and those installed on the airframe are not significant.

Fig. 8, 9, 10 and 11 are showing overhauled or new engines installed on a specific aircraft, fuel consumption depending on thrust, determined on the basis of data from the test cell.



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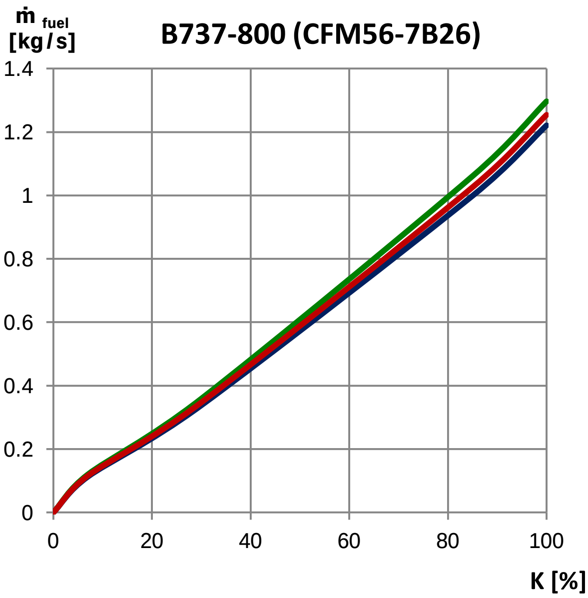

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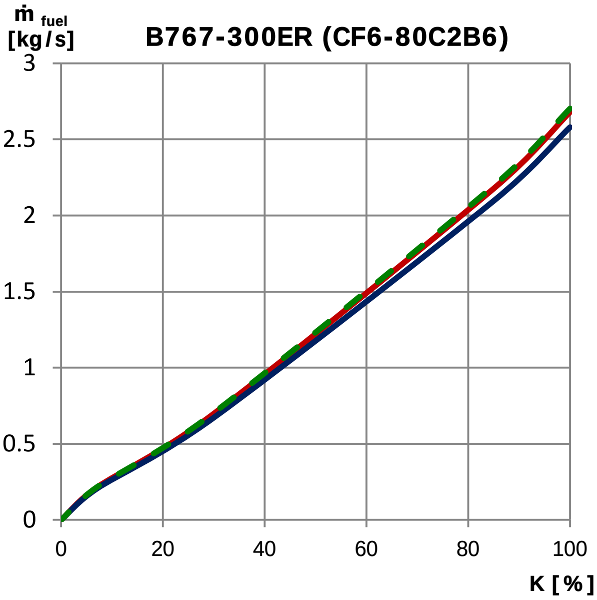


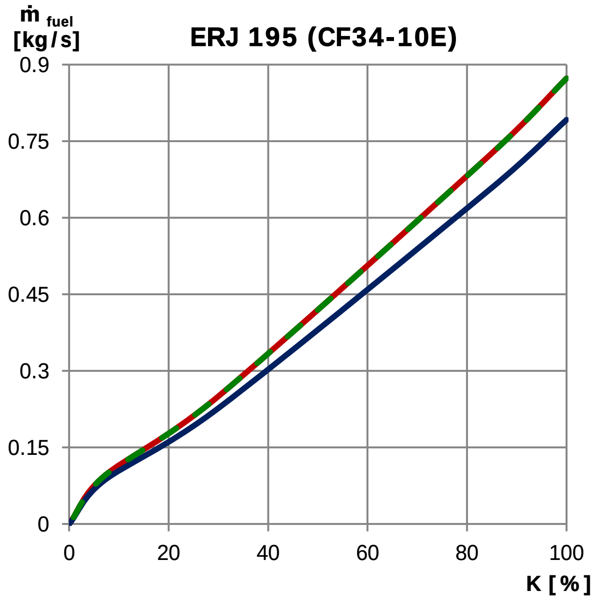


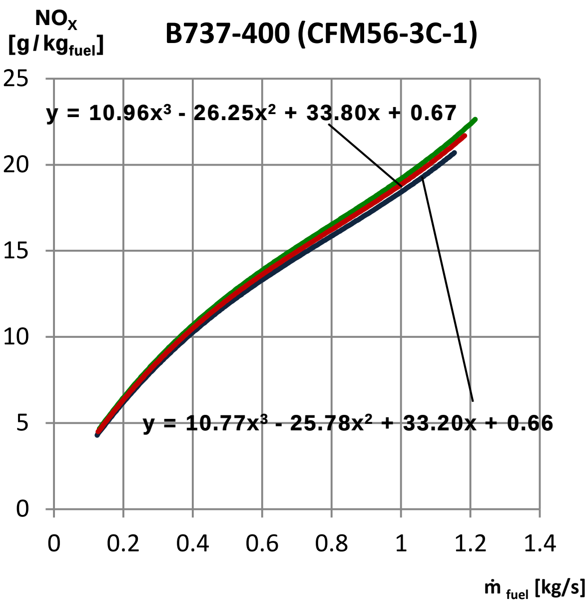
Figure 10:

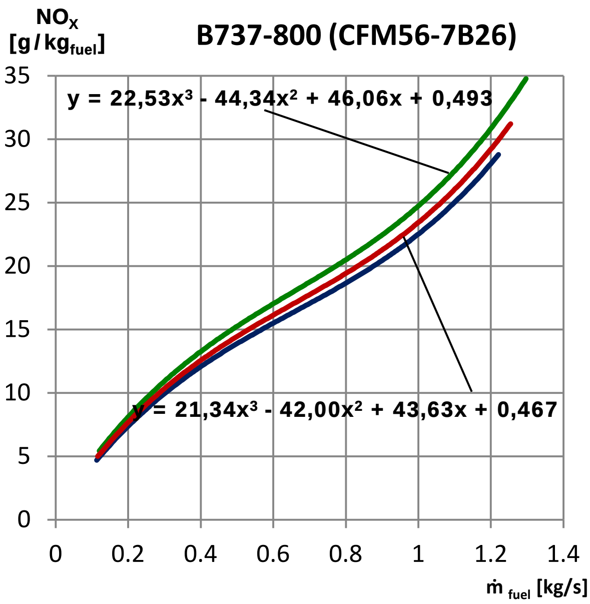
Figure 11:

Engine No.1 Engine No.2 "Ideal"

Figures 8, 9, 10, 11: Fuel consumption recorded at the test cell for engines installed on specific aircraft compared to the "ideal" engine depending on the thrust

Significant difference in fuel consumption for the same thrust settings between the "ideal" engine and those installed on the airframe is observed (in many cases more than 10%). Engines installed on the same aircraft differ between each other as well when fuel efficiency is concerned. Fig. 12, 13, 14 and 15 below are showing the dependence of nitrogen oxides emission from fuel consumption, again for engines mounted on the airframes, compared with the “ideal”. The performances of each describes a polynomial of the third degree.





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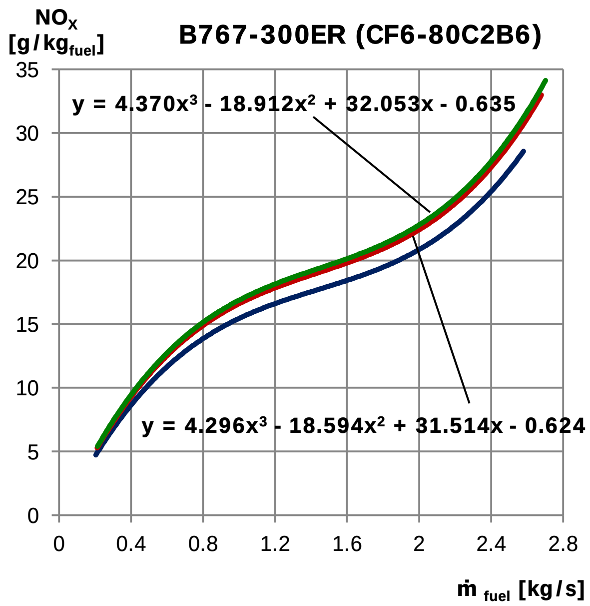

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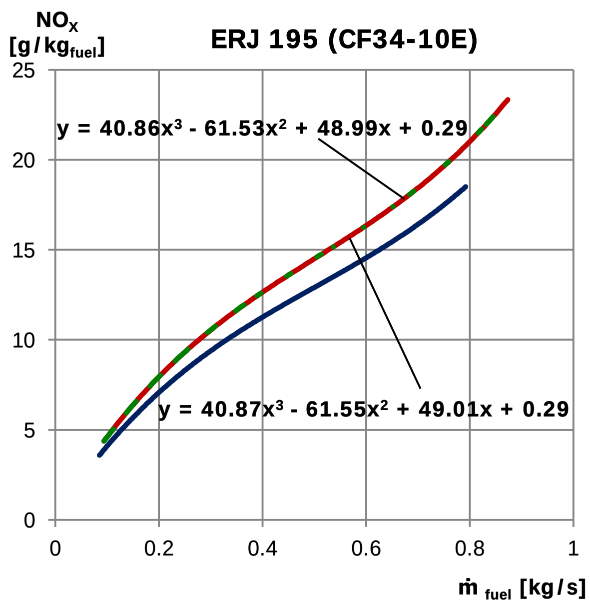


Figure 15:

Engine No.1 Engine No.2 "Ideal"

Figures 12,13,14, 15: Nitrogen oxides emission calculated based on a test cell results for engines installed on specific aircraft compared to the "ideal" engine depending on the fuel consumption

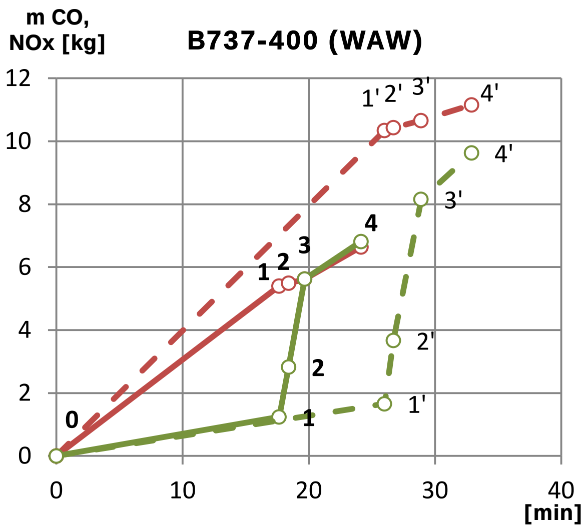
Pursuant to the records of each flight, taking into account the speed of the aircraft, the altitude and the thrust lever angle, algorithm was developed that specifies the current aircraft phase of flight and its duration. Using determined the equation of nitrogen oxides emission (Fig.12, 13, 14, 15) and carbon monoxide (Fig. 4, 5, 6, 7) as a function of fuel consumption per second for each engine installed on the aircraft, their quantity is calculated every second of the flight for a known fuel consumption and summed for the designated flight phase.

For the same phases of an aircraft flight, fuel consumption is determined and CO_2 emission after multiplication by a currently in force factor of 3,157.

5. Fuel consumption, CO and NO_x emissions during aircraft different flight phases

This section contains the examples of the results of calculations that were carried out for more than 7000 flights to several airports, by aircraft types considered in this paper.

Based on test cell data, performances of the installed on each aircraft engines were determined. As a result, for each aircraft fuel consumption and emissions in the landing and takeoff cycle and in other phases of flight were calculated. Due to limitations of the paper size, on fig.16,17,18 and 19 B737-400 and B767-300ER emissions of CO, NO_x and CO_2 are shown for maneuvers which are the part of the landing and takeoff cycle in the particular airport, comparing them to those resulting from the presently in force definition of LTO cycle.



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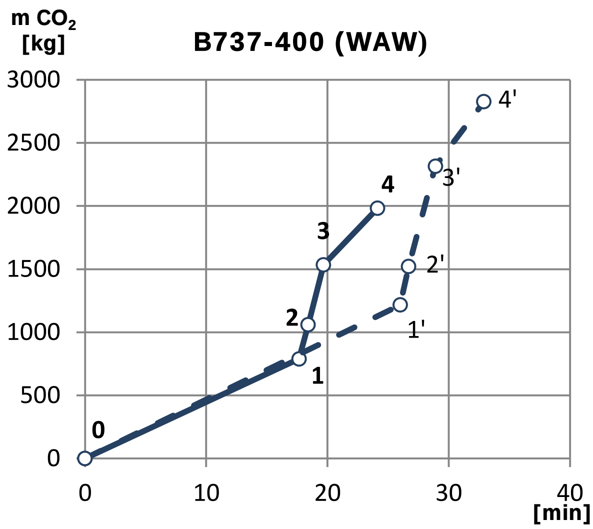

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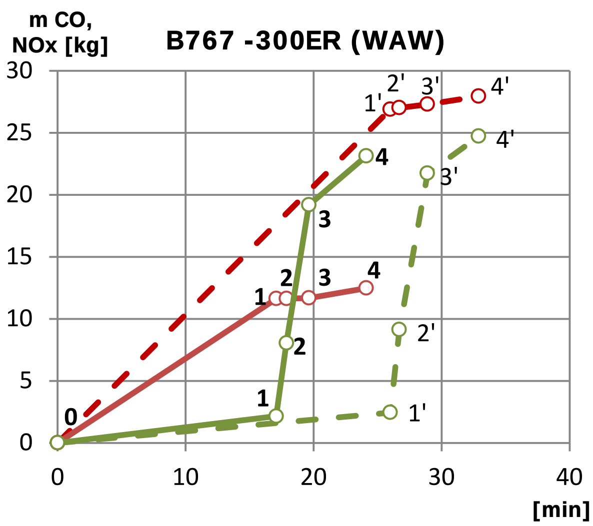

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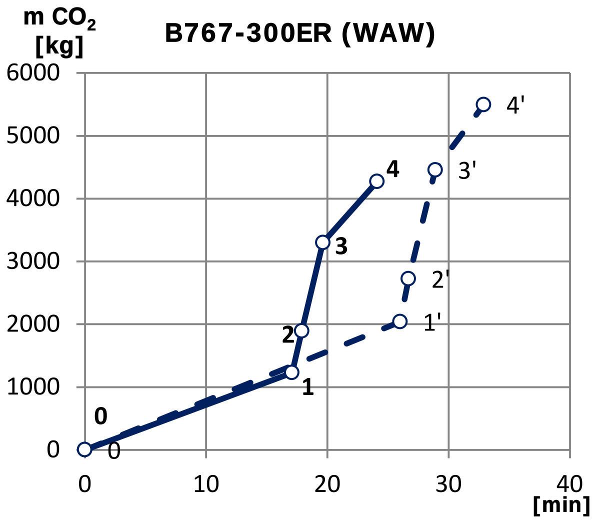


Figure 19:

ICAO's real CO [kg] NOx [kg] ICAO's real CO2 [kg]

Figures 16,17,18, 19: Emissions of carbon monoxide, nitrogen oxides and carbon dioxide during landing and takeoff cycle of the specific aircraft and one with "ideal" engines. where: Taxiing; 1-2 Takeoff; 2-3 Climb to 3000 feet;3-4 Approach from 3000 feet. Index (') for ICAO's LTO[7].

Shown on above figures, both the emission of carbon dioxide and the engine exhaust toxic compounds of the particular aircraft confirm the fact that airport emissions created during landing and takeoff cycle when taking into account the actual duration of individual maneuvers and corresponding fuel consumption differ significantly from those calculated in accordance with current definition of the LTO cycle. In the table 5 below, as an example fuel consumption and emissions of B737-400 are shown compared to 737-400 equipped with "ideal" engines.

Table 5: B737-400 CHARLES DE GAULLE (CDG)

Maneuver	Duration [s]	Fuel	CO emission	NO_x emission
Takeoff	48	91	93	1678
Climb	74	148	132	2749
Descent	227	117	874	953
Taxiing	1276	294	6840	1332
Total	**1626**	**650**	**7939**	**6711**
[%] compared to „ideal" total	**82**	**69**	**71**	**70**

The usefulness of such calculations for airlines is very important, because knowledge of the duration of the aircraft maneuvers at the airport gives arguments in negotiations with the air traffic control for their optimization.

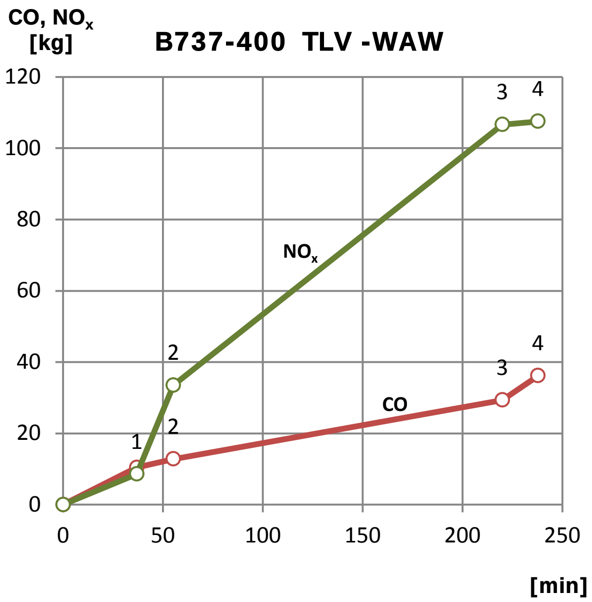
Thus, for example, shortening the time of climb for B737-400 by 10 seconds provides savings in fuel of about 20 kg per aircraft.

Medium-sized airline performs an average of 20,000 flights per year. So could save ,only in the reduction of the time of climb approx. 400 tons of fuel per year.

Serious further reductions can be expected when approach time is shorter by one minute. Fuel consumption of B737-400 in such case is reduced by 35 kg per aircraft, which gives 700 tons savings a year.

For the airport environment maneuvers reduced time is also important. At the airport of medium size, with about 300 aviation operations per day, CO_2 emissions would be reduced by nearly 7000 tons per year and NOx emissions by 70 tons, and only if all operations potentially were performed by medium range twin engine aircraft.

Fig.20,21,22 and 23 are showing the total amount of emissions during the flights of the particular aircraft on the certain routes as examples.



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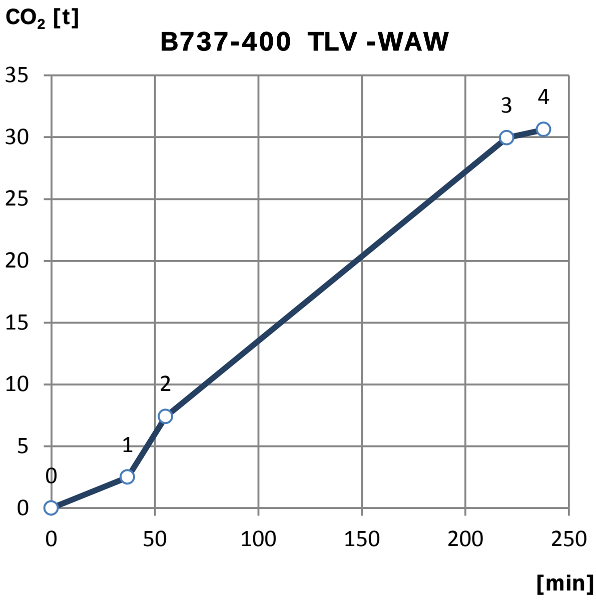

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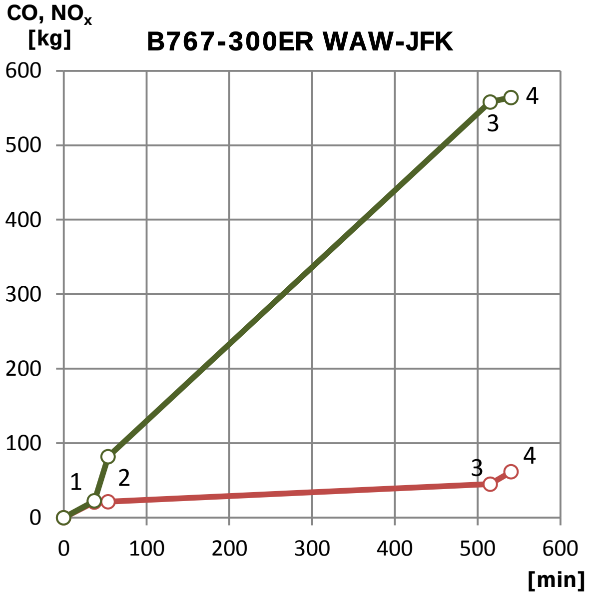

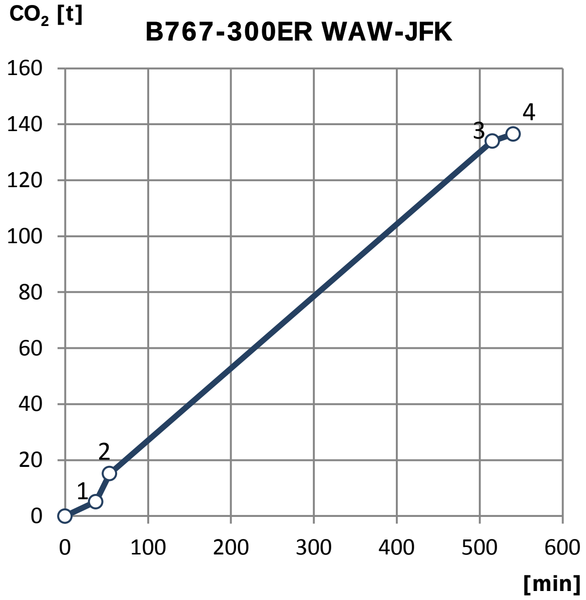

Figure 22: **Figure 23:**

Figures 20, 21, 22, 23: Carbon monoxide, nitrogen oxides and carbon dioxide emissions of the specific aircraft during flights.
where:
0-1 Landing and takeoff cycle, 1-2 Climb from 3000 feet to the cruise altitude, 2-3 Cruise, 3-4 Approach to 3,000 feet

Noteworthy is a minimum emission of toxic compounds of the aircraft engines exhaust gases during the landing and takeoff cycle compared to the entire flight.

Important is the fact that the use of 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 emissions quantity for each flight.

6. Summary

Developed at the Institute of Aviation and the Airline methodology of usage of the data from on-board flight data recorder, allows immediate assessment of the emissions of CO_2, NO_x and CO in the particular airport and on specified route for each aircraft.

It also allows to determine for each operator important factors such as: fuel consumption per passenger, per seat or per one ton of freight.

It supports the analysis of the effectiveness of various techniques of aircraft takeoffs, climb, or approach.

Systematic fuel consumption increase by aircraft, for the same conditions is a signal 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.

The consequence of the depth analysis of the flights is improvement of the operating parameters of an aircraft and its power plants, which increases the safety of flying.

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

7. Further action plan

In order to allow more precisely emissions estimation manufacturers should include in the ICAO Aircraft Engine Emissions Databank sheets also EGT values at provided thrust settings.

It is necessary to include in emission calculations engine deterioration, which has influence on its efficiency.

Jet stream influence on aircraft fuel consumption is also an important factor, hence requires more studies.

In the Airports potential threats to the ground staff should be obtained after detailed studies of the carbon monoxide and dioxide concentration distribution zones. Same has to be performed with $PM_{2,5}$. Medical Services will be able to determine safeness of the working environment.

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