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COMPARING METHODS OF CALCULATING AIRCRAFT ENGINE EMISSIONS OF HARMFUL EXHAUST COMPONENTS DURING THE TAKEOFF AND LANDING CYCLE IN THE AIRSPACE OF AN AIRPORT

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Abstract

An airport authority needs accurate information about the actual amount of harmful emissions being generated within its airspace, to be able to take measures leading to their reduction. This article presents two methods for estimating the amount of these emissions from aircraft engines during the take off and landing cycle (LTO) in the airspace of a medium-sized airport: one based on the total amount of the aircraft annually operated in it, and a second, more precise, one for a specific airline annually operating at this airport. The conclusions stemming from the comparison of these methods can support the introduction of operational and technical procedures reducing harmful emissions in the airport airspace during LTO cycle.

Keywords: harmful emissions, exhaust gases, aircraft engines, LTO cycle
Type of the work: research article

1. INTRODUCTION

European leaders agreed on 11 December 2020 to reduce, by 2030, the EU's greenhouse gas emissions to at least 55% below 1990 levels. All countries made an important commitment to the 2015 Paris Agreement to readdress their national determined contributions (NDCs) every five years. Although aviation accounts for about three percent of the total emission of harmful gases from human activities, their concentration, especially of carbon monoxide, in the limited airspace of an airport may have an impact on the health of employees directly involved in work on the airport apron.

In the EU, direct emissions from aviation accounted for 3.8% of total CO_2 emissions in 2017. The aviation sector generates 13.9% of the emissions from transport, making it the second largest source of transport greenhouse gas (GHG) emissions ,after road transport [1]. To achieve climate neutrality, the European Green Deal sets out the need to reduce transport emissions by 90% by 2050 (compared to 1990-levels); the aviation sector will have to contribute to this reduction [1]. Boeing predicts that commercial aircraft fleet will double in size, from 21,600 in 2014 to about 43,500 in 2034. Both Airbus and Boeing have orders from airlines for commercial aircraft deliveries through at least 2030. This means that airplanes powered by turbofan engines will be in operation well beyond 2050.

There are many studies in the literature devoted to the emission of harmful exhaust gases of internal combustion engines – in Poland these include [8],[10],[11]. The topic of jet engine emissions has been

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considered in numerous scientific articles, published both in Poland and abroad [2], [3], [9], [12]. Meeting the goals specified for aviation-casued emissions requires not only structural and technological changes to airplanes and engines, but also operational and technical changes within airport airspace. For the latter, the aircraft emissions as well as operational and technical procedures in the LTO cycle should be analyzed.

The takeoff and landing (LTO) cycle defined by the International Civil Aviation Organization (ICAO) [7] for subsonic aircraft is graphically depicted in Fig.1. The parameters defining this cycle vary and take on magnitudes depending on whether the engines are intended to power subsonic or supersonic aircraft. Additionally, for subsonic aircraft engines, NO_x emission is calculated differently depending on date of their manufacture, and only for those with thrust above 26.7 kN. Details can be found in [5]. Precise measurements cannot be made during engine operation. They are performed only by the manufacturer at the engine test cell according to the procedures described in Annex 16, Volume 2 [5]. Test results of each engine type are recorded on a special form, and engines must meet the required standards. These standards are recommended by Committee on Aviation Environmental Protection (CAEP). Forms are available in the ICAO Engine Exhaust Emissions Data Bank [6]. Table 1 presents a description of the LTO cycle "definition" according to the ICAO, showing at what ranges and operating conditions of the jet engine the quantitative values of emissions of the harmful substances are determined for subsonic airplanes.

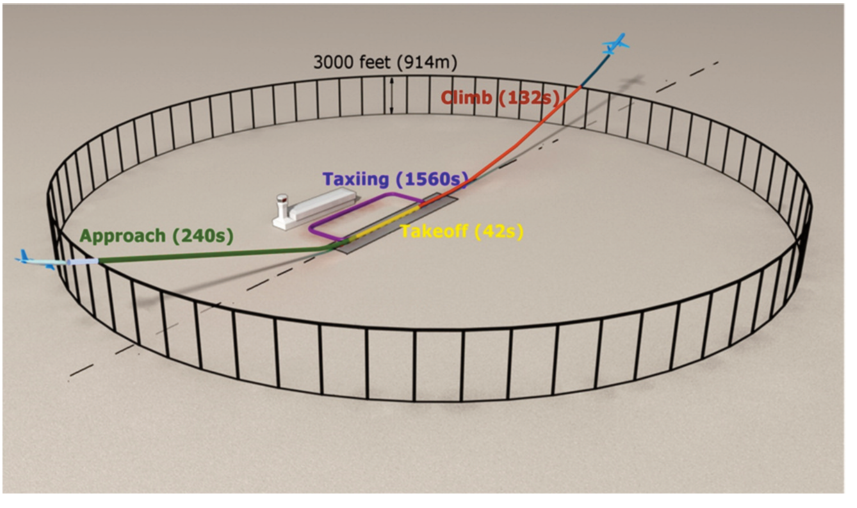

Figure 1. Graphical presentation of the LTO cycle as defined by the ICAO [4].

Table 1. Thrust settings and time duration of subsonic aircraft flight phases.

Flight Range (Phase)	**Engine thrust in [%]**	**$K_{TO.}$Duration [min]/[sec.]**
Takeoff	100	0.7/42
Climb	85	2.2/132
Approach	30	4.0/240
Taxiing	7	26.0/1 560

The directed stream of a jet engine's exhaust gases mixes with the surrounding air, gradually "blurring" into the atmosphere. 99.3%–99.5% of exhaust gases is comprised of N_2, O_2, CO_2 and H_2O. The remaining 0.7%–0.5% contains NO_x, CO, HC, including soot.

2. EMISSIONS VOLUME OF HARMFUL COMPONENTS OF AIRCRAFT ENGINE EXHAUST GASES AT AN AIRPORT OVER THE LTO CYCLE – CALCULATION METHOD BASED ON AVERAGED DURATION OF MANEUVERS

In [4] it was presented that based on the data provided for a mid-sized airport, the average number of engines per day emitting exhaust gases during the LTO cycle was determined. Also on the basis of the data contained in the ICAO Engine Emissions Data Bank [6], for each engine type its emissions were calculated over the LTO cycle according to the ICAO definition, taking into account the daily number of flight operations for that engine type. Operational practice in aviation is, nonetheless, more complex than this simplification of assuming constant parameter values, as in the ICAO LTO cycle determination methodology. Therefore, to more realistically estimate the amount of harmful compounds of jet engine exhaust emitted at medium-sized airport, averaged aircraft maneuvering times were assumed. They were calculated on the basis of the maneuver times, at the same mid-sized airport, recorded on the flight data recorders of six aircraft types belonging to a specific airline. The results are presented in Table 2 below.

Table 2. Duration of aircraft maneuvers based on data from flight data recorders compared to ICAO [4].

Maneuver	**Average duration of maneuvers calculated from flight data recorders [sec.]**	**Average duration of maneuvers calculated from flight data recorders [min.]**	**Duration of ICAO LTO maneuvers [min.]**	**Correlation Coefficient**
Takeoff	43	0.72	0.7	1.01
Climb	76	1.27	2.2	0.57
Approach	267	4.45	4	1.11
Taxiing	1 149	19.15	26	0.74

Considering the aircraft maneuvering times averaged from the data on their flight recorders, it was calculated that emissions during the “real” maneuver time of the LTO cycle are much smaller than those calculated on based of the current LTO cycle definition. The relative reductions in the estimated emissions of particular harmful compounds were as follows: by 26% for CO_2, by 25% for HC, by 27% for CO and by 13% for NO_x, which is shown in Table 3 below.

Table 3. Annual emissions at the airport in the LTO cycle [4].

LTO cycle	**Emission of CO_2 [t]**	**Emission of NO_x [t]**	**Emission of CO [t]**	**Emission of HC [t]**
ICAO	219 343	822	819	65
Including “real” maneuver times of aircraft (Tab. 2)	162 750	712	601	49

3. SPECIFIC AIRLINE EMISSIONS VOLUME OF HARMFUL COMPONENTS AT THE AIRPORT OVER THE LTO CYCLE – CALCULATION METHOD BASED ON DURATION OF AIRCRAFT MANEUVERS AND ENGINE FUEL CONSUMPTION TAKENFROM FLIGHT DATA RECORDER

As noted above, in order to more precisely determine the amount of emissions from aircraft at an airport, not only the maneuver duration, but also the operating ranges of engines during different flight phases are important. Several thousand flight records of Embraer 170/175, Boeing 737-800, Embraer 190/195 and B787 aircraft were analyzed in the airspace of a mid-sized airport during the LTO cycle of a specific airline. They show that the aircraft engines in all cases were operated at smaller thrust ranges during taxi, take-off, climb and approach than would be indicated by their values consistent with the ICAO LTO definition. The specific airline studied operates a number of types of aircraft; for each type the number of flight operations at the given airport is shown in the Table 4.

Based on the data contained in [6], the characteristics of the engines installed on the above-mentioned types of aircraft were determined. An example of such characteristics for CFM56-7B26 engine powered the B737-800 aircraft is shown in Figures 2, 3, and 4.

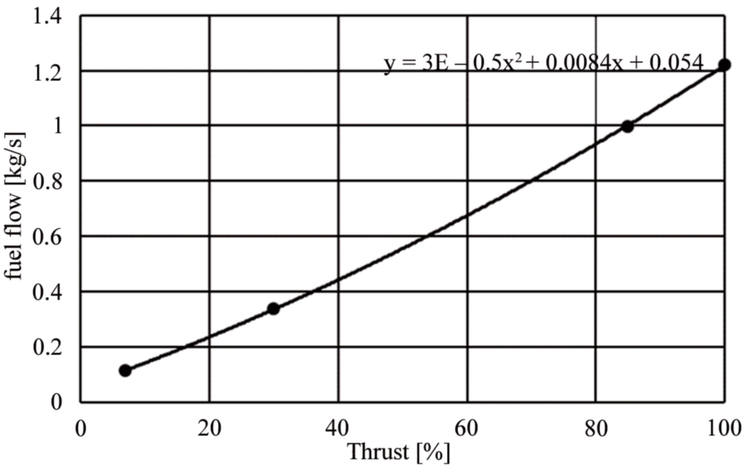

Figure 2. Dependence of fuel consumption on thrust level for the CFM56-7B26 engine.

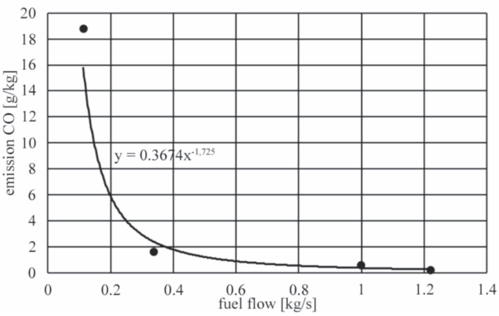

Figure 3. Dependence of CO emission on fuel CFM56-7B26 engine.

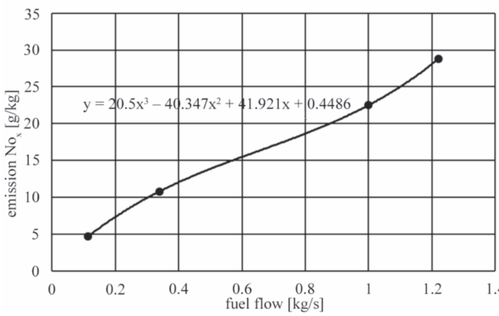

Figure 4. Dependence of NO_x emission on fuel consumption for the for the CFM56-7B26 enginex.

Table 4. Number of aviation operations for each type of aircraft.

Aircraft type	Number of flight operations
EMB 195	2814
EMB 190	4331
EMB 175	5513
EMB 170	3046
Q 400	10966
B787-8	722
B787-9	1527
B737-800	1912
B737-400	66
B737-700	165

Next, the dependence between fuel consumption and emissions were described by equations. The calculations were carried out for NO_x emissions and CO for each engine type, knowing from the aircraft flight data recorders the fuel flow per second and actual duration of individual maneuvers.

If:

y – specific instantaneous emission
x – fuel flow per second
n – number of maneuvers
Y_i – specific maneuver emission
T – specific maneuver time
$Y_{\sum}$ – total LTO specific emission

Then, for example, if instantaneous NO_x emission is described by the polynomial function:

$$y = ax^3 + bx^2 + cx + d \tag{1}$$

The total NO_x emission during a specific maneuver is described by the definite integral:

$$Y_i = \int_0^T y(t)\,dt \tag{2}$$

The total NO_x emission during the LTO cycle is described as the sum of the emission of the individual maneuvers:

$$Y_{\Sigma} = \sum_{i=1}^{n} Yi \tag{3}$$

Table 5 presents the resulting calculations of fuel consumption and emissions for the specific airline at the medium-sized airport during the LTO cycle. For comparison, emissions in the LTO cycle according to the ICAO definition are also presented for the same airline.

Table 5. Fuel consumption and emissions during LTO cycle of the specific airline.

LTO	Fuel consumption	CO_2 emission	NO_x emission	CO emission
	[t]	[t]	[t]	[t]
Specific Airline LTO – ICAO	16 356	50 785	218	222.5
Specific Airline LTO	9 073.5	28 159.5	130	90

The average LTO cycle time at the medium-sized airport of the aircraft operated by the specific airline is approximately 34% shorter than that as per the ICAO-defined LTO cycle – hence such a significant difference in the emissions of individual components of the exhaust gases. It should also be emphasized that the crews use thrust derate during takeoff, and thus lowering engine operation ranges, i.e. lower fuel consumption, which is also of great importance for the amount of emissions during this maneuver and the climb phase. The entries on the flight data recorders indicate lower engine operation ranges during taxiing as well as times of this phase of cycle than for the given in ICAO LTO cycle. Actual fuel consumption for the specific airline in the LTO cycle in the airspace of the medium-sized airport studied is approximately 45% lower than that calculated for the LTO cycle as defined by ICAO. The emission of carbon dioxide is lower by about 45%, that of nitrogen oxides by about 40% and that of carbon monoxide by about 60%.

If such a method could be applied for all the airlines performing operations at this specific airport, we would be able to calculate values close to the real amount of emissions in the airport airspace. Using the above-mentioned emissions figures for one specific airline, however, it is possible to estimate the emission values from all airlines in that airport. These are presented in Table 6 in comparison to the LTO – ICAO taken from Table 3.

Table 6. Annual emissions at the airport in the LTO cycle.

LTO cycle	Emission of CO_2 [t]	Emission of NO_x [t]	Emission of CO [t]
ICAO (Tab. 3)	219 343	822	819
Including "real" maneuvers time and fuel consumption of aircraft	120 639	493	328

4. SUMMARY

Taking into account the "real" time of the flight phases of the LTO cycle, the estimated emission of harmful components was found to be lower than as calculated for this cycle defined by ICAO: 26% lower for CO_2, 25% lower for HC, 27% lower for CO, and 13% lower for NO_x. Much lower estimated emissions, as reported for the specific airline considered in the article, are calculated when flight data recorders records taken into account. They are significantly lower than those calculated for the ICAO-defined LTO cycle, with CO_2 lower by 45%, CO by 60% and NO_x by 40%.

Unfortunately, at present it is only possible to estimate the amount of emissions of specific exhaust gas components from aircraft engines in the airspace of a specific airport, i.e. only taking into account the averaged times of the individual flight phases in the LTO cycle. In the future, however, in order to determine the actual amounts of emissions from flight operations in the airport airspace, it will be necessary to determine them on the basis of aircraft flight parameters records and the characteristics of the engines installed on the aircraft. This will enable a more precise assessment of the effectiveness of organizational, operational and technical measures aimed at reducing the emissions of carbon dioxide, nitrogen oxides, carbon monoxide and hydrocarbons in the LTO cycle. For this, the entries from the flight data recorders of all operators at a given airport will be necessary; unfortunately, this is currently not possible due to the lack of a data processing system and the reluctance of airlines to provide such data.

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