Implementation of the LTO cycle in flight conditions using FNPT II MCC simulator

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Abstract. The landing and take-off cycle (LTO) is an approval process of jet engines aimed at evaluation of the aircraft impact on the environment in the airports area. The measurements are carried out in the stationary conditions, with given engine operating parameters. The mentioned methodology results in discrepancies between approval test and real emissions. As part of the presented research, a typical landing and take-off cycle was implemented using the modern FNPT II flight simulator. The emission has been determined on the basis of emission factors which are calculated for specific engine and recorded times of each phases of LTO test during simulation research. Subsequently, the obtained values were compared with approval data. The analysed results allowed to indicate differences in the total emission between the standard LTO test and the actual take-off and landing cycle received during simulation research. The obtained results prove that the LTO methodology is a good tool to compare the emissivity of aircraft engines. However, it should not be used to estimate the impact of air transport on the natural environment within airports.

1. Introduction

Air transport is the youngest and most dynamically developing branch of transport. The increase in the demand for air transport, both passenger and cargo, is caused by the competitiveness of this branch primarily in terms of transport time and safety [1]. The air transport evolution forecasts are published annually. The Airbus Global Market Forecast indicates that the air traffic doubles every 15 years. This means that by 2033 the number of aircraft will double in relation to today's (2018) [2]. Such a dynamic growth in the number of passengers carried out also a spectacular increase in the number of aircrafts, which in turn will generate an increase in the negative impact of air transport on the environment [3]. In order to limit it, standards and restrictions are introduced to assess the current level of emissions [4].

Internal combustion engines are characterized by variable emission of harmful exhaust gas compounds depending on the operating conditions. In the interests of the natural environment, activities related to the assessment of pollutant emissions from means of transport are carried out. Tests are being developed to determine the toxicity of the combustion engines itself as well as the impact of transport on the human environment [5]. The issue of environmental impact of aircraft is included in Annex 16 of the Chicago Convention, which is in force in countries belonging to the ICAO – International Civil Aviation Organization [6]. Mentioned ICAO Annex 16 contains 2 parts: the first concerns at emission and the second one is about aircraft noise. The emission part include the description of the methodology for assessing emission of harmful exhaust compounds from civil aircraft engines by universal LTO test (Landing and Take-off).

2. Determination of the impact of take-off and landing operations in the vicinity of airports on the natural environment - LTO test

In mentioned ICAO Annex 16, the universal LTO procedure (Landing and Take-off) has been proposed for assessing emissions of harmful exhaust compounds from civil aircraft engines. This test is a mapping of operations performed within the airport, thus they are: approach (landing), taxiing, take-off and climb of the aircraft. In the case of a test for civil aircrafts, the engine load in each phase is respectively: take-off – 100% Fc_{max} (maximum thrust), climb – 85% Fc_{max}, landing – 30% Fc_{max}, taxiing – 7% Fc_{max} [7]. The entire LTO test in accordance with the regulations takes about 30 minutes. In order to ensure repeatability of results, the durations of the individual phases of the procedure have been averaged and are the same for each engine. According to this assumption, for civil aircrafts it was established that the start phase time is 0.7 min, the climb phase – 2.2 min, the landing phase lasts 4 min, and the taxiing phase is 26 min [6]. The emission obtained according to the LTO test is defined as the mass of the harmful compound per mass of fuel used in the test. It is expressed as the mass of compound in 1g referenced to 1000 g of consumed fuel.

During the reference LTO cycle, the engine tests must be carried out with the set of necessary thrust to determine the emissions of harmful exhaust compounds and smoke from the engine, so that mass values of emissions and opacity can be determined for characteristic values of nominal thrust, in accordance with the decision of the certification authority of the aircraft. During the first test phase (take-off) the engine works using 100% of the engine thrust (Fig. 1, No. 1). This phase is characterized by the lowest emission of unburned hydrocarbons (HC) and carbon monoxide (CO) as well as the highest emission of nitrogen oxides NO_x which is a result of the highest temperature in combustion chamber during whole cycle. The climb phase (Fig. 1, No. 2) only slightly differs from the start. The engine works on slightly weaker parameters, but it does not change the emission structure significantly. During landing (Fig. 1, No. 3) the engine works using about 30% of the maximum thrust. There is much higher emission of carbon monoxide and hydrocarbons than during take-off or approach because of lower temperature during combustion process. In the last mentioned phase – taxiing (Fig. 1, No. 4) – the engine operates at about 7% of the maximum thrust. Taxiing phase is characterized by the longest duration time and also the highest HC and CO emission. This makes that this phase is the most significant part of LTO in terms of emission determination.

The emission values in Figure 1 are presented in the form of emission index (EI). The emission index is the value of pollutant emissions related to the unit quantity of the processed raw material. In this case, the unit [g/kg] means the gram of pollution per kilogram of burnt fuel.

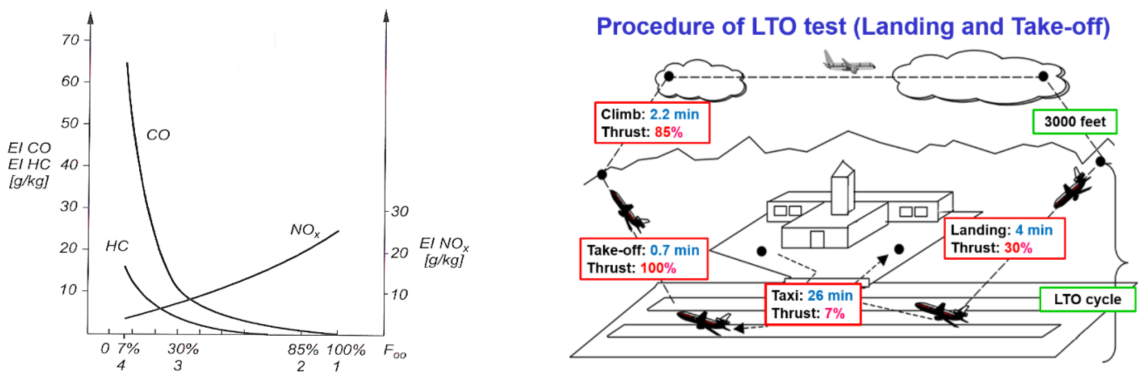

Figure 1. Approximate course of changes in emission factors: EICO, EIHC, $EINO_x$, as a function of the sequence. Four characteristic stages of the engine's LTO test were marked below the sequence mark: 1 – take-off, 2 – climb, 3 - landing, 4 - taxiing [6, 7]

Procedures for assessing the emission test according to LTO do not include measurement of particles. Many studies conducted at the Poznan University of Technology and not only indicate that this component may be the most dangerous for human health and life. It would be reasonable to include measurements of both mass (PM) and number (PN) of particulates when assessing the toxicity of aircraft engines [8, 9, 10].

The airport is undoubtedly a point source of emission of harmful compounds. Air pollution is not only the result of air operations, but also the operation of the port, service and other vehicles in the vicinity of the airport. Emission from an aircraft related to the flight depends on the type of engine, congestion, flight time and many more. Exhaust emissions at airport ground level resulting from the landing and take-off (LTO) phase of flights are generally separated from the cruise level impact [11]. An analysis of the LTO cycle in the airport area emphasized that HC and CO emissions accounted for 97.3% and 94.3% of the total mass of LTO pollution under taxi conditions, respectively. The NO_x emission by jet engines during LTO cycle are arranged on modes of take-off, climbing and landing and accounted for 26.7%, 53.6% and 10.5% from total mass of NO_x pollution, correspondingly [12].

Estimated exhaust emissions from aircraft engines in the LTO test are based to a large extent on the assumed duration of individual phases. In the modelling process of the airport as an emission source, a uniform LTO test is adopted, although the individual test phases may have a significantly different timeshare, in particular taxiing.

3. Research method

3.1. CKAS Motion Sim5 simulator

Nowadays simulators are frequently used for the purpose of research. The use of simulators allows for studies to be conducted, which can realize the full normalization of test conditions [13]. Due to the availability of technically advanced equipment in the Simulator Research Laboratory of the Institute of Combustion Engines and Transport Poznan University of Technology, it was decided to use it for the presented research. The simulator was used to determine the actual LTO test operation times.

The research was carried out using the CKAS MotionSim5 flight simulator (Figure 2). It is a system using software and hardware that combines the reliability of a modern desktop computer installed on a specially made motion platform, with a cockpit equipped with control devices identical or similar to those in real aircraft. The simulator is classified as Flight and Navigation Procedure Trainer which can also be used to practice tasks associated with Multi Crew Cooperation (FNPT II MCC).

Figure 2. CKAS Motion Sim5 simulator, outer and inner view [14]

The CKAS MotionSim5 Flight Simulator Training Device is designed to simulate four general types of light aircraft: single piston engine aircraft, two piston engine aircraft, light aircraft with two turboprop engines and light jet aircraft. It is not intended to simulate a particular aircraft model, but to simulate the handling and function of a typical aircraft of each class.

The simulator is equipped with a screen with continuous image projection (200 ° x 40 °) obtained through 3 Full HD projectors. The movement of the cabin is matched by an electric motion system with six degrees of freedom. This results in high accuracy in making the move, and the system tilts the fuselage in any possible direction by 18 ° and moves it by 150 mm.

Using the position of the instructor might be any change in the weather conditions, simulation of failures and faults and conducting simulation and within virtually any airport in the world. The operation of on-board devices in the simulator, such as a shuttlecock, pedals, engine controls, audio panel, etc., is identical or very similar to the operation of instruments in real aircraft. Figure 2 shows also the cockpit view in the MotionSim5 simulator.

3.2. The aircraft and its engines

During the tests performed using the flight simulator, the largest of the planes available for simulation was selected – a VLJ (Very Light Jet) aircraft. This choose was dictated by capabilities of CKAS MotionSim5 flight simulator, but also engine mounted in that aircraft was one of the smallest included in the LTO emission database, published on the Internet website of EASA. For further analysis of emission factors in the LTO test and simulation assessment of pollutants within the airport, the Dassault Falcon 100 aircraft was selected (shown in Fig. 3, Table 1), driven by 2 engines produced by Allied Signal: TFE731-2-2B, with a draft of 15.5 kN each (Table 1).

Figure 3. Dassault Falcon 100 aircraft and view of engine [15, 16]

Table 1. Dassault Falcon 100 aircraft technical specifications [15, 16]

Manufacturer	Production year	engines	thrust	BEM	MTOW	V max	Range
Dassault Aviation (FR)	1971-1989	2 × TFE731-2-2B	Each engine: 15.6 kN	4880 kg	8500 kg	907 km/h	3560 km

3.3. LTO test mapping

The LTO test is a very good tool for the emission assessment of aircraft engines, because by defining the time of individual phases and the load on the drive unit, it is possible to ensure repeatable conditions. Currently, during the estimation of emissions within the airport, toxic emission data obtained in the standardized LTO test are also used. According to the authors, such use of the LTO test is wrong, because the working times of individual phases may vary depending on the infrastructure configuration within the airport.

Chosen to the further analysis Poznań-Ławica airport is 7th airport in Poland in terms of the number of handled passengers. It is also the smallest airport which handles more than 1 million passengers per year. In 2017 there was more than 25 thousand operations and nearly 5 000 of them was General Aviation operations. Such significant participation of GA indicates that airport has an apron (APN) dedicated to this type of aviation. The regulations showed in AIP (Aeronautical Information Publication) includes fact, that Aprons 2 and 3 are designated to general aviation. The most frequently used landing direction (due to prevailing winds) is the 28 direction. For this reason, the average taxiway of an GA aircraft may be several kilometres. For the purposes of the analyses, the longest taxiway was adopted – about 6 km.

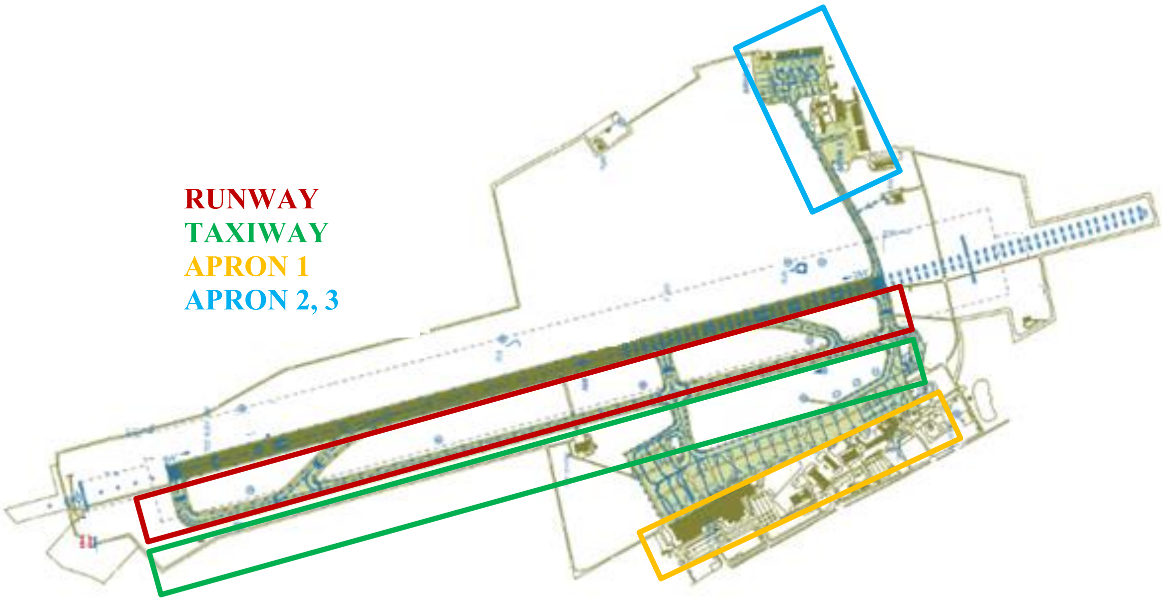

Figure 4. Visualization of Poznań-Ławica airport infrastructure [17]

The simulations of the LTO test within the Poznań-Ławica airport showed a large convergence in the duration of take-off, climb and approach phases. In each of the mentioned cases, the time of simulations is not equal with times proposed in the LTO test, however, these differences did not exceed 25% (Fig. 5). Very large discrepancies were observed when comparing the duration of the taxiing phase. In the LTO recommendations, taxiing takes 26 minutes, while during the simulation the time was 9.9 minutes, which is a shortening of taxiing by approx. 62% (Figure 5 and Table 2).

For the described reasons, the authors suggest that in order to reliably assess the environmental impact of an airport, it is necessary to calculate taxi times individually for each location. This issue is very simple, because the taxi time can be determined from the knowledge of the average distance that the aircraft covers in the airport and the speed of travel during taxiing. The taxiing distance can be calculated from the knowledge of the landing direction and the available aircraft's aprons. On the other hand, the speed can be assumed from the permissible taxi-driving norms, which are for a straight line travel of 20 kt (knots), while the speed is limited to 10 kt during turning [17]. The taxiing time is related to configuration of airport infrastructure. Poznań-Ławica airport has not very expanded taxiways solution so the time when aircrafts are moving on the ground is quite long. Usually airports have more developed taxiways structure so time may be even shorter than in the analysed case.

Table 2 summarizes the basic data used for the calculation. The setting of the engine thrust for individual phases shall be in accordance with the requirements of ICAO Annex 16. Fuel flow and emission factors were adopted on the basis of ICAO databank (for the TFE731-2-2B engine). Two durations of individual phases were adopted: the first one compliant with the standards, the second obtained during the tests. This time is the average value obtained on the basis of a series of flights performed on CKAS Motion Sim5 simulator in the Simulator Research Laboratory. As it was mentioned and described Poznań-Ławica was chosen to determine this time.

Table 2. List of parameters for individual phases of the LTO cycle contained in ICAO Annex 16 together with the duration and engine settings adopted for testing purposes

Phase	Thrust [%]	Fuel Flow [kg/sec]	Duration time [min]	
			REGULATIONS	RESEARCH
Take-off	100	0.205	0.7	0.67
Climb	85	0.173	2.2	1.88
Approach	30	0.067	4	5
Taxi/Idle	7	0.024	26	9.9

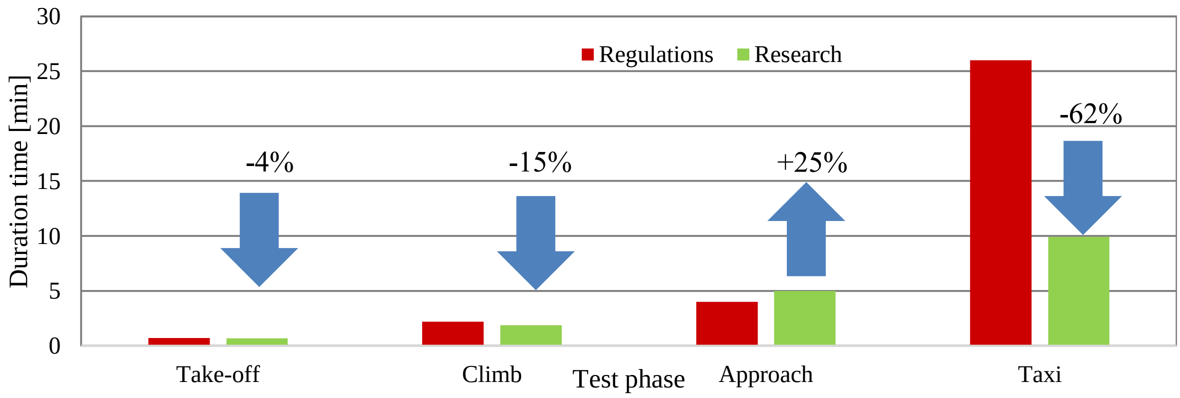

Figure 5. Differences between LTO time phases in regulations and research

4. Analysis of the research results

The aim of the measurements was to determine the exhaust emissions of the aircraft during the LTO test, taking into account the actual duration of the specific air operations. Using the emission factors of individual toxic compounds obtained during the approval process, the emission was estimated. In addition to gaseous toxic compounds (CO, HC, NO_x), particulate matter (PM) has been taken into account. Although the measurement of particulates during the LTO test is not required (only determination the Smoke Number) during the approval of new engine designs, a PM mass emission factor may be determined.

The figure 6 shows the emission of nitrogen oxides (NO_x) and hydrocarbons (HC). The take-off of an aircraft involves the use of maximum engine thrust. Therefore, the conditions in the combustion chamber are characterized by a very high pressure and temperature, which causes directly the emission of nitrogen oxides. Due to the above fact, the emission factor of nitrogen oxides during the aircraft take-off is the largest. The emissions of nitrogen oxides during take-off were 131.3 g and 125.1 g respectively for standard LTO test and the study. The values of NO_x emissions in individual phases have a significant share in the total emissions mainly due to the much longer time of a given air operation than it can be found in the case of take-off.

The hydrocarbon emission (Fig. 6b) during the take-off and the climb phase had a small share. This is mainly due to the very short duration of these phases and the small hydrocarbon emission factor. High temperature and pressure occurring in the combustion chamber during take-off and climbing forces very good combustion resulting in a low mass of unburned fuel. The most important difference in the test was shown by taxiing, due to the very high share of hydrocarbon emissions caused by small thrust and the large difference in taxi between standard LTO test and the study.

a) b)

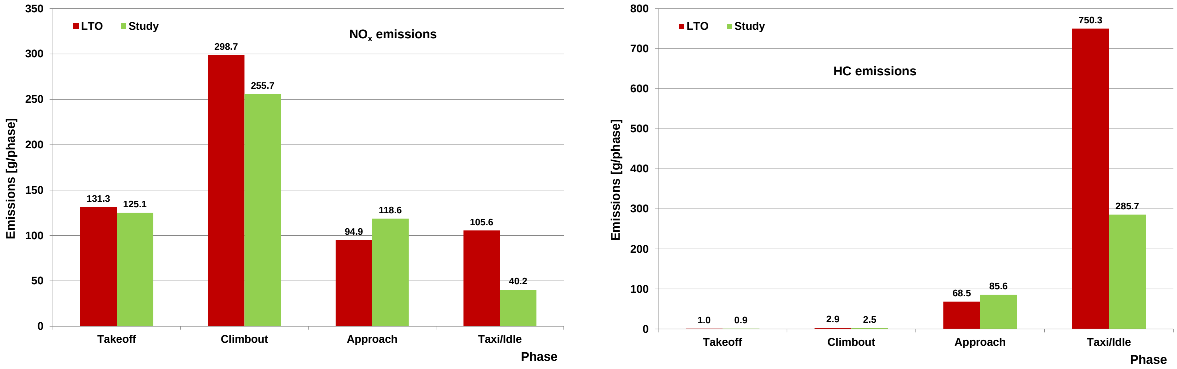

Figure 6. Total emissions of NOx (a) and HC (b) during individual LTO phases

Emission of carbon monoxide (Fig. 7a) during the individual phases of the LTO test was similar to the case of hydrocarbons. The above fact results from the combustion process, the conditions of which have the same effect on HC and CO emissions. Due to the good combustion during operation of engines with high power, most of the carbon from the fuel is oxidized to carbon dioxide, so the CO emission is small (take-off and climb phase). Due to unfavorable combustion conditions during taxiing, this phase shows the greatest exhaust fumes pollution with carbon monoxide.

Particulate matter is not directly contaminants for the LTO test. However, most of the research performed within the issue of particulate matter emissions from aircraft engines [18, 19] indicates the need to extend the LTO test by measuring its mass and number. In the case of the study carried out, the mass of particulates has a significant share in each of the four test phases (Fig. 7b). This is due to the occurrence of many particle formation processes, including nucleation and accumulation. During take-off and climbing, particles arise mainly in the nucleation process, which leads to the creation of a relatively small mass but a very large number of particles with small diameters. Those small particles (also called nanoparticles) are very dangerous for human health, because they can easily penetrate lungs and get to the blood. In the case of landing and taxiing, a portion of the particulate matter arises in the accumulation process. The resulting particles are usually characterized by a larger size and mass.

a) b)

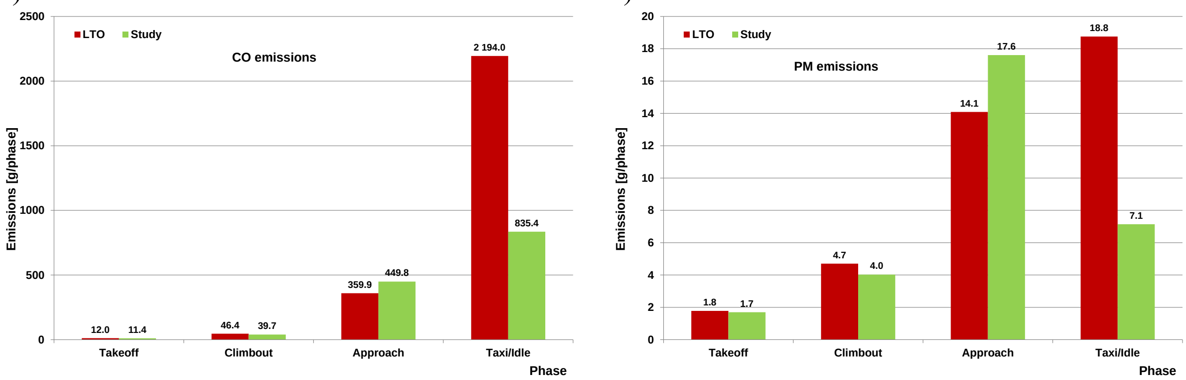

Figure 7. Total emissions of CO (a) and PM (b) during individual LTO phases

The emission of carbon monoxide has the highest mass fraction in the whole test among tested compounds. This is due to the fact that the majority of the test duration conditions of the engine's operation are conducive to the formation of CO. However, taking into account the duration of individual phases, according to simulation study, it turns out to be 49% lower. The emission of nitrogen oxides in the whole test was 630 g, while in the study it was 14% lower. The highest NO_x emission intensity occurred during take-off and climb phase. The largest difference in the emission of individual harmful compounds occurred in the case of hydrocarbon and reached 54%. Particulate matter has a small share in the total exhaust emission. This is due to the fact that the particles emitted by jet engines are characterized by large number and small dimensions. Adjusting the LTO test to a given airport, it was obtained that the emission of particles may be reduced by 23% (Fig. 8).

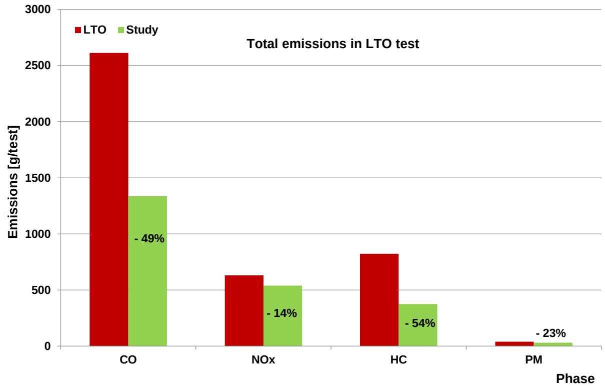

Figure 8. Total mass of individual exhaust compounds in the LTO test

5. Conclusions

To make accurate exhaust emission calculations from all modes of transport, the actual conditions should be assumed. For example in road transport the emission measurements are performed in real driving conditions to receive the data in similar conditions in which the vehicle is operated by the user. In aviation the situation is similar, the LTO test conditions represent the engine operation parameters during the phases of: taxi, approach, take-off and climb. Each phase time duration is also defined, so this test procedure is proper in case of aircraft engines comparison. Unfortunately the same times are taken into account for calculations of environmental impact of an airport. As our simulation study showed the correlation of specific phases duration with the LTO test was very good in terms of take-off, climb and approach, where the difference did not exceed 25%. But the taxi/idle phase time was 62% shorter than in the LTO test. The time differences result in different emission of toxic compounds, which was also calculated.

The mass of individual toxic compounds were obtained using the emission factors in different phases of the LTO test and measured times of the specific phases simulated on the CKAS MotionSim5 flight simulator. The airport chosen for analyses was Poznań-Ławica airport. The emission of CO, NO_x, HC and additionally PM emission which is not obligatory for the LTO test was taken in account. The best correlation was received in the case of NO_x, because this compound formation intensity rises with pressure and temperature in the combustion chamber which are very high at take-off and climb. The biggest share in CO and HC emission occurs during the approach and taxi/idle phase, when the in-cylinder pressure and temperature is low. At that phases obtained times were much shorter than in the LTO test, so the obtained CO and HC mass is respectively 48 and 54% smaller than during standardized LTO procedure. The mass of additionally considered PM, assuming the simulated times is 23% lower.

The work showed that for individual airport, the environmental impact report should be prepared with airport specific LTO phase times. The future investigations will be focused on comparison of the simulated duration of each part of LTO test to its real value for different airports.

References

[1] Merkisz J, Pielecha J, Markowski J, Galant M, Jasiński R and Gallas D 2015 The analysis of air transport in Poland *International Conference on Air Transport INAIR 2015, 12-13 November, Amsterdam*
[2] Airbus 2016 Global Market Forecast
[3] Jasiński R, Pielecha J, Markowski J, Galant M and Gallas D 2016 External environmental costs of air transport *International Conference on Air Transport INAIR 2016, 09-12 November, Wien*
[4] Merkisz J, Pielecha J, Lijewski P, Merkisz-Guranowska A and Nowak M 2013 Exhaust emissions from vehicles in real traffic conditions in the Poznan agglomeration *Air Pollution 2013, 3 - 5 June, Siena, Italy*
[5] Yim et al 2015 *Environ. Res. Lett*. **10** 034001
[6] Annex 16: Environmental protection, vol. I: Aircraft noise, 4th ed. ICAO
[7] Merkisz J, Galant M, Karpiński D and Kubiak K 2014 Evaluation of possibility to use the LTO cycle for emission test on example of the model turbine engine GTM-120 *Journal of Mechanical and Transport Engineering* **66** no. **2** pp 25-33
[8] Fuc, P., Rymaniak, L., & Ziolkowski, A. (2013). The correlation of distribution of PM number emitted under actual conditions of operation by PC and HDV vehicles. *Air Pollut*, *21*(174), 207-213.
[9] Jasiński R, Pielecha J and Markowski J 2016 Emission of particulate matter during aircraft landing operation *E3S Web of Conferences* **10** pp 1-5
[10] Merkisz J and Pielecha J 2015 Nanoparticle Emissions from Combustion Engines. Springer Tracts on Transportation and Traffic 8
[11] Lu C 2017 *Economies* **5** 44
[12] Zaporozhets O Synylo K 2017 *Energy* **140** 1350 – 1357
[13] Galant M and Merkisz J 2017 Analysis of the possibilities of using eeg in assessing pilots' psychophysical condition *Zeszyty Naukowe Politechniki Śląskiej. Seria Transport* **95**
[14] Merkisz J, Galant M and Bieda M 2017 Analysis of operating instrument landing system accuracy under simulated conditions *Zeszyty Naukowe Politechniki Śląskiej. Seria Transport* **94**
[15] www.globair.com
[16] www.wikipedia.com
[17] Aeronautical Information Publication (AIP) Poland *Polish Air Navigation Services Agency*
[18] Markowski J Pielecha J Jasinski R 2017 Model to assess the exhaust emissions from the engine of a small aircraft during flight *Procedia Engineering* **192** 557-562
[19] Jasinski R 2017 Number and mass analysis of particles emitted by aircraft engine *MATEC Web Conf.* **118** 0023