# The Transport Aircraft Pollution Cost Reduction Strategy

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*The civil air transport sector analysis shows continous growth in the next decade with significant environmental consequences, in terms of air pollution and climate change. The increasing public awarness for future climate changing produces different measures for civil air transport sector pollution mitigation. One of the measures for managing civil air transport sector development is pollution charges introduced by Swissland and Sweden. The research presented in this paper are sets of operational procedures implementation to reduce turbo fan passenger aircraft emission in space around the airport, as well as related pollution charges. The pollution in space around the airport is defined by LTO cycles established by ICAO. Generally, ICAO method finds the relation between emission pollution and engine characteristics, fuel flow and time in mode. The developed mathematical model based on aircraft performance model, presented in paper for aircraft 767-300, can be used as airline tool for airline pollution charges mitigation or cancellation.*

**Keywords:** *aircraft pollution, emission charges, continuous descent, derated takeoff.*

## 1. INTRODUCTION

We all are aware of recent economic crisis, which is coming into all segments of society, but we must also be prepared for future developments and post crisis events. The world of air transport system is changing in a rapid way, also as a consequence of economics crisis and escalating environmental concerns. Concerns over global warming are now also focused on air carriers and general aviation. All of these issues need to be addressed for future air traffic systems, and new technology needs to be applied to the basic aircraft configuration, engines, and subsystems and the airspace in which they operate. ACARE has set up targets for the year 2020 in order to reduce $NO_x$ and $CO_2$ emission per passenger per nautical mile. This reduction is significant. It is by 20 % in the case of $CO_2$ and 80 % in the case of $NO_x$ [1].

Pollution by air transport is directly related to pollutants released after fuel consumption. The most important pollutants, which are linearly related to fuel consumption, are carbon dioxide ($CO_2$), $SO_2$ and water vapor. The production of pollutants, such as oxides of nitrogen ($NO_x$), CO and HC are not linearly related to fuel consumption. One of the measures for managing air transport industry development is pollution charges, introduced by Switzerland and Sweden and recently by UK. This paper analyzes the effect of major pollutants, $CO_2$ and $NO_x$ trough developed pollution during takeoff and landing flight phase.

The increase in fuel consumption causes the linear increase of $CO_2$ emission. The production process of $CO_2$ is quite opposite to the production process of $NO_x$, i.e. the lower $CO_2$ emission produces the higher emission of $NO_x$, as stated in [2]. In turbo fan engine, combustion chamber high temperatures, desirable from the viewpoint of minimizing fuel consumption and also minimizing $CO_2$, CO and HC production, create higher $NO_x$ emission.

ICAO Oxides of Nitrogen Emission Standards were adopted in November 2005, and they apply to engines manufactured after 31 December 2007. In this paper it is suggested a simple and efficient way to meet ICAO Oxides of Nitrogen ($NO_x$) Emission Standards with respect to fuel consumption, which require definition of the best airframe and offered engines on the market combination. This optimal combination cuts emission of $NO_x$ with lower fuel consumption or $CO_2$ emission. The combination of airframe and engine must be certified for operational use, from EASA and FAA (Federal Aviation Authority).

The development of an engine for one particular aircraft frame is time consuming and expensive process. In today's air traffic the system of air pollution measurement is defined for flight altitude up to 914.4 m (3000 ft) QFE by LTO emission cycles (landing, takeoff) published by [3]. This air pollution measurement system is based on Emissions Related Landing Charges Investigation recommendation, published by [4]. Today, there is not yet the methodology for pollution charges calculation based on real pollutant emission produced during real aircraft operations for given aircraft configuration in takeoff and landing and real applied throttle setting. For example, ICAO Engine Emissions Databank published by [3], for engine CF6-80C2B6F, assumes only the application of 100 % takeoff thrust. Contrary to this, derated thrust is established method for takeoff operations, when *ATOW* is lower than *MTOW*. This *ATOW* requires lower thrust setting, which implies lower pollution as described by [5]. Derated takeoff thrust has flight safety and operations limitation and shall not be used when the runway is contaminated with standing water, slush, snow or ice. The second example is CDA method,

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which requires idle thrust during approach. Again, ICAO Engine Emissions Databank in [3] for engine, CF6-80C2B6F assumes only the application of 30 % thrust setting during approach operations. The CDA procedure has flight safety and operational limitations:

- requires more time to complete operations than classic descent, approach and landing operations which imply the reduction of air space capacity and induce delay [6],
- it may sometimes not be possible to fly a CDA due to airspace constraints or overriding safety requirements [7],
- requires special air crew training,
- requires higher meteorological minimums [8].

These two examples clearly imply need for detailed pollution analysis, actual thrust and flaps setting during takeoff and landing operations, contrary to the rigid LTO method of pollution assessment. The indirect benefit which can be achieved through detailed takeoff and landing operations analysis is the definition of optimal throttle/flaps setting for minimum fuel consumption. The market oriented airlines have the main target to reduce direct operating costs. Nowadays, one of the costs is environmental pollution cost represented by pollution charges, which is generated by fuel consumed during flight and time spent in flight phases.

Therefore, a further investigation of the influence of real aircraft configuration (flaps and throttle setting) for real pollution emission quantification and presentation is suggested. This paper investigates the application of different flaps and throttle setting in takeoff and landing phase flight regime as the first pollution cost mitigation methodology for assessment of real pollution emission and emission distribution. Such problem set up introduces real quantification and their influence on environmental pollution.

The generated environmental pollution has been measured through time, height and distance during takeoff phase (acceleration, rotation and initial climb to altitude of 914.4 m QFE) and landing flight phase (approach from 914.4 m QFE, rotation and deceleration until full stop). The achieved results are then used for pollution costs calculation (or pollution charges calculation) and emission presentation, according to consumed flight fuel and elapsed flight time. Besides highlighting of different flaps and thrust setting contribution to the minimum pollution emission, the aim of this paper is to provide contribution to airframe engine combination, as a second method of pollution cost mitigation and an airline strategic tool in the process of environmental pollution cost reduction.

The paper reviews the benefit from the application of different flaps/throttle setting application and different engine-airframe combination as measures of pollution charges mitigation. The air operator can determine best airframe engine matching to achieve the minimum pollution cost and in that way to achieve direct operating costs reduction. Other beneficiaries, such as national CAA, have the tool to determine, by adopting the proposed methodology, how much pollutants are produced from aircraft operation. The rigidity of ICAO LTO pollution calculation model will be shown in comparison process, where pollution cost calculated by proposed methodologies, will be compared based on real aircraft data and real operation, and ICAO LTO methodology based on aircraft statistical data and standard operations.

## 2. THE AIR POLLUTION CALCULATION

The primary influence of flight fuel and time determination, discussed in this research, is emission of $CO_2$ and $NO_x$ calculation. The emission of $CO_2$ and $NO_x$ depends on the type of fuel, fuel burned and flight level where fuel is burned. We can set up direct relationship of fuel burned and $CO_2$ emission for transport aircraft. For kerosene Jet A1 fuel used in transport turbo fan aircraft, 1 kg of fuel burned produces 3.15 kg of $CO_2$, as published in Boeing 1988. Other potential climate impact of transport aircraft is from oxides of nitrogen, water vapor, oxides of sulfur, condensation trails and cirrus cloudiness.

The emission related to airframe is connected with $CO_2$ emission, but engine emission is related to trade between $CO_2$ emission reduction and $NO_x$ emission increase. ICAO published aircraft engine emission certified data which include Emission Indices, time of flight mode, throttle setting and fuel flow, as stated in [3]. ICAO has formed the Aircraft Engine Exhaust Emissions Databank published in [3], providing Emission Indices for CO, HC, $NO_x$ and smoke, for each one of the four-engine throttle settings (takeoff, climb-out, approach and idle). These data are regularly used to estimate aircraft emission, with full power application.

This analysis based on these data and method is independent of pilot operations, such as thrust derate, aircraft weight and flaps setting. ICAO standard emission calculations are useful as a certification benchmark for engine performance and they are not accurate for calculation of emission from real aircraft operations. For more accurate calculations of emission, in this investigation, we are using BM2, published in [9], which involves correction of ICAO certification data for atmospheric conditions and aircraft operations.

The calculation of emissions below 914.4 m (3000 ft) relies on the information in the BM2, or the "Boeing curve fitting method", which is an internationally accepted operational emissions method published by [10]. This method calculates emissions indices based on fuel flow and ICAO certification data. The data taken from [3] and the four-certification power settings at SLS conditions are used to compute pollutants emissions, corrected for real atmospheric conditions. Prior to the application of BM2, the aircraft engine performance in this investigation was modeled as closely as possible to real engine performance (B767-300 aircraft with CF6-80A, PW4060 and PW4056 engines was used for this paper) and ICAO aircraft engine certification data were used, as input to the methodologies presented in this analysis. The BM2 was used in this research, because it can calculate pollutant emission with variations of altitude, thrust and flaps setting and flight segment time. The aircraft manufacturers offer on the market the airframe with default engine installation. In fact, the aircraft manufacturers do not manufacture aircraft engines. The engine manufacturers, actually develop engines by aircraft manufacturers design criterion, but today air carriers, when purchasing the aircraft, make final choice about aircraft engine. This choice is difficult for airline and depends on market where airline offers their service.

In presented investigation, several aircraft configurations with different engines and different throttle/flaps setting will be analyzed, in order to explore conditions for minimum takeoff and landing pollution charges, which are the function of time, fuel and pollution emission. The first part of the paper is about defining real aircraft takeoff/landing flight model. The second part explains the methodology for minimal pollution cost *PC*, in takeoff and landing flight phase. The third part of the paper summarizes the results and presents future innovative changes.

## 3. THE TAKEOFF AND LANDING MODEL ASSUMPTIONS

In this paper, twin turbo fan aircraft Boeing 767-300 is accepted as reference aircraft for pollution charges mitigation strategy investigation, equipped with three types of turbo fan engine, PW4060, PW4056 and CF6-80A [11,12]. The basic idea is to compare engine airframe combination and different throttle/flaps setting to produce minimum pollution, as well as related minimum pollution charges. The combination of aircraft structure and engines is according to EASA certificate which guarantees the highest level of air safety. The application of different throttle/flaps setting is also certified. Flight safety operations and their application is only limited by obstacles in airport obstacle accountability area.

The base for pollution calculation is a modified classic flight mechanic model, for *takeoff* and *landing* aircraft performance calculation, published in [13]. The analysis are demonstrated on the Airport Nikola Tesla in Belgrade, Republic of Serbia (ICAO 4 dig. code: LYBE) on runway 12 in ISA conditions. In order to determine real emission quantity, it is necessary to use real aerodynamic data and aircraft engine data, published in PEM [14].

In our investigation, we used aircraft low speed drag polar for different flaps setting. Engine characteristic are also taken for different throttle setting. The reference 1$g$ stalling speed for calculation of $v_2$ speed for takeoff and $v_{ref}$ speed for landing flight phase are taken from PEM. By analyzing the interdependence of characteristics of turbo-fan engines [15-17], realistic characteristics of the engine [14,18,19], we applied quadratic polynomial approximation of realistic parameters of engine's parameters. The data for aircraft engines PW4060 were obtained from [20], PW4056 were obtained from [18] and CF6-80A were obtained from [21].

## 4. THE TAKEOFF AND LANDING POLUTTION COST

In our investigation, we introduced the pollution parameter: cost of pollution or cost to eliminate produced pollution.

The investment for produced pollution neutralization is the base for pollution charges. The standard air industry direct operating cost function is related only to flight fuel and flight time. This function can be upgraded with cost of elimination of pollution. This pollution costs comprise the influence of two most important pollutants of combustion process of turbo fan engine: $CO_2$ and $NO_x$. Since emission of $CO_2$ is linearly related to consume fuel, we can calculate cost of $CO_2$ pollution from consumed fuel. However, the emission of $NO_x$ can be expressed as product of *EINOx*, fuel flow and time in mode.

$$NOx = \frac{EINOx}{1000} \cdot FF \cdot t \,. \tag{1}$$

Emission of $NO_x$ in kg is the function of three elements as shown in (1). We introduce new costs, costs of cleaning pollution or pollution charges, *PC* in USD. The costs of cleaning are the sum of emitted mass of $CO_2$ multiplied by the cost of $CO_2$ pollution cleaning and emitted mass of $NO_x$ multiplied by the cost of $NO_x$ pollution cleaning.

$$PC = \frac{g_f}{1000} \cdot 3.15 \cdot c_{pCO_2} + FF \cdot t \cdot \frac{EINOx}{1000} \cdot c_{pNO_x} \tag{2}$$

$$PC = \frac{m_{CO_2}}{1000} \cdot c_{pCO_2} + m_{NO_x} \cdot c_{pNO_x} \tag{3}$$

where the cost of $CO_2$ pollution cleaning $c_{pCO_2}$ in USD per t of $CO_2$ (middle value of cleaning $CO_2$ pollution is 28 USD/t, [20]) and cost of $NO_x$ (middle value of cleaning $NO_x$ pollution 3.4 USD/kg, [20]) pollution $c_{pNO_x}$ in USD per kg of $NO_x$. Emission of $NO_x$ pollutant is not linearly related to fuel consumption and must be calculated by using BM2 published in [9].

BM2 for the given aircraft engine and ICAO Engine Exhaust Emission Databank build up the relation with fuel flow and Reference Emission Index of $NO_x$ emission, *REINOx* [g $NO_x$/kg fuel], for ISA SL conditions. Reference Emission Index of $NO_x$ emission, *REINOx* [g $NO_x$/kg fuel] is a function of corrected fuel flow or corrected fuel flow obtained from PEM, $FF_{cor}$ as shown in Figure 1.

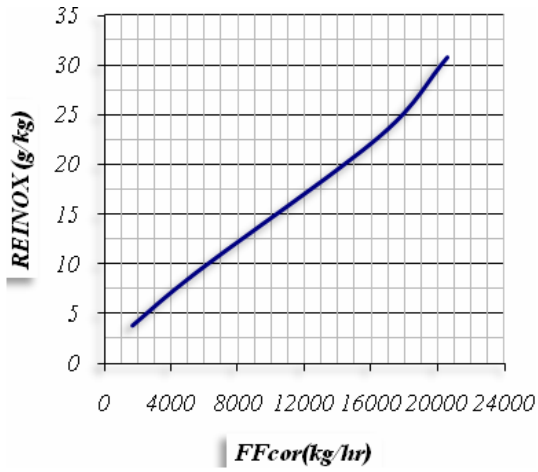


**Figure 1. Relation between *REINOx* and *FF*$_{cor}$, ICAO databank for CF 6 80 turbo fan engine installed on aircraft B767300**

$$FF_{cor} = \frac{FF}{\delta} \theta^{3.8} e^{0.2M^2} \,. \tag{4}$$

Then, *EINOx*, must be adjusted for the atmospheric and flight condition by (5).

$$EINOx = REINOx \cdot e^{H} \cdot \sqrt{\frac{\delta^{1.02}}{\theta^{3.3}}} . \qquad (5)$$

The elements for calibration on real atmospheric condition and detail computation can be found in [9]. The analysis of BM2 shows that *EINOx* are the function of flight altitude and *REINOx*. For the given engine, *REINOx* increase with corrected fuel flow (at ISA condition). This increase has been shown in Figures 1, 2 and 3. Other elements of (5) are related to flight altitude or ambient pressure and ambient temperature.

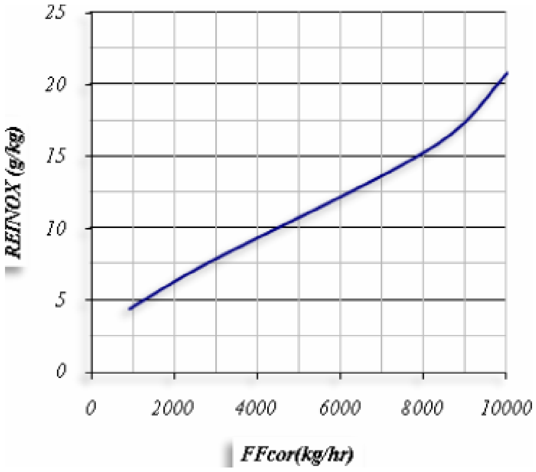


**Figure 2. Relation between *REINOx* and $FF_{cor}$, ICAO databank for CFM56 7b turbo fan engine installed on aircraft B767300**

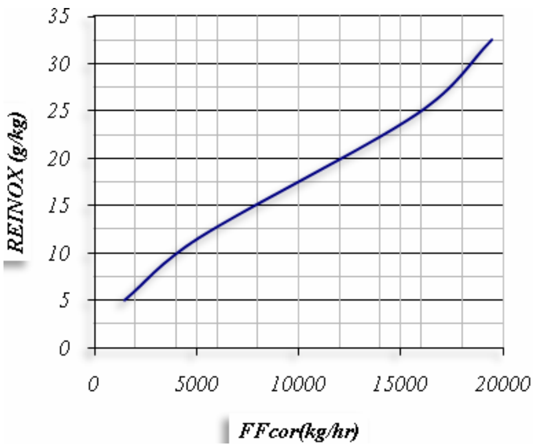


**Figure 3. Relation between *REINOx* and $FF_{cor}$, ICAO databank for PW4056 turbo fan engine installed on aircraft B767300**

By using standard value of pollution cleaning cost published by [20], we can calculate cost associated with air pollution or pollution charges value. Our aim is also to achieve the operational application of achieved results in the form of real throttle/flaps setting applicable in takeoff and landing operations.

## 5. THE AIRCRAFT TAKEOFF FLIGHT MODEL

In this part of the paper we are presenting the unique takeoff model (Fig. 4), which can be used for different flaps/throttle setting in the takeoff performance calculation. The aerodynamic and engine data for this model are imported from PEM published by aircraft manufacturer. To present the realistic aircraft engine data in the takeoff model, we used the following charts: installed takeoff corrected net thrust, generalized net thrust, maximum climb thrust, minimum idle in flight thrust, corrected fuel flow table.

The terminal altitude for takeoff analysis is 914.4 m (3000 ft) QFE, the same as LTO cycles, and the altitude for the start of landing analysis is 914.4 m (3000 ft) QFE. In order to determine the takeoff performance, we modified basic flight mechanic equations, where we first calculated the takeoff distance, distance to rotate and distance to achieve 914.4 m (3000 ft) QFE [13]. Limitations on the basis of which we calculate the takeoff are:

- available thrust is equal to the maximum takeoff thrust (limitations from PEM) to altitude 304.8 m (1000 ft)

$$T_{\text{max to}} = T , \qquad (6)$$

- available thrust is equal to the maximum climb thrust (limitations from PEM) from altitude 304.8 m (1000 ft) to 914.4 m (3000 ft)

$$T_{\text{max cl}} = T_{\text{cl}} , \qquad (7)$$

- fuel flow is the function of takeoff altitude, takeoff speeds and takeoff/climb thrust,
- takeoff is straight, without turns or change of flight direction,
- the equation which describes flight during initial climb in each segment of takeoff climb is calculated under assumption of small climb angle [22], $\gamma < 13$, which results in the following simplification, $\cos\gamma \approx 1$, $\sin\gamma \approx \gamma$,
- the center of gravity position does not have influence on drag value obtained from low speed polar (from PEM),
- the aircraft takeoff mass change is small; we assume that aircraft mass during takeoff is constant,
- ISA condition, takeoff from dry runway, no wind, no runway slope.

The basic elements for the takeoff analysis are $L1$, $t1$, $L2$, $t2$, $L3$, $t3$, $L4$, $t4$, $L5$ and $t5$.

Distance to accelerate to liftoff speed from $v = 0$:

$$L1 = \int_{0}^{V_{\text{lof}}} \frac{v}{g\left(\frac{T}{G} - \frac{1}{2}\frac{\rho v^2 \left(C_x - \mu C_z\right)}{G} - \mu\right)} \mathrm{d}v \qquad (8)$$

where $T$ is available all engine takeoff thrust in N, $v$ is true air speed in m/s, $v_{\text{lof}} = 1.10\ v_{\text{s1g}}$, $v_{\text{s1g}}$ is aircraft stalling speed at n = 1 taken from PEM for aircraft mass and aircraft takeoff configuration.

Time to accelerate to liftoff speed, from $v = 0$:

$$t1 = \int_{0}^{V_{\text{lof}}} \frac{1}{g\left(\frac{T}{G} - \frac{1}{2}\frac{\rho v^2 \left(Cx - \mu Cz\right)}{G} - \mu\right)} \mathrm{d}v . \qquad (9)$$

Distance to rotate aircraft and accelerate, from $v_{\text{lof}}$ to $v_2$:

$$L2 = \frac{T - \frac{1}{2}\rho v_{\text{trans}}{}^2 C_{x\text{rot}} S}{G} \frac{v_{\text{trans}}{}^2}{0.44g} \qquad (10)$$

where $v_{\text{trans}}$ is average speed calculated from $v_{\text{lof}}$ and $v_2$, $C_{x\text{rot}}$ is aerodynamic drag coefficient after rotation.

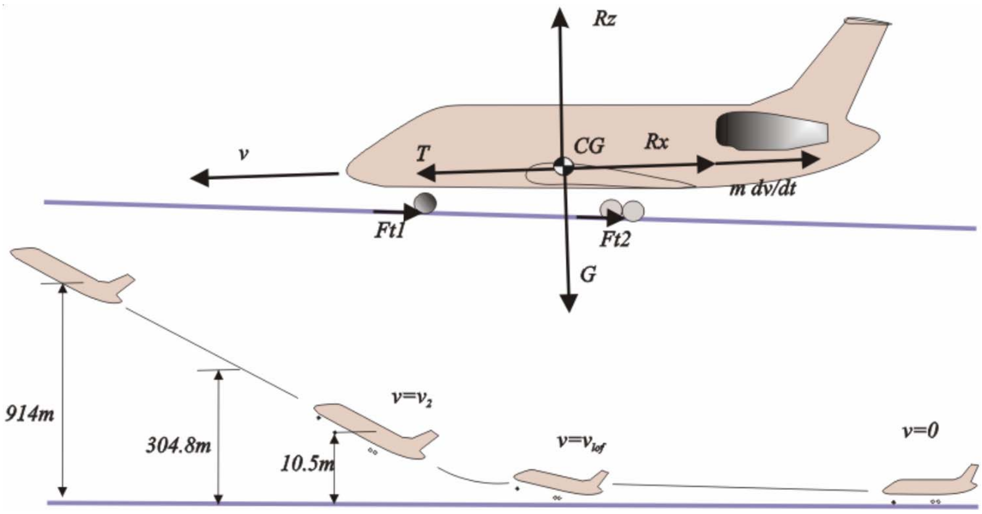


**Figure 4. The forces acting on transport aircraft during takeoff roll and takeoff operation elements**

Time to rotate aircraft and accelerate from $v_{\mathrm{lof}}$ to $v_2$:

$$t2 = \frac{L2}{v_{\mathrm{trans}}} . \tag{11}$$

Climb gradient $\gamma$, after aircraft rotation, at speed $v_{\mathrm{trans}}$:

$$\gamma = \frac{T - \frac{1}{2}\rho v_{\mathrm{trans}}{}^2 C_{x\mathrm{rot}} S}{G} . \tag{12}$$

Distance to climb aircraft at climb gradient to altitude 10.7 m (35 ft):

$$L3 = \frac{10.7}{\gamma} . \tag{13}$$

Time to climb aircraft at climb gradient to altitude 10.7 m (35 ft):

$$t3 = \frac{L3}{v_{\mathrm{trans}}} . \tag{14}$$

Climb gradient after aircraft rotation, at speed $v_2$ from 10.7 m (35 ft) to 304.8 m (1000 ft) in aircraft configuration with gear up and flaps in takeoff configuration:

$$\gamma_{\mathrm{clf}} = \frac{T - \frac{1}{2}\rho v_2{}^2 C_{x\mathrm{clf}} S}{G} \tag{15}$$

where $C_{x\mathrm{clf}}$ is aerodynamic drag coefficient, on the angle of attack achieved after rotation, with aircraft in gear up configuration.

Distance to climb aircraft, at climb gradient, from 10.7 m (35 ft) to 304.8 m (1000 ft):

$$L4 = \frac{304.8 - 10.7}{\gamma_{\mathrm{clf}}} . \tag{16}$$

Time to climb aircraft, at climb gradient from 10.7 m (35 ft) to 304.8 m (1000 ft):

$$t4 = \frac{L4}{v_2} . \tag{17}$$

Climb gradient after reaching 304.8 m (1000 ft) and thrust reduction to maximum climb thrust and flaps up, gear up configuration:

$$\gamma_{\mathrm{cl}} = \frac{T_{\mathrm{cl}} - \frac{1}{2}\rho v_2{}^2 C_{x\mathrm{cl}} S}{G} \tag{18}$$

where $C_{x\mathrm{cl}}$ is aerodynamic drag coefficient after rotation, flaps up and gear up configuration (from PEM).

Distance to climb aircraft at climb gradient from 304.8 m (1000 ft) to 914.4 m (3000 ft):

$$L5 = \frac{914.4 - 304.8}{\gamma_{\mathrm{cl}}} . \tag{19}$$

Time to climb aircraft at climb gradient from 304.8 m (1000 ft) to 914.4 m (3000 ft):

$$t5 = \frac{L5}{v_2} . \tag{20}$$

Takeoff parameters, from segment $i$ = 1, …, 5, are $L_{\mathrm{TO}}$, $t_{\mathrm{TO}}$, $g_{\mathrm{TO}}$, $m_{\mathrm{TO\ NO_x}}$ and $m_{\mathrm{TO\ CO_2}}$.

Total takeoff distance from $v$ = 0 to 914.4 m (3000 ft):

$$L_{\mathrm{TO}} = \sum_{i=1}^{5} L_i . \tag{21}$$

Total takeoff time from $v$ = 0 to 914.4 m (3000 ft):

$$t_{\mathrm{TO}} = \sum_{i=1}^{5} t_i . \tag{22}$$

Fuel needed to takeoff from $v$ = 0 to 914.4 m (3000 ft):

$$g_{\mathrm{TO}} = FF \cdot t_{\mathrm{TO}} . \tag{23}$$

Total amount of $NO_x$ emission during takeoff:

$$m_{\mathrm{TO\ NO_x}} = g_{\mathrm{TO}} \frac{EINOx}{1000} . \tag{24}$$

Total amount of $CO_2$ emission during takeoff:

$$m_{\mathrm{TO\ CO_2}} = g_{\mathrm{TO}} \cdot 3.15 . \tag{25}$$

## 6. AIRCRAFT LANDING FLIGHT MODEL

Contrary to classic landing operations, which results in the application of thrust after application of landing flaps configuration (full flaps, gear down), we have explored the CDA method application in landing. The starting altitude for landing analysis with the application of CDA is 914.4 m (3000 ft) QFE (Fig. 5). In order to set up landing analysis, we modified basic flight mechanic equations for landing, in which we first calculated the distance for approach from 914.4 m (3000 ft) to 15.24 m (50 ft), then distance to rotate, distance to parachute and distance to decelerate, from speed at touchdown to $v$ = 0, [5]. Limitations on the basis of which we calculated landing are:

- presented thrust is equal to low idle thrust:

$$R_x > T_{\text{idle}} , \tag{26}$$

- fuel flow during approach and landing is equal to low idle fuel flow,
- change of approach angle is small $\dot{\gamma}_{\text{app}} = 0$ and we adopt approach angle $\gamma_{\text{app}} = 3^{\text{o}}$,
- equations that describe flight in landing in each approach segment are calculated for accepted assumption of small approach angle, or $\gamma_{\text{app}} < 15^{\text{o}}$ which leads us to $\cos\gamma_{\text{app}} \approx 1$, $\sin\gamma_{\text{app}} \approx \gamma_{\text{app}}$,
- approach and landing are straight, without turns or change of flight direction,
- c.g. position do not have influence on drag value obtained from low speed polar for given landing configuration (published in PEM),
- the aircraft approach and landing mass change is small, we assume that aircraft mass during landing and approach are constant,
- ISA condition, landing on dry runway, no wind, no runway slope.

The basic elements of approach and landing are $Ll1$, $tl1$, $Ll2$, $tl2$, $Ll3$, $tl3$, $Ll4$ and $tl4$.

Distance to approach aircraft at angle of approach (3° or descent gradient $\gamma_{\text{app}}$ = 0.05240) from 914.4 m (3000 ft) to 15.24 m (50 ft):

$$Ll1 = \frac{914.4 - 15.24}{\gamma_{\text{app}}} . \tag{27}$$

Time $tl1$, in sec, is time for aircraft approach at angle of approach (3°) from 914.4 m (3000 ft) to 15.24 m (50 ft):

$$tl1 = \frac{Ll1}{v_{\text{app}}} . \tag{28}$$

Distance to rotate aircraft and decelerate from $v_{\text{app}}$ to $v_{\text{rot}}$ = 1.10 $v_{\text{s1g}}$:

$$Ll2 = \frac{T_{\text{idle}} - \frac{1}{2}\rho v_{\text{trans}}{}^2 C_{x\text{rot}} S}{G} \frac{v_{\text{trans}}{}^2}{0.69g} = \gamma_{\text{rot}} \frac{v_{\text{trans}}{}^2}{0.69g} \tag{29}$$

where $vt_{\text{rans}}$ is average speed, calculated from $v_{\text{rot}}$ and $v_{\text{app}}$, $C_{x\text{rot}}$ is aerodynamic drag coefficient after rotation.

Time to rotate aircraft and decelerate from $v_{\text{app}}$ to $v_{\text{rot}}$ = 1.10 $v_{\text{s1g}}$:

$$tl2 = \frac{Ll2}{v_{\text{trans}}} . \tag{30}$$

Distance to descend aircraft at descent gradient from altitude 15.24 m (50 ft) to touch down at $h$ = 0:

$$Ll3 = \frac{15.24}{\gamma_{\text{rot}}} . \tag{31}$$

Time to descend aircraft at descent gradient from altitude 15.24 m (50 ft) to touch down at $h$ = 0:

$$tl3 = \frac{Ll3}{v_{\text{rot}}} . \tag{32}$$

Distance to decelerate form $v_{\text{rot}}$ to $v$ = 0:

$$Ll4 = \int_{v_{\text{rot}}}^{0} \frac{v}{g\left(\frac{T_{\text{app}}}{G} - \frac{1}{2}\frac{\rho v^2\left(C_{x\text{ro}} - \mu_{\text{b}} C_{z\text{ro}}\right)}{G} - \mu_{\text{b}}\right)} \mathrm{d}v \tag{33}$$

where $T_{\text{app}}$ is available all engine idle thrust in N, $v$ is true air speed in m/s, $C_{x\text{rot}}$ is denoted to aerodynamic drag coefficient at deceleration, $C_{z\text{rot}}$ is denoted to aerodynamic lift coefficient at deceleration.

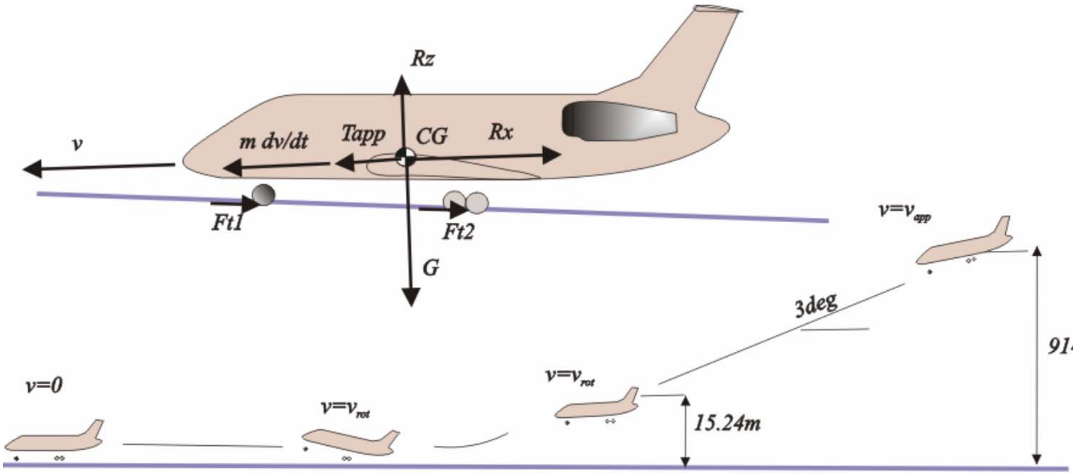


**Figure 5. The forces acting on transport aircraft during landing deceleration and landing operation elements**

Time to decelerate from rotation speed to full stop speed $v = 0$:

$$tl4 = \int_{v_{\mathrm{rot}}}^{0} \frac{v}{g\left(\frac{T_{\mathrm{app}}}{G} - \frac{1}{2}\frac{\rho v^2\left(C_{x\mathrm{rot}} - \mu_{\mathrm{b}} C_{z\mathrm{rot}}\right)}{G} - \mu_{\mathrm{b}}\right)} \mathrm{d}v \,. \quad (34)$$

Landing parameters, from segment $i = 1, \ldots, 4$, are $L_{\mathrm{LN}}$, $t_{\mathrm{LN}}$, $g_{\mathrm{LN}}$, $m_{\mathrm{LN\,CO_2}}$ and $m_{\mathrm{LN\,NO_x}}$.

Total landing distance from 914.4 m (3000 ft) to $v = 0$:

$$L_{\mathrm{LN}} = \sum_{i=1}^{4} Ll_i \,. \quad (35)$$

Total landing distance from 914.4 m (3000 ft) to $v = 0$:

$$t_{\mathrm{LN}} = \sum_{i=1}^{4} tl_i \,. \quad (36)$$

Fuel spent to landing from 914.4 m (3000 ft) to $v = 0$:

$$g_{\mathrm{LN}} = FF \cdot tl_{\mathrm{LN}} \,. \quad (37)$$

Total amount of $NO_x$ emission during landing:

$$m_{\mathrm{LN\,NO_x}} = g_{\mathrm{LN}} \frac{EINOx}{1000} \,. \quad (38)$$

Total amount of $CO_2$ emission during landing:

$$m_{\mathrm{LN\,CO_2}} = g_{\mathrm{LN}} \cdot 3.15 \,. \quad (39)$$

## 7. OPTIMIZATION OF TAKEOFF AND LANDING CONFIGURATION FOR MINIMUM POLLUTION CHARGES

Now, it is possible to define $PC_{\mathrm{TO}}$ and $PC_{\mathrm{LN}}$. After application of different takeoff and landing flaps/throttle configuration, we can compare the achieved results. The first results were achieved by the application of ICAO LTO method for determination of total pollution cost produced in takeoff and landing $PC_{\mathrm{icaoTO}}$ and $PC_{\mathrm{icaoLN}}$, respectively. The second results were achieved by the application of method presented in the paper for determination of $PC_{\mathrm{TO}}$ and $PC_{\mathrm{LN}}$, for the same cost of pollutant cleaning. The first analysis was done for twin turbo fan aircraft 767300, equipped with engines CF 6 80, with application of *MTOT*, *MCL* and *IDLE* thrust during approach and landing. The results obtained from previously described flight model and data gathered from PEM, are shown in Table 1.

The first conclusion, which can be derived from Table 1 and Table 2, is that there is more than 50 % of difference between pollution charges, calculated by ICAO methodology and pollution charges, calculated by presented takeoff pollution model. This implies that pollution charges should be calculated by real pollution and polluters classification should be done by real produced quantity of pollutant during takeoff and landing flight operation. The reason of lower pollution is a shorter time in the mode in real operations than in standard ICAO methodology.

**Table 1. The comparison of takeoff pollution charges for aircraft B767300 with engine CF 6 80 at *MTOT*, *MCT* throttle setting, *MTOW* = 185000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented takeoff model | | | | | |
| FLAPS 1 SETTING | 96 | 418 | 1316 | 10.26 | $PC_{\mathrm{TO}}$ = 71.85 |
| FLAPS 5 SETTING | 95 | 414 | 1305 | 10.13 | $PC_{\mathrm{TO}}$ = 71.18 |
| FLAPS 15 SETTING | 96 | 420 | 1324 | 10.28 | $PC_{\mathrm{TO}}$ = 72.19 |
| ICAO LTO – takeoff | 174 | 773 | 2436 | 17.65 | $PC_{\mathrm{icaoTO}}$ = 128.58 |

**Table 2. The comparison of landing pollution charges for aircraft B767300 with engine CF 6 80 at *IDLE* throttle setting, *MLW* = 145000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented landing model | | | | | |
| FLAPS 25 SETTING | 241 | 107 | 340 | 0.65 | $PC_{\mathrm{LN}}$ = 11.79 |
| FLAPS 35 SETTING | 243 | 108 | 343 | 0.66 | $PC_{\mathrm{LN}}$ = 11.89 |
| ICAO LTO – landing | 240 | 327 | 1031 | 4.13 | $PC_{\mathrm{icaoLN}}$ = 43.07 |

The results in Table 1 were obtained for *MTOM*, which implies lower $PC_{\mathrm{TO}}$ for lower *ATOM*. The lower takeoff mass requires lower takeoff distances and lower time in mode. It can be also concluded from Table 1, Table 3 and Table 5 which configuration produces the lowest pollution cost. This is the configuration B767300 with engine 4056. Comparing the same takeoff configuration, for different engines, Table 1, Table 3 and Table 5, it is obvious that the lowest pollution configuration is generated by FLAPS 5 SETTING in the case of *MTOT*, *MCT* throttle setting.

**Table 3. The comparison of takeoff pollution charges for aircraft B767300 with engine PW4056 at *MTOT*, *MCT* throttle setting, *MTOW* = 185000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented takeoff model | | | | | |
| FLAPS 1 SETTING | 109 | 447 | 1409 | 11.88 | $PC_{\mathrm{TO}}$ = 80.05 |
| FLAPS 5 SETTING | 95 | 390 | 1229 | 10.36 | $PC_{\mathrm{TO}}$ = 69.85 |
| FLAPS 15 SETTING | 96 | 395 | 1247 | 10.50 | $PC_{\mathrm{TO}}$ = 70.80 |
| ICAO LTO – takeoff | 174 | 728 | 2295 | 19.55 | $PC_{\mathrm{icaoTO}}$ = 131.07 |

If we compare the same landing configuration, for different engines, Table 2, Table 4 and Table 6, it is obvious that the lowest pollution configuration is generated by FLAPS 35 SETTING in the case of *IDLE* throttle setting. In the case of landing, we present difference in pollution charges of more than 70 % from ICAO LTO pollution model. We should not forget that descent is done in the case of CDA approach at *IDLE* thrust. The second conclusion, which can be derived for the best engine airframe match, is presented in Table 7 and Table 8. The application of derated takeoff thrust offers more than 58 % of difference between pollution charges calculated by ICAO methodology and pollution charges calculated by presented takeoff pollution model. This implies real benefit from the application of derated thrust as a method for pollution mitigation during takeoff.

**Table 4. The comparison of landing pollution charges for aircraft B767300 with engine PW4056 at *IDLE* throttle setting, *MLW* = 145000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented landing model | | | | | |
| FLAPS 25 SETTING | 241 | 107 | 340 | 0.65 | $PC_{LN}$ = 11.79 |
| FLAPS 35 SETTING | 243 | 108 | 343 | 0.66 | $PC_{LN}$ = 11.89 |
| ICAO LTO – landing | 240 | 337 | 1062 | 4.05 | $PC_{icaoLN}$ = 43.67 |

**Table 5. The comparison of takeoff pollution charges for aircraft B767300 with engine PW4060 at *MTOT*, *MCT* throttle setting, *MTOW* = 185000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented takeoff model | | | | | |
| FLAPS 1 SETTING | 114 | 487 | 1537 | 12.30 | $PC_{TO}$ = 85.07 |
| FLAPS 5 SETTING | 113 | 478 | 1508 | 13.21 | $PC_{TO}$ = 87.36 |
| FLAPS 15 SETTING | 115 | 486 | 1532 | 13.385 | $PC_{TO}$ = 88.63 |
| ICAO LTO – takeoff | 174 | 773 | 2436 | 17.65 | $PC_{icaoTO}$ = 128.58 |

**Table 6. The comparison of landing pollution charges for aircraft B767300 with engine PW4060 at *IDLE* throttle setting, *MLW* = 145000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented landing model | | | | | |
| FLAPS 25 SETTING | 241 | 107 | 340 | 0.55 | $PC_{LN}$ = 11.44 |
| FLAPS 35 SETTING | 243 | 108 | 343 | 0.56 | $PC_{LN}$ = 11.54 |
| ICAO LTO – landing | 240 | 337 | 1062 | 4.05 | $PC_{icaoLN}$ = 43.67 |

**Table 7. The comparison of takeoff pollution charges for aircraft B767300 with engine PW4056 at DERATE = 89 %, throttle setting, *MTOW* = 185000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented takeoff model | | | | | |
| FLAPS 1 SETTING | 126 | 459 | 1447 | 10.78 | $PC_{TO}$ = 77.38 |
| FLAPS 5 SETTING | 125 | 455 | 1433 | 10.64 | $PC_{TO}$ = 76.52 |
| FLAPS 15 SETTING | 110 | 450 | 1419 | 11.94 | $PC_{TO}$ = 80.55 |
| ICAO LTO – takeoff | 174 | 728 | 2295 | 19.55 | $PC_{icaoTO}$ = 131 |

**Table 8. The comparison of takeoff pollution charges for aircraft B767300 with engine PW4056 at DERATE = 89 %, throttle setting, *ATOW* = 165000 kg**

| Aircraft B767300 | Total time [s] | Total fuel [kg] | Total $CO_2$ emission [kg] | Total $NO_x$ emission [kg] | Pollution cost [USD] |
|---|---|---|---|---|---|
| Presented takeoff model | | | | | |
| FLAPS 1 SETTING | 110 | 400 | 1263 | 9.386 | $PC_{TO}$ = 67.44 |
| FLAPS 5 SETTING | 109 | 399 | 1257 | 9.317 | $PC_{TO}$ = 67.05 |
| FLAPS 15 SETTING | 97 | 396 | 1250 | 10.50 | $PC_{TO}$ = 70.88 |
| ICAO LTO – takeoff | 174 | 728 | 2295 | 19.55 | $PC_{iacoTO}$ = 131.07 |

## 8. CONCLUSION

In this paper, we developed analytical model, based on real aircraft performance model for aircraft 767300, which precisely determines pollution charges for chosen flaps/throttle setting mitigation or cancellation. The input data are taken from aircraft manufacturer PEM, which guarantees the results application in real takeoff and landing operations.

The new takeoff and landing pollution calculator, developed in this research, is a tool which allows airline to choose flaps/throttle setting pollution charges mitigation or cancellation (if produced pollution is under predetermined pollution level). The major takeoff and landing pollution calculator properties is flexibility. It can be used on daily basis to achieve local airport pollution limitation or to minimize pollution charges.

During strategic decision making, takeoff and landing pollution calculator provides for the given route network optimal airframe engine match which produces lowest pollution and in that way the lowest pollution charges. In brief, in the paper we offered the solution for five optimization problems:

- we have defined the takeoff flaps/throttle configuration for minimum pollution charges,
- we have defined the landing flaps/throttle configuration for minimum pollution charges,

- we have defined the influence of derated takeoff thrust setting on pollution charges, when *ATOW* << *MTOW* and when runway and obstacle represent no limit,
- we have defined the influence of CDA approach and landing procedure on pollution charges, when operationally applicable,
- we have presented the method for analyzing aircraft pollution, which is tested on aircraft engine matching problem. The result is optimal airframe engine combination.

In the paper we have defined a unique way of pollution quantification, which is as much accurate and can replace ICAO LTO model. The adoption of this model, offered to airline operator, provides the possibilities to develop strategy for pollution charges reduction and in that way total direct operating costs reduction.

The new approach for defining the unique takeoff model has been defined in the paper, with combination of real flight data from PEM and modified classic flight mechanic aircraft flight model. The most important contribution is the definition of optimal flaps/thrust configuration for minimum pollution charges, expressed by pollution cost. It was also explored the influence of different aircraft engines installed in the same aircraft airframe on pollution charges.

The presented technique is especially applicable to short-haul flights, where *ATOW* is lower than *MTOW* and subsequently *ALW* lower than *MLW*.

The practical benefit from the proposed method, flaps/throttle and engine installation for minimum pollution cost or minimum pollution charges for air operator can be synthesized in the methodology of airframe engine matching to achieve minimum pollution cost and achieve direct operating costs reduction. Indirect benefit can be obtained from the information on how much the cleaning of total pollution from aircraft operation costs.

Besides this real quantity of pollutants emitted in air or sprayed on ground in the area of runway, the proposed method can predict to airline, by presented pollution calculation model, the level of pollution produced by airline operations. If that level of pollution is below the accepted level of pollution, this leads to pollution charges cancellation. The achieved results clearly highlight that the present ICAO LTO pollution calculation model acts as an obstacle to sustainable air transport industry development.

The ICAO LTO model offers one solution: purchase of the latest technology aircraft, which produces the lowest pollution. This is a rigid and expensive solution, from airline point of view. This is a great difficult for the airline, the airline has a new burden, pollution charges which increase direct operation cost, without the chance to decrease pollution charges by the application of standard operation procedures, such as derated takeoff, thrust setting and CDA approach. The most important paper contribution is the real aircraft pollution calculation and determination of real benefit from the proper engine airframe match and takes off/landing flap/throttle setting for minimum pollution costs.

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## NOMENCLATURE

| | |
|---|---|
| ACARE | Advisory Council of Aeronautical Research in Europe |
| *ALW* | actually landing weight |
| *ATOW* | actually takeoff weight |
| BM2 | Boeing method 2 |
| *C* | coefficient |
| CAA | Civil Aviation Authority |
| CDA | continuous descent approach |
| EASA | European Aviation Safety Agency |
| *EINOx* | emission index [g of $NO_x$ / kg of fuel] |
| FAA | Federal Aviation Authority |
| *FF* | fuel flow [kg/s] |
| *G* | aircraft weight [N] |
| *g* | 9.81 [m/s$^2$] |
| $g_f$ | fuel consumed during flight phase [kg] |
| ICAO | International Civil Aviation Organization |
| ISA | international standard atmosphere |
| LTO | landing and takeoff |
| *MCL* | maximum climb thrust |
| *MLW* | maximum landing weight |
| *MTOT* | maximum takeoff thrust |
| n | load factor |
| *PC* | total pollution cost |
| PEM | performance engineers manual |
| *S* | reference wing area [m$^2$] |
| SL | sea level |
| SLS | sea level static |
| *T* | total available thrust [N] |
| *t* | time spent during flight phase [s] |
| $v_2$ | 1.20 $v_{s1g}$, safety speed |
| *v* | true air speed [m/s] |
| $v_{app}$ | 1.30 $v_{s1g}$ |
| $v_{rot}$ | 1.10 $v_{s1g}$ |
| $v_{s1g}$ | aircraft stalling speed at n = 1 , taken from PEM for aircraft actual (takeoff or landing) mass and aircraft actual configuration (takeoff or landing) |

### *Greek symbols*

| | |
|---|---|
| $\delta$ | relative pressure |
| $\theta$ | relative temperature |
| $\mu_b$ | braking friction coefficient during braking to full stop, recognized at speed $v = 0$ |
| $\mu$ | runway friction coefficient |
| $\rho$ | air density, taken from ISA model |

### *Superscripts*

| | |
|---|---|
| app | approach |
| cor | corrected |
| l | segment landing parameter |
| LN | total lending parameter |
| rot | rotation |
| TO | takeoff |
| *x* | aerodynamic drag |
| *z* | aerodynamic lift |

## СТРАТЕГИЈА СМАЊЕЊА ТРОШКОВА ЗАГАЂЕЊА ТРАНСПОРТНОГ АВИОНА

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Анализа развоја цивилног ваздушног саобраћаја у следећој декади, указује на значајан раст, али са значајним последицама на животну средину, у смислу загађења ваздуха и климатских промена. Општи став јавности и пораст општег интереса за заштиту животне средине, доводи до стварања нових оквира за развој мера за смањење емисије загађења од цивилног ваздушног саобраћаја. Једна од мера је увођење такси за загађење, које су прве увеле Швајцарска и Шведска. Истраживање које је представљено у овом раду, представља скуп оперативних процедура за смањење емисије загађивача турбо-фенског транспортног авиона, током операција на аеродрому и око њега, а тиме и такси за загађење. Загађење у области око аеродрома се одређује према *ЛТО* (*LTO*) циклусу, који је установио *ИЦАО* (*ICAO*). Овај метод успоставља везе између емисије загађивача и карактеристика мотора авиона, протока горива и времена трајања појединих операција. Развијени математички модел, представљен у раду, се може користити за смањење такси за загађење или њихово укидање.