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The turbo fan aircraft pollution charges mitigation strategy

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Abstract

The air transport industry development analysis, indicate that transport demand will continue to increase in near future. The environmental implications which follow transport demand are significant, in terms of air pollution and climate change. The environmental impacts might act as an air transport industry constraint to growth. The increasing attention and concern for future climate changing produce different measures for air transport industry development steering. It is essential that air transport industry development is managed in an appropriate manner, to achieve sustainable development. The one of measure for managing air transport industry development is pollution charges introduced by Swissland and Swede. The research presented in paper is sets of operational procedures implementation to reduce turbo fan passenger aircraft emission in space around airport, as well as related pollution charges. The space around airport under pollution is defined according by LTO (landing and take-off) cycles, established by ICAO, as well as pollution measurement method. Also, ICAO published emission pollution calculation method and data base-Engine Exhaust Emissions Data Bank. The ICAO method of emission pollution measurement is base for pollution charges. Generally, ICAO method find relation between emission pollution and engine characteristic (emission index), fuel flow and time in mode (time spent in taxi, take off initial climb, approach and landing). The pollution charges increase airline direct operating costs. The mathematical model based on aircraft performance model, presented in paper for aircraft 767300, can be use as airline tool, for airline pollution charges mitigation or cancellation. In the paper is presented pollution charges mitigation model which combine de rate takeoff, operational take off and initial climb procedure and continuous descent, operational approach and landing procedure, with aim to reduce turbo fan passenger aircraft pollution, as well as related pollution charges. Combination of proposed operations procedures, reduce two most important parameters in ICAO pollution measurement method, fuel flow and time in mode and as consequence pollution charges. The application of presented method is in area of environmentally sustainable transport (EST), transport and climate change and valuation of internal and external benefits and costs.

Keywords: aircraft pollution, emission charges; continuous descent; de rated take off;

1. INTRODUCTION

As we all aware of recently economic crisis, which coming into all segments of society, but we must, also, be prepare for future developments and post crisis events. The world air transport system is changing in 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 (Advisory Council of Aeronautical Research in Europe) 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 in is for 20% in the case of CO_2 and 80% in the case of NO_x VV.AA (2002). 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. The one of measure for managing air transport industry development is pollution charges, introduced by Swissland and Swede and recently by UK.

This paper, analyses 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 of the production process of NOx, i.e. the lower CO_2 emission produces the higher emission of NOx, as stated in Nikolic *et al.* (2006). In turbo fan engine, combustion chamber high temperatures, which are desirable from the viewpoint of minimizing fuel consumption and also minimizing CO_2, CO and HC production, create higher emission of NO_x.

The International Civil Aviation Organization (ICAO) Oxides of Nitrogen Emission Standards were adopted in November 2005, and they apply to engines manufactured after 31 December 2007. In this paper is suggested 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 (European Aviation Safety

Agency) and FAA (Federal aviation Authority). The development of an engine for one particular aircraft frame is time consuming and expensive process.

In today air traffic is defined system of air pollution measurement for flight altitude up to 3000ft QFE, by LTO emission cycles (landing, take off) published by ICAO (2009). This air pollution measurement system is based on Emissions Related Landing Charges Investigation recommendation, published by Group of Experts (2000). Today, is not jet present methodology for pollution charges calculation, based on real pollutant emission, produces during real aircraft operations, for given aircraft configuration in takeoff and landing and real applied throttle setting. For example, ICAO ENGINE EXHAUST EMISSIONS DATA BANK published by ICAO (2009), for engine CF6-80C2B6F, assumes only application 100% take off thrust. Contrary to this, de rated thrust is established method for takeoff operations, when ATOW (Actually Takeoff Weight) is lower than MTOW. This ATOW require lower thrust setting, which imply lower pollution as described by Filippone (2008). De rated take-off thrust have flight safety and operations limitation and shall not be used when:

- the runway is contaminated with standing water, slush, snow or ice,
- the runway is wet unless the increased stopping distance is accounted for,
- when the possibilities of wind shear, temperature inversions or downdrafts have been forecasted or reported,
- lift dumpers and /or air brakes are inoperative,
- one of more anti-skid units are inoperative,
- wing anti-icing is on, tail anti-icing is on,
- the operator has to establish a means to periodically verify the availability of takeoff rated thrust to ensure that the engine deterioration does not exceed authorized limits.
- other limitations may apply according to company standard operating procedures.

The second example is CDA (Continuous Descent Approach) method, which requires idle thrust during approach. Again, ICAO ENGINE EXHAUST EMISSIONS DATA BANK published in ICAO (2009) for engine, CF6-80C2B6F assumes only application of 30% thrust setting, during approach operations. CDA procedure has flight safety and operational limitation:

- require more time to complete operations, than classic descent, approach and landing operations, which imply reduction of air space capacity and induce delay, Erkelens L.J.J. 1999,

- it may sometimes not be possible to fly a CDA due to airspace constraints or overriding safety requirements, CAA 2009,

- require specially air crew training,

- require higher meteorological minimums, Hullah 2005.

These two examples clearly imply need for detail pollution analysis, for actual thrust and flaps setting during takeoff and landing operations, contrary to rigid LTO method of pollution assessment. The indirect benefit, which can be achieved through detail take off and landing operations analysis, is definition of optimal throttle/flaps setting, for minimum fuel consumption.

The market oriented airline, have main target to reduce direct operating costs. Now days, one of 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 influence of real aircraft configuration (flaps and throttle setting) for real pollution emission quantification and presentation, is suggested.

This paper investigate 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 setup introduce real quantification and their influence on environmental pollution. The generated environmental pollution has measured trough time, height and distance during takeoff phase (acceleration, rotation and initial climb to altitude of 3000ft QFE) and landing flight phase (approach from 3000ft QFE, rotation and deceleration until full stop). The achieve results are than, 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 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 process of environmental pollution cost reduction.

In the paper will be shown potential benefits from 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 minimum pollution cost and in that way to achieve, direct operating costs reduction. The Civil Aviation Authority-CAA can determine, by adoption of proposed methodology, how much pollutants are produced, from aircraft operation. Also, for airport land use planning, in paper will be proposed emission footprint, which is important pollution presentation because contain information of pollution volume and concentration of polluters in footprint. The rigidity of ICAO LTO pollution calculation model will be shown in comparison process, where will be compared pollution cost calculated by proposed methodologies, 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, which discussed in this paper, is emission of CO_2 and NO_x calculation. The emission of CO_2 and NO_x depend on 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, 1kg of fuel burned produce 3.15kg of CO_2 as publish in Boeing 1988. Other potential climate impact of transport aircraft are from oxides of nitrogen, water vapor, oxides of sulphur, 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 ICAO 2009. ICAO has formed the Aircraft Engine Exhaust Emissions Data-Bank published in ICAO 2009, providing *Emission Indices* for CO, HC, NOx and smoke, for each one of the four-engine throttle setting (take-off, climb-out, approach and idle). This data is regularly use for estimation of aircraft emission, with full power application. This analysis based on this data and method is independent of pilot operations such as thrust de rate, 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 paper, we use Boeing Method 2, published by Baughcum, S. L., *et al.* (1996), which involves correction of ICAO certification data for atmospheric conditions and aircraft operations.

The calculation of emissions below 3000ft relies on the information in the Boeing Method 2 (BM2), or the "Boeing curve fitting method," which is an internationally accepted operational emissions method published by Working Group (2003). This method calculates emissions indices on based of fuel flow and ICAO certification data. The data taken from ICAO (2009) and the four-certification power settings at sea-level static (SLS) conditions are used to compute pollutants emissions, corrected for real atmospheric conditions. Before application of BM2, the aircraft engine performance in this paper 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 paper. The Boeing Method 2 (BM2) was used in this paper, because it can calculate pollutant emission with variations of altitude, thrust and flaps setting and flight segment time.

The aircraft manufactures offer on market airframe, with default engine installation. In fact, the aircraft manufactures, do not manufacture aircraft engines. The engine manufactures actually develop engines by aircraft manufactures design criterion, but today air carrier, when purchase aircraft, makes final choice about aircraft engine. This choice is difficult for airline and depends on market where airline offers their service. In the paper, several aircraft configuration with different engines and different throttle/flaps setting will be analyzed, in order to explore conditions for minimum take off and landing pollution charges, which are function of time, fuel and pollution emission. The first part of paper is about defining real aircraft take off/landing flight model. The second part explains methodology for minimal pollution cost *PC*, in takeoff and landing flight phase. The third part of paper, summarize results and present future innovative changes.

3. THE TAKE OFF AND LANDING MODEL ASSUMPTIONS

In the paper, twin turbo fan aircraft Boeing 767-300 is accepted as reference aircraft for pollution charges mitigation strategy investigation, equipped with three type of turbo fan

engine, PW4060, PW4056 and CF6-80A (EASA 2009, EDMS 2009). 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 guaranty highest level of air safety. 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 produce pollutions will be also presented by pollutant emission footprint. This new idea of pollution emission footprint or pollutant total quantity and total volume, can be determine, by jet engine exhaust velocity value and distribution of velocity (Boeing 2009). Such pollution footprint, with total pollution volume will provide to airport authority important support in airport land use and protection decision-making process.

The base for pollution calculation is modified classic flight mechanic model, for *takeoff* and *landing* aircraft performance calculation, published in Jenkinson L. R., et *al.* (1999). The analysis are demonstrated on 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, from PEM (Performance Engineers Manual) published by Boeing (1988). In this paper, we use aircraft low speed drag polar for different flaps setting, engine characteristic for different throttle setting and reference *1g* stalling speed for calculation of v_2 speed for takeoff and v_{ref} speed for landing flight phase. By analyzing interdependence of characteristics of turbo-fan engines (Kahayas N. 2007. Raymer D. 2006., Mair, W.A., and Birdsall, D.L. 1992.) in addition, realistic characteristics of engine (Boeing 1988., Filippone 2004. and W. McCormick 1995.), we apply quadratic polynomial approximation of realistic parameters of engine's parameters. The data for aircraft engines PW4060 are obtained from Boeing (2000), PW4056 are obtained from W. McCormick (1995) and CF6-80A are obtained from Filippone (2004).

4. THE TAKE OFF AND LANDING POLUTTION COST

In this paper we introduce pollution parameter: cost of pollution or cost to eliminate produced pollution. The investment for produced pollution neutralization is base for pollution charges.

The standard air industry direct operating cost function is related only to flight fuel and flight time, but it can be replaced with cost of elimination of pollution. This pollution costs comprise influence of two most important pollutant 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.

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

Where EINOx in grams of NO_x per kg fuel is denote to emission index, FF in kg/s is fuel flow and t in sec is time spent in flight mode. Emission of NO_x in kg is function of three elements as shown in equation (1). We introduce new costs, costs of cleaning pollution or pollution charges, PC in USD. The costs of cleaning are sum of emitted mass of CO_2 multiplied with cost of CO_2 pollution cleaning and emitted mass of NO_x multiplied with cost of NO_x pollution cleaning.

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

Where g_f in kg is denoted to fuel consumed during flight and t in s is denoted to time spent during flight phase.

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

Where 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, EUROONTROL (2007)) and cost of NO_x (middle value of cleaning NO_x pollution 3.4 USD/kg, EUROONTROL (2007)) pollution c_{pNOx} 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 Baughcum, S. L., et al. (1996). BM2 for given aircraft engine and ICAO Engine Exhaust Emission Data Bank build up relation with fuel flow and Reference Emission Index of NO_x emission, REINOx (gNOx/kg fuel), for ISA SL conditions. Reference Emission Index of NO_x emission, REINOx (gNOx/kg fuel) is a function of corrected fuel flow or corrected fuel flow obtained from PEM, FF_{cor} as shown in Fig. 1.

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

Where θ is denoted to relative temperature, δ is denoted to relative pressure. Then, emission index *EINOx,* must adjust for atmospheric and flight condition by equation (5).

$$EINOx = REINOx \cdot e^H \cdot \sqrt{\frac{\delta^{1.02}}{\theta^{3.3}}} \tag{5}$$

The elements for calibration on real atmospheric condition and detail computation can be found in Baughcum, S. L., *et al.* (1996). Analysis of Boeing Method 2 shows that *EINOx* are function of flight altitude and *REINOx*. For given engine *REINOx* increase with corrected fuel flow (at *ISA* condition) increase as shown Fig. 1, Fig. 2 and Fig. 3.
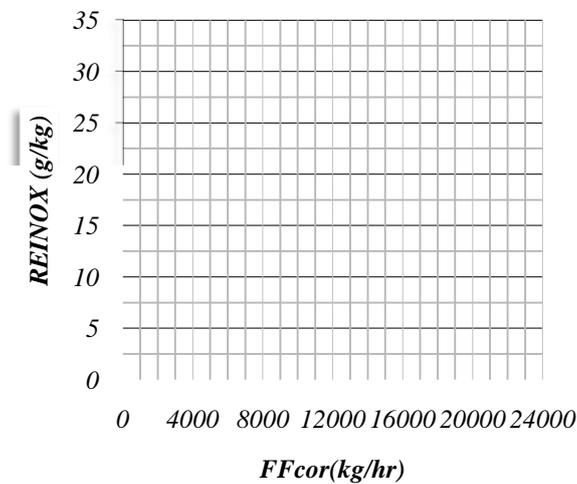
Fig. 1. Relation between REINOx and FFcor, ICAO data bank for CF 6 80 turbo fan engine installed on aircraft B767300
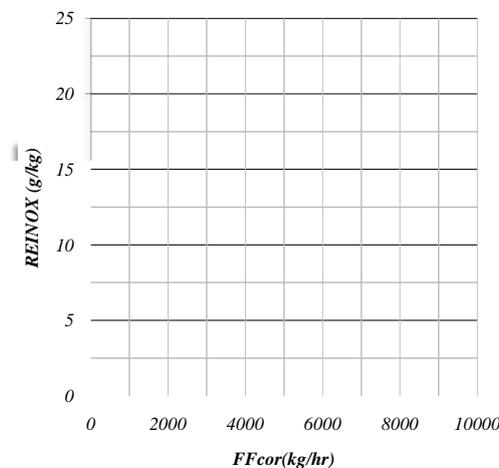
Fig. 2. Relation between REINOx and FFcor, ICAO data bank for CFM56 7b turbo fan engine installed on aircraft B767300
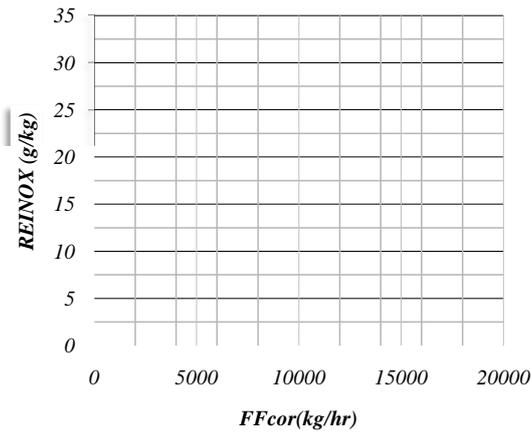
Fig. 3. Relation between REINOx and FFcor, ICAO data bank for PW4056 turbo fan engine installed on aircraft B767300

Other elements of equation (5) are related to flight altitude or ambient pressure and ambient temperature. By using standard value of pollution cleaning cost published by EUROCONTROL (2007) we can calculate cost associated with air pollution or pollution charges value. Our aim is, also, to achieve operational application of achieved results, in form of real throttle/flaps setting applicable in takeoff and landing operations.

5. THE AIRCRAFT TAKE OFF FLIGHT MODEL

In this part of paper is presented unique take off model, which can be use for different flaps /throttle setting in take off performance calculation. The aerodynamic and engine date for this model is imported from PEM published by aircraft manufacturer. For presentation realistic aircraft engine data in take off model, we used following charts: installed take off 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 3000ft QFE, same as LTO cycles, and altitude for start of landing analysis is 3000ft QFE. In order to determine take off performance, we modified basic flight mechanic equations, where we first calculate take off distance, distance to rotate and distance to achieve 3000ftQFE, Jenkinson L. R., et *al.* (1999). Limitations on which basis we calculate take off are:

- available thrust is equal to the maximum take off thrust (limitations from PEM) to altitude 1000ft

$$T_{\max to} = T \hspace{5cm} (6)$$

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

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

- fuel flow is function of take off altitude, take off speeds and take off/climb thrust,

- take off is straight, without turns or change of flight direction,

- the equation which describe flight during initial climb in each segment of take off climb are calculated, for accepted assumption of small climb angle Houghton E.L. & Brock A.E. 1970., $\gamma < 13$, which results in simplification, $\cos\gamma \approx 1$, $\sin\gamma \approx \gamma$.

- center of gravity position do not have influence, on drag value, obtained from low speed polar (from PEM) ,

- the aircraft take off mass change is small, we assume that aircraft mass during takeoff is constant,

- ISA condition, take off from dry runway, no wind, no runway slope.
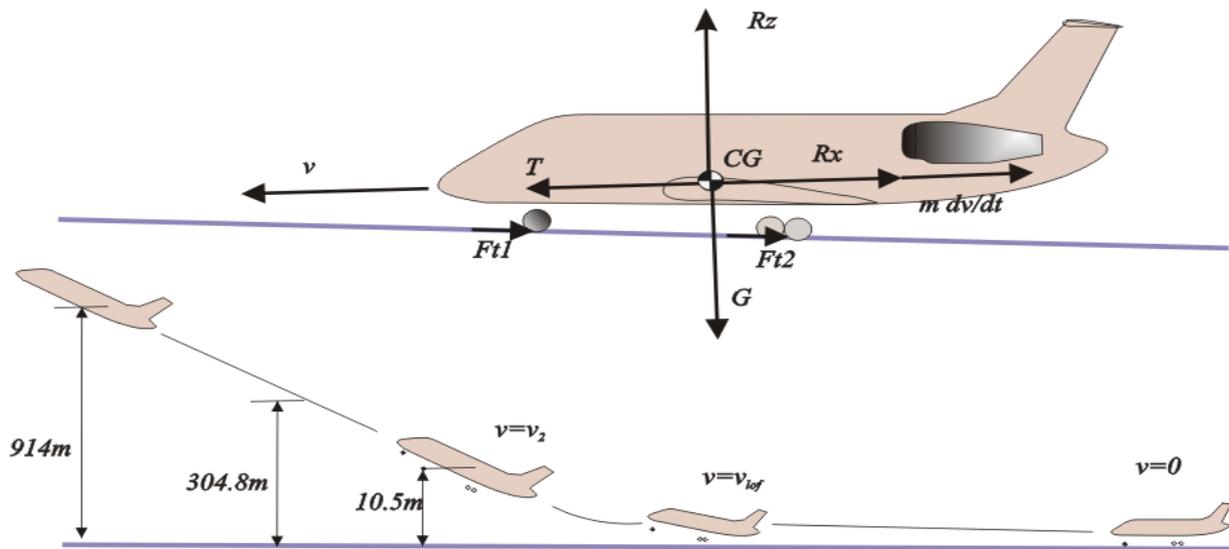
Fig. 4 The forces acting on transport aircraft during take off roll and takeoff operation elements

The basic elements of takeoff analysis are:

- distance to accelerate to lift off speed from $v=0$

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

where T is available all engine thrust in N, G aircraft weight in N, v aircraft speed in m/s, $v_{lof} = 1.10 v_{s1g}$, v_{s1g} is aircraft stalling speed at load factor $n=1$ taken from PEM for aircraft mass and aircraft configuration, v aircraft speed during takeoff in m/s, C_x is aerodynamic

drag coefficient, C_z is denoted to aerodynamic lift coefficient, ρ is air density taken from ISA model, g is 9.81m/s^2 and μ is denoted to runway friction coefficient.

- time to accelerate to lift off speed from $v=0$

$$t1 = \int_0^{Vlof} \frac{1}{g\left(\dfrac{T}{G} - \dfrac{1}{2}\dfrac{\rho v^2 (Cx - \mu Cz)}{G} - \mu\right)} dv \qquad (9)$$

- distance to rotate aircraft and accelerate from v_{lof} to $v_2 = 1.20 V_{s1g}$

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

where v_{trans} is average speed calculated from v_{lof} and v_2, C_{xrot} is aerodynamic drag coefficient after rotation; S is reference wing area in m^2.

- time to rotate aircraft and accelerate from v_{lof} to $v_2 = 1.20 V_{s1g}$

$$t2 = \frac{L2}{V_{trans}} \qquad (11)$$

- climb gradient after aircraft rotation at speed v_{trans}

$$\gamma = \frac{T - \dfrac{1}{2}\rho v_{trans}{}^2 C_{xrot} S}{G} \qquad (12)$$

where v_2 is safety speed.

- distance to climb aircraft at climb gradient to altitude 10.7m(35ft)

$$L3 = \frac{10.7}{\gamma} \qquad (13)$$

- time to climb aircraft at climb gradient to altitude 10.7m(35ft)

$$t3 = \frac{L3}{V_{trans}} \qquad (14)$$

- climb gradient after aircraft rotation at speed v_2 from 10.7m(35ft) to 304.8m(1000ft) in gear up, flaps in take off configuration

$$\gamma_{clf} = \frac{T - \dfrac{1}{2}\rho v_2{}^2 C_{xclf} S}{G} \qquad (15)$$

where C_{xclf} is aerodynamic drag coefficient after rotation and gear up configuration.

- distance to climb aircraft at climb gradient from 10.7m(35ft) to 304.8m(1000ft)

$$L4 = \frac{304.8 - 10.7}{\gamma_{clf}} \qquad (16)$$

- time to climb aircraft at climb gradient from 10.7m(35ft) to 304.8m(1000ft)

$$t4 = \frac{L4}{V_2} \tag{17}$$

- climb gradient after reaching 1000ft and thrust reduction to maximum climb thrust and flaps up, gear up configuration

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

where C_{xcl} is aerodynamic drag coefficient after rotation, flaps up and gear up configuration (from PEM).

- distance to climb aircraft at climb gradient from 304.8m(1000ft) to 914.4m(3000ft)

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

- time to climb aircraft at climb gradient from 304.8m(1000ft) to 914.4m(3000ft)

$$t5 = \frac{L5}{V_2} \tag{20}$$

Take off parameters, from segment $i=1,..,5,$:

- total take off distance from $v=0$ to 3000ft

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

- total take off time from $v=0$ to 3000ft

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

- fuel needed to take off from $v=0$ to 3000ft

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

- total amount of NO_x emission during take off

$$m_{toNOx} = g_{to} \frac{EINOx}{1000} \tag{24}$$

- total amount of CO_2 emission during take off

$$m_{toco_2} = g_{to} \cdot 3.15 \tag{25}$$

6. AIRCRAFT LANDING FLIGHT MODEL

Contrary to classic landing operations, which results in application of thrust after application of landing flaps configuration (full flaps, gear down), we are explore application CDA method in landing. The

starting altitude for landing analysis with application of CDA is 3000ft QFE. In order to set up landing analysis, we modified basic flight mechanic equations for lending, in which we first calculate distance for approach from 3000ft to 50ft, than distance to rotate, distance to parachute and distance to decelerate from speed at touchdown to *v=0,* Filippone(2008). Limitations on which basis we calculate landing are:

- presented thrust is equal to low idle thrust

$$R_x > T_{idle} \qquad\qquad (26)$$

- fuel flow during approach and landing is equal to low idle fuel flow,
- change of approach angle is small $\dot{\gamma}_{app} = 0$ and we adopt approach angle $\gamma_{app} = 3^0$,
- equations that describe flight in landing in each approach segment are calculated for accepted assumption of small approach angle, or $\gamma_{app} < 15^o$ which leads us to $\cos\gamma_{app} \approx$ 1, $\sin\gamma_{app} \approx \gamma_{app}$,
- approach and landing is 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.
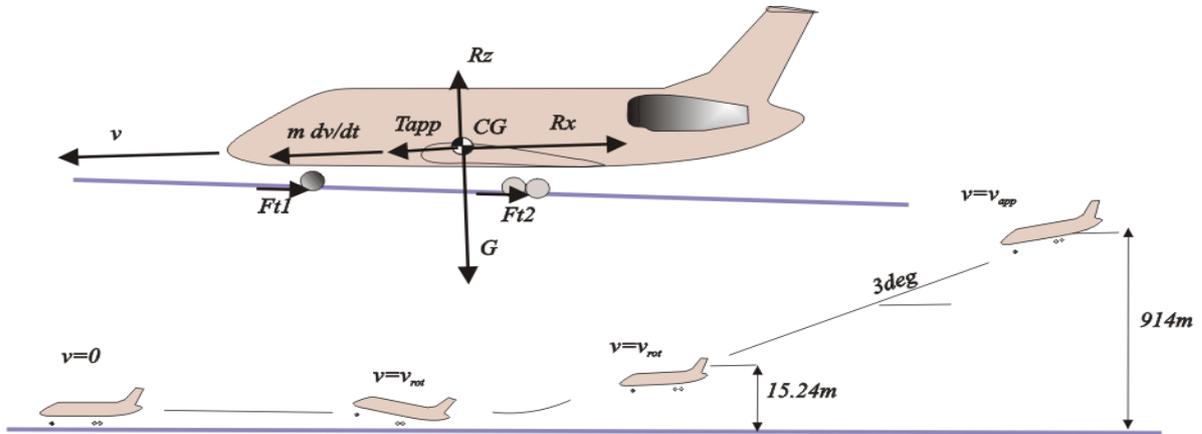
Fig. 5 The forces acting on transport aircraft during landing deceleration and landing operation elements

The basic elements of approach are:

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

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

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

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

where $v_{app} = 1.30 v_{s1g}$, v_{s1g} is aircraft stalling speed at load factor $n=1$ taken from PEM for aircraft landing mass and aircraft landing configuration.

- distance to rotate aircraft and decelerate from v_{app} to $v_{rot} = 1.10 v_{s1g}$

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

where v_{trans} is average speed calculated from v_{rot} and v_{app}, C_{xrot} is aerodynamic drag coefficient after rotation, S is reference wing area in m^2.

- time to rotate aircraft and accelerate from v_{app} to $v_{rot} = 1.10 v_{s1g}$

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

- distance to decent aircraft at descent gradient from altitude 15.24m(50ft) to touch down at $h=0$

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

- time to decent aircraft at descent gradient from altitude 15.24m(50ft) to touch down at $h=0$

$$tl3 = \frac{Ll3}{V_{rot}} \tag{32}$$

— distance to decelerate form v_{rot} to $v=0$

$$Ll4 = \int_{Vrot}^{o} \frac{v}{g\left(\frac{T_{app}}{G} - \frac{1}{2} \frac{\rho v^2 \left(C_{xro} - \mu_b C_{zro} \right)}{G} - \mu_b \right)} dv \tag{33}$$

where T_{app} is available all engine idle thrust in N, G aircraft weight in N, v aircraft speed in m/s, $v_{rot} = 1.10 V_{s1g}$, V_{s1g} is aircraft stalling speed at load factor $n=1$ taken from PEM for aircraft mass and aircraft landing configuration, v aircraft speed during landing

deceleration in m/s, C_{xrot} *is* aerodynamic drag coefficient at deceleration, C_{zrot} is denoted to aerodynamic lift coefficient at deceleration, ρ is air density taken from ISA model at SL, g is 9.81m/s^2 and μ_b is denoted to braking friction coefficient during braking to full stop speed $v=0$.

- time to decelerate from rotation speed to full stop speed $v=0$

$$tl4 = \int_{Vrot}^{o} \frac{1}{g\left(\dfrac{T_{app}}{G} - \dfrac{1}{2} \dfrac{\rho v^2 \left(C_{xro} - \mu_b C_{zro} \right)}{G} - \mu_b \right)} dv \tag{34}$$

Landing parameters, from segment $i=1,..,4$, are :

- total landing distance from 3000ft to $v=0$

$$L_{LN} = \sum_{i=1}^{4} Ll_i \tag{35}$$

- total landing distance from 3000ft to $v=0$

$$t_{LN} = \sum_{i=1}^{4} tl_i \tag{36}$$

- fuel spent to landing from 3000ft to $v=0$

$$g_{LN} = FF \cdot tl_{LN} \tag{37}$$

- total amount of NO$_x$ emission during landing

$$m_{LN\,NOx} = g_{LN} \frac{EINOx}{1000} \tag{38}$$

- total amount of CO$_2$ emission during landing

$$m_{LNco_2} = g_{LN} \cdot 3.15 \tag{39}$$

7. OPTIMIZATION OF TAKE OFF AND LANDING CONFIGURATION FOR MINIMUM POLLUTION CHARGES

Now, it is possible to define total pollution cost, for takeoff PC_{TO}, and total pollution cost for landing, PC_{LN}. After application of different take off and landing flaps/throttle configuration, we can compare achieve results. The first results were achieved by application of ICAO LTO method for determination of total pollution cost produced in takeoff and landing achieved, PC_{icaoTO} and $PC_{icaoLN,}$ respectively. The second results were achieved by application of method presented in paper for determination of total pollution cost produced in takeoff and landing achieved, PC_{TO} and $PC_{LN,}$ respectively, for same cost of pollutant cleaning.

Table 1. The comparison of take off pollution charges for aircraft B767300 with engine CF 6 80 at *MTOT*, *MCT* throttle setting

Aircraft B767300 *MTOW*=185000kg Engine CF 6 80 *MTOT, MCT*	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 1 SETTING	96.33	418.04	1316.91	10.26	PC_{TO} =71.85
Presented take off model FLAPS 5 SETTING	95.54	414.39	1305.34	10.13	PC_{TO} =71.18
Presented take off model FLAPS 15 SETTING	96.92	420.35	1324.10	10.28	PC_{TO} =72.19
ICAO LTO- Take off	174.00	773.35	2436.06	17.65	PC_{icaoTO} =128.58

The first analysis is done for twin turbo fan aircraft 767300, equipped with engines CF 6 80, with application of maximum take off thrust-*MTOT*, maximum climb thrust-*MCL* and IDLE thrust during approach and landing. Results obtained from previous described flight model and data gathered from Performance Engineers Manual-PEM, are shown in Table 1.

The first conclusion, which can be derive from Table 1. and Table 2. is more than 50% of difference between pollution charges, calculated by ICAO methodology and pollution charges, calculated by presented take off pollution model. This imply 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 shorter time in mode in real operations than in standard ICAO methodology. The results presented in Table 1. are obtained for *MTOM, which* imply lower PC_{TO} for lower *ATOM,* because lower take off mass require lower take off distances and lower time in mode.

It can be also, conclude which configuration produces the lowest pollution cost from Table 1. Table 3. and Table 5., this is configuration B767300 with engine 4056. Comparing same take off configuration, for different engine, Table 1., Table 3. and Table 5., it is obvious that the lowest pollution configuration generate FLAPS 5 SETTING in case of *MTOT*, *MCT* throttle setting. If we compare same landing configuration, for different engine, Table 2., Table 4. and Table 6, it is obvious that lowest pollution configuration generate: FLAPS 35 SETTING in case of IDLE throttle setting. In case of landing is presented difference in pollution charges of more than 70% from ICAO LTO pollution model. We should do not forget that descent is

done in case of CDA approach at IDLE thrust.

Table 2. The comparison of landing pollution charges for aircraft B767300 with engine CF 6 80 at IDLE throttle setting

Aircraft B767300 $MTOW$=185000kg Engine CF 6 80 IDLE	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 25 SETTING	241.06	107.98	340.15	0.65	PC_{LN} =11.79
Presented take off model FLAPS 35 SETTING	243.09	108.89	343.02	0.66	PC_{LN} =11.89
ICAO LTO- Landing	240.00	327.36	1031.18	4.13	PC_{icaoLN} =43.07

Table 3. The comparison of take off pollution charges for aircraft B767300 with engine PW4056 at $MTOT, MCT$ throttle setting

Aircraft B767300 $MTOW$=185000kg Engine PW4056 $MTOT, MCT$	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 1 SETTING	109.50	447.51	1409.66	11.88	PC_{TO} =80.05
Presented take off model FLAPS 5 SETTING	95.54	390.45	1229.9	10.36	PC_{TO} =69.85
Presented take off model FLAPS 15 SETTING	96.92	395.91	1247.11	10.50	PC_{TO} =70.80
ICAO LTO- Take off	174.00	728.81	2295.74	19.55	PC_{icaoTO} =131.07

Table 4. The comparison of landing pollution charges for aircraft B767300 with engine PW4056 at IDLE throttle setting

Aircraft B767300 $MLW=145000kg$ Engine PW4056 IDLE	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 25 SETTING	241.06	107.98	340.15	0.65	PC_{LN} =11.79
Presented take off model FLAPS 35 SETTING	243.09	108.89	343.02	0.66	PC_{LN} =11.89
ICAO LTO- Landing	240.00	337.44	1062.94	4.05	PC_{icaoLN} =43.67

Table 5. The comparison of take off pollution charges for aircraft B767300 with engine PW4060 at *MTOT, MCT* throttle setting

Aircraft B767300 Engine PW4060 *MTOT, MCT* *MTOW=185000kg*	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 1 SETTING	114.59	487.96	1537.07	12.30	PC_{TO} =85.07
Presented take off model FLAPS 5 SETTING	113.58	478.83	1508.31	13.21	PC_{TO} =87.36
Presented take off model FLAPS 15 SETTING	115.686	486.61	1532.83	13.385	PC_{TO} =88.63
ICAO LTO- Take off	174.00	772,79	2434.28	20.89	PC_{icaoTO} =139.511

Table 6. The comparison of landing pollution charges for aircraft B767300 with engine PW4060 at IDLE throttle setting

Aircraft B767300 Engine PW4060 IDLE	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 25 SETTING	241.06	107.98	340.15	0.55	PC_{LN}=11.44
Presented take off model FLAPS 35 SETTING	243.09	108.89	343.02	0.56	PC_{LN} =11.54
ICAO LTO- Landing	240.00	337.44	1062.94	4.05	PC_{icaoLN} =43.67

The second conclusion, which can be deriving for the best engine airframe match, is presented in Table 7. and Table 8. The application of de rated takeoff thrust offer 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 application of de rated thrust as a method for pollution mitigation during takeoff.

Table 7. The comparison of take off pollution charges for aircraft B767300 with engine PW4056 at DERATE =89%, throttle setting

Aircraft B767300 *MTOW=185000kg* Engine PW4056 DERATE=89%	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 1 SETTING	126.10	459.63	1447.83	10.78	PC_{TO} =77.38
Presented take off model FLAPS 5 SETTING	125.125	455.13	1433.65	10.64	PC_{TO} =76.52
Presented take off model FLAPS 15 SETTING	110.44	450.72	1419.78	11.94	PC_{TO} =80.55
ICAO LTO- Take off	174.00	728.81	2295.74	19.55	PC_{icaoTO} =131.07

Table 8. The comparison of take off pollution charges for aircraft B767300 with engine PW4056 at DERATE =89%, throttle setting

Aircraft B767300 ATOW=165000kg Engine PW4056 DERATE=89%	Total time in sec	Total fuel in kg	Total CO_2 emission in kg	Total NO_x emission in kg	Pollution cost or pollution charges in USD
Presented take off model FLAPS 1 SETTING	110.14	400.9	1263	9.386	PC_{TO} =67.44
Presented take off model FLAPS 5 SETTING	109.84	399	1257	9.317	PC_{TO} =67.05
Presented take off model FLAPS 15 SETTING	97.39	396.99	1250	10.50	PC_{TO} =70.88
ICAO LTO- Take off	174.00	728.81	2295.74	19.55	PC_{iacoTO} =131.07

8. THE EMISSION FOOTPIRINT

If we use calculated takeoff dynamic, presented by takeoff run distance and elapsed time, engine exhaust gases speed (Fig. 6.) and distribution we can predicted pollution volume. The pollution space has two projections, on the surface parallel to runway, called in this paper, emission footprint, presented by Fig.7. The other projection of pollution volume, will perpendicular to runway surface, parallel to runway centerline. This model is developed under assumption of neglecting exhaust gas expansion in time, which is function of gas dynamic, temperature and pressure.
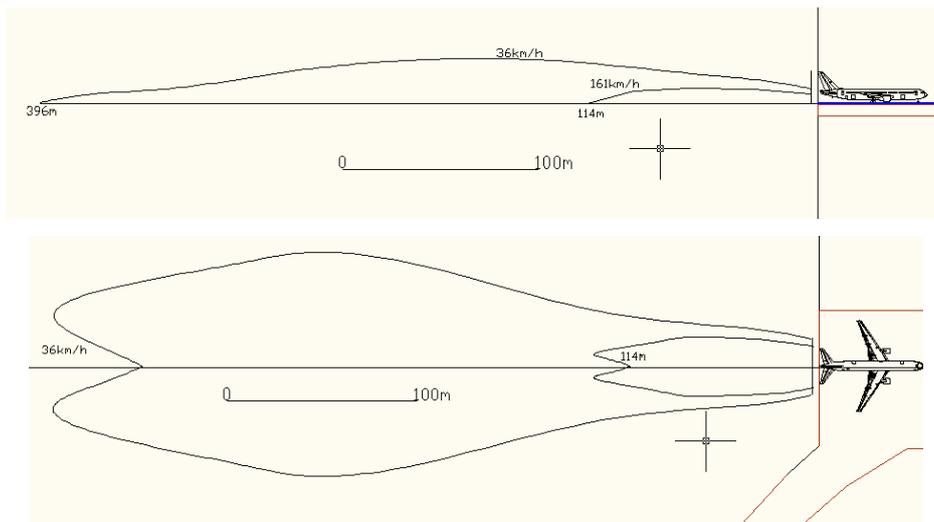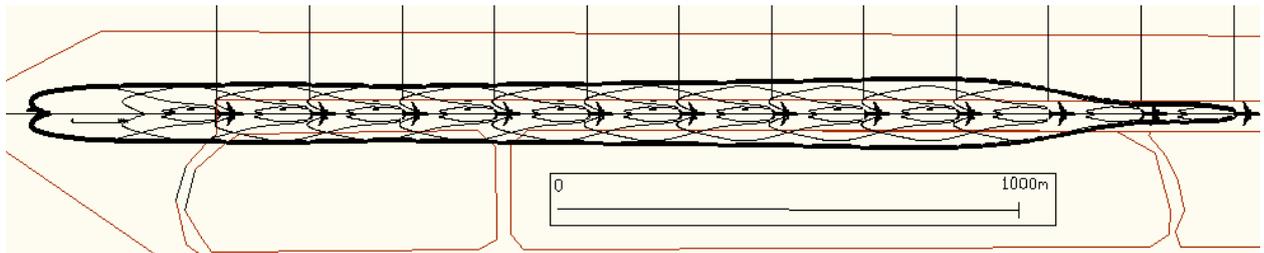

Fig. 6 The exaust gases distribution for aircraft B767300 with engine CF 6 80 at full take off throttle setting

Taking in account distance, achieved during takeoff acceleration, we can make the first prediction of exhaust gasses distribution, during takeoff and in that way, pollution in airport area (Fig. 8.).
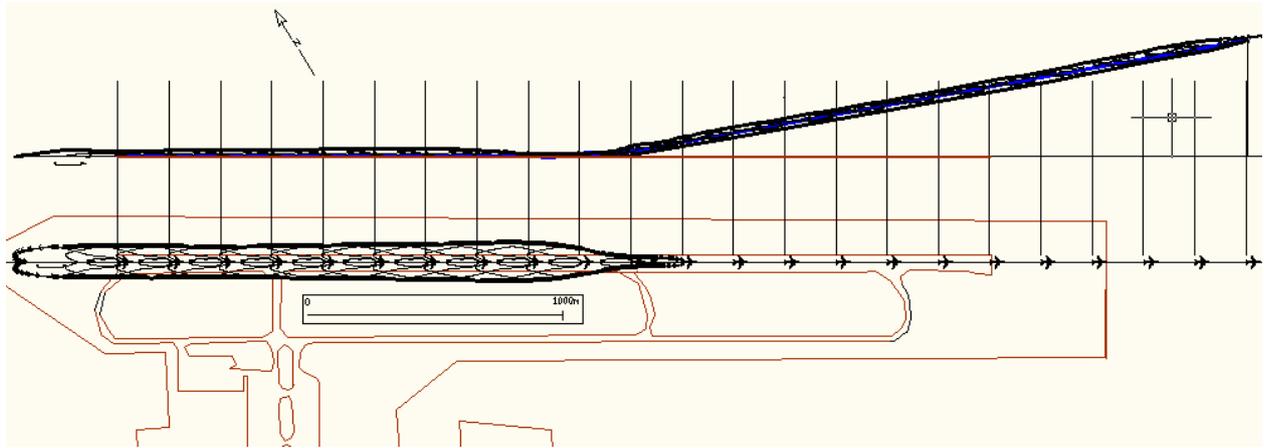
Fig. 7 The exaust gases distribution in vertical and horiyontal projection, after take off for flaps settings 5, for aircraft B767300, with engine CF 6 80 at full take off throttle setting

Fig. 8 The horizontal exaust gases distribution after take off for flaps settings 5, for aircraft B767300, with engine CF 6 80 at full take off throttle setting

9. CONCLUSION

In the paper, we develop analytical model based on real aircraft performance model, for aircraft 767300, which precisely determine pollution charges for chosen flaps/throttle setting mitigation or cancellation. The input data are taken from aircraft manufacturer Performance Engineers Manual, which guaranty results application in real take off and landing operations. The new takeoff and landing pollution calculator, developed in this paper, is toll which allow airline to choose flaps/throttle setting pollution charges mitigation or cancelation (if produced pollution is under predetermined pollution level). The major take off 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, take off and landing pollution calculator, provide, for given route network, provide optimal airframe engine match, which produce lowest pollution and in that way lowest pollution charges.

In the brief, in the paper we offer the solution for five optimization problems:

— we define take off flaps/throttle configuration for minimum pollution charges,

— we define landing flaps/throttle configuration for minimum pollution charges,

— we define influence of de rated take off thrust setting on pollution charges, when is *ATOW<<MTOW* and when runway and obstacle are no limit,

— we define influence of CDA approach and landing procedure on pollution charges, when is operationally applicable,

— we, also, present method for analyzing aircraft pollution, which is tested on aircraft engine matching problem. The result is optimal airframe engine combination.

In the paper is defined unique way of pollution quantification and distribution, which as much accurate and can replace LTO model, publish by ICAO. Adoption of this model, we can offer to airline operator possibilities to develop strategy for pollution charges reduction and on that way, total direct operating costs reduction. The pollution distribution model, presented in this paper, determines pollution in air space and on the ground, during takeoff and landing operations. Such polluted area, obtained by this model can be predicted and specially protected and threat.

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

Presented technique is especially applicable on short-haul flights, where *ATOW* (Actually Take Off Weight) is lower than *MTOW* (Maximum Take Off Weight) and subsequently *ALW* (Actually Landing Weight) lower than *MLW* (Maximum Landing Weight).

The practical benefit from proposed method, flaps/throttle and engine installation for

minimum pollution cost or minimum pollution charges, for air operator can be synthesized in 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 cleaning of total pollution, from aircraft operation, costs. Beside this real quantity of pollutants emitted in air or sprayed on ground in area of runway can be predicted. From presented pollution calculation model, airline can proof level of pollution produced by airline operations, but also if that level of pollution is below accepted level of pollution, this lid to pollution charges cancelation.

Achieved results, clearly highlight that present ICAO LTO pollution calculation model act as an obstacle to sustainable air industry development. The ICAO LTO model offers one solution: purchase latest technology aircraft, which produce lowest pollution. This is rigid and expensive solution, from airline point view. This is great difficult to airline, airline have new burden, pollution charges which increase direct operation cost, without chance to decrease pollution charges by application of standard operation procedures, such as de rated take off, thrust setting and CDA approach. The most important paper contribution is real aircraft pollution calculation and determination of real benefit from proper, engine airframe match and takes off/landing flap/throttle setting for minimum pollution costs.

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