GAS TURBINE EMISSIONS IN AIRPORTS VICINITY DURING LTO CYCLES

By

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Abstract

"Gas Turbine Emissions In Airports Vicinity During LTO Cycles" or more specifically "Land And Take-Off Pollutant Calculator" and this Msc thesis is used like a tool that would be helpful for an airport or Regulatory Authority to calculate the overall amount of gas turbine emissions in one airport or aerodrome and this vicinity. It contains an aircraft library that relates the most common aircrafts that are operating in the major airports of the world. Also have a relation between the gas turbine engines and this fuel consumption and pollutants production. During this Msc thesis is described a real example for Lisbon International Airport (LIS – IATA, LPPT – ICAO) based on data provided by ANA-Airports of Portugal.

Acknowledgements

This thesis has been a very knowledgeable (and sometimes challenging) experience in terms of programming, knowledge and development of English language. This has been made possible with the help of some people that I would like to thank very much.

I would like to cheerfully thank to my entire teacher's to especially to my Dr. Jorge Barata for my integration in AeroG and to my supervisor Dr. André Silva and for the helpful guidance during these five years.

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Notations

A/C- Aircraft

ALAQS-Airport Local Air Quality Studies

ANA – Airports of Portugal

APU - Auxiliary Power Unit

CAEP - Committee on Aviation Environmental Protection

CO - Carbon Monoxide

CO_2 - Carbon Dioxide

COAP – Carbon Monoxide in approach conditions

COCL – Carbon Monoxide in climb conditions

COID – Carbon Monoxide in idle conditions

COTO – Carbon Monoxide in take-off conditions

EDMS - Emissions and Dispersion Modeling System

EPA - Environmental Protection Agency

EU - European Union

FAA - Federal Aviation Administration

FFAP – Fuel Flow in approach conditions

FFCL – Fuel Flow in climb conditions

FFID – Fuel Flow in idle conditions

FFTO – Fuel Flow in take-off conditions

GND - Ground

GPU - Ground Power Unit

GSE - Ground Support Equipment

HC – Hydrocarbon

HCAP – Hydrocarbon in approach conditions

HCCL – Hydrocarbon in climb conditions

HCID – Hydrocarbon in idle conditions

HCTO – Hydrocarbon in take-off conditions

Hz - Hertz

ICAO - International Civil Aviation Organization, Montreal

IEA - International Energy Agency

IPCC - Intergovernmental Panel on Climate Change

INAC - National Institute of Civil Aviation (Portugal)

LTO - Landing and Take-off Cycle

LPPT – ICAO code for Lisbon Airport

NENGINES – Number of engines in aircraft type

NO - Nitrogen Oxide

NO_2 - Nitrogen Dioxide

NO_x - Oxides of Nitrogen

NOAP – Carbon Monoxide in approach conditions

NOCL – Carbon Monoxide in climb conditions

NOID – Carbon Monoxide in idle conditions

NOTO – Carbon Monoxide in take-off conditions

O_3 - Ozone

PM - Particulate Matter

SID - Standard Instrumental Departure

TMAP – Time spent in approach phase (in seconds)

TMCL – Time spent in climb phase (in seconds)

TMID – Time spent in taxi phase (in seconds)

TMTO – Time spent in take-off phase (in seconds)

UHC – Unburned Hydrocarbons

VOC - Volatile organic carbon

WMO - World Meteorological Organization

UNEP - United nations environment programme

Chapter 1

Introduction

1.1 – Context

Today and in next year's is expected a continue growing of the aerospace industry. Combined with this expansion there are also problems of environmental impact such as noise and pollution. To increase the environmental impact in public health also appears that some major airports around the world are located in large cities or within their limits. Sometimes these cities already suffer from problems related to air quality associate to his industry and road transport. All over the World, diverse entities and organizations begin to create restrictions on emission of polluters to the air because of the people that reside in the periphery of airports and airfields.

Pollutant			EU	CH
Nitrogen dioxide	NO2	(µg/m3/a)	40	30
Particle Matter	PM10	(µg/m3/a)	40	20
Sulfur dioxide	SO2	(µg/m3/a)	20	30
Ozone	O3	(µg/m3/8-hr)	120	-

Table 1 - Air Quality Standards in Europe

A very visible example is the European directive that imposes emission limits already in 2010. In this context, I will use the Portela International Airport in

Lisbon for object of study, which is not only inside of the city but also most of his traffic arrival (period in which the aircraft fly at a lower speed) is performed over the city center. The airport has seen a continuous growth, and presented in the year of 2008 a total of 144,771 movements and almost 14 million passengers.

How can we account the impact of aircrafts in an airport and in his vicinity?

Several studies have been conducted in several airports and many agencies have prepared tables until about pollution carried by aircraft in LTO cycles.

What are LTO cycles and the extent to which these scales may be useful?

The LTO cycles are called Landing and Take-off cycles, were defined by ICAO in 1993 and representing the period that an aircraft descends below 3000 feet until it rise above this same value like we could see in the figure 1.

On the way, appear to make the landing, taxi, finally take-off and climb out. By definition of ICAO, the approach phase have 4 minutes of time and the engine have 30 percent of the maximum thrust of the engines, the taxi phase have 26 minutes of time and only 7 percent of relative thrust. The take-off phase corresponds to 100 percent of thrust engine during 0.7 minutes and finally climbs out phase that have 2.2 minutes and 85 percent of maximum engine thrust. The use of the tables provided by various organizations such as ICAO sometimes are not entirely useful because of the records for the pollution in these course are only for standardized times and has reference to engines that are not the same on the real aircrafts. The tests made at airports, showed in this Msc thesis, demonstrated that some values of CO_2 and NO_X could be different from the ICAO tables (Schafer et al. 2003). This facts and necessities bring me to the development of this thesis and all that it supports.

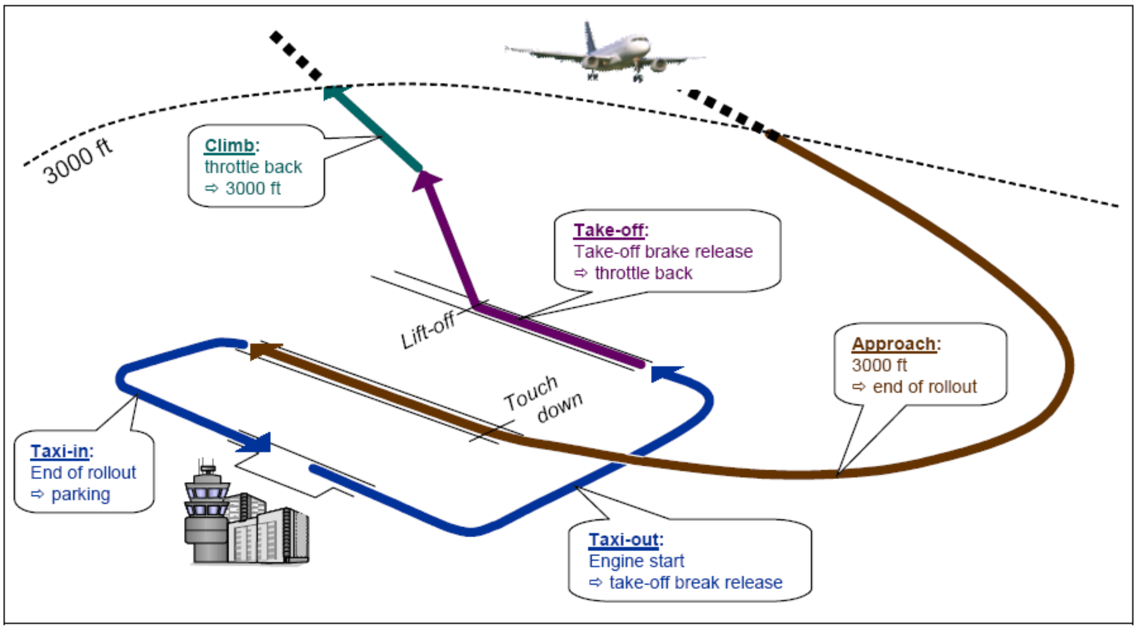


Figure 1 - LTO cycle

1.2 - Main Objectives

The main objectives of this thesis is developing a computer program that enables and assists all studies related to pollution caused by aircraft gas turbine around an airport. Gas turbine emissions in LTO cycles during airports vicinity is basically a computer program developed in the programming language "Fortran" and that allows an airport or regulatory authority to calculate the amount of emissions produced by one or more aircraft during the various cycles of LTO made in a specific airport or aerodrome. This program allows not only calculating these emissions, but also adapting them to each airport depending on traffic and time of LTO since they differ from airport to airport.

1.3 - Structure of the Thesis

This thesis is made in five chapters: Introduction (Purpose); Review of Literature; Methodology; Discussion, Analysis & Interpretation of the Data; Conclusions and further research.

In the first chapter is described the context, the main objectives and the structure of the thesis. Here is showed “Why do this program?”, “Why now?”, “Why here?” the aims of study and finally the structure of the thesis.

The second chapter is a review of what is already know and it covers past research, studies and articles from relevant journals, books, newspapers, etc.

The third chapter describes the main program and how it was made (the structure of the program) and the use of blocks, the databases used and the formulas that were used to make the things happened without mistakes.

The chapter four describes a summary of main findings.

The fifth and last chapter refers the conclusions of these thesis and further research.

Chapter 2

Review of Literature

2.1– Air traffic growing

According to the IEA (International Energy Agency) and IPCC *(*Intergovernmental Panel on Climate Change) (figure 2), the air transport use near 15 percent of world's annual consumption of transportation fuel (Egli, Robert A. 1991), in fact could seems to be a small percentage but it is an huge value when we say that represents more than 200 million tonnes of fuel consumption (600 million tonnes of CO_2) per year and near about 2% of the earth global emissions of CO_2 (see figure 3). In the future these results could be worst. The question is why? Because although the engines are more and more efficient (figure 4) the number of aircraft grows in a larger percentage, and some of actual aircrafts, which are big polluters, will be in the skies for more than 10 years.

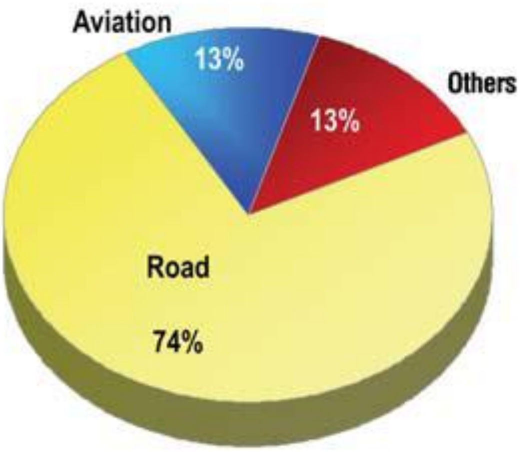


Figure 2 - Global CO2 Emissions per Transport Sector (%)
Source: IPCC

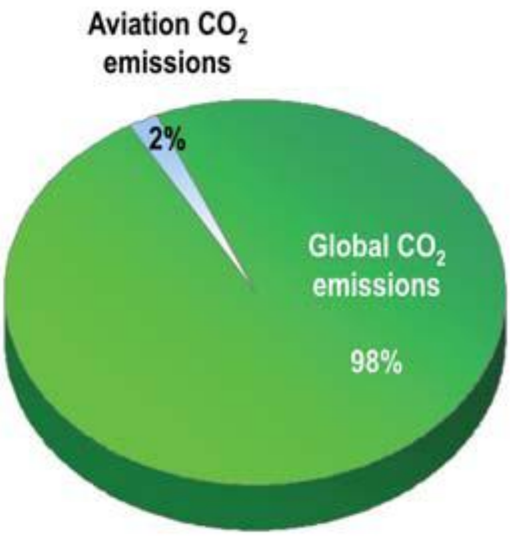


Figure 3 - Aviation Contribution Global CO2 Emissions Aviation (Domestic and International) accounts for about 2 % of all global CO2 emissions. Source: IPCC

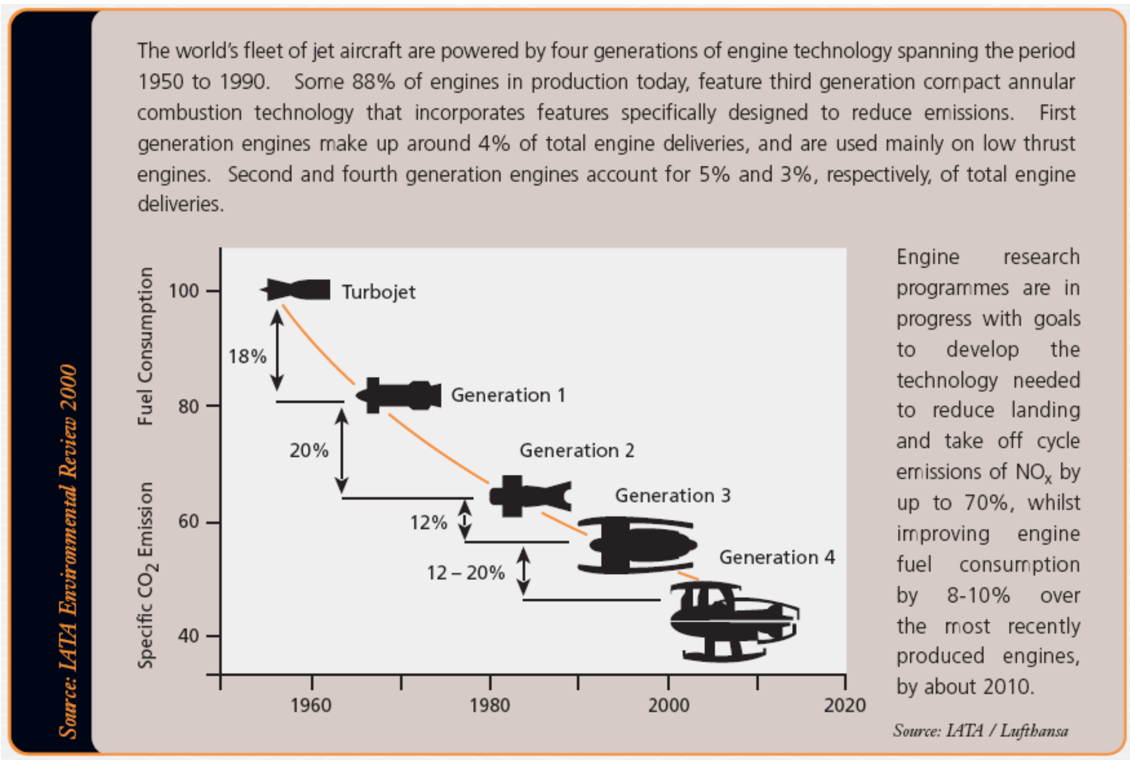


Figure 4 - Engine efficiency during the last decades.
Source: IATA / Lufthansa

Despite the introduction of more efficient aircrafts, the fuel consumption increased 37 percent from 1977 to 1988. With new technologies the emissions could decrease, but not all emissions, in fact, NO_X emissions could increase (Dewes, Winfried et al. 2000). Air-traffic will grow (figure 5) about to 4% to 5% per year in the next years (according to Joyce Penner and IPCC Special Report, 1999); it means that it will double in 15 years.

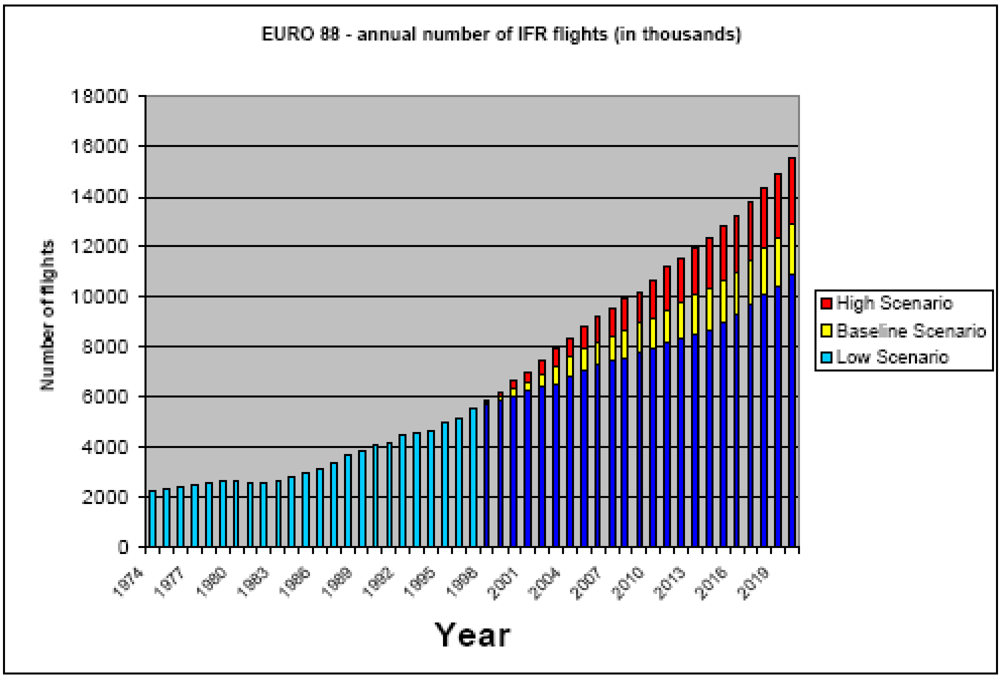


Figure 5 - Air Traffic Forecast for the Eurocontrol Area
Source: Eurocontrol

In QuinetiQ (2004) report showed that in the last years was made near 9 millions of commercial flights for year. All these flights produce a lot of pollution. Like the Seattle airport council policy chief (Debby McElroy) said: “We have to reduce our emissions so that we can continue to add flights”, and in conformity to Thomas Frank (2008) the project for Atlanta’s airport will cut about 40 000 tonnes of carbon dioxide emissions. Another example of good projects in airports is the Zurich Airport management (With the title: “More Grow with Less Impact”), and like we could see in the figure 6 it’s possible to make Debby McElroy words a real fact. Some research groups like AERONET (composed by Universities, Airlines and producers of aircraft or engines) are trying to study the emissions of pollutants, the atmospheric impact and regulations in order to report to the government's advices and inform the real problem caused by the aircraft industry.

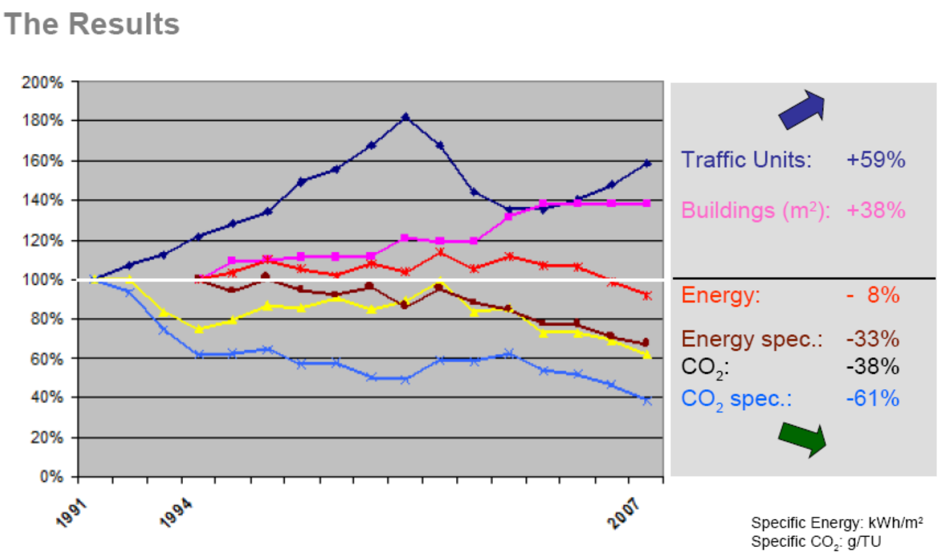


Figure 6 - Pollution and air traffic in the last years.
Source: Unique Airport

2.2 – Airports and studies

As we saw in the previous paragraph the air traffic is growing. The emissions from air traffic have been investigated since 60's in order to understand their role in several physico-chemical phenomena. The main substances released by aircraft engines into the atmosphere are carbon dioxide, carbon monoxide, water vapors, nitrogen oxides, sulphur gases, non methane volatile organic compounds, soot and other particles (D. Romano et al. 1997).

While the emissions of road traffic or housing and industries are decreasing due to more stringent emission limits, the air traffic emissions are growing. Due to this growth, concerns regarding the pollution caused by aircrafts also have grown. The airports must have to present an emission inventory by specie, and try to reduce him to solve the problem of emissions at ground level. Some studies are made from various organizations. One of them is from IPCC (Intergovernmental Panel on Climate Change) that together with

WMO (World Meteorological Organization) and UNEP (United Nations Environment Programme) have one study of seven possibility's scenarios of the air traffic expansion and is pollution (figure 7). In six of them the emissions will grow, two of them for very dramatic cases, and only in one case will maintain (IPCC – 1999).

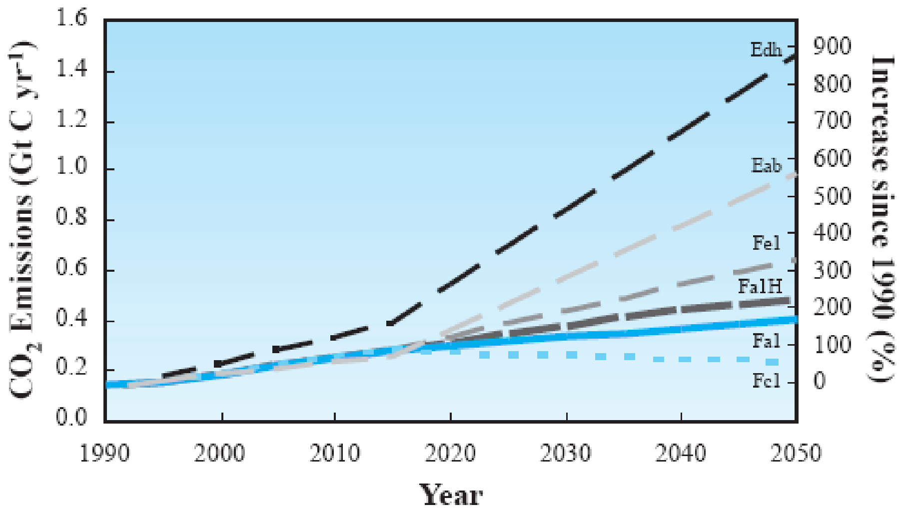


Figure 7 - Possible future scenarios for CO_2 emissions.
Source: IPCC

Seattle International airport some years ago had make a proposal to the aircraft pilots to turn's off jet's engines while parked and they have rejected. Now the airport is moving to approve the idea that will save the environment and also much money. The airlines will pay for a 31 million dollars project and will recoup that money in only 2 or 3 years in jet fuel savings (Frank, Thomas, 2008). Greek airports was studied in 2005, and this studies related also the LTO cycles with engines but they have a problem, they use the same standard times them ICAO. Like we can see in table 2 on the next page, the real times could be different from ICAO standard times. Something excellent was the data models used were we could see the polluters in three different airports by values and the percentage of all aircraft types in each airport (Sidiropoulos, C. et al 2005). According to another tests made in London-Heathrow, Frankfurt-Main and Vienna was found that when the aircrafts were in idle conditions the NO_X emissions were sometimes much lower than described in ICAO databank engine tests. These studies give some importance to the APU (Auxiliary Power Unit) emissions, something that could be attractive to future considerations of the program. Atlanta airport have another example when we talk about concerning with the air traffic.

Aeroporto	Taxi/ Iddle out	TakeOff (até 150 m)	Subida (até 1000 m)	Taxi/ iddle in	Aproximação (abaixo dos 1000 m)
Bragança	8.7	0.7	2.2	5.1	4.0
Corvo	8.7	0.7	2.2	5.1	4.0
Faro	11.1	0.7	2.2	5.0	4.0
Flores	8.5	0.7	2.2	5.1	4.0
Funchal	14.1	0.7	2.2	5.0	4.0
Graciosa	7.8	0.7	2.2	5.2	4.0
Horta	9.1	0.7	2.2	5.0	4.0
Lisboa	10.1	0.7	2.2	5.0	4.0
Porto	8.1	0.7	2.2	5.0	4.0
Pdelgada	6.1	0.7	2.2	5.0	4.0
Pico	5.1	0.7	2.2	6.0	4.0
Psanto	5.1	0.7	2.2	5.0	4.0
S.Jorge	7.7	0.7	2.2	5.2	4.0
S.Maria	7.4	0.7	2.2	5.2	4.0
Terceira	9.1	0.7	2.2	5.0	4.0
Vila Real	7.6	0.7	2.2	5.2	4.0
Cascais	7.8	0.7	2.2	5.1	4.0

Table 2 - Real LTO times taken in Portuguese airports.
Source: Torres, Pedro. 2008

This last airport made very studies, particularly to the air quality using EDMS (Emission and Dispersion Modeling System). According to them the air traffic had grow nearly 50 percent in the last 10 years. In fact, VOC (volatile organic carbon) will increase 80 percent, NO_X value had double and the principal problem could be the $PM_{2.5}$ emissions because of the health problems caused to the population in the airport vicinity. Another study in London was made not only to account the polluters but also to the dispersion of the pollution too. It was discovered that during the day at several hours, and with some wind orientations, hospitals and schools were exposed to high values of polluters. The most problematic polluter found was NO_2 that in some days had high values near the limit imposed by EU Directive limit value to meet by 2010. This study reveals one of the problems of other study in the same place, when the subject was the possibility of construct a third runway in London Heathrow. The EU limits of pollution will be passed and because of that, Heathrow airport continues to have only two runways. If we observe the location of Lisbon's airport and the orientation of the most used runway we could see the same problem that was seeing in London first study. Like we know the aircrafts try when possible to taking off and landing in the opposite direction to the wind. According to this study, we could see that the wind brings the aircraft pollution to the center of the city like we could see in figures 8 (Lisbon map) and 9 (Jeppesen landing chart).

In Copenhagen the study that was made was not very different from the first one in London, in fact the only difference was that the aircraft movements were followed by computer and studied together with the measurements taken by sensors. This study (made by Winther M. et al. 2006) is more a dispersion study, something that we will not make in this thesis. As reported by the same airport, the APU usage is restricted during parking at the gate. His usage is made only 5 minutes after on blocks. To reduce the APU usage and sometimes GPU (Ground Power Units) some airports have an electric GSE supply a provision of 400 Hz of electrical power to the aircraft. Another fact to not forget is that not only the aircrafts pollute but also the GSE (Ground Support Equipment) like handling and refueling vehicles (Fleuti, Emanuel. 2008). When possible, is recommended to refueling the aircraft directly to ground pipes and with this we have no emissions by the refueling vehicles. Reduce taxiing time and taxiing with one or more engines inoperative and avoiding unnecessary idling of aircraft is another way to reduce the emissions and saving much money. In Zurich another study was made were the author (Schürmann et al. 2007) had measured the NO_X, CO and VOC emissions. The results were quite interesting. The reason was that the measurements were higher than in ICAO's tables as opposed to other studies.

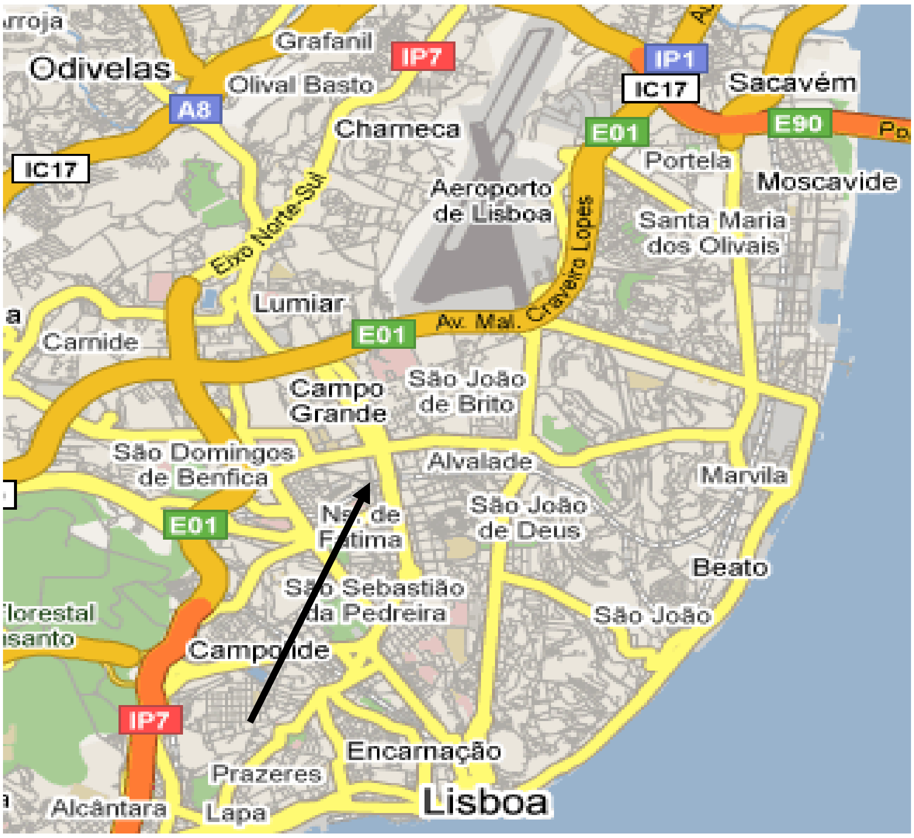


Figure 8 - Lisbon map and arrival's orientation
Source: Google maps

Figure 9 - Jeppesen landing chart for LPPT (Lisbon Airport)
Source: Jeppesen

2.3 – Pollution

Pollution from aircrafts (noise and air) has been a reason for apprehension since jet aircraft initial took to the skies in the 1950s. At that occasion it was the highly observable plumes of exhaust gases, the huge noise and their effect on local air quality which attracted the interest of regulators and the technical community. In the latest years the debate has shifted to inquiring the effect of aircraft emissions on the superior atmosphere and how the aviation community should react. The oldest and greater pollutant aircrafts are being substitute to lower pollutant aircrafts with the aim to lower pollutant emissions (see figure 10). The pollution is not restricted only to these things, but also to pollution of soil and the water itself. Awareness has been delicate by the estimate rate of growth of air transport.

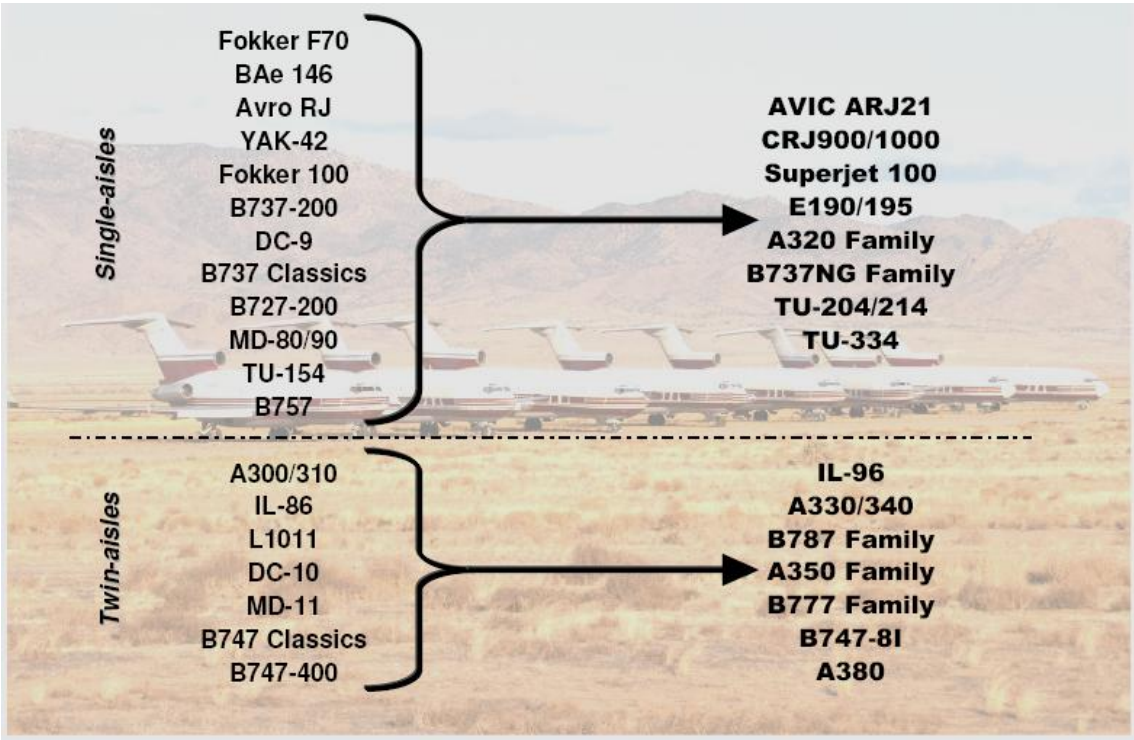


Figure 10 - Aircraft substitution from old and great polluters to new and lower pollutants. Source: Boeing

2.3.1 – Noise Pollution

Aircraft noise is the most significant reason of unfavorable society reaction related to the operation and raise of airports both in developed and developing nations. This is projected to keep on the case in most regions of the earth for the predictable future. Aircraft noise pollution could be defined as the sound produced by any airplane or his components, during a variety of phases of a flight, while taxiing, on the ground while is parked, such as auxiliary power units, during the preparation of the propeller and jet exhaust during take-off, under the departure side and arrival paths, on-route or even as flying over the landing. A good example of reducing noise pollution is the continuous flight descending that you can see in the next figure (Figure 11).

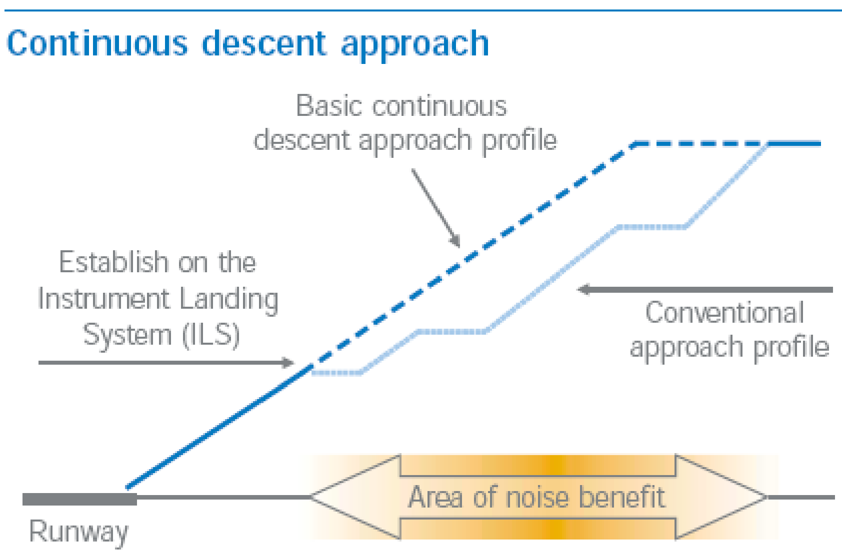


Figure 11 - Example of continuous descent approach.
Source: Eurocontrol

Other source of noise pollution is the Aerodynamics. Aerodynamic noise pollution takes place from the airflow surrounding the aircraft fuselage and the control surfaces. This variety of noise increases with aircraft speed and also at lower altitudes due to the density of the atmosphere. Reducing or restricting the consequences of aircraft noise on population and the communities they live is most important priorities of FAA, ICAO and other organizations. Recently manufactured aircraft are obliged to obey with the

Noise Standards set out in ICAO Annex 16 - Volume I. The noise produced by aircrafts (mainly by gas turbine engines) operations in an airport or in the surrounding area depends upon a number of factors including: the types of aircraft used in the airport, the overall number of daily movements, general operating conditions, the time of day that the aircraft operations occur, the runways that are used, climate circumstances, monthly or annual take-offs and landings, topography, and airport-specific flight procedures.

The noise effects caused by the aircraft operations are not quantifiable and can depend on a extent of factors associated to the individual listener's cultural, socio-economic, psychological and physical situation, and may diverge from no effect to severe irritation. Aircrafts produced in our days are about 75% quieter than they were decades ago and the aircraft producers are working to reduce this even more. These developments are reflected in CAEP (Committee on Aviation Environmental Protection) Certification Standards and ICAO's continuing promotion of achieves to noise reduction technologies.

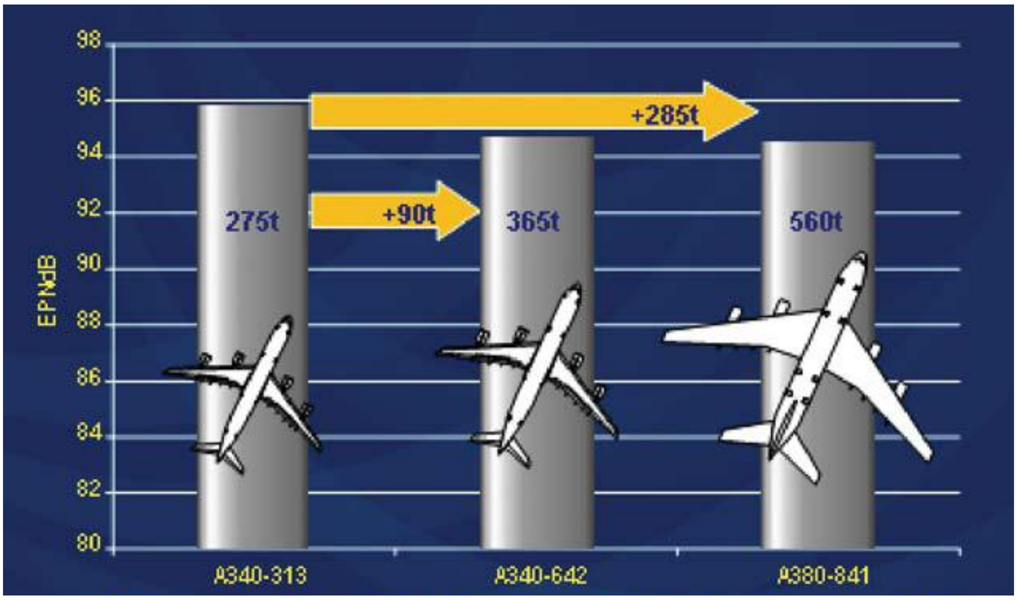


Figure 12 - Capacity growth without noise increase.
Source: Airbus

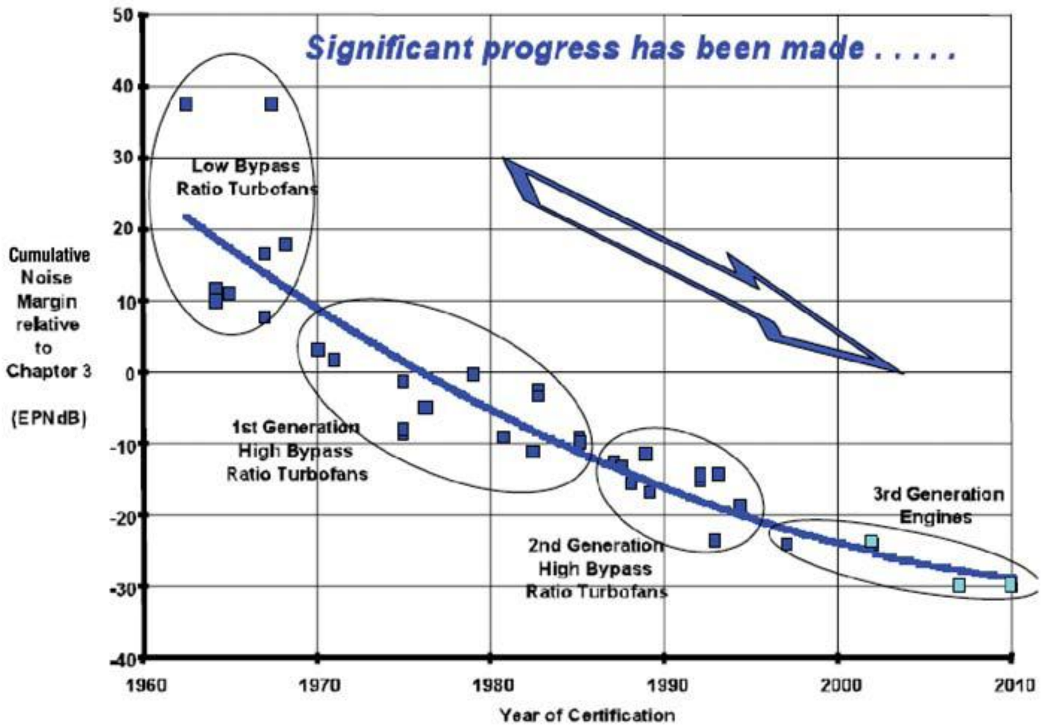


Figure 13 – Aircraft Noise Level Trend

Source: IPCC

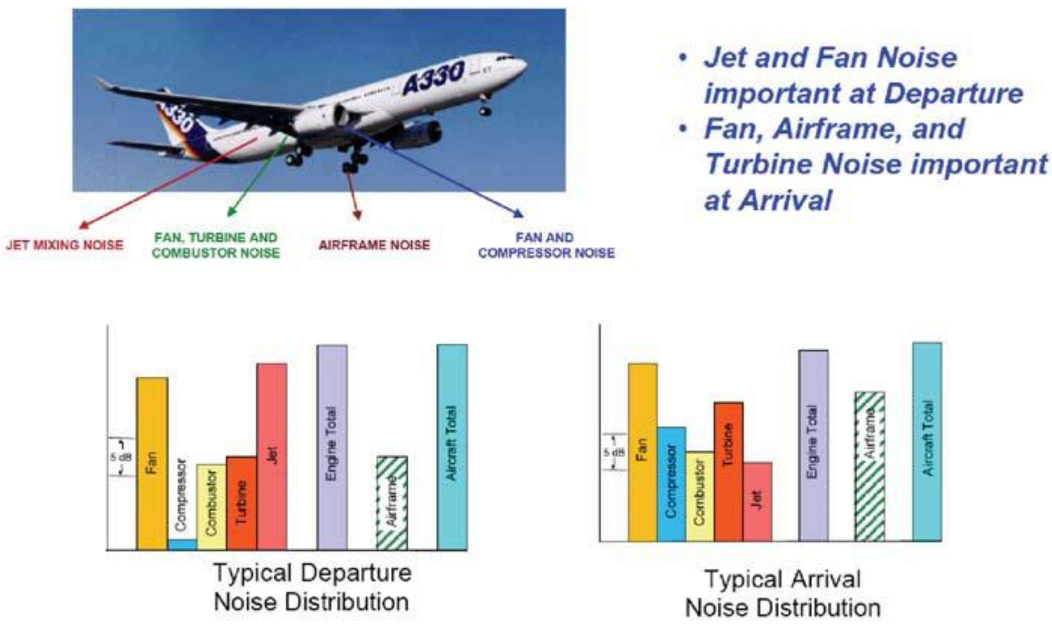


Figure 14 – Noise Component contributions
Source: Airbus

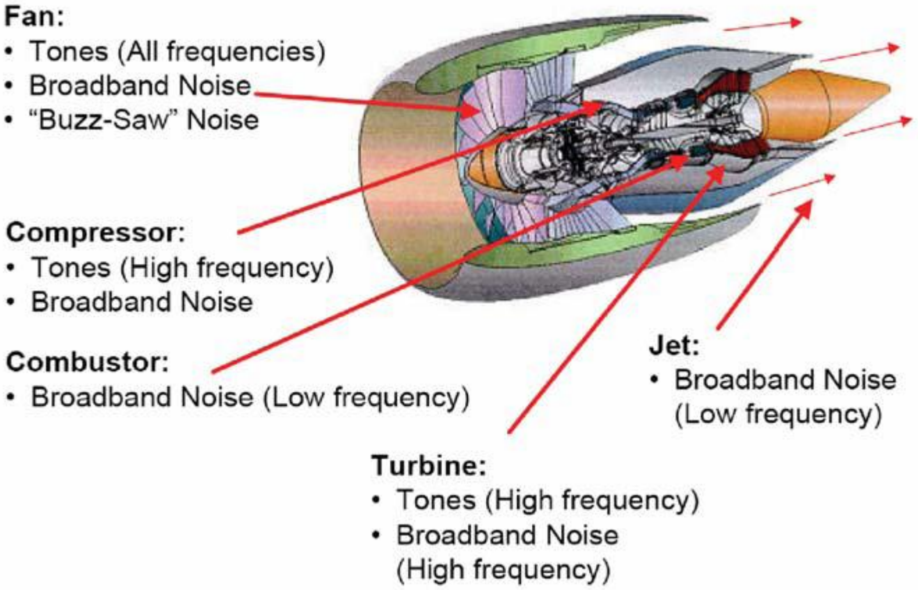


Figure 15 – Engine Noise Source Identification
Source: ICAO

Since the introduction of jet aircraft in the late 1950s and early 1960s about a 20 decibel reduction in perceived takeoff noise level has been achieved (Figure 13). Compared with early turbojets and first-generation turbofans, current-generation turbofans show an important decrease in total engine noise. In addition, the bigger advances in airframe and propulsion system designs (engine and nacelle), combined with improvements in aircraft performance have further contributed to reducing aircraft noise (figures 17, 18 and 19). Over the same period, the advances have also been made that reduced the noise of propeller-driven regional aircraft. Against the background of this significant progress on the way to reduced aircraft noise and in view of the predictable growth of the world aircraft fleet, manufacturers are committed to continuing their efforts to further diminish the impact of aircraft noise in and around the airport communities.

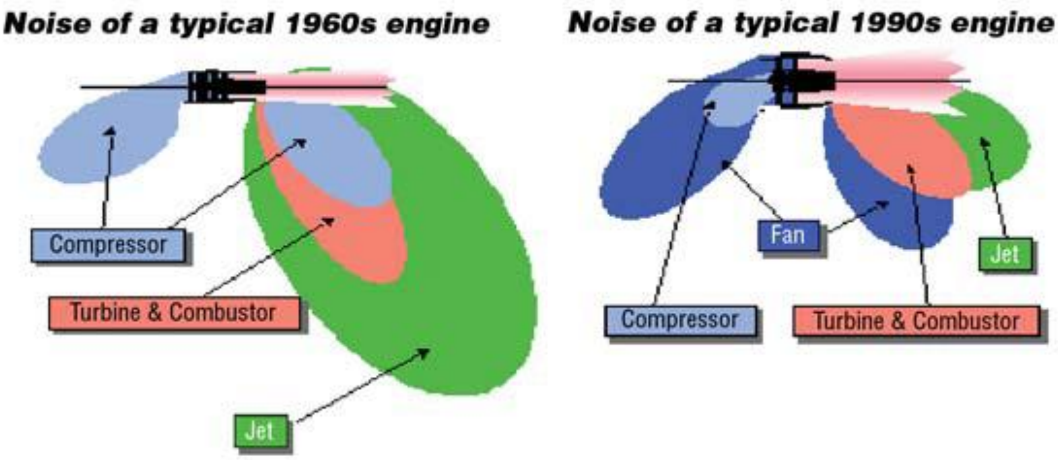


Figure 16 – Contrast of sound emissions between old and new gas turbine engines
Source: ICAO

Figure 17 – Jet Exhaust Noise Reduction
Source: Boeing

Aircraft operating restrictions have the potential to provide fast and significant reductions of noise around airports but they can also impose impacts and constraints that may influence other aspects of an airport’s operation (e.g. extra financial burden in operators, imposing fleet or route changes on other airports). Consistent with its goal of achieving maximum compatibility between the safe, economically effective and orderly development of civil aviation, and taking into consideration the quality of the environment ICAO advises his Contracting States not to introduce any operating restrictions at airports before undertaking a cost-effectiveness assessment of available measures to address the noise problem in accordance with the balanced approach.

Figure 18 – Blade configuration to reducing noise emissions.
Source: Rolls Royce

Figure 19 – Nacelle configuration designed to reduce noise emissions
Source: Boeing

2.3.1.1 - Noise Certification Reference Points - Defined

In noise certification, aircraft noise levels are measured at three certification points:

1- **Fly-over**: 6.5 km from the brake release point, under the take-off flight path;

2- **Sideline**: the highest noise measurement recorded at any point 450 m from the runway axis during take-off;

3- **Approach**: 2 km from the runway threshold, under the approach flight path.

Cumulative levels are defined as the arithmetic sum of the certification levels at each of the three points.

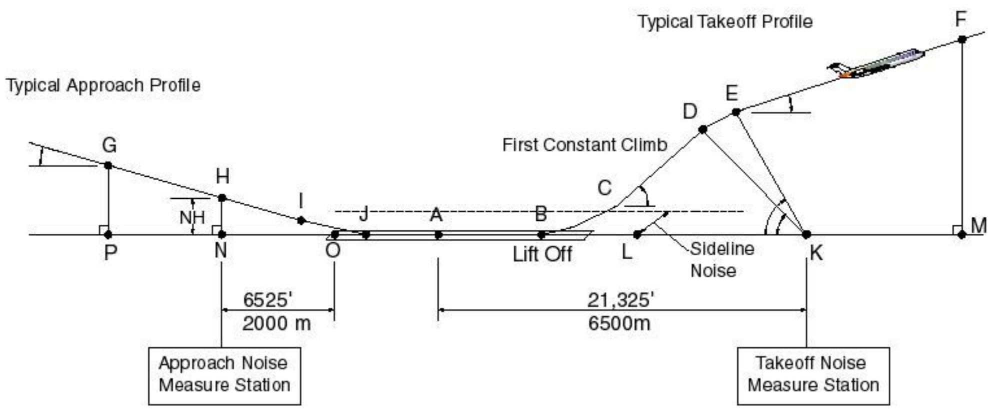


Figure 20 – Noise certifications reference points
Source: FAA

2.3.2 – Air Pollution

Once the primary report of ICAO's Annex 16, Volume II – Aircraft Engine Emissions was adopted in 1981, it pays attention on the control of aircraft engine emissions which were supposed as potentially affecting the air quality in the vicinity of airports. The subject of overall atmospheric pollution was not originally considered for aircraft engine certification. Based on the comprehension then available, the gaseous emissions determined to be in need of control were: oxides of nitrogen (NO_X), carbon monoxide (CO) and unburned hydrocarbons (UHC). Also designated for control was smoke, mostly for visual reasons at that occasion.

Review of Emissions:

A number of changes to the provisions of Annex 16 have been initiated since the initial issue of Annex 16, Volume II; for instance, permissible levels of the emissions, mainly NO_X have been made more stringent.

Oxides of Nitrogen:

The description "oxides of nitrogen" (NO_X) includes both nitric oxide (NO) and nitrogen dioxide (NO_2). Both compounds have historically been of concern for their relationship with ozone, but more recently there has also been concern about exposure to NO_2 in its own right. There may therefore be an emerging need to distinguish between the emissions of the separate types of oxides of nitrogen. Overall, much more NO_X is produced at high engine power than at idle, but the relative amounts of NO and NO_2 produced also vary with engine power. In general terms, at idle power, the majority of the NO_X produced is in the form of NO_2, while at high power settings, more NO than NO_2 is produced. Moreover, outside of the engine, in the exhaust plume, NO typically is oxidized in the atmosphere, often through reaction with ozone, to form NO_2. The situation has become even more complicated, however, since it has been discovered that the relationship between NO_X and ozone can be site specific.

This means that regulating engine NO_x output does not necessarily have the same, or even a direct, effect on the ozone concentration at all locations. It has always been understood that there are trade-off issues concerning engine emissions. It is known that NO_x is formed in the hottest parts of the combustion chamber and the production of NO_x can be reduced by keeping temperatures as low as possible and by keeping residence time at higher temperatures as low as possible also. However, for maximum thermodynamic efficiency, and consequently for lowest fuel consumption, high temperatures are very desirable. From the very beginning of emissions control efforts therefore, a balance has always been struck between reducing NOx and reducing fuel consumption. Originally, the pressure to minimize fuel consumption was economic, but today there is the added need to minimize fuel consumption in order to minimize emissions of the greenhouse gas carbon dioxide. It is also apparent now that there are trade-offs between NOx and particulate and hydrocarbon emissions.

Carbon Monoxide:

Carbon monoxide is formed as a result of incomplete combustion within the engine. It is unique in the list of emissions in that there have been no changes to its significance and it continues to be of relatively low importance compared with the other emissions.

Unburned Hydrocarbons:

Unburned hydrocarbons (HC) include a fairly long list of compounds, also arising from incomplete combustion within the engine. Some of these are now known to be highly toxic or carcinogenic with varying concentrations and exposure time, thereby summoning the need to distinguish between the different species. It is also apparent that for the identified species, as with species that comprise NOx, chemical interactions continue to occur in the exhaust plume. The implication in both cases is that measurement of emissions taken immediately downstream of the engine, as is now the practice for engine certification purposes may not be adequate for the purposes of evaluating all environmental impacts. Hydrocarbons (HC) and NOx are both known to be involved in producing ozone, but some studies have revealed that this also is a site-dependent effect. For example, in the vicinity of Los Angeles airport, analysis indicates that decreasing hydrocarbons decreases ozone in much of the eastern part of the LA basin, but decreasing NOx has little effect on ozone in the downtown area. In Pasadena meanwhile, decreasing airport NOx emissions initially increases ozone. This is another example of, why it is very difficult to draw any general conclusions concerning engine design measures which might be taken to trade off one type of emission against another.

As mentioned above, several different hydrocarbon compounds are emitted by an engine. Before any decision can be made concerning whether specific compounds need to be regulated, it is necessary to know what compounds are produced, how they react outside the engine with other emissions and/or ambient air chemicals, and what the ultimate environmental impacts are. After that, it will then be necessary to determine if such compounds can be included in a certification scheme. It is generally recognized that hydrocarbons produced by modern engines are minimal but as mentioned above, several different hydrocarbon compounds are emitted by an engine. It is necessary to know what compounds are produced, how they react with other emissions and/or ambient air chemicals and what the ultimate environmental impacts are. After these measurements and analysis have been completed it will be necessary to determine how such compounds should be handled in emissions inventories.

Smoke:

As mentioned above, smoke was originally controlled because of its appearance and the perception that it was undesirable. It was considered to be mainly a matter of visibility; and by that measure modern engines are essentially smoke-free. However, it is now known that the particulate matter that makes up smoke is still largely present in engine emissions, but reduced particle size makes it less visible than before. Particulate matter continues to be emitted by modern engines, but the particles are generally smaller in size and often fewer in number as well. In order to quantify the particulate emissions and to capture the trends as engine technology advances, measurements are now focusing on the total mass of particulate matter, along with a consideration of the particle size and number. Again, it is of interest to consider what is taking place in the engine exhaust plume. The particles leaving the engine are predominantly black carbon, but other primary particles, often too small to measure, may also be present; in addition to the precursor gaseous components which will later add to the particle mass. Apart from the NOx and CO, these gaseous components and smaller particles are volatile hydrocarbons and sulphur compounds. These volatile compounds can then condense into volatile particles downstream from the engine exhaust to form new particles of environmental concern. These same volatile species also condense on the existing soot particles, coating their surface. As with the NOx components, the quantities of these particles and volatile compounds vary with engine power setting in both absolute and relative terms. The proportion of volatile components is greatest at idle, while black carbon predominates at high power settings. The need to pay more attention to the size, number and composition of particles for health-related reasons is complicated by the difficulties encountered in trying to take the necessary measurements in the high temperature/high gas velocity environment at the engine exhaust plane. Furthermore, there is the complication that the volatile particles form downstream of the engine exhausts, and thus are not present where certification measurements are taken. Considerable research work is in progress to try to resolve these issues.

Sulphur:

Sulphur and its compounds have always been acknowledged as environmentally undesirable, but, since their presence in the exhaust was solely a function of their presence in the fuel, and was not affected by the design and operation of the engine, they were not regulated by Annex 16, Volume II, but were controlled through fuel specifications. It has been discovered, however, that if fuel sulphur content increases, not only does the concentration of sulphates in the exhaust increase, adding to volatile particle contributions as would be expected, but the amount of condensed hydrocarbons in those particles also rises in concert with the increase in the sulphate in the volatile particles. These results raise the possibility that engine technology may be involved in determining volatile particle contributions, in addition to the direct effect that fuel sulphur content has on the availability of sulphur to add to particle mass.

In the next figures we will see the advances before and after the restrictions on aircraft emissions and the percentage of NO_x all over the atmosphere.

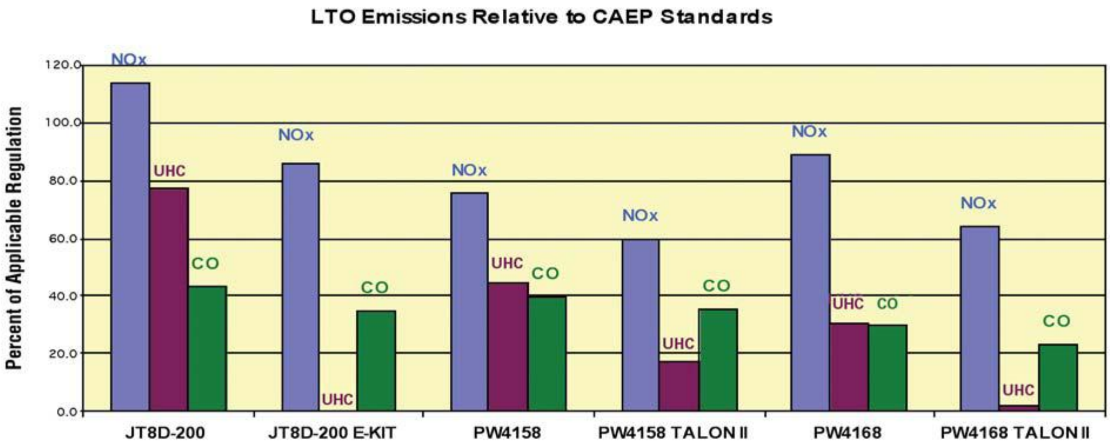


Figure 21 - Reductions in Pollutants from Aviation by Engine Type. After and Before CAEP. Source: Pratt & Whitney.

The subject of emission sources is a complex topic. This complexity is compounded by the fact that sources of airport emissions other than those associated with aircraft include ground support equipment (e.g. passenger buses, mobile lounges, fuel trucks, aircraft tractors, etc.), landside vehicles (cars, taxis, trains, etc.) and stationary power generation plants. This makes it difficult to determine the specific contribution of aircraft to the local air quality situation.

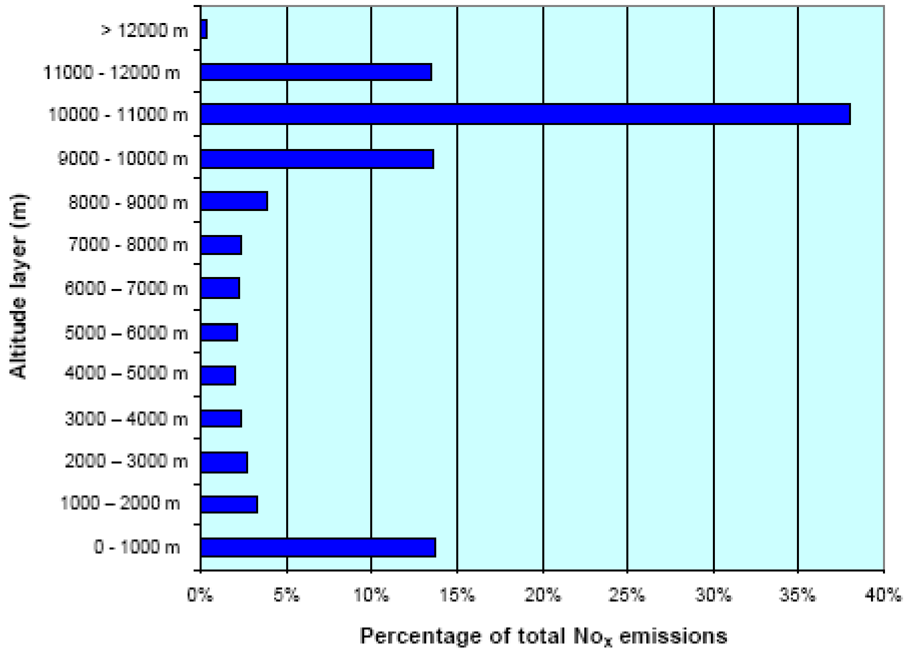


Figure 22 - Percentage of NO_x all over the atmosphere.
Source: IPCC

2.4 – New jet fuel

Alternative Fuels:

Currently, most civil aviation aircraft around the world use kerosene derived from on crude oil. This fuel provides a good balance of properties required for an aviation fuel, such as energy density, operational issues, cost and safety. Given these characteristics, aircraft operations and their supply infrastructures on the ground are fully adapted to its use. However, concerns over rising fuel costs, energy supply security, and the environment, have led to the need to investigate the development of alternative fuels. A viable alternative aviation fuel could offer important benefits such as stabilizing world fuel price fluctuations and reducing the uncertainty and vulnerability that comes from too much reliance on crude oil as the one main fuel source. In addition, alternative fuels could increase the environmental performance of air transport, allowing it to substantially reduce CO_2 emissions. Aircraft and engine manufacturers are currently investigating synthetic jet fuels (e.g. from coal, natural gas, or other hydrocarbon feedstock) as well as bio-fuels. The type of fuel that is of immediate interest to aviation is termed a “drop-in” fuel, (i.e. a direct substitute fuel) that can be used without substantial modification to engine or aircraft (see articles on Alternative Fuels later in this Part of the report).

Evolution of Alternative Fuels:

• **Present and short-term** - synthetic jet fuel processed using the Fischer-Tropsch process.

• **Medium-term** – possible use of bio-fuels with necessary changes in the engine configuration.

• **Longer-term** - cryogenic hydrogen and liquid methane are being considered, but a number of technological challenges have to be solved prior to their use.

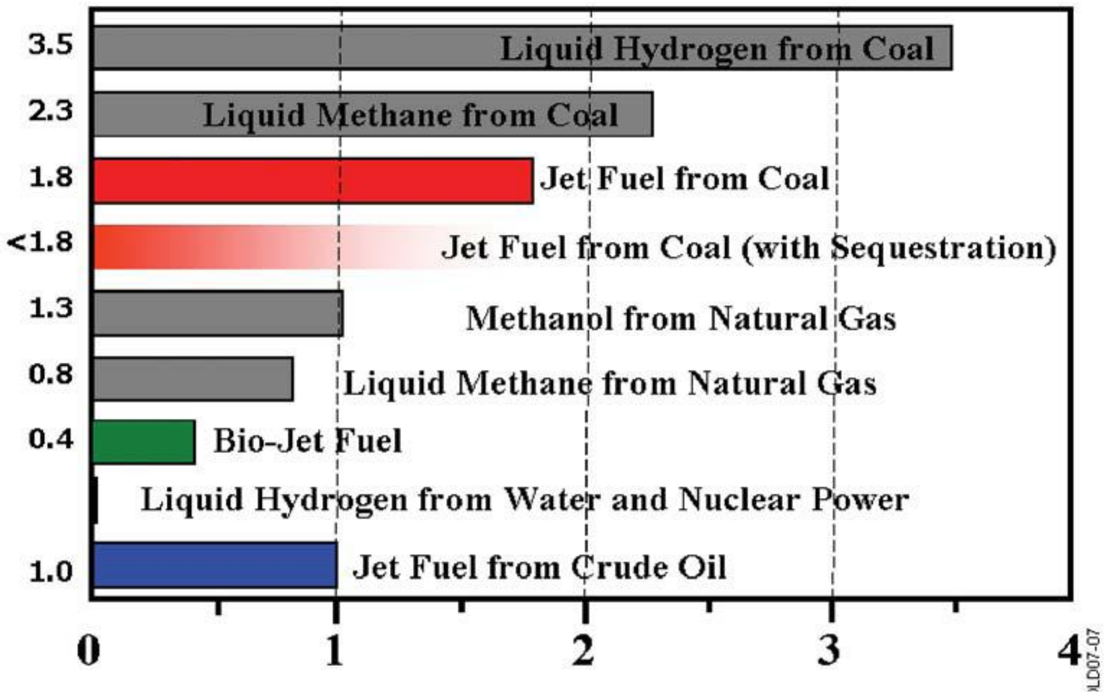


Figure 23 – Relative CO2 emissions as compared to jet fuel
Source: SAE

Further steps on Global Emissions:

Among the main issues considered by ICAO/CAEP during the last CAEP meeting in

February 2007, were the assessment of the evolution of emissions over the years and future trends; and items related to market-based measures to reduce emissions, such as aviation emissions trading. Much effort is being channeled to the modeling activities and to the better understanding of the interdependencies of actions to reduce aviation emissions. All the work done by ICAO/CAEP and the information accrued from the scientific advances in the understanding of aviation impacts on the environment will be brought to the attention of the next ICAO Assembly.

Chapter 3

Methodology

3.1 - The Main Program

As stated in the course of the chapter one, this software is the development of a method of accounting for emissions conducted by one (or several) aircraft in a given cycle of LTO. The time for each phase within that cycle may be pre - defined or adapted to each situation.

The entire program was developed in the programming language "Fortran". The databases are taken from reports of the ICAO and adapted to the purposes required. The bases were prepared in Microsoft Office (Excel) and subsequently converted into xxx.dat files so that they can be recognized by the program.

The development of the program has a structure in blocks in order to be easily modified or adapted without losing sight the main structure. The blocks that comprise the program are: Aircrafts, LTO, and engines.

The final results or (outputs) are in xxx.dat so that they can be printed. These results can be presented to an aircraft or if it is necessary to conduct the test for the various aircraft program provides for the total group of aircraft of the same type and the overall result of all aircraft.

3.2 - The databases

The database used to make the program was the ICAO Engine Emissions Databank (Version of 05 February 2009) available from CAA (Civil Aviation Authority – United Kingdom). This information in the databank was obtained from engine manufacturers by the ICAO Committee on Aviation Environmental Protection (CAEP).

This database is composed of about 400 engine types and defines not only the emissions of each engine, as divided in steps of LTO. Also shown is the maximum available thrust of each engine. These databases show as the versions of various engines and if they still continue to be manufactured.

These same data bases were collected that were found necessary as the different engines, its unique ID, and their emissions per phase of LTO. After that, they were ordered and prepared to form a table in Excel.

Once developed, the database in Excel data was converted into a file of type xxx.dat, in order to be recognized in "Fortran" program and be utilized in further calculations.

Once created the first file with, engine, fuel flow and polluters, has been created a file in which be related aircraft with their engines. In this file would also include the number of engines for each aircraft. This information was obtained on the websites of the manufacturers as well as regulators.

3.3 - The structure

As mentioned earlier this program was established in blocks to make everything much simpler and easy to change (figure 26). The subroutines that were created are LTO, Aircrafts, and Engines.

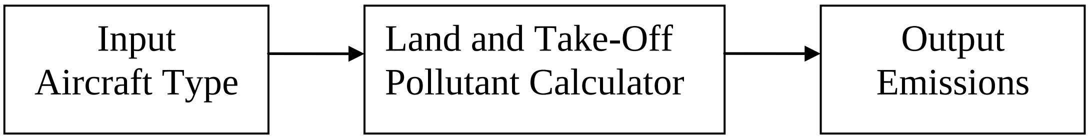


Figure 24 – Program configuration

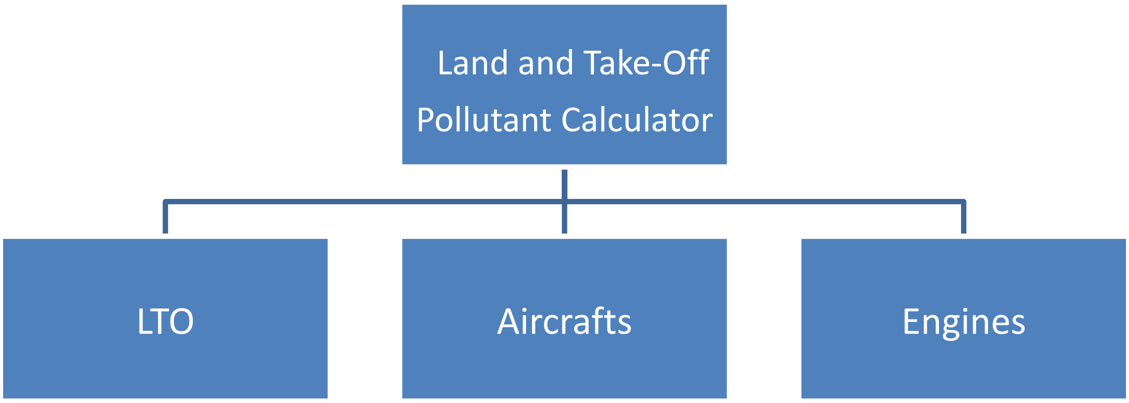


Figure 25 – Program elaboration in blocks.

In LTO subroutine the program user can make an option between LTO times (which is predefined with LTO standard times by ICAO) and introduce the time in minutes by each phase of LTO.

In Aircrafts subroutine the user can chose an aircraft (or more than one) between 67 (71 was the number of aircrafts but this work does not include turboprop engine emissions). This subroutine relates the aircraft type chosen by the user and gives the engine type and the number of engines of that type in the aircraft.

The engines subroutine read the information of the aircraft engine, and gives to the main program the rates of emissions and the specific fuel consumption of that engine.

Finally the main program joins all the data and makes the calculation of spent fuel and the emissions in this LTO cycle.

Equations used:

Emissions of CO:

$$\mathrm{CO} = \big(\mathrm{COAP} \times \mathrm{FFAP} \times (\mathrm{TMAP} \times 60) + \mathrm{COID} \times \mathrm{FFID} \times (\mathrm{TMID} \times 60) + \mathrm{COTO} \times \mathrm{FFTO} \times (\mathrm{TMTO} \times 60) + COCL \times FFCL \times TMCL \times 60 \times \mathrm{NENGINES} \qquad (1)$$

Emissions of CO2:

$$\mathrm{CO2} = \big(3.1564 \times \mathrm{FFAP} \times (\mathrm{TMAP} \times 60) + 3.1564 \times \mathrm{FFID} \times (\mathrm{TMID} \times 60) + 3.1564 \times \mathrm{FFTO} \times (\mathrm{TMTO} \times 60 + 3.1564 \times FFCL \times TMCL \times 60 \times \mathrm{NENGINES} \qquad (2)$$

Emissions of HC:

$$\mathrm{HC} = \big(\mathrm{HCAP} \times \mathrm{FFAP} \times (\mathrm{TMAP} \times 60) + \mathrm{HCID} \times \mathrm{FFID} \times (\mathrm{TMID} \times 60) + \mathrm{HCTO} \times \mathrm{FFTO} \times (\mathrm{TMTO} \times 60) + HCCL \times FFCL \times TMCL \times 60 \times \mathrm{NENGINES} \qquad (3)$$

Emissions of NOx:

$$\mathrm{NO} = \big(\mathrm{NOAP} \times \mathrm{FFAP} \times (\mathrm{TMAP} \times 60) + \mathrm{NOID} \times \mathrm{FFID} \times (\mathrm{TMID} \times 60) + \mathrm{NOTO} \times \mathrm{FFTO} \times (\mathrm{TMTO} \times 60) + NOCL \times FFCL \times TMCL \times 60 \times \mathrm{NENGINES} \qquad (4)$$

Emissions of SO2:

$$\mathrm{SO} = \big(0.1 \times \mathrm{FFAP} \times (\mathrm{TMAP} \times 60) + 0.1 \times \mathrm{FFID} \times (\mathrm{TMID} \times 60) + 0.1 \times \mathrm{FFTO} \times (\mathrm{TMTO} \times 60) + 0.1 \times FFCL \times TMCL \times 60 \times \mathrm{NENGINES} \qquad 5$$

3.4 - The output results

The final results are shown initially to the user and subsequently recorded for a file type xxx.dat so that it can be seen or printed.

The output results describe:

- Aircraft type, engine type of the aircraft, and the number of engines.
- The emissions of CO, CO_2, HC, NO and SO_2.
- The fuel burned.

If we need, we could make the calculations for more than one aircraft at the same time and the results are showed by aircraft type and in the final of the document we have the sum of all emissions.

Chapter 4

Discussion, analysis & interpretation of the data

Now is showed the example of Lisbon International Airport. According to the files provided by ANA - Airports of Portugal we will then conduct a practical demonstration of our program. In this example we begin by calculating the pollution emitted in one day, and in one month. We calculate the one day of of January, after the month of January 2009. After that we calculate the same day and month but in different way, will be conducted a contrast with the standard LTO times and the average time from the report of the Agency of Environment (Torres, Pedro. 2008) showed in chapter 2. The data used for this practical example are in Annex A.1.

Using LTO standard times the results for one day were:

Emissions of CO…………………….…………2 995 862 grams

Emissions of CO2……………………..952 249 500 grams

Emissions of HC…………………….…..…….333 171 grams

Emissions of NO…………………….….……3 849 571 grams

Emissions of SO2…………………….……….301 688 grams

Fuel Burned…………………….………...301 688 468 grams

Using medium LTO measured times the results for one day were:

Emissions of CO…………………….……….……1 842 481 grams

Emissions of CO_2……………………..……..788 004 250 grams

Emissions of HC………………….…………...209 502 grams

Emissions of NO………………….…..………3 635 464grams

Emissions of SO_2……………...……………..249 653grams

Fuel Burned…………………..…………249 653 859grams

Using LTO standard times the results for one month were:

Emissions of CO…………………………103 339 008 grams

Emissions of CO_2………..…………..30 833 934 000 grams

Emissions of HC…………….…………….13 094 175 grams

Emissions of NO………….……..………124 591 048 grams

Emissions of SO_2………..……..…..………9 768 703 grams

Fuel Burned………………...……..…...9 768 703 000 grams

Using LTO measured times the results for one month were:

Emissions of CO…………………………63 329 392 grams

Emissions of CO_2…………………..25 548 772 000 grams

Emissions of HC…………………...…….8 110 736 grams

Emissions of NO……………...………117 730 232 grams

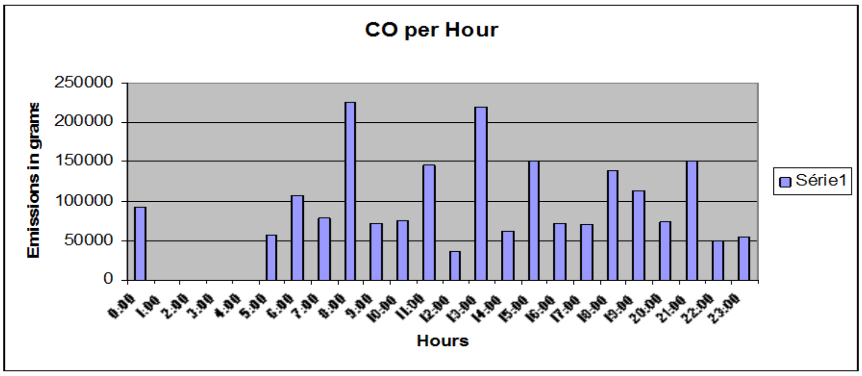
Emissions of SO_2…………….…..………8 094 276 grams

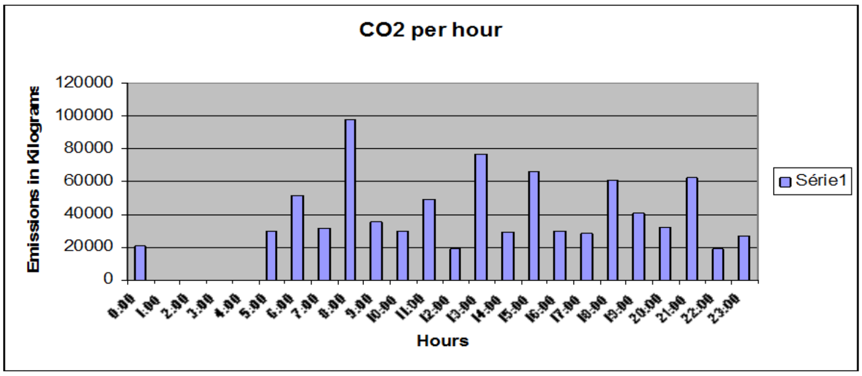
Fuel Burned……………………..…...8 094 276 000 grams

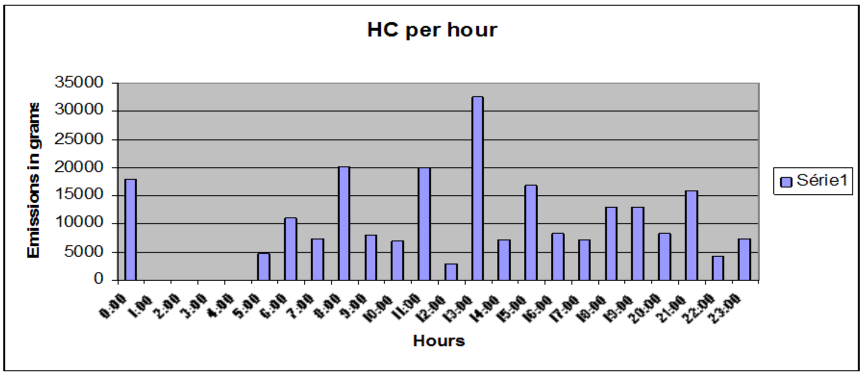
After make a comparison between emissions from an LTO cycle with standard times and measured times we have the following conclusion:

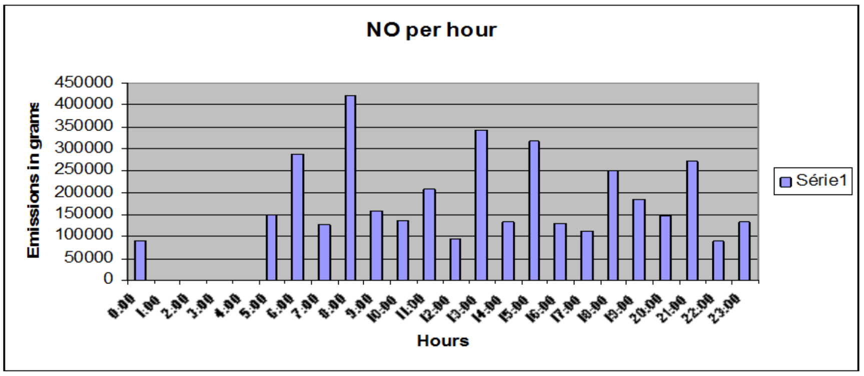
In this case, Lisbon is exposed to least near 38 percent of CO and HC, less 6 percent of NO and least near 17 percent of fuel consumption, CO_2 and SO_2. This is significant values when we talk about the environment. The airports where the aircrafts takes LTO times greater those ICAO standard times will produce more amounts of polluters. This alteration could be caused by delays, turnarounds or holdings.

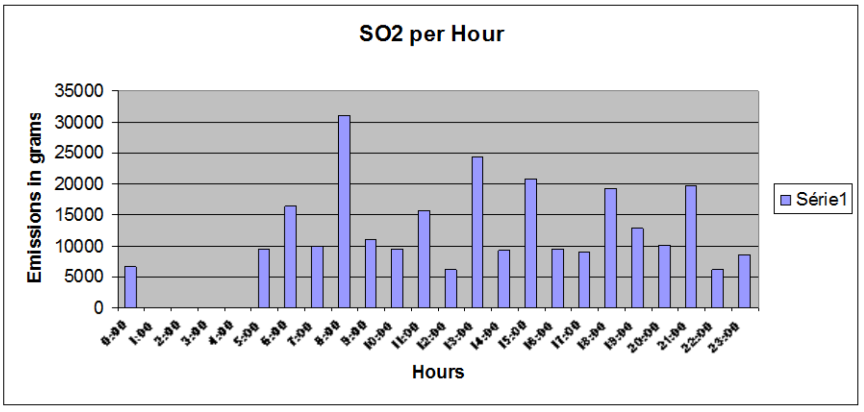
The graphs below were prepared based on flights on 18 January 2009 and may subsequently be used to determine if emissions exceed the limits imposed by law.

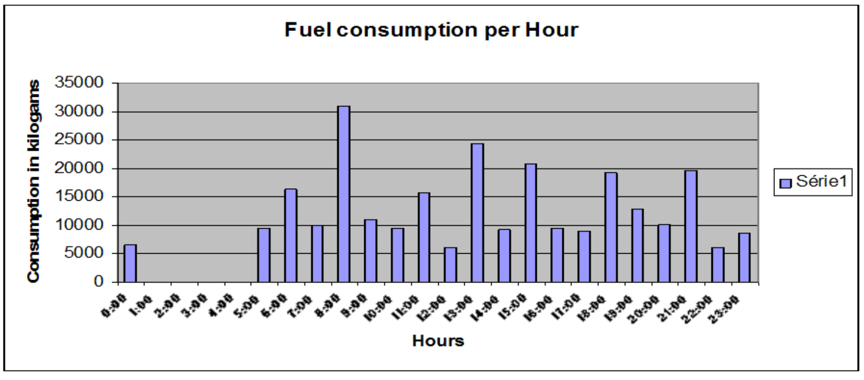





HC per hour
Emissions in grams
35000
30000
25000
20000
15000
10000
5000
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Hours
Série1


NO per hour
Emissions in grams
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Hours
Série1


SO2 per Hour
Emissions in grams
35000
30000
25000
20000
15000
10000
5000
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Hours
Série1


Fuel consumption per Hour
Consumption in kilograms
35000
30000
25000
20000
15000
10000
5000
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Hours
Série1

Chapter 5

Conclusions and further research

After the development of this program and all the research done, we can conclude that this program is very useful for airports and other organizations to calculate emissions of gas turbine engines during an LTO cycle. It was also proved that the tables created for each aircraft emissions by ICAO may serve as a model, but are not applicable in real cases. That's because each airport has his time for the different phases. Even if we focus in only one airport these times can diverge as the aircraft are constantly subject to advances or delays in schedule due to several factors. These may arise from a simple delay of a passenger to the waiting time for takeoff or land at a busy airport.

The program is developed in modules (aircraft, engines, and LTO times) to ensure that corrections or changes, as it upgrades, can be made without changing his main structure. Other important aspects of this program are: the fact that the database be established in Office (Excel) and converted to «xxx.dat files», and that we can make the calculation of one or several aircraft at once and can set the time of the LTO phases (landing, taxi, take-off and climb) for each aircraft, and finally, the results appear in xxx.txt file showing not only the total values of pollution but also for each type of aircraft too.

Recommendations

In future, the program can be adapted to recognize the times of arrival and departure of aircraft considering the delays on take-off. It may also create a database that links the pairs “origin-destination" with the aircraft and consequently calculate the emissions without the need to introduce the models of aircraft. It could as well set up an extra module in order to consider the emissions of other vehicles related to the aircraft operations like: catering, refueling, road traffic and the trolley cars. Another thing that could be done is an adaption for Visual Basic in order to be easier to handle for a common user.

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Annex:

A.1

Movements in one day (18 January 2009) and movements in one month (January 2009):

The aircraft in red were not counted because they do not have gas turbine engines.

A319	118
A320	108
A321	24
ERJ-145	22
Beech 1900D	15
Fokker 100	12
A310	10
A330-200	10
B757-200	10
B737-300	8
A340-300	6
B737-800	6
B737-700	4
Cannadair 200	4
DO228	4
ATR-42	3
B747-400	2
ERJ-135	2
	366

A320	3291
A319	3116
ERJ-145	747
A321	600
Fokker 100	450
A332	413
A310	398
Beech 1900D	353
B737-700	230
B737-800	195
A340-300	177
ERJ-135	171
B737-300	167
B757-200	145
B737-400	127
ATR-42	98
DO228	82
A318	51
B747-400	48
A30B	47
B767-200	44
A306	22
F2TH	22
H25B	17
B737-900	16
Cessna 550	13
BE40	10
Cessna 560	10
Cessna 56X	9
Falcon 900	9
Learjet 31	9
	11087