THE IMPACT OF AIRCRAFT WEIGHT ON AIRCRAFT TAKE-OFF EMISSIONS

Nicolas DUCHÊNE
ENV-ISA, Paris.
EUROCONTROL Experimental Centre, Brétigny-sur-Orge.

1. INTRODUCTION

1.1 Airport Air Quality Background

The European Environment Agency (EEA) recognized that "aviation is the fastest growing transport mode in Europe" and that it is an important and growing contributor to climate change: "its climate impacts will soon exceed those of passengers' vehicles and by 2030, the impact is predicted to be twice as large" (EEA, 2003 & 2004). According to EUROSTAT, the number passengers transported by air in the European Union 25 (EU25) grew by 8.8% in 2004, to reach 650 millions (EUROSTAT, 2006). The immediate consequence of such intensification of air traffic is a greater stress on the environment. Not only do aircraft emissions in-flight contribute directly to global warming due to CO_2 emissions, but they also have an indirect effect through the formation of condensation trails (contrails) and increased formation of cirrus clouds (EEA, 2004). Additionally, a direct consequence of the growth in air traffic is a rise in aircraft emissions in the vicinity of airports, i.e. where its effects on human health are greatest.

The EEA stated recently (EEA, 2005) that "air pollution is the environmental factor with the greatest impact on health in Europe and is responsible for the largest burden of environment-related disease". A recent estimation indicated that 20 million Europeans suffer respiratory problems every day (EEA, 2005). Combining these facts with the constant growth in air traffic in the last decade it is clear why local air quality is becoming an increasingly important issue for airports, particularly if the expansion of the airport is needed.

The increasingly stringent air quality standards mean that the methods for measuring and predicting the air quality near airports must strive to be more and more accurate. In this context the EUROCONTROL Airport Local Air Quality Studies (ALAQS) project contributes to international efforts to harmonise airport air quality modelling worldwide through contributions to ICAO CAEP (International Civil Aviation Organization Committee for Aviation Environmental Protection) and AERONET. The project has provided a test-bed toolset that can be used to demonstrate the different emissions inventory methodologies through case studies at different airports with the aim of converging to best practice methods.

1.2 Study Background

Aircraft emissions calculations in this study are based on the ICAO defined LTO cycle (Landing and Take-off) and on ICAO emission certification data. The LTO cycle covers operations below the mixing height, generally assumed to be 3000 ft altitude above ground level (AGL), although the true mixing height varies seasonally and from airport to airport. NOx, HC, CO and fuel flow are reported for take-off (TO), climb-out

(CL), approach (AP) and taxi (TX) engine throttle settings. Finally, for calculating emissions, the ICAO method assumes times-in-mode (TiM) and engine settings for each segment as detailed in Figure 1 and Table 1. This paper examines the limitations of the standard ICAO LTO cycle when applied to Local Air Quality modelling and discusses the impact of Take-off weight on the emissions inventory.

Modelling of civil jet aircraft engine emissions have been, until now, ruled by certification methodologies defined in 1981 (Lister, 1003).. These international emission standards were established by the International Civil Aviation Organization (ICAO) and are set out in Annex 16 Volume II. While the standards are reviewed on a regular basis (e.g. the NO_x values have been amended twice since 1981) the underlying technical basis has remained unchanged. The procedures require aircraft and engines to undergo a type test certification at specified thrust settings before entry into service. The resulting engine emissions are entered into the ICAO engine emissions database, making the database the most complete publicly available databases of aircraft emissions. Consequently, it is commonly used for calculating aircraft emissions even though the ICAO Engine Exhaust Emissions Data Bank has been primarily developed for certification rather than for emission evaluation purposes, which induces limitations discussed later in this paper.

The reference LTO (Landing and Take-off) cycle is defined based on four specific thrust levels corresponding to nominal Arrival/Departure modes:– Taxi-in/out, Take-off, Climb-out, Approach and covers emissions produced by moving aircraft from ground level up to 3000ft as shown in Figure 1. Specific operating times for each operating mode have been defined by the ICAO (Table 1).
The standard ICAO LTO emission calculation uses the reference LTO cycle and the emission factors and fuel flow from the ICAO emissions factors database. For the appropriate aircraft / engine combination, the sum of the four LTO modes products of time-in-mode x fuel flow x emission index is calculated.

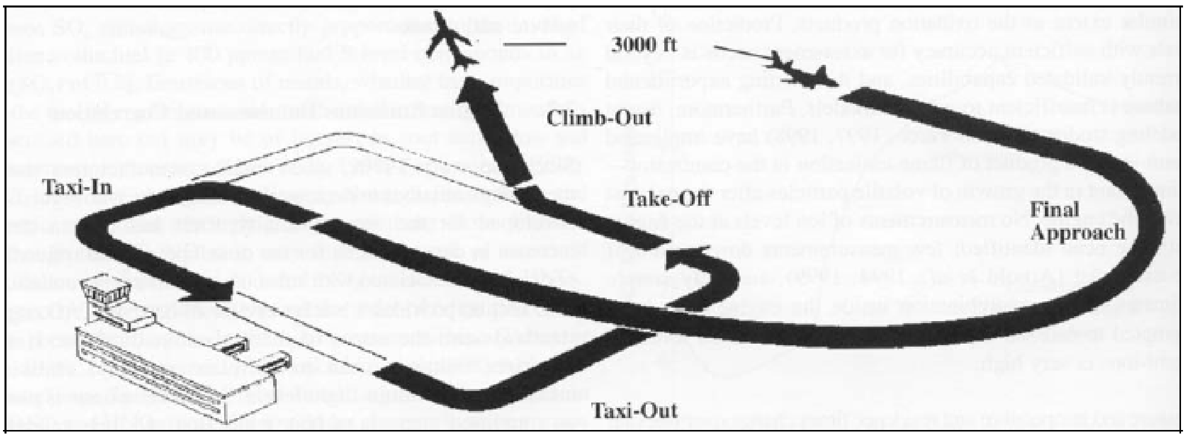

Figure 1: ICAO reference LTO cycle (from Fleuti, 2004)

The different modes are not described with more detail. Operational factors such as aircraft weight, pilot operating procedures (e.g. noise trajectories or derate thrust) are not accounted for. The variability of aircraft operations resulting from the range of situations that can be encountered depending on the aircraft; airport or airline of interest is not considered in the ICAO reference LTO cycle. However, it is possible to determine more detailed times-in-mode to allow for more precise results. This is the objective pursued in this study which analyses the impact on emissions of various take-off weights for departing aircraft with the intention of calibrating emission modelling tools.

Table 1: ICAO reference LTO cycle for calculating aircraft emissions.

Operating mode	Thrust Setting (% of full thrust)	Time in operating mode (minutes)
Take-off	100 %	0.7
Climb-out	85 %	2.2
Approach	30 %	4.0
Taxi / ground idle	7 %	26.0

The ICAO LTO is a useful baseline but it does not reflect real operations and can lead to inaccurate estimation of aircraft emissions as reported by various ALAQS reports (Celikel, 2004) and by Fleuti (Fleuti, 2004). The ICAO LTO Take-off mode defines 100% rated thrust (maximum thrust available for take-off under ISA conditions). Whilst 100% thrust take-offs need to be regularly demonstrated for safety purposes (once every 5 to 10 days depending on local regulations) most take-offs will be made with reduced or\derated thrust to reduce engine wear and tear if the conditions permit (runway length and condition. take-off weight, meteo).
Consequently, from a modelling point of view, the ICAO LTO cycle should be redefined for accurate modelling of emissions that reflect how aircraft are actually operated at a given airport. However, the standard LTO endorsed by ICAO is useful in other contexts, e.g. emissions charges, so the standard cannot be changed without careful consideration of the consequences.

The next section of this paper explains the tools used and the methodology chosen to compare the take-off and climb-out emissions for the most common aircraft types at different take-off weight. The results of the comparison are then discussed, and in conclusion some future axes of research are highlighted.

2. TOOLS AND METHODOLOGY

The aircraft emissions have been calculated using the EUROCONTROL ALAQS-AV tool (Celikel, 2005), The detailed aircraft profiles from which emissions are derived originate from the INM 6.1 tool (Integrated Noise Model), a Federal Aviation Administration (FAA) model for evaluating aircraft noise around airports. The particular interest in the INM profiles resides in that each aircraft type has a set of climb-out profiles to account for the variability in aircraft take-off weight. Moreover, the interest for joined noise and emission studies (i.e. tradeoffs studies) is expected to increase in the near future therefore it is important to investigate the use of noise profiles to conduct emission calculations. The ALAQS-AV and INM tools are described in more details thereafter.

Aircraft emissions calculations presented in Table 3have been performed according to the following equation and summed up for the two modes considered (take-off and climb-out):

$$\textbf{Emissions}_{\textbf{mode}} = \textbf{TiM}_{\textbf{mode}} \textbf{ x Emission Factor}_{\textbf{mode}} \textbf{ x Fuel Flow}_{\textbf{mode}} \textbf{ x Nber of engine}$$

2.1 Description of the Computer Programs Utilized

Airport Local Air Quality Studies – Arc View (ALAQS-AV)

The Airport Local Air Quality Studies (ALAQS) project was initiated by EUROCONTROL Experimental Centre in 2003 to answer to the growing need for environmental tools specific for the aviation sector. The ALAQS-AV tool has been developed and it is an emission inventory tool specialized for airports air quality evaluation. It includes databases from a wide range of sources (international and European organizations; manufacturers, airport operators…) and its embedment within a Geographical Information System (GIS ArcView 9.1) allows for a very fine geographical description of the airport's emission sources. The main objective of the ALAQS project is to harmonise the methodologies for estimating airport air quality in Europe and to issue best practices to following in that field (Celikel, 2005).

Integrated Noise Model (INM)

The FAA INM tool evaluates the impact of aircraft noise in the vicinity of airports since 1978. It is used for assessing the noise impact due to new or extended runways configurations depending on traffic and fleet mix (new or old) and it can also evaluate the impact of new operational procedures. The results in the form of noise contour maps can easily be exported to commercial GIS software. The profiles and procedures used for estimating aircraft noise in INM are based on several guidance documents published on behalf of the Society of Automotive Engineers (SAE), and especially the SAE-AIR-1845 report entitled "Procedure for the calculation of airplane noise in the vicinity of airports" (FAA, 2006). The version 6.1 of INM has been used to extract the aircraft profiles which are used to calculate emissions in this study.
It is important to notice that INM uses the concept of 'stage length' to emulate take-off weight. Any given aircraft type can have several vertical profiles (departure/arrival) which approximate its weight.

2.2 Aircraft / Engine Combinations Under Consideration

The choice for the aircraft of interest in the study is based on the JP Fleet 2004 Database which consists of a list of all the commercial aircraft worldwide, together with the individual aircraft registration number and the engine(s) they are fitted with. The most used aircraft in JP Fleet (December 2004 version) which have a match in the INM 6.1 tool have been chosen to perform the emission comparisons. In addition to that, the aircraft grouping from the German AzB (Anleitung zur Berechnung von Fluglarm – Guidance on the computation of aircraft noise) has been used in order to consider different categories of aircraft according to their engine properties (jet, propeller…) and their size. As a result, the following list of aircraft formed the basis to compare take-off emissions.

Table 2: Aircraft / engine combinations used for the emission comparisons.

AzB category	Identifier	Aircraft Name	Engine Fitted	Max Take-off Weight (tonnes)	Nber of profiles in INM
Jet Business	YK40	Yakovlev Yak 40	D-36	16.7	1
Jet Small	A320	Airbus A320	V2527-A5	74.3	5
Jet Regional	T134	Tupolev Tu134	D-30 (II series)	48.5	3
Jet Medium	B763	Boeing 767-300	PW4060	174.7	7
Jet Large	B744	Boeing 747-400	CF6-80C2B1F	390.2	7
Propeller	C206	Cessna U206A Super SkyWagon	TIO-540-J2B2	1.6	1
Turboprop	C160	Transall C-160NG	TYNE	49.0	2

The emission indices and fuel flow for aircraft engines are obtained from the publicly available ICAO Engine Exhaust Emissions Data Bank Issue 14 for jet engines and from AP-42 Table II-1-7 for turbofan engines.

2.3 Aircraft Profiles in ALAQS-AV

Aircraft profiles in ALAQS-AV are described point by point, the initial point corresponding to the aircraft idling at the beginning of its take-off roll and the last point considered for emission calculation being at 3000 ft. For each point of the trajectory, the following information are needed:

- Horizontal distance from the starting point (m)
- Vertical height at the point of interest (m)
- True air speed (m/s)
- Effective net engine thrust from INM profiles
- ICAO power engine mode (matching with ICAO LTO cycle modes)

The operational thrust is not actually used in the emission calculations, since the emission indices are obtained on an engine mode basis according to the ICAO definition. However, since a method based on operational thrust levels is expected in the near future to derive more detailed emission factors, the operational thrust is included in the ALAQS-AV profiles in harmony with the INM profiles.

Another question of specific interest is the definition of the take-off mode: at which altitude does the thrust cut back from take-off to climb-out occur? It has been declared by the ICAO CAEP (Committee on Aviation Environment Protection) that a suitable altitude for thrust cut back (for emission modelling purposes) is 1000 ft (304.5 m) (ICAO CAEP, 2003). Consequently this limit for the take-off mode has been considered in the default ALAQS-AV profiles. In addition, a common limit height of 3000 ft is generally accepted as a limit up to which airport local emissions occur. Therefore the ALAQS-AV profiles stop at 3000 ft (914.5 m) in the study presented here.

Finally it is worth noticing that a limitation concerning the INM profiles is that they have been specifically derived to estimate noise contours and therefore caution is needed when using them for emission calculations. This is the reason why the times-in-mode for the various profiles are compared with operational times-in-mode from real flown trajectories in a matter of validating them. However this analysis was only feasible for A320 aircraft due to a lack of available data for other aircraft.

2.4 Pollutants of Interest for the Present Study

All the pollutants in the ICAO Engine Exhaust Emissions Data Bank are then considered in the study (CO, HC, NO_x and PM_{10}). The method to derive PM_{10} emission factors from the ICAO SN (Smoke Number) is referred by the ICAO as first order approximation version 2.0 (ICAO CAEP, 2005). This method is quite conservative since the maximal smoke number was used to derive the PM_{10} emission index instead of detailed mode specific SN because it was not available in the ICAO Engine Exhaust Emissions Data Bank.

2.5 Aircraft Profiles Compared

In the following section, the emissions due to the minimum take-off weight (TOW) and the maximum TOW profiles are compared for each aircraft. The effect of TOW on the take-off emissions for CO, HC, NO_x and PM_{10} are then analysed. In a matter of achieving the best compliance with operational profiles, two distinct cases for the definition of the take-off mode are discussed: in the first one the thrust cut back (i.e. engine mode from take-off to climb-out) occurs at 1000 ft (ICAO CAEP, 2003) and in the second case the take-off mode stops as soon as the aircraft wheels' off (European Commission, 2001). Finally, the times-in-mode resulting from the simulations are compared with times-in-mode from real operations for A320 aircraft to evaluate the reliability of the INM profiles when dealing with emissions calculations.

3. DISCUSSION OF THE RESULTS

3.1 Case 1: Thrust cut back occurs at 1000 ft

The results from the calculations are reported in details in Table 3. For each aircraft, the emissions due to the minimum and maximum TOW are reported as well as the emissions resulting from the ICAO LTO methodology with the times-in-mode from Table 1 and the emission indices from the engines in Table 2. Emissions of CO, HC and NO_x are expressed in kilograms while emissions of PM_{10} are in grams.

It is remarkable in almost all cases the emissions computed with the ICAO LTO method are greater than the ones from the INM maximum TOW profiles (Table 3). The only exceptions concern the B744 and the C160 for which the ICAO LTO method gives a smaller estimate (10% to 20% for all pollutants). The overestimation of most results from the ICAO LTO cycle is not surprising as it is widely reported in the literature (European Commission 2001, Lister et al., 2003, Schäfer 2003, Fleuti et al., 2004).

Table 3: Emissions from INM profiles and ICAO LTO method (case 1).

	TOW (t)	CO (kg)	HC (kg)	NO_x (kg)	PM_{10} (g)	Horizontal extent of the emissions (km)
A320	61.5	0.10	0.01	4.54	22.38	7.43
	73.5	0.13	0.01	5.79	28.39	9.92
	ICAO LTO	0.19	0.01	7.52	40.18	
B744	259	0.44	0.07	21.85	68.87	8.60
	382.4	0.78	0.12	39.45	123.18	19.69
	ICAO LTO	0.73	0.12	32.05	114.20	
B763	120	0.16	0.03	11.10	40.28	6.82
	246	0.25	0.04	17.13	62.69	11.86
	ICAO LTO	0.36	0.04	20.89	83.68	
C160	59.9	0.04	0.10	0.93	n/a	9.86
	70.3	0.07	0.14	1.36	n/a	15.6
	ICAO LTO	0.06	0.12	1.13	n/a	
C206	1.4	6.67	0.07	0.00	n/a	6.06
	ICAO LTO	6.99	0.07	0.00	n/a	
T134	42.4	0.66	0.03	4.17	309.69	8.46
	50.8	0.87	0.04	5.46	406.11	11.92
	ICAO LTO	1.08	0.05	6.04	497.12	
YK40	14	0.08	0.00	4.49	57.19	8.43
	ICAO LTO	0.12	0.00	6.72	89.23	

A comparison of the emissions calculated based on operational times-in-mode recorded in flight and using the ICAO LTO for various aircraft types (from A319 to B767) showed that on average the ICAO LTO NO_x emissions corresponding to the take-off and climb-out modes are higher than the operational ones by 27% (Fleuti et al., 2004). In Table 3 the difference between ICAO LTO NO_x and INM minimum TOW profiles NO_x was in average 32% which proves that the INM profiles can be used to model aircraft operations in a more reliable way than the ICAO LTO method. On the contrary the INM maximum TOW profiles are likely to give higher estimates of the pollutants emitted by aircraft so their use for emission calculations should be restrained.

Another difference between the minimum and maximum TOW is the extent of the area over which the pollution is dispersed. In the worst case (Boeing 747-400), the distance over which emissions occur is more than doubled: from 8.60 km to 19.69km as shown in Figure 2. In general, the distance flown by aircraft to reach the limit altitude of the study of 914.4m is between 35% (A320) and 75% (B767-300) longer when it is flying at its maximum TOW rather than at its minimum TOW.

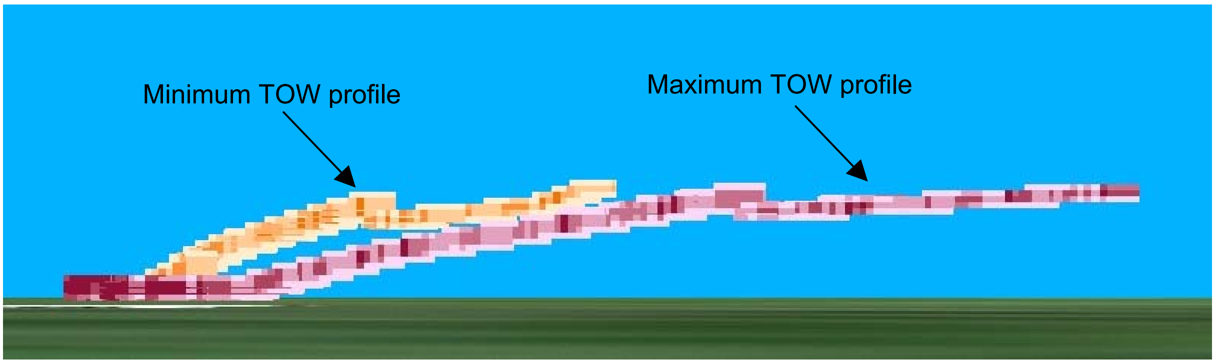

Figure 2: INM Climb-out profiles for Boeing 747-400

The recommendation to use INM minimum TOW profiles to calculate aircraft climb-out emissions doesn't mean that the aircraft actually flies at its minimum TOW as this would be against all the airlines practices which aim at maximising the use of their aircraft. It should rather be seen as the best available method to estimate air pollution from aircraft. This is a direct consequence of the ICAO emission factors and fuel flow which have been designed to align closely to operating practice in the 80's. As one can imagine, those changed drastically since then (Lister et al., 2003). This has been highlighted by Schäfer et al. in 2003 which reported that actual measured emission indices for NO_x were lower than the ICAO ones by about 50% (83 aircraft examined, mainly Airbus and Boeing ones). Therefore in one way the use of a minimum take-off weight profile shortcuts the overestimation of emission indices by the ICAO.

An attempt was made in Table 4 to find a relationship between the weight increase and the subsequent increase in emissions. An increase in weight of 20% in the case of an Airbus A320 induces emission up by 25% to 30% depending on the specie of interest. Similar results have been found for Tupolev T134: emission rose by 31% for a 20% bigger aircraft. On the contrary, in the case of the Transall C160 a smaller weight variation (17%) leads to greater emissions (around 47%). Finally, when considering the Boeing aircraft, the higher the weight variation the smaller the effect on emissions. These findings suggest that the relation between aircraft weight and emissions is at least specific for each aircraft category. Further investigations within aircraft categories are necessary to conclude about the existence of an aircraft weight to aircraft emissions relationship.

Table 4: Relationship between an increase in TOW and emissions.

	Increase in weight	Increase in CO	Increase in HC	Increase in NO_x	Increase in PM_{10}
A320	0.20	0.26	0.29	0.28	0.27
B744	0.48	0.79	0.77	0.81	0.79
B763	1.05	0.57	0.50	0.54	0.56
C160	0.17	0.48	0.47	0.47	n/a
T134	0.20	0.31	0.31	0.31	0.31

3.2 Case 2: Thrust cut back at aircraft' wheels off

The previous example assumed that the aircraft engine mode is at full power (100% engine thrust) up to 1000 ft as prescribed in the ICAO documentation (ICAO CAEP, 2003). However, current operational practices suggest that the actual thrust cut back point occurs much closer to the ground. This is the reason why European experts suggested to consider a shift from take-off to climb-out engine modes as soon as the aircraft leaves the ground (European Commission, 2001). This point of view was backed up recently in a report by Gaffal et al. (2006) where the analysis of actually flown trajectories showed that the engine take-off mode stops around 10 ft above ground.

The results obtained are presented in Table 5. They are expressed as a difference in the quantities emitted during the climb-out profile compared to the emissions from case 1 (Table 3). It is obvious from the results that the difference is rather small: it never reaches more than 1 kg for all pollutants and all take-off weights. Especially for CO and HC there is nearly no change in emissions. On the contrary when considering the NO_x and PM_{10} emissions, small variations can be observed (resp. 0.85kg and 3.27g) which are rather small compared to the totals (resp. 17.13kg and 57.19g). The difference in trend between CO and HC in one hand and NO_x on the other hand is explained by the fact that NO_x is emitted in greater quantity when the engine are at higher temperatures (i.e. when aircraft take-off), therefore the reduction of the take-off time-in-mode has a direct (but limited) influence on the quantity of NO_x emitted.

Table 5: Variation in pollutants emitted when take-off roll stops at wheels off

	TOW (t)	CO (kg)	HC (kg)	NO_x (kg)	PM_{10} (g)
A320	61.5	0.00	0.00	-0.12	-0.32
	73.5	0.00	0.00	-0.17	-0.43
B744	259	0.00	0.00	-0.29	-0.43
	382.4	0.00	0.00	-0.25	-0.36
B763	120	0.00	-0.01	-0.76	-1.31
	246	0.00	0.01	-0.85	-1.46
C160	59.9	0.00	0.00	-0.00	n/a
	70.3	-0.02	-0.05	-0.44	n/a
C206	1.4	0.11	0.00	-0.00	n/a
T134	42.4	0.00	0.00	-0.11	-1.58
	50.8	0.00	0.00	-0.13	-1.86
YK40	14	-0.01	0.00	-0.50	-3.27

3.3 Comparison of operational and INM derived times-in-mode for Airbus A320

The following section focuses on Airbus A320 aircraft as some operational data was available, especially the times-in-mode (both take-off and climb-out) for aircraft taking off. The times-in-mode from various sources of information are reported in Table 6. The INM times-in-mode data was directly retrieved from the run of the ALAQS-AV software. The operational data for six A320 has been obtained from the study performed by the Technical University of Munich (Gaffal et al., 2006) in the course of the ALAQS project. Also, some operational times averaged over a fleet of Airbuses and Boeings (A319, A320, A321, A330, A340, B757 and B767) was retrieved from observations made at Zurich airport (Fleuti, 2004). Finally, the ICAO LTO times-in-mode have also been included for comparison purposes.

Table 6: Times-in-mode from INM profiles and from real operations.

	Take-off Weight (t)	Take-off (s)	Climb-out (s)	Total (s)
INM A320 case 1	61.5	62.36	26.87	89.23
(Take-off up to 1000 ft)	73.5	82.87	29.62	112.49
INM A320 case 2	61.5	23.10	66.13	89.23
(Take-off at ground level only)	73.5	31.10	81.39	112.49
Average over six A320 flights	60.8	34.17	72.17	106.34
Average over nine flights (Airbuses and Boeings at Zurich airport)	n/a	96.00	30.00	126.00
ICAO LTO cycle	n/a	42.00	132.00	174.00

From Table 6, it is clear that the ICAO LTO values (174 s) are higher than all other data, both operational and INM derived. This is mainly due to an overestimation of the time spent climbing (more than 130s, highest value in the table). On the contrary, the values derived from the INM minimum TOW profiles are the smallest times-in-mode reported. Even though the average take-off weight from the six A320 was smaller than the INM minimum take-off weight (60.8t against 61.5t) the subsequent climbing time was greater than the INM minimum TOW derived one (106s against 89s). Finally, the times-in-mode from Zurich airport showed big discrepancies both in the total time and in the time split in each mode. The take-off lasted 96s as opposed to 30s for the climb-out, which is the opposite of the trends observed in all the other cases. This could be a consequence of the average of times-in-mode over all aircraft categories (small, regional, business, medium and big jets) and also the result of specific airport procedure in place at the airport (e.g. the use of reduced take-off thrust which implies a longer take-off period but at a lower engine thrust).

The big discrepancies observed in the times-in-mode reported in Table 6 draws attention to the critical importance of the conditions in which an aircraft is operated. Besides its take-off weight, there are numerous factors that influence aircraft performances. Between others, the most important are:

- The ambient conditions (esp. temperature and headwind)
- The airlines procedures and operating choices
- The airport procedures
- The aging of the aircraft engines
- The maintenance of the aircraft and of its engines

It has been reported by Lukachko et al. (1997) that the engine aging can be responsible for up to 15% change in the NO_x emission index of aircraft engine, the emissions of NO_x decreasing when the engine's age increases as a result of a less efficient combustion process. This partly explains the conclusion of Schäfer et al. (2003) which experimented discrepancies up to 100% when measuring the emissions within the same family of aircraft / engine. However, those effects are expected to have only a small effect compared to other uncertainties of emission inventories (Lukachko, 1997). Nevertheless, a way to minimize the error due to the variations in aircraft profiles and times-in-mode would be to derive more detailed emission index and fuel flow that would allow to consider a greater number of operational modes than the four set up by the ICAO, especially for high engine thrust which are responsible for most of the NO_x emitted on an airport.

4. CONCLUSIONS

A comparison of the emissions due to various aircraft departing profiles (up to 3000 ft) has been performed. Seven aircraft types between the most common ones have been considered: A320, B763, B744, Transall C160, Cessna C206, Tupolev T134 and Yakovlev 40. Climb profiles corresponding to the minimum take-off weight and to the maximum take-off weight for each aircraft of the list have been derived from INM (Integrated Noise Model). The emissions resulting from each profile were calculated using the ICAO Engine Exhaust Emissions Data Bank which consists of emission index (in g/kg of fuel burnt) and fuel flow (kg/s) associated to specific levels of engine thrust. Additionally, emissions have also been calculated according to the ICAO LTO cycle methodology. As widely reported in the literature, the emissions from the ICAO LTO cycle parameters lead in general to an overestimation in CO, HC, NO_x and PM_{10} emitted. On the contrary, when using the INM minimum take-off weight profiles, the subsequent emissions were the closest compared to operational NO_x emissions reported in the literature (respectively 32% and 27% lower than the ICAO calculated value) – even though the INM take-off still use 100% thrust. Therefore the use of the INM noise profiles for calculating aircraft emissions is relevant, even though it could be enhanced as discussed later. An attempt was made to identify a relationship between the increase in weight and the increase in emissions but it seemed to be different for each aircraft category of interest in this study. However, additional research in that field could investigate if such a relationship exists, either on an aircraft type of aircraft group basis.

Additionally, the impact of thrust cut back altitude on emissions has been shown to be limited on the take-off emissions: the variation in altitude from 1000 ft to ground level lead to changes in emissions of less than one kilogram. Probably as the ‘cut back’ is asset right at the start of the take-off run. The take-off thrust is then kept until trim-up and accelerate phase which can occur between height of 5000 to 10000ft

When comparing operational and INM derived times-in-mode, big discrepancies have been observed. There was no clear pattern that emerged when trying to relate the times-in-mode to the take-off weight. There were a number of explanations for this fact. First of all, the INM profiles have been created specifically to generate noise contour maps, and as such their use for emission calculations must be controlled (even thought the lowest take-off weight profiles gave the best match with operational data). Another reason lays within the fact that operational practices have a tremendous importance on the times-in-mode and on the subsequent quantities emitted. At the moment, operational pilot practice such as derated thrust, noise-related trajectories, or even the variation in climb profiles as a consequence of a change in ambient conditions (temperature, headwind…) are not considered in most emission inventory tools. The development of a method allowing the use of emission indices and fuel flow relating actual operations (i.e. to real engine thrusts) rather than to the ICAO four defined mode would be greatly beneficial. An approach to solve that issue based on the derivation of emission index from the operational fuel flow is currently under discussion in the ICAO CAEP (Committee for Aviation Environmental Protection. Best practice implies knowing emissions factors for all thrust settings and also the company policy as regards use of reduced and de-rated thrust.

However, there will still be some limitations due to the use of generic emission factors per engine type: the influence of the airframe is not considered, and more importantly the variability in emissions within one aircraft / engine family can be huge (up to 100%) as it depends on the age of the engine, on the way maintenance has been applied, and also on the ambient conditions.
Therefore an analysis of the impact of the various variables would allow identifying the area on which it is worth to put the most efforts into modelling accurately the emissions from the engine(s) of aircraft.

5. BIBLIOGRAPHY

Celikel, A., Duchene, N., Fleuti, E., Fuller, I., Hofmann, P. and Moore, T. (2004) *ALAQS Case Study: Emission Inventory for Zurich Airport with different methodologies,* EUROCONTROL Experimental Centre EEC/SEE/2004/010

Celikel, A., Duchene, N., Fuller, I. and Peeters, S. (2005) *Airport Local Air Quality Studies: Concept Document,* EUROCONTROL Experimental Centre EEC/SEE/2005/003

European Commission (2001), *AEROCERT Final Report*, EC Contract N° AI-97-SC.242

European Commission (2003), *Development of the technical basis for a New Emission Parameter covering the whole AIRcraft operation: NEPAIR – Final Technical Report,* EC Contract N° G4RD-CT-2000-00182

European Environment Agency (2003), *Europe's environment: the third Assessment*, EEA Summary Report, Copenhagen

European Environment Agency (2004), *Ten key transport and environment issues*, EEA report N°3/2004, Copenhagen

European Environment Agency (2005), *Environment and health,* EEA report N°10/2005, Copenhagen

EUROSTAT (2006), *Air passengers transport up 8.8% in 2004,* EUROSTAT news release 10/2006, Luxembourg

Federal Aviation Administration (2005), INM model documentation, FAA website **http://www.faa.gov**/about/office_org/headquarters_offices/aep/models/inm_model/

Fleuti, E. and Polymris, J. (2004), *Aircraft NO_x within the operational LTO cycle,* UNIQUE (Flughafen Zurich AG) and Swiss Flight Data Services, **www.aero-net.org**

Gaffal, R., Wittenzellner, M. and Kloiber, F. (2006) *Calibration of emission inventories with actual flown aircraft profiles on approach and take-off*, EUROCONTROL Experimental Centre Contract A03 Task 4.3.2

ICAO CAEP, 2003, Rapporteur WG3, *Guidance on the Use of LTO Emissions Certification Data for the Assessment of Operational Impacts*, Report CAEP/6-IP/5, ICAO Committee on Aviation Environmental Protection

ICAO CAEP, 2005, Rapporteur WG3, *Emissions – Technical issues: Alternative emission methodology*, Report CAEP/7-AEMTG WP4, ICAO Committee on Aviation Environmental Protection

Lister, D.H. and Norman, P.D. (2003) *EC-NEPAIR: Work Package 1 – Aircraft engine emissions certification – a review of the development of ICAO Annex 16, Volume II,* QinetiQ and UK Department for Transport

Lukachko, S.P., Waitz, I.A. (1997) Effects of the engine aging on aircraft NO_x emissions, **The American Society of Mechanical Engineers,** ref 97-GT-386.

Schäfer, K., Jahn, C., Sturm, P., Lechner, B., and Bacher, M., (2003) Aircraft emission measurements by remote sensing methodologies at airports, **Atmospheric Environment, 37** 5261-5271