ESTIMATION OF HISTORICAL AVIATION CO_2 EMISSIONS

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ABSTRACT

The European Directive 2008/101/EC, including aviation in the European Emissions Trading Scheme (ETS), was approved on November 18, 2008, defining the main features of the system to be entered into force starting 1st of January 2012. The aim of the rule is to keep CO_2 emitted by all operators landing at and taking off from European airports at the level of a predetermined base year.
This base year emission level is legally defined as the average of CO_2 emissions on the 2004, 2005 and 2006 years. Then, it raises the problem of calculating emissions made in the past and verifying the level of accuracy of the result. The philosophy of emissions trading is based on a cap and trade mechanism to start the granting of free permits and the trade of the rest of amounts. Therefore, a correct quantitative base is of paramount importance for the performance of the system and has great economic repercussions. This paper discusses the different alternatives to model the emissions for the base year estimation and cover the existing data gaps while keeping the calculation within a reasonable level of accuracy.
Some improvements with respect to existing methodologies are suggested in order to improve the process of working with a huge data base of several million flights, as EUROCONTROL uses for emission inventory. A methodology to cover data gap and calculate their magnitude is also proposed.
The last part of the paper advises on ways of action in case of changes in the geographical scope of the problem either by increasing the EU members or by building agreements with other countries with similar emissions trading mechanisms.

Keywords: aviation emissions trading, emissions modelling, European ETS

1. CIVIL AVIATION IN THE EUROPEAN UNION EMISSIONS TRADING SYSTEM

The European Union (EU) adopted an Emissions Trading Scheme (ETS) in 2003 (ref. [1]) as the most cost efficient market mechanism, intended for optimizing the cost of reducing Greenhouse Gas Emissions (GGE) from different industrial sectors (energy generation, oil refining, steel industry, timber, cement and ceramic, paper), all of them coming from fixed sources and representing roughly 50% of European emissions. The EU ETS started on 1st of January, 2005, with the purpose of helping EU Member States to comply with the target established in the Kyoto Protocol for the EU as a whole (a reduction of 8% GGE in 2012 with respect to the 1990 levels). Each country was assigned an individual goal, according to its present emission levels, the aggregation of which, leads to the global 8% reduction target.

As international civil flight emissions, on the contrary than domestic ones, were not included in the Kyoto Protocol, but left in the hands of the International Civil Aviation Organization (ICAO), this body initiated different analysis to determine the best way to control emissions produced by those flights on a worldwide basis. In the ICAO 37th General Assembly, held in September-October 2007, some recommendations on market based measures were adopted, outlining Emissions Trading as the most efficient way forward in terms of environmental cost/benefit analysis, after evaluations comparing this tool versus Voluntary Agreements, environmental charges and taxes.

However, it was not possible to reach an agreement on a worldwide system for emissions trading in the international aviation sector and the European Union decided to take the initiative of including the civil flights making a stop at its airports in the already working European Emissions Trading Scheme. An evaluation of possible European strategies to fight aviation GGE, reinforcing the findings of ICAO that point out Emission Trading as the one having the minimum cost/benefits results, is included as ref. [2].

On legal grounds, the European action raises some doubts and a number of non EU countries are challenging the inclusion of non EU operators in the system, pointing out that the ICAO recommendation on emissions trading systems requires State level agreement for its application. In December 2009, three US airlines (American, Continental and United) launched a legal challenge to the rule in a British Court that might modify the reach of the rule.

On November 18, 2008 Directive 2008/101/EC, in ref. [3], was approved, amending the existing ETS Directive (2003/87/EC), with the purpose of adding civil aviation to the sectors allowed to trade CO_2 emission permits.

The amended Directive considers EU civil aviation as a whole sector where operators (commercial airlines or other aircraft users) are the subject of emission limits and, therefore, the entities allowed to trade permits, starting on January 1, 2012. The maximum level of emissions (the cap of the trading system) is established at 97% of the historical emissions, to be understood as the average of the annual CO_2 emissions in the calendar years 2004, 2005 and 2006 from aircraft performing an aviation activity included in the amended Directive. After reserving a 3% of the permits for protecting new entrants or operators with a high level of growth, the rest of the emissions cap will originate an equivalent amount of permits, to be distributed for free among the operators, proportionally to their Revenue Ton-kilometers (RTK) performed in the year 2010. The 97% cap will pass to be 95% in 2013. The long term objective is a continuous reduction of the cap until reaching a situation with no free permit at all, always as a single sector, independent of national goals.

This system will have important economic repercussions for the affected operators. Those emitting more than their free permit quotas in 2012 and beyond, will be forced to buy additional permits in the open market to compensate the exceeded amount. On the contrary, if an operator emits less than its quota, the operator is allowed to sell the unused permits and make a profit. Then, the calculation of historical emissions plays a key role in the efficiency of the system. If the number is too small, the amount of distributed emission allowances would be insufficient and there would be a high demand for purchasing permits, which price would increase with heavy financial effects on the operators' economy. However, an over-estimate of the historical emissions might put in danger the environmental impact of the regulation, demanding very minor actions for compliance by the individual carriers.

According to a cooperation agreement between the EU and the European Organisation for the Safety of Air Navigation (EUROCONTROL), signed on December 30, 2008, EUROCONTROL will, among other things, lead the work to provide an accurate calculation of the historical aviation emissions. In March 2009, a proposal by the Innaxis Research Institute and the Polytechnic University of Madrid (UPM) was selected by EUROCONTROL for helping in the development of the optimum methodology for the estimation of those emissions and review the precision of the calculation and the error margin of the results in the reference terms of ref. [4].

EUROCONTROL selection by the EU responds to the availability of a huge data base of several million flights operated in the 2004-2006 period, used for emission inventory purposes. This information allows the calculation of individual flight emissions, eliminating the need of aggregated estimations of insufficient accuracy, but needs a deep analysis of the completeness of the data, an estimation of the magnitude of possible losses in the available data and an adequate methodology to fill those gaps.

This paper discusses the different alternatives considered for approaching the problem and describes the improvements adopted with respect to existing methodologies and the results obtained in this case application, measured in terms of accuracy and error margins.

Additionally, it provides some advice on ways of action in case of future changes in the geographical scope of the problem either by changing the number of EU members or by the adoption of agreements with other countries with similar ETS mechanisms or wishing to participate in the European Scheme. This last possibility has become real in December 2009, when Iceland, Lichtenstein and Norway signed a treaty with the EU with that purpose (ref. [5]).

One additional product of this exercise is to produce an input for the Monitoring, Reporting and Verification mechanism (ref. [6]), needed to check whether the operators' data are correct. EUROCONTROL has identified around 6000 operators to be subject to EU ETS. The surveillance functions are attributed to the EU State in which the operator is registered or, if it is registered in a non-EU country, to the EU State in which the operator produces the most of its CO_2 emissions, as figures in ref. [7].

2. PREPARATION OF THE DATABASE

EUROCONTROL, as the body that manages the provision of Air Navigation Services in the airspace of 38 countries, including the 27 members of the EU, has different data sources to identify or estimate the air traffic to be used in the historical emissions calculation. The most complete of those sources is PRISME (Pan-European Repository of Information Supporting the management of EATM), whose data are obtained primarily from CRCO (Central Route Charging Office) and CFMU (Central Flow Management Unit). CRCO gathers the traffic information required for billing the operators and collects the money for further redistribution to each one of the States providing Air Navigation Services. The CFMU data are used for the purpose of Air Traffic Flow and Capacity Management (ATFCM) and includes the actual four dimensional data of all flights in EUROCONTROL air space.

A preliminary analysis of the available data showed that the data of four EU countries (Estonia, Latvia, Lithuania and Poland) were not available in PRISME. Estonia and Latvia are not EUROCONTROL members and Poland and Lithuania joined recently the Organisation, after the study years. At the same time, some flights arriving to or departing from French overseas departments (French Guiana, Guadeloupe, Martinique and Reunion) did not pass through the EUROCONTROL airspace and there were no registered data.

At EUROCONTROL request, national civil aviation authorities of those countries provided the missing data in time, with the exemption of Lithuania. This country entered in the CRCO zone on January 1, 2008 and the data from that year was available, but not those of the historical emission period. The only information for the 2004-2006 period were the scheduled flight programs contained in the OAG worldwide database and collected by EUROCONTROL WISDOM (World Interconnected Sources Database of Operational Movements). Then, WISDOM data was used for scheduled flights and an estimation was built for non-scheduled ones, based on 2008 data:

$$F_{ns200x} = F_{ns2008} \text{ x } (F_{s200x} / F_{s2008}) \qquad (1)$$

where F_{ns} are non-scheduled flights in years 2008 and 200x
F_s are scheduled flights in years 2008 and 200x

The EU Directive includes in the ETS all flights which arrive at or depart from an aerodrome situated in the territory of a Member State, with some exemptions covering up to 10 flight categories, designed by small letters (*a)* to (*j)* (ref. [3]). A second part of the process was to filter those flights out of the CO_2 calculation, using the flight type identification registered in the CRCO data base. The following four types were fully identified and eliminated:

- *(b)* military flights performed by military aircraft and customs and police flights, identified by code letters M, X and P;
- *(d)* any flights performed exclusively under visual flight rules (VFR) as defined in Annex 2 to the Chicago Convention, identified by code letter V;
- *(e)* flights terminating at the aerodrome from which the aircraft has taken off (circuit flights) and during which no intermediate landing has been made, identified by code letter O;
- *(f)* training flights performed exclusively for the purpose of obtaining a licence, or a rating in the case of cockpit flight crew where this is substantiated by an appropriate remark in the flight plan provided that the flight does not serve for the transport of passengers and/or cargo or for the positioning or ferrying of the aircraft, identified by code letter T.

Two other types of flights show small possibilities of misidentification:

- *(h)* flights performed by aircraft with a certified maximum take-off mass of less than 5700kg may suffer problems of rounding if the MTOW communicated to EUROCONTROL was close to the limiting figure;
- *(j)* flights which, but for this point, would fall within this activity, performed by a commercial air transport operator operating either:

- fewer than 243 flights per period for three consecutive four-month periods; or
- flights with total annual emissions lower than 10000 tonnes per year. Flights performed exclusively for the transport, on official mission, of a reigning Monarch and his immediate family, Heads of State, Heads of Government and Government Ministers, of a Member State may not be excluded under this point.

  This requirement is based on the knowledge of all traffic; however, there is a small part of the traffic that is estimated at macro-level because the data is unavailable, and for this traffic, the *De-minimis* requirement cannot be applied.

Two more exemptions were covered partially:

- *(c)* flights related to search and rescue (code letter R), fire fighting flights, humanitarian flights (code letter H) and emergency medical service flights authorised by the appropriate competent authority.

  Some or these flights may not be rightly codified at all times.
- *(g)* flights performed exclusively for the purpose of scientific research or for the purpose of checking, testing or certifying aircraft or equipment whether airborne or ground-based (code letters E and N).

  Same than in the previous case.

Finally, it was not possible to filter two types of flights:

- *(a)* flights performed exclusively for the transport, on official mission, of a reigning Monarch and his immediate family, Heads of State, Heads of Government and Government Ministers, of a country other than a Member State, where this is substantiated by an appropriate status indicator in the flight plan.

  As a general rule, occupants of those flights are not identified and it is impossible to determine whether are included or not in the exemption
- *(g)* flights performed in the framework of public service obligations imposed in accordance with Regulation (EEC) No 2408/92 on routes within outermost regions, as specified in Article 299(2) of the Treaty, or on routes where the capacity offered does not exceed 30 000 seats per year.

  While there is a list of public service obligation imposed in UE routes, it will take an exhaustive work to eliminate manually all these flights and route capacity data are not always available

This lack of information may artificially increase the accounted emission levels by a small amount as it will be indicated in the next chapter. All details are included in ref. [8].

3. EMISSIONS CALCULATION AND CORRECTION SCHEME

The CO_2 emissions of a flight are directly proportional to its fuel consumption. An overwhelming majority of the aircraft affected by the EU ETS is consuming kerosene type fuel, specifications Jet A and Jet A1 and the Directive establishes an emission factor of 3.15 kg of CO_2 per kilogram of kerosene.

As according to ICAO rules all flights operating under Instrumental Flight rules (IFR) must submit a flight plan, detailing operating weights, intended trajectories and forecasted fuel burn, before taking off, the CRCO and CFMU combined data contain flight distances and a first approach to the amount of fuel to be consumed. The proposed calculation method has to be used in accredited calculation ways for passing from a weight, type of aircraft, covered distance group of data to fuel consumption and, consequently, emitted CO_2.

The following diagram depicts the process of the reconciling methodology:

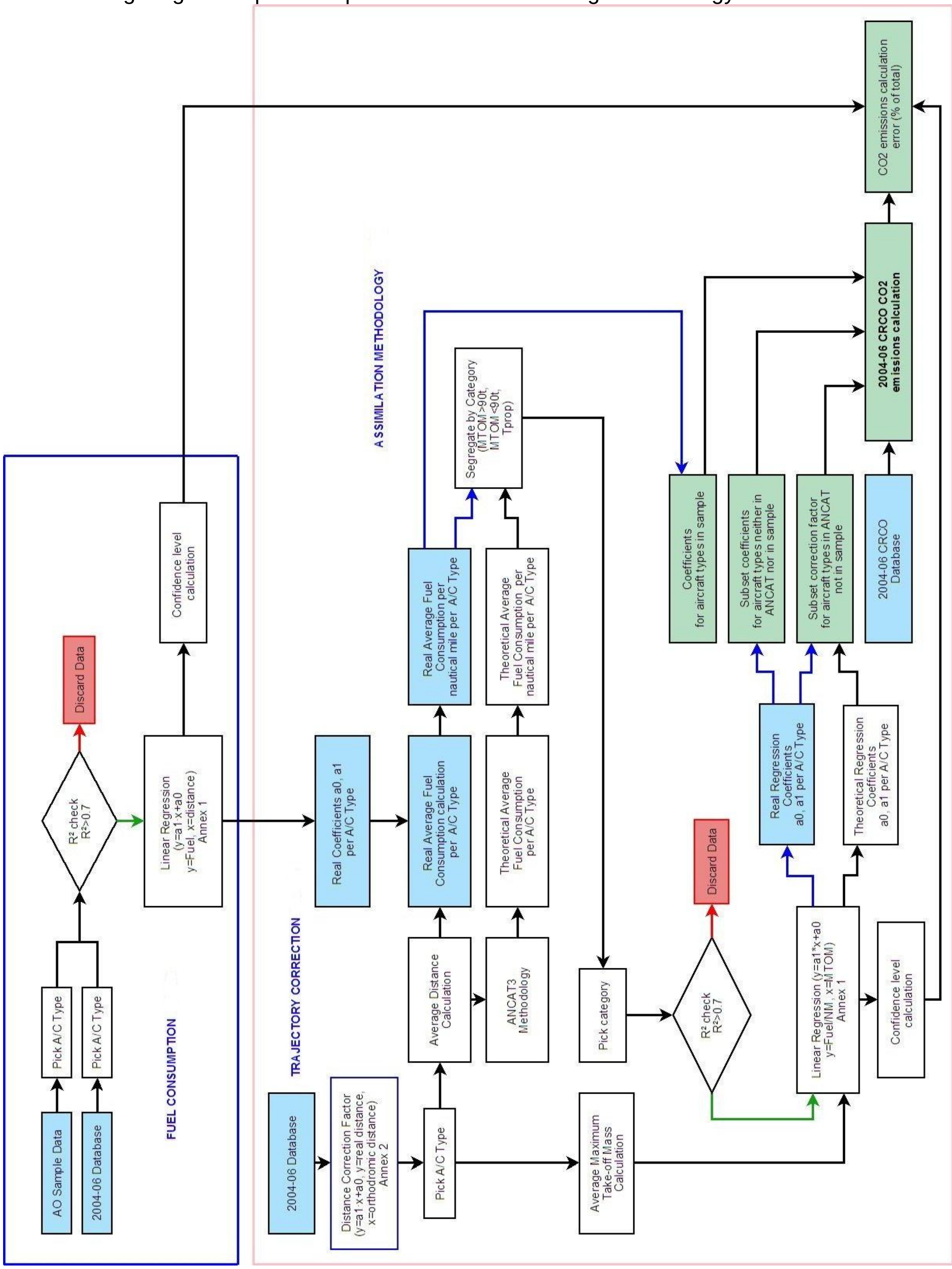


Figure 1. Methodology

Among the different ICAO accepted models, the choice was between the fast calculation, low accuracy, ANCAT-3 methodology and the more detailed AEM simulator. The first calculates fuel burn based in flown distance and aircraft type, while the second takes into account flight plans details like actual aircraft weight, and has a wider data base in terms of type of aircraft and model of installed engines.

For the vast majority of the data needed to be analyzed, there was sufficient information for the implementation of both methodologies. However, none of them are able to account for certain factors that have an influence on the fuel consumption, hence on the CO_2 emissions. In order to increase the accuracy of the historical emissions estimation, making it as close as possible to its actual value, there is the need of evaluate a number of relevant factors not included in the model options. To this purpose, it was proposed the collection of actual fuel consumption information from volunteer aircraft operators, its analysis, and the establishment of a *reconciling* methodology for the adjustment of actual fuel consumption to those obtained from the selected methodology. This kind of correction has been previously tested and has been proven to offer good results, as in ref. [9]. As this process would need to be done independently of the model choice, ANCAT-3 was selected due to its calculation speed and its higher flexibility in order to accommodate data changes, taking the so called *Detailed Methodology*, including data of the 19 most used aircraft types.

The ANCAT-3 methodology can be consulted in ref. [10]. It does not take into account a set of relevant parameters that have an impact on fuel consumption. The following factors were distinguished as the most influential:

- actual take-off weight of the flight,
- non optimal flying altitude;
- holding in the airport terminal area (TMA),
- meteorological conditions,
- actual taxi times on the ground,
- engines de-rating level, related with the actual take-off weight;
- fuel consumed by the Auxiliary Power Unit (APU).

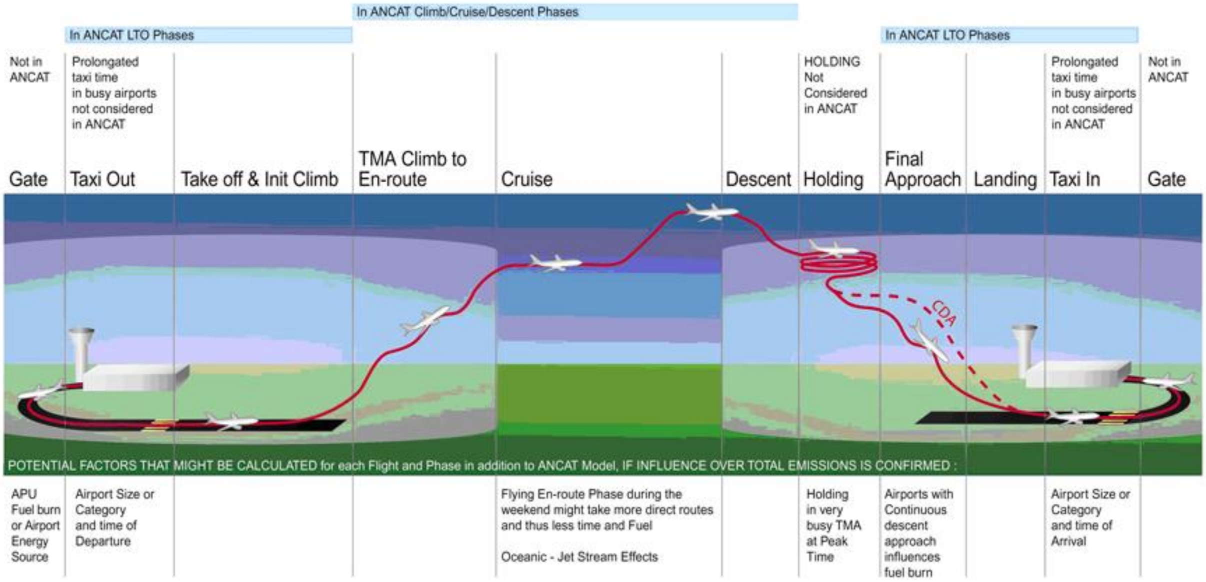


Figure 2. Fuel consumption influencing factors not included in ANCAT (source: EUROCONTROL)

The sample data received from the operators comprised the fuel consumption from a gate-to-gate perspective (from starting the engines to put them out); and thus, allowed to quantify the main factors that influence the fuel consumption. The only lost consumption may occur if the APU is running with engines off, for supplying electricity and air conditioning. While many airlines and most of private operators include this consumption in their flight data, others account for it in maintenance practices.

Maintaining the analysis at a macro-level and checking the representativeness of the sample ensured that the fuel data sample was descriptive enough to provide an overall correction that included all different factors present in the European aviation network, since the actual data captured the influence of different airports (congested, non-congested), meteorological conditions, different airlines strategies, route deviations or different holding patterns. The methodology is described hereunder.

3.1 Adjustment of the fuel consumption coefficients

3.1.1 Calibration sample representativeness check and removal of the insufficient or non-representative sample data.

The sample data was statistically analyzed to check its representativeness, verifying that the conclusions of the calibration process could be extrapolated to the whole set of flights included in the database. This depended on the amount of data provided by the aircraft operators, and also on their quality in terms of aircraft type and operation environment coverage.

3.1.2 Trajectory correction factor (for flights where there is no distance in the CFMU database).

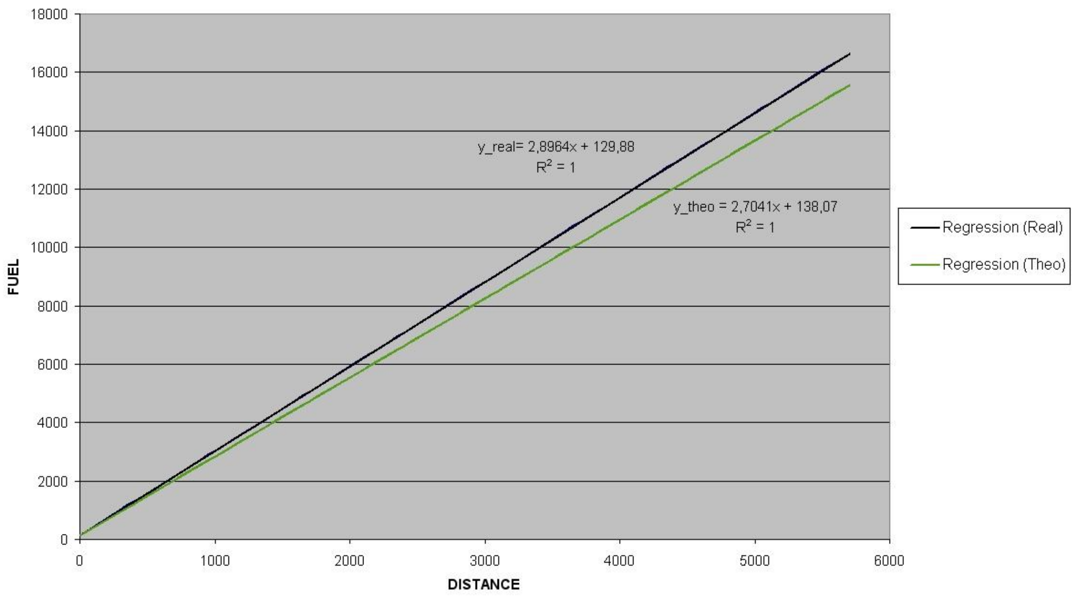
For flights for which there was no information on distance (from the CFMU database or from the information provided by National Authorities, as applicable), it was necessary to estimate the flown distance.
The proposed solution for this estimation was to study the relationship between orthodromic (shortest trajectory between origin and destination airports) distance and flight plan distance, which was done by means of a linear regression of known distances of flights and their corresponding orthodromic distance. The slope of the linear regression represented the distance correction factor coefficient to be applied.

3.1.3 Calculation of fuel consumption coefficients for aircraft types included in the sample.

For those aircraft types for which the sample has passed the representativeness check defined in 3.1.1, an analysis of the fuel consumption per aircraft type as a function of the flight distance was carried out.
Fuel consumption coefficients for a given aircraft type was calculated by computing the regression line, so that:

$$y = \beta_0 + \beta_1 x \qquad (2)$$

where ***y*** is the fuel consumption and ***x*** is the distance flown.
For each aircraft type regression, the **correlation coefficients** β_0 and β_1 were calculated. Aircraft samples for which $R^2 < 0.70$ were discarded.
For the retained aircraft types (valid samples), equation (2) was used to estimate fuel consumption on a flight by flight basis.



In the function above, the coefficients β_0 and β_1 accounted in an aggregated manner for the different factors influencing the fuel consumption (meteorological conditions, airline strategy, taxiing, holding...).

3.1.4 Assimilation of the rest of aircraft types.

The results of 3.1.3 allowed the researchers to develop fuel consumption functions for a set of aircraft types, the actual consumption of which was provided by the volunteer operators. Similar correction factors were applied to the other types not included in the data sample, but integrated in the ANCAT-3 data base. For the rest of aircraft types, however, an assimilation methodology was needed to estimate their fuel consumption coefficients.

The purpose of the assimilation methodology was to define a set of formulae that, by entering an aircraft type's Maximum Take Off Mass (MTOM), resulted in a fuel coefficient that multiplied by the distance travelled allowed to compute the total fuel consumed, hence CO_2 emissions.

In order to complete this task, the following steps were followed:

1. For each aircraft type of the valid sample[1], the average distance flown and the average MTOM were calculated for the 2004-2006 period.
2. Using the formula obtained in section 3.1.3, the fuel consumption was calculated for the average distance travelled by each aircraft type of the sample.
3. For each aircraft type, the result of (2) was divided by the average distance travelled, acquiring the *real average fuel consumption per nautical mile*.
4. Using ANCAT-3 Methodology, the fuel consumption was calculated for the average distance travelled by each aircraft type of the sample.
5. For each aircraft type, the result of (4) was divided by the average distance travelled, acquiring the *theoretical average fuel consumption per nautical mile*.
6. The aircraft types were segregated into three subsets:
    a. jets over 80 tons, covering all the long range types
    b. jets below 80 tons, for business jets, regional and short/medium range aircraft
    c. turboprops.

    The rationale for this segmentation was based on the methodology developed by EUROCONTROL and explained in ref. [11], and relied on the empiric observation that, for each of these three subcategories, fuel consumption per nautical mile showed a strong linear dependence with MTOM.

[1] Only those aircraft types for which the sub-sample has been considered valid according to the criteria defined in section 3.1.1 and 3.1.3 are retained.

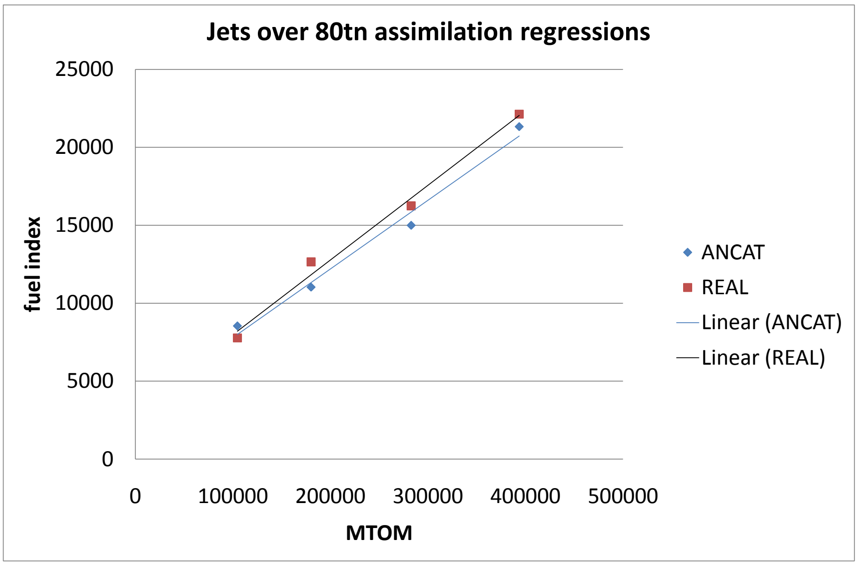


Figure 3. Jets over 80tn assimilation regression

7. Two linear regressions were done for each subset. The first was the regression of the average MTOM and the result of (3), this regression is referred to as *real regression*. The second regression was that of the average MTOM and the result of (5), this regression is referred to as *theoretical regression*.
8. The *real regression* and the *theoretical regression* were analyzed against each other, to find the correction factor of each subset.
9. A confidence interval for the *real regression* was determined.
10. Depending on the aircraft type, the coefficients used for the calculation of fuel consumption were selected as follows:
    - The data of the sample was considered to be more exact than ANCAT; therefore, the coefficients to be used when an aircraft was present on the sample were those calculated in 3.1.3.
    - The assimilated aircraft in ANCAT maintained the assimilation factor, unless both, the primary and the assimilated, were in the sample, in which case, the coefficients calculated as per 3.1.3 were applied to both types.
    - For those aircraft not included in the sample, but defined by ANCAT, the ANCAT fuel consumption coefficients were corrected (shifted) by the correction factor acquired in (8), i.e. by the ratio between *real regression* and the *theoretical regression* for that MTOM value.
    - For those aircraft not included in the sample, but belonging to the same family of one of the aircraft types included in the sample, the fuel consumption coefficients of the aircraft included in the sample were used, with a correction obtained from the ratio between the MTOM of the two models.

- For the rest of aircraft neither in ANCAT-3 nor in the sample, the *real regression* equation was used to calculate the fuel consumption coefficient.

3.2 Recalculation of CO_2 historical emissions

The output of the previous subsection was a new set of fuel consumption coefficients that accounted for the additional fuel consumption influencing factors, as well as a correction factor for unknown flight plan distance between aerodromes.
These new factors needed to be implemented into the methodology developed by EUROCONTROL and described in ref. [8] in the following manner:

1. Acquisition of Data: No change was necessary on this section.
2. Calculation of actual route length: For those flights where the flight plan route was unknown, the trajectory correction factor was implemented following the methodology described in section 3.1.2.
3. Calculation of emissions on a flight-by-flight basis: Depending on the type of aircraft, the fuel consumption coefficients acquired as per section 3.1.3 or section 3.1.4 (as applicable) was implemented. The confidence interval for each individual flight was calculated for a given confidence level.
4. Directive exemptions: It was necessary to recalculate the emissions of the directive exemptions.
5. Gap emissions estimation: Gap emissions estimation was recalculated based on the new fuel consumption coefficients.
6. *De minimis* Exemption Filtering: This section needed to be recalculated since the emissions estimation had changed.
7. Total CO_2 historical emissions: Recalculation was needed to compute final estimation of total CO_2 historical emissions.
8. Calculation of global confidence interval: The confidence level of the resulting value for total CO_2 historical emissions was calculated.

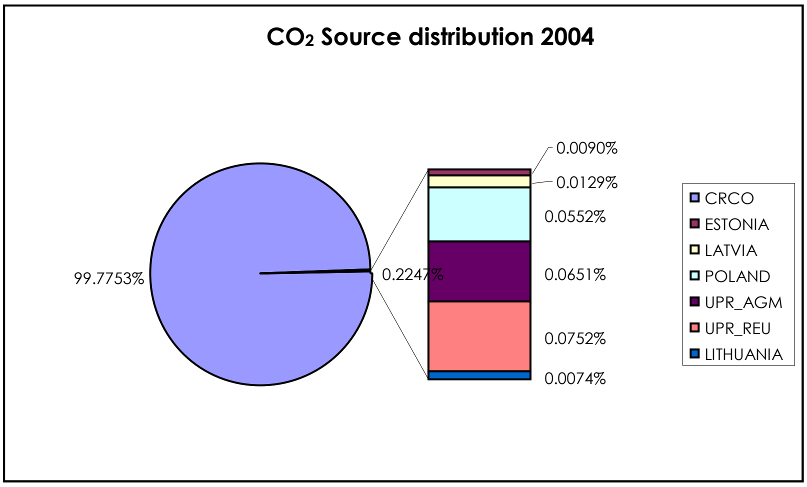
4. PRECISION ANALYSIS

4.1. Gap analysis

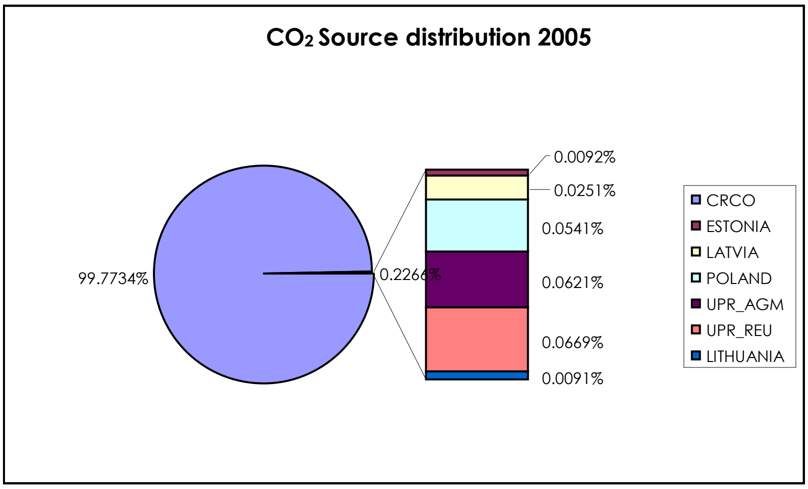
The following figures show how the gaps of the database affect the overall estimation of the historical emissions.
In table 1 we can appreciate the first gap, traffic estimated for Lithuania, which is very small, since most of the traffic is accounted for by CRCO and the neighboring states.

Table 1. Distribution of CO2 per source of data (after exemptions):

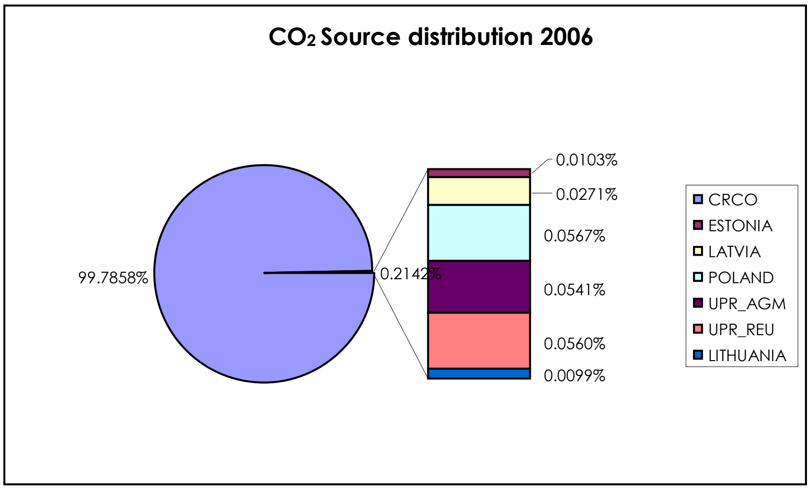
% CO_2	SOURCE							
YEAR	CRCO	ESTONIA	LATVIA	POLAND	UPR_AGM	UPR_REU	LITHUANIA	Total
2004	99.7753%	0.0090%	0.0129%	0.0552%	0.0651%	0.0752%	0.0074%	100%
2005	99.7734%	0.0092%	0.0251%	0.0541%	0.0621%	0.0669%	0.0091%	100%
2006	99.7858%	0.0103%	0.0271%	0.0567%	0.0541%	0.0560%	0.0099%	100%



Graph 1. 2004 Source distribution.



Graph 2. 2005 Source distribution.

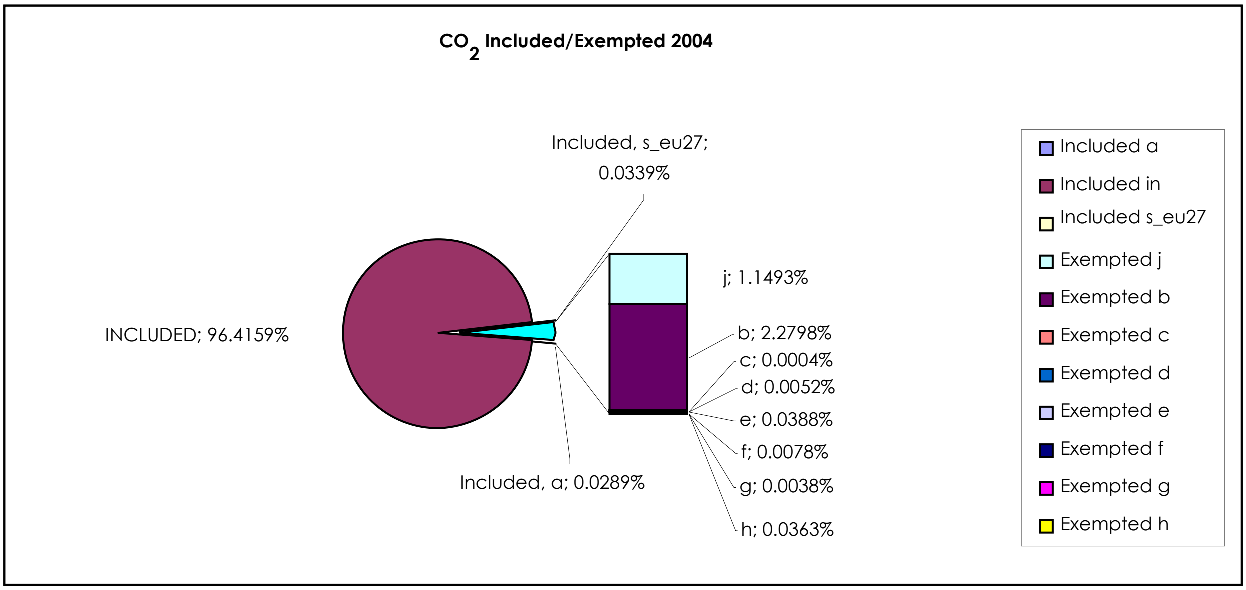


Graph 3. 2006 Source distribution.

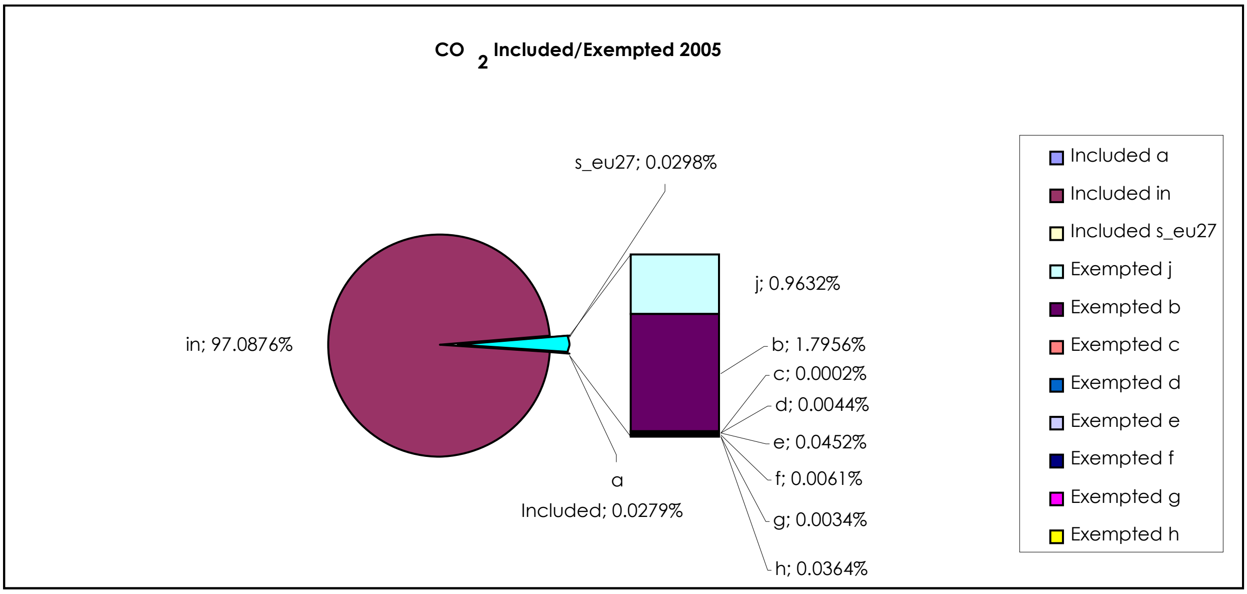
The following tables and graphs show the distribution and impact of the different exemptions. The exemptions are labelled as it was explained in section 2.

Table 2. CO_2 emissions distribution.

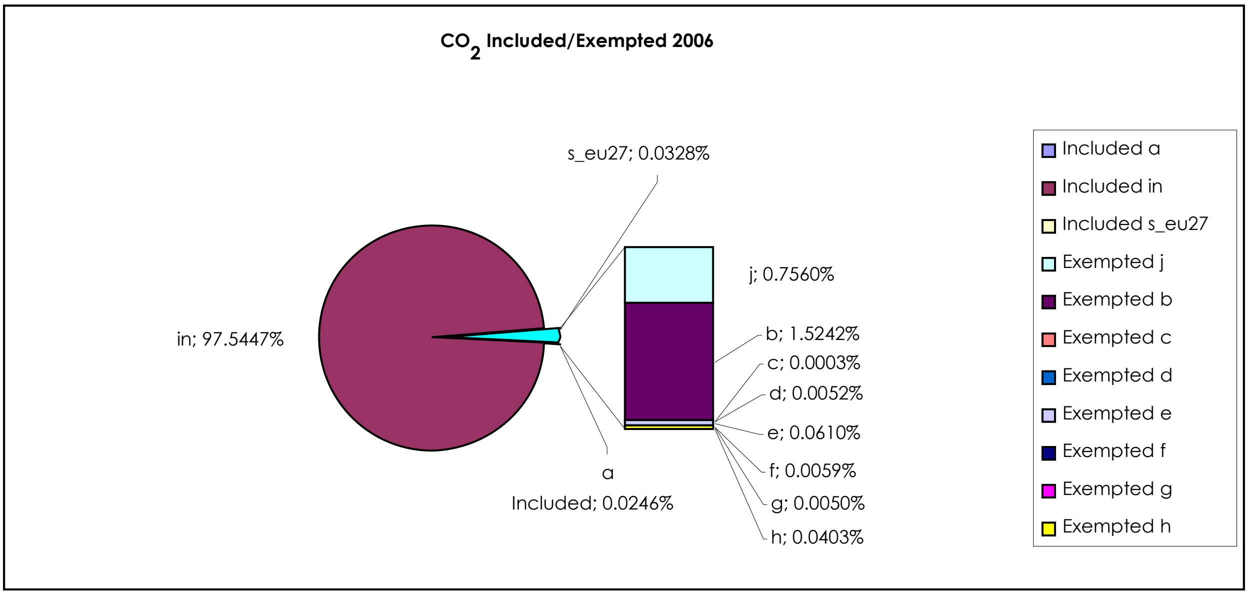
		Included			Exempted								
% of CO2	Exemption	a	in	s_eu27	j	b	c	D	e	f	g	h	Total
	2004	0.0289%	96.4159%	0.0339%	1.1493%	2.2798%	0.0004%	0.0052%	0.0388%	0.0078%	0.0038%	0.0363%	100.%
	2005	0.0279%	97.0876%	0.0298%	0.9632%	1.7956%	0.0002%	0.0044%	0.0452%	0.0061%	0.0034%	0.0364%	100.%
YEAR	2006	0.0246%	97.5447%	0.0328%	0.7560%	1.5242%	0.0003%	0.0052%	0.0610%	0.0059%	0.0050%	0.0403%	100.%



Graph 4. 2004 CO2 emissions distribution per exemption.



Graph 5. 2005 CO2 emissions distribution per exemption.



Graph 6. 2006 CO2 emissions distribution per exemption.

4.2 The representativeness of the sample

The methodology described in section 3 needed to follow certain principles to ensure the procedure had a strong scientific basis.
It was necessary to determine whether the samples were representative of the whole population of data or, on the contrary, if the data samples showed any bias or gap. While some of the above factors were simply expected to add a random noise to the theoretical fuel consumption, other factors were likely to introduce a bias in the theoretical estimation if they were not properly taken into account. It was therefore necessary to ensure that the sample was representative of the whole population of flights as far as these influencing factors were concerned.

4.2.1 Linear Regression

The objective of this task was to adjust the parameters of a model function so as to best fit a data set. In our case, a linear regression model is proposed.
Given the collection of points (x_i, y_i), where x_i is the flight distance and y_i is the fuel consumption, for $i = 1,...,n$, being n the total number of flights performed with a specific aircraft type included in the sample, we determined the regression line that best fitted the collection points. This regression line was as follows:

$$y = \beta_0 + \beta_1 \cdot x \qquad (3)$$

Correlation coefficient

Prior to obtaining the regression coefficients, we confirmed the existence of a linear dependence between x and y. For this purpose, we obtained the linear Pearson correlation coefficient r, whose expression is:

$$r = \frac{b_{xy}}{b_x b_y} \qquad (4)$$

where the moments to the centre b_x and b_y were calculated as follows:

$$b_{xy} = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y}) \qquad (5)$$

$$b_x^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \qquad (6)$$

This coefficient can be $-1 \le r \le 1$.
The correlation is 1 in the case of an increasing linear relationship, -1 in the case of a decreasing linear relationship, and some value in between in all other cases; indicating the degree of linear dependence between the variables. The closer r^2 is to 1, the stronger the linear relationship between the variables. Therefore, r^2 provides an indication of the error between the variable y and its regression (for example, if r^2 is 0.95, then 95% of the variance of y can be explained by changes in x):

- if r^2 is close to 1, it indicates that the variable y has a strong linear dependence on x and the error between the variable y and its regression is low.
- if r^2 is close to 0, the variables are not related and the error between the variable y and its regression is high.

For the purpose of our study, those aircraft samples for which $r^2 < 0,70$ were discarded.

Calculation of linear regression coefficients

Using the Least Squares Method, we found the β_0 and β_1 that minimized the following sum of squares (SS):

$$SS(\beta_0, \beta_1) = \sum_{i=1}(y_i - \beta_0 - \beta_1 \cdot x_i)^2 \qquad (7)$$

The coefficients that minimized SS were calculated by using the following equations:

$$\beta_0 = y - \beta_1 \cdot \bar{x} \tag{8}$$

$$\beta_1 = \frac{b_{xy}}{b_x^2} \tag{9}$$

Calculation of confidence interval

The confidence level and confidence interval were calculated at several levels throughout the methodology. First, we found the confidence level for each type of aircraft by analysing the amount of samples, and the amount of flights that took place with each type. Second, we found the confidence level for each subset of the assimilation methodology (turboprops, jets over 80 tonnes, and jets below 80 tonnes). Finally, we found the confidence level of the total amount of flights given in the sample provided by the AOs, and the total amount of flights affected by the Directive (about 23 million flights).

Finally, we computed the confidence intervals on parameters:

Confidence interval for β_1:

$$CI(\beta_1) = \beta_1 \pm t_{n-2,e/2} S_{\beta_1} \tag{10}$$

Confidence interval for β_0:

$$CI(\beta_0) = \beta_0 \pm t_{n-2,e/2} S_{\beta_0} \tag{11}$$

where the standard deviation of the coefficients were:

$$S_{\beta_0} = S\sqrt{\left(\frac{1}{n} + \frac{\bar{x}^2}{S_{xx}}\right)} \tag{12}$$

$$S_{\beta_1} = \frac{S}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \tag{13}$$

To compute these coefficients we needed:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y(x_i))^2}{n-2}}, \quad S_{xx} = \sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n} \tag{14}$$

where $y(x_i)$ was the regression evaluated at x_i distance.

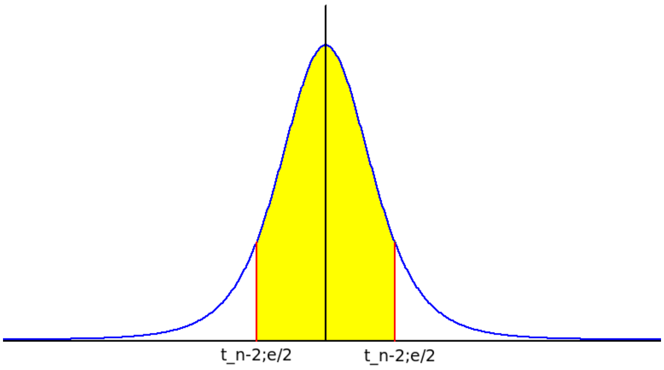
It can be proved that:

$$\frac{\beta_0}{S_{\beta_0}} \to t_{n-2;e/2} \qquad \frac{\beta_1}{S_{\beta_1}} \to t_{n-2;e/2} \tag{15}$$

i.e., the above variables follow a Student's T distribution with n-2 degrees of freedom.

$t_{n-2;e/2}$ is determined by the relationship

$$P\left(|T| < t_{n-2;e/2}\right) = 1 - e \tag{16}$$



Graph 7. Normal Distribution Confidence Interval

The Confidence Interval estimate for the mean of y (lineal regression) given a particular x is as follows:

$$\beta_0 + \beta_1 x \pm t_{n-2;e/2} S \sqrt{\frac{1}{n} + \frac{(x-\bar{x})^2}{S_{xx}}} \qquad (17)$$

The Confidence Interval estimate for an individual value of y given a particular x is as follows:

$$\beta_0 + \beta_1 x \pm t_{n-2;e/2} S \sqrt{1 + \frac{1}{n} + \frac{(x-\bar{x})^2}{S_{xx}}} \qquad (18)$$

4.2.2 Distance Correction

Using the Least Squares Method, we found the coefficients δ_0 and δ_1 that minimized the following sum of squares:

$$SS(\delta_0, \delta_1) = \sum_{i=1}^{n} \left(x_i^{real} - \delta_0 - \delta_1 x_i^{orth} \right)^2 \qquad (19)$$

and using the method described in 4.2.1, we obtained the correction function:

$$x^{real} = CF(x^{orth}) = \delta_0 + \delta_1 x^{orth} \qquad (20)$$

This function described the relationship between the orthodromic distance and the flight plan distance, and allowed to estimate the actual route length x^{real} as a function CF (x^{orth}) for those flights whose actual route length was not available.

4.2.3 Error Propagation

Propagation of error (or propagation of uncertainty) is the effect of variables' uncertainties or errors on the uncertainty of a function based on them.
In our case, we needed to estimate several quantities (corresponding to the emissions of different aircraft types) and then add them together to get the final result. Error propagation was used to combine the errors due to the different estimations and get the confidence interval of the total estimated historical emissions.
Being *q* the total emissions calculated from the addition of the emissions of different subsets of flights $x_i \left(i.e.: x_T = x_1 + x_2 + ... + x_n \right)$ where each x_i corresponds for example to the

emissions due to a certain aircraft type and has an associated confidence interval δ_l, we needed to calculate the absolute uncertainty for q.

$$q = f(x_1, x_2, ..., x_n) \tag{21}$$

As the errors are independent and random in each variable, then the error is given by:

$$\delta q = \sqrt{\left(\frac{\partial f}{\partial x_1}\delta x_1\right)^2 + \left(\frac{\partial f}{\partial x_2}\delta x_2\right)^2 + ... + \left(\frac{\partial f}{\partial x_n}\delta x_n\right)^2} \tag{22}$$

As we have:

$$q = f(x_1, x_2, ..., x_n) = x_1 + x_2 + ... + x_n \tag{23}$$

The total error is obtained by adding the absolute uncertainties in quadrature:

$$\delta q = \sqrt{(\delta x_1)^2 + (\delta x_2)^2 + ... + (\delta x_n)^2} \tag{24}$$

Confidence interval (for one year): ± 0.02%
Adjusted fuel consumption: 2.6% above theoretical ANCAT results

	2004	2005	2006
Error Rate	0,0204%	0,0198%	0,0193%

This analysis assumes there is no systematic error in the methodology that may make the errors additive.
The two major uncovered gaps go in opposite directions: The impossibility of filtering Public Obligations flights slightly increases the historical emissions, while the airlines not reporting APU consumption with engines off reduces the calculation numbers. In both cases the differences are clearly below 0,1% of the total emissions.

5. FUTURE DEVELOPMENTS

A modification of Member States entails the recalculation of Historical Aviation CO_2 Emissions, since the cap of emissions is based on that value, and would not be logical to base the reduction of emissions on a different scope.
The main factor that affects the methodology for including a State into the ETS is the source of air traffic information used to calculate the Historical Aviation CO_2 Emissions. As explained in the methodology used by EUROCONTROL (ref. [8]), the information is fully reliable after the State has become a contracting State to the EUROCONTROL Multilateral Agreement for Route Charges.
The CRCO governs the EUROCONTROL route charges system and becomes the main source of flight information data for the calculation of the Historical Aviation CO_2 Emissions.
The different methodologies applied will depend on the level of information available, contingent on whether the entering State is in the EUROCONTROL Multilateral Agreement for Route Charges, and since when, as described bellow:

Case 1 - EUROCONTROL CRCO Multilateral Agreement Contracting State since or before January 1st, 2004

In this case, EUROCONTROL has the flight information of the years 2004, 2005, and 2006; and the developed methodology should be used for the direct calculation of Historical Aviation CO_2 Emissions.

Case 2 - EUROCONTROL CRCO Multilateral Agreement Contracting State after January 1st, 2004

In the case of an adherence of a EUROCONTROL member with incomplete information, the following methodology should be applied:
The new Member State shall provide, if available, IFR air traffic information of 2004, 2005, and 2006. If this data is provided, it is cross-checked with CRCO data for reliability. If the data is found reliable, it shall be used for the calculation of Historical Aviation CO_2 Emissions. If the data is found unreliable or it is not provided by the State, the next steps shall be executed:

- Since the entering State is a EUROCONTROL Member, there will be CRCO data for the previous years before the accession into the ETS. The emissions represented by the gap shall be weighted for those years, and averaged in percentile.
- The percentile found in the previous paragraph shall be applied to the CRCO data for the years 2004, 2005, and 2006 to estimate the gaps and calculate the Historical Aviation CO_2 Emissions. Any source of information available to improve the estimation should be considered for this task.

Case 3 - Non-EUROCONTROL CRCO Multilateral Agreement Contracting State

In the case of an adherence of a non-EUROCONTROl Member, only information of flights entering Eurocontrol airspace for the years 2004, 2005, and 2006 will be available. Hence, the following methodology should be applied:
The entering State shall provide, if available, IFR air traffic information of 2004, 2005, and 2006. If this data is provided, it shall be cross-checked with CRCO data for reliability. If the data is found reliable, it shall be used for the calculation of Historical Aviation CO_2 Emissions. If the data is found unreliable or it is not provided by the State, the next steps shall be coordinated between the entering State and EUROCONTROL:

- A monitoring period shall be applied to weight the gap in percentile (Emissions of flights entering the EU-27 EUROCONTROL airspace vs. other flights' emissions to which the Directive applies).
- The percentile found in the previous paragraph shall be applied to the CRCO data for the years 2004, 2005, and 2006 to estimate the gaps and calculate the Historical Aviation CO_2 Emissions.

6. CONCLUSIONS

The main conclusion of this study is that the methodology used by EUROCONTROL to calculate the CO2 emissions as described by the Directive, represents a very good approximation given the data available, once the suggested adjustments have been introduced.

The reconciling methodology accomplishes the purpose of identifying improvement opportunities in the methodology used by EUROCONTROL. The main approach taken to achieve these improvements is a macro-scale correction of the fuel consumption coefficients of the ANCAT 3 Methodology used by EUROCONTROL. The proposed statistical approach relies on the representativeness of the fuel consumption sample submitted by the operators. The result is a set of correction factors depending on the type of aircraft. Although these factors has been calculated based on 2007-2008 actual consumption data, it is assumed that the European flight space structure has not changed significantly between the 2004-2006 period and the two following years. Therefore, the aggregated difference between calculated and actual consumptions remains the same.

The reconciling factors do not vary the fundamental principles of the initial methodology; however, allowed to improve the accuracy of the assessment thus reducing the risk of underestimating or overestimating the total emissions for 2004-2006.

The methodology presented for the possible change of scope of the Emissions Trading Scheme ensures that this change does not suppose unfairness among the Member States, or unbalance the aircraft operators' economic market, while maintaining a continuous reduction of emissions allowances.

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