A new Danish inventory for IFR flights used to improve national fuel use and emission estimates

Morten WINTHER

National Environmental Research Institute, Frederiksborgvej 399, 4000 Roskilde, Denmark
Fax: +45 4630 1212 - e-mail: mwi@dmu.dk

Abstract
This paper describes 1) a new model developed for calculating the fuel use and emissions for all IFR (Instrumental Flight Rules) jet and turbo-prop flights in Denmark, Greenland and the Faroe Islands in 1998 and 2) recommendations to improve the current model used for national estimates based on the new model results. The new model uses the new detailed CORINAIR (COoRdination of Information on AIR emissions) calculation principle. It was feasible to set up the inventory system. Air traffic data was provided by EUROCONTROL and information on aircraft types and airport codes was obtained from ICAO (International Civil Aviation Organization). All aircraft were grouped into 24 representative aircraft types for which fuel use and emission data were available in the CORINAIR databank per LTO and for distance classes. Cruise results were estimated for each flight by adjusting for the given flight length. Except for international Landings and Take Offs (LTO< 3000ft) in Copenhagen Airport it is recommended to update all fuel use and emission data in the current model for national estimates. The improved data can be derived from the new model results. There is also a need to further scrutinize for which purposes the aviation fuel is used in Danish Airports. The present study's results could be valuable in a cross-check examination of statistical data versus model estimates.

Keywords: EUROCONTROL, Air traffic, Emission inventories, ANCAT/EC2, MEET, TEMA2000, LTO, cruise, CO, NO_x*, VOC,* CO_2*.*

1. Introduction

Like other transport modes aviation have many environmental effects such as noise, odour, land use and air pollutant emissions. On the air pollution side two environmental effects must be given extra attention: Global warming and ozone depletion. These effects will be fortified in the future given the prospect of a 5% increase per year in travel by air for the next 20 years. Also air pollutants emitted at cruise flying levels are found to be more harmful compared to emissions from sources at the Earth's surface, and in addition most fuel use and emissions occur in this flying phase.

In order to bring down emissions according to national target plans and international agreements and also for monitoring the state of the environment Denmark is obliged to make annual air emission estimates for all sectors including aviation. For this purpose Denmark participates in the extensive European air emission inventory programme CORINAIR (COoRdination of Information on AIR emissions), see CORINAIR (1999). The inventory system includes calculation methodologies for most sub-sectors and a software for storage and further data processing. In CORINAIR the aircraft inventory is based on aviation fuel sale statistics and the emissions should be estimated per aircraft type in four groups; domestic and international emissions from landing and take offs (LTO < 3000 ft) and cruise (> 3000 ft).

The objective of this paper is to explain the procedure for estimating the fuel use and emissions from IFR (Instrumental Flight Rules) flights according to the new CORINAIR guidelines (CORINAIR, 1999) and to recommend improvements of the current method, see CORINAIR (1996), used to calculate the Danish aircraft emissions (Winther, 1999). For specific domestic flights the new results are also compared to other model results. The calculation procedure is made operational by establishing an emission inventory model for jet and turbo-prop flights from airports in Denmark, Greenland and the Faroe Islands in 1998.

2. Methods

Several types of information must be available in order to set up a proper emission inventory system for aircraft. These are consistent flight data, descriptions of aircraft categories and fuel use and emission data to support the final calculation procedure. The current CORINAIR methodology has been recently revised and more updated and detailed fuel use and emission data have become available. A major improvement is the inclusion of fuel use and emission numbers for cruise flying conditions. The figures are given for different distance classes and a variety of representative aircraft types.

2.1 New CORINAIR method

Aircraft categories and flight data

ICAO (International Civil Aviation Organization) classify all single aircraft according to aircraft designator code, aircraft type, number of engines and engine principle (ICAO, 1998). The designator codes usually derive from the manufacturers model number or model name, or from a common military type number. Airports are also provided with four letter codes indicating e.g. routing area and state, see ICAO (1999). In the present study this information was used in connection with 1998 EUROCONTROL (European Organization for the Safety of Air Navigation) data on IFR flights from Denmark, Greenland and the Faroe Islands.

Essential recordings for each flight were date and time of departure, type designator, origin and destination airport codes and great circle distance. Some flights were excluded from the inventory due to lack of fuel use and emission data, namely all piston engined flights, military aircraft and helicopter operations. Omitted were also flights with no indication of great circle distance, i.e. flights with same origin and destination airport code. Many of these flights were actually military movements.

Representative aircraft and groupings

In 1998 all civil jet and turbo-prop flying in Denmark was made by 145 different aircraft types. To facilitate the calculations these were grouped into 24 representative aircraft classes for which fuel use and emissions were available in the CORINAIR databank (see www.eea.int/aegb/). The procedure was to find the approximate MTOW (Maximum Take Off Weight) numbers in Frawley (1999) for all aircraft and to append representative types with similar size and engine principle. In many situations the representative aircraft type comprised several models with numerous MTOW's (and seating capacities) and due to this the indicated weight numbers must be regarded only as approximate values.

Representative aircraft	MTOW [tonnes]	Fuel [kg/LTO]	NO_x [kg/LTO]	VOC [kg/LTO]	CO [kg/LTO]	Dom. LTOs	Int. LTOs
A310	142	1,541	23.2	5.5	25.8	145	2,046
A320	73.5	802	10.8	1.9	17.6	231	4,644
A330	220	2,232	36.1	2.1	21.5	16	176
A340	275	2,020	35.4	18.8	50.6	0	237
B727	95	1,413	12.6	7.2	26.4	601	3,078
B737 100	52	920	8.0	0.6	4.8	6	2,259
B737 400	63	825	8.3	0.7	11.8	7,319	23,992
B747 100-300	362	3,414	55.9	37.3	78.2	0	0
B747 400	362	3,402	56.6	1.8	19.5	2	498
B757	116	1,253	19.7	1.2	12.5	1	1,172
B767 300ER	182	1,617	26.0	0.9	6.1	85	3,666
B777	247	2,563	53.6	22.8	61.4	0	3
BAC1-11	40	682	4.9	21.4	37.7	0	161
Bae146	42	570	4.2	1.0	9.7	128	3,813
Dash8 400	27.3	340	3.2	0.0	2.4	66	1,379
DC10	259	2,381	41.7	22.8	61.6	11	1,040
DC9	55	876	7.3	0.8	5.4	651	10,954
F100	43	744	5.8	1.4	13.7	9	785
F28	33	666	5.2	32.9	32.7	28	2,387
F50	20.8	216	1.9	0.0	1.6	25,532	21,118
MD82-88	64	1,003	12.3	1.9	6.5	15,584	28,706
RJ 100	18	246	1.5	0.5	5.7	1,489	4,372

S2000		22.8	247	1.4	0.1	1.7	183	1,400
Shorts 300	360	12.3	133	0.5	1.6	7.3	11,208	8,427
Total							63,295	126,313

Table 1 MTOWs, LTO fuel use and emission factors and no. of LTOs for rep. aircraft

The simulated fuel use and emissions for jets originated from the models behind the ANCAT/EC2 (1998) and MEET (1999) projects. For turbo-props and small jets the data came from the model developed by FFA (2000). The large jets were generic – meaning that the world-wide population of engines fitted to the aircraft in question was considered during simulations. Since the fuel use and emission data derive from different models inter-aircraft comparisons must be made with care for some aircraft. Also due to model boundary conditions the uncertainties on cruise fuel use and emission data are greater for the shortest flights.

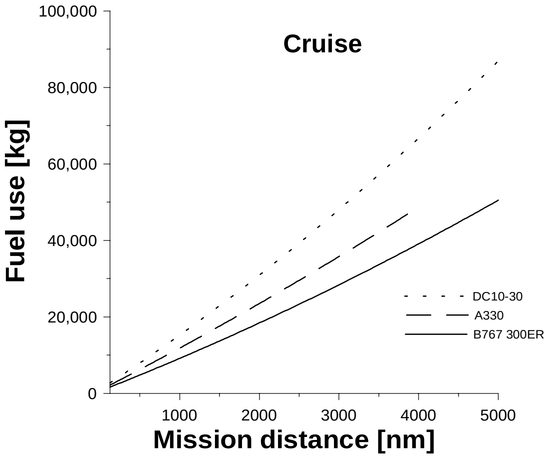


Figure 1 Fuel use per distance

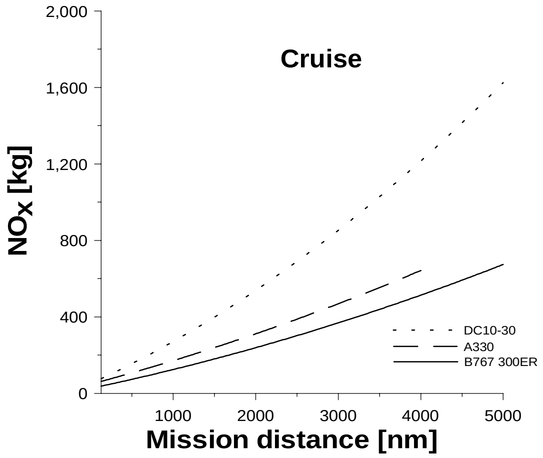


Figure 2 NO_x emission per distance

Fuel use and emissions calculation

For each flight the fuel use and emissions was computed separately for LTO and cruise. LTO results were calculated according to the following sum formula:

$$E_{LTO} = \sum_{i=1}^{5} E_i \qquad (1)$$

Where E_i is the fuel use or emission contribution from each of the five LTO-modes: Approach/landing, taxi in, taxi out, take off and climb out for each representative aircraft. Original data for large jets taxi in and out was given for 13 mins, while more appropriate time intervals was 5.5 mins in Copenhagen Airport and 2.5 mins in other airports present in the

Danish inventory. The fuel use and emission numbers were down-scaled in the calculation procedure according to this rationale.

To estimate cruise results, fuel use and emissions for standard flying distances were either interpolated or extrapolated – in each case determined by the great circle distance stated by EUROCONTROL. Accordingly two equations were used.

If the great circle distance, y, is smaller than the maximum distance for which fuel use and emission data are given in the CORINAIR data bank the fuel use or emission E (y) becomes:

$$E(y) = E_{x_i} + \frac{(y - x_i)}{x_{i+1} - x_i} \cdot (E_{x_{i+1}} - E_{x_i}) \qquad y<x_{max},\ i = 0,1,2\ldots max-1 \quad (2)$$

In (2) x_i and x_{max} denominate the separate distances and the maximum distance, respectively, with known fuel use and emissions. If the flight distance y exceeds x_{max} the maximum figures for fuel use and emissions must be extrapolated and the equation then becomes:

$$E(y) = E_{x_{max}} + \frac{(y - x_{max})}{x_{max} - x_{max-1}} \cdot (E_{x_{max}} - E_{x_{max-1}}) \qquad y>x_{max} \quad (3)$$

Total results were summed up and categorised according to each flight's airport and country codes.

2.2 Current CORINAIR method

In the current CORINAIR method information is obtained on the number of domestic and international LTOs per aircraft type and in some cases also their respective LTO times-in-modes. The most detailed data are available for Copenhagen Airport, where an EIA (Environmental Impact Assessment) has been made (Copenhagen Airport, 1996). In this work all large aircraft types are grouped into 20 different representative aircraft types. A survey is also made to find the most frequently used engine type for each of these aircraft and in parallel LTO times-in-modes have been measured in the airport. Other Danish airports only submit their statistics for domestic and international LTOs in total numbers for large and small aircraft (Statistics Denmark, 1999) with no information on actual LTO time durations.

In ICAO (1995) fuel flow and emission indices are given for all four LTO modes and each representative aircraft engine type. The indices are combined with the actual LTO times-in-modes, in order to calculate the total LTO fuel use and emission factors for flights leaving Copenhagen Airport. The number of flights per representative aircraft are found in the airport's own air traffic statistics regardless of destination (Copenhagen Airport, 1999). These flights are all assumed to be international, since no division per aircraft type into domestic and international flights can be provided by the airport. The assumed flight number is compared to the total number from Statistics Denmark (1999). The flight number difference is subtracted from the F50 flight number and added to domestic flights. The latter flights are also represented by a F50.

The total LTO fuel use and emissions are calculated as the LTO fuel use and emission factors times the number of LTO per representative aircraft. The calculations are done separately for domestic and international flights. In the same two flight categories the cruise energy use is estimated as the difference between the total fuel use from aviation fuel sale statistics and the corresponding LTO fuel use totals. Finally the domestic and international cruise emissions are derived as fuel related cruise emission factors multiplied with the fuel use. Due to scarce data on cruise fuel use and emission factors, results are not broken down further on aircraft types.

3. Results

3.1 New method

Danish international flights (by fuel use almost solely from Copenhagen Airport) stand for almost two thirds of all flights and have even larger shares of fuel use and emissions; in total between 80 and 90%. This is explained by the presence of larger sized aircraft in service and longer flying distances. For LTO the international shares are close to 80% - due to larger aircraft and more flights – and for cruise around 90% because of larger aircraft and more and longer flights. North Atlantic flights between Denmark and Greenland/Faroes reveal the same trend by shares as for Danish international flights, although fuel use and emissions are only between 2 and 3% in total numbers. Contributions from international flights from Greenland and the Faroe Islands have no importance to the total emission budget. Almost one third of all flights are Danish domestic flights. Opposed to international flights they have more moderate fuel use and emission shares compared to flight numbers. The reason why is the use of smaller aircraft and shorter trips.

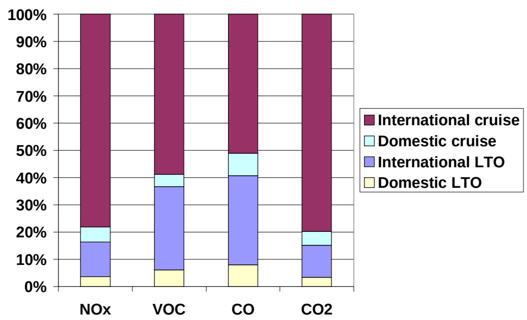


Figure 3 Danish aviation emission shares

3.2 New and current method

Two modifications of the database for flights have been made in order to evaluate the new model with the current version. First of all flights from Denmark bound for Greenland and the Faroe Islands are regarded as international, in order to suit the official fuel sale statistics. Next a distinction is made between flights from Copenhagen airport and all other airports in the

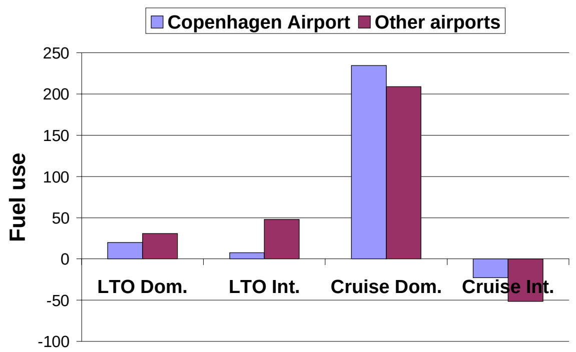
Kingdom of Denmark to support the current model's available fuel use and emission data. To obtain new model results fuel use and emissions was computed with (2) and (3).

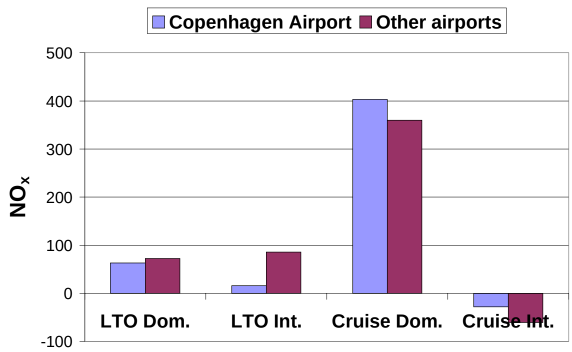
Total differences

In grand totals the fuel use computed with the new methodology only amounts to 80% of the jet fuel sold in Danish airports. Almost the same model difference occurs for NO_x, while the new methodogy calculates 40% more CO and inversely only 36% of the old VOC emissions estimate. Since international flights use almost 97% of all Danish jet fuel according to fuel sale statistics, variations in total fuel use and emission figures between the two methods are almost the same as the differences that appears for this sector.

A very bad fuel use agreement is obtained for domestic air traffic alone; the new fuel estimate is almost twice as high as fuel sale numbers. New emission estimates for national flights are 177, 72 and 236% more for NO_x, CO and VOC, respectively.

Although helicopter operations are excluded from the new methodology, the smaller calculated fuel use amount and the large domestic fuel use deviation must primarily be explained by other factors. Many parameters have a potential effect on the precision of the fuel balance. These are the use of jet petrol for non-aviation purposes or military flying, fuel tankering and inaccurate domestic-international energy statistics. Factors which can affect the actual city-pair estimations are stacking at airports, the omittance of flights with the same origin and destination airports, model simulation uncertainties during cruise, inaccurate LTO times-in-modes or unrepresentative groupings for some of the aircraft into representative types.





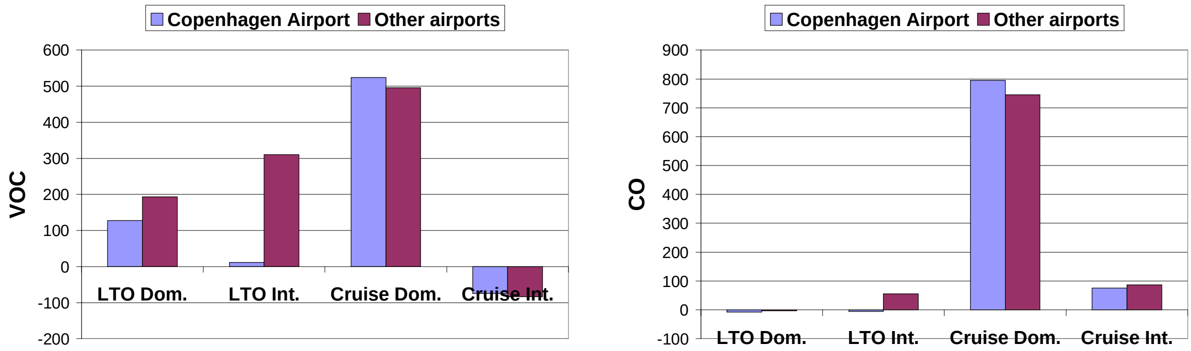


Figure 4 Difference in percent between new and current CORINAIR method

Differences for LTO

Looking into the differences in LTO fuel use and emission estimates the most similar results are obtained for international LTOs in Copenhagen airport. This is also the part of the current model were precise details are given in terms of different aircraft types and LTO times-in-modes. For LTO the weakest part of the current methodology regards all domestic air traffic and international air traffic in the provincial airports. In these inventory categories the estimates are based on fuel use and emission information for only one aircraft (F50) and this data scarcity is reflected in the result deviations.

Apparently F50 is a little to small to be the fully representative choice of aircraft, since much flying is made with the larger jets MD80 and B737 thus influencing the total fuel consumption. In particular the fuel use is underestimated by the current model for international LTOs in provincial airports. Here the new methodology with a detailed fleet mix computes almost 50% more fuel.

Most comparable emission results for the three LTO classes appear for domestic LTO CO emissions, where the two model estimates are of similar size. The NO_x emissions are over 60% up to almost twice as high for the new methodology in the three sectors. For VOC the differences are even bigger; the new estimates are from twice to over forth the emission amount computed with the current method.

Differences for cruise

For cruise the fuel use is found in the current methodology as the difference between national fuel sale numbers and calculated fuel use for LTO. The break down of cruise fuel use for flights from Copenhagen Airport and provincial airports are made according to the total number of flights irrespective of aircraft type. For domestic flights the aircraft size distributions in Copenhagen Airport and other airports are comparable, while larger aircraft in general make international flights from Copenhagen Airport. The latter airport therefore tend to get a too small cruise fuel use amount in the current method.

3.3 New method and the TEMA2000 model

Individual model results widely depend on the modelling principles and the selected engine types, which determine the fuel flows and emission indices to be used in the simulation procedure. A comparison of results obtained with different models will enevitably reflect these individual choises. In CORINAIR the fuel use and emission factors are produced by weighting fuel use and emission performances for the most frequently used engines worldwide. The Danish TEMA2000 model[1] (Trafikministeriet, 2000) use fuel use and emissions for domestic flights simulated with the ATEMIS model (Kalivoda and Feller, 1995). The latter model use real world flight profiles and one aircraft/engine combination for each aircraft type.

Aircraft type	Destination	Distance	Fuel	$EINO_x$	EIVOC	EICO
MD 82	Århus	95	103	107	78	75
F50	Århus	95	121	132	0	82
DC9	Århus	95	92	107	21	29
B737 400/B737 500	Århus	95	115	110	65	73
B737 400/B737 600	Århus	95	99	104	39	83
MD 82	Aalborg	99	106	112	78	75
F50	Aalborg	99	122	144	0	91
DC9	Aalborg	99	94	110	24	32
B737 400/B737 500	Aalborg	99	113	116	70	77
B737 400/B737 600	Aalborg	99	102	111	39	82

Table 2 Ratio between CORINAIR and TEMA2000 fuel use and EI results

The flight distances in TEMA2000 and the present study's great circle distances are almost the same. For fuel use the largest variations in results are observed for F50; the present study computes about 20% more fuel. In TEMA2000 the F50 simulations are not based on the actual engine fitted to the aircraft. Instead emission indices[2] (EI) from another engine type is used together with fuel flow rates for F50. In CORINAIR the actual engine type (PW125B) is used with no VOC emissions reported. Except for F50 – with a smaller $EINO_x$ in TEMA2000 – the modelled $EINO_x$ have about equal numbers for all aircraft on both routes.

For CO and VOC the present study's EI's are lower and most remarkably are the deviations for DC9. The EI's are only one third and one fourth of the TEMA2000 figures for CO and VOC, respectively. For DC9 several engines are used in combination in CORINAIR. One of the engines with a minor share of 8% is behind the DC9 in TEMA2000.

[1.] TEMA2000 is developed for the Danish Ministry of Transport by COWI Consulting Engineers and Planners
[2] EI: Emissions in g per kg fuel burned

Though a little lower the present study's CO and VOC EI for B737-400 are comparable to the numbers for B737-500 and MD82 in TEMA2000. In CORINAIR the generic engine is mainly a weighting of three engines of which the engines in TEMA2000 have a 45 and 40% share for B737-500 and MD82, respectively. The present study's EIVOC for B737-400 is substantially lower than the B737-600 index in TEMA2000. The engine in the latter aircraft is not among the engines used by CORINAIR.

4. Recommendations and conclusions

This study has shown the feasibility of the new CORINAIR methodology for making city-pair aircraft emission inventories. Consistent data for individual flights and general classifications of aircraft types and airports exist together with fuel use and emission data for representative aircraft types. In this way EUROCONTROL provides information for individual IFR flights which correspond to essential data from ICAO on aircraft designators and airport codes. All information can be combined to build up the inventory system. In order to make the final grouping of aircraft into representative aircraft, additional aircraft descriptions can be obtained from aircraft directories.

Much time is needed to build an aircraft emission inventory following the new CORINAIR guidelines. Even though it would be less time consuming to make an inventory update each year, the working time required will exceed the amount of time typically available for inventories - not least considering the requirements for emission estimates in other CORINAIR sectors. Therefore it is recommended to maintain the current methodology for national emission reporting. Instead of a shift to the new model version, one should make an update of the current model's background data for fuel use and emissions.

Real improvement of the current version for LTOs - except for international LTOs in Copenhagen Airport – could be achieved by applying new LTO fuel use and emission factors derived from the new methodology as aggregated figures. For cruise it is recommended to break down the fuel use used by flights from Copenhagen Airport and other Danish airports according to their LTO fuel use estimates. This should be done separately for domestic and international traffic. Also the cruise emission indices should be updated. Both for domestic and international flights these can be derived from the new methodology results.

It is recommended to use the TEMA2000 numbers if fuel use and emissions are evaluated for those domestic trips flown with the aircraft comprised in TEMA2000. For domestic emission inventories the CORINAIR data should be used primarily because of data consistency and because CORINAIR contains data for small jets and turbo-props not present in TEMA2000. The latter reason fully compensates for the inaccuracy in results for some aircraft due to model boundary conditions.

This study’s findings clearify the need to further scrutinize for which purposes the aviation fuel is used in Danish Airports. A way to do this is to examine the most detailed data on aviation fuel delivered to the airports. Also airport authorities responsible for aviation fuel suppliance should be asked and their information verified by analysing other data available. Most urgent is the need for a more precise distinction between fuel used for national and international flights. In this specific field the present study’s results could be valuable in a cross-check examination of statistical data versus model estimates.

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