AIRCRAFT EMISSIONS

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This paper was written by Kristin Rypdal (Statistics Norway). It was reviewed by Niels Kilde, Steve Seide and Karen Treanton.

ABSTRACT

The current tiered methodologies in the Greenhouse Gas Inventory Reference Manual provide a good framework for *good practice* for estimating and reporting the emissions from aviation. The main difficulty and uncertainty lies in the distribution of fuel between domestic and international use. Only domestic use is to be included in the national total when reporting to the United Nations Framework Convention on Climate Change (UNFCCC). Consequently, *good practice* methodologies are particularly needed in order to collect relevant and accurate data on domestic fuel used for aviation. Emissions of nitrous oxide (N_2O) and methane (CH_4) from aviation are highly uncertain, but do not contribute much to national totals.

1 INTRODUCTION

The total contribution of aircraft emissions to total anthropogenic carbon dioxide (CO_2) emissions was considered to be about 2 percent in 1990 (IPCC, 1990). However, air traffic in the world is growing, and will likely continue to grow. Though there is an improvement in fuel efficiency of new aircraft, the long lifetime of aircraft and the expected growth in air traffic imply that this emission source in the future will increase in importance.

The UNFCCC Secretariat has concluded that the method to estimate bunker (ships and aircraft) emissions is incomplete and not consistent between Parties, and that most parties have not specified the methodology used. Reported data also indicate that, for shipping and aircraft bunkers, CO_2 accounts for 98 percent of the CO_2 equivalent emissions.

The effect of emissions from aircraft at high altitudes (especially nitrogen oxides (NO_x) and water vapour) is of particular concern. In the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines),* emissions from aircraft are to be reported in an equal manner to emissions from other sources, not specifying the altitude of the emissions and applying the same Global Warming Potential (GWP) values. Nitrogen oxides and water vapour are not included in the Kyoto Protocol.

1.1 Nature, magnitude, and distribution of sources

Emissions from aircraft originate from fuel burned in aircraft engines. Greenhouse gas emissions are the combustion products and by-products. CO_2 and NO_x are most important, but also methane, nitrous oxide and other by-product gases are emitted. The fuel use and emissions will be dependent on the fuel type, aircraft type, engine type, engine load and flying altitude.

Two types of fuels are used. *Gasoline* is used in small piston engined aircraft only. Most aircraft run on kerosene, and the bulk of fuel used for aviation is kerosene.

In general, there exist two types of engines; *reciprocating piston* engines, and *gas turbines* (Olivier (1991) and EEA (2000)). In *piston engines*, energy is extracted from a combustion chamber by means of a piston and crank mechanism that drives the propellers to give the aircraft momentum. In *gas turbines* compressed air is heated by combustion in a combustion chamber and the major part of this is used for propulsion of the aircraft. A part of the energy contained in the hot air flow is used to drive the turbine that in turn drives the compressor. Turbojet engines use only energy from the expanding exhaust stream for propulsion, whereas turbofan and turboprop engines use energy from the turbine to drive a fan or propeller for propulsion.

The air traffic is often divided into four categories (EEA 2000):

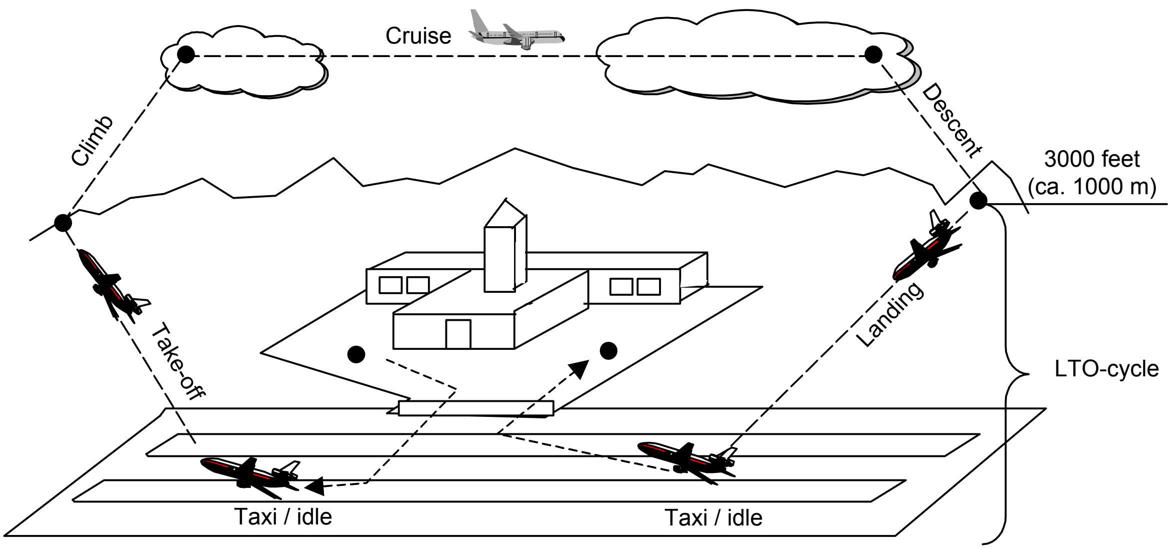
- Civil IFR (Instrumental Flight Rules) flights;
- Civil VFR (Visual Flight Rules) flights, also called general aviation;
- Civil Helicopters, and
- Operational Military flights.

Most emissions originate from the first category, which covers the scheduled flights of “ordinary” aircraft.

Operations of aircraft are usually divided into two main parts (Figure 1) (EEA 2000):

- The *Landing/Take-off* (LTO) *cycle* which includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). This therefore includes taxi-in and out, take-off, climb-out, and approach-landing. The LTO is defined in ICAO (1993), and
- *Cruise* which here is defined as all activities that take place at altitudes above 3000 feet (1000 m). No upper limit of altitude is given. Cruise, in the inventory methodology, includes climb to cruise altitude, cruise, and descent from cruise altitudes.

Figure 1 Standard flying cycle



1.2 The current state of inventory methodologies

The current methodology proposes two Tiers. The most simple methodology (Tier 1) is based on knowledge of fuel use only, while the Tier 2 is also based on information of the number of LTOs. In both Tiers emissions from domestic and international air traffic are to be estimated separately. The fuel used for international air traffic is defined *as all fuel sold for aviation in the reporting country not used for domestic aviation*.

1.2.1 Tier 1

The simplest methodology is based on an aggregate figure of fuel consumption for aviation to be multiplied with average emission factors. The emission factors have been averaged over all flying phases based on an assumption that 10 percent of the fuel is used in the LTO phase of the flight.

The following are the default emission factors:

CO_2 : 19.5 tonne C/PJ;

CH_4 : 0.5 kg/PJ, and

N_2O : 2 kg/PJ

Aggregate emission factors are also given for NO_x, carbon monoxide (CO), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOCs).

1.2.2 Tier 2

In the Tier 2 methodology, a distinction is made between emissions below and above 1000 m (3000 feet). The emissions in these two flying phases are estimated separately.

LTO emissions

Emissions and fuel used in the LTO phase are estimated from statistics on the number of LTOs (aggregate or per aircraft type) and default emission factors or fuel use factors per LTO (average or per aircraft type).

For the aircraft type based approach (Table 1), the table covers aircraft types frequently used for domestic and international aviation. The methodology also gives aggregate emission factors per LTO (Table 2). The aggregated emission factors are proposed for national and international aircraft separately, and for old and average fleet.

TABLE 1

DEFAULT FUEL USE AND EMISSION FACTORS FOR SOME AIRCRAFT TYPES FOR LTO CYCLE. KG/LTO

Aircraft type[a)]	CO_2	CH_4[b)]	N_2O[c)]	NO_x	CO	NMVOCs	SO_2[d)]	Fuel
A300	5470	1.0	0.2	27.21	34.4	9.3	1.7	1730
A310	4900	0.4	0.2	22.7	19.6	3.4	1.5	1550
A320	2560	0.04	0.1	11.0	5.3	0.4	0.8	810
BAC1-11	2150	6.8	0.1	4.9	67.8	61.6	0.7	680
BAe 146	1800	0.16	0.1	4.2	11.2	1.2	0.6	570
B707*	5880	9.8	0.2	10.8	92.4	87.8	1.9	1860
B727	4455	0.3	0.1	12.6	9.1	3.0	1.4	1410
B727*	3980	0.7	0.1	9.2	24.5	6.3	1.3	1260
B737-300	2905	0.2	0.1	8.0	6.2	2.0	0.9	920
B737*	2750	0.5	0.1	6.7	16.0	4.0	0.9	870
B737-400	2625	0.08	0.1	8.2	12.2	0.6	0.8	830
B747-200	10680	3.6	0.3	53.2	91.0	32.0	3.4	3380
B747*	10145	4.8	0.3	49.2	115	43.6	3.2	3210
B747-400	10710	1.2	0.3	56.5	45.0	10.8	3.4	3390
B757	4110	0.1	0.1	21.6	10.6	0.8	1.3	1300
B767	5405	0.4	0.2	26.7	20.3	3.2	1.7	1710
Caravelle*	2655	0.5	0.1	3.2	16.3	4.1	0.8	840
DC8	5890	5.8	0.2	14.8	65.2	52.2	1.9	1860
DC9	2780	0.8	0.1	7.2	7.3	7.4	0.9	880
DC10	7460	2.1	0.2	41.0	59.3	19.2	2.4	2360
F28	2115	5.5	0.1	5.3	54.8	49.3	0.7	670
F100	2340	0.2	0.1	5.7	13.0	1.2	0.7	740
L1011*	8025	7.3	0.3	29.7	112	65.4	2.5	2540
SAAB 340	945	1.4(E)	0.03(E)	0.3(E)	22.1(E)	12.7(E)	0.3(E)	300 (E)
Tupolev 154	6920	8.3	0.2	14.0	116.81	75.9	2.2	2190
Concorde	20290	10.7	0.6	35.2	385	96	6.4	6420
GAjet	2150	0.1	0.1	5.6	8.5	1.2	0.7	680

Source*: IPCC Guidelines* on National Greenhouse Gas Inventories. Reference Manual, page 1.96.

*The emission factors for domestic aviation have been derived from an average of a number of typical aircraft. For domestic aircraft, the average fleet is represented by Airbus A320, Boeing 727, Boeing 737-400, Mc Donell Douglas DC9 and MD 80 aircraft. The old fleet is represented by Boeing B737 and Mc Donell Douglas DC9. For international traffic the average fleet is represented by Airbus A300, Boeing 767, B747 and Mc Donell Douglas DC10, whilst the old fleet is represented by the Boeing B707, Boeing 747 and Mc Donell Douglas DC8. Sulphur content of the fuel is assumed to be 0.05% S for both LTO and cruise activities

TABLE 2

DEFAULT FUEL USE AND EMISSION FACTORS FOR AVERAGE AIRCRAFT FOR LTO CYCLE AND CRUISE

Domestic	Fuel	SO_2	CO	CO_2	NO_x	NMVOCs	CH_4	N_2O
LTO (kg/LTO) - Average fleet	850	0.8	8.1	2680	10.2	2.6	0.3	0.1
LTO (kg/LTO) - Old fleet	1000	1.0	17	3150	9.0	3.7	0.4	0.1
Cruise (kg/ton)		1.0	7	3150	11	0.7	0	0.1
International	**Fuel**	**SO_2**	**CO**	**CO_2**	**NO_x**	**NMVOCs**	**CH_4**	**N_2O**
LTO (kg/LTO) - Average fleet	2500	2.5	50	7900	41	15	1.5	0.2
LTO (kg/LTO) - Old fleet	2400	2.4	101	7560	23.6	66	7	0.2
Cruise (kg/ton)		1.0	5	3150	17	2.7	0	0.1

Source: IPCC Guidelines on National Greenhouse Gas Inventories. Reference Manual, page 1.98.

Cruise emissions

The cruise emissions will be dependent on the length of the flight (among other variables). In the Tier 2 methodology, the fuel used in the cruise phase is estimated as total fuel use minus fuel used in the LTO phase of the flight (Figure 2). This is performed for domestic and international aviation separately.

The estimated fuel use is to be multiplied with aggregate emission factors (Table 2) in order to estimate the emissions. According to the default emission factors, methane is not emitted in the cruise phase of the flight.

2 METHODOLOGICAL ISSUES

We will here highlight some issues of particular concern related to the proposed methodologies. Some of these issues are common to both Tiers, while some are specific.

The main difficulty in applying the methodology is to get the correct data on fuel use. The energy statistics in most countries only give data on total sales or supply of fuel for aviation, without distinguishing between domestic and international as required for reporting of emissions of greenhouse gases. The *IPCC Guidelines* do not give any advice on how to obtain these data as required.

Kerosene is also used for heating purposes. Kerosene used for aviation and kerosene used for heating is usually distinguished in the energy statistics (different qualities), but there may be countries where these data are aggregated.

The emission factors of CO_2 per fuel basis are well determined as aviation fuel has a well-defined quality. This means that country-specific values of CO_2 emission factors (on a per fuel basis) should never deviate much from default values. The emission factors of N_2O and CH_4 must be considered to be highly uncertain. However, as the latter pollutants do not contribute much to total emissions in the overall inventory, this is not of a great concern. Countries should be encouraged to determine better emission factors for CH_4 and N_2O to improve the default values in the future.

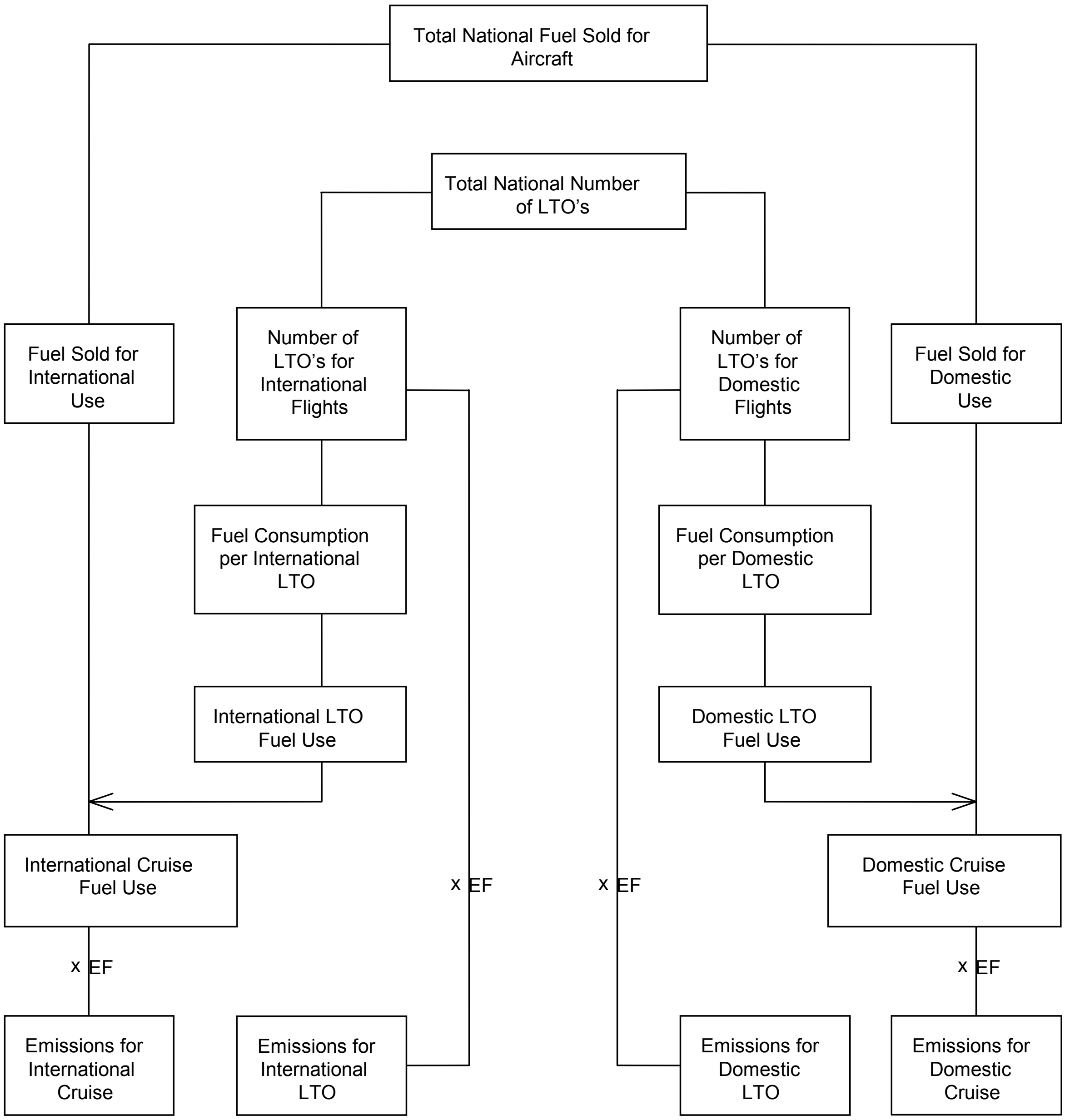
2.1 Tier 1

The Tier 1 methodology is very simple, but is usually appropriate for estimating CO_2, CH_4 and N_2O emissions with the current knowledge of emission factors.

The main reasons for encouraging the use of higher tiers are as follows:

- Increased transparency with respect to reporting of other pollutants in other inventories (e.g. CORINAIR);
- Gives the possibility to obtain time series reflecting changes in technology;
- Gives the possibility to verify the estimates;
- Allows (possible future) reporting of emissions from cruise and LTO separately, and
- Gives more accurate NO_x estimates.

Figure 2 Tier2 methodology for estimating emissions from aircraft



2.2 Tier 2

Data to be used in the Tier 2 methodology (the aggregated number of LTOs) are likely to be available in most countries. However, the LTO per aircraft type is not always available. In both cases, the methodology will require that the number of LTOs be available for domestic and international aviation separately, which may not always be the case.

There are some weaknesses in the Tier 2 methodology:

- The aggregate emission factors and fuel use factors are based on fuel use of average aircraft. If the average aircraft is different in a particular country the estimated fuel use may be wrong. This may be the case in countries with a higher proportion of small or large aircraft than assumed in Table 2. The default aircraft are, in fact, quite large and will overestimate LTO emissions in most countries;
- If the estimation is based on Table 1, some common aircraft will not be found in the table. These may be new aircraft with presumably lower fuel consumption than average (e.g. MD80, MD90 and new generation 737s) and perhaps also some special type of aircraft that may be in use outside USA and Western Europe, and

- LTO data are available for scheduled flights only (category 1). Flights with e.g. helicopters, taxi flight, pleasure flights etc. will not be covered by the methodology. In most countries these emissions are insignificant, but in some countries they will have to be taken into account.

The emission factors given in the Tier 2 methodology reflect the state-of-the-art knowledge (ICAO (1995) and ANCAT/EC (1998)). The knowledge on emissions during the LTO part of the flight is, however, far better than the knowledge on emissions during cruise. The emission factors for methane and nitrous oxide are generally highly uncertain. The methane data are taken from Olivier (1991), but the source of the nitrous oxide data in the *IPCC Guidelines* is not quite clear. The default value is, however, consistent with AERONOX (1995). Nitrous oxide emission per TJ oil is presented to be 3.5 times higher for aviation than for other forms of oil combustion.

As almost all types of aircraft are widely used all over the world, the default fuel use factors and emission factors for individual aircraft should in principle be applicable to all countries. The national average may vary from country to country depending on the average aircraft fleet and average distance flown.

However, as the current methodology is based on *total fuel use for aviation*, most of the weaknesses presented above will not influence the accuracy of the reported direct greenhouse gas emission figures to a large extent.

2.3 Other aircraft methodologies

More detailed methodologies have been developed to better estimate fuel use and NO_x emissions from aircraft based on more exact data on flying conditions (e.g. ANCAT/EC2). As mentioned, this level of sophistication is not really necessary for the current reporting requirements.

A "high tier" methodology has been developed for the UNECE Emission Inventory Guidebook that enables emission estimates to be made from flight movement data only. This will be a simplification of the ANCAT/EC2 methodology. This methodology requires data on cruise flight distances and gives fuel use factors for individual aircraft per mile cruised in addition to LTO. This methodology may help countries to estimate their fuel use for domestic and international air traffic directly, if other sources of data not are available. The methodology may also be used for verification of other data.

The UNECE Emission Inventory Guidebook also provides a methodology for estimating emissions from military aircraft, helicopters and propelled aircraft. Emissions of water vapour, may, if required, be estimated from the CO_2 emissions, assuming a stoichiometric equation.

2.4 Selection of *good practice* methods

The current guidelines form the background for selecting *good practice* methodologies based on the available data in the reporting country. Use of Tier 2 rather than Tier 1 will increase flexibility, transparency and comparability more than the accuracy. However, *good practice* may also be used to estimate the emissions from more advanced approaches not mentioned in the current guidelines. Such methodologies may involve modelling the emissions for specific aircraft from various flight modes, depending on altitudes, cruise distances etc. However, it should be emphasised that such advanced methodologies will, in particular, improve the estimates of nitrogen oxides emissions, but will not have any effect on the carbon dioxide estimates and only small effect on methane and nitrous oxide estimates.

2.4.1 Activity Data

The options for determining *good practice* activity data will depend on the available data and options for data collection in the reporting country. The most important activity data are the consumption of kerosene (and aviation gasoline) used for domestic and international aviation, respectively. When using Tier 2, data on the number of LTOs are also needed. It is assumed that total fuel used for aviation is available from the fuel statistics in all countries.

Good practice methodologies for determining the domestic fuel used include:

- Determining the domestic fuel use from surveys: In most countries there will be just a few airline companies involved in domestic air transport. Consequently, it will be easy to request annual data from these companies. This will be difficult if there are very many airline companies in the country, too few (due to confidentiality) or the airline companies themselves may find it difficult to distinguish their domestic fuel usage from the international one, and

- Determining the domestic fuel use from sales statistics: In a lot of countries, sales statistics may give a split between domestic use and international use since they may be taxed at different rates. This is easier, but less transparent, than option 1.

If options 1 and 2 not are possible, the domestic fuel use has to be estimated from aircraft movement data and fuel use factors. This may be time consuming and not always very accurate.

2.4.2 Emission factors

The choice of emission factors for aircraft will depend on the national aircraft fleet:

- Are data on national type of aircraft in use available? If not the default data have to be used;
- Are the emission factors for national aircraft fleet close to the default values in Table 2? If this is so the default values are appropriate, if not, the use of aircraft specific default values are encouraged;
- Are the aircraft types used in the country included in Table 1? If yes, the table is directly useful. If not, data for missing aircraft have to be supplemented or use of data for similar aircraft type in the table is necessary, and
- Is there a high proportion of flights with helicopters and small aircraft in the country? If yes, the emissions from these will have to be estimated separately.

As aircraft have a fixed technology, it is usually not appropriate to use country-specific emission factors unless documented very thoroughly and are found to be better than the default values. Reasons for such deviations may be different technologies/aircraft types, different flying conditions and/or high level investigations of national emissions.

2.5 Uncertainty assessment

There is uncertainty connected to both activity data and emission factors:

Activity data The uncertainty will depend on the data collection methodology. The uncertainty will be lowest for option 1 above and higher for all other options. With option 1, covering all airline companies, the uncertainty will most likely be less than ± 5 percent The uncertainty may be very high if appropriate data on domestic and international fuel consumption are not obtained.

Emission Factors (uncertainty ranges will be subject to discussion)

- The CO_2 emission factor is well determined (within ± 5 percent);
- The uncertainty of the methane emission factor may be as high as a factor of 2, and
- The uncertainty of the nitrous oxide emission factor may be orders of magnitude.

2.6 Completeness

Only the emissions from domestic aviation are to be reported as a part of national totals. Emissions from bunkers (international aviation) are to be reported as a memo-item.

As the methodology is based on a fuel balance, also emissions from aircraft types not included in the methodology (small aircraft, new aircraft, and helicopters) will be indirectly included. Emissions from military aircraft are reported separately (see reporting issues). However, movement of military aircraft may be partially included in standard LTO-figures. This implies that if one of the default methodologies is followed, all CO_2 is accounted for. Emissions of NO_x at high altitudes are of particular concern. Methodologies for estimating aircraft NO_x emissions are given in the *IPCC Guidelines*.

Emissions from water vapour are not included in the reporting guidelines (and are not to be reported). It is, however, straightforward to estimate them using the current methodology (stoichiometric considerations).

2.7 Other important issues

2.7.1 Baseline determination

Emissions of CO_2 will be proportional to the fuel use. Preferably, fuel use should be determined by the same methodology for all years. If this is not possible, data collection should overlap at least one year in order to check for consistency.

Emissions of CH_4 and NO_x (and N_2O) will depend on technology. Different aircraft type will have different technologies. In order to estimate a correct time series to account for change of national aircraft fleet, countries should use the Tier 2 methodology based on individual aircraft types for 1990 and other years. If this is not necessary or possible (see options for good practice methodologies) the same set of emission factors should be used for all years.

2.7.2 Detection of mitigation measures

Mitigation measures may be directed towards changes in specific fuel use or specific emissions of aircraft. As the recommended methodologies are based on a fuel balance, measures directed towards reductions in specific fuel use will be seen as reductions in total fuel consumption. In order to keep track of changes in specific emissions, the Tier 2 methodology, based on individual aircraft, will have to be used.

3 REPORTING AND DOCUMENTATION

It is likely that all countries have emissions from aircraft. Consequently, reporting of “NO” (Not Occurring) is never appropriate. The current methodology has options for easy estimation so it should not be necessary to apply “NE” (Not Estimated).

The UNFCCC Secretariat has intimated that bunker emissions are reported separately from national totals for only 27 Parties. Some countries are not reporting because data are missing or because emissions most likely are insignificant. Many countries report emissions from marine and aviation bunkers together.

3.1 Current reporting *IPCC Guidelines*

In the current reporting *IPCC Guidelines* emissions from aircraft are reported as one separate item. No distinction is made between altitudes. Reporting shall include emissions from fuel used by all civil domestic passenger and freight traffic inside a country. This includes emissions from all stages of the flights (take-off, climb, cruise, descent and landing). Emissions from ground operations and stationary combustion are reported elsewhere. Reporting would become more transparent if a distinction was made between emissions in various altitudes (1000 meters).

Emissions from aircraft bunkers are reported as a separate item (memo item). This includes emissions from fuel sold to aircraft to be used for all international aviation in the reporting country. These emissions are not to be reported as part of national totals.

Emissions from *military aircraft* used domestically are to be reported in an “other” category (IA5). This category is not transparent in the current reporting guidelines. These emissions are, however, to be reported if data are available. Emissions from military aircraft used internationally shall, in principle, be included in the separate aircraft bunker item discussed above.

3.2 Documentation

It is particularly important to document the origin of the fuel use data and explain how the split between national and international aviation has been made.

The number of LTOs (preferably separately for domestic and international) is useful for documentation of verification of reported data. Use of other emission factors than default should be explained.

3.3 Confidential business information

Confidentiality may be a problem for reporting if there are less than three airline companies operating domestic traffic in the country or if one airline company is dominating the market. This may be the case in some countries.

4 INVENTORY QUALITY

4.1 Internal inventory QA/QC systems

There are some options for internal checking of data, viz:

- As the guidelines provide a Tiered methodology, more Tiers may be used for cross-checking the output;
- The country must ensure that the fuel reported for domestic aviation and bunkers sums up to the total fuel sold for aviation in the country, and
- The number of passenger kilometres travelled is known in most countries. The ratio between fuel used for domestic aviation and the passenger kilometres travelled shows the fuel used per passenger kilometres travelled. This figure may be compared with similar ratios for other countries. Emission estimates may also be compared in the same manner.

4.2 External inventory QA/QC systems

Some of the options suggested for internal QA (quality assurance)/QC (quality control) are also suitable for external QA/QC.

Additional options are:

- Checking reported emission data against output from large scale aircraft inventories (e.g. ANCAT/EC, AERONOX, NASA), and
- Checking total fuel data against data from IEA (International Energy Agency) energy statistics.

5 CONCLUSIONS

The current tiered methodologies in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual* provide a good framework for *good practice* for estimating and reporting the emissions from aviation. The main difficulty and uncertainty, lies in the distribution of fuel between domestic and international use. Relevant activity statistics is often not directly available. This makes CO_2 emission estimates from domestic aviation quite uncertain in many countries. Emissions of nitrous oxide and methane from aviation are highly uncertain due to little knowledge of magnitude of emission factors, but do not contribute much to national totals.

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