ISSN 1880-8468

Technical Report of
International Development Engineering
国際開発工学報告

TRIDE-2010-05 March 23, 2010

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Review on the Applications of Bottom-up Approach for Aviation Emission Inventory and Carbon Calculator

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1. Introduction

Civil aviation is one of the world's fastest growing transport means (Kahn-Ribeiro et al., 2007). International Civil Aviation Organization (ICAO)'s[1] analysis shows that aviation scheduled traffic (revenue passenger-km, RPK) has grown at an average annual rate of 3.8% between 2001 and 2005 despite the downturn from the terrorist attacks and SARS (*Severe Acute Respiratory Syndrome*) during this period, and is currently growing at 5.9% per year. Thus, it is increasingly important to provide accurate estimate the impact of aviation on climate change.

This report reviews the currently available methodologies for estimating aviation emissions. It begins with the effects of aviation on climate change in Section 2, followed by the factors influencing aircraft fuel consumption and emissions in Section 3. Section 4 provides detail descriptions about tiered methodologies developed by IPCC. This report further categorizes those tiered methodologies into top-down and bottom-up approach. The applications of bottom-up approaches for aviation emission inventory at country or regional level are discussed in Section 5. Section 6 summarizes the applications of bottom up approach for carbon calculator. Based on the previous sections, Section 7 reveals the uncertainty sources of all methodologies and improvements made by related studies. A brief summary and recommendation of methods is offered in the final section.

2. Effects of Aviation on Climate Change

In 1999, Intergovernmental Panel on Climate Change (IPCC)[2] released its report, *Aviation and the Global Atmosphere*, conducted at the request of the ICAO. The report was the first comprehensive assessment of aviation's impacts on climate change using the climate metric Radiative Forcing (RF)[3].

IPCC estimates that aviation emissions currently account for about 2 percent of global human-generated carbon-dioxide emissions. The 2 percent estimate includes emissions from all global aviation, including both commercial and military. Global commercial aviation, including cargo, accounted for over 80 percent of this estimate (Forster et al., 2007).

Emissions from aviation come from combustion of jet fuel (jet kerosene and jet gasoline) and aviation gasoline[4] (IPCC, 2006). Aircraft engine emissions are roughly composed of about 70% CO_2, a little less than 30% H_2O and less than 1% each of NO_x, CO, SO_x, NMVOC, particulates and other trace components including hazardous air pollutants. Little or no N_2O emissions occur from modern

[1] ICAO is a UN organization that aims to promote the establishment of international civilian aviation standards and recommended practices and procedures.

[2] To develop a better understanding of the effects of human-induced climate change and identify options for adaptation and mitigation, two United Nations organizations established IPCC in 1988 to assess scientific, technical and socio-economic information on the effects of climate change. IPCC releases and periodically updates estimates of future greenhouse gas emissions from human activities under different economic development scenarios.

[3] RF is used to gauge the effects of aviation on climate change. It expresses the perturbation or change to the energy balance of the earth atmosphere system in watts per square meter (Wm^{-2}). Positive values of RF imply a net warming, while negative values imply cooling.

[4] A fuel used only in a small piston engine aircraft, and which generally represents less than 1 percent of fuel used in aviation.

gas turbine (IPCC, 1999). Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines. Besides these emissions, aviation also yields formation of persistent linear contrails and aviation-induced cloudiness (AIC).

These emissions and cloud effects modify the chemical and particle microphysical properties of the upper atmosphere, resulting in the changes of RF of earth's climate change impacts, which can potentially lead to climate change impacts and ultimately result in damage and welfare/ecosystem loss (Lee et al, 2009a).

Many climate experiments found an approximately linear relationship between a change in global mean RF and a change in global mean surface temperature (ΔT_s), when the system reached a new equilibrium, with some proportionally constant, i.e.

Equation 1 – Radiative Forcings

$$\Delta T_s = \lambda RF$$

where:
λ is the climate change parameter (K (W m^{-2})$^{-1}$, the value of which has been found to be model specific but stable across forcings.

The IPCC (1999) report concluded that aviation represents 3.5% of the total anthropogenic RF in 1992 (excluding AIC), which was projected to increase to 5% for a mid-range emissions scenario by 2050.

The RF effects of aviation were re-evaluated quantitatively by Sausen et al. (2005) for the year 2000, which resulted in a total RF og 47.8 mW m^{-2} (excluding AIC), which was not dissimilar to that given by IPCC (1999) for 1992 traffic (48.5 mW m^{-2}, excluding AIC), despite the increase in traffic over the period 1992-2000.

3. Factors Influencing Aircraft Fuel Consumptions and Emissions

3.1 Energy Intensity Model

Lee et al. (2001) introduced the term Energy Intensity (E_I) as a measure for the technological performance of individual aircraft on aircraft fleet. E_I expresses the energy consumption per available seat-mile and depends on the physical determinants of aircraft operation and on consumer demand for air travel. One basic model useful in describing the mechanics of a commercial aircraft in flight is the Breguet range (R) equation.

Equation 2 – The Breguet Range Equation

$$R = \frac{V(\frac{L}{D})}{g\,SFC} \ln\left[1 + \frac{W_{fuel}}{W_{payload} + W_{structure} + W_{reserve}}\right]$$

In this equation, propulsion, aerodynamic and structural characteristics are represented by three parameters: specific fuel consumption (SFC), lift-to-drag ratio (L/D) and structural weight ($W_{\text{structure}}$). Given the technological characteristics as well as other operability parameters, including the amount of payload (W_{payload}) and fuel on board (W_{fuel}), the Breguet range equation can be used to determine maximum range for a level, constant speed flight. Because SFC, L/D and speed (V) are assumed to be constant during the flight, the take-off, climb and descent portions of flights are not well represented. However, application of this equation is a useful predictor of fleet operation.

The Breguet range equation can be reorganized to obtain an equation for aircraft energy usage (E_U) in terms of fuel burn or energy per available seat-km (ASK). In this formulation, the influence of aircraft capacity is explicitly included. With further modification, E_I can be expressed in terms of fuel burn or energy per RPK through inclusion of the load factor (fraction of seats filled), a measure of capacity utilization. The E_I can be further modified to include the effects of other inefficiencies in utilization, such as ground and flight delays. When all of these effects are included, E_I can be directly translated into aircraft emissions characteristics and can be used as a rough surrogate for technology maturity and operational efficiency.

The ratio of aircraft operating empty weight (OEW) to maximum take-off weight (MTOW) is used as a measure of structural efficiency. This is a measure of the weight of aircraft structure relative to the weight it can carry (the structure itself + payload + fuel). The error in specification of $W_{\text{structure}}$ is estimated to be ±5% based on assessments made by Lee et al. (2001). Although aircraft structural weights vary for the same type of aircraft depending on configuration modifications, a comparison weight reported by some studies points to a small error in the specification of structural weight. Reported W_{fuel} and W_{payload} are assumed to be accurate within ±5%. Lee et al. (2001) assumed that a 40-min fuel reserve is required. Using this value, the error in fuel reserve, W_{reserve} is assumed conservatively to ±10 min or 25% of the fuel reserve. In the performance of a flight, reserve fuel is an extra weight, as it is typically not used during a flight.

Further variability in the specification of technology parameters derives from changes during a flight. For example, SFC and *L/D* are not constant during a flight and may deviate from cruise by as much as 50% at take-off. Furthermore, reported parameters are for new aircraft, and usage leads to degradation in engine and aircraft performance. Variations in weight due to fuel burn are accounted for in the Breguet range equation.

Infrastructure characteristics also affect efficiency. In particular, delays on the ground and in the air can increase E_{I}. Extra fuel is burned on the ground during various non-flying operations, and hours spent in the air (airborne hours) do not account for more than 0.75-0.9 of total operational hours of the aircraft (block hours). The ratio of airborne to block hours can be treated as a ground-time efficiency (η_{g}). Similarly, non-cruise portions of the flight, poor routing, and delays in the air constitute inefficiencies related to spending fuel during the flight beyond that which would be required for a great circle trip at a constant cruise speed. This inefficiency can be measured by the ratio of minimum flight hours to airborne hours (η_{a}). The minimum flight hours represents the shortest time required to fly a certain stage length and reveals any extra flight time due to the non-ideal flight conditions. The multiplication of η_{g} and η_{a} gives the flight time efficiency (η_{ft}).

Equation 3 – The Breguet Range Equation as Predictor of Fleet Operation

$$E_I = \frac{Q \times W_f}{\#\,Seats \times \alpha \times SL \times \eta_{ft}} \equiv \frac{1}{\eta_I}$$

$$E_I = \frac{Q \times W_f}{\frac{W_p}{W_i}} \times \frac{g \times SFC}{V(\frac{L}{D})} \times \frac{1}{\ln\left(1 + \frac{W_f}{W_p + W_s + W_r}\right) \times \eta_{ft}}, \quad E_U \equiv \alpha E_I \equiv \frac{1}{\eta_{ft}},$$

$$E_U = \frac{Q \times W_f}{Seats} \times \frac{g \times SFC}{V\left(\frac{L}{D}\right)} \times \frac{1}{\ln\left(1 + \frac{W_f}{W_p + W_s + W_r}\right) \times \eta_{ft}}$$

Where E_I is energy intensity (in kg-fuel/RPK or megajoules/RPK), E_U is energy usage (in kg-fuel/ASK or megajoules/ASK), η_I is fuel efficiency (in RPK/kg-fuel or RPK/megajoule), η_U is fuel efficiency (in ASK/kg-fuel or ASK/megajoule), α is passenger load factor (RPK/ASK), Q is lower heating value of jet fuel, SL is stage length as calculated using the range equation, W_f is fuel weight, W_i is weight of a passenger plus baggage (90.7 kg), W_p is payload weight, W_r is reserve fuel weight, and W_s is structural weight.

The operational factors inherent in E_{I} include aircraft usage and size characteristics. These are reflected in RPK and ASK data, respectively, as well as in operating hours, which is proportional to stage length, as all large commercial aircraft fly at approximately the same altitude and same Mach[5]

[5] Speed of an object moving through air, or any fluid substance, divided by the speed of sound

number. Influence coefficients reflecting the impact of technological and operational parameters on E_I are also derived.

By rearranging the Breguet range equation, Lee et al. (2001) modeled aircraft E_I as in the Equation 3. E_U (megajoules/ASK) captures the efficiency of mechanical performance of aircraft systems as measured by potential utility. E_U is practically independent of load factor. This is because of the weak dependence of range on α due to changes in payload and structural weight. Over the range of load factors typical for current aircraft (0.75–0.9), E_U is constant to within 3% and can thus be considered a reference value.

The 95% confidence interval (2σ) in E_I due to uncertainties in the technology and operability parameters is ±22.3%, based on the mean value of all the propagated errors for the 31 aircraft types in their study. SFC and *L*/*D* have the largest impacts on the propagated error. Because the 2σ error interval for the calculated E_I is approximately ±30%, based on a curve fit to the actual *E*I calculated, the propagated error of the technology and operability parameters account for about 74% of the total variance in the calculated fuel efficiency values.

Utilizing a Taylor series expansion of the E_I equation, technological and operational influences on aircraft fuel burn can be quantified. Overall, a 2.7% reduction in E_I can be achieved by simultaneous improvements in engine, aerodynamic, and structural efficiencies of 1%. Structural efficiency does not have as strong influence as SFC or *L*/*D*. Improvement in E_I due to 1% reduction in structural weight varies between 0.7% for larger aircraft and 0.75% for smaller aircraft. Based on these influence coefficients and the historical constancy of ft and OEW/MTOW, Lee et al. (2001) estimated that reductions in aircraft E_I since 1959 can be attributed to improvements in SFC (57%) and *L*/*D* (22%), as well as to increased load factor (17%) and other changes, including seating capacity (4%). Again, these characteristics are interdependent, and it is important to note that improvements in some categories are achieved at the expense of improvements in others. If less fuel is carried as a reserve, E_I can also be reduced.

All aircraft body-engine combinations have almost the same fuel efficiency improvement potential with respect to technology improvements. This is largely because aircraft of the types this study considered have similar geometric configurations. Thus, for all types of commercial jet aircraft, whether short-range or long-range, the emissions reduction potential due to technology advancement is about the same.

3.2 Energy Usage Model: Efficiency of Aircraft Technological Parameters

Fuel burn for airplanes is a matter of constant detailed design, considering both the aerodynamics of shape and lift and the engine efficiency (Swan and Adler, 2006). According to Babikian et al. (2002)'s model, aircraft technology characteristics were described by three aircraft performance metrics, which relate directly to the energy usage of aircraft in cruise flight according to the specific air range (SAR) equation. Engine efficiencies were quantified in terms of thrust specific fuel consumption (TSFC), the thrust produced by the engine divided by the rate of fuel flow. Aerodynamic efficiencies were assessed in terms of maximum lift over drag ratio (L/D_{MAX}). Finally, structural efficiency was evaluated using OEW divided by maximum take-off MTOW, a measure of structural weight necessary to carry the structure itself, fuel and payload.

The technological parameters can be used to estimate the cruise values of E_U ($E_{U,CR}$). $E_{U,CR}$ can be calculated using SAR equation which is the basic model for describing the physics of aircraft in steady cruise flight, and it quantifies the distance flown per unit of energy consumed.

Aircraft operations-airport served, stage lengths flown, and flight altitudes-have a particularly significant impact on the E_U of regional aircraft. They fly shorter stage lengths than large aircraft, and as a result, spend more time at airports taxiing, idling, and maneuvering into gates, and in general spend a greater fraction of their block time in non-optimum, non-cruise stages of flight. A useful efficiency metric for evaluating the amounts of time aircraft spend on the ground compared to in the air is the ratio of airborne hours to block hours (η_g). Aircraft that fly short stage lengths have lower η_g because of the need to taxi and maneuver more often for every unit of time spent in the air. They therefore incur a fuel consumption penalty relative to longer-flying aircraft. Aircraft flying stage lengths below 1000 km have E_U values between 1.5 to 3 times higher than aircraft flying stage lengths above 1000 km.

Equation 4 –Energy Usage at Cruise Phase for Regional Jets

$$E_{U,CR} = \frac{1}{SAR_{JET} \times Capacity}$$

$$E_{U,CR} = \frac{TSFC \times W}{Velocity \times \left(\frac{L}{D}\right) \times Capacity}$$

where:
$W = W_{FUEL} + W_{PAYLOAD} + W_{STRUCTURE} + W_{RESERVE}$

Equation 5 – Energy Usage at Cruise Phase for Turboprop

$$E_{U,CR} = \frac{1}{SAR_{TURBOPROP} \times Capacity}$$

$$E_{U,CR} = \frac{PSFC \times W}{\eta_{PR} \times \left(\frac{L}{D}\right) \times Capacity}$$

where:
$W = W_{FUEL} + W_{PAYLOAD} + W_{STRUCTURE} + W_{RESERVE}$
η_{PR} = propeller efficiency

Regional jet aircraft of the US aviation system is found to spend a significant part of their airborne hours climbing to or descending from cruise altitudes. During these stages of flight, the energy usage of an aircraft is different than during the energy-intensive climb stage. The larger the fraction of airborne time an aircraft spends climbing, the longer it spends at high rates of fuel consumption. This characteristic of short stage length flight contributes to the higher E_U of regional aircraft. It is worth noting that the airborne efficiency metric also captures the influence of other in-flight inefficiencies, such as indirect routings, flight plan changes due to airway congestion and time spent performing holding patterns above congested airports. Each of these inefficiencies, in addition to take-off and climb effects, increases the average energy usage above that incurred during cruise.

Babikian et al. (2002) concluded that regional aircraft have values of energy usage on the order of 1.5-2 times greater than larger aircraft. The difference in E_U is not caused by significant differences in technological sophistication, but rather by operational differences associated with the airborne efficiency.

3.3 Impact of Aircraft Size on Fuel Efficiency

Across aircraft sizes, fuel consumption is almost linear in weight, which in turn is almost proportional to seating capacity. Aircraft (measured in seats per service) can be divided into two groups: the single-aisle and the twin-aisle aircraft, also known as narrow-body and wide-body aircraft, respectively (Givoni and Rietveld, 2009a). Other than larger seat capacity, the wide-body aircraft can typically also fly further, probably the result of technological constraints but also market demand. The narrow-body aircraft typically have maximum range of about 6000 km (e.g. B737-700; 6230 km, A320:5700) while wide-body aircraft typically can fly more than 10,000 km (e.g. B777-300: 11,029 km, A330-200: 12,500). Another group of aircraft size, a subgroup of narrow-body aircraft, is the regional jets, with seat capacity of fewer than 100 seats.

The choice of aircraft size depends on a variety of factors related to market condition, including competitive conditions related to regulation of markets, airport policies and cost parameters. Givoni and Rietveld (2009a) assumed that the scope of changing aircraft size is limited on long-haul routes, as at these distances only large aircraft can be used. On low-demand routes, between regional airports or from regional to hub airport, there is also almost no scope for changing aircraft size and only small capacity aircraft are usually considered. Thus, the choice of aircraft size is more relevant at the shorter distances and high-demand routes, typically the hub-to-hub markets.

Equation 6 – Specification of Givoni and Rietveld's Model (2009a) in Estimating Choice of Aircraft Size

$$\ln Seat/Flight = \beta_0 + \beta_1 \ln Market\ size + \beta_2 \ln Dist + \beta_3 \ln HH + \beta_4 LCC + \beta_5 Europe + \beta_6 North\ America + \beta_7 RWy1 + \beta_8 \ln Rwy2 + \beta_9 Hub1 + \beta_{10} Hub2 + \beta_{11} Slot1 + \beta_{12} Slot2$$

where:
Seat/Flight: average number of seats per flight
Market size: route density, no of weakly seat (two-way)
Dist: great circle distance (km)
HH: Herfindahl-Hirschman index (the sum of square airlines' market share on the route)
LCC: dummy, at least one low cost carrier operates on the route
Europe: dummy, route is within Europe
N. America: dummy, route is within N. America
Rwy1: no. of runways (larger airport on the route)
Rwy2: no. of runways (smaller airport on the route)
Hub1: dummy, one of the route airports is a hub (transfer passengers > 15%)
Hub 2: dummy, two of the route airports are hubs (transfer passengers > 15%)
Slot1: dummy, one of the route airports is slot coordinated (level 3)

Usually two seating configurations are considered. For short-haul flights these are 1-class (high density) and 2-class (standard) configurations, while for long-haul flights these are 2-class (high density) and 3-class (standard) configurations. On hub-to-hub routes, low-cost carriers do not usually operate and standard 2-class configuration is most common (Givoni and Rietveld, 2009b).

It is found that regression analysis of over 500 routes in the US, Europe and Asia provides empirical evidence that the choice of the aircraft size depends on market size with an elasticity of 0.35 resulted from the model in equation 6, indicating that in the airline industry carriers give priority to increases in frequency. Another result is that aircraft size increases with distance, a natural result of the trade-off between cost of loading/unloading, and cost of flying. Further, the presence of low cost carriers leads to somewhat larger aircraft (Giovani and Rietveld, 2009a).

Morrell (2009) also attempted to examine the relationship between fuel/emission efficiency and aircraft size or capacity, including both passenger and cargo. It is evaluated for both short/medium-haul and long-haul operations. This study assumed that single-aisle aircraft represents short/medium-haul routes while twin-aisle for long-haul operations.

Fuel efficiency was computed by dividing fuel burn by the typical number of two-class seats. These are reported in Flight International's Annual Aircraft Directories, from information provided by manufacturers in standard configurations. On short/medium-haul routes the number of business class seats is generally varied by moving a curtain or divider along the cabin.

For short/medium-haul flights, fuel burn per seat was calculated for seven of the most commonly used short/medium-haul jet aircraft for a 90 min sector. It was found that fuel efficiency is positively related to aircraft seating capacity, and for every 1% increase in seat capacity a 0.83% reduction in fuel might be obtained.

In the case of long-haul flights, a 6-h sector was taken and a typical three-class seating was used[6] together with the available space for cargo in the lower deck compartment. Numbers of seats were taken from the standard configurations provided by the manufacturers in the Flight Directory, and these may differ appreciably from those used by particular airlines.

There are two approaches that could be used to incorporate lower deck cargo. First, by relating fuel burn to passenger and cargo payload carried (tone-kms); and, second, by estimating the fuel required to carry the lower deck cargo, subtracting it from fuel burn and diving by passenger and baggage payload. The first is used by Morrell (2009), since it is simpler and the concern is not the fair allocation of emissions between passenger and cargo.

Seats were converted to tones using 80 kg per seat (passengers and carry-on bags bur excluding checked baggage), while a typical cargo density of 167 kg per cubic meter was applied to the hold

[6] Seat pitches of around 60 inches for first class, 38-40 inches for business class and 31-31 inches for economy.

volume to give a realistic payload. Lower deck cargo is the difference between this payload and 24 kg multiplied by the full passenger complement (based on realistic network carrier checked baggage weights).

Yet, for these aircraft, there was no discernable relationship between fuel efficiency and passenger and cargo capacity. However, if the double-deckers (B747s and A380) were removed from the sample, there was a reasonably good correlation of fuel efficiency against payload, but with a smaller coefficient (0.4) than for single-aisle aircraft. Furthermore, leaving out the very large aircraft resulted in a 0.65% improvement in fuel efficiency for every 1% increase in maximum payload for both single- and twin-aisle aircraft.

It should be noted that Morrell (2009)'s analysis has not taken into account the extra range that many of the long-haul types can operate over. By taking a 6-h sector, none of them has reached the point where extra range is traded against payload and cargo capacity is reduced. These are hit by a double penalty: the loss of cargo payload and for flights of over around 4000 km an increase in fuel are required to carry the extra fuel and the structures needed to accommodate the fuel.

4. Tiered Methodology for Estimating Emissions from Aviation

IPCC (2006) provides a three-tiered methodology in the "Greenhouse Gas Inventory Reference Manual" as a framework for estimating and reporting the emissions from aviation particularly CO_2, CH_4 and N_2O. The first-tier "Tier 1" is the simplest methodology, based only on an aggregate number for fuel consumption to be multiplied with average emission factors.

Equation 7 – Tier 1 Algorithm

$$E_p = AR_{fc} \times EF_p$$

where:

E_p = annual emission of pollutant for each of the LTO and cruise phases of domestic and international flights

AR_{fc} = activity rate by fuel consumption for each of the flight phases and trip types

EF_p = emission factor of pollutant for the respective flight phase and trip type

Equation 8 – Tier 2 Algorithm

$$E_p = \sum_{at} AR_{fc,at} \times EF_{p,at}$$

where:

E_p = annual emission of pollutant for each of the LTO and cruise phases of domestic and international flights

$AR_{fc,at}$ = activity rate by fuel consumption for each of the flight phases and trip types, for each aircraft type

$EF_{p,at}$ = emission factor of pollutant for the respective flight phase and trip type, for each aircraft type

The second "Tier 2" methodology estimates emissions in two-flying phases: the landing and take-off (LTO)[7] and cruise phases[8]. Fuel burn is higher in the LTO phase than cruise phase as the aircraft engines are working harder. As the aircraft reaches fuel cruise altitude the engines can work less hard and also less fuel is burnt at higher altitudes due to the thinner atmosphere.

[7] All activities near the airport that take place under the altitude of 914 meters (3000 feet) including taxi-in and out, climbing and descending (IPCC, 1997).

[8] Defined as all activities that take place at altitudes above 914 meters (3000 feet), no upper limit is given.

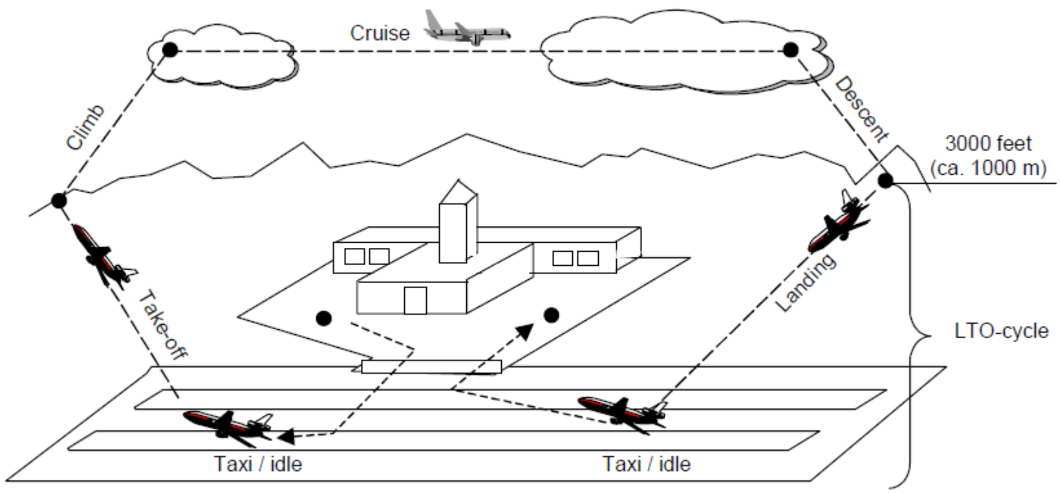

Figure 1 – Standard Flying Cycles
Source: EEA, 2009

In Tier 1 and 2, the fuel sold is assumed to be equal to the fuel used. Moreover, the fuel used in the cruise phase is estimated as a residual: total fuel use (sold) minus fuel used in the LTO phase of the flight. Fuel use is estimated for domestic and international aviation separately. Tier 2 method is preferable instead of Tier 1 if the LTO data are available for individual aircraft. It should be noted that the accuracy of these two methodologies rely heavily on the quality of fuel statistics or fuel consumption data. It is important to account for all fuel used for aviation in the country. The methods are based on total fuel use, and should completely cover CO_2 emissions. However, the allocation between LTO and cruise will not be complete for Tier 2 method if the LTO statistics are not complete. Also, Tier 2 method focuses on passenger and freight carrying scheduled and charter flight, and thus not all aviation. On the other hand, if the fuel statistics is not reliable, bottom-up approach or Tier 3 will provide much higher accuracy.

The higher tier accommodates the fact that emissions depend on the number and type of aircraft operations, the types and efficiency of the aircraft engines the fuel used; the length of flight; the power setting; the time spent at each stage of flight; and to a lesser degree, the altitude at which the exhaust gases are emitted. Accordingly, “Tier 3” goes further in details by using movement data for individual flights including, at a minimum, information on the origin and destination, aircraft type, and data of individual flights. Hence, these methodologies are bottom-up, flight-based, rather than top-down calculation-based on the fuel consumed as in Tier 1 and 2. EEA (2009) distinguishes Tier 3 method into two categories: Tier 3A which takes into account cruise emissions for different flight distances and Tier 3B in which the calculation of fuel burnt and emissions throughout the full trajectory of each flight segment using aircraft- and engine-specific aerodynamic performance information.

Regardless the method, the completeness and accuracy of activity data collected on domestic aviation separately from international aviation affected the level of uncertainty of the estimates. Generally, all flights departing and arriving in the same country are defined as domestic flights, while for journeys departing from one country and arriving in another country are international flights. However, energy statistics used in Tier 1 often do not accurately distinguish between domestic and international fuel use or between individual source categories. Based on past experiences compiling aviation emission inventories, IPCC (2006) suggests that difficulties have been identified regarding the international/domestic split, particularly in obtaining the information on passenger and freight drop-off and pick-up stops in the same country. If national energy statistics do not already provide data consistent with the definition made by IPCC (2006), countries are urged to estimate the split between domestic and international fuel consumption, using the approaches set below:

1. *Top-down* data can be obtained from taxation authorities in cases where fuel sold for domestic use is subject to taxation, but that for international use is not taxed.

2. *Bottom-up* data can be obtained from surveys of airlines companies for fuel used on domestic and international flights, or estimates from aircraft movement data and standard table of fuel consumed or both. For examples: statistical offices or transport ministries as part of national statistics, airport records, air traffic control records, air carrier schedules, etc.

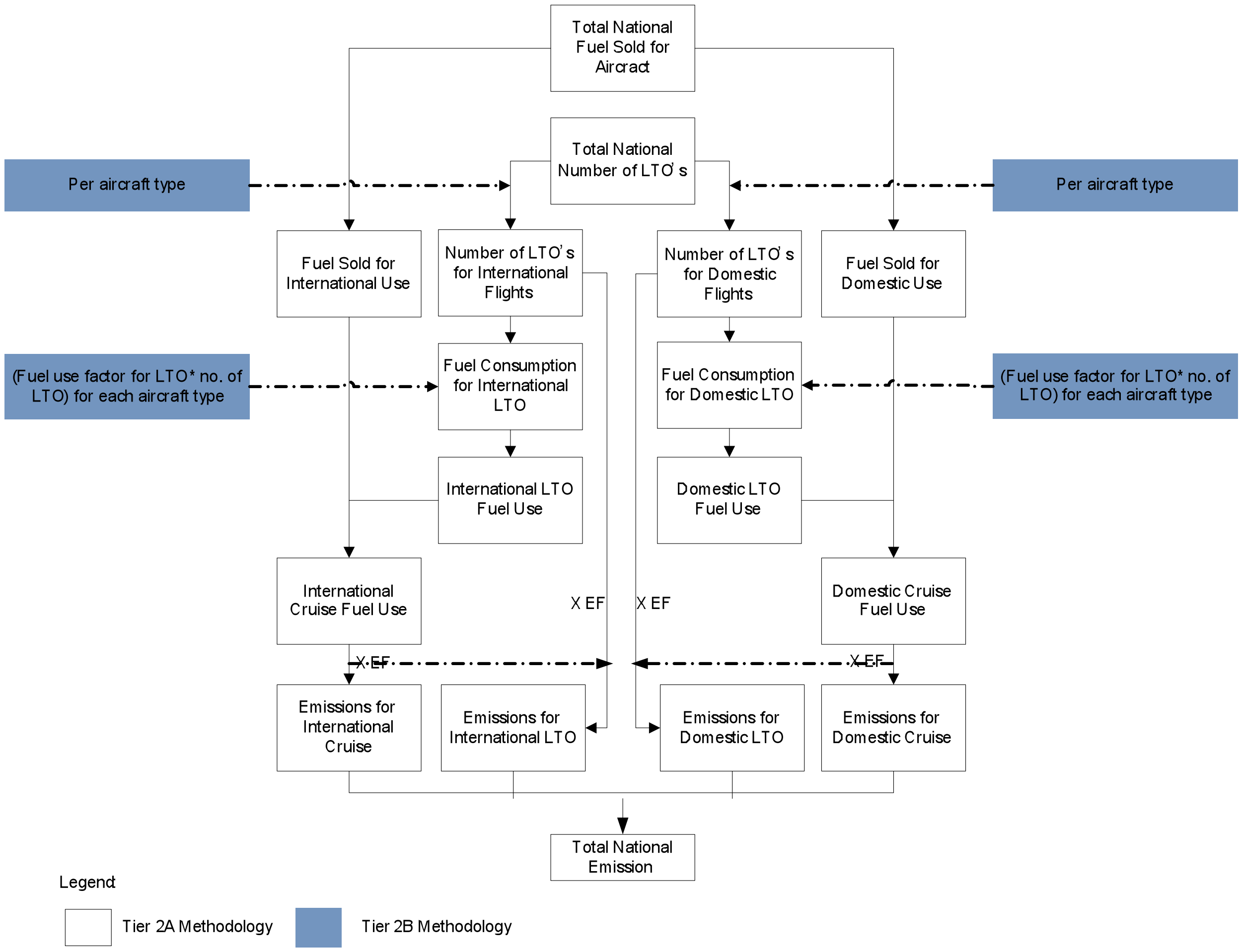

Figure 2 – Tier 2A and Tier 2B Methodology (Modified from EEA, 2009)

The choice of methodology depends on the type of fuel, the data available and the relative importance of aircraft emissions. IPCC (2006) suggested that it is a good practice to first identify *key categories* in a national inventory in order to choose the proper methodology to use. *A key category* is one that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend or the uncertainty in emissions and removals. Given the current limited knowledge of CH_4 and N_2O emission factors, more detailed methods will not significantly reduce uncertainties.

However, if an emission is considered as a key category and the use of a higher tier would improve the estimate or the split between international/domestic flights, a country is encouraged to develop method for collecting data for Tier 2 or Tier 3 method. Methodological approaches for identifying this key category are provided in details by IPCC (2006).

Lee et al. (2005) pointed out that the reasons why higher tier methodologies should be undertaken are that they give the possibility to obtain time series reflecting changes in technology, verify the estimates, report emissions from cruise and LTO separately, and provide more accurate NO_x estimates. Tier 2 is used in spite of tier 3 if LTO and aircraft type data are available but no information on cruise distance.

5. Application of Bottom-up Approach for Aviation Emission Inventory

As indicated above, Tier 3 methodology requires more detailed data and adopts bottom-up disaggregated approach to estimate emissions accurately reflecting actual air transport activity. Activity data is collected to identify the actual flight movement data including trajectory of each flight and time-in-mode for LTO phases.

5.1 Tier 3A

In Tier 3A, cruise phase, fuel use and emissions are estimated using great circle distance-the shortest distance ignoring the extra distance due to airspace and navigational constraints- between two airports. The aircraft and flight details can be obtained from Civil Aviation records, airport records, ATC such EUROCONTROL[9], or the Official Airline Guide (OAG) timetable. This will identify the aircraft that were used in the inventory period, the number of LTOs for each and the mission distance flown.

The emission factors for Tier 3A methodology are listed in spreadsheets available from the EMEP/EEA Guidebook website (EEA, 2009) containing fuel consumption, emission (kg) and emission indices (g/kg fuel) of NO_x, HC and CO for the different phases of flights (LTO, taxi out, take-off, climb-out, climb/cruise/descent, approach landing, and taxi in) of different distances in nm ranging from 125 nm to 2,000 nm (1 nm equals to 1.852 km). The data is available for a set of representative aircraft types, particularly for IFR-flights. As for non-IFR flights, a range of emission factors is shown in MEET for piston-engined aircraft, helicopters and military flights (1997) and also ANCAT, British Aerospace/Airbus (for military aircraft). Nonetheless, at present it is not possible to recommend the default emission factors due to limited information available (IPCC, 2006).

By referring to the spreadsheets, an estimate of emissions and fuel used during LTO phase can be obtained based on the associated representative aircraft and the distance that is actually being flown. The total quality of fuel used for the mission is the sum of fuel used for LTO plus the fuel used in all operations above 3,000 ft (914 m) or cruise phase. By referring again to the table of pollutants (NO_x, CO and HC) emitted versus mission distance, an estimate of cruise phase emissions will be acquired.

The earliest inventories applying “bottom-up approach” in which an aircraft movement database was compiled, as reviewed in Henderson et al. (1999), include the NASA, ANCAT and DLR 3-D. Furthermore, in these inventories, aircraft/engine combinations in operation were identified (to differing levels of details) and calculations of fuel burned and emissions along great-circle paths between cities were made. Flight operation data were calculated as the number of departures for each city pair by aircraft and engine type-which, combined with performance and emissions data, gave fuel burned and emissions by altitude along each route. Different approaches were taken for constructing underlying movement databases especially for NASA inventory, while the DLR 3-D inventory used ANCAT/EC2 civil movement database. The summarized differences are provided in detail by Henderson et al. (1999). The rest of this section focuses on ANCAT approach since it is continuously developing.

5.1.1 ANCAT/EC2

The essential components of ANCAT/EC2 inventory include: an aircraft movement database; a representation of the global fleet in terms of aircraft and engines; a fuel-flow model; calculation of emissions at altitude from fuel flow; and LTO data (Lee et al., 2002).

The global aircraft movement database was compiled from a mixture of air traffic control (ATC) and scheduled data (where ATC data were unavailable). ATC data were obtained from 38 non-European countries and Europe (from EUROCONTROL which covers 15 member states). A notable exception was the United States, for which only scheduled data were available. These data were factored up by 10% to compensate for this problem.

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[9] On behalf of participating states, EUROCONTROL receives and stores detailed traffic information of all flights operated entirely or in part in the European Civil Aviation Conference (ECAC) area in its Pan-European Repository of Information Supporting Management of EATM (PRISME) data warehouse. The database consists of: (i) information from the (last) filed flight plan; (ii) aircraft type; (iii) airport of departure/airport of destination (city pair); (iv) the ICAO designator for aircraft operating agency followed by the flight identification.

Sixteen civil jet aircraft types were selected based upon size and performance/technology level to represent the world's fleet of narrow and wide-bodied aircraft for short, medium and long-haul operations. Even with these representative aircraft, this would imply almost 100 different aircraft/engine combinations. Since such combinations could not be accurately assigned to particular routes or airlines, a further simplifying assumption was made. A list of engines fitted to these aircraft was obtained from current databases and generic fuel flow characteristics were applied, weighted for engine populations.

The use of energy and, therefore, emissions, depends on the aircraft operations and the time spent at each stage. ICAO databank specified engine power settings and times-in-mode for the LTO-cycle based on manufacturers' submitted Certification data. In this model, a correction of the 'standard' assumed ICAO taxi time was being reduced from 26 to 14 minutes since the former ICAO assumption reflected the worst case, while the current taxi times were generally much shorter.

Since fuel flow data are often proprietary, they were modeled using PIANO (Project Interactive Analysis and Optimization)[10] (Lee et al., 2002). PIANO was used for the representative aircraft and generic engines to generate fuel profiles covering the flight cycle (excepting the LTO), including steps in cruise.

5.1.2 FAST Model

Another application is the FAST Model (Future Aviation Scenario Tool) which was originally developed for the UK Department of Trade and Industry (DTI) and was subsequently used in the European Fifth Framework Project TRADEOFF (Lee et al., 2005; Sausen et al., 2005; Gauss et al., 2006). The basic FAST model was designed around the methodology employed for the ANCAT/EC 1&2 inventories based upon a dataset of aircraft movements for some years which indicates the frequency of flights of specific aircraft between city pairs. From this database, the aircraft types were grouped, with representative aircraft types assigned. PIANO aircraft performance model was also used. To up- date the representative aircraft data, it was decided to use this draft list from the Expert Group. However, some modifications were made since not all types listed in the Expert Group List were available in the PIANO aircraft performance model (Lee et al., 2005).

In ANCAT/EC2 inventory, aircraft performance was being simulated at optimal cruise altitudes for their mission distance. These optimized flights were then globally redistributed, with respect to altitude, according to a limited dataset from one airline. For the TRADEOFF 2000 inventory, a more refined technique was developed in FAST model, as follows. Preliminary movement data from AERO2k project, using approximately 53,000 flights (actually a combination of EUROCONTROL and FAA data, explained further in section 4.2), were analyzed for the limited list of ANCAT/EC2 representative types to determine whether there was a relationship between aircraft type, mission distance and average altitude flown (Fichter et al., 2005; Gauss et al., 2006). It was found that this relationship provided a satisfactory and robust means of specifying average maximum cruise altitudes by aircraft type and mission distance. The consequence of *not* doing this and simply allowing an optimization of the mission profile underestimated the amount of fuel used and misrepresented the vertical distribution of traffic, and therefore emissions.

Thus, this parameterization was adopted for the FAST model with some further analysis for the new representative aircrafts. The maximum flight altitudes for the representative aircraft types by mission distance were determined by identifying the maximum flight level for each flight in the sample month (in this case, December). The average maximum flight level was calculated for each of the representative aircraft types and groups of distance increments of 500 km. The next real flight levels (e.g. 290, 310, 330) to this average value was then used in the PIANO model.

5.1.3 ANCAT 3

EUROCONTROL further developed a more complex model, the ANCAT3, which calculates fuel consumption and emissions in LTO and cruise phase based on 19 generic aircraft types representing the world's passenger jet fleet (Graichen, 2007). This method is identical to the "detailed"

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[10] A sophisticated aircraft performance model widely used in the aviation industry, http://www.lissys.demon.co.uk and has been extensively used in other inventory-type work including FAST/TRADEOFF and AERO2k.

methodology of CORINAIR/ EMEP (EEA, 2006). Calculations are performed for individual flights. A mapping table indicates the generic aircraft type which should be used for aircrafts not included in the model. Calculations of fuel burn and emissions are performed separately for LTO and cruise to take different operating conditions between the two phases better into account. The cruise length is determined using great circle distances between airports and adding a factor to adjust the difference between real route and the optional theoretical route.

There are several reasons why theoretical fuel burn calculated using ANCAT3 might differ from real fuel burn (Graichen, 2007):

- Load factors: the take-off weight of an aircraft has a high influence on total fuel burn for a trip. The take-off weight depends on the actual number of passengers, their luggage and any cargo that might be transported as well. Fuel burn values in ANCAT3 use typical load factors which might not fully reflect reality.
- Route flown: the implementation of ANCAT3 at EUROCONTROL uses typical flight routes based on the great circle distance between two airports. Due to atmospheric conditions, available air space, and airport congestion, the actual routes might be longer or shorter than the typical distances used in the model.
- Aircraft types: to reduce the complexity of the data requirements, only a limited number of different generic aircrafts are included in the model. In reality, fuel burn does not only depend on the aircraft type but also on the engine which might be different between two aircrafts of the same type.
- Aircraft performance: the age of an aircraft, maintenance standards, and the actual operation all have an influence on fuel consumption. Again, these factors are only included as approximate values through average fuel consumption rates.

5.1.4 UK SERAS

Through The South East and East of England Regional Air Services Study (SERAS) (DfT, 2003), UK also applied Tier 3A and produced estimates based on the assumptions that aircraft use "great circle" route. In addition, the SERAS estimates were based on the assumption that UK's share of international flights is one-half of the total traffic. The model used fuel burn data for representative aircraft 'types' for domestic, short-haul and long-haul services.

In SERAS, passenger and freight aircraft movement forecasts were split by six seat band classes (less than 70 seats, 71-150 seats, 151-250 seats, 251-350 seats, 351-500 seats, and more than 500 seats) Representative aircraft are chosen for each seat band class and aggregated them into 15 destination regions (10 international and 5 domestic).

SERAS carried out a cautious approach in recalculating the fuel burn data to reflect differences in average aircraft age and engine technology by including only known aircraft types and performance data. More disaggregated fuel burn data was multiplied by ATM data by destination and aircraft size to give forecasts of total aviation fuel usage. Aircraft fuel usage in tones is multiplied by 3.15[11] to give CO_2 emissions. Surface access related CO_2 emissions were calculated by multiplying total vehicle km by an average emission rate of 147 grams per km.

5.1.5 UK NETCEN

Still for UK's GHG inventory, the other example of Tier 3A application is the improved model of National Environment Technology Center (NETCEN) (Watterson et al., 2004). The previous NETCEN model was similar to IPCC Tier 2 (CORINAIR 'Simple') in that it uses fleet-averaged emission factors based on fuel uplifted at all UK airports for the non-LTO flight stages but more detailed information for the LTO cycle. The improved NETCEN method includes emissions per LTO cycle based on detailed airport studies and engine-specific emission factors from the ICAO database. In cases where different engines might be used on a single type of aircraft, a weighted average of the emissions from the different engines was used.

[11] More precisely 3.157 which is a constant representing the number of tones of CO_2 produced by burning a tone of aviation fuel (ICAO, 2009)

Equation 9 – NETCEN Method on Treatment of Time-in-mode during LTO phase

$$E_{LTO_{a,m,p,s}} = N_s \times T_{a,m,s} \times F_{a,s}(t_{a,m,s}) \times I_{a,p,s}(t_{a,m,s})$$

where:

$E_{LTO_{a,m,p,s}}$	is the emissions in mode m of pollutant p for a specific aircraft type s at airport type a (kg)
a	is the airport type
m	is the mode
p	is the pollutant
s	is the specific aircraft type
N_s	is the number of engines on aircraft type s
$T_{a,m,s}$	is the time in mode m for a specific aircraft type s at airport type a (s)
$F_{a,s}(t)$	is the weighted average fuel flow for an engine on aircraft type s at airport type a for thrust t (kgs^{-1})
$I_{a,p,s}(t)$	is the weighted average emission factor of pollutant p for an engine on aircraft type s at airport type a for thrust t (kg / kg fuel)
$t_{a,m,s}$	is the engine thrust setting during mode m for aircraft type s at airport type a (%)

For the cruise phase, fuel use and emissions are estimated using distances (based on great circles) traveled from each airport for a set of representative aircraft. Since aircraft do not fly the shortest distances, NETCEN study increased the distance travelled between airports by 9.5% for all years, yet this requires further review.

Equation 10 – NETCEN Method for Calculating Emission during Cruise Phase applying Linear Regression

$$E_{Cruise_{d,g,p}} = m_{g,p} \times d + C_{g,p}$$

where:

$E_{Cruise_{d,g,p}}$	is the emissions in cruise of pollutant p for generic aircraft type g and flight distance d (kg)
d	is the flight distance
g	is the generic aircraft type
p	is the pollutant (or fuel consumption)
$m_{g,p}$	is the slope of regression for generic aircraft type g and pollutant p (kg / km)
$c_{g,p}$	is the intercept of regression for generic aircraft type g and pollutant p (kg)

Emissions from additional sources (such as aircraft auxiliary power units) are also included. Furthermore, in order to avoid double counting of cruise emissions, the entire cruise emissions have been associated with the departure airport.

SERAS' estimates (for international aviation in 2000 were about 25% lower than (26.1 Mt of CO_2) the estimates resulted from the improved NETCEN methodology (32.2 Mt of CO_2) (Pejovic et al., 2008). The likeliest reason for the smaller estimate is that the modeling assumed that all aircraft fly great circle distances.

5.2 Tier 3B

Tier 3B relies on detailed database consists of 4-D flight trajectories (latitude, longitude, altitude, and time) enabling calculation of more accurate fuel consumption and emissions along the full trajectory. To use Tier 3B, sophisticated computer models are involved to address all equipment, performance and trajectory variables and calculations for all flights in a given year. Thus, models used for Tier 3B can generally specify output in terms of aircraft, engine, airport, region, global totals, as well as by latitude, longitude, altitude and time, for fuel burn and emissions of CO, HC, CO_2, H_2O, NO_x, and SO_x.

5.2.1 AERO2k and SAGE: Comparison

To date, there are two well-recognized model applying Tier 3B methodology (IPCC, 2006), the AERO2k (Eyers et al., 2004) developed by the European Commission (EC) and System for Assessing Aviation's Global Emissions (SAGE) by United States Federal Aviation Administration (FAA) (Kim et al., 2007).

For the activity data, AERO2k has taken the best available civil and military flight information for the year 2002. For civil aviation, this included radar tracked flight data from North America and Europe showing actual latitude, longitude, and altitude along the flight path. Routing information was used to place timetabled flight from the rest of the world onto global grid. The collection of data for 2002 was spread over six representative periods of one week, the six weeks chosen to take account of diurnal, weekly and seasonal variation in air traffic. Data for the rest of the world were extracted from the BACK Aviation commercial database and added to the chosen representative weeks.

The collection of data required the collaboration of aviation authorities in order to gather as many measured flight trajectory data as possible. Schedule data from the Back Aviation database does not include any flight trajectory information and it was necessary to complete this data with flight route and aircraft performance information when available. For the days of the year for which no data were collected, flight data were derived from inventories realized for the data collection periods while trends were obtained from Back Aviation scheduled flights database.

Instead of using a portion (e.g. a day, week, month, etc.) of the world flight schedules and flight plans as used in AERO2k or other past studies, SAGE aimed to include all commercial flights worldwide using non-proprietary databases mainly the Enhanced Traffic Management System (ETMS) which provides radar data and reported flight plans and the OAG which only provides planned schedules of flights by commercial airlines. Approximately 45% of ETMS flights (or about 22.5% of all global flights modeled in SAGE) include radar data covering North America, parts of western Europe and South America. Besides the two, SAGE also includes various supporting data. The current worldwide coverage in SAGE includes approximately 30 million commercial flights per year which allow SAGE to be used to model flights for all years from 2000 to 2006.

Due to the use of OAG flight schedules for areas outside of ETMS coverage, unscheduled and cancelled flights cannot be directly modeled. Instead, their effects are indirectly accounted for through the use of scaling factors that generally increase the number of flights. The factors are a function of the scheduled OAG flights (operations) at an airport, and were developed based on a comparison analysis of ETMS and OAG flights.

As part of the movements, delays are modeled in SAGE through a sub-model called WWLMINET. It is a worldwide version of LMINET, a queuing model developed by NASA that predicts hourly airport ground and approach airborne delays. WWLMINET starts with a flight demand that is propagated through a network of queues. The delays associated with serving that demand level are determined. The WWLMINET network currently contains 102 US airports, 122 European airports, and 33 other airports outside US and Europe. Together, these 275 airports represent approximately 75% of global commercial air traffic as defined by OAG schedules. Airports not included in this network are assumed to have no delays.

AERO2k uses 40 representative aircraft types which were selected representing 300 different types or variants within the world's fleet. AERO2k applies three main steps in the selection process: (i) grouping aircraft by seat capacity, engine technology, maximum take-off weight (MTOW) and configuration; (ii) determination of the numbers of aircraft within a particular seat capacity/technology category; and (iii) availability of suitable performance data.

Generic emissions characteristics were developed by weighting the emission index for NO_x for the number of engines in the fleet's population, for each of the four thrust settings of the LTO cycle. In the next step, the generic emission characteristics were compared with real engine data and the closest fit determined by a polynomial least-square regression. The final choice of engine was not determined solely using this method; one additional criterion was used in the selection process. Once all the representative aircraft had been assigned an engine using the above method, the selected engines were compared for similarity of emissions characteristics. Where close similarities were found, for instance within families of engines from one manufacturer, the most representative engine was chosen. In this way the number of engines was consolidated.

Instead of using generic aircraft types and engines as the starting point, SAGE does not carry out this step but intends to preserve as much of the specificity of each flight as possible and, accordingly, resulting in inclusion of over 200 different aircraft types. In SAGE, the aircraft type for each flight is identified through the use of aircraft codes specified in ETMS and OAG flight plans and schedules, respectively. These codes are mapped to the aircraft listings within the SAGE performance databases. It is estimated that about 90% of flown distances modeled in SAGE reflect good to perfect aircraft mapping, while the remaining are substitutions, such as Ilyushin IL86 with an Airbus A343 (A343 and A341 are some examples of a good map).

The engine type is assigned based on one of three methods. The first and preferred method (14%) is through an exact assignment by identifying the tail number of the aircraft from Bureau of Transportation Statistics (BTS) Airline On-time Performance Data through matching of flight ID numbers and aircraft type. Once this is accomplished, the tail number is matched to the one in BACK Aviation's world fleet database and the exact engine is assigned. The BACK world fleet database contains a listing of worldwide commercial flight built since 1940 and provides various aircraft-specific information including tail numbers, engine types, weight, size, seating and airline. Since the BTS data cover only the top 10 US airlines, the second method is to assign engines based on popularity within the world fleet (77%). The BACK world fleet database is used to develop distributions of engine counts based on airline and aircraft categories as provided in the BACK database. The third method involves the use of default engines for each specific aircraft type (9%).

In AERO2k, fuel used for each flight was calculated using performance data from PIANO aircraft performance tool. By employing the latest publicly available information on emission factors, emissions were calculated based on aircraft height, weight, speed, throughout the flight. New information on non-volatile particulate emissions has been added to provide a first gridded estimate of particulate emissions from civil aviation. Extensive validations have also been performed to ensure the integrity of the data processing and output.

In case of SAGE, aircraft performance is modeled dynamically using a combination of the data and methodologies found in the FAA's Integrated Noise Model (INM) and BADA version 3.6. The reason is largely because they are publicly available, and this are in accordance with FAA's intent to keep all SAGE methods and data sources non-proprietary. BADA provides aircraft performance data for cruise (speed schedule, fuel flow), while INM provides performance for landing and takeoff (LTO) modes. Atmospheric information pertinent to flight performance, such as temperature and pressure, are based on the International Standard Atmosphere (ISA), where temperature and pressure at sea-level are defined as 288.15 K (59 degree F) and 101325 Pa (1 atm), respectively. Relative humidity and the specific heat ratio are assumed to be constant at 60% and 1.4, respectively.

These two models leave many rooms for improvements. Specifically for AERO2k, to improve the estimate, the model still require to increase the number of week data, the number of aircraft models and engine combinations, improve detail of LTO assumptions such as reduced throttle settings or idle settings, and incorporate additional tail number and fleet data to provide granularity of fleet make up (Eyers et al., 2004). Uncertainties also occur in SAGE model such as not correcting for winds aloft, uncertain aerodynamic and engine performance, and simplified assumption about aircraft take-off weight and flight speed (Kim et al., 2007). Additional uncertainties associated with the use of currently available trajectory inventories and aircraft performance data remain important to be continuously improved.

5.2.2 Combination of RAMS Plus and AEMIII Model

More recently, Pejovic et al. (2008) attempted to improve SERAS and NETCEN's Tier 3A method by using the RAMS simulation which allows actual flight paths to be modeled. RAMS Plus simulates the four dimensional profile of each flight as a series of events. A detailed flight profile is obtained describing the operation of the aircraft at each of these events. This allows the fuel burn for each element of the journey to be calculated.

RAMS Plus simulations were conducted using traffic, route network, and sector data provided by National Air Traffic Services in UK (NATS). A 24-h air traffic sample for Friday, 3rd September 2004 was used with 7,074 flights, each with specified departure and destination airports and simulation entry times. To permit calculation of the total fuel burn for the traffic, fuel burn rates from the performance tables of the EUROCONTROL Experimental Centre (EEC) BADA Revision 3.6 were incorporated into RAMS Plus. Flight speed and rate of climb/descent were also defined according to the BADA performance tables. This dataset has detailed coverage, describing 91 aircraft types directly and a further 204 by equivalence to a directly specified type. Each aircraft in the traffic sample was allocated to one of these 91 performance groups. In the few instances where the aircraft type specified in the traffic sample could not directly related to one of the 204 types supported by BADA, the aircraft was substituted with an aircraft type with similar operating characteristics (size, range, optimum cruise speed, and altitude).

Table 1 – Uncertainties Sources of RAMS Plus and AEMIII Model

Uncertainty Sources	Details
BADA aircraft performance data provides climb rates and fuel burn consumption for three aircraft mass scenarios (low, nominal, and high) for each aircraft type without take off mass data in the traffic sample.	• Assumed that all aircraft are at nominal mass which is likely to underestimate CO_2 emissions where route length is close to the maximum range for the aircraft type. • The simulator does not calculate reductions in aircraft mass due to fuel burn while in flight. • BADA aircraft types are each defined for a selection of given airframe-engine combinations; data on the exact type of each aircraft in the traffic sample is not available
The calculation of flight trajectories outside UK airspace due to detailed routes are defined only within UK airspace	• Assumed that international (EU and non-EU) departures follow a great circle route from the edge of UK airspace to the destinations leading to underestimate cruise distance. • The daily CO_2 estimates are adjusted to correct underestimation of the fuel burn by assuming an additional 4.9% for EU departures and 6% for international departures. This could be rectified using additional data, however, this type of data is not readily available.
Extrapolation of a 1-day sample to generate an annual estimate	• The date of the traffic sample is not severely affected by severe weather or other operational difficulties, which would significantly increase the number of diverted landings. • Comparison with the CAA statistics leads to a conclusion that the 1-day traffic sample may overestimate air transport movements by 10% for calculation of the monthly (September) mean emission values, with this overestimation largest for non-EU international routes and in part as a consequence of reduced traffic on weekends. • The assumption that the distribution of routes and aircraft types does not vary throughout the year affects the calculated value. Instead, seasonal variation in route length and disaggregating the CO_2 emissions into domestic, EU and other international traffic are used to improve the estimate further.

Source: Pejovic et al., 2008

The configuration of RAMS Plus with the UK air traffic sample has two limitations. Firstly, as detailed data on airport configurations and ground movements was not available, it cannot be used to calculate emissions for this phase of the flight. Secondly, the available air traffic sample only allowed emissions within UK airspace to be calculated. Since one of the objectives of the study was to estimate UK CO_2 emissions which can be allocated to the UK CO_2 budget for all domestic and international traffic departing from UK airports, it was necessary to perform additional calculations using the Advanced Emission Model (AEM) tool.

Pejovic et al. (2008) utilized AEMIII which is a stand-alone system used to estimate aviation emissions (CO_2, H_2O, SO_x, NO_x, HC, CO, Benzene, VOC, TOG) and fuel burn. It is able to analyze flight profile data, on a flight-by-flight base, for air traffic scenarios of almost any scope (from local studies around airports to global emissions from air traffic) (Jelinek et al., 2004). The model uses flight profile information (in this technique refers to RAMS Plus) to calculate information about fuel consumption and emission produced. It uses the ICAO Engine Exhaust Emissions Data Bank (05/2003), the EUROCONTROL Base of Aircraft Data (BADA v3.5) and an improved version (EEC-BM2) of the Boeing Method2 (BM2) in order to produce the emission estimations for all phases of flight. It is used here for its capability to simulate segments of the flight trajectory outside of the air traffic simulation zone.

Table 2 – Summary of Application Bottom-up Approach for Aviation Emission Global Inventory

Model	Trajectory	Aircraft Performance	Atmospheric/ Operational Conditions	Emission Data
Tier 3A: Generic Aircraft Type & Origin and Destination				
ANCAT/ EC2	• ATC data of 38 non-European countries; • EUROCONTROL (15 member states); • US scheduled flight data (factored up 10%)	• Sixteen civil jet aircraft types of almost 100 different aircraft/engine combinations • Fuel flow (excepting LTO) modeled using PIANO	Simulated at optimal cruise altitude, according to a limited dataset from one airline	• ICAO databank specified engine power settings and times-in-mode for the LTO-cycle • 'Standard' assumed ICAO taxi time was being reduced from 26 to 14 minutes
FAST (Future Aviation Scenario Tool)	Designed around the methodology of ANCAT/EC 1&2 inventories based upon a dataset of aircraft movements for some year which indicates the frequency of flights of specific aircraft between city pairs	• ANCAT/EC2 aircraft database • PIANO aircraft performance model, updated through the Expert Group List	Maximum flight altitudes for the representative aircraft types by mission distance based on preliminary movement data from AERO2k project	ANCAT/EC 2
ANCAT 3	• EUROCONTROL data (all flights entering air space of 29 member countries 2003 – 2006 • Flights operate partially outside EUROCONTROL only flight plans are available	19 generic aircraft types representing the world's passenger jet fleet	n/a	• ICAO (LTO cycle) • CORINAIR/EMEP
UK SERAS	15 destination regions (10 international and 5 domestic).	• Representative aircraft 'types' for domestic, short-haul and long-haul services. • Split by six seat band classes	• Recalculating the fuel burn data based on average aircraft age and engine technology by including only known aircraft types and performance data. • Average load, flight distance and flight altitude assumptions	• Aircraft fuel usage in tones is multiplied by 3.15 to give CO_2 emissions. • Surface access CO_2 emissions: multiplying total vehicle km multiplied by EFs of 147 g/km.

Model	Trajectory	Aircraft Performance	Atmospheric/ Operational Conditions	Emission Data
UK Improved NETCEN	• Detailed activity data by CAA (airport, aircraft type, intl/domestic, sector length of GCD) • To avoid double counting of cruise emissions, all associated with departure airport.	CAA specifies aircraft type but not engine types. Thus, a weighted average of emissions from different engines was used.	n/a	• ICAO databank (LTO) • Emissions from aircraft auxiliary power units (APU) are also included • Cruise phase: EMEP/CORINAIR (GCD factored up by 9.5%)
Tier 3B: Actual Route Flown & Detailed Aircraft Information				
AERO2k	• Radar-tracked flight data showing actual longitude, latitude and altitude along the flight path • Scheduled flight data from BACK Aviation database • All airports are at sea level and not affecting time to climb to cruise altitude and overall aircraft performance; the horizontal distance travelled during LTO cycle is not accounted for.	• 40 representative aircrafts representing 300 different types of fleets • PIANO performance tool	• Atmospheric conditions not considered • No data on wind • Take-off weight is calculated from the GCD plus allowances for diversion and delay[1] • Payload mass 60.9% (ICAO standard) • Flight speed which gives 99% of the max specific air range (SAR)	• Generated in Emission Parameterization Module varying with Mach number, throttle setting and altitude • ICAO emission databank
SAGE	• Radar-based flight trajectory and speed data for ETMS flights • Artificial flight trajectory and constant cruise speed for OAG flights	• More than 200 types of aircraft included • BADA aerodynamic performance data • BADA fuel flow model • FAA INM	• ISA temperature, pressure and density No head or tail wind • SAE AIR[2] 1845 take-off weight based on stage length • SAE AIR 1845 take-off and landing procedure • Full power take-off	Boeing Fuel Flow Method 2 (BFFM2) applied to ICAO EI database for NO_x, HC, and CO emissions
RAMS Plus and EUROCONTROL AEM III[3] (in Pejovic et al., 2008; Jelinek, et al., 2004)	• Traffic, route network, and sector data (UK NATS) • A 24-h air traffic sample used with 7,074 flights • The AEM completes the whole flight profile by adding LTO legs from departure and arrival airports and linking to the first and last known position of the aircraft according to the flight file from RAMS	• 91 aircraft types directly and a further 204 by equivalence to a directly specified type. • BADA (altitude and attitude dependent performance and fuel burn data of >150 aircraft types)	n/a	• ICAO (LTO) • BADA Revision 3.5 • For above 3,000 ft: an improved version (EEC-BM2) of the Boeing Method2 (BM2)

Note:
[1]Reserve allowances for long-haul flights includes an additional 5% of the fuel required to complete the mission, plus fuel for a 200nm diversion and 30 minute low altitude hold; for short-haul 5% allowance to complete the mission plus fuel for 100nm diversion and a 45 minute low altitude hold (Eyers et.al, 2004)
[2]Society of Automotive Engineers Aerospace Information Report 1845 provides engine and aerodynamic performance equations and coefficients for standard LTO procedures cover over 9,000 unique aircraft/engine combinations including all engine types in the ICAO data bank (Kim et al, 2007)
[3]Since the configuration of RAMS Plus with UK air traffic sample has some limitations, it was necessary to perform additional calculations using AEM tool (Pejovic et al., 2008)

Normally, emissions estimations should begin at the flight's pushback time, which is the moment when an aircraft departs from its gate. This time was not available for their scenario. For some flights, the start-of-take-off time was provided and for some the profile began at some altitude above the ground. However, using the AEM tool it was possible to adjust flights' entry times and to complete the flight profile by adding the missing legs. AEMIII includes a database for taxi times for about 3,000 airports. The AEM completes the whole flight profile by adding LTO legs from departure and arrival airports and linking to the first and last known position of the aircraft according to the flight file from RAMS. Timings for the taxi-in and taxi-out phases of the flight are airport-dependent and are predefined in the AEM model.

The air traffic sample available had detailed information only on flights within UK airspace. For international departures, the AEM completes the flight profile assuming that the aircraft uses the shortest (great circle) distance between the point of departure from UK airspace and the destination airport. On average, journeys are about 10% longer than this great circle route because of airspace constraints and meteorological factors (IPCC, 1999).

One of the benefits of this estimation technique is that it allows analysts to further disaggregate the sample to identify CO_2 contributions from those flights and aircraft that are the largest emitters. One additional analysis by aircraft group (based on size) revealed some interesting observations. Aircraft group categories are based on RAMS Plus default allocations for aircraft size and consist of five categories: Heavy (e.g. B747/777 and A330/340), Light Medium (e.g. A319/320, B727/737 and Fokker70/100), Light (e.g. Beech, Cessna or Embraer aircraft and LJ45), Small (e.g. Dash8, Embraer145, and Fokker50), and Ultra Medium (e.g. B757 and DC8). CO_2 emitted per flight-km of each aircraft group was estimated as a function of distance for short-haul flights (total distance less than 2,000 km), medium-haul flights (total distance between 2,000 and 5,000 km) and long-haul flights (greater than 5,000 km).

The result shows that figures from the AERO2k model for the year 2002 are well within the range of this estimate. The SAGE model produced slightly larger estimates for 2004 for international flights, which can likely be explained by the more detailed flight profiles used for airspace outside the UK. The underestimation of the distance in the cruise phase of the flight (and hence fuel burn and CO_2) for international flight, however, is still less than 4% compared with the SAGE estimate and less than 2% when total CO_2 estimates are compared.

6. Application of Bottom-up Approach for Configuration- and Distance-based Carbon Calculator

Carbon calculators are used by Governments for international emissions reporting, for businesses' declarations of corporate social responsibility, and also by individuals wishing to reduce their own environmental impact (Miyoshi and Mason, 2009; Jardine, 2009).

6.1 Tier 2A: DEFRA Method

UK DEFRA developed their own emissions calculator methodology to promote consistency by using data and factors across Government departments. In terms of aviation, DEFRA studied average emission level of air transport and presented emission factors for domestic and international flights on several routes using default average factors for CO_2 emissions and average flight distances and load factors.

A number of criticisms in the assumptions used in the calculation of the emission factors released in July 2007 have been raised by the aviation industry. Following the feedbacks, the factors were revised (DEFRA, 2009). The new average factors have been calculated in the same basic methodology, using the aircraft specific fuel consumption/emission factors from EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook (2006). The principal changes to the calculation methodology, data and assumptions include:

a. A significantly wider variety of representative aircraft have been used to calculate emission factors for domestic, short- and long-haul flights.
b. Average seating capacities, load factors, and proportions of passenger km by the different aircraft types have all been calculated from CAA (Civil Aviation Authority) statistics for UK registered airlines for the year 2006 (the latest available complete dataset).

c. Short-haul flights average load factor changed from 65% to 81%. The revised figure is the average for all European international flights calculated from CAA statistics for the selected aircraft. This figure may be compared to an average of 79.7% for all international flights from DfT Transport Statistics for 2006.
d. Long-haul flights average and load factor has been changed from 79.7% to 78%. The revised figure is the average for all non-European international flights calculated from CAA statistics for the selected aircraft.
e. Freight transported on passenger services has also been taken into account. Accounting for freight makes a significant difference to long-haul emission factors.
f. An uplift of 10% to correct underestimation of emissions by the CORINAIR methodology compared to real-world fuel consumption.
g. Since the CAA data show that almost all freight carried by passenger aircraft is done on scheduled long-haul flights, freight load is treated in one of 2 ways under DEFRA methodology. First, emissions are allocated in the proportions of the respective weights of passengers and freight, giving a freight load of 28.8% for long haul and less than 1% for short-haul. A second variant takes into account the additional weight necessary for passenger services (seats, galley, etc) and allocates a lower percentage to freight (11.9% for long haul). The final average CO_2 emission factors for all freight for 2009 GHG conversion factors for domestic, short- and long-haul flights are 1.92 $kgCO_2$/tkm, 1.40 $kgCO_2$/tkm, and 0.59 $kgCO_2$/tkm, respectively.

Table 3 – DEFRA Seating Class-based Emission Factors for Passenger Flights for 2009

Flight Type	Load Factor (%)	gCO_2/ pkm	Number of Economy Seats	% of avg gCO_2/ pkm	% of Total Seats
Domestic flights (Average)	65.2	171.0	1.00	100	100
Short-haul flights (Average)	80.9	98.3	1.05	100	100
Economy class	80.9	93.6	1.00	95	90
First/business class	80.9	140.5	1.50	143	10
Long-haul flights (Average)	77.8	112.2	1.37	100	100
Economy class	77.8	81.9	1.00	73	80
Economy+ class	77.8	131.1	1.60	117	5
Business class	77.8	237.5	2.90	212	10
First class	77.8	327.6	4.00	292	5

Note:
*Include the uplift of 10% to correct underestimation of emissions by the CORINAIR methodology and do not include the 9% uplift for Great Circle Distance, which needs to be applied separately.
**Besides average factors, the emission factors are also derived based on the seating class. A review was carried out on the seating configuration from a selection of 16 major airlines and average seating configuration information from Boeing and Airbus websites. 24 different aircraft variants including those from the Boeing 737, 747, 757, 767 and 777 families, and the Airbus A319/A320, A330, and A340 families were considered.
Source: DEFRA, 2009

6.2 Tier 2B: Miyoshi and Mason Method

Miyoshi and Mason (2008) attempted to adopt a disaggregated (bottom-up) approach in order to develop more accurate calculated reflecting actual air transport activity. Their study aims to demonstrate current emission levels by route, stage length, aircraft type used, number of seats supplied on each aircraft and the distance flown on each route. It focuses on three air transport market: the UK domestic routes, the intra-EU routes serving UK and the North Atlantic routes.

Fundamentally, their approach follows the acknowledged methodologies based on revised 1996 IPCC Guidelines.

1. Aircraft type, cruise altitude and sector distance are used to calculate the fuel consumption and therefore emissions during the LTO cycle and cruising stage on each route. Emissions during LTO cycle, by aircraft type, are obtained from IPCC (1997) guidelines and the Emission Inventory Guidebook 2006. Subsequently, fuel consumptions during cruise stage are calculated using performance tables from BADA Revision 3.4 and 3.6 (EEA data were used for the aircraft mission from the BADA dataset).

2. These calculations are based on the most frequently used cruise altitude for each route. On shorter sectors lower cruise altitudes are generally used and here the fuel efficiency of the aircraft is less than if a higher altitude is used.
3. To allow for the climb from leaving exiting the Take-off phase (at 3,000 ft) to the operated cruise altitude (perhaps 30,000 ft), the model adds 10-15 minutes to the cruise time depending on the length of the sector and ultimate cruise altitude.
4. Traffic data for 2006 (1626 routes and 59 aircraft types) on UK domestic routes and the intra-EU routes serving UK airports was obtained by the UK Civil Aviation Authority. The GCD is used for sector distances following NASA's 1994 methodology.
5. The estimate is made based on the assumptions of typical seat configuration (the number of seats supplied) and 75% load factor across a range of sector length for different aircraft.
6. The emission levels per sector can be segmented into groups based on the type of airline operations: network carriers from outside EU and European Environment Agency (EEA) countries, charter airlines, network carriers in EU, low cost carriers and regional airlines. It is assumed that low cost carriers tend to operate new fuel-efficient aircraft, have high seating density and report exceedingly high load factors. Together this means passengers on low cost carriers tend to have relatively low carbon emissions on a gram per passenger kilometer basis compared with passengers on network or regional carriers.

6.3 Tier 3A: ICAO Method

ICAO methodology (2009) employs a distance-based approach to estimate an individual's aviation emission using data currently available on a range of aircraft types. Table 4 shows the steps carried out and data used in this methodology.

6.4 Tier 3B: Sabre Holdings Method

Jardine (2009) introduces a new carbon calculator methodology developed by Sabre Holdings. Sabre® is a computer reservations systems (GDS) used by airlines, railways, hotels, travel agents and other travel companies. The Sabre database contains information about all flights including the data of travel, airline, departure point and destination, as well as technical details about the plane used for the flight (model and seating configuration). Further, the model used SAGE model to give modeled fuel burn for a large number of aircraft types (more than 200, see section 5.2 for details). Thus, it is not necessary to assume a 'typical' plane for the flight. Instead, the characteristics of the actual plane can be modeled. Another data source is the Passenger Name Record (PNR) containing information about the individual flights and is utilized for booking flights for passengers. The PNR contains information about the point of origin, destination, airline, plane type used and can access seating configuration. The latter two parameters, used in conjunction with the SAGE model provide accurate CO_2 emissions calculations on a flight-by-flight basis.

As in ICAO carbon calculator, based on the departure point and destination provided by the PNR, Sabre model calculates the distance between them by a simple GCD calculation from known attitude and longitude coordinates. However, no factor is applied since the extra fuel burn for stacking and deviation from GCD is accounted for in SAGE. Using the PNR details on the plane type used for the flight, the Sabre Holdings model developed fuel burn formulas as a function of distance for each plane type.

Afterwards, the fuel burn per seat is calculated. First, emissions related to cargo are removed, based on data from US Form 41 traffic data. Second, fuel burn is allocated per seat. The model contains seating configuration data disaggregated by airline and plane model, based on data held in the Sabre Holdings reservation system. This allows more accurate representation of the efficiency of a particular airline.

Finally, CO_2 emissions per seat can be calculated by multiplying by an emissions factor of 3.157 kg CO_2/kg Fuel, the same as ICAO's. It should be noted that this is for CO_2 only and does not include a multiplier for the additional climate impacts of emissions at altitude.

Table 4 – ICAO Carbon Calculator Methodology

Steps	Data	Descriptions
User input	Origin and Destination Airports	• Only includes individual routings for single flight numbers with multiple stops • For connecting flights with different flight numbers, user can choose to calculate each journey legs separately and adding them up
Trip Distance	ICAO Location Indicators contains longitude and latitude for the airports	Calculates the Great Circle Distance based on those coordinates and corrected by a factor: • < 550 km → + 50 km • Between 550 and 5500 km → + 100 km • > 5500 km → + 125 km
Traffic Data	Assigned passenger load factor	Based on 17 international route groups plus 5 domestic areas
Aircraft Mapping	Aircraft fuel consumption database EMEP/CORINAIR	If not in the database, the aircraft is mapped into one of the 50 equivalent aircraft types available in the database
Fuel Burn Data	Extrapolated from Emission Inventory Guidebook of EMEP/CORINAIR • Tier 3A method	• The factors considered include: load factor, flight distance, the proportion of overall payload by passenger traffic, cabin class flown, type of equivalent aircraft. • The amount of fuel used on a route is the weighted average of total fuel burnt based on the frequencies of the scheduled aircraft types flown.
Economy Class (Y) Seat Capacity	Cabin floor plans from, the "Manual on Airplane Characteristics for Airport Planning"	
CO_2 per Economy Passenger	CO_2 per pax = 3.157 * (total fuel * pax-to-freight factor)/(number of y-seats * pax load factor)	• Pax-to-freight factor is the ratio calculated from ICAO statistical database based on no. of passengers and the tonnage of mail and freight, transported in a given route • An average passenger mass with baggage is assumed as 100 kg, plus a 50 kg add-on to account of the onboard equipment (e.g. seats, toilets, galleys and crew) • 3.157 is constant representing the no. of tones of CO_2 produced by burning a tone of aviation fuel.
Cabin Class	Depending on user selection	• A multiplicative cabin class factor is applied to adjust the CO_2 per Y-passenger, on those routes where multiple class passenger services are available • The cabin class correction factor is used only on equivalent aircraft types that support such differentiation, and on flights > 3,000 km • Employs simplified approach by using two cabin class factors ("economy" and "premium") with ratio 1:2

Source: ICAO, 2009

Table 5 –Passenger- and Distance-based Aviation Carbon Emission Calculator

Parameter	Tier 2A DEFRA	Tier 2B Miyoshi and Mason	Tier 3A ICAO	Tier 3B Sabre Holdings
Traffic Data	UK CAA	UK domestic and the intra-EU routes serving UK airports (UK CAA)	17 international route groups plus 5 domestic areas	The Passenger Name Record (PNR)
Distance Flown	10%	Around 10%	Up to 11% (based on distance flown range)	Accounted for in FAA/SAGE
Aircraft Mapping	Indicative short, medium, long haul calculated from range of typical aircraft	59 aircraft types	Based on scheduled aircraft mapped onto 50 equivalent aircraft types	Scheduled aircraft mapped onto >200 equivalent aircraft types (SAGE database)
Fuel Burn Data	EMEP/CORINAIR	• ICAO, BADA • Cruise: most frequently used altitude per route • Adds 10-15 min to the cruise time for the climb	EMEP/CORINAIR	FAA/SAGE
Freight Factor	<1% domestic and short-haul; 28.8% long-haul	n/a	47-88% depending on route and wide/narrow body; 34 classes	20% wide body; 10% narrow body; 1% regional jets
Per seat/passenger	Passenger	Passenger	Passenger	Seat
Load Factor	65.2% domestic; 80.9 short-haul; 77.8% long-haul	75%; real load factor for long-haul international flights (AEA, 2004)	Assigned passenger load factor	n/a
Seating Configuration	Representative from CAA data (2006)	Typical seat configuration	Economy-class (Cabin floor plans)	Specific to airline and aircraft model
Cabin class adjustment (economy:premium)	Range of ratios for different seat classes in domestic, short- and long-haul	n/a	1:2 based on space allocation	1:1.1 narrow body; 1:1.5 wide body; based upon relative weight
Multiplier for non-CO_2 pollutants	No	No	No	No, but may be applied to ax term

7. Uncertainty Sources and Improvements Made by Current Methodologies

This report focused on bottom-up approach or Tier 3 application for two purposes: global emission inventory and carbon calculator. In the following subsection, the uncertainty sources of this approach along with its evolutions are discussed.

7.1 Aircraft Mapping

As mentioned previously, Tier 3 approach considers the type of aircraft used in an individual flight. Due to information limitation, these individual flights are often represented by several set of generic aircraft types based on engine technology, seating capacity, configuration, MTOW, etc. The classification is further consulted with the availability of suitable performance data. It should be noted though that the actual aircraft performance: the age of an aircraft, maintenance standards, and the actual operation all have an influence on fuel consumption. Again, these factors are only included as approximate values through average fuel consumption rates. Even in Tier 3A, the potential evolution of engine mix for a given aircraft type is ignored.

Tier 3B's AERO2k model attempted to improve the representativeness of generic emission characteristics by weighting the emission index for NO_x for the number of engines in the fleet's population for each of the four thrust settings of the LTO cycle. Further, the generic emission characteristics were compared with real engine data and closest fit determined by a polynomial least-square regression. In the improved NETCEN which adopted Tier 3A method, where different engines might be used in a single type of aircraft, a weighted average of the emissions from different engine was used. It also considered the airport type in specifying aircraft performance.

On the contrary, Tier 3B's SAGE model skipped the step and included 200 different aircraft type instead. It used BACK world fleet database which recorded all aircraft type produced since 1940. The database provides tail numbers, engine types, weight, size, seating and airlines. As can be seen, with the evolving data and methodologies through Tier 3B models, the activity data's accuracy and completeness are increasingly improved.

7.2 Emission Factors

EEA (2009) suggests that it is a key priority to update the fuel consumption and emission factors in order to better reflect the emission performance of today's aircraft in use both for LTO and cruise.

7.2.1 LTO

It is also recognized that ICAO's thrust settings and time-in-mode for the LTO cycle, may not reflect the actual operational time-in-mode vary from airport to airport depending on traffic, environment consideration, aircraft types and topographical conditions. ICAO estimates that the uncertainties of the different LTO factors are approximately 5-10%, while for cruise stage, it is assumed to be 15-40%.

7.2.2 Cruise

Emission factors for cruise operations are characterized by a high degree of uncertainty (Romano et al., 1997; IPCC, 2006; EEA, 2009). First, current methods usually use great circle distance and add it with an adjustment factor to reflect the actual route flown (about 10%). Some studies pointed out that it may be the reason of smaller estimates. Additionally, cruise altitude is usually assumed to be constant (the optimal altitude), although recent study applied frequent cruise altitude used for each route differ by distance.

According to Babikian, et al.'s (2002), aircraft that fly short stage lengths have lower ratio of airborne hours to block hours because of the need to taxi and maneuver more often for every unit of time spent in the air. The time for taxiing and maneuvering will also vary for different airport condition. They therefore incur a fuel consumption penalty relative to longer-flying aircraft. Aircraft flying stage lengths below 1000 km have E_U values between 1.5 to 3 times higher than aircraft flying stage lengths above 1000 km. Thus, taking into account the actual altitude and distance flown will likely improve the accuracy of estimate since lower cruise altitude equals to higher fuel consumption rate and hence also the emissions and also the rate of production of NO_x.

Table 6 – Input Data, Assumptions, Prerequisites and Applications of Current Methodologies

METHOD	INPUT DATA: Activity	INPUT DATA: Technology Stratification	ASSUMPTIONS	PREREQUISITES	APPLICATIONS
TOP-DOWN APPROACH					
Tier 1: Pure fuel-consumption based	• Aggregate quantity of fuel consumption data for aviation • Split into domestic and international flights	Average EFs: the default for CO_2, CH_4, N_2O and NO_x (Emission Factor Database, IPCC)	• 10% of the fuel is used for the LTO phase of the flight • Methane EFs are averaged over all flying phases	• Aviation gasoline aircrafts • Jet-fueled aviation when aircraft operational use data are not available	
BOTTOM-UP APPROACH					
Tier 2A: Generic Aircraft LTO	• Fuel sales sub-divided into domestic and international use, as for Tier 1 • Total LTO numbers for domestic and international	Use average fleet mix (i.e. Generic aircraft EFs) and average factors for LTO and cruise	• EFs are suggested for an old and an average fleet by representative aircraft • CH_4 are assumed to be zero unless new information becomes available	• For jet fuel use in jet aircraft engines • Recommended to distinguish international flights into short (<1000 nm)[1] and long (>1000 nm)	*CO_2 Calculator:* DEFRA
Tier 2B: Aircraft-specific LTO	• Fuel sales sub-divided into domestic and international use, as for Tier 1 • LTO numbers for domestic and international per aircraft type	Use aircraft specific LTO EFs and average EFs for cruise[2]	Should include all aircraft types frequently used for domestic and international aviation	If LTOs per aircraft type available but no information on cruise distances	*CO_2 Calculator:* Mayoshi and Mason
Tier 3A: Generic Aircraft Type & Origin and Destination	• Includes IFR and non-IFR flights • Details on origin (departure) and destination (arrival) airports and aircraft type • For military/pleasure aircraft: no. of hours flight or fuel used can be activity indicator	*IFR Flights:* Emissions per flight distance EMEP/ CORINAIR (EEA, 2009)[3] *Non-IFR Flights:* At present no default EFs is being recommended, but range of EFs are shown in MEET (1997)	• Takes into account cruise emissions for different flight distances • Average fuel consumption and emission data (LTO and cruise) for an array of representative aircrafts • The use of energy referring to engine power settings and times-in-mode for each stage of the LTO cycle specified by ICAO.	• If OD of flights and air movements data available • The total estimated fuel use for domestic aviation must be compared to sales statistics or direct reports from the airline companies. • For pollutants not given in the spreadsheet, EEA (2009) recommends using Tier 2 approach based on the estimate fuel use calculated using the Tier 3A approach.	*Global Inventory:* • ANCAT/EC2 • FAST • ANCAT3 • UK SERAS • UK Improved NETCEN *CO_2 Calculator:* ICAO Carbon Calculator

METHOD	INPUT DATA Activity	 Technology Stratification	ASSUMPTIONS	PREREQUISITES	APPLICATIONS
Tier 3B: Full Flight Trajectory & Detailed Aircraft Info	Radar tracked trajectory data showing longitude, latitude, altitude and time throughout the whole phase of flight, in addition to basic data similar to Tier 3A	• Aircraft and engine specific aerodynamic performance information • EFs contained within the models necessary to employ the methodology	Calculation of fuel burnt and emissions throughout the full trajectory of each flight segment	• Sophisticated computer models are required to address all the equipment, performance and trajectories variables and calculations for all flights in a given year • Must based on input data that take into account air-traffic changes, aircraft equipment changes or any input-variable scenario	*Global Inventory:* • AERO2k • SAGE • RAMS Plus • AEM III *CO_2 Calculator:* Sabre Holdings Model

Note:

[1]Where nm = nautical miles, 1 nm = 1,852 km.
[2] Emission factors are based on the specific national aircraft fleet and typical airport TIM (International Civil Aviation Organization Engine Exhaust Emissions Databank). Another possibility is US EPA (1985): *Compilation of air pollutant emission factors*, Vol. II: Mobil sources, 4th Edition, or US Office of Environment and Energy (1991) *FAA Aircraft Emission Database User's Manual*.
[3] Emission factors for the Tier 3 methodology are available from the EMEP/EEA Guidebook website (www.eea.europa.eu/emep-eea-guidebook)
Source: IPCC (2006); EEA (2009)

The inclusion of 4D radar-tracked flight activity data into the estimation procedure of Tier 3B as in AERO2k and SAGE is one significant way to improve the accuracy. SAGE also adjusts take-off weight to account for fuel tinkering (the practice of purchasing fuel in regions with lower prices), by systematically increased flight weights by two stage lengths. Such uncertain factors are not modeled in AERO2k. However, AERO2k model also takes into consideration aircraft in-flight weight changes which in turn result in variations in fuel burn and emissions (Eyers et al., 2004; Kim et al., 2007).

7.3 Operational Efficiencies for Carbon Calculator Methodology

In the case of developing a carbon calculator that accurately reflects the actual air transport activity, a more cautious approach should be carried out in detailing the operational arrangements. One factor is the aircraft size used which does not depend only on the aircraft model but also its configuration (number and class of seats, distribution between seating and cargo capacity). This configuration gives significant influence on fuel burner per passenger-km, differs among airlines and is usually based on market consideration.

Givoni and Rietveld's (2009a) findings show that the choice of the aircraft size depends on market size, indicating that in the airline industry, carriers give priority to increases in frequency. Another result is that aircraft size increases with distance, a natural result of the trade-off between cost of loading/unloading, and cost of flying. Furthermore, the presence of low cost carriers leads to somewhat larger aircraft with higher seating density and relatively newer and fuel-efficient aircraft (Mayoshi and Mason, 2009; Morrell, 2009). Morrell (2009) suggests that there is a strong linear relationship between fuel efficiency and size for modern commercial aircraft, with a higher coefficient for single-aisle than twin-aisle aircraft. Cautious approach on such trend will improve the assumed average load factor accuracy which influences an aircraft take-off weight and hence fuel consumption.

Accordingly, recent carbon calculators such as Tier 3A's ICAO and Tier 3B's Sabre Holdings model use more rigorous approach in assigning load factor, seat configuration, cabin class adjustments, and cargo factor to each individual flight.

8. Summary and Recommendation

IPCC developed tiered methodology to estimate aviation emissions aiming for harmonious reports for worldwide countries. Using tier 1, emissions are estimated purely based on fuel consumption which is assumed to be equivalent with the amount of fuel sold. On the other hand, through the higher tier methodology -Tier 2 and Tier 3 - more specificity is taken into account to some extent. Whilst Tier 2 is based on the number of LTOs and fuel use, Tier 3 use more extensive aircraft type and more detailed movement data which, at minimum, consists of information on the origin and destination, aircraft type, and date of individual flights.

This report categorized Tier 2 and Tier 3 methodology into bottom-up approach since they take into account at least the aircraft type to capture the individual flight conditions. It reviews the applications of bottom-up approach in estimating aviation emission for two objectives. First is the application for composing emission inventory at country or regional level. Second is for developing carbon calculator which considers seat configuration, distance and other operational factors.

Global databases of aircraft performance during LTO and cruise stage for representative aircraft mapping and obtaining emission factors for each type of pollutants have been available and can be accessed widely. Nevertheless, every application for different regions/countries should verify the representativeness of those average aircraft type to the types of aircraft operating. When aircraft types used are relatively homogeneous, top-down approach may be sufficient.

In applying top-down approach, it is important to take into account all fuel used for aviation and to distinguish between domestic and international flights. Both requirements remain encountering significant challenges, especially for non-scheduled flights, military flights and general aviation. For countries that have a good quality of fuel statistics, top-down approach may provide sufficiently accurate results. In cases where air traffic data required for bottom-up approach are not available and therefore leave top-down approach as the only alternative, each country is urged to estimate the split obtained from fuel taxation data or surveys of airline companies.

Another common allocation problem is measuring fuel consumption by airline for international flights. Most airlines operate internationally and, thus, allocating them based on country will be problematic. The agreed approach used by most estimates is by basing on the departing airport and each flight's emissions are allocated to the country from which they departed.

Furthermore, energy usage of an aircraft throughout all phases of a full "gate-to-gate" flight varies greatly for different types of aircraft according to the level of advancement, size, distance flown, propulsion system type, and various operational efficiencies including altitude of operation and traffic volume. In order to incorporate those factors into the estimation, some attempts have been made:

(i) Worldwide flight schedules have been available which includes types of aircraft use for each flight;

(ii) Actual air traffic data availability have been considerably progressing including radar-tracked flight data flight showing longitude, latitude and altitude along the flight path. It can further improve the accuracy of cruise fuel consumption by applying actual distance flown instead of relying solely on factored-up GCD and by applying actual altitude compared with the optimum altitude;

(iii) Cautious approaches in assigning load factor, seat configuration, cabin class adjustments and cargo factor to each individual approach have also been carried out especially to calculate carbon emission per passengers;

(iv) Advanced models with sophisticated computer assistance have been able to estimate annual emissions by using a year-full actual air traffic data and complete the "gate-to-gate" flight path. Although most estimates extrapolate the annual traffic from 1-day, 1-week or 1-month traffic data by applying some assumptions to address differences between weekend and weekday or to address seasonal variation. Extrapolations are found to result in overestimate.

Needless to say, detailed data are not available for all countries. Thus, in case such detailed information can be obtained, bottom-up approach is recommended.

Conclusively, the choice of which method to be used depends heavily to the availability of data where locally and publicly available data should be used as much as possible.

APPENDIX
List of Abbreviation

AIC	Aviation-induced Cloudiness
AEM	Advanced Emission Model
ATC	Air Traffic Control
ANCAT	Abatement of Nuisance Caused by Air Transport
ASK	Available Seat Kilometer
BTS	Bureau of Transportation Statistics
BADA	Base of Aircraft Data
BM2	Boeing Method 2
DEFRA	United Kingdom Department for Environment, Food and Rural Affairs
DfT	United Kingdom Department for Transport
DLR	Deutsche Forschungsanstalt fur Luft- and Raumfahrt, German Aerospace Center
DTI	United Kingdom Department of Trade and Industry
CAA	United Kingdom Civil Aviation Authority
EEA	European Environment Agency
EC	European Commission
EF	Emission Factor
EMEP	European Monitoring and Evaluation Program
ETMS	Enhanced Traffic Management System
FAA	United States Federal Aviation Authority
FAST	Future Aviation Scenario Tool
GCD	Great Circle Distance
GDS	Global Distribution Systems
GHG	Greenhouse Gas Emission
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LTO	Landing and Take-off
MTOW	Maximum Take-off Weight
NASA	National Aeronautics and Space Administration
NATS	United Kingdom National Air Traffic Services
NETCEN	United Kingdom National Environment Technology Center
OAG	Official Airline Guide
OEW	Operating Empty Weight
OD	Origin-Destination
PIANO	Project Interactive Analysis and Optimization
PNR	Passenger Name Record
RF	Radiative Forcing
RPK	Revenue Passenger Kilometer
SAGE	System for Assessing Aviation's Global Emission
SAR	Specific Air Range
SARS	Severe Acute Respiratory Syndrome
SERAS	South East and East England Regional Air Service Study
SFC	Specific Fuel Consumption
TSFC	Thrust Specific Fuel Consumption

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ACKNOWLEDGMENT

This work was supported by the Global Environment Research Fund (S-6-5) of the Ministry of the Environment, Japan.