JOURNAL OF AIRCRAFT
Vol. 45, No. 1, January–February 2008

Analysis of Carbon-Dioxide Emissions from Transport Aircraft

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DOI: 10.2514/1.31422

The problem of allocation of fuel consumption and carbon-dioxide emissions from transport aircraft is presented. An accurate comprehensive program for transport aircraft has been developed. The model includes a geometry deck with 12 subsystems, a separate engine input deck with basic parameters, a database of engine performance from independent simulation, an aerodynamics model for all flight conditions, and an operational deck. Validation of the model is discussed from the point of view of aerodynamics and payload-range performance. The aircraft considered are the Boeing B-737-500, B-747-400, and B-777-300, and the Airbus A340-300. Parametric studies are shown in terms of flight distance, passenger load, baggage allowance, operation with an en route stop, and direct flight. Calculations of best flight range and average passenger load have been considered. Data are presented in matrix form to be used for allocation of carbon dioxide in carbon trading schemes and for the critical evaluation of emissions from civil and commercial operations. It is shown that emissions per passenger per nautical mile range from 0.5 to 1.5 times the reference conditions, which is taken from the design range at full passenger load. It is also shown that fuel and emission savings can be achieved from optimal flight distance.

Nomenclature

C_D	=	drag coefficient
C_L	=	lift coefficient
C_P	=	combustion heat of jet fuel
D	=	aerodynamic drag
k	=	induced drag factor
M	=	Mach number
m_f	=	fuel mass
m_f^*	=	available fuel mass
m_{res}	=	fuel reserve
T	=	net engine thrust
v_{out}	=	ground speed at taxi-out
X	=	aircraft range
x_{out}	=	taxi-out distance

Introduction

IN RECENT years, environmental emissions from aircraft have become a critical issue in aviation, involving the industry, and international and local regulators. The issue has been taken up by the International Panel for Climate Change (IPCC) [1] and by several government bodies that routinely commission research into aviation emissions (for example, Watterson et al. [2]).

Combustion gasses, particularly at high altitude, are perhaps the most critical aspect of emission from civil and commercial aviation. Aircraft noise is limited to terminal area operations. Noise disappears as the aircraft moves away from the receiver. By contrast, the emission of combustion gasses, such as CO_2, is a permanent trace of air transport; CO_2 is estimated to remain in the atmosphere for anywhere up to 100 years. Although science is unclear on the whole carbon cycle (in particular, the absorption by land, oceans, and vegetation), its effect as a greenhouse gas has now been fully established. Nevertheless, until very recently, the problem of aircraft noise has been the main drive toward cutting environmental emission. The predicted growth of air transport in the next few decades (particularly in Asia) indicates that emissions may grow exponentially from the current levels.

The effects of CO_2 are smaller than methane (CH_4), N_2O, and other pollutants when compared by unit weight. However, at present, CO_2 is considered the most dangerous greenhouse gas, due to the sheer amount of fossil fuels burnt from all sources. In fact, within the context of the Kyoto Protocol, only emissions of CO_2 are to be regulated.

In response to the preceding concerns, various lobby groups, including energy advisers, carbon footprint calculators, and carbon trading schemes, rely on gross estimates of CO_2 emissions from air transport. They provide estimates that in this paper are proved to be 50–100% in excess of the actual data. For example, a common calculator provides an average CO_2 per passenger over 1000 n miles equal to 330 kg. By this reasoning, a 2000 n mile trip would produce 660 kg per passenger, without accounting for the effects of climb and descent. The U.S. and U.K. calculators do not specify loads or aircraft and are very simple calculations. In the U.K., most calculators use the Department for the Environment (DEFRA) guidelines, which are just a simple long- and short-haul $CO_2/\mathrm{pax}/\mathrm{km}$ reading (where "pax" stands for passengers). These data could be adjusted to take into account the indirect use of energy at air terminals, ground transport to and from airports, but this point is not made clear in the calculators.

At the very bottom of the problem there is the amount of aviation fuel sold. This figure would give the total amount of CO_2 emitted. An approximate value is 3.15 kg of CO_2 per kilogram of aviation gas, although the exact amount depends on the carbon content of the fuel.

However, to establish the framework for CO_2 analysis, it is necessary to predict where and how much carbon is emitted. Also, it is necessary to identify the critical parameters for an informed decision at all levels, including carbon trading schemes, optimal aircraft operations, aircraft design, etc. The critical parameters are the aircraft, the engine performance, and several operational parameters: flight distance (including allocated flight corridors, rerouting to alternative airports), flight schedule (cruise altitude, climb program, ground operations), useful load (passengers and cargo), etc.

A number of crude methods (relying on airports databases) are being applied to estimate the emissions from the number of aircraft movements. These estimates are broken down by aircraft type, and make use of various approximations relating to the operations of the aircraft.

The need to account for CO_2 emissions is now part of some official atmospheric emissions inventory of greenhouse gasses. The largest part of emissions from aviation comes from civil instrument flight rules (IFR) under the International Civil Aviation Organization

Received 4 April 2007; revision received 8 June 2007; accepted for publication 12 June 2007.

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(ICAO) qualification. These are emissions from transport aircraft under scheduled flights.

Some standard methods used for the estimation of fuel use are based on bunker fuel sales and on cumulative distance flown. Data are kept for all categories of aircraft, including military (in the United Kingdom). Therefore, the total amount of aviation fuel used is a reliable datum. These methods cannot account for detailed use of fuel and the split between different types of aircraft. In particular, the split between landing and takeoff (LTO) and cruise fuel use is important in terms of complying with local emission targets.

The IPCC classifies the methods in three classes (tiers). Tier 1 is a category based on simple estimation methods. Tiers 2 and 3 need detailed activity data, but do not rely on specific aircraft performance. The European Civil Aviation Conference (ENAC) has three categories of methods, called ANCAT (Abatement of Nuisances Caused by Air Transport). ANCAT 1 is the simplest and relies on the total amount of fuel sold; it does not require details of the aircraft. ANCAT 3 is the most detailed method, requiring the movements by aircraft type and details of arrivals/departures of domestic/international flights.

A global modeling system called the FAST (future aviation scenario tool) is used for the calculation of the aircraft emissions by using international air traffic movement databases. FAST builds upon the ANCAT methodology. Each database is limited to 1 year. During this time, data on flights between city pairs (or their frequency) are recorded, along with the aircraft type. The databases lack precise estimation of fuel consumption, and most often the average passenger load (which is a proprietary figure of the airlines). Estimates of fuel consumption are done by using external programs.

At least seven different allocation methods have been proposed by the IPCC and evaluated. These methods rely on bunker fuel sold, country of departure or destination, nationality of the carrier, etc. None of these methods relies on the actual characteristics of the aircraft. If the principle of "polluter pays" comes into effect, then it is necessary to have more accurate methods for dealing with the environmental effects of air transport.

By contrast, the present study is based on a very detailed analysis of selected transport aircraft. This study has at least two broad motivations: 1) to identify where fuel is burned, and those parameters that have an appreciable effect from an operational point of view; 2) to provide a rational background for dealing with environmental issues created by large passenger transport aircraft.

The aircraft that have been selected for this analysis are the B-747-400, B-737-500, B-777-300, and A340-300. The cumulative fuel consumption of these aircraft amounted to 34% of the total emissions from transport aircraft in the year 2000. Therefore, analysis of the emissions from these aircraft is a representative data set [3]. Furthermore, the operation of B-777, B-747, and A-340 corresponds to about 50% of the transatlantic fuel consumption and 87% of the transpacific fuel consumption. The operation of the B-737 (various versions) is the mainstay of the so-called budget airlines. Therefore, the choice of these four aircraft is representative of the whole of air transport across the world.

The details are split into three categories: 1) aircraft model, 2) operational scenario, and 3) mission analysis. The overall fuel consumption is calculated "exactly," on the basis of the split among flight segments. The term exact means that the iterative procedure attempts to match the fuel requirements to the payload weight down to a fraction of a kilogram. This is impossible in practice, because the weight is not clearly defined.

Aircraft Model

Simulation of aircraft performance must rely on a comprehensive code that has the capability of modeling the major aspects of a typical transport operation. Comprehensive models are not necessarily detailed. Yet their importance lies in the multidisciplinary approach that produces a reasonably accurate simulation of the aircraft as a system.

Detailed models of transport aircraft do not exist, hence some assumptions are required. The major difficulty is the integration of the airplane's aerodynamics with the engine's performance. This difficulty does not arise from modeling itself, but from lack of reference data, such as critical engine characteristics and geometrical details of the aircraft. Another critical aspect, discussed further in the validation section, is that airline operators consider the flight data as commercially sensitive.

To this end, the airplane is described by a set of parameters in the category of geometry, performance limits, engines, or operational conditions. More specifically, the model consists of the following:

1) The geometry deck is divided into 12 subsystems (fuselage, wing, winglet, tail plane, fin, engines, flaps, slats, aileron, rudder, elevator, landing gear), for a total of about 100 geometry points (not all of them are required for all aircraft).

2) Limitation parameters include weights (seven parameters), maximum operating Mach number, passengers, seating, crew, center of gravity range, etc.

3) Operational parameters include design range, flap position at takeoff and landing, maximum lift coefficient in takeoff and landing configuration, auxiliary power unit (APU) fuel consumption, etc.

4) User settings include features such as baggage per passenger, weight of onboard services per passenger, etc.

5) The engine model is described separately.

From the geometry frame, several dozen parameters are derived, including the wetted areas, centroids, and form factors of each component. The geometry is derived from digital drawings and compared with manufacturer's specifications. Linear dimensions have an error on the order of 0.5%, and planform areas have errors of up to 1%.

Areas of quadrilateral elements are calculated in closed form by using geometrical relationships. Areas of elements defined by several points (cross sections, fuselage nose, engine's side view) are calculated with a stochastic method, based on a Monte Carlo approach. The method is based on shooting random numbers within the bounding box of the reference area. This area is calculated with any precision required from the set input points.

The only concern about overall accuracy is at the intersection between elements, due to filleting and overlapping of surfaces. Figures 1–3 show examples of how the airplane geometry is constructed from basic technical drawings. The dots are the reference points used in each view. Other geometrical quantities, such as the tire dimensions and engine dimensions are taken from independent databases. These are not indicated in the graphs. An example of calculation of the wing area is shown in Fig. 4 for the wing of the B-777. The exposed area is 361.83 m^2 in the horizontal plane. This area, corrected for wing dihedral becomes 362.27 m^2. The reference wing area is calculated by extending the wing inside the fuselage as

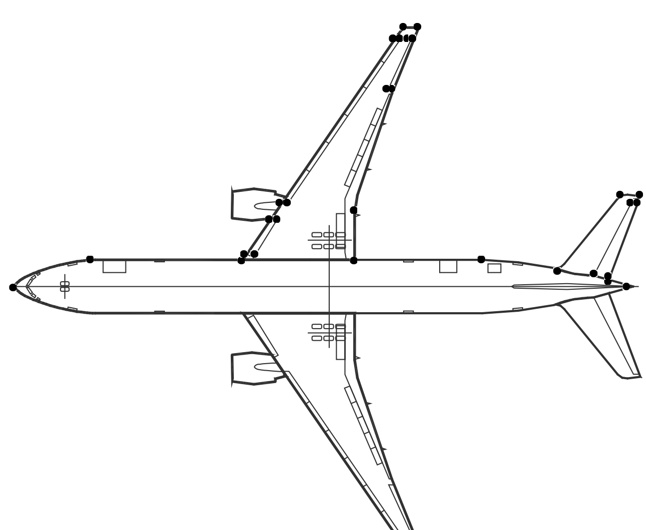


Fig. 1 Construction of airplane geometry from top view. Example shown is B-777-300.

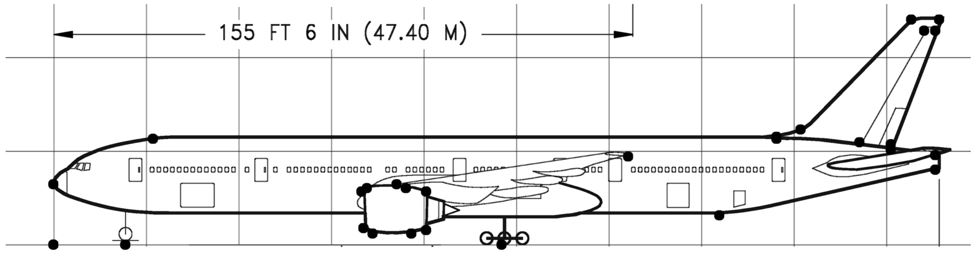


Fig. 2 Construction of airplane geometry from side view. Example shown is B-777-300.

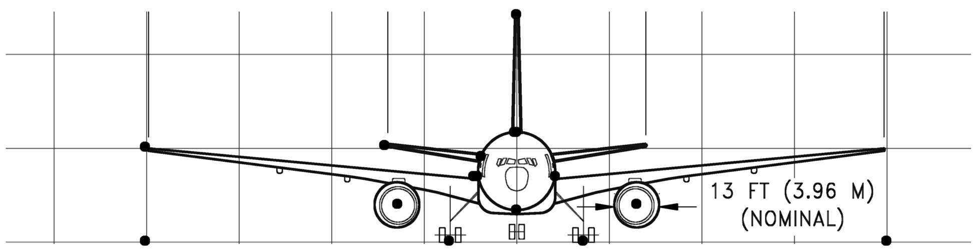


Fig. 3 Construction of airplane geometry from front view. Example shown is B-777-300.

indicated in Fig. 4. This is 444.89 m^2, instead of the 427.80 m^2 reported by Boeing.

Aerodynamics

The aerodynamic drag is calculated with the principle of components. A procedure allows one to calculate the aircraft's drag at most configurations, including takeoff and landing. The aircraft is split into major subsystems, as described in the preceding section. Reference areas and wetted areas are calculated for each of these elements. The drag components included in the analysis are the lift-induced drag from the main lifting surfaces, the skin-friction drag from all the lifting surfaces, the fuselage, and other wetted areas (engines, winglets), the form drag of undercarriage components, the pressure drag of deflected flaps and ailerons, the compressibility drag, the interference drag at major intersections, and the excrescence drag. The ram drag of the engines is considered in the engine's analysis. In fact, by calculating the net thrust at all flight conditions, there is no need to take into account the engine's drag.

For the induced drag, a steady-state lifting surface model of the wing planform is produced. This type of aerodynamic model is well established (Katz & Plotkin [4]) and was deemed the most appropriate from the point of view of a comprehensive analysis. Because detailed data of the wing sections are not available, the problem was treated as a mean camber line using the NACA 230 series. A number of parametric studies have been carried out to verify the effects of the tip's upward deflection in flight. For the wing of the B-777-300, with an upward tip deflection of 1 m from the ground to cruise condition, the induced drag coefficient decreases by about 0.09%. This has been found negligible in the context of the overall approximations. The spanwise loading is not effected in any appreciable amount. The induced drag coefficient is calculated from

$$C_{D_i} = kC_L^2 \tag{1}$$

Both coefficients are part of the lifting surface solution. For the B-777-300 it was found that $k = 0.0394$. The lift-curve slope is calculated from a small perturbation around a reference angle of attack by using a wing–tail combination (no fuselage can be considered in a lifting surface method). For example, the lift-curve slope of the B-777-300 is $C_{L_\alpha} = 0.0817/\,\text{deg}$.

The basic parameters of the planform are the chord distribution, the overall span, the sweep, and dihedral angles. The aerodynamic calculation included the spanwise lift distribution and the induced drag.

The laminar skin-friction drag is based on Eckert's reference temperature method, and makes use of the Chapman–Rubesin constant (White [5]). It assumes that the wall temperature is equal to the adiabatic wall temperature. The turbulent skin-friction drag of the lifting surfaces is calculated using van Driest's turbulent flow theory II [6] in the implementation shown by Hopkins and Inouye [7,8]. This implementation uses Kármán–Schoenerr's implicit formula for the skin friction. The laminar-turbulent transition on the wings is calculated with Blumer–van Driest's semi-empirical correlation [9], which is substantiated by experimental data. This formula relies on the average level of freestream turbulence, which is set to a default 0.2%.

For the fuselage, the nose drag is calculated with the turbulent nose cone theory (see White [5]). The tail drag is calculated by a combination of Hoerner's semi-empirical formula [10] for a conical upsweep and skin-friction analysis.

The wave drag (or compressibility drag) is calculated for the main wing using a combination of the Korn's equation for the divergence Mach number M_{dd}, Lock's power equation for the critical Mach number, and the definition of drag divergence ($dC_D/dM = 0.10$). This procedure requires a number of parameters, namely the wing

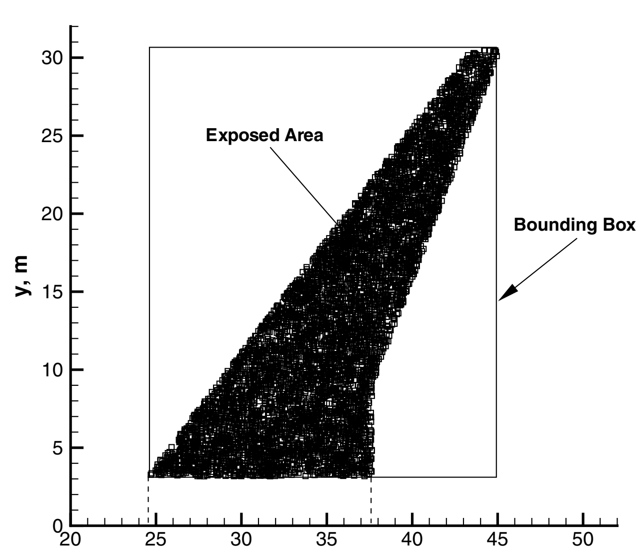


Fig. 4 Stochastic calculation of wing area (compare with wing in Fig. 1).

sweep, the average wing thickness, the lift coefficient, and the Korn factor, which is a technology determinant of the transonic capability of a wing. A similar method has been implemented by Malone and Mason [11].

The interference drag is calculated at the intersection between wing–fuselage, wing–pylon, vertical tail–fuselage, and fin–fuselage. The interference drag relies on the proper accounting of five factors: 1) the normal intersection between streamlined bodies, 2) the oblique intersection between bodies on a plane normal to the freestream (effect of dihedral), 3) the intersection between bodies with a sweep, 4) the effects of lift, and 5) fairing effects. Additionally, one can take into account effects such as rough surface. The presence of gaps and probes of any sort must be accounted for with other empirical methods. Data from Hoerner [10] have been interpolated or extrapolated to find the corrective coefficients.

The calculation of the undercarriage drag is done according to the practical method of the engineering system data units (ESDU data item 79015 [12]). In practice, this is achieved by calculating the drag of each unit and summing up the undercarriage units. A number of essential parameters are required, which are taken from the airplane model. Briefly, the method relies on the calculation of the drag created by wheels (in- and out-of-ground effects), vertical and oblique struts, bay doors, and bay cavity. The drag of the bay is calculated from interpolating drag functions at typical aspect-ratios of the cavity.

The flaps drag is calculated according to McCormick's semi-empirical formula [13], which makes use of the flap deflection and the overall flap area, because both data are readily available in the airplane model. More refined models do not necessarily add to the accuracy, because the prediction of the aircraft's drag must be viewed in the context of the whole system.

Finally, the drag in takeoff and landing configuration is calculated from the basic cruise configuration, with the addition of undercarriage drag and flaps drag.

Engine Model

The simulation of the engine, along with the aerodynamics, is paramount in aircraft flight performance. The engine performance has been simulated with the computer program GSP V.10, a simulation tool for gas turbine engines with graphic interface. The program was developed by Visser and Broomhead at the National Aerospace Laboratory/NLR (The Netherlands) [14]. The underlying model is the one-dimensional compressible axial flow through the engine. A full analysis includes the steady-state aerothermodynamic properties (pressure, temperature, mass flow, velocities) of the gas flow through the major components of the engine.

The model of the engine is done through a logical connection between subsystems. Each subsystem is defined via a number of design and operational parameters or control parameters. Dozens of engine parameters can be independently examined, for example, the inlet/outlet aerothermodynamic parameters at each component, the thrust-specific fuel consumption, the net thrust, and the engine's emissions. The key global parameters of the engine used in the flight simulation are thrust, fuel flow, mass flow, exhaust gas temperature, and thrust-specific fuel consumption (TSFC). Aerothermodynamic parameters exchanged between engine components are not stored, because they are not relevant in the present context.

The engine simulator is run outside the environment of the FLIGHT code. The parametric analysis includes the effects of Mach number and altitude at fixed throttle. The data are organized in a matrix and interpolated at each operational point of the aircraft. A difficulty arises when the aircraft requires operation at partial throttle, such as climbout and final approach. In fact, the matrix of engine performance is not sufficient to provide fuel flow and other aerothermodynamic parameters without further approximations.

GSP has an inbuilt routine for the calculation of the basic emission indices for the database of ICAO engine emissions. This is particularly useful at cruise conditions. For the LTO cycle, engine emissions are fed as input to the FLIGHT program via the engine deck data.

Most modern transport airplanes are powered by different engines, usually from two or three manufacturers; each engine may have several thrust ratings. For example, the Boeing B-777-200/300 series are powered by at least 18 different engines from General Electric, Rolls-Royce, and Pratt & Whitney, with thrust ratings between 331.5 and 409.8 kN. Therefore, the airplane model is a coupled airframe–engine model.

Very few data on aircraft engines are available in the public domain. If one excludes the external dimensions and thrust rating, a few additional data can be inferred from the ICAO databank [15]. More detailed geometrical characteristics (for example, fan blades) are calculated from photographs or drawings. Other data are set to default values from previous engines (for example, the rotor-stator clearance that is used for compressor noise). The remaining characteristics are calculated with the engine model, but are not validated directly. The ICAO databank does not provide the TSFC at cruise conditions. Any reference to average fuel flow is misleading, because the actual value is

$$\dot{m}_f = \mathrm{TSFC}D = \mathrm{TSFC}T \quad (2)$$

where D is the aerodynamic drag of the aircraft and T is the net thrust. Because D is calculated from the aerodynamic model, and TSFC is an engine parameter, the fuel flow is a combined effect of the airframe–engine integration. Engine installation losses have been set at 0.20%. This effect was not investigated.

The data required by the engine model are described as follows: The inlet requires design mass flow and pressure ratio (two parameters). The fan requires bypass ratio, core side pressure ratio, duct side pressure ratio, and fan efficiency (four). The low-pressure (LP) compressor requires design pressure ratio and design efficiency (two), and the high-pressure (HP) compressor requires design pressure ratio and design efficiency (two). The duct requires total pressure loss (one). The combustor requires design efficiency, relative pressure loss, and one of the following: 1) fuel flow, 2) fuel-to-air ratio, or 3) exit temperature. High- and low-pressure turbines require design efficiency (two parameters). The nozzle requires a drag coefficient (one). Additionally, the spools' rotational speeds must be set, although these speeds do not intervene directly in the aerothermodynamic equations. In all, about 20 essential parameters are required, along with other noncritical parameters that can be left as default for all turbofan engines.

A number of other options can be set, such as compressor bleed, heat sink losses, and deterioration of one or more components. Crucially, the cross-sectional areas are not required by the model, and the essential performance parameters are the design mass flow and the TSFC (or fuel flow).

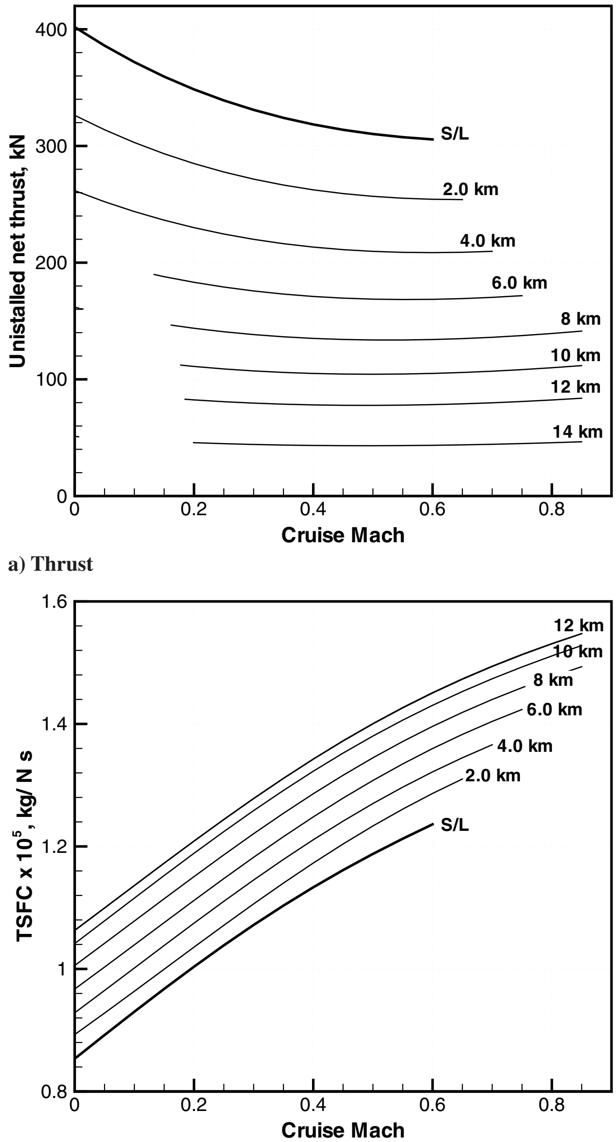
Figure 5 shows some examples of engine simulation. The case is the General Electric GE90-98B that powers the Boeing B-777-300. The fuel flow is calculated directly from Eq. (2). Other data, such as the mass flow and the nozzle temperature, are inessential in this context, but are important in noise simulation.

Aircraft Flight Model

Most operational parameters, such as the climb and descent schedule, are set by the user. These parameters are generally kept constant during the flight analysis.

The climb model relies on standard climb schedules, for which a number of user settings are required. A typical climb schedule includes an initial climb to 3000 ft at constant calibrated air speed in knots (KCAS), a level acceleration to a given true air speed in knots (KTAS), a second segment climb at constant KCAS, and a final section, which can either be a climb to the initial cruise altitude (ICA) at constant Mach number or an acceleration to the cruise Mach number at ICA. The parameters required include the KCAS during the first- and third-segment climb and the amount of level acceleration at 3000 ft.

Likewise, descent from the final cruise altitude is done in segments. A special treatment is possible for a final descent at higher-



a) Thrust

b) TSFC

Fig. 5 Simulation data for the General Electric GE-90-98B.

than-average glide slopes, although the aircraft has limited maneuver possibility at glide slopes above 4 deg [16].

The cruise can be specified as a continuous climb or a step climb. The ICA is always a conventional flight level. The step climb is always 2000 ft and is set arbitrarily in the present version of the code. Flight level 310 and 330 have been considered as default. Long-haul flights are confined to flight levels 310-330-350, although in practice many airlines fly at higher altitudes. The flight performance is calculated by integrating point-by-point the differential equation for the fuel flow, rather than using the conventional Breguet range equation.

The aerodynamics is calculated in real time at all flight conditions. This strategy, although more accurate, tends to slow down the calculations. The model does not consider the effects of change of the center of gravity of the airplane on the aerodynamic drag.

A flow chart of the main modules of the program is shown in Fig. 6. The noise module is described in more detail in [16], and is not used in the present analysis.

Fuel and Weight Planning

The payload and the weight of the passenger service items is calculated directly from the number of passengers and the bulk cargo. The weight per passenger is fixed; the weight of the service items (food, drinks, magazines, onboard entertainment, and associated overheads) depends on the type of operators; likewise, the number of crew members depends on the type of service. These data can be input directly in the set of operational parameters. The calculation of the ramp weight is more complicated and is done iteratively. Given the required range and the cruise Mach number, the mission fuel is calculated with the following procedure:

1) Set a reasonable value for the ramp weight.
2) Calculate the taxi-out fuel.
3) Calculate the takeoff fuel to clearing of screen at 50 ft.
4) Calculate the climb to ICA fuel.
5) Calculate the cruise fuel for required range minus en route climb and descent.
6) Calculate the descent fuel.
7) Calculate the landing fuel.
8) Calculate the taxi-in fuel.
9) Calculate the contingency fuel.
10) Calculate the ramp weight.
11) Check convergence and return to step 2.

The maneuver fuel is included as an extension of the range. In particular, the algorithm takes into account the fact that the aircraft will have to make on average one U-turn away from the origin airport or into the destination airport. This is one way of accounting for average atmospheric winds. One U-turn adds about 10 n miles to the range required.

The auxiliary power unit is calculated at each flight segment and added step-by-step in the fuel planning. The APU is a self-contained power plant that delivers energy for onboard services (air conditioning, heating, lighting). The fuel consumption of this unit depends on the atmospheric conditions and on the load selection. Minimum fuel consumption is at ready-to-load (on the ground) and maximum is with full aircraft at cruise conditions. The latter one uses 50% more fuel. The unit 331–350 used on the Airbus A-330 and A-340 uses 175–210 kg/hr, but only 120 kg/hr at ready-to-load. The FLIGHT code applies the full load at airborne conditions and the ready-to-load on the ground. An increase in taxi-time increases the overall APU fuel. An increase of APU operation by 1 min at an average level of 210 kg/hr means a savings of 4 kg of fuel. This figure, multiplied by the number of movements per year, leads to considerable waste and pollution.

Convergence is found in 5–7 iterations. Convergence is understood as a change in weight on the order of 20 kg (or less) between iterations. This is in fact an accuracy that cannot be achieved in practice, due to uncertainty in the weight of the useful load. Once the fuel planning is calculated, a series of other calculations are carried out. Only the environmental parameters are discussed next. These are CO_2, kg; CO_2/pax, kg; CO_2/pax/n mile, kg; fuel/pax/n mile, kg; fuel/seat/n mile, kg; energy intensity (MJ/pax/n mile); design energy intensity (MJ/seat/n mile); energy intensity (MJ/pax/n mile) (cruise only); design cruise energy intensity (MJ/seat/n mile).

The emissions for business passengers are weighted by the amount of floor space occupied by a business seat, and by the additional service provided. This obviously depends on the airline and on the aircraft, but as a general rule it is a factor of 1.5 for a continental flight and 2.0 for an intercontinental flight.

In addition to the preceding list, the landing and takeoff emission cycle is calculated.

Flight Performance Calculations

In summary, the basic routine calculations performed by FLIGHT include 1) aircraft geometry, wetted area components, centroids, etc.; 2) atmospheric properties at all altitudes [international standard atmosphere (ISA) and non-ISA]; 3) best ICA from takeoff conditions; 4) field performance: Federal Aviation Regulations (FAR) balanced field length, all engines operating (AEO) and one engine inoperative (OEI) performance, time, fuel, distance to takeoff and landing, initial climb flight path to screen height; 5) climb performance (fuel, time, distance to ICA for segment climb); 6) cruise performance, based on integration of point performance (with specified stepped climb and continuous climb); 7) descent

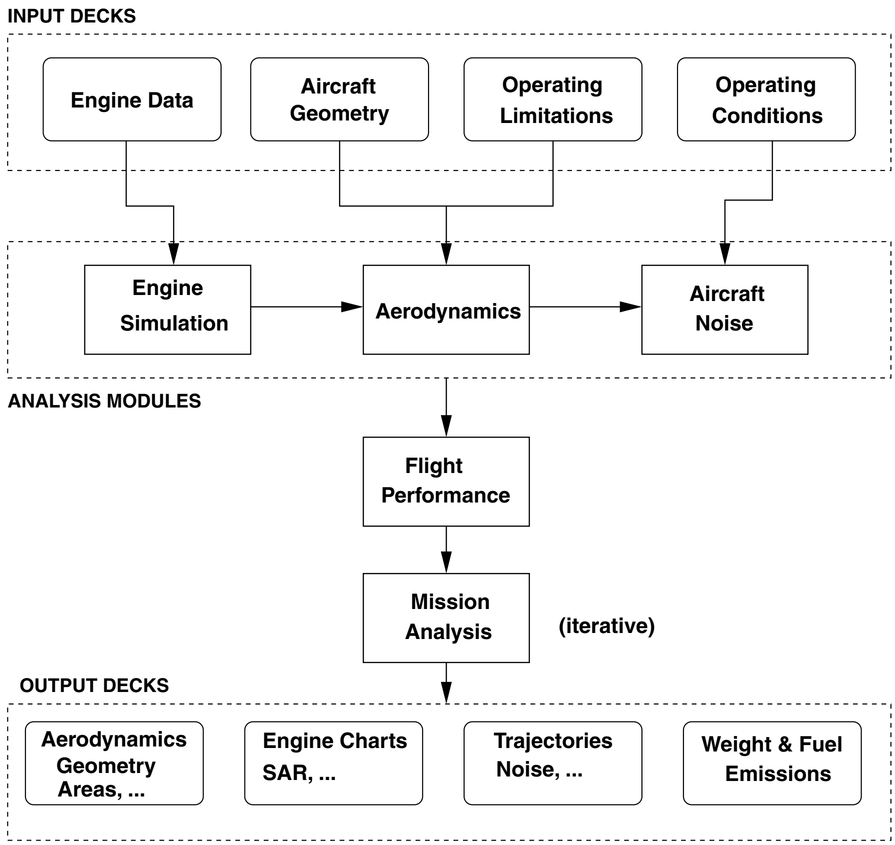


Fig. 6 Flowchart of FLIGHT program.

performance; 8) approach performance to ground level; 9) landing performance to halt; 10) LTO cycle emissions (hydrocarbons, CO, CO_2, NO_x); 11) contingency fuel, based on at least four contingency scenarios; 12) economic Mach number; 13) full mission performance (fuel profile, ramp weight, weight breakdown of payload and services, payload efficiency); 14) payload-range performance; 15) flight trajectory, with 12 real-time output parameters; 16) overall sound pressure level (OSPL) at FAR points, both at takeoff and landing.

In addition, the code provides ancillary calculations, such as drag breakdown, volumes, aerodynamic charts, specific air range charts, limit rotation at takeoff (tail strike), limit bank angle at landing (wing strike), and several other ones. Each flight segment has its own report that can be analyzed independently.

An outer loop facility exists to calculate the optimal cruise Mach number in the entire stage length and passenger load range, as described previously [17]. However, only a constant (nominal) Mach number was considered in the present analysis for all aircraft models.

Model Validation

Validation of a flight mechanics simulation code is made difficult by the scarcity of reference data. Aircraft manufacturers are not keen to release or publish key data, such as aerodynamics (drag coefficients) and installed engine performance. Likewise, the technical literature does not report many realistic data, although some sparse data from older airplane versions can be found. For example, the Boeing B-747-100 model can be compared with the data provided by Hanke and Nordwall [18]. A comparison between the calculated aerodynamic characteristics of this aircraft and the data reported by these authors is shown in Fig. 7. The drag is shown at three levels of the lift coefficient C_L, typical of cruise conditions. In all cases the correlation is good, particularly around the cruise Mach number. Additional checks have been done on the zero-lift drag coefficient, cruise L/D, and specific air range.

On the other hand, engine manufacturers tend to be secretive about the engines themselves, including internal geometry and essential air

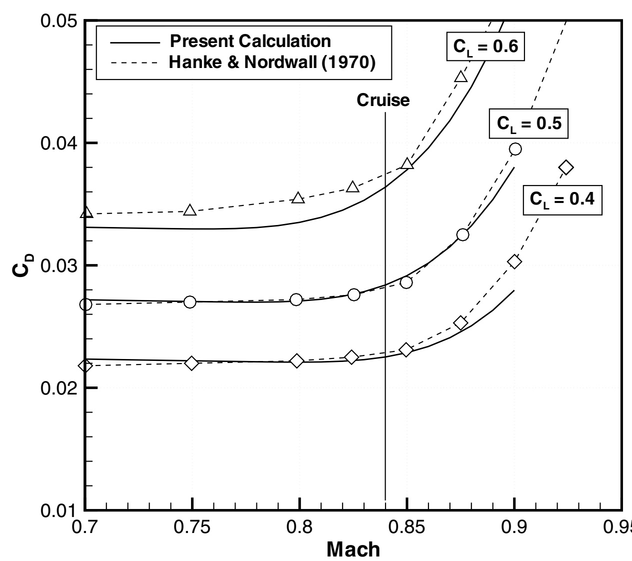


Fig. 7 Aerodynamic drag of Boeing B-747-100 at cruise conditions.

and fuel flow characteristics. The engine performance must rely exclusively on simulation. As a consequence, the validation must rely on indirect data.

An industry-standard performance code called PIANO† does all of this, but it is not clear how it is possible to match the manufacturer's performance with any flight simulation code, unless one has direct access to the manufacturer's data, all the manufacturer's assumptions, and the performance charts are calculated with the same code. The reasons for inaccuracy cannot otherwise be resolved. A few examples are given next.

†Information available at www.lissys.demon.co.uk.

1) Match the engine's TSFC: the design range cannot be matched (the calculated range is usually higher).

2) Match the design range: the TSFC is too high.

3) Calculate the TSFC with engine simulator: the design range is higher than the certified range.

4) Match the TSFC from ICAO database: the range is considerably higher than the certified maximum range.

These results are found for most combinations of passenger and cargo loads and indicate that there is inconsistency among the data available in the public domain.

A first line of investigation is to match the claimed fuel flow at cruise conditions, although in most cases the all-up weight of the aircraft is not available. The second check is on the range of the aircraft. It is important to match the range under the conditions specified in the flight manual, or in the performance data that are available from various sources (for example, Jane's [19]). For this purpose, one needs to make an arbitrary assessment regarding the fuel reserve policy, which is not clearly mentioned in the performance data.

Boeing [20] indicates that the conditions assumed for the payload-range charts of the B-747-400 are standard day, no winds, 200 n mile diversion, 10 min trip air time, 30 min hold at 1500 feet. However, it is important to specify also the power extraction and the air bleed from the engines and the operating procedures at climb, cruise, and descent. A useful derivative of the range-payload charts is the change in zero-fuel weight (ZFW) with respect to the change in cruise range, at a constant brake-release gross weight (BRGW). In fact, what matters is the overall fuel consumption. For example, at $\mathrm{BRGW} = 295.0$ tons, for a required range $X = 4000$ n mile, the sensitivity is about -16 kg/n mile. This means that to fly one additional nautical mile, the aircraft must shed about 16 kg of payload. A closer look at the 747's payload-range charts indicates that this sensitivity depends only on the payload, not on the range. In other words, if the payload is fixed (and so is the ZFW), the value of $d\,\mathrm{ZFW}/dX$ is the same, regardless of the range required. An exception is when the range is limited by fuel capacity. Averaging between extreme values of the payload provides $d\,\mathrm{ZFW}/dX$ variable between -18 and -15 kg/n mile (with a high payload).

The computational analysis is quite elaborate, because it requires one to check these sensitivities at a fixed BRGW, whereas the code works at a specified cruise range. However, an iterative analysis around this point shows that $d\mathrm{ZFW}/dX \simeq -15$ kg/n mile, a lower value than the one reported by Boeing. In the computational model, no air bleed was assumed. The APU fuel was used for powering all the services. After all the reasonable assumptions were done, it was not possible to have a closer match between these two values.

Another indirect parameter is the energy intensity, e.g., the amount of energy required per seat per nautical mile (MJ/seat/n mile). This datum can be calculated by dividing the fuel capacity by the number of seats of the particular configuration and by the design range of the aircraft. Analysis of this type is presented in other publications (Peters et al. [21], Lee et al. [22]). However, if the aircraft carries cargo (as it often happens), this parameter is misleading. Also, note that this energy parameter would imply that the aircraft is to arrive without any fuel left, although in the real case the aircraft would land with its mandatory fuel reserve. For this reason, it is considered more appropriate to subtract the fuel reserve from the fuel capacity. To compare the simulation with the aircraft's capabilities, as reported by the manufacturers, the energy efficiency (EE) and the fuel efficiency (FE) are modified as follows:

$$\mathrm{EE} = C_P(m_f^* - m_{\mathrm{res}})/\mathrm{seats}/\mathrm{design\text{-}range} \tag{3}$$

where C_P is the specific combustion heat of the aviation gas (Jet A or Jet A-1), m_f^* is the fuel capacity of the aircraft, corrected for the nonusable fuel, and m_{res} is the fuel reserve. This quantity must be the same in the simulation and the certification documents. Hence, the fuel efficiency is

$$\mathrm{FE} = \mathrm{EE}/C_P \tag{4}$$

Consider, for example, the Boeing B-747-400. This airplane has an $\mathrm{FE} = 0.05765$ kg/seat/n mile in the 416 seat configuration and $\mathrm{FE} = 0.04557$ kg/seat/n mile in the 524 seat (3 class) configuration. This calculation is based on the nominal fuel capacity of 174,122 kg (216,840 l). If, instead, one makes allowance for the nonusable fuel (about 0.4% of the tanks), the performance is reduced. A full summary is given in Table 1.

The problem gets more complicated with the Boeing B-777-300. This aircraft has a certified maximum range of 11,030 km, a usable fuel capacity of 135,880 kg, and an operating empty weight $(\mathrm{OEW}) = 160,530$ kg. The fuel capacity for this aircraft is nearly 46% of the maximum takeoff weight (MTOW): a very large figure. The sum of OEW and the fuel capacity reaches nearly the MTOW.

If one uses the General Electric GE-90-98B engine, which has a relatively flow TSFC, the aircraft reaches its range with a full load at about 70% of the fuel capacity, as reported by Boeing [23]. (These figures have been double-checked with the data published on Boeing's official web site.) On the other hand, the sum of the OEW, the fuel capacity, full passenger load, crew, and onboard services far exceeds the certified ramp weight for this aircraft. With the data available, the fuel/seat/n mile of the 364 seat configuration is 0.0624 kg, a relatively high value, when compared with other aircraft in this category of weight. Unless the MTOW is increased, not all the fuel capacity is required for the certified maximum range. This result poses a problem in the calculation of the design parameters indicated in Table 1. Hence, the validation of this model is not possible with the data available.

If one considers the data of Table 1 as a reference, the FLIGHT simulation should be capable of achieving the same result under reasonably similar conditions (full load, standard weight per passenger, average type of onboard services, average number of flight crew, standard winds, etc.). The simulation must rely on further assumptions, such as the usable fuel, the fuel consumption of the APU in all the flight segments, the weight of the cargo, etc. The data of Table 1 are integral quantities, in the sense that they present the overall performance of the aircraft under "standard" conditions.

With all the uncertainties mentioned, it is impossible to achieve an accuracy of less than 1% of the actual performance, and in fact, a result within 2% is to be considered excellent. For a Boeing B-747-400, a 1% approximation on the certified range means an uncertainty on the order of 100 n miles.

The model does not take into account the trim effects. For example, in the present formulation, it is not possible to correct the drag due to the movement of the center of gravity of the aircraft. This is an operation that is routinely done on large aircraft, such as the Airbus A340-300, by using so-called trim tanks, in aft and forward position. Airbus reports that an optimal management of the center of gravity can reduce the fuel consumption at cruise by as much as 1.5%. Again, this leads to the 1–2% approximation that is considered acceptable.

Some data need further consideration. In particular, the CO_2 emissions per passenger per nautical mile depends on the seating capacity of the aircraft. Boeing does not differentiate between the two versions when they provide the maximum range of the aircraft, nor do they specify whether cargo is carried as well. However, from the point of view of the regulators, the 524 seat configuration is more energy efficient, and less likely to incur additional taxes for the passenger.

Table 1 Design energy and fuel efficiency for the Boeing B-747-400 with GE CF6-80CB1 engines

Configuration	416 pax	524 pax	Unit
Fuel efficiency	0.0577	0.0456	kg/seat/n mile
Energy efficiency	2.2884	1.9832	MJ/seat/n mile
CO_2 emissions	0.1615	0.1445	kg/seat/n mile

Results and Discussion

The aircraft modeled are the Boeing B-737-500 (with CFM-56C1 engines), Boeing B-747-400 (with CF6-80C2B1 engines), Boeing B-777-300 (with GE-90-92B engines), and Airbus A340-300 (with CFM56-5C4P engines).

Each aircraft has been studied from a different point of view. For example, the Boeing B-737 is used for regional services, and is particularly popular with budget airlines that target the leisure industry. The critical operational parameters for this aircraft are the passenger load, flight distance, baggage allowance, and effects of onboard services. These aircraft operate in large numbers from regional and national airports.

By contrast, the Boeing B-747-400 and the B-777-300 are used for long-haul cruise, and are important in the transatlantic and transpacific passenger transport. The B-747 is also used in large numbers for freight operations. One of the critical aspects that is analyzed for the B-747 model is the best cruise range. For these aircraft, it was deemed important to do parametric studies on the effects of taxi-out and taxi-in times, because they tend to operate from large hubs and congested airports.

Parametric analyses have been done with the load factor (e.g., the number of passengers), stage length, taxi-out time, APU time, and load level for direct flights and flights with an en route stop.

In most cases, the aircraft models carry no bulk cargo. For the large aircraft, it was assumed a small 2 ton cargo. Allocation of carbon emission per passenger would not be possible if large amounts of cargo would have to be taken into account. In fact, the revenue of major airlines is evenly split between the two sources.

Flight with En Route Stop

The aerospace industry has developed aircraft for very long range, such as the Boeing B-777-200LG (long range), capable of cruising a distance of about 9800 n miles: a nonstop flight between London and Sidney, Australia. This is close to the ultimate *global range* of 20,000 km, advocated by Küchemann [24]. The global range is half the Earth's circumference at the equator. A global-range aircraft would be capable of flying from any airport to anywhere around the world. This section questions the utility of such an aircraft at a time of considerable demands on the environmental performance of transport aircraft. The problem is addressed only from the point of view of fuel consumption (and hence CO_2 emissions), and does not include provisions for important problems, such as additional demands on air traffic management, increased cycle costs, noise footprint, time-related costs, etc.

As a matter of fact, flights with an en route stop are very common. Most major airlines use selected airports as hubs. There are cases in which airlines offer cheaper rates for flights with a stop, even if this is in the opposite direction (transatlantic flights from Europe or continental flights in the United States). Finally, there are very long-haul flights (Northern Europe to South Asia and Australia) that require en route stops because of limited range. The effects of fuel consumption in terms of fuel/pax/n mile is obvious in cases where the stop is at an inconvenient location. Therefore, the cases that are discussed in this section are limited to flights from origin airport A with a stop at an airport C on the way to the final destination B. A further parameter would be the position of C with respect to the origin. However, only the case of a stop at midway is considered.

The aircraft is to carry enough fuel to reach the intermediate airport, with the mandatory fuel reserves; it refuels at this base, takes off again, and flies to its final destination. The costs of landing at B and the direct operating costs incurred by the operator for increasing the time of the return journey are not considered in this context. It is also assumed that the flight altitude and the cruise speed is the same for all the cruise segments, and that the aircraft carries the same payload.

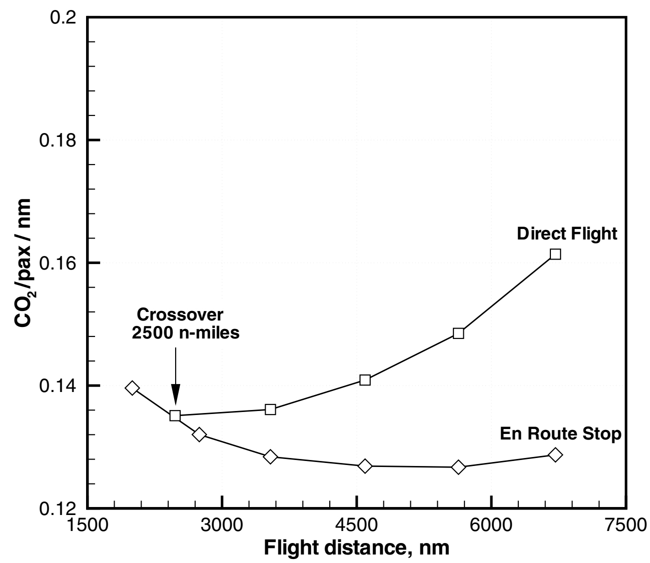
The analysis considers the B-747 in the 416 passenger seat configuration, with General Electric GE CF6-80C2B1 turbofan engines, standard fuel tanks, takeoff and landing from sea level airports, average headwind −10 kt (at all flight segments), 2 tons of bulk cargo (fixed), 12 min taxi-out (fixed), 8 min taxi-in (fixed), 14 crew members (fixed), cruise at flight levels FL = 310, 330 (fixed), stepped climb profile not dependent on gross weight, stepped descent, final approach with a 3 deg landing slope, dry runway conditions at departure and arrival, and cruise Mach $M = 0.85$.

In addition, the reserve fuel is calculated on the basis of 250 n miles (463 km) extension of the cruise for long-range service, with a 30 min holding at 1500 ft (457 m) altitude, and a 5% mission fuel reserve for contingency.

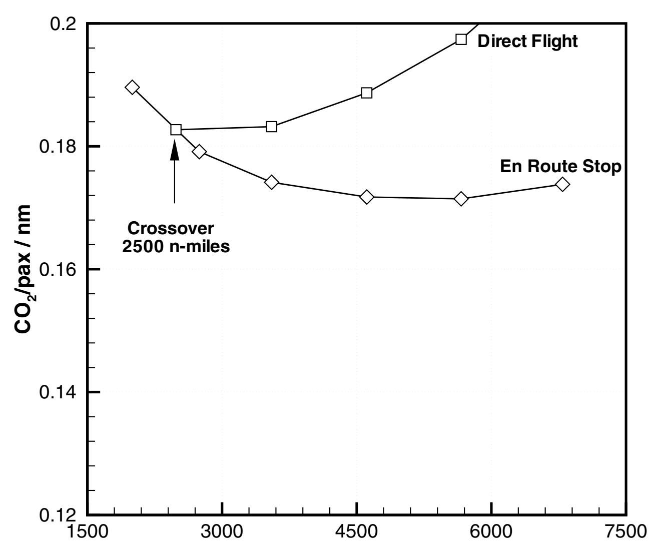
The results are shown in Fig. 8. For the flight with an en route stop, the cumulative values of fuel and CO_2 emissions are a factor of two of the results obtained for range equal to half the stage length. The maximum flight distance considered is 6714 n miles (12,441 km). The conclusions of the analysis at $X = 6,714$ n miles are as follows:

1) The total flight time (not including the stopover) is 922 min for a direct flight and 934 min with an en route stop. Hence, the total flight time increases by 12 min. At least 45 min will have to be allowed for servicing the aircraft. Therefore, the total service time will increase by about 1 h.

2) The fuel cost of a flight with an en route stop decreases by about 16%. The main reason for this is attributed to the fact that the aircraft equipped for a shorter flight has a considerably lower takeoff weight. In fact, a closer analysis indicates that an aircraft equipped for a full range will have to carry an additional 90 tons of fuel. On the other



a) 100% passenger load



b) 70% passenger load

Fig. 8 CO_2/pax/n mile for a long-range flight.

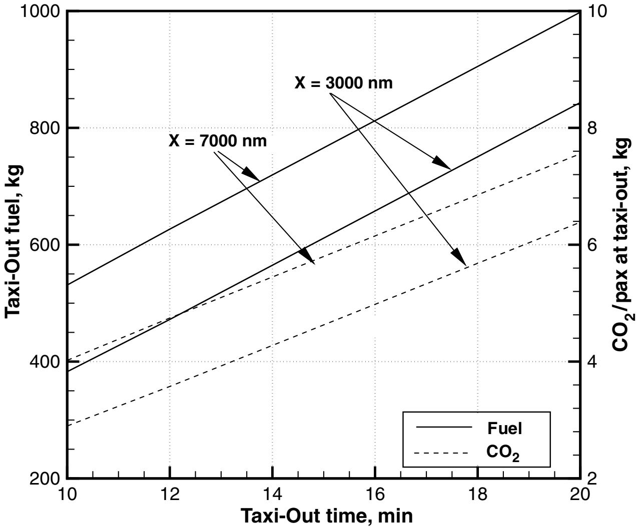


Fig. 9 Carbon emissions of B-747-400 as a function of taxi-out time.

hand, a flight with an intermediate stop is done with a lower takeoff weight. Additionally, this flight will cut the cruise range by the distance to climb and the en route descent (a distance on the order of 250 n miles). In spite of the additional climb fuel, it appears that this solution is more economical, on the basis of fuel consumption only.

3) The increase in total climb fuel is only 2%. On the other hand, the cruise fuel is decreased, thanks to the reduced cruise segment.

A parametric analysis of the flight with different distances indicates the following:

1) The flight with an en route stop is more economical for long-haul flight at all passengers loads of commercial interest.

2) The difference in fuel and $CO_2/\text{pax}/\text{n mile}$ between the two operations decreases with the decreasing flight distance. The crossover point is estimated at 2500 n miles (or 4600 km).

Effects of Taxi Times

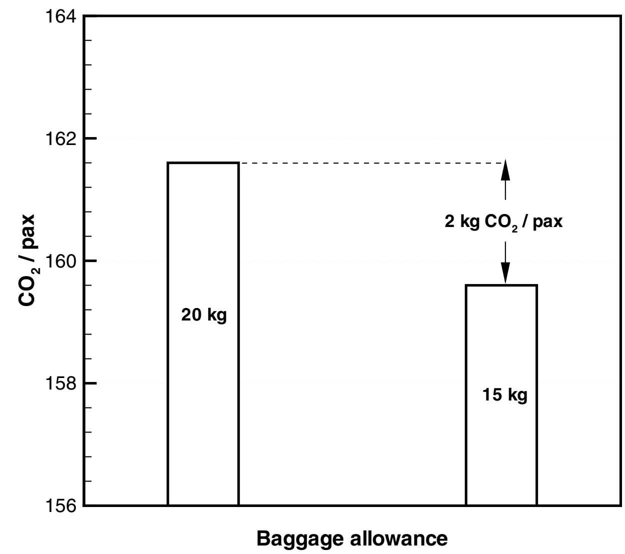
The aircraft will always try to roll out of the ramp to the start of the runway in the shortest time possible. However, due to congestion at many large airports at peak hours of the day, taxi-out is heavily dependent on the air traffic control and delays at departure.

The calculation of this fuel component is strongly dependent on the aircraft size, on the distance between gate and start of the runway, and on the level of traffic. Engine performance is optimized for cruise conditions, therefore taxiing leads considerable wastage. In general, it is best to give a burst of power and then reduce gradually to idle mode. For some aircraft (both jet- and propeller-driven), fuel economy is achieved by operating with one engine shut down part of the time. Airbus provides estimates for its aircraft that would save up to 100 kg of fuel per movement. However, there is a concern that the shutdown engine may not start at brake release, and that the remaining engine has excessive jet blast in ground operations. Therefore, this practice is not often followed.

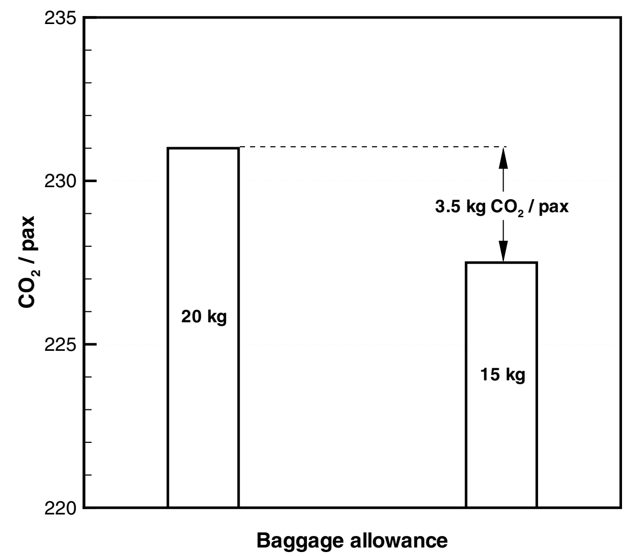
Data regarding taxi-out are confidential. In absence of concrete data from the airport or the airline operators, some generalizations can be made according to the following considerations. First, an average taxi time t_{out} and an average taxi speed is assumed. Then, the longest distance between gate and runway is estimated. The fuel used for taxi-out is

$$m_f = \dot{m}_{f,1} t_1 + \dot{m}_{f,2}(t_{\text{out}} - t_1) \tag{5}$$

where $t_1 = x_{\text{out}}/v_{\text{out}}$. The engine's fuel flow $\dot{m}_{f,1}$ is calculated directly from the requirement of rollout speed at ground configuration, and depends on the ramp weight. The fuel flow $\dot{m}_{f,2}$ corresponds to idle conditions, with the aircraft at rest at some point on the tarmac. Engine performance at idle conditions is part of the engine's parameters used by the FLIGHT code, and is taken from the ICAO databank, rather than from engine simulation.



a) X = 1000 nm, load = 100%



b) X = 1500 nm, load = 100%

Fig. 10 Emission savings of the B-737-500 for reduced baggage allowance.

Calculation of the taxi-in fuel is similar. Parametric studies on the effect of taxi fuel are done by increasing the taxi time at the same airport. An alternative to choosing the taxi-out and taxi-in time is to use the average taxi time from airport categories. For example, averages are available at major international hubs and regional airports.

Large aircraft, such as the B-747-400, have an allowance for taxi-out fuel that is on the order of 1500 l. The default calculation is done with a 10- or 12-min taxi-out time. The analysis has been extended to 20 min. The effects on overall fuel consumption and CO_2 emissions are calculated on the basis of Eq. (5). This effect is shown in Fig. 9 for two different flight missions: 7000 (very long-haul flight) and 3000 n miles (typical transatlantic flight). The chart indicates that there is a difference of nearly 200 kg of fuel burned by the aircraft equipped for long range, mostly due to the rolling resistance during maneuver out of the gate. Furthermore, the result proves that it is more efficient to get the heavy aircraft quicker to the brake-release point. When possible, heavier aircraft should be given departure priority. At large airports, this means savings on the order of several tons of fuel every day.

The taxi-in fuel has the same implications as the taxi-out. However, due to the lighter weight on arrival, taxi-in fuel

Table 2 Correction factors on CO_2 emissions of B-737-500

X, n mile	Load factor 1.00	0.90	0.80	0.70	0.60
1500	**1.000**	1.075	1.172	1.299	1.471
1000	1.050	1.132	1.237	1.373	1.558
750	1.122	1.210	1.324	1.471	1.685
500	1.278	1.379	1.509	1.678	1.902

Table 3 Correction factors on emissions of B-747-400

X, n mile	Load factor 1.00	0.90	0.80	0.70	0.60
6714	**1.000**	1.081	1.181	1.313	1.485
5634	0.920	0.999	1.096	1.223	1.388
4593	0.873	0.950	1.045	1.169	1.329
3539	0.843	0.920	1.012	1.135	1.293
2477	0.837	0.915	1.008	1.132	1.291

consumption is sensibly lower. A queueing system on arrival based on weight priority can save fuel as in the case of taxi-in. In fact, it is not uncommon that gates are blocked by other aircraft, or aircraft maneuvering on the taxiway.

The problem of taxi fuel at smaller airports is of more marginal importance. Aircraft in the weight range of the Boeing 737 tend to operate at these airports. However, the fuel and emission savings should not be discounted, because of the large number of movements over the day.

There are a number of ways to further reduce the fuel consumption in ground operations. First, one may think of parking the aircraft not at the terminal but open spaces closer to the start of the runway. Second, the aircraft could be given the go ahead when a slot becomes available, whereas in reality many busy airports have aircraft on a queue to the runway.

Effects of Passenger Baggage

Some airlines have attempted to reduce the gross takeoff weight of their aircraft by limiting the amount of onboard services and the passenger baggage allowance. This strategy can be followed only for regional flights (under 1500 n miles) that operate to holiday destinations and serve passengers who are to be away for a limited amount of time. This policy cannot be commercially viable in general, and in particular on long-haul flights.

The analysis considers the Boeing 737, version 500, with CFM-56-3B1 turbofan engines, standard fuel tanks, takeoff and landing from sea level airports, average headwind equal to -10 kt, no bulk cargo, 10 min taxi-out (fixed), 8 min taxi-in (fixed), five crew members (fixed), cruise at flight levels FL $= 310$ and 330 (fixed), stepped descent, fixed climb profile, and cruise Mach $M = 0.78$. The baggage allowance is reduced from a standard 20 to 15 kg: a decrease of 25%. The average passenger weight is taken as 80 kg.

The result of this analysis is shown in Fig. 10 for two typical flight distances and full passenger load. It is estimated that the reduction of the baggage allowance saves 2 kg of carbon per passenger over a 1000 n mile trip. This datum, multiplied by the number of passengers and the number of movements per year becomes a more substantial figure. From the point of view of fuel consumption, this is estimated as 0.64 kg/pax. Savings from partial loads are more limited.

Effects of Distance and Passenger Load

The next analysis is a parametric effect of the flight distance and passenger load for all the aircraft considered in this study. Typical passenger loads down to 60% were assumed, along with flight distances from the design range and below. The main aspects of the analysis are the carbon emission per passenger. To make the data comparable, and to allow the extrapolation of carbon emission from

Table 4 Correction factors on CO_2 emissions of B-777-300

X, n mile	Load factor 1.00	0.90	0.80	0.70	0.60
5950	**1.000**	1.076	1.168	1.294	1.449
5000	0.956	1.030	1.122	1.245	1.396
4000	0.924	0.997	1.088	1.208	1.357
3000	0.902	0.975	1.066	1.186	1.335
2500	0.907	0.980	1.072	1.193	1.343
2000	0.917	0.993	1.086	1.209	1.361

more simple methods (as used by the environmental concerns), these emissions have been normalized. The normalization indicates how the emissions change with the passenger load and the flight distance in relative terms.

The reference data are the carbon emission at the design range at full passenger load (for B-747, B-777, A-340) and the emissions at 1500 n miles at full passenger load (for the B-737). The corrective factors are summarized in Tables 2–4.

The carbon emissions of the Boeing B-747-400, discussed earlier, are shown in Fig. 11. These emissions increase with the increasing flight distance, because of the increasing block fuel required to fly long range. The result shown here is another aspect of that discussed

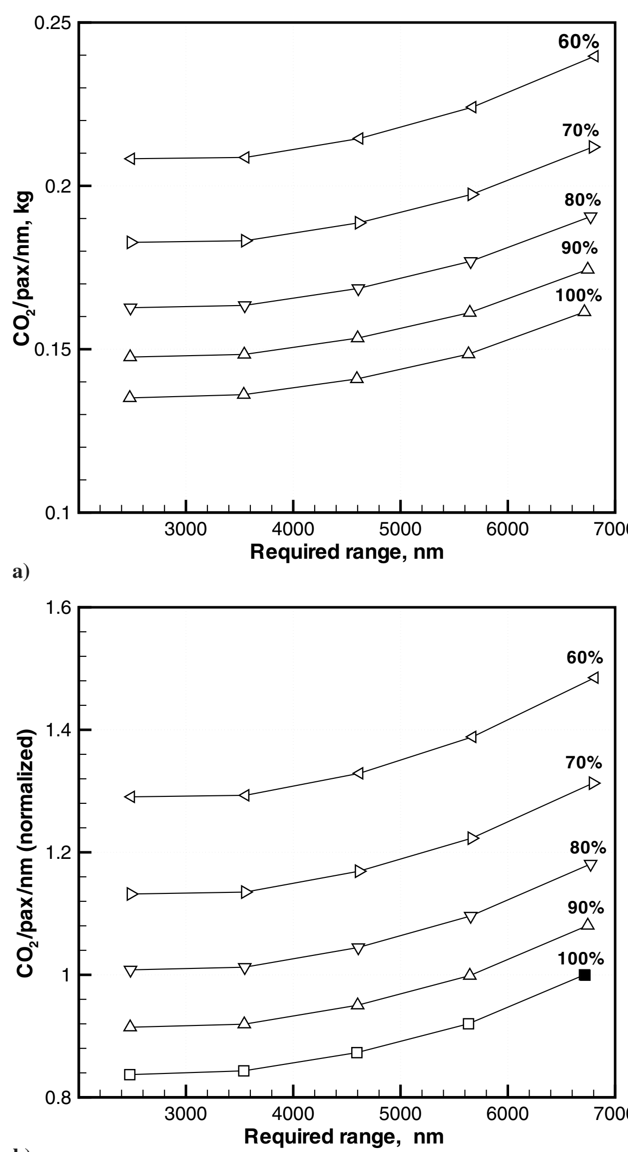


Fig. 11 Carbon emissions for the Boeing B-747-400.

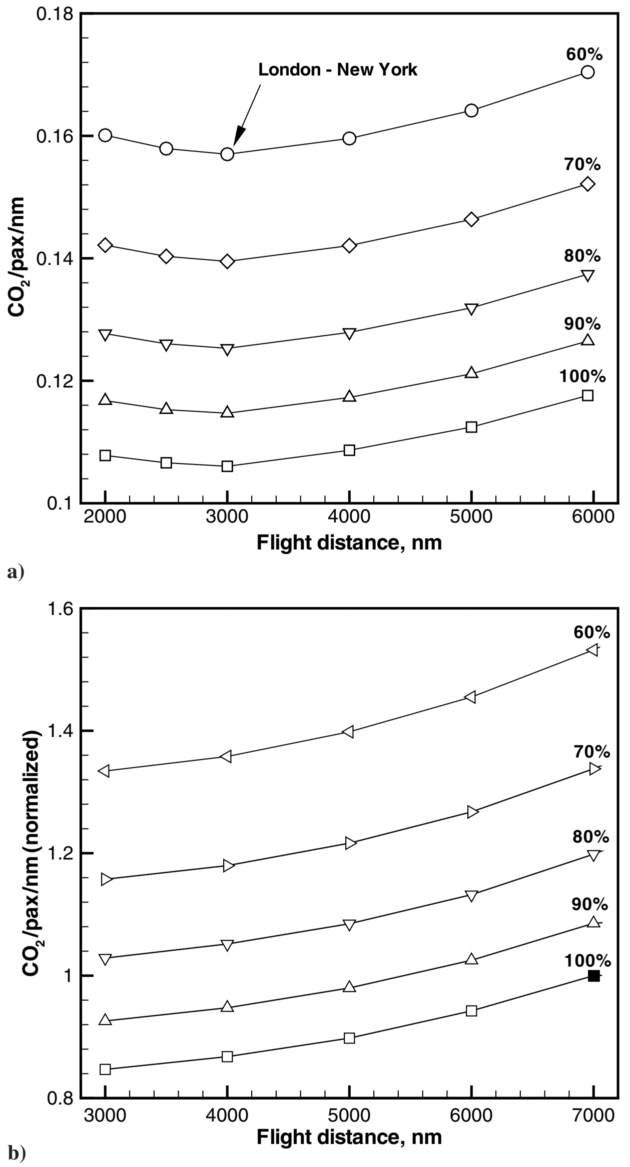


Fig. 12 Calculated emissions for Boeing B-777-300 at constant load factor.

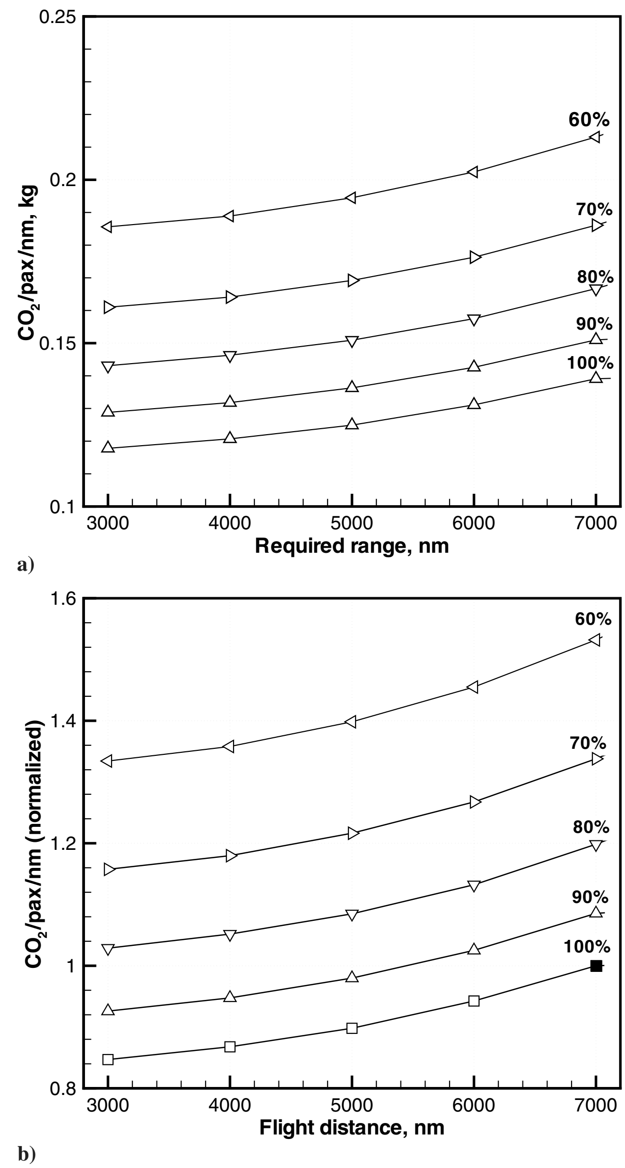


Fig. 13 Calculated emissions for Airbus A-340-300 at constant load factor.

in Fig. 8: an increase in carbon emissions per nautical mile with the increasing distance.

Figure 12 shows the calculated emissions for the Boeing B-777-300 powered by General Electric GE-90-98B turbofan engines. The graph shows data at constant passenger load and increasing flight distance. In Fig. 12b, the carbon emissions have been normalized. In particular, it can be noted that at the design range the emissions can increase by 45% if the aircraft is flown with only 60% of the seats filled. Another result worthy of note is that the 3000 n miles range (roughly, the London to New York route) is the most efficient for this aircraft. For this type of service, the CO_2 emissions per passenger are reduced to 90% of the value at the design range. As in the case of the Boeing B-747-400, the optimal condition from the point of view of CO_2 emissions and fuel consumption is achieved with a flight well below the design range. Again, the reason for this result is the large amount of fuel that the aircraft has to carry to provide long-haul services. The emissions shown are for the entire flight and include all the fuel burned from leaving the gate to arrival at the gate.

A similar analysis for the Airbus A340-300 is shown in Fig. 13. The aircraft considered has CFM56-5C4P turbofan engines, in the 295 seat configuration, and all the standard options. The operational conditions (atmosphere, takeoff, and landing altitudes) are the same as the previous cases.

Cumulative Effects of Passenger Load

By using the analyses shown so far, one can extrapolate further performance data. In particular, due to linearity between fuel consumption and passenger load at a fixed cruise range, the fuel consumption from operations at 70% load factor is different from operations at 60 and 80% load factors. This aspect is highlighted by the following efficiency parameter

$$\Delta m_{\mathrm{CO}_2}\% = 100\frac{m_{\mathrm{CO}_2}(70)}{0.5[m_{\mathrm{CO}_2}(60) + m_{\mathrm{CO}_2}(80)]} \qquad (6)$$

which is the difference in carbon emissions arising from operating two aircraft at a 70% load, or one aircraft at 60% load and the other at 80% passenger load. The analysis is presented in Fig. 14 for the Boeing B-747-400. The graph also shows how the emissions increase considerably for relatively short range (about 2500 n miles).

This conclusion has been verified for other large aircraft at most cruise ranges. However, it is not as relevant for the Boeing 737. In other words, it is more efficient to operate two long-haul flights at a 70% load factor, rather than one flight at 60% load and one flight at 80% load. Fuel and carbon emission savings are estimated at 1.5%. From the point of view of the airline operators, it might be more

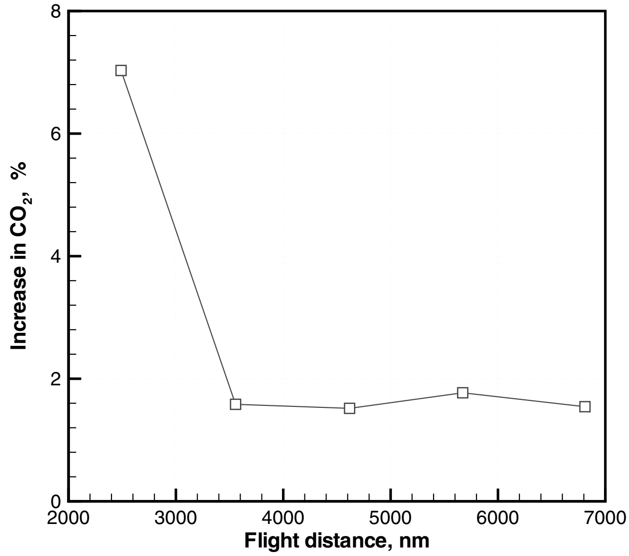


Fig. 14 CO_2 savings from operation of B-747-400 at constant load factor 70%.

efficient to divert passengers from highly loaded aircraft to scheduled services that are poorly booked.

Conclusions

This paper has presented an investigation into the breakdown of carbon-dioxide emissions from the operation of transport aircraft. The aim of the study was a detailed investigation of how these emissions can be reduced. The analysis has targeted the main parameters that can be controlled by the airline industry, namely load factor, flight distance, ground operations, baggage allowance, onboard services, and long-haul flights with and without an en route stop. A further parameter of considerable importance for the industry is the pairing between origin and destination airports, because the average passenger load depends on the demand for such services. Because marketing is also involved in the efficiency of the process, an analysis based on destination cannot be done rigorously. The data have been presented in terms of CO_2 because regulations are set to target emissions rather than fuel consumption. However, reduction of fuel consumption and carbon dioxide are directly correlated. Hence, the analysis shown also serves to analyze how aviation fuel is used.

The aircraft model developed for this purpose includes a geometry input file with over 100 airplane parameters, an engine model with about 40 parameters, and over 25 operational parameters. This model is believed to be more accurate than the methods currently available in the open domain. Nevertheless, the validation of the model could only be done in part, due to the lack of accurate flight data. It was shown that the most reliable measure of accuracy is a set of integral parameters that summarize the overall performance of the aircraft from departure to destination. The method is quite general, hence the user community can populate the model with more accurate data than the author can access.

Air transport remains a very efficient means of mass transport compared with road vehicles and personal transport. Carbon calculators available to lobby groups do not necessarily represent the true cost of aviation to the environment. However, the massive expansion of air traffic, along with the longer distances flown, are most responsible for the overall carbon emission.

To provide ready-to-use data for the correct allocation of emissions from transport aircraft, the results obtained for the various aircraft have been summarized in Tables 2–5. The tables give the correct emission factors with respect to a reference condition.

On the basis of this research and previous results, the fuel and carbon-dioxide savings from aircraft operations can be summarized as follows. Savings of up to 1.5% is achievable from 1) control of the center of gravity of the airplane, 2) constant aircraft loading over a given route, and 3) operating the aircraft at the optimal Mach number.

More specifically, the conclusions on the aircraft model include the following:

1) Overall accuracy on wetted area is within 3%, because detailed information on filleting areas, gaps, protrusions, and wing–fuselage intersection is not available.

2) Accuracy on aerodynamic drag was verified for a single case, the Boeing B-747-100. A good correlation with reference data was found for cruise conditions over the entire range of lift coefficients. However, further validation would be needed.

3) Accuracy on the overall performance is more difficult to estimate, because the few data available are not well specified. As an example, the derivative of the ZFW with respect to the aircraft range at a fixed BRGW was calculated for the Boeing B-747-400. The result was optimistic, compared with Boeing's data.

The conclusions on the engine are as follows:

1) A detailed engine model is required to calculate the aircraft performance in realistic terms. Even then, some assumptions are necessary to deal with operation at partial throttle. The main effects on the TSFC and fuel flow have been simulated correctly. The performance at takeoff and landing conditions has been scaled from the ICAO databank.

2) The data found in the open domain are often incompatible with the certified aircraft performance. They require further verification before being used for realistic simulation of flight performance.

The conclusions on aircraft emissions are as follows:

1) There is a optimal flight distance, in some considerably lower than the design range of the aircraft, that gives minimum carbon emission and fuel consumption. Transatlantic flights and some transpacific flights can be operated at this optimum condition.

2) A flight with an intermediate stop is convenient above a certain range, which for the Boeing B-747-400 has been estimated at about 2500 n miles. Intermediate stops for medium-range flight consume more fuel. The analysis has not included the cost of stopping at the intermediate airport, nor the time-related costs.

3) For a fixed airport pairing (origin–destination) it is more efficient to operate two flights at 70% load factor, rather that one flight at 60% load and another at 80% load. The fuel saving is estimated at about 1.5% at the design range of the aircraft.

4) The effect of baggage allowance is only relevant for short- to medium-haul flights.

5) Considerable savings could be achieved by improving the ground operation of the aircraft.

Further work is required in the validation phase. However, a closer cooperation is required among the various departments to close the gap between the data available and the data made available to the public.

Table 5 Correction factors on CO_2 emissions of A-340-300

	Load factor				
X, n mile	1.00	0.90	0.80	0.70	0.60
7000	**1.000**	1.0855	1.198	1.338	1.532
6000	0.943	1.0252	1.132	1.267	1.455
5000	0.898	0.9799	1.085	1.216	1.398
4000	0.868	0.9475	1.052	1.180	1.358
3000	0.847	0.9260	1.029	1.157	1.334

Acknowledgments

This research was funded by The Carbon Consultancy, Wiltshire, United Kingdom, under grant R-101763. The author thanks Hugo Kimber for the many useful discussions and for providing the industry data used for the analysis presented.

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