Global Fuel Burn and Emissions to 2050

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ABSTRACT

Global fuel burn and emissions inventories provide the underlying foundation for climate research within the Federal Aviation Administration’s (FAA) Aviation Climate Change Research Initiative (ACCRI). These inventories and projections are provided to ACCRI researchers for a 2006 baseline year (31.3 million flights) and future years to 2050. They are computed using the FAA’s Aviation Environmental Design Tool (AEDT), designed to assess interdependencies between aviation-produced noise, emissions and fuel burn. The operational data comprising the 2006 inventories cover roughly 80% of global operations, including all commercial operations following Instrument Flight Rules. Future projections represent a range of scenarios that consider both aircraft technology and system-wide operational improvements. This paper discusses the baseline 2006 data, as well as the method for forecasting future operational data. The paper also overviews the AEDT methods for computing aircraft performance, including the resultant fuel burn and emissions. Aggregate fuel burn and emissions inventory data are provided.
INTRODUCTION

The Aviation Climate Change Research Initiative (ACCRI) was initiated in 2008 by the Federal Aviation Administration (FAA) with participation from the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA). The main objective of ACCRI is to identify and address key scientific gaps and uncertainties associated with aviation-related climate impacts while providing timely scientific input to inform optimum mitigation actions and policies. The ACCRI approach to meet this objective is to support aviation-specific climate change research that is policy-relevant and solution-focused (1).

The assessment of the effects of aviation on climate requires sophisticated computer models that accurately represent the complex chemical and microphysical processes associated with aviation’s contribution to climate change. The models themselves have substantial uncertainty, which can be associated with a number of factors, not the least of which is the underlying representation of the aircraft operations and related fuel burn and emissions. To further the understanding and interpretation of the results generated by the various climate models being used to support ACCRI, it is essential to harmonize the underlying fuel burn and emissions data input to the tools. Stanford University (2) recently led an assessment of available global aviation fuel burn inventories. The researchers concluded that the inventory discussed herein is the most comprehensive available to date. The study also cited wide variations in the distributions of aircraft-related pollutants across available inventories. These variations further highlight the need for the ACCRI researchers to utilize a single source for input to their climate tools. This is essential for a current baseline year, as well as for future years. Accurate representation of a range of assumptions on future scenarios which consider aircraft technology and operational improvements provides policy makers with a measure of the factors which contribute most substantially, and as such helps to inform appropriate mitigation measures. This paper describes the procedure and methods to produce such inputs to the climate models that include fuel burn and emissions for each flight segment anywhere in the world for an entire year (2006).

This paper focuses on the underlying aircraft operational data used to support ACCRI, including the associated fuel burn and emissions for a 2006 baseline case, as well as the method for forecasting future operational data to 2050, including the range of scenarios considered with regard to aircraft technology and operational improvements. The potential introduction and full-life-cycle CO₂ benefits of alternative aviation fuels and the potential effect of market-based measures were not considered in the scenarios. The paper also provides an overview of the methods used for computing aircraft performance, fuel burn and emissions, including an overview of the FAA’s Aviation Environmental Design Tool (AEDT). Aggregate aviation-related fuel burn and emissions inventory data for the baseline and future years are provided.

AVIATION ENVIRONMENTAL DESIGN TOOL (AEDT)

The FAA’s AEDT is a software system that dynamically models aircraft performance in time and space and computes fuel burn, emissions and noise. Full-flight airport gate-to-gate analyses are possible with AEDT for study sizes ranging from a single flight to scenarios at the airport, regional, national and global levels.
AEDT is made up of a number of key computational modules and supporting databases as shown in Figure 1 and discussed further herein.

**Core Module:** Four internationally vetted algorithms were promulgated from legacy FAA environmental tools and implemented in the AEDT computational modules. Specifically, the Society of Automotive Engineers (SAE) AIR-1845 (3) method for computing performance and noise of aircraft operating in the vicinity of airports (i.e., the terminal area), was taken from FAA’s Integrated Noise Model (INM).(4) The Boeing Fuel Flow Method 2 (BFFM2), adopted by ICAO CAEP for computing CO, HC, and NOx pollutants, and the EUROCONTROL Base of Aircraft Data (BADA) for computing aircraft performance en-route (i.e. above the terminal area) and fuel consumption for the entire duration of the flight, were taken from FAA’s System for Assessing Aviation’s Global Emissions (SAGE).(5) Additionally, the methods from European Civil Aviation Conference (ECAC) Doc-29 not covered in the SAE AIR-1845 were taken from FAA’s Model for Assessing Global Noise from Transport Aircraft (MAGENTA).(6)

Mapping these algorithms to specific implementation in the four AEDT computational modules is as follows:

- Aircraft Performance Module (APM) implements BADA, SAE and ECAC (performance portion)
- Aircraft Emissions Module (AEM) implements BFFM2 algorithms (emissions portion)
- Aircraft Acoustics Module (AAM) implements SAE and ECAC (acoustic propagation portion)
- Aircraft Metrics Module (AMM) implements SAE and ECAC (metric accumulation portion).

**Fleet Database:** The fleet data in AEDT is based on the OAG Aviation (formally BACK Aviation) Registration Databases, (7) which contains all registered (and currently operating) aircraft worldwide. For each registered aircraft, this database provides the detailed aircraft information required by AEDT (i.e., engine, number of seats, etc.). In addition, the Fleet Database contains a comprehensive mapping of registered aircraft types to aircraft-specific modeling data from the core modules.

**Airport Database:** The starting point for the AEDT airport database is the U.S. Department of Defense’s Digital Aeronautical Flight Information File (DAFIF) airports database.(8) DAFIF is global in scope, and includes a substantial amount of complimentary data, including IATA / ICAO (International Air Transport Association, International Civil Aviation Organization) airport identifiers, airport reference points, and runway information.

**Operations Database:** In a general sense, aircraft movement data is input to AEDT at the individual flight level. Depending upon the scenario being analyzed, a user can input a single flight or a user can input an entire year’s worth of flights, which depending upon the year can be tens of millions of flights. The minimum information needed by AEDT
for a given flight includes origin, destination, aircraft/engine type, and trajectory. Depending upon the analysis being conducted other information may be needed such as departure time, arrival time, etc. Within the context of ACCRI, the movement data is a global representation of flights for an entire year, often referred to as the common operations database (COD).

**THE COMMON OPERATIONS DATABASE**

The 2006 Common Operations Database that supports ACCRI includes approximately 31.3 million flights, intended to represent global commercial operations operating under Instrument Flight Rules (IFR) for the entire year. The COD is constructed from three main sources of flight information, presented in increasing order of fidelity:

**International Official Airline Guide (IAOG):** This is the most basic source of flight schedule information; it does not include time-space-position (trajectory) information. The IOAG is global in scope, and consists of commercial operator-reported flight schedule information. An operator will report any operations in advance of its departure, and will periodically update this information as needed. For each flight, IOAG will provide departure and arrival times, origin-destination (OD) pair, as well as an aircraft type (defined by the IATA aircraft code). Within AEDT, the source of IOAG data is OAG Aviation.(9)

**Enhanced Tactical Flight Management System (ETFMS):** Within Western Europe, ETFMS provides radar-based flight schedule information; it does not include trajectory information. ETFMS provides similar data to IOAG (albeit actual operations and not simply carrier-reported scheduled data), while also providing detailed airframe and engine type for each flight. The ETFMS data is proved by EUROCONTROL as part of a joint FAA/EUROCONTROL Collaborative Agreement.(10)

**Enhanced Traffic Management System (ETMS):** The highest fidelity source of flight information in the COD, ETMS, provides a complete runway-to-runway radar-based trajectory and flight schedule information for all commercial flights within North America and portions of Western Europe (specifically, the United Kingdom and Ireland).(11) The Airline Quality Performance System (ASQP) data set is used to augment the ETMS portion of the COD. It provides detailed flight information, including actual departure/arrival information, duration of any taxi procedures, and the tail number of the actual aircraft used during the flight. This data exists for airlines that carry at least 1% of all US domestic passengers.(12)

The AEDT Movements Consolidation Module (MCM) integrates the three primary sources of movement data in developing the COD. The MCM uses the AEDT fleet database as
well as the ASQP data to further enhance the COD by augmenting flights with detailed aircraft variant and engine information, including number of seats.

For the ETFMS portion of the COD, as well as the ETMS portion covered by ASQP, precise aircraft/engine information is available as these flights link directly to global registration information in AEDT’s fleet data base.

For portions of ETMS not covered by ASQP and all of the IOAG data, carrier-based distributions are developed for each ICAO aircraft type. Fleet-wide distributions are also developed for the less-common case in which carrier information are not available for a particular flight. Figure 2 provides the data flow associated with the MCM process.

The other key component of the COD, besides the flight schedule data, is the trajectory data associated with each individual operation. For most of the ETMS portion of the COD this is straightforward, as ETMS includes complete trajectory information. For all IOAG, ETFMS-based flights, and a small number of ETMS-bases flights which don’t have complete trajectory information, the trajectory needs to be constructed. The first step in this process is to construct the horizontal component, that is, the latitude and longitude points (lat/long) along the flight path.

The preferred approach to assigning lat/lon points to the flight path is to use published waypoints and airways information. Weather systems and airspace congestion aside, radar data closely match published waypoint/airway information within the DAFIF. An iterative process is used between origin and destination airport to determine the shortest path along these specified flight paths.

On occasion the iterative process may not result in a valid horizontal trajectory. In such cases, a Great Circle path is assumed for the 2006 dataset, roughly 16% of all flights world-wide used a great circle trajectory.

AEDT’s APM is used to develop the vertical portion of the flight trajectory for flights in which a radar trajectory is not available. The APM “flies” the aircraft to a target altitude which is statistically derived from ETMS-based data, on an origin-destination-based distance and an aircraft-type basis. In other words, the vertical distribution for these flights is statistically similar to that found in ETMS-based radar data.

For future years’ scenarios, radar trajectories are not available. As such, all trajectories are Great Circle, adjusted with a distance-based factor to better represent radar-based flight paths (as Great Circle represents the shortest path, and actual flights will typically deviate from this path). The adjustment factor is computed as follows:

\[
\text{Radar}_{\text{estimated}} = \text{Great Circle}_{\text{calculated}} \times (0.999 + 1.703 \times \text{Great Circle Distance}^{-0.522})
\]

Where:

\[
\text{Radar}_{\text{estimated}} = \text{Estimated Radar Metric (Distance, Fuel Burn, Emissions)};
\]

\[
\text{Great Circle}_{\text{calculated}} = \text{Calculated Great Circle Metric (Distance, Fuel Burn, Emissions)}; \text{ and}
\]

\[
\text{Great Circle Distance} = \text{Great Circle Distance (Nautical Miles)}.
\]
GLOBAL FUEL BURN

Due to the large volumes of data and substantial computational requirements, the 31.3 million flights in the 2006 global COD are processed by a server-based instantiation of AEDT. The process results in segment-based fuel burn and emissions data for each flight. Emission pollutants generated include: CO, HC, NOx, and PM. The chorded data is further processed into 1-degree-by-1-degree grids, each 500 ft in height. Figure 3 shows global gridded fuel burn for the 2006 COD.

The baseline value of 188.2 million metric tones (MMT) in 2006 does not include fuel burn associated with aviation-related operations (e.g., auxiliary power units, ground support equipment, etc.) or fuel burn from VFR flights. Non-scheduled flights in regions for which radar data are not available are also not accounted for. Together fuel burn from aviation-related operations, flights operating under visual flight rules (VFR) and non-scheduled flights amount to approximately 10 to 12% additional fuel burn. For comparison, the International Energy Agency (IEA) reported aviation fuel use of 236Mt for 2006.(13) The IEA value also includes military and general aviation. The AERO2k 2002 Inventory estimated global military, general and commercial aviation usage separately, with military and general aviation comprising approximately 12 to 13% of the total.(14) Taking into account the scope of the IEA data and that of the COD, the bottom-up modelling approach used by AEDT seems to result in comparable fuel burn to that reported by IEA.

FLEET EVOLUTION AND SCENARIOS

The fleet evolution process is consistent with the published methodologies of ICAO/CAEP.(15) Older aircraft are retired and demand is grown according to the latest ICAO/CAEP, statistically-derived retirement curves and global forecast, respectively. The aircraft used to account for the demand growth and retirement-related replacement are the latest in-production aircraft as of 2006, the base year for ACCRI.

For fuel burn, two future scenarios were developed as follows:

**Baseline:** No fuel-related technology improvement beyond that which is achieved from fleet evolution. No operational improvement beyond that needed to maintain current (2006) operational efficiency.

**Scenario 1:** Based on a combined aircraft technology and operational improvement consistent with maintaining a 2% per-annum improvement in aviation system efficiency.

The 2% per annum fuel efficiency, which is an ICAO/CAEP target, is the basis for Scenario 1 and includes both an operational and technology component. For the operational component, a 10% fleet-wide improvement is assumed in 2050. The 10% is generally consistent with published NextGen and SESAR targets. It assumes that roughly 100% of published NextGen/SESAR operational benefits are achieved by 2050. The 10% equates to a 0.23% per annum global fleet-wide improvement. The residual improvement of roughly 1.77% per annum is assumed to be attributed to aircraft technology.
For NOx, as with fuel burn, two future scenarios were developed as follows:

**Baseline:** No NOx-related technology improvement beyond that which is achieved from fleet evolution. No operational improvement beyond that needed to maintain current (2006) operational efficiency.

**Scenario 1:** A NOx-related technology improvement consistent with published ICAO/CAEP scenarios to 2026, extended to 2050 based on NASA N+3 and N+4 targets of “better than 75%”. A summary of the NOx-related technology improvements is presented in Table 1.(16)

Table 2 presents a summary of the total flights, fuel burn and NOx, by analysis year for each of the scenarios provided to the ACCRI researchers.

**FORMAT FOR ACCRI RESEARCHERS**

The various models used by the ACCRI research community had different input requirements, but in general data were provided in either gridded or chorded format. Table 3 provides a summary of the various ACCRI modeling organizations and their model requirements.

**SUMMARY AND CONCLUSIONS**

The 2006 COD is believed to be the most comprehensive compilation of global flight operations from commercial aviation. Along with the FAA’s AEDT, the COD was used to generate global gridded and chorded fuel burn and emissions data for use as a standardized source of input data to climate modelers engaged in FAA’s ACCRI program. In addition to 2006 baseline data, future year scenarios were also computed using AEDT. These scenarios considered a range of aircraft technology and operational improvements in generating future gridded and chorded results and provided a standardized set of input data for the climate researchers.

When comparing the results from the various models, the standardization of input data is essential to ensuring model differences can be attributed to the fundamental scientific approaches used by the tools, i.e., methods, assumptions, etc. It also helps guide policy makers toward appropriate mitigation measures, by helping to understand model-to-model uncertainty and facilitate more appropriate comparison of results between models.
ACKNOWLEDGEMENTS

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REFERENCES

9. OAG Aviation (2010b), ”OAG Scheduling Data,” [URL removed].

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**TABLE 1. Summary of NOx Improvements for Scenario 1**

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2016</th>
<th>2026</th>
<th>2036</th>
<th>2050</th>
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<tr>
<td>Dp/Foo (% of 2006 Level)</td>
<td>100% (Ref)</td>
<td>67%</td>
<td>47%</td>
<td>33%</td>
<td>20%</td>
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<td>Fuelburn (MMT)</td>
<td>NOx (MMT)</td>
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<td>2006</td>
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<td>2016</td>
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<td>902.80</td>
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<td>514.39</td>
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### TABLE 3. ACCRI Data Types by Research Organization

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<th>Organization</th>
<th>Gridded Data</th>
<th>Chorded Data</th>
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<tr>
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<td>N/A</td>
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<tr>
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<td>2006</td>
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<td>University Corporation for Atmospheric Research</td>
<td>2006,2016,2026,2036,2050</td>
<td>N/A</td>
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FIGURES

Figure 1. Diagram of AEDT with key modules and databases
Figure 2. Overview of MCM process.
Figure 3. Total global aircraft fuel burn in 2006