Prototype Implementation and Concept Validation of a 4-D Trajectory Fuel Burn Model Application

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Federal Aviation Administration

Highlights from the Federal Aviation Administration’s Support of the National Airspace System

AIAA Guidance, Navigation, and Control Conference
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Overview

EUROCONTROL Base of Aircraft Data (BADA)

Prototype Fuel Burn Calculator Implementation

Comparison of fuel consumption rate with known data

Lessons learned
EUROCONTROL Base of Aircraft Data (BADA)

http://www.eurocontrol.int/eeec/public/standard_page/proj_BADA.html
EUROCONTROL
Base of Aircraft Data
(BADA)

http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html
EUROCONTROL
Base of Aircraft Data (BADA)

“BADA (Base of Aircraft DAta) is an Aircraft Performance Model (APM) with corresponding database. BADA is being maintained and developed by the EUROCONTROL Validation Infrastructure Centre of Expertise located at EUROCONTROL Experimental Centre (EEC) in Brétigny-sur-Orge, France.

The main application of BADA is trajectory simulation and prediction within the domain of ATM (Air Traffic Management).

BADA revisions are scheduled annually. Its current version (BADA 3.8) provides a set of ASCII files containing performance and operating procedure data for 318 different aircraft types.”
# BADA ASCII Files:

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<table>
<thead>
<tr>
<th>AIRLINES PROCEDURES FILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>File_name: CRJ1__.APF</td>
</tr>
<tr>
<td>Creation_date: Apr 30 2002</td>
</tr>
<tr>
<td>Modification_date: Apr 30 2002</td>
</tr>
<tr>
<td>LO= 14.75 to --.-- / AV= --.-- to --.-- / HI= --.-- to 24.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COM CO</th>
<th>Company name</th>
<th>-----climb-------</th>
<th>--cruise--</th>
<th>-----descent-------</th>
<th>--approach--</th>
<th>model-</th>
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<tbody>
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</table>
```
BADA ASCII Files:

AC/Type: CRJ1__
Source OPF File: Apr 30 2002
Source APF file: Apr 30 2002

climb - 250/290 0.74 low - 17760
cruise - 250/290 0.74 nominal - 21000 Max Alt. [ft]: 41000
descent - 250/290 0.74 high - 23995

<table>
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<tr>
<th>FL</th>
<th>CRUISE</th>
<th>CLIMB</th>
<th>DESCENT</th>
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<tr>
<td></td>
<td>[kts]</td>
<td>[kg/min]</td>
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<tr>
<td>lo</td>
<td>nom</td>
<td>nom</td>
<td>nom</td>
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</table>

| 0  | 151   | 2460  | 2540  | 2320  | 37.1 | 145   | 810   | 8.1  |
| 5  | 152   | 2450  | 2470  | 2300  | 36.7 | 146   | 830   | 8.0  |
| 10 | 153   | 2430  | 2450  | 2280  | 36.4 | 152   | 890   | 8.0  |
| 15 | 160   | 2520  | 2520  | 2340  | 36.4 | 164   | 960   | 6.0  |
| 20 | 161   | 2500  | 2500  | 2320  | 36.1 | 196   | 1250  | 6.0  |

...
### BADA ASCII Files:

#### AIRLINERS PROCEDURES FILE
- **File Name:** CRJ1__.APF
- **Creation Date:** Apr 30 2002
- **Modification Date:** Apr 30 2002

<table>
<thead>
<tr>
<th>CD 1</th>
<th>FL</th>
<th>CAS</th>
<th>LO</th>
<th>AV</th>
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<tr>
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<td>2300</td>
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<td>8.0</td>
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<tr>
<td>15</td>
<td>160</td>
<td>2520</td>
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<td>2340</td>
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<tr>
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<td>161</td>
<td>2500</td>
<td>2500</td>
<td>2320</td>
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<td>1250</td>
<td>8.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

#### BADA PERFORMANCE FILE
- **April 30, 2002**
- **AC/Type:** CRJ1__
- **Source APF file:** Apr 30 2002

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<tr>
<th>CD 1</th>
<th>Flight Envelope</th>
<th>Nominal</th>
<th>Maximum</th>
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<td>2B19</td>
<td>Flight envelope</td>
<td>196</td>
<td>196</td>
<td></td>
</tr>
</tbody>
</table>

#### CRJ1__ PERFORMANCE DATA
- **CRJ1__**
- **Actype:** 2 engines Jet
- **Source:** Lauda Air Flight Planning Manual

<table>
<thead>
<tr>
<th>CD 1</th>
<th>Wing Area and Buffet coefficients (SIM)</th>
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<th>Maximum</th>
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<tbody>
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<tr>
<td>196</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>CD 1</th>
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<tr>
<td>...</td>
<td></td>
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</tbody>
</table>
BADA Phases of Flight

- **TO** Take-off Configuration
- **IC** Initial Climb Configuration
- **CR** Cruise Configuration
- **AP** Approach Configuration
- **LD** Landing Configuration

**Vertical profile of aircraft's track**

- $H_{MAX, IC}$ = Nominally 2000 feet AGL
- $H_{MAX, AP}$ = Nominally 8000 feet AGL
- $H_{MAX, LD}$ = Nominally 3900 feet AGL

**AGL** = Above Ground Level (based on elevation of airport)

**Destination airport**
Prototype Implementation (pFBC)

Written as a Java application

Implemented BADA Version 3.6

Implemented turboprop and jet engines only

Processes scenarios consisting of 4-D trajectories
i.e., it uses BADA as a fuel burn calculator, not as a flight synthesizer
Using BADA for flight synthesis

The BADA Aircraft Performance Model is primarily intended for “trajectory simulation and prediction”; i.e., to synthesize the state of an aircraft.

Use the BADA APM equations to get from the state at [i-1] to the state at [i].
Using BADA as a fuel burn calculator

The pFBC uses the given 4-D state of an aircraft and the BADA Model to calculate the fuel burn consumption rate.

The 4-D aircraft state aircraft state come from input scenarios that are obtained from recorded air traffic data or from simulation programs.

Use the BADA APM equations to calculate the fuel consumption rate at each state.

\[
m[i] = m[i-1] - \left( \frac{f[i-1] + f[i]}{2} \right) \times \left( \frac{t[i] - t[i-1]}{60} \right)
\]

where
- \(m\) is the mass of the aircraft
- \(f\) is the fuel consumption rate
- \(t\) is the time of the 4-D trajectory point
Psuedocode: pFBC

pFBC {
    Initialization;
    Synthesize initial flight;
    Find future state changes;
    Calculate fuel burn;
}

Psuedocode: Initialization

Initialization {
    For each aircraft in scenario {
        Retrieve aircraft-specific data;
        Estimate take-off weight;
        For each 4-D trajectory point {
            Collect weather data;
            Calculate true airspeed;
        }
    }
}

- From database tables
- Based on flight distance
- Since we’re given “ground speed” not airspeed
Psuedocode: Synthesize Initial Flight

Synthesize Initial Flight {
    For each aircraft in scenario {
        Estimate initial weight at 1st trajectory point;
        Determine initial phase of flight;
    }
}

Because our 4-D trajectories do not necessarily start at the departure airport.
Psuedocode: Find Future State Changes

Find Future State Changes{
    For each aircraft in scenario {
        For each 4-D trajectory point {
            If state changes {
                Interpolate 4-D trajectory point ;
            }
        }
    }
}

Because we wanted each segment to be within a single configuration phase
Psuedocode: Calculate Fuel Burn

Calculate Fuel Burn {
  For each aircraft in scenario {
    Set initial fuel consumption rate to 0.0;
    For rest of 4-D trajectory points {
      Calculate Fuel Consumption Rate;
      Calculate fuel burned over track segment;
    }
  }
}

Calculate Fuel Consumption Rate {
  Calculate lift coefficient;
  Calculate drag coefficient;
  Calculate thrust of overcome drag;
  Calculate thrust to accelerate/decelerate;
  Calculate thrust to climb/descend;
  Calculate total thrust;
  Calculate fuel consumption rate;
}

\[ m[i] = m[i-1] - \left( \frac{f[i-1] + f[i]}{2} \right) \times \left( \frac{t[i] - t[i-1]}{60} \right) \]

where
- \( m \) is the mass of the aircraft
- \( f \) is the fuel consumption rate
- \( t \) is the time of the 4-D trajectory point
Verification

We verified that we had properly implemented the BADA APM equations through normal software unit testing, but this didn’t tell us if the pFBC provided meaningful results.

We would like to have compared pFBC output with real data; but real data is generally proprietary and difficult to obtain.

This paper addresses the verification of a single flight of an aircraft using opportunistic data the aircraft’s Flight Data Recorder.
We had access to its Flight Data Recorder data for a 6-hour flight from Atlantic City Int’l Airport to Los Angeles Int’l Airport.

Specifically:
- Time
- Latitude
- Longitude
- Altitude
- Fuel consumption rate
Verification of the Calculation of Fuel Consumption Rate

Fuel Burned vs. Flight Time

Fuel Consumption Rate vs. Flight Time During Ascent

Fuel Consumption Rate vs. Flight Time During Cruise

Fuel Consumption Rate vs. Flight Time During Descent
Fuel Burned vs. Flight Time

Difference:
- 342 lbs
- 2.0%
Fuel Consumption Rate vs. Flight Time During Ascent
Fuel Consumption Rate vs. Flight Time During Cruise
Fuel Consumption Rate vs. Flight Time During Descent
Lessons Learned

This comparison verified the technique; and we learned a lot:

For this verification we knew the aircraft’s take-off weight; but for our production implementation we need to improve our estimation of take-off weight.

For this verification the weight of our initial 4-D trajectory point was the take-off weight, which we knew. For our production implementation we need to improve our estimation of the initial weight.

We know from this experience and from other studies that 4-D trajectory data is noisy; we need to improve our data smoothing technologies.

This verification identified some problems with our weather retrieval techniques; which we have addressed.

We need more verification and in our production implementation we plan to conduct detailed studies to verify the integrity of the results.
Contact Information:

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