An Assessment of BADA Fuel Flow Methodologies for In-Trail Procedure Evaluation

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Quantification of fuel burn is a key metric while evaluating fuel-efficient air traffic procedures. BADA fuel flow models are primarily used to evaluate these procedures in simulation environment. In this paper we quantify fuel savings from an In Trail Procedure (ITP) by employing BADA Thrust Specific Fuel Consumption model. We compare two BADA fuel flow models i.e. Thrust Specific Fuel Consumption (TSFC) and BADA Fuel Flow tables. We extend the BADA Fuel Flow table model by dynamically reducing aircraft weight due to fuel burn, and compared the two models with actual Flight Data Recorder data; we found better accuracy with the TSFC model. We then employed the TSFC model in simulation, to quantify the fuel savings from a prototype ITP procedure. Results show 585.6 kg of fuel savings, in a given wind condition, for a Perth-Darwin flight by climbing to a more fuel-efficient altitude while still satisfying safety requirements.

Keywords- BADA fuel flow, In-Trail Procedure, Thrust Specific Fuel Consumption, Wind Model

I. INTRODUCTION

Air traffic service providers around the world are striving to minimize aviation greenhouse emission by fuel-efficient operations in the system [1]. This includes innovative air traffic procedures such as In-Trail Procedures, Continuous Descent Approaches, Required Navigation Performance (RNP) procedures etc [2].

The close linkage between fuel usage and aviation emissions necessitates the assessment and application of fuel models that deliver accurate estimates of aircraft fuel flow for a variety of air traffic procedures. Most fuel consumption models are primarily based on EUROCONTROL’s Base of Aircraft Data (BADA) [3].

The BADA fuel consumption model uses energy balanced thrust model and Thrust Specific Fuel Consumption (TSFC) model. BADA also provides aircraft performance data and fuel flow tables at different altitudes for different phases (climb, cruise, descent) of flight. Some extensions have been made to the BADA model notably in [8], [9].

In this paper we compare the BADA TSFC model and the BADA Fuel flow tables (with weight correction) against the actual Flight Data Recorder (FDR) fuel burn data. The two fuel flow models (TSFC, and Fuel flow tables with weight reduction) are incorporated in a high fidelity air traffic simulation system ATOMS [4] co-developed by the authors. ATOMS performs real time computation of aerodynamic parameters and takes into consideration the weight reduction, wind profile and atmospheric properties while calculating fuel flow. It can also compute fuel flow, using linear interpolation, from BADA fuel flow tables based on aircraft flight phase and altitude. We extend the BADA Fuel flow tables computations in ATOMS by incorporating aircraft weight reduction due to fuel burn during the flight.

We then select the better-performing model to evaluate the fuel savings from a proof-of-concept case study for an In-Trail Procedure (ITP) [5] in non-radar Australian airspace using simulation.

This paper is organized as follows: in the next section we discuss BADA aerodynamic fuel flow model and BADA fuel flow table, which we extend to account for dynamic weight reduction due to fuel burn. In the following section we compare the two models with BADA fuel Flow tables and with the actual flight’s Flight Data Recorder fuel burn data. Next, we prototype an ITP procedure in an air traffic simulator. Fuel savings from ITP are then quantified using the BADA aerodynamic fuel model, and we conclude with some discussions.

II. BADA AERODYNAMIC FUEL FLOW MODEL

The fuel burn of an aircraft basically depends on airframe drag, engine-specific fuel consumption, distance of the route to be flown, vertical flight path, and aircraft weight [6]. TSFC is a measure of engine efficiency, defined as fuel flow rate in pounds per hour divided by engine thrust in pounds (lb/hr/lb).

In BADA, thrust T and the fuel consumption f for cruise phase are calculated as follows:

\[ T = D = \frac{1}{2} \rho V^2 SC \]
\[ f = \eta \times T \times C_{fcr} \]

where D is drag, V is the true air speed, and is \( \rho \) air density. The thrust specific fuel consumption, in kg/minute/kN, is specified as a function of airspeed V:
\[ \eta = C_f \times \left( 1 + \frac{V}{C_f^2} \right) \]

Coefficient of drag \( C_D \) is computed based on the coefficient of lift \( C_L \):

\[ C_D = C_{D0,CR} + C_{D2,CR} \times (C_L)^2 \]

The coefficient of lift \( C_L \) is expressed as a function of the altitude, via air density \( \rho \), and the airspeed \( V \):

\[ C_L = \frac{2mg}{\rho V^2 S} \]

Table 1 describes the coefficients used in above equations from BADA aircraft performance tables.

In the rest of this paper we call this model the “BADA aerodynamic fuel model”.

<table>
<thead>
<tr>
<th>Model/Category</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>( m )</td>
<td>Kg</td>
<td>Mass</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>( S )</td>
<td>m^2</td>
<td>Reference wing surface area</td>
</tr>
<tr>
<td>CD0,CR</td>
<td>( R )</td>
<td>dimensionless</td>
<td>Parasitic drag coefficient (cruise)</td>
</tr>
<tr>
<td>CD2,CR</td>
<td>( R )</td>
<td>dimensionless</td>
<td>Induced drag coefficient (cruise)</td>
</tr>
<tr>
<td>Fuel flow</td>
<td>Cf1</td>
<td>Kg/min/kN</td>
<td>1st thrust specific fuel consumption coefficient</td>
</tr>
<tr>
<td></td>
<td>Cf2</td>
<td>knots</td>
<td>2nd thrust specific fuel consumption coefficient</td>
</tr>
<tr>
<td></td>
<td>Ccfr</td>
<td>dimensionless</td>
<td>Cruise fuel flow correction coefficient</td>
</tr>
</tbody>
</table>

III. BADA FUEL FLOW TABLES

BADA also provides a set of aircraft performance summary tables: for each aircraft type, the performance tables specify the true air speed, rate of climb/descent, and fuel flow, for conditions of climb, cruise and descent at various flight levels and for low, nominal and high mass levels.

BADA Fuel Flow tables provide a simple alternative for fuel flow computation. They are a good alternative when computational cost is a factor, especially where the cruise phase dominates fuel flow in a flight.

We investigate an extension of BADA Fuel Flow tables, correcting for weight change due to fuel burn. By interpolating the Fuel Flow values at different flight and different mass levels, and continuously reducing the aircraft mass by the fuel consumption amount at each time step, a higher accuracy of aircraft fuel flow can be achieved. We use the following equations:

\[ W(t+1) = W(t) - W_f(t) \]

\[ W_f(t) = \begin{cases} 
\text{Interpolat e1(Alt, FuelFlow } \text{BADA) for Climb} \\
\text{Interpolat e2(W(t), Alt, FuelFlow } \text{BADA) for Cruise} \\
\text{Interpolat e1(Alt, FuelFlow } \text{BADA) for Descent} 
\end{cases} \]

where \( W(t) \) and \( W(t+1) \) is the aircraft’s weight at time step \( t \) and \( t+1 \), \( W(t) \) is the aircraft’s fuel flow at time \( t \), Alt is the aircraft’s altitude at time \( t \), and FuelFlowBADA is the fuel values from BADA Performance Table.

In the rest of this paper we call this the “dynamic weight fuel model”.

A. For Climb and Descent Phases:

For the climb and descent phases, since only a single nominal fuel flow value is given for each flight level, the fuel flow at a particular altitude \( Alt \) is computed by interpolating the fuel values at the flight levels above and below \( Alt \) from BADA tables, regardless of the actual weight. The interpolation formulae are expressed as follows:

\[ \text{Interpolat e1(W, Alt, FuelFlow } \text{BADA) } = \alpha \times (\text{FuelFlow(FL}_A,W_i) - \text{FuelFlow(FL}_B,W_i)) \]

where the interpolation coefficient

\[ \alpha = \frac{Alt - FL_B}{FL_A - FL_B} \]

and \( A \) and \( B \) are the levels right below and above altitude \( Alt \) and FuelFlow(FL,W) is the BADA fuel value at flight level FL and mass level W, which is ignored during climb and descent phases.

B. For Cruise Phase

For the cruise phase, fuel flow values at low, nominal and high masses are given for each flight level. Therefore, the fuel flow at a particular altitude \( Alt \) and weight \( W \) is computed by interpolating the fuel values from BADA tables, at the flight levels above and below \( Alt \) and mass levels above and below the current mass. The interpolation formula is expressed as follows:

\[ \text{Interpolat e2(W, Alt, FuelFlow } \text{BADA) } = \beta \times (\text{FF}(W_H) - \text{FF}(W_L)) \]

where the interpolation coefficient

\[ \beta = \frac{W - W_L}{W_H - W_L} \]

and

\[ \text{FF}(W) = \text{Interpolat e1(W, Alt, FuelFlow } \text{BADA) } \]

is the interpolation of the BADA fuel values according to altitude, \( L \) and \( H \) are the mass levels below and above the current weight \( W \).
IV. COMPARING THE TWO MODELS

A. Test Flight for Comparison

We compare the two models, using ATOMS air traffic simulation, where a sample flight from Melbourne to Sydney is simulated. Table II shows the test flight parameters.

<table>
<thead>
<tr>
<th>Test Flight Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Origin</strong></td>
</tr>
<tr>
<td><strong>Destination</strong></td>
</tr>
<tr>
<td><strong>Aircraft</strong></td>
</tr>
<tr>
<td><strong>Engine type</strong></td>
</tr>
<tr>
<td><strong>Engines</strong></td>
</tr>
<tr>
<td><strong>Waypoint Route</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td><strong>Cruise speed</strong></td>
</tr>
<tr>
<td><strong>Cruise altitude</strong></td>
</tr>
</tbody>
</table>

For every time step of the simulation, fuel flow is recorded for both the models. The following assumptions were made for the experiment:

- The acceleration during an increment is constant.
- The flight path angle ($\gamma$) is small, therefore $\cos \gamma = 1$, or the aircraft weight equals the required lift.
- For flight simulation, waypoints-airway route, auto pilot control based on flight plan.

B. Fuel consumption and aircraft’s mass over time

Figure 1 and Figure 2 present the fuel consumption (kg/s) and the aircraft’s mass (kg) over time, for different fuel computation approaches. The plots show that aircraft’s mass monotonically reduces according to the amount of fuel burnt, with the assumption that the only reduction factor for aircraft’s mass is the fuel.

C. Comparison of the Dynamic weight and BADA Aerodynamic model

We compare the BADA aerodynamic fuel model and the Dynamic weight fuel model with the BADA fuel table values. Figure 3 and Figure 4 present the fuel consumption results generated by ATOMS for the test flight, under the three different models.
The maximum differences between the Aerodynamic and the Dynamic Weight approaches, compared to the BADA Fuel Flow table values, are 0.5 kg/s and 0.01 kg/s respectively. This variance is more significant for the aerodynamic model during Climb and Descent phases of flight, whereas during the cruise phase the two models are close to the BADA Fuel Flow table values.

The results also indicate that allowing for reducing weight due to fuel burn does not result in a significant difference between the BADA Fuel Flow tables and the Dynamic Weight Reduction model. The Aerodynamic fuel model computes the fuel consumption based on a more complicated and higher fidelity formula involving the aircraft’s aerodynamic forces; we see that this gains significantly more, compared to just using the BADA Fuel Flow tables, than just allowing for weight reduction.

**D. Comparison with Flight Data Recorder**

We compared the results from BADA aerodynamic fuel model, and the BADA Fuel Flow with dynamic weight reduction model, with actual airline reported Flight Data Recorder (FDR) data for several flights in Australian airspace. A sample set of six flights is presented in Table III, which shows the actual FDR fuel burn and the fuel burn computed in simulation using the two models along with the variance between them.

The BADA Dynamic Weight model overestimates the fuel burn, whereas the Aerodynamic model usually underestimates it, though not by a large amount. The BADA aerodynamic fuel model produces a value for fuel burn that is within 0.32% to 7.26% of the actual value. The corresponding variation with the BADA Dynamic Weight Model ranges from 9.57% to 16.97%. This illustrates the better performance of the BADA aerodynamic fuel model as compared to BADA Dynamic Weight model.

The BADA aerodynamic fuel model is therefore used in the ITP fuel saving evaluation that is described in the rest of this paper.

### V. QUANTIFICATION OF FUEL SAVINGS FROM AN IN-TRAIL PROCEDURE

#### A. In-Trail Procedure (ITP)

ITP is a procedure that allows an aircraft to climb/descend through the altitude of another nearby aircraft that is ahead on the same track in oceanic/non-radar airspace [5]. Currently, this is not permitted because such a climb/descent would violate the same-altitude separation requirements used for most oceanic/non-radar tracks. In many cases, the result is that the aircraft is not permitted to fly an efficient altitude profile. This leads to higher fuel consumption on oceanic/non-radar tracks. Given that oceanic/non-radar tracks involve large distances, ITP procedures may enable substantial fuel savings.

In this section we attempt to estimate the fuel savings from an ITP procedure in Australian non-radar airspace. The estimation is done using fast time simulation in ATOMS, of ITP procedures in a hypothetical non-radar coverage area in Australian airspace. We perform analysis of fuel savings arising from ITP procedures for a simple scenario, with a given wind profile under nominal conditions. Nominal conditions do not include human error, communication errors, degradation in engine and airframe performance, etc.

#### B. Air Traffic Simulation

ATOMS is used to simulate non-radar flights in Australian airspace with ITP scenarios. A wind model was developed and integrated into ATOMS to compute the effect of wind on aircraft ground speed and hence on fuel consumption at different altitudes. For computation of fuel, BADA’s aerodynamic fuel flow model is used.

Aerodynamic parameters are computed dynamically, taking into account atmosphere, wind and weight of the aircraft. Fuel flow is computed for a given altitude and summed to get an aggregate fuel consumption value.

#### C. Processing Wind Data for In-Trail Procedure

In order to estimate the most fuel-efficient altitude for ITP climb/descent procedures under various wind conditions, a grid based wind model is used in ATOMS.

Wind data is an image file, which shows the atmospheric and wind information in a grid format for Australia wide region (source: Bureau of Meteorology Figure 5). Each cell in the grid covers 5 degrees of latitude and 5 degrees of longitude. There

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**TABLE III. FDR FUEL AND BADA FUEL BURN COMPARISON AND VARIANCE COMPARED TO FDR DATA**

<table>
<thead>
<tr>
<th>Origin</th>
<th>Dest.</th>
<th>Aircraft</th>
<th>Engine</th>
<th>BADA Tables (kg)</th>
<th>BADA Aer. (kg)</th>
<th>BADA Dy. Weight (kg)</th>
<th>FDR Fuel Burn</th>
<th>Variance BADA Aerodynamic</th>
<th>Variance BADA Dynamic Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>YMML</td>
<td>YPAD</td>
<td>B763</td>
<td>JT9D-7R4D</td>
<td>4791</td>
<td>4785</td>
<td>5477</td>
<td>4800</td>
<td>-0.32%</td>
<td>+14.10%</td>
</tr>
<tr>
<td>YMML</td>
<td>YSSY</td>
<td>A332</td>
<td>CFM56-5-A1</td>
<td>5572</td>
<td>5566</td>
<td>6266</td>
<td>5697</td>
<td>-2.30%</td>
<td>+9.99%</td>
</tr>
<tr>
<td>YPDN</td>
<td>YPPH</td>
<td>B738</td>
<td>CFM56-3B-2</td>
<td>8383</td>
<td>8380</td>
<td>9984</td>
<td>9036</td>
<td>-7.26%</td>
<td>+10.49%</td>
</tr>
<tr>
<td>YPPH</td>
<td>YSSY</td>
<td>A332</td>
<td>CFM56-5-A1</td>
<td>20479</td>
<td>20472</td>
<td>22432</td>
<td>19178</td>
<td>+6.75%</td>
<td>+16.97%</td>
</tr>
<tr>
<td>YSSY</td>
<td>YBBN</td>
<td>B763</td>
<td>JT9D-7R4D</td>
<td>5727</td>
<td>5723</td>
<td>6972</td>
<td>6000</td>
<td>-4.62%</td>
<td>+16.20%</td>
</tr>
<tr>
<td>YSSY</td>
<td>YMML</td>
<td>B763</td>
<td>JT9D-7R4D</td>
<td>5103</td>
<td>5100</td>
<td>5745</td>
<td>5243</td>
<td>-2.74%</td>
<td>+9.57%</td>
</tr>
</tbody>
</table>
are six altitude levels specified, ranging from 16500 ft to 44500 ft; it is assumed that there is a linear variation between these levels. The data is stored in a matrix and profiled by interpolating two known wind quantities at two different points and across altitudes to ensure no discontinuity in the wind calculation. Given the aircraft’s location (latitude/longitude) and altitude, and interpolating between the nearest grid points and levels respectively (assuming linear characteristics of the atmosphere between these points in space), a representative value for wind aloft, temperature and density is calculated.

The aircraft’s ground speed is computed based on the true airspeed and the wind speed using the vector representation [7].

\[ \frac{V}{g} = \sqrt{\left(\frac{V}{W} \sin(\theta - \psi)\right)^2 + \left(V \cos(\theta - \psi)\right)^2} \]

An increased ground speed will reduce the time in flight, hence affecting the aggregate fuel consumption. Figure 6 shows the variation in the ground speed, given true airspeed and wind speed, for the Perth–Darwin flight used in this experiment.

D. Experiments

Based on the assumption that Australian northern territory is non-radar airspace, we simulated an ITP for a Perth–Darwin flight.

The flight path of the aircraft consists of origin airport, top of climb, ITP start waypoint, ITP end waypoint, top of descent and destination airport. The flight plan is shown in Table IV.

The aircraft is in cruise altitude when ITP is initiated. The reference aircraft is ahead of ITP aircraft on the same track. The following ITP safety conditions are met before ITP is initiated:

- Initiation range of no less than 15 NM when positive ground speed differential is 20 knots or less.
- Initiation range of no less than 20 NM when positive ground speed differential is 30 knots or less.
- Maximum altitude change of 4000 feet.

The reference point is for both aircraft to continue at the initial flight level, with no ITP; the total fuel burn for this scenario is the baseline. For an ITP scenario, the total fuel consumption at different flight levels, between the two reference waypoints that denoted the non-radar track, was computed. These were compared against the baseline total fuel consumption. The level that yielded minimum fuel consumption, or maximum fuel saving, was identified. Fuel consumption was computed only for the non-radar track starting from the ITP start waypoint and ending at the ITP end waypoint.

<table>
<thead>
<tr>
<th>TABLE IV. A SAMPLE FLIGHT PLAN OF TWO FLIGHTS ON NON RADAR TRACK USED IN ITP FUEL EFFICIENT ALTITUDE DETERMINATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
</tr>
<tr>
<td>Perth</td>
</tr>
<tr>
<td>Darwin</td>
</tr>
<tr>
<td>Aircraft Type</td>
</tr>
<tr>
<td>Cruise Speed</td>
</tr>
<tr>
<td>Cruise Altitude</td>
</tr>
<tr>
<td>Non-Radar Track</td>
</tr>
<tr>
<td>ITP start waypoint</td>
</tr>
<tr>
<td>ITP end waypoint</td>
</tr>
</tbody>
</table>

Figure 7 illustrates the process flow of the ITP experiment for quantification of fuel savings.
The fuel flow is computed for the each individual cell in the wind grid from the ITP start point to the end of the ITP track. This process is done for each available altitude i.e. four flight levels above and four flight levels below. This fuel flow (for each wind grid) for each given altitude level is then summed to find the most fuel-efficient altitude for the ITP procedure.

Figure 7. Process flow for ITP experiment

Figure 8. ATOMS snap shot showing the ITP aircraft (behind) and reference aircraft on a hypothetical non-radar track.

Figure 8 shows a run time snapshot of ATOMS with the ITP experiment. Both the flights, call sign MXG011 and QFA402 are bound for Darwin. The hypothetical non-radar track starts at “NURAK” and ends at “DOPUK”. Both aircraft are on the same track before ITP is commenced. The ITP aircraft (MXG011) initiates the ITP.

The algorithm computes the fuel consumption from ITP start waypoint to ITP end waypoint, for 4 flight levels above and 4 flight level below. This computation is done for each wind grid at that altitude, and summed to get an aggregate value.

The altitude involving the least fuel burn is then fed into the flight management system of the ITP aircraft in simulation, which then initiates a climb or descent procedure to reach that desired altitude, as illustrated in Figure 9.

Figure 9. An illustration of ITP experiment showing in-trail climb to a different altitude.

E. Results

Table V shows the fuel consumption for the simulated ITP aircraft on Perth–Darwin route. The cruise altitude for the ITP aircraft was 33,000 ft. The most fuel-efficient approach is for the ITP aircraft to climb to 34,000 ft, as shown in Table V and Figure 10. The different fuel consumptions are due to different winds at different altitudes across the region.

<table>
<thead>
<tr>
<th>Altitude (ft)</th>
<th>Fuel Burn (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29000</td>
<td>20882.73</td>
</tr>
<tr>
<td>30000</td>
<td>20748.20</td>
</tr>
<tr>
<td>31000</td>
<td>21183.55</td>
</tr>
<tr>
<td>32000</td>
<td>20798.86</td>
</tr>
<tr>
<td>33000</td>
<td>20372.38</td>
</tr>
<tr>
<td>34000</td>
<td>19786.52</td>
</tr>
<tr>
<td>35000</td>
<td>21046.04</td>
</tr>
<tr>
<td>36000</td>
<td>20838.14</td>
</tr>
<tr>
<td>37000</td>
<td>20654.51</td>
</tr>
</tbody>
</table>

By comparing the fuel consumption against the fuel consumed at the reference altitude of 33,000 ft, we can see that for the simulated Perth–Darwin flight an ITP climb to 34,000 ft lead to fuel savings of 585.86 kg.
F. Conclusions

The BADA aerodynamic fuel flow model shows better accuracy than BADA Fuel Flow tables, especially in climb and descent phases. This can be attributed to the fact that the aerodynamic model uses run time flight aerodynamic parameters computed by taking into account actual take-off weight of the aircraft, atmospheric properties and wind data. However, the BADA Fuel Flow tables provide a simple approach for fuel flow computation and are a good alternative when fuel flow computation in cruise phase is only required, and also where computational cost is a factor.

Simulation of a Perth–Darwin flight, using the BADA aerodynamic fuel flow model, has shown that a savings of 585.6 kg (3%) of fuel can be achieved by changing to a more fuel-efficient altitude using an ITP procedure. With different wind conditions this can vary, perhaps resulting in higher fuel savings, especially on oceanic tracks, which are of much longer distance and so have scope for greater fuel savings.

We intend to extend our work by incorporating higher traffic density and other safety constraints in simulation, and by carrying on more detailed experiments in different wind conditions.

REFERENCES

[2] User manual for base of aircraft data (BADA), EUROCONTROL Experiment Center, Bretigny, France, Rev No:3.6, 2004