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

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As new technologies are implemented to enhance the National Airspace System it is important to consider their impact on the environment and on the cost of operations. One of the major considerations for both is the amount of fuel consumed by aircraft. This paper describes a unique methodology that can be used to estimate the total fuel consumed by aircraft based on their 4-D trajectories and the weather through which they flew. This methodology is based on the European Organisation for the Safety of Air Navigation (EUROCONTROL) BADA (Base of Aircraft Data) fuel burn model. The paper then describes how the BADA fuel burn model and weather data provided by the National Weather Service were implemented in a prototype application and how this prototype was validated using actual data recorded during a flight for a specific aircraft. The paper concludes with a summary that includes suggestions for improvements that should be incorporated when implementing the production version of the application.

I. Introduction

The Federal Aviation Administration (FAA) created the National Airspace System (NAS) to provide a safe and efficient airspace environment for civilian, commercial, and military aviation. The NAS is composed of a network of air navigation facilities, air traffic control facilities, and airports, along with the technologies and the rules and regulations to operate the system. Even though this system is among the safest in the world, its efficiency is impacted by weather and traffic. Furthermore, the FAA forecasts an increase in flight operations of 19 percent at the 35 major U.S. airports by 2018.

To address the challenges and improve the NAS even further, the interagency Joint Development Planning Office (JPDO) was established in December 2003 under the "Vision-100" legislation (Public Law 108-176). The JPDO mandated a NAS next generation (NextGen) operational concept for 2025.[1] The NextGen concept envisions a trajectory-based separation management system that requires precise management of the aircraft's current and future position. The separation management function of today, which currently relies heavily on the cognitive skills of the air traffic controller to visualize aircraft trajectories on the radar display and to issue resolutions via voice instructions to pilots, will be replaced by a distributed system of separation management components implementing performance-based separation standards. This future system will rely heavily on enhanced automation with conflict resolution advisories that are communicated through digital data links between an aircraft and the ground facilities and between an aircraft and other aircraft.

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Since automation investments are at the heart of the NextGen concept, cost benefit analyses must follow to support these decisions. As a result, the FAA's NextGen Implementation Plan[2] calls for a reduction in traffic delays, operating costs in terms of fuel reductions, and environmental impacts in terms of carbon dioxide emissions. The cumulative estimates are substantial for initial deployment of capabilities by 2018 amounting to 21 percent in traffic delays, 1.4 billion gallons of fuel, and nearly 14 million tons of carbon dioxide reductions.

Besides the overall cumulative benefits, each individual automation improvement and sub-system investment must also be evaluated in terms of its overall impact on the environment and on operating costs. One of the major considerations for both is the amount of fuel consumed by the aircraft. This paper describes a unique methodology developed by the FAA's Conflict Probe Assessment Team (CPAT) at the William J. Hughes Technical Center located at the Atlantic City International Airport in New Jersey to estimate the total fuel consumed by aircraft based on their 4-D trajectories and the weather (i.e., winds and air temperatures) they encountered.

II. Prototype Implementation of Fuel Burn Model Application

The prototype Fuel Burn Calculator (pFBC) application estimates the fuel burned for each flight in a scenario, which consists of a number of aircraft flight paths. In these scenarios each aircraft is defined by its 4-D trajectory, which consists of a temporal component (time) and three spatial components (latitude, longitude, and altitude). These scenarios can be obtained either from recorded air traffic data or from a fast-time simulation. The pFBC uses equations documented within the European Organisation for the Safety of Air Navigation (EUROCONTROL) BADA (Base of Aircraft Data) fuel burn model[3] to estimate the fuel burn.[a]

The pFBC processes each flight in the scenario individually using four steps: initialization, synthesize initial flight, find future state changes, and calculate fuel burn; which are described in the following subsections.

II.A. Initialization

The pFBC performs the following tasks during the *initialization* step for each flight:

- retrieve aircraft-specific data,
- estimate take-off weight,
- collect weather data,
- calculate true airspeed, and
- process altitude data.

Each of these are discussed in detail in the following subsections.

II.A.1. Retrieve Aircraft-Specific Data

The BADA data is distributed as a set of text files. The CPAT has developed software that extracts the data from these files and populates an Oracle© database table. This data includes information such as: the aircraft weight, the aircraft's wing surface reference area, the parasitic drag coefficients, the induced drag coefficients, the 1st and 2nd thrust specific fuel consumption coefficients, the 1st and 2nd descent fuel flow coefficients, the cruise fuel flow correction coefficient. All of this data is described in the BADA User Manual.[3] In addition, the nomenclature and units for this data will be specified in this paper as they are used.

[a]This prototype implementation is based on Version 3.6 of the BADA Users Manual and implements the equations for turboprop and jet engines and does not implement the equations for piston engines.

II.A.2. Estimate Take-off Weight

An accurate estimate of the initial weight of the aircraft is crucial to an accurate estimate of its fuel consumption rate; because as an aircraft burns fuel it becomes lighter and its performance improves. In order to estimate the weight of the aircraft at it's initial 4-D trajectory point, the pFBC first estimates the take-off weight of the aircraft. To do this, the pFBC estimates the flight's total flight distance using Eq. 1.

$$d_{flight} = d_{depart} + d_{dest} \tag{1}$$

where

d_{flight} (nautical miles) is the estimated flight distance for the flight,

d_{depart} (nautical miles) is the great circle distance from the flight's departure airport to the flight's initial 4-D trajectory point, and

d_{dest} (nautical miles) is the great circle distance from the flight's initial 4-D trajectory point to the flight's destination airport.

The pFBC then uses this total flight distance in a table look up to estimate the aircraft's take-off weight, m_{TOW}, using tables that were populated in earlier studies using the FAA's Integrated Noise Model.[4] This take-off weight is an estimate of the weight of the aircraft based solely on the flight distance.

II.A.3. Collect Weather Data

The weather data used by the pFBC consists of the air temperature, the wind direction, and the wind magnitude. This data may be provided either from data files provided by the National Weather Service (NWS) in Rapid Update Cycle (RUC) weather files[5] or it may use the International Standard Atmosphere (ISA) model,[6] which is an atmospheric model that models the atmosphere as an ideal gas over a wide range of altitudes. If the pFBC uses the ISA model, it calculates the air temperature based on the altitude and assumes there is no wind.

RUC files are GRIB-formatted[b] files containing forecasted weather conditions in a 3-dimensional grid. The GRIB format, the available weather parameters, and the grids are defined in Office Note 388.[7] The RUC files used by the pFBC use the RUC 236 grid, which covers the continental United States containing 151 points along the lines of latitude and 113 points along the lines of longitude. At each of these nodes the pFBC uses the following weather data at 37 isobaric levels:

- *HGT* (meters) is the geopotential altitude,
- *TMP* (Kelvin) is the air temperature, and
- *UGRD* and *VGRD* (meters/second) are the u- and v-components of the wind, which are aligned with the line of latitude and the line of longitude at the RUC node.

The 37 isobaric levels begin at 100 millibars, which is at an approximate altitude of 16,000 meters, and go to 1,000 millibars, which is at an approximate altitude of 175 meters, at 25 millibar increments. These RUC files are created hourly by the NWS. Based on a predetermined schedule various hourly forecasts are generated at each analysis hour. This includes a zero-hour forecast (called the *anl* forecast) that represents the best estimate of the actual weather at the analysis hour. The pFBC obtains this data from Oracle© database tables populated by software developed by the CPAT that extracts this data from the RUC weather files.

The accuracy of the RUC data varies both by isobaric level and by forecast time; specifically it has been documented:[8]

- The Root Mean Square (RMS) of the altitude errors varies from about 8.5 to 13 meters in the *anl* forecast and from about 10.5 to about 19 meters in the non-zero forecast hours.

[b] GRIB (GRidded Binary) is a data format commonly used in meteorology to store historical and forecast weather data.

- The RMS of the air temperature errors varies from about 0.5 to about 1 degree in the *anl* forecast and from about 0.9 to about 1.6 degrees in the non-zero forecast hours.
- The RMS of the errors in the u- and v-components of the wind vary from about 2.8 to about 3.8 meters/second in the *anl* forecast and from about 3.9 to around 6 meters/second in the non-zero forecast hours.

II.A.4. Calculate True Airspeed

The pFBC calculates the true airspeed of the aircraft for each of the aircraft's 4-D trajectory points based on the aircraft's groundspeed and the wind data using Eq. 2, which is based on the standard wind triangle.

$$V_{TAS}[i] = \left| \begin{pmatrix} V_{ground}[i] \times sin\left(\theta_{AC}[i]\right) \\ V_{ground}[i] \times cos\left(\theta_{AC}[i]\right) \end{pmatrix} - \begin{pmatrix} V_{wind}[i] \times sin\left(\theta_{wind}[i]\right) \\ V_{wind}[i] \times cos\left(\theta_{wind}[i]\right) \end{pmatrix} \right| \tag{2}$$

where

$V_{TAS}[i]$[c] (knots) is the aircraft's true airspeed,

$V_{ground}[i]$ (knots) is the groundspeed estimated from consecutive 4-D trajectory points,

$\theta_{AC}[i]$ (degrees clockwise from north) is the aircraft's course estimated from consecutive 4-D trajectory points,

$V_{wind}[i]$ (knots) is the magnitude of the wind as described in Section II.A.3, and

$\theta_{wind}[i]$ (degrees clockwise from north) is the direction the wind is blowing toward as described in Section II.A.3.

II.A.5. Process Altitude Data

For each of the aircraft's 4-D trajectory points, the pFBC smooths the altitude data by fitting a least squares linear line using three time-sequenced data points and computes the ascent/descent rate as the slope of this fitted line. This smoothing is necessary because the pFBC often uses scenarios created from recorded air traffic data that often contains noisy data.

II.B. Synthesize Initial Flight

The pFBC performs the following tasks during the *synthesize initial flight* step for each flight:

- estimate initial weight, and
- determine initial phase of flight.

Both of these are discussed in detail in the following subsections.

II.B.1. Estimate Initial Weight

Section II.A.2 discussed how the pFBC estimates each aircraft's take-off weight during *initialization*. Unfortunately, for most of the flights in a scenario environment, the initial 4-D trajectory point is not at or even near the departure airport but somewhere along the aircraft's flight path. Therefore, the pFBC needs to estimate the weight at the initial 4-D trajectory point based on the estimated take-off weight and how far the aircraft is from the departure airport. The pFBC does this using Eq. 3.

$$m[0] = m_{AC} + \left(\zeta - \frac{d_{depart}}{d_{flight}}\right) \times \left(m_{TOW} - m_{AC}\right) \tag{3}$$

where

[c]Throughout this paper, $[i]$ represents the ith 4-D trajectory point for an aircraft in the scenario, with $i = 0$ representing the initial 4-D trajectory point.

$m[0]$ (kilograms) is the mass of the aircraft at the initial 4-D trajectory point,

m_{AC} (kilograms) is the empty mass of the aircraft from the BADA data,

ζ (dimensionless) is the user-specified fuel reserve factor where $\zeta > 1.0$,

d_{depart} (nautical miles) is the great circle distance from the flight's departure airport to the flight's initial 4-D trajectory point as described in Section II.A.2,

d_{flight} (nautical miles) is the estimated flight distance for the flight as described ins Section II.A.2, and

m_{TOW} (kilograms) is the estimated take-off mass of the aircraft as described in Section II.A.2.

This equation assumes that the weight of the fuel at take-off is equal to $m_{TOW} - m_{AC}$ times a user-specified fuel reserve factor (ζ). Inspection of this equation shows that if the initial 4-D trajectory point is at the departure airport the initial weight of the aircraft is equal to the empty weight of the aircraft, m_{AC}, plus the weight of the fuel, whereas if the trajectory point is near the end of the flight, the initial weight of the aircraft is equal to the weight of the aircraft plus the reserve fuel.

II.B.2. Determine Initial Phase Of Flight

In the BADA fuel burn model there are different sets of values for an aircraft type's drag coefficients for each of five configurations corresponding to five phases of flight: take-off (TO), initial climb (IC), cruise (CR), approach (AP), and landing (LD). These different configurations represent the differences in flight characteristics due to the positioning of flaps, extension of landing gear, etc. Figure 1 shows these configurations along with the vertical profile of a typical flight. This is a simplistic plot of a flight with the dotted line showing the altitude of an aircraft as it changes a function of the distance that the aircraft travels. The graphic shows that an aircraft gains altitude as it leaves its departure airport, maintains a cruise altitude, then descends as it approaches its destination airport, often with a period of time in which the aircraft maintains an approach altitude.

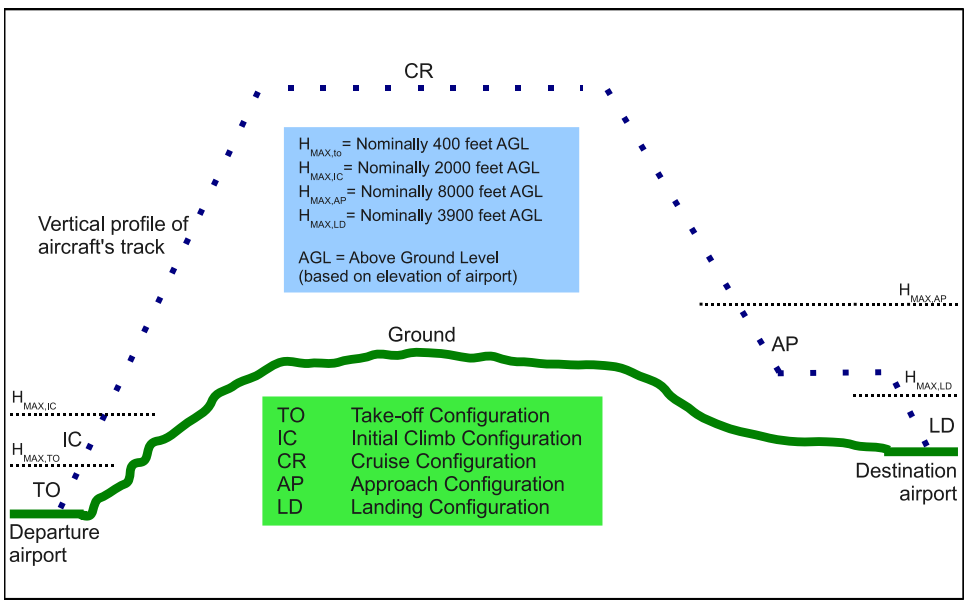

Figure 1. BADA Phases of Flight

The pFBC determines the aircraft's initial phase of flight by first determining if the aircraft's initial 4-D trajectory point is nearer to the departure airport or to the destination airport. If it is nearer to the departure airport, the pFBC assumes that the initial phase of flight is either TO, IC, or CR; otherwise the pFBC assumes that the initial phase of flight is either, CR, AP, or LD. The pFBC then compares the altitude at the initial 4-D trajectory point with the appropriate altitude configuration parameters to establish the initial phase of flight.

II.C. Find Future State Changes

While the BADA fuel burn model uses the five phases of flight described earlier, the pFBC defines two additional phases of flight: CR_ASC and CR_DSC. These represent the situations in which the aircraft is in the BADA cruise configuration, but is actually ascending or descending. This is done because there are optional fuel burn equations that may be used during an aircraft's descent; this is discussed in detail later. With this in mind, the permissible phase of flight changes are depicted in Fig. 2.

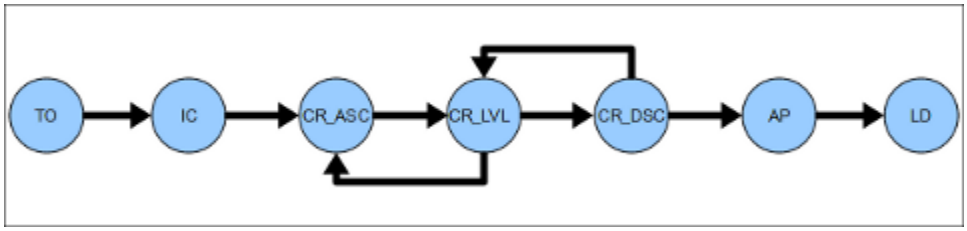

Figure 2. Permissible State Changes

To find the future state changes, the pFBC loops through all of the 4-D trajectory points, beginning at the initial 4-D trajectory point, and interpolates the transition points where the aircraft transitions from one phase of flight to another.

II.D. Calculate Fuel Burn

The pFBC uses an iterative approach that assumes the aircraft's weight ($m[i-1]$) and its fuel consumption rate ($f[i-1]$) are known at time $t[i-1]$.[d] Then, in each iterative cycle, the pFBC uses the BADA fuel burn model equations to calculate the fuel consumption rate at time $t[i]$. The pFBC then estimates the fuel burned during the interval using the average fuel consumption rate for the interval using Eq. 4 where the calculation of the fuel burned is described in Section II.D.8.

$$m[i] = m[i-1] - \left(\frac{f[i-1]+f[i]}{2}\right) \times \left(\frac{t[i]-t[i-1]}{60}\right) \tag{4}$$

where

$m[i]$ (kilograms) is the mass of the aircraft at the end of the interval,

$m[i-1]$ (kilograms) is the mass of the aircraft at the beginning of the interval,

$f[i-1]$ (kilograms/minute) is the fuel consumption rate at the beginning of the interval calculated as described in Section II.D.7,

$f[i]$ (kilograms/minute) is the fuel consumption rate at the end of the interval calculated as described in Section II.D.7, and

$t[i-1]$ and $t[i]$ (seconds) represent the times of the two consecutive 4-D trajectory points.

The pFBC iterates through the following tasks during the *Calculate Fuel Burn* step for each flight:

- calculate lift coefficient,
- calculate drag coefficient,
- calculate thrust to overcome drag,
- calculate thrust to accelerate/decelerate,
- calculate thrust to climb/descend,

[d] pFBC assumes that $f[0] = 0.0$.

- calculate total thrust,
- calculate fuel consumption rate, and
- calculate fuel burned.

Each of these are discussed in detail in the following subsections.

II.D.1. Calculate Lift Coefficient

In order to calculate the lift coefficient the pFBC must first calculate the density of the air using Eq. 5.

$$\rho[i] = \rho_s \times \left(\frac{T[i]}{T_s}\right)^{\left[\left(\frac{g_0}{\gamma \times R}\right)+1\right]} \tag{5}$$

where

$\rho[i]$ (kilograms/meter^3) is the density of air,

ρ_s (kilograms/meter^3) is the density of air at sea level a constant equal to 1.225 kilograms/meter^3,

$T[i]$ (Kelvin) is the air temperature as described in Section II.A.3,

T_s (Kelvin) is the air temperature at sea level a constant equal to 288.16 Kelvin,

g_0 (meters/second^2) is the acceleration due to gravity a constant equal to 9.81 meters/second^2,

γ (Kelvin/meter) is the lapse rate a constant equal to 0.0065 Kelvin/meter, and

R (joules/kilogram/Kelvin) is the specific gas constant equal to 287.04 joules/kilogram/Kelvin.

The pFBC then calculates the lift coefficient using Eq. 6 (BADA Eq. 3.6-5).[e]

$$C_L[i] = \frac{2 \times m[i] \times g_0}{\rho[i] \times V_{TAS}^2[i] \times S \times cos\left(\phi[i]\right)} \tag{6}$$

where

$C_L[i]$ (dimensionless) is the lift coefficient,

$m[i]$ (kilograms) is the weight of the aircraft as calculated in Eq. 4,

g_0 (meters/second^2) is the acceleration due to gravity a constant equal to 9.81 meters/second^2,

$\rho[i]$ (kilogram/meter^3) is the density of air as calculated in Eq. 5,

$V_{TAS}[i]$ (meters/second) is the aircraft's true airspeed as calculated in Eq. 2,

S (meters^2) is the wing surface reference area from the BADA data, and

$\phi[i]$ is the bank angle (assumed to be zero).

[e]Many of the equations presented in this paper are based on equations documented in the BADA User Manual.[3] In these cases, the BADA equation number is also provided.

II.D.2. Calculate Drag Coefficient

The pFBC then calculates the drag coefficient, which is dependent upon the phase of flight.

- In the AP phase of flight, once the true airspeed drops below the minimum cruise speed Eq. 7 (BADA Eq. 3.6-2) is used.
- In the LD phase of flight, once the true airspeed drops below the minimum approach speed Eq. 8 (BADA Eq. 3.6-3) is used.
- In all other phases of flight Eq. 9 (BADA Eq. 3.6-1) is used.

$$C_D[i] = C_{D0,AP} + C_{D2,AP} \times C_L^2[i] \tag{7}$$

$$C_D[i] = C_{D0,LDG} + C_{D0,\Delta LDG} + C_{D2,LDG} \times C_L^2[i] \tag{8}$$

$$C_D[i] = C_{D0,CR} + C_{D2,CR}^2 \times C_L^2[i] \tag{9}$$

where

$C_D[i]$ (dimensionless) is the drag coefficient,

$C_L[i]$ (dimensionless) is the lift coefficient as calculated in Eq. 6,

$C_{D0,AP}$ (dimensionless) is the parasitic drag coefficient in the approach configuration from the BADA data,

$C_{D0,CR}$ (dimensionless) is the parasitic drag coefficient in the cruise configuration from the BADA data,

$C_{D2,AP}$ (dimensionless) is the induced drag coefficient in the approach configuration from the BADA data,

$C_{D2,CR}$ (dimensionless) is the induced drag coefficient in the cruise configuration from the BADA data,

$C_{D0,LDG}$ (dimensionless) is the additional parasitic drag coefficient when the landing gear is extended from the BADA data,

$C_{D2,LDG}$ (dimensionless) is the additional induced drag coefficient when the landing gear is extended from the BADA data, and

$C_{D0,\Delta LDG}$ (dimensionless) is the parasitic drag coefficient when the landing gear is extended from the BADA data.

II.D.3. Calculate Thrust To Overcome Drag

The thrust to overcome drag is equal to the drag force given by Eq. 10 (BADA Eq. 3.6-4).

$$T_{drag}[i] = D[i] = \frac{C_D[i] \times \rho[i] \times V_{TAS}^2[i] \times S}{2} \tag{10}$$

where

$T_{drag}[i]$ (Newtons) is the thrust to overcome drag,

$D[i]$ (Newtons) is the drag force,

$C_D[i]$ (dimensionless) is the drag coefficient as calculated in Eq. 7, Eq. 8 or Eq. 9,

$\rho[i]$ (kilograms/meter^3) is the density air as calculated in Eq. 5,

$V_{TAS}[i]$ (meters/second) is the aircraft's true airspeed as calculated in Eq. 2, and

S (meters^2) is the wing surface reference area from the BADA data.

II.D.4. Calculate Thrust To Accelerate/Decelerate

The thrust to accelerate/decelerate the aircraft is calculated using Eq. 11, which assumes that the acceleration is constant over the segment.

$$T_{accel}[i] = m[i-1] \times a_{avg} = \frac{m[i-1] \times (V_{TAS}[i] - V_{TAS}[i-1])}{t[i] - t[i-1]} \tag{11}$$

where

$T_{accel}[i]$ (Newtons) is the thrust required to accelerate/decelerate the aircraft,

$m[i-1]$ (kilograms) is mass from Eq. 4,

a_{avg} (meters/second^2) is the average acceleration calculated from the two consecutive 4-D trajectory points assuming constant acceleration over the interval,

$V_{TAS}[i-1]$ and $V_{TAS}[[i]$ (meters/second) are the aircraft's true airspeeds as calculated from Eq. 2, and

$t[i-1]$ and $t[i]$ (seconds) represent the times of the two consecutive 4-D trajectory points.

II.D.5. Calculate Thrust To Climb/Descend

The thrust required to climb/descend the aircraft is calculated using Eq. 12.

$$T_{PE}[i] = \frac{m[i-1] \times g_0 \times (h[i] - h[i-1])}{d_s} \tag{12}$$

where

$T_{PE}[i]$ (Newtons) is the thrust required to increase the potential energy of the aircraft from trajectory point i-1 to 4-D trajectory point i,

$m[i-1]$ (kilograms) is mass as calculated in Eq. 4,

g_0 (meters/second^2) is the acceleration due to gravity a constant equal to 9.81 meters/second^2,

$h[i-1]$ and $h[i]$ (meters) are the altitude of the aircraft at 4-D trajectory point i-1 and i, and

d_s (meters) is the great circle distance calculated between the two consecutive 4-D trajectory points.

II.D.6. Calculate Total Thrust

The total aircraft thrust is modeled as the sum of three individually calculated thrust components: the thrust to overcome drag, the thrust necessary to accelerate/decelerate, and the thrust necessary to ascend/descend, as shown in Eq. 13.

$$T_{total}[i] = T_{drag}[i] + T_{accel}[i] + T_{PE}[i] \tag{13}$$

where

$T_{total}[i]$ (Newtons) is the total thrust,

$T_{drag}[i]$ (Newtons) is the thrust to overcome drag as calculated in Eq. 10,

$T_{accel}[i]$ (Newtons) is the thrust required to accelerate/decelerate the aircraft as calculated in Eq. 11, and

$T_{PE}[i]$ (Newtons) is the thrust required to increase/decrease the potential energy of the aircraft from trajectory point i-1 to 4-D trajectory point i as calculated in Eq. 12.

II.D.7. Calculate Fuel Consumption Rate

When the aircraft is in either the TO, IC, AP, or LD phase of flight and for idle descent conditions, the fuel consumption rate is calculated by first calculating the specific fuel consumption using Eq. 14 (BADA Eq. 3.9-1) for aircraft with jet engines and Eq. 15 (BADA Eq. 3.9-3) for aircraft with turboprop engines.

$$\eta[i] = C_{f1} \times \left(1 + \frac{V_{TAS}[i]}{C_{f2}}\right) \tag{14}$$

$$\eta[i] = C_{f1} \times \left(1 + \frac{V_{TAS}[i]}{C_{f2}}\right) \times \left(\frac{V_{TAS}[i]}{1000}\right) \tag{15}$$

where

$\eta[i]$ (kilograms/minute/kilo-Newton) is the thrust specific fuel consumption,

$V_{TAS}[i]$ (knots) is the aircraft's true airspeed as calculated in Eq. 2,

C_{f1} (kilograms/minute/kilo-Newton for jets and kilograms/minute/kilo-Newton/knot for turboprops) is the 1st thrust specific fuel consumption coefficient from the BADA data, and

C_{f2} (knots) is the 2nd thrust specific fuel consumption coefficient from the BADA data.

The nominal fuel consumption rate is calculated using Eq. 16 (BADA Eq. 3.9-2), the minimum fuel consumption rate is calculated using Eq. 17 (BADA Eq. 3.9-5), and the fuel consumption rate, f, is set to the greater of f_{nom} and f_{min}.

$$f_{nom} = \eta[i] \times T_{total}[i] \tag{16}$$

$$f_{min} = C_{f3} \times \left(1 - \frac{h[i]}{C_{f4}}\right) \tag{17}$$

where

f_{nom} (kilograms/minute) is the nominal fuel flow,

f_{min} (kilograms/minute) is the minimum fuel flow corresponding to idle thrust or descent conditions,

$\eta[i]$ (kilograms/minute/kilo-Newton) is the thrust specific fuel consumption as calculated in Eq. 16 or Eq. 17,

$T_{total}[i]$ (kilo-Newtons) is the total thrust as calculated in Eq. 13,

C_{f3} (kilograms/minute) is the 1st descent fuel flow coefficient from the BADA data,

C_{f4} (feet) is the 2nd descent fuel flow coefficient from the BADA data, and

$h[i]$ (feet) is the aircraft's altitude.

During CR the fuel consumption rate is calculated using Eq. 18 (BADA Eq. 3.9-6); and the fuel consumption rate, f, is to f_{cr}.

$$f_{cr} = \eta[i] \times T_{total}[i] \times C_{fcr} \tag{18}$$

where

f_{cr} (kilograms/minute) is the cruise fuel flow,

$\eta[i]$ (kilograms/minute/kilo-Newton) is the thrust specific fuel consumption,

$T_{total}[i]$ (kilo-Newtons) is the total thrust as calculated in Eq. 13, and

C_{fcr} (dimensionless) is the cruise fuel flow correction coefficient from the BADA data.

II.D.8. Calculate Fuel Burned

Finally the pFBC uses the fuel consumption rate to calculate how much fuel was expended to get from the previous 4-D trajectory point and subtracts this from the aircraft's weight as indicated in Eq. 4.

III. Validation of the Prototype Implementation

During its development the pFBC was subjected to a number of verification techniques. This paper addresses one specific validation technique where CPAT compared its output with data recorded by a Flight Data Recorder (FDR) data from an actual flight made by a Bombardier Global 5000 owned by the FAA. The flight was from the Atlantic City International Airport in New Jersey to the Los Angeles International Airport in California that lasted a little over six hours (301.5 minutes).[f] For the validation the pFBC was run using V3.7 BADA data, which does not contain the aircraft model data for a Bombardier Global 5000. Therefore the BADA aircraft model data for a Bombardier CRJ900 was used. In addition, for the validation run, the modeled take-off weight was matched to the actual take-off weight by manipulating the fuel reserve factor, ζ, described in Section II.B.1. This was done because in this unique situation, the actual take-off weight was provided by the pilots.

The data recorded by the FDR consists of 839 parameters recorded at a rate of four times per second. In addition, the data provided to the CPAT consisted of multiple days and therefore numerous flights. Therefore the first validation step was to parse the data into Oracle© database tables. One of these tables contains a select subset of the data sampled at 1-second intervals. The other tables contains data derived from the FDR data suitable for input to the pFBC; this data is sampled at 10-second intervals.

III.A. Validation of the Retrieval of Weather Data

With regards to validating the weather data, it was not necessary to validate how accurately the pFBC weather data matched the weather data collected by the FDR, but how well the pFBC retrieved RUC forecasted data from the database. This was done by identifying RUC nodes of opportunity where the track data indicated that the aircraft flew close to a RUC node and then comparing the RUC forecasted weather data at this node with the pFBC weather data. Table 1 lists the nine RUC nodes of opportunity that were identified for this validation process. The table lists the time, the aircraft's position,[g] and the distance from this track point to the RUC node.[h] This table shows that all of the selected nine nodes of opportunity are within 1.0 nautical mile of the RUC node.

Table 1. Aircraft Data at Nodes of Opportunity

RUC node	flight time	aircraft latitude	aircraft longitude	aircraft altitude	distance to node
126,58	530 s	39.244722°	-75.256667°	15200.0 ft	0.08 nm
121,57	1380 s	39.140000°	-77.596389°	32883.3 ft	0.69 nm
107,55	3740 s	38.956111°	-84.018333°	39883.3 ft	0.69 nm
99,54	5190 s	38.773056°	-87.686389°	39983.3 ft	0.88 nm
92,53	6460 s	38.535000°	-90.890556°	39916.7 ft	0.12 nm
85,52	7780 s	38.218611°	-94.078333°	40016.7 ft	0.54 nm
79,51	8980 s	37.858333°	-96.789167°	39883.3 ft	0.45 nm
70,49	10780 s	37.055833°	-100.808056°	39966.7 ft	0.46 nm
52,46	13770 s	35.523611°	-108.696111°	40016.7 ft	0.38 nm

Since the altitude of the track points did not coincide with any of the RUC data's 37 isobaric levels, the weather data retrieved by the pFBC at the aircraft's altitude was interpolated in the altitude dimension. The results of this interpolation for the temperature data is shown in Table 2. The RMS of these temperature differences is 0.71 Kelvin. The results of the interpolation for the wind data is shown in Table 3. For this

[f] It should be noted that this flight was not made specifically for this validation effort; instead this was opportunistic data that was made available to CPAT for the validation.

[g] The aircraft position is the latitude and longitude recorded by the FDR, which is based on the aircraft's inertial guidance system.

[h] The distance to the RUC node is the great circle distance between the recorded position and the RUC node assuming a spherical earth with a radius of 3,437.747 nautical miles.

Table 2. Temperature Differences at Nodes of Opportunity

RUC node	Air Temp pFBC	Air Temp RUC	Δ Air Temp
126,58	261.7 K	262.6 K	-0.9 K
121,57	217.9 K	219.2 K	-1.3 K
107,55	209.9 K	210.2 K	-0.2 K
99,54	209.5 K	209.8 K	-0.2 K
92,53	206.3 K	207.5 K	-1.2 K
85,52	207.7 K	208.3 K	-0.6 K
79,51	208.5 K	208.4 K	0.1 K
70,49	215.5 K	215.1 K	0.4 K
52,46	225.1 K	225.2 K	-0.1 K

Table 3. Wind Differences at Nodes of Opportunity

RUC node	NS-comp pFBC	EW-comp pFBC	NS-comp RUC	EW-comp RUC	Δ NS-comp	Δ EW-comp
126,58	-14.3 m/s	0.1 m/s	-13.7 m/s	0.3 m/s	-0.6 m/s	-0.2 m/s
121,57	-13.2 m/s	1.6 m/s	-13.9 m/s	1.9 m/s	0.7 m/s	-0.4 m/s
107,55	-3.3 m/s	13.9 m/s	-4.1 m/s	13.0 m/s	0.8 m/s	0.9 m/s
99,54	-4.9 m/s	17.3 m/s	-4.8 m/s	18.5 m/s	-0.1 m/s	-1.2 m/s
92,53	-2.0 m/s	12.8 m/s	-1.8 m/s	13.3 m/s	-0.2 m/s	-0.5 m/s
85,52	5.8 m/s	22.8 m/s	6.4 m/s	25.0 m/s	-0.6 m/s	-2.3 m/s
79,51	20.0 m/s	29.1 m/s	22.1 m/s	29.7 m/s	-2.0 m/s	-0.6 m/s
70,49	38.7 m/s	9.2 m/s	40.9 m/s	8.2 m/s	-2.1 m/s	1.0 m/s
52,46	-5.8 m/s	5.8 m/s	-5.9 m/s	6.0 m/s	0.1 m/s	-0.2 m/s

table the wind magnitude and wind direction have been decomposed into their north-south and east-west components for easier comparison. The RMS of the wind components differences is 1.05 meters/second. These results are well within the accuracy of the RUC data as discussed in Section II.A.3.

III.B. Validation of the Fuel Burn Calculations

Over the entire flight the total amount of fuel burned according to the FDR was 17,457 pounds; the total amount calculated by the pFBC was 17,799 pounds. This is a difference of only 342 pounds,[i] which means that the pFBC estimated 2.0% more fuel burned over the six hour flight than what was recorded by the FDR. This is shown graphically in Fig. 3, which shows the total fuel burned as a function of flight time calculated by the pFBC and as recorded by the FDR.

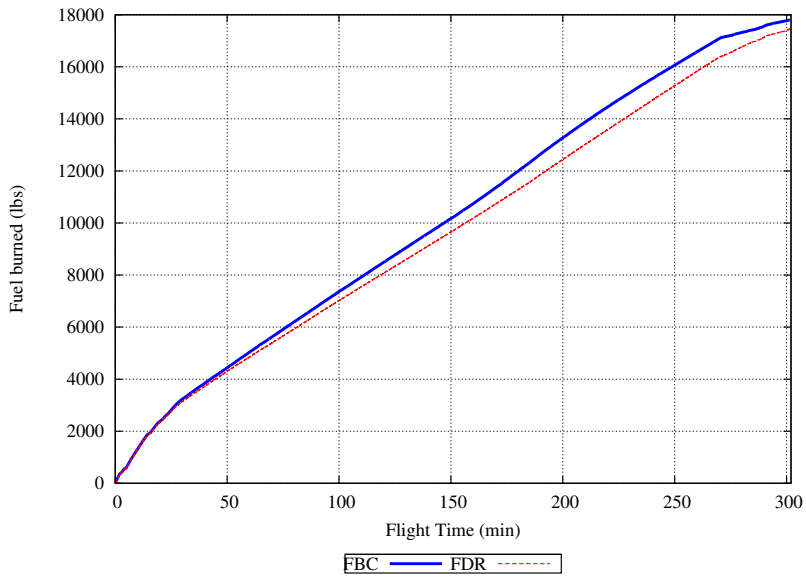

Figure 3. Fuel Burned Vs. Flight Time

While this indicates that the pFBC performed well overall, the pFBC's accuracy did vary when its results were compared with three segments of the flight:

- ascent (comprised of the TO, IC, and CR_ASC phases of flight),
- cruise (comprised primarily of the CR_LVL with occasional transitions into the CR_ASC and CR_DSC phases of flight), and
- descent (comprised of the CR_DSC, AP, and LD phases of flight).

III.B.1. Fuel Burn During Ascent

Figure 4 shows the fuel consumption rate as a function of the flight time during ascent from take-off to 40,000 feet. This portion of the flight was the first 29.5 minutes of the flight, during which the FDR recorded a total of 3,142 pounds of fuel burned; while the pFBC calculated a total fuel burn during this period of 3,205 pounds. This represents a difference of 63 pounds or that the pFBC calculated 2.0% more than what was actually burned according to the FDR.

[i]The discrepancy in these numbers, and in others, is within this paper is due to rounding,

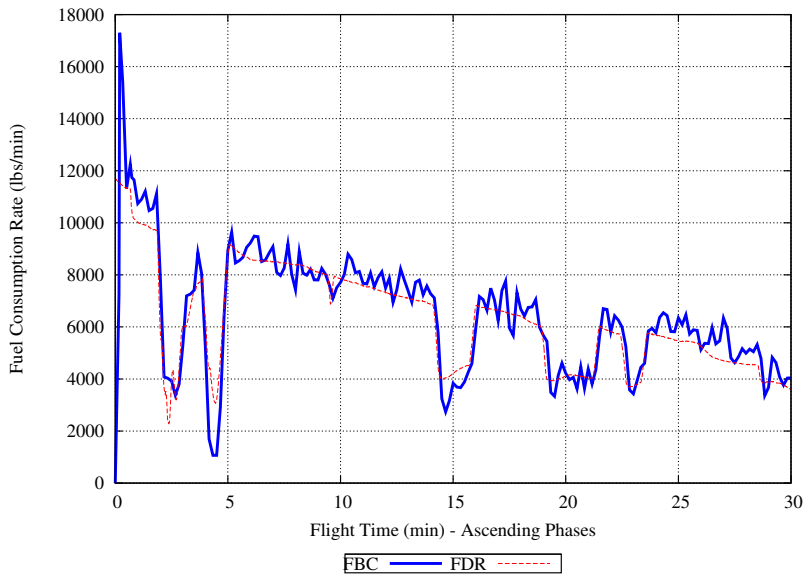

Figure 4. Fuel Consumption Rate Vs. Flight Time During Ascent

III.B.2. Fuel Burn During Cruise

The level cruise portion of this flight, which was at an altitude of 40,000 feet, lasted from about 29.5 minutes into the flight to about 270.5 minutes into the flight. It is difficult to show graphically the fuel consumption rates recorded by both the FDR and by the pFBC over this entire time period because of the length of time and the consequential number of data points. However, Fig. 5 does show these fuel consumption rates as a function of the flight time during a typical 30 minute segment of the flight. During this specific segment the FDR recorded a total of 13,278 pounds of fuel burned, while the pFBC calculated a total fuel burn during this same segment of 13,908 pounds. This is a difference of 631 pounds or 4.7% more than what was actually burned. This can be accounted for by looking at the fuel consumption rate during the level cruise portion of the flight calculated by the pFBC which had an average of 3,463.1 pounds per hour, while during the same time period the fuel consumption rate recorded by the FDR had an average of 3,305.7 pounds per hour. This indicates that on the average during cruise the pFBC estimated the fuel consumption rate as 157.4 pounds per hour greater, which over the 241 minutes results in a total of 632.3 pounds.

III.B.3. Fuel Burn During Descent

Figure 6 shows the fuel consumption rate as a function of the flight time during descent from 40,000 feet to landing. This portion of the flight consisted of flight time from about 270 minutes into the flight to the end of the flight, which was about 301.5 minutes into the flight. During this descent portion of the flight, the FDR recorded a total of 1,090 pounds of fuel burned; while the pFBC calculated a total fuel burn during this period of 686 pounds. This is a difference of 404 pounds or 37.1% less than what was actually burned. This is by far the poorest results with regards to the pFBC, which can most likely be attributed to the fact that the pFBC is modeling the performance characteristics of the aircraft while the FDR data is recording the actual fuel consumption as the pilot is making in-flight adjustments to account for the flight conditions.

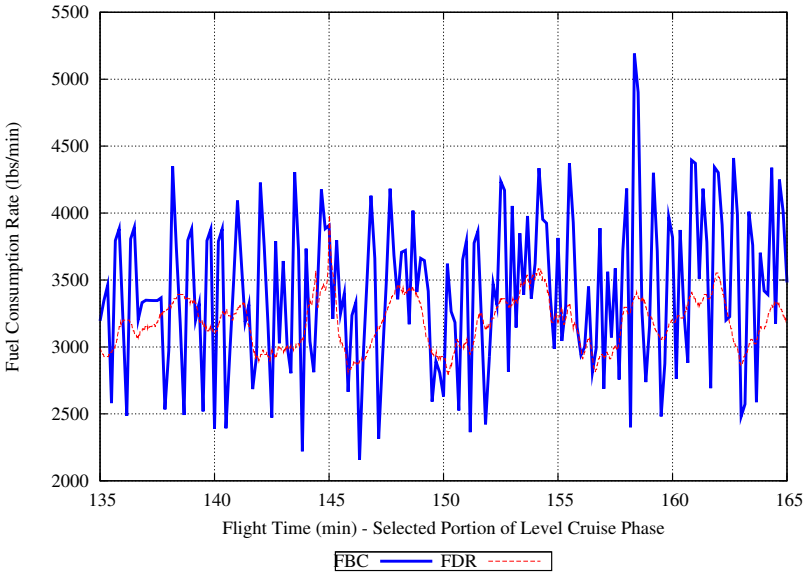

Figure 5. Fuel Consumption Rate Vs. Flight Time During Selected Interval of Cruise

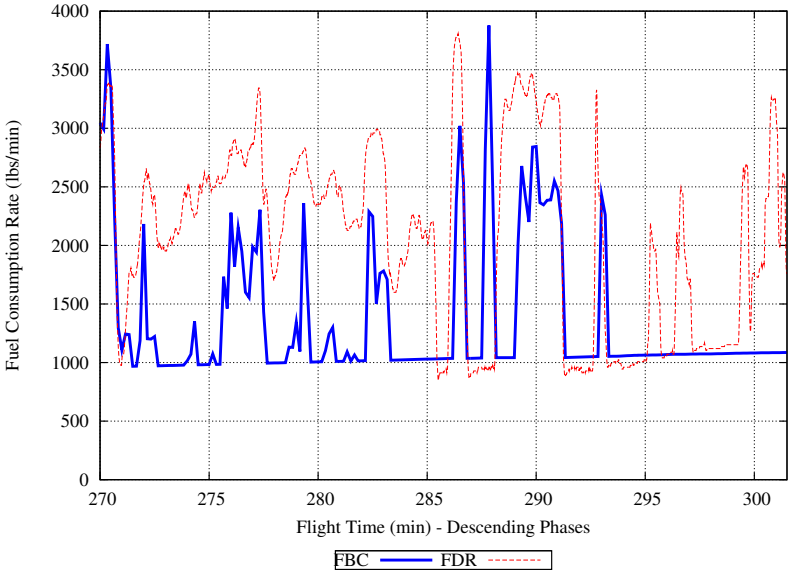

Figure 6. Fuel Consumption Rate Vs. Flight Time During Descent

IV. Summary

Comparing the RUC nodes of opportunity verified that the weather package used by the pFBC performed satisfactorily. Comparing the fuel burn calculations made by pFBC with recorded FDR data from an actual flight using its recorded FDR data verified that the BADA fuel burn model reasonably models the fuel consumption rate of the specific aircraft used for the validation. It is reasonable to assume that the pFBC will also perform reasonably for other aircraft. In addition to using recorded FDR data, the pFBC was also used to provide fuel burn estimates to researchers within the FAA's Simulation and Analysis Group at the William J. Hughes Technical Center. This included scenarios created by the Airspace Concept Evaluation System (ACES), which is a fast-time simulation tool developed at the National Aeronautics and Space Administration's Ames Research Center.[9] Another included scenarios created by AwSim™, which is a general-purpose aircraft trajectory simulator used to provide realistic air traffic data.[10] The validation described in this paper and these runs identified a number of areas for improvement:

1. A different technique must be used to estimate the aircraft's take-off weight. For the validation the take-off weight was not an issue because it was known and could be matched using the fuel reserve factor. But when the pFBC was used with the scenario data, it was apparent that the pFBC's technique for estimating the take-off weight requires improvement.

2. The application needs to be initialized differently. Figure 4 shows that at the initial point (i.e., at time = 0) the fuel consumption rate is zero. This, of course, does not reflect reality.

3. Figure 4 also shows that the fuel consumption rate calculated by the pFBC is noisy. The prototype attempts to smooth the data, but the data smoothing processes need to be reevaluated and improved.

4. The process used to retrieve RUC weather data needs to be redesigned. This became apparent when using the pFBC with the ACES scenarios, which are 24-hour scenarios and retrieving the weather data resulted in unacceptable run times.

5. pFBC only implemented the BADA equations for turboprop and jet engines; the equations for piston engines should be added.

6. This validation of pFBC using a single aircraft verified the approach. The production implementation will need to be validated against a wider range of aircraft.

List of Acronyms and Abbreviations

4-D	Four dimensional
ACES	Airspace Concept Evaluation System
AGL	Above Ground Level
AP	BADA Approach Configuration
AwSim	AwSim™
BADA	EUROCONTROL Base of Aircraft Data
CPAT	Conflict Probe Assessment Team
CR	BADA Cruise Configuration
CR_ASC	BADA Cruise Configuration, ascending portion
CR_DSC	BADA Cruise Configuration, descending portion
CR_LVL	BADA Cruise Configuration, level portion
DST	Decision Support Tool
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
pFBC	Prototype FuelBurnCalculator application
FDR	Flight Data Recorder
GRIB	GRidded Binary
HGT	Geopotential altitude
IC	BADA Initial Climb Configuration
ISA	International Standard Atmosphere
JPDO	Joint Planning Development Office

LD	BADA Landing Configuration
NAS	National Airspace System
NWS	National Weather Service
RMS	Root Mean Square
RUC	Rapid Update Cycle
TMP	Air temperature
TO	BADA Take-Off Configuration
UGRD	U-component of the wind vector
VGRD	V-component of the wind vector

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References

[1]Joint Planning and Development Office, *Concept of Operations for the Next Generation Air Transportation System, Version 2.0*, June 2007, URL:http://www.jpdo.gov/library/NextGen_v2.0.pdf [cited June 29th, 2010].

[2]Federal Aviation Administration, *FAA's NextGen Implementation Plan*, March 2010, URL:http://www.faa.gov/about/initiatives/nextgen/media/ngip_3-2010.pdf [cited June 29th, 2010].

[3]Eurocontrol Experimental Centre, *User Manual for the Base of Aircraft Data (BADA) Revision 3.6 EEC Note No. 10/04*, July 2004, URL:http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html [cited June 29th, 2010].

[4]URL:http://www.faa.gov/about/office_org/headquarters_offices/aep/models/inm_model/ [cited June 29th, 2010].

[5]URL:http://ruc.noaa.gov/ [cited June 29th, 2010].

[6]International Civil Aviation Organization (ICAO), *Manual of the ICAO Standard Atmosphere, ICAO Document No. 7488*, 2nd ed., July 1964.

[7]National Centers for Environmental Prediction, *Office Note 388*, 2004, URL:http://www.nco.ncep.noaa.gov/pmb/docs/on388/ [cited June 29th, 2010].

[8]Benjamin, S. G. et al., "An Hour Assimilation - Forecast Cycle: The RUC," *Monthly Weather Review*, Vol. 132, February 2004, pp. 495–518.

[9]Raytheon ACES Team, *CDRL 19.3 System/Subsystem Design Description (SSDD)/ Software Design Document (SDD)*, September 29 2006.

[10]URL:http://www.freeflight.com/aerospace/products/awsim/ [cited June 29th, 2010].