

Fuel Burn Modeling of Turboprop Aircraft

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13. ABSTRACT (Maximum 200 words) This report documents work done to enhance turbo-propeller aircraft fuel consumption modeling in the Federal Aviation Administration's Aviation Environmental Design Tool (AEDT). Fuel consumption and flight performance data were collected from aircraft flight manuals. These data were used to develop methods for predicting aircraft fuel consumption as a function of the aircraft flight state. The primary method developed for this report showed a difference from the flight manual reported fuel consumption of about 12% in cruise mode.					
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FUEL BURN MODELING OF TURBOPROP AIRCRAFT *

DISSERTATION

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PREFACE

This report is the final deliverable of an internship which is part of the fifth year curriculum of the faculty of Aerospace Engineering at the Delft University of Technology. The two authors had the privilege of conducting their internship at the John A. Volpe National Transportation Systems Center. There they worked in the Environmental Measurement and Modeling Division. The main assignment consisted of finding a method to model the fuel burn of turboprop aircraft flying over America's national parks. To do this the authors first had to get familiarized with the Aviation Environmental Design Tool (AEDT), which is a model capable of calculating the noise and fuel burn emissions of aircraft. This was done by validating fuel burn data of twelve commercial jets. Next the main assignment was conducted. Fuel flow data was gathered and analyzed in order to come up with a method that can accurately model fuel burn of national park flights. Both the familiarization with AEDT and the fuel burn modeling are described in this report.

The authors would like to thank Dr. A. Choudry for giving the authors the opportunity of doing their internship abroad at the renowned John A. Volpe Center. The authors also would like to thank D. Senzig from the Volpe Center for guiding them through the process and supporting them wherever needed.

Cambridge, MA, February 2, 2010

J.E. Geudens & K. Wils

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ABSTRACT

The Aviation Environmental Design Tool is being developed by the Federal Aviation Authority to assess aircraft noise and emissions. This capability is used to support domestic and global air transportation policy makers. However, in its current state AEDT is not capable of accurately modeling fuel burn of turbopropeller aircraft that fly at the national parks of the United States. The goal of this paper is the development of a method to calculate the fuel flow of these turboprop aircraft. The proposed method is developed using publicly available pilot information manual data from various aircraft manufacturers. It uses aircraft weight, pressure altitude and true airspeed to predict the fuel flow during cruise with a maximum error of 12% with respect to fuel flow values listed in the pilot information manual. It is recommended that the method is validated using in-flight fuel flow measurements. When implemented in AEDT the proposed method can be used to assess the environmental impact of turbopropeller aircraft flying at the U.S. national parks and thereby support policy making .

INTRODUCTION

Over the last years, the burn of fossil fuels has remained a much debated subject and new agreements are currently being made on the production of greenhouse gasses¹. In America, the Clean Air Act was drawn up and revised in 1990 as a federal law to improve the air quality by regulating the emission of air pollutants². In order to allow policy makers to set the correct limitations to these emissions, a model that can accurately simulate and predict the emissions of aircraft is required.

A fair amount of research has already been done on how to model the fuel burn of aircraft, especially fuel burn during cruise flight. However there are still several flight regimes which are not yet covered. An example of these are low speed, low altitude flights.

To model fuel burn, a combination of two different models has been used over the years by the Department of Transportation (DOT). These two models are Eurocontrols' Base of Aircraft DATA (BADA) and SAE1845. They are combined in the Federal Aviation Administrations' main aviation environmental tool called the Aviation Environmental Design Tool (AEDT). This model is the DOT's next-gen model which combines the acoustics of the aircraft together with its emissions and fuel consumption in one single model where in the past these were calculated separately (Senzig et al., 2009).

The goal of this paper is the development of a method to calculate the fuel flow of turboprop aircraft flying at national parks in the United States. It is investigated if there is a general relation between parameters which are readily available in AEDT (i.e. pressure altitude, thrust, weight, airspeed etc..) and the fuel flow of a turboprop thus allowing for the fuel burn to be predicted using a specific equation.

In the 'Method' section the workflow used to obtain the proposed fuel flow equations is explained. In addition the manner in which the current capability of AEDT to model fuel flow of national park flights is assessed, is given. The next section, 'Results', states the fuel flow equations obtained using the explained method. Also the fuel flow calculation results of those equations are given both in tabular and in graphical form. Then the presented results are reviewed and analyzed in the 'Discussion' section. Resulting conclusions are also given in this section. Finally, in the last section recommendations for further research are stated.

¹ United Nations Framework Convention on Climate Change (UNFCCC), 2009, Copenhagen, Denmark, URL: <http://unfccc.int/2860.php> [Last accessed on 26 January 2010]

² U.S. Environmental Protection Agency (EPA), "Understanding the Clean Air Act," 2008, URL: <http://www.epa.gov/air/caa/peg/working.html> [Last accessed on 16 December 2009]

METHOD

To obtain a model to determine the fuel burn of turboprop aircraft different methods are available. The first method is to base the model on in-flight fuel flow measurement data. The second method involves using performance tables containing fuel flow data which are often provided in the pilot information manual (PIM) of aircraft. In general the in-flight fuel flow measurement data is more accurate as each segment of the flight can be catalogued. This is not the case for the performance tables in the flight information manuals as usually only different cruise settings are given and nothing is mentioned on take-off, landing, climb and descent conditions. The optimal case would be when both methods are available so that one could be used to check the validity of the other.

At the time of this writing the authors did not have any access to in-flight fuel flow measurements and therefore this model is completely based on fuel flow data found in pilot information manuals. As a consequence the model proposed in this paper is limited to the cruise phase.

The proposed method will be used to model the fuel burn of turboprop aircraft flying over national parks. As these aircraft fly on low altitudes and because from this flight level on the BADA model is used³, only data points up to 16,000 feet Above Mean Sea Level (AMSL) are considered. Furthermore national park flights typically operate below or equal to 60% of total SHP available (FAA, 2000).

Performance data found in the pilot information manuals of the following aircraft is used to build and test the model on⁴:

- Beech 1900D Airliner
- Beech King Air A100
- Beechcraft King Air C90
- Beech Super King Air 300
- Pilatus PC-12
- Piper PA-42 Cheyenne III
- Socata (Group Aerospatiale) TBM700-A

An overview of the detailed specifications of each of the listed turboprop aircraft can be found in Appendix A⁵. In addition an example of how performance tables are presented in a PIM is given in Appendix B.

From the performance tables in the PIMs the following parameters are abstracted: torque, fuel flow, RPM, true airspeed (KTAS), pressure altitude and weight. Note that only parameters that are available in AEDT are extracted from the performance tables. For example, the inlet outside air temperature (IOAT) is available in the PIM, however IOAT is not implemented in AEDT and therefore this parameter is not used in the proposed fuel flow calculation method. Exceptions on this are

³ Actually BADA starts at 10,000ft AFE (Above Field Elevation). Since most airports in the United States have an elevation below 6,000ft AMSL it is taken that BADA starts at 16,000ft AMSL (Dinges, 2008).

⁴ Three more PIMs are available to the authors however due to the nature of the performance data (no weight variance given or indicated instead of true airspeed stated), these could not be used to develop the model with. Also it should be noted that the TBM700-A almost has no data points under 60% of maximum SHP. Therefore it is only used to test the accuracy of the method on the full SHP range of its data points (see Appendix G).

⁵ Note that all the aircraft used to generate the equations use engines of the Pratt & Whitney PT6A family.

torque and RPM. These are not available in AEDT, but they are extracted to be able to calculate SHP and eventually propeller thrust for each of the data points. For sake of simplicity only standard atmospheric conditions are considered. This means that only data points with ISA temperatures are used.

In addition to the parameters found in the pilot information manuals, shaft horse power (SHP) and propeller thrust⁶ are calculated for each data point and added to the data set. To calculate the horsepower the following formula was used:

$$SHP = \frac{RPM \times Torque \times 2\pi}{33000} \quad (1)$$

To calculate the propeller thrust a map interpolator is used which was provided by Hartzell Propeller Inc., a propeller manufacturing company (Hartzell, 1992). To output the propeller thrust for each data point Hartzell's map interpolator requires airspeed, pressure altitude, propeller RPM and SHP as inputs. In addition it uses input map files that are propeller type specific. These map files are provided by Hartzell (Hartzell, 1992) for each of the tested aircraft⁷.

Next for each of the aircraft, the various parameters are plotted against the fuel flow to investigate the nature of their influence on the fuel flow. Using the observed relation of the various parameters on fuel flow an equation to predict the fuel flow can be constructed. However it has to be kept in mind that at each data point obtained from the pilot information manuals more than one parameter varies at a time. In other words the direct effect of a certain parameter on the fuel flow cannot be directly established from the available data. Therefore different functions of each parameter are tested in the fuel flow equation. In general the different fuel flow equations tested are of the form:

$$FF = c_1 \cdot P_1 + c_2 \cdot P_1^2 + c_3 \cdot P_2 + c_4 \cdot P_2^2 + \dots + c_n \cdot P_n + c_{n+1} \cdot P_n^2 \quad (2)$$

Where P_1 - P_n are the various parameters (weight, KTAS,...) for each data point. For each of the tested fuel flow equations coefficients c_1 - c_n are aircraft specific. These are obtained using a statistical package named *Statistica 9* (Statsoft, 2009). In *Statistica* a non-linear least squares regression analysis is performed on the data points of each aircraft to determine the regression coefficients for the equations. The analysis uses the Levenberg-Marquardt estimation method with a convergence criterion of 10^{-6} and parameter start values of 0.1.

The last step is to test the accuracy of the different fuel flow equations and evolve to one which can accurately model the fuel flow of each of the aircraft mentioned before. This is done by plugging the regression coefficients generated by *Statistica* into the equation together with the parameter values for each data point and comparing the resulting fuel flow with the values stated in the PIM. Note that the power regime of the flights above the national parks is defined as $\leq 60\%$ of maximum SHP (FAA, 2000). Since the model will be primarily used for these type of flights the equations are tested only on data points which fall into the stated power regime⁸.

⁶ Note that propeller thrust and not total thrust is added. To obtain total thrust from propeller thrust, the thrust originating from the jet exhaust of the turboprop engine should be added. In general this is approximately 5-10% of propeller thrust (El-Sayed, 2008).

⁷ Each of the tested aircraft has a version that uses a Hartzell propeller.

⁸ Note that the data encompassing the whole SHP range (not only the tested $\leq 60\%$ max. SHP range) is used to generate the regression coefficients.

By comparing the predicted fuel flow with the 'real' fuel flow for a specific equation it is analysed which parts of the flight envelope are (un)accurately modeled and whether this can be improved by changing the function of the different parameters. By comparing the fuel flow prediction results of the tested equations with each other, the equation that most accurately models the fuel flow is found. Most accurately here denotes those equations that are not only capable of predicting the correct fuel flow on average but that are also able to capture data spread and thus outliers.

AEDT review method

It is also investigated how capable the current build of AEDT is of modeling national park flights. To date AEDT uses the equations and coefficients of Eurocontrol's Base of Aircraft DATA (BADA) to predict fuel flow (Dinges, 2008). BADA uses equation (3), with thrust specific fuel flow coefficients C_{f1} and C_{f2} to calculate the thrust specific fuel consumption (TSFC) for turboprop aircraft. By multiplying the obtained TSFC with thrust and a cruise fuel flow correction factor (C_{fcr}) the cruise fuel flow can be calculated for each data point (equation (4)) (Nuic, 2009).

$$TSFC = C_{f1} \cdot \frac{V_{TAS}}{1000} - \frac{C_{f1}}{C_{f2}} \cdot \frac{V_{TAS}^2}{1000} \quad (3)$$

$$FF_{cr} = TSFC \cdot Thrust \cdot C_{fcr} \quad (4)$$

The thrust specific fuel flow coefficients for the aircraft listed in the 'Method' section are currently only available for the Beechcraft King Air C90 and the Piper PA-42 Cheyenne III. Aircraft for which the fuel flow coefficients are not listed in BADA (version 3.7; Eurocontrol, 2009) use the coefficients of a similar aircraft. These synonym aircraft are defined within BADA. The specific fuel flow coefficients for each of the tested aircraft can be found in Appendix C.

For each aircraft, equation (3) and (4) are used with the fuel flow coefficients from BADA 3.7, the true airspeed from the PIM and the propeller thrust obtained using the map interpolator to calculate the fuel flow for each data point.

In addition to the aforementioned test, the regression method explained in the previous section is used on BADA equation (3) to check whether the equation itself is capable of accurately predicting the fuel flow if the specific fuel flow coefficients are adapted. In order to come up with new values for the specific fuel flow coefficients for each aircraft, equation (3) is put in the regression method of *Statistica* together with the PIM data. The coefficient values thus obtained are then again used with equation (3) and (4)⁹ to calculate the fuel flow for each of the PIM data points. Coefficients for each aircraft can be found in Appendix C.

Both fuel flow calculated using the original BADA coefficients and using the new values of the coefficients are then compared to the fuel flow listed in the PIM to evaluate AEDT's current capability to model fuel flow of national park flights.

⁹ Note that here it is assumed that C_{fcr} is 1 in equation 4. This is because the data used to calculate the new values for C_{f1} and C_{f2} only cruise phase data is used. Therefore no correction for the cruise needs to be made.

RESULTS

In this section two equations that are obtained using the workflow stated in the ‘Method’ section are given. Only these two are presented and discussed since these two outperform any other of the equations tested. As mentioned earlier these equations are the ones that are not only capable of most accurately predicting the correct fuel flow on average but that are also able to capture data spread and thus outliers. A full list of the tested equations can be found in Appendix D.

In addition to the equations, the fuel flow prediction results of both equations and those of the BADA equation are given in this section. Note that the BADA fuel flow equation using the original BADA coefficients will be referred to as $BADA_{orig}$. $BADA_{new}$ denotes the BADA fuel flow equation that uses the specific fuel flow coefficients that are obtained by the regression analysis. Finally graphs depicting the fuel flow prediction using the different equations are given in this section.

The two new fuel flow equations are of the following form:

$$FF_9 = a_1 \cdot W + a_2 \cdot h + a_3 \cdot KTAS + a_4 \cdot KTAS^2 + a_5 \cdot T \quad (5)$$

$$FF_{21} = b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot h + b_4 \cdot h^2 + b_5 \cdot KTAS \quad (6)$$

Where W is the aircraft weight in pounds, h is pressure altitude in feet, $KTAS$ is true airspeed in knots and T is thrust in pounds. Coefficients a_1 - a_5 and b_1 - b_5 , which are found using the regression analysis on the two equations, can be found in Appendix C for each tested aircraft.

Note that there is a difference in the manner fuel flow is obtained between the two new fuel flow equations and the BADA equations (equation (3) and (4)). The BADA method first calculates the TSFC and then multiplies that by thrust and a cruise flow correction factor to yield the fuel flow. Equations (5) and (6) are not based on TSFC and calculate the fuel flow directly.

In Table I-IV the fuel flow calculation errors with respect to the ‘real’ fuel flow listed in the PIMs are given for the different equations. Note that Table I-IV only compromise the results of the data points that reflect national park flights, thus data points with SHP \leq 60% of maximum SHP and the pressure altitude \leq 16,000feet AMSL. The greyed out entries in Table I denote those aircraft who use synonym aircraft within BADA.

In Table I-IV MIN and MAX respectively denote the minimum and maximum percentage error for the used equation. The entry AVG denotes the average error of all the considered data points and AVG(ABS) is the average of the absolute error of all the data points.

TABLE I **$BADA_{orig}$ fuel flow calculation results**

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-44.3%	58.4%	11.0%	-18.0%	-24.7%	-62.0%
MAX	-15.3%	119.2%	46.5%	12.7%	22.8%	38.3%
AVG	-32.6%	95.5%	24.2%	-1.2%	-1.4%	-26.6%
AVG(ABS)	32.6%	95.5%	24.2%	7.2%	10.7%	37.4%

TABLE II $BADA_{new}$ fuel flow calculation results

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-12.8%	-14.6%	-8.1%	-11.6%	-20.1%	-35.8%
MAX	14.0%	8.3%	12.6%	11.0%	19.0%	32.5%
AVG	-0.1%	0.8%	-0.5%	1.5%	0.8%	0.1%
AVG(ABS)	5.5%	6.2%	5.1%	5.5%	9.1%	15.8%

TABLE III FF_9 fuel flow calculation results

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-6.4%	-3.8%	-1.8%	-2.3%	-3.5%	-11.3%
MAX	2.7%	2.4%	1.4%	1.6%	2.8%	9.5%
AVG	-0.5%	-0.4%	0.0%	0.0%	0.0%	-2.4%
AVG(ABS)	1.1%	1.4%	0.6%	1.0%	1.3%	5.1%

TABLE IV FF_{21} fuel flow calculation results

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-10.6%	-5.2%	-6.7%	-4.2%	-6.6%	-7.3%
MAX	8.1%	1.8%	5.1%	2.4%	5.3%	11.7%
AVG	-0.5%	-0.8%	0.0%	-0.6%	0.1%	-0.8%
AVG(ABS)	3.5%	1.9%	3.0%	1.5%	2.6%	4.0%

Note that the average error over all the data points approaches zero for equations $BADA_{new}$, FF_9 and FF_{21} . This is explained by the fact that the equations are tested on the data that is used to generate the regression coefficients. More significant are thus AVG(ABS) and the MIN and MAX values.

Figures 1 till 4 show the fuel flow prediction results graphically for the Beech 1900D Airliner and the Pilatus PC-12. In both figures fuel flow is plotted against the thrust. In all figures FF denotes the fuel flow values that are listed in the PIMs. The variation in these PIM fuel flow values is caused by differences in altitude and weight. Fuel flow graphs for the other aircraft can be found in Appendix E.

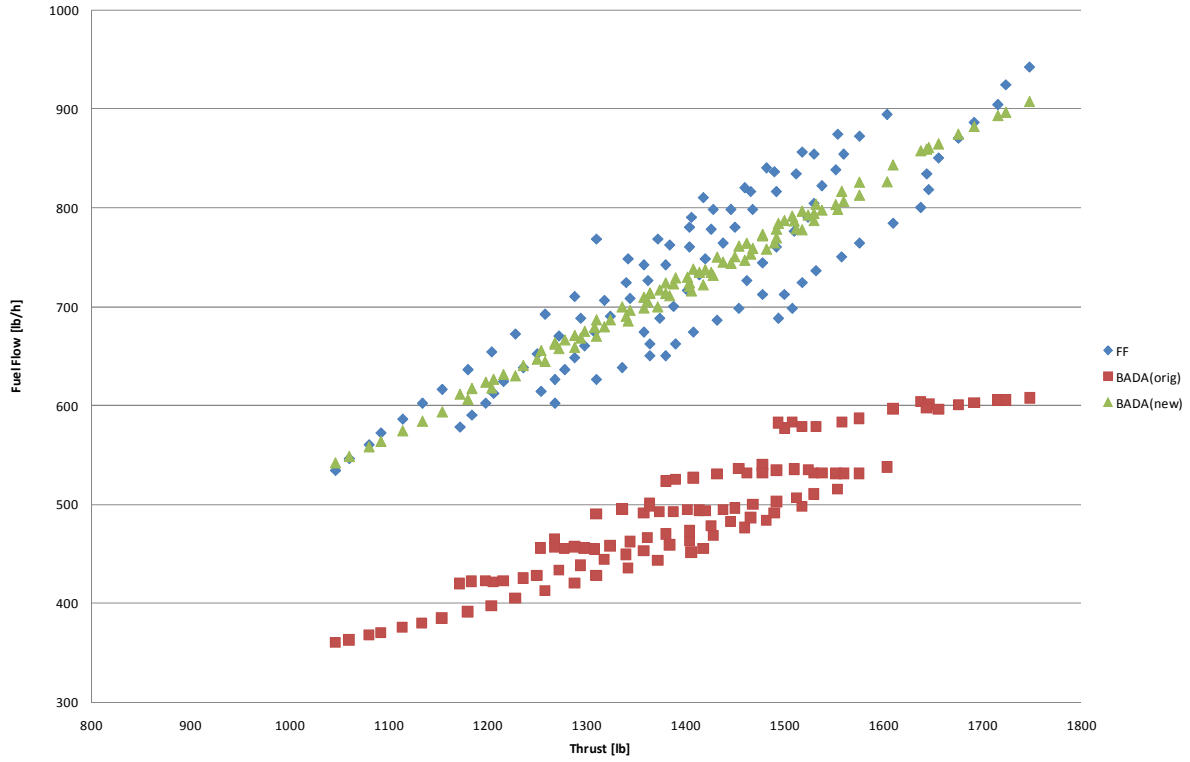


Figure 1: 1900D fuel flow calculation results with BADA equations

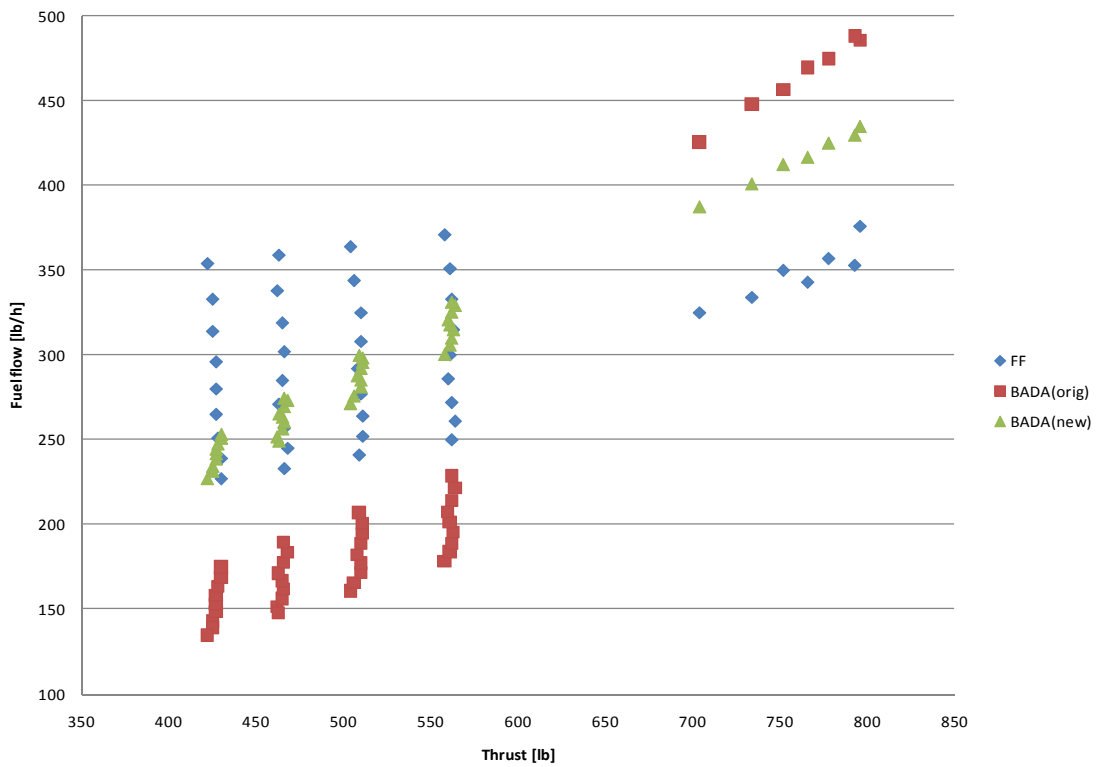


Figure 2: PC-12 fuel flow calculation results with BADA equations

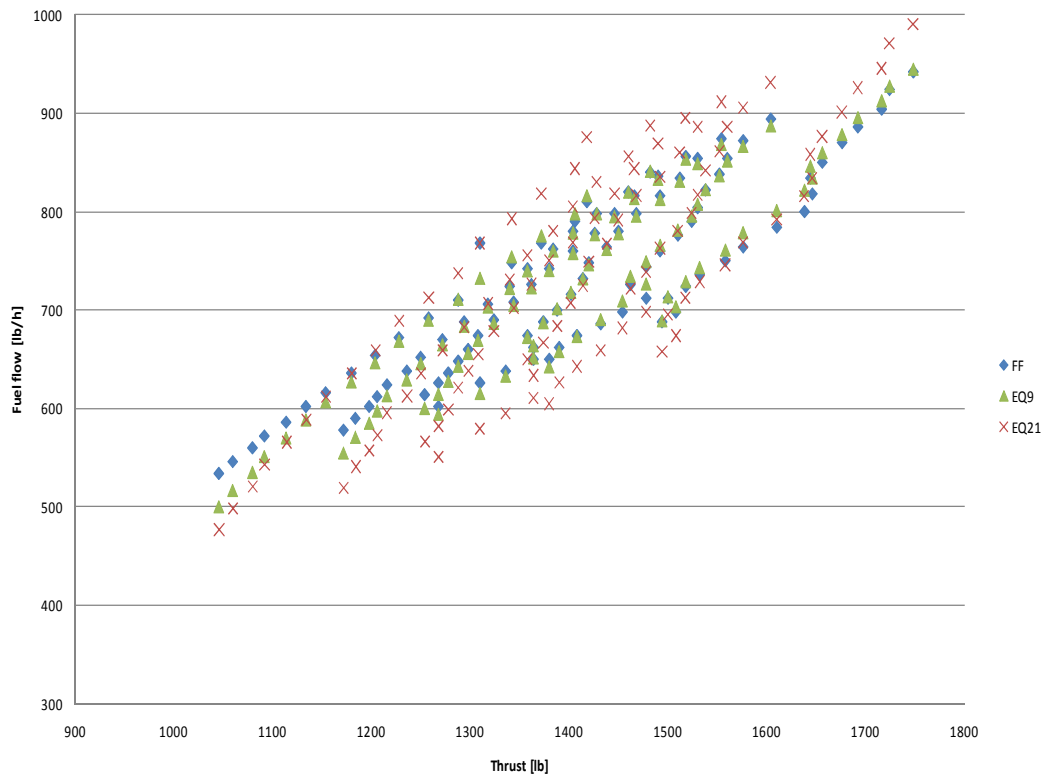


Figure 3: 1900D fuel flow calculation results with FF_9 and FF_{21}

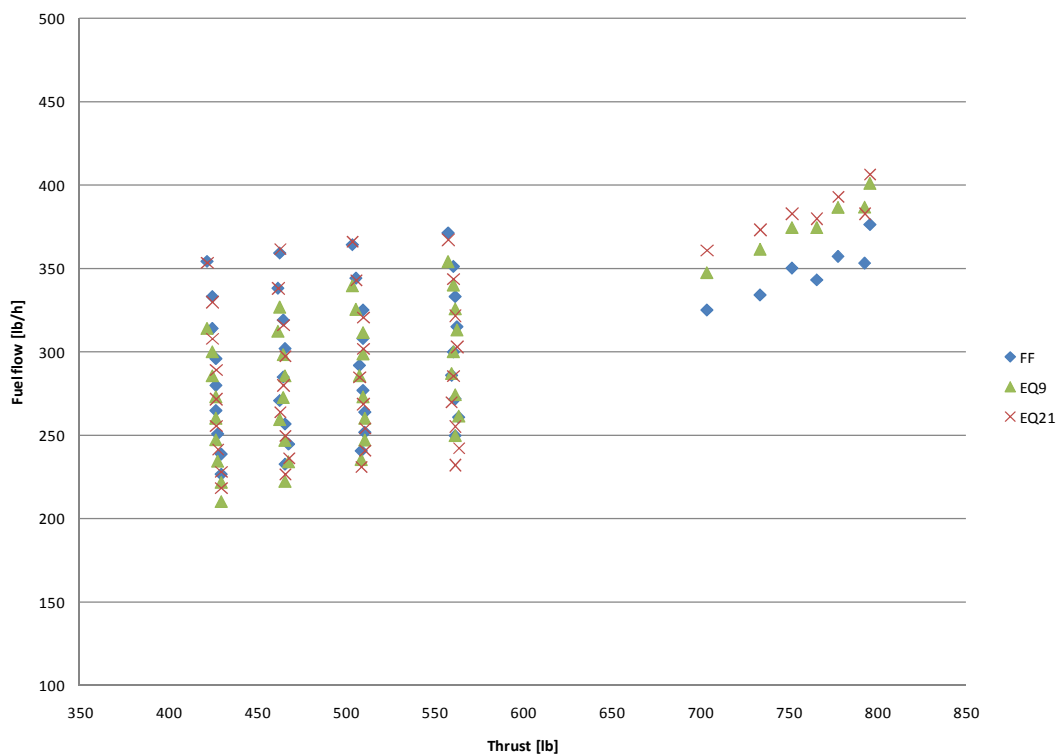


Figure 4a: PC-12 fuel flow calculation results with with FF_9 and FF_{21}

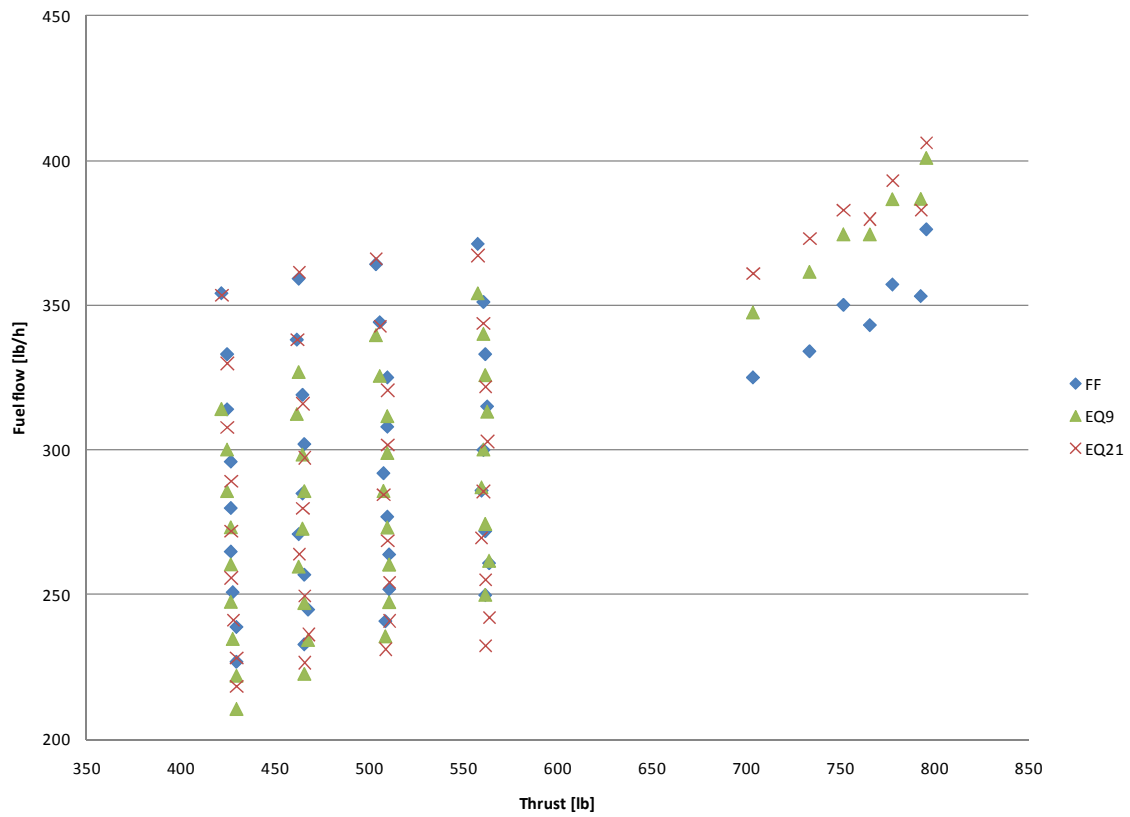


Figure 4b: PC-12 fuel flow calculation results with FF_9 and FF_{21} (different scale)

DISCUSSION

In this section the results as presented in the previous section are discussed and analyzed. In addition conclusions are given in this section. First the results obtained with the BADA equations are treated. Then the influence of the various parameters on the fuel flow is briefly dealt with. Next, the results obtained with FF_9 and FF_{21} are discussed. Finally the implementation in AEDT and the limitations of the proposed equation are given.

BADA 3.7 results

In Table I it can be seen that the two aircraft which have original BADA coefficients (C90, PA-42) have the best accuracy when using the $BADA_{orig}$ coefficients¹⁰. When synonym aircraft are used, the BADA equation fails to model the fuel flow correctly. Therefore the use of synonym aircraft to model fuel flow should be avoided if possible. Note that even for the original aircraft $BADA_{orig}$ fails to capture the outliers. This can be seen in the Figures E.7 and E.9 of the PA-42 and C90.

In Table II and Figures 1 and 2 it can be seen that the $BADA_{new}$ equations, which have specific fuel flow coefficients based on the performance data in the PIMs, do a better job in estimating the fuel flow compared to $BADA_{orig}$. On average the absolute deviation lies between 5% and 16%. When comparing the results of the $BADA_{new}$ with $BADA_{orig}$ for the two aircraft which have original coefficients it can be concluded that $BADA_{new}$ outperforms $BADA_{orig}$ when only taking account of the percentage values as listed in Table II. However when looking at their figures (E.7 & E.9) in Appendix E it also becomes clear that $BADA_{new}$ is not as capable of capturing the spread in the data as $BADA_{orig}$. The average deviation remains reasonably low because the variance in the parameters of the data points is rather limited. When the spread of these parameters increases as is the case for the PC-12, the average deviation increases to 16%.

Thus it can be concluded that when the spread of the data points is increased, the accuracy of $BADA_{new}$ will become worse. Finally it can be concluded that an equation relying solely on thrust and true airspeed is not sufficient to model the fuel flow of turboprop aircraft flying at national parks. Therefore the influence of other parameters on fuel flow is investigated.

¹⁰ Note though that these results are obtained using the thrust as calculated with the Hartzell map interpolator. In Appendix F, the results when using the thrust obtained with BADA thrust equations (Nuic, 2009) are given. In Table F.II it can be observed that BADA fails to correctly calculate thrust (except for the 1900D).

Parameter influence

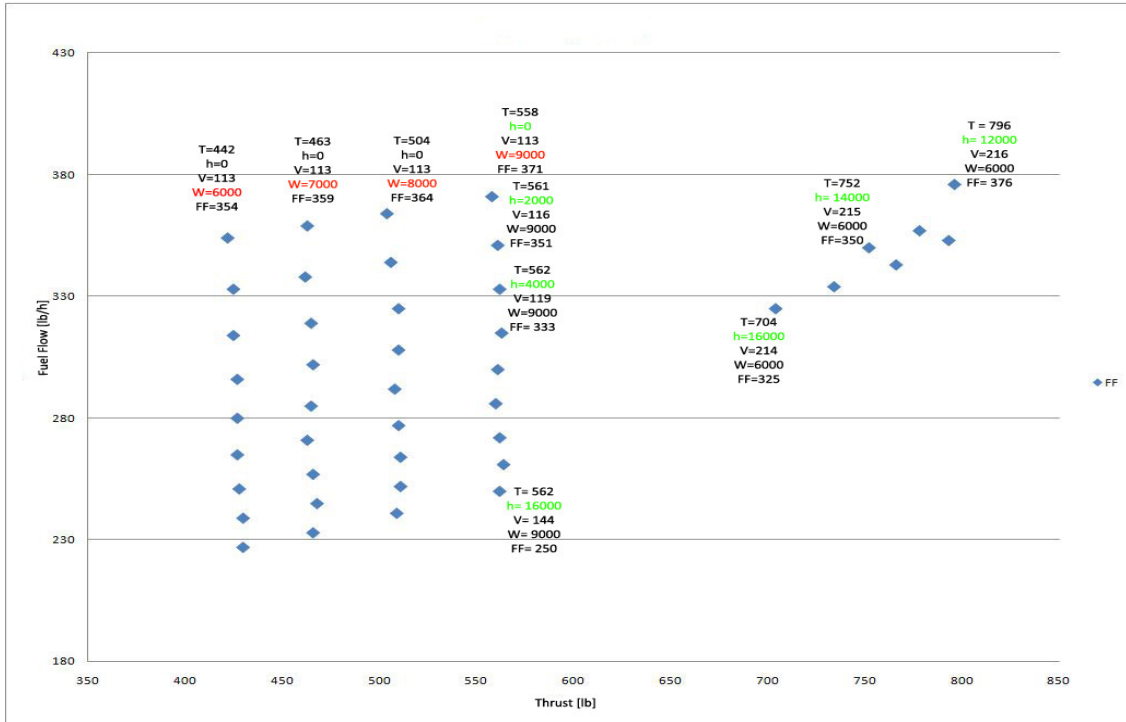


Figure 5: PC-12 fuel flow vs. thrust

In Figure 5 the fuel flow is plotted against the thrust for the PC-12 using the PIM data. In this figure the influence of certain parameters on the fuel flow can be seen. First the effect of the weight can be seen in the top left of the graph. Four data points with equal values for altitude and airspeed are highlighted. The points show that when weight increases also thrust and fuel flow increase and this can be modeled by means of a linear or quadratic function.

Next the effect of altitude can be observed in the top right corner of Figure 5. Here weight and KTAS (approximately) remain constant on three points. It can be seen that an increase in altitude leads to a decrease in fuel flow and thrust. This relation can also be modeled by means of a linear or quadratic function. The effect of KTAS is not explicitly present in Figure 5. However when looking at the middle which are positioned vertically above each other, one can deduce while taking into account the effect altitude that an increase in KTAS will result in an increase in thrust. The increase in KTAS cancels the effect of increasing altitude on thrust as now the points are situated approximately above each other. The direct effect of KTAS on fuel flow is not explicitly visible in Figure 5. From the graph also no explicit relation between thrust and fuel flow can be established.

Similar patterns for the parameters weight, KTAS and altitude are observed looking at the plots of the other aircraft. Therefore different equations with linear and quadratic terms of the various parameters are tested.

Fuel flow equation results

When looking at Table III and IV it can be observed that both FF_9 and FF_{21} outperform $BADA_{orig}$ and $BADA_{new}$ in terms of MIN, MAX and AVG(ABS) values. They both succeed in keeping the minimum and maximum error below 12% for all the aircraft. FF_9 has the best overall performance since its MIN, MAX and AVG(ABS) values are lower than those of FF_{21} except for the PC-12. This can be related to the fact that FF_{21} succeeds better in capturing the data points when they become

dispersed as can be observed in Figure 4. The reason for this is that in FF_{21} thrust is omitted as a parameter.

When there are points which have equal thrust but a range of fuel flow values, like on the left side of Figure 4, an equation mainly based on thrust fails to reproduce the vertical spacing between the points. This can also be seen in Figure 2 where the listed equations are solely based on thrust and KTAS. When altitude is added as in FF_9 , the data points are expanded further and they approach the real values better. Omitting thrust from the equation, which is the case for FF_{21} , makes the equation better capable of mapping the modeled values to the real fuel flow values for points of equal thrust. As the effect of thrust on the fuel flow is composed out of the effects of weight, altitude and KTAS, thrust can be omitted from the equation.

As FF_9 is better in overall, but FF_{21} is better at capturing the dispersion in data points of the PC-12 more dispersed data points are required for the other aircraft to be able to further analyze which one of the two equations should be used¹¹. However, it can already be concluded that both FF_9 and FF_{21} are better capable of modeling the cruise fuel flow of turboprops than the BADA equations. And by looking at the present results the authors propose that FF_{21} is used.

Implementation & limitations

As both the equations FF_9 and FF_{21} use parameters which are readily available in AEDT (weight, altitude, KTAS and thrust) they can be directly implemented in AEDT. However as mentioned in footnote 10, when using FF_9 it must be ensured that the thrust which is calculated by BADA 3.7 is not used. Instead a new thrust calculation method must be implemented in AEDT to yield good fuel flow results. A possible alternative to the BADA thrust calculation is the one provided by Hartzell Propeller Inc.

To be able to use FF_9 and FF_{21} for aircraft which are not mentioned in this paper, cruise performance data points are required. More specifically data points containing pressure altitude, weight, KTAS, thrust and fuel flow. Using these points the regression coefficients for the aircraft can be calculated using the regression analysis described in the 'Method' section.

As the spread of data points directly influences the values of the regression coefficients, one must make sure that the used data is as dispersed as possible. Therefore also care should be taken when directly using the coefficients for FF_9 and FF_{21} as presented in this paper, since the data points used to determine these are limited both in number and in spread. The ideal data set to generate the coefficients consist of data points in which only one parameter varies at a time. In addition the data set should also represent an as large as possible part of the cruise flight envelope of the national park flights. In other words, the more various the data set used to generate the coefficients, the more generally the coefficients will yield good fuel flow results. In the ideal case, fuel flow data originating from in-flight measurements is used instead of data from PIMs.

However, note that the best results will still be obtained when generating different sets of coefficients for different parts of the flight envelope. Therefore, if it is known that only the cruise fuel flow of data points having an SHP between 30 and 60% of the maximum SHP will need to be modeled, using only data points in that range to generate the regression coefficients will yield the best modeling results.

¹¹ Both equations were also tested on the full SHP range and the results can be found in Appendix G. Both equations are still able to keep the deviations under 12%

Still, the authors are of the opinion that when using a complete data set as described above, the equations are capable of adapting themselves to the variety of data that comes with different areas of the cruise flight envelope. Thus yielding good fuel flow modeling results over the entire cruise flight envelope of national park flights. This can be partially observed in Figure 4. In addition when the regression coefficient for both equations are generated using data points encompassing either take-off, climb or descent conditions it is thought that the equations will be capable of modeling the fuel flow for that condition with a similar accuracy as the cruise condition. However before implementing any of the proposed equations into AEDT, it is strongly recommended that the results presented here are validated using in-flight fuel flow measurements.

In summary, this paper provides two methods to calculate the cruise fuel flow of turboprop aircraft flying under 16,000ft AMSL with an expected maximum error of approximately 12%. Thus enhancing AEDT's capability to model cruise fuel flow of flights over national parks. This method can be directly implemented in AEDT as it only uses parameters which are already available within AEDT. By following the workflow as described in the 'Method' section new aircraft can be added. However as noted before the nature of the data set used to generate regression coefficients is of utmost importance. As the use of a limited data set, as is the case in this paper, limits the applicability of the equations.

RECOMMENDATIONS

From the previous 'Discussion' a number of recommendations for future research are provided. As mentioned before, it is important that the proposed method is validated using in-flight fuel flow measurements. Next, the data set should be expanded (e.g. by in-flight measurement data) to encompass the entire cruise flight envelope for all listed aircraft, thus enabling to test whether FF_9 or FF_{21} yields the most accurate modeling results. A more complete data set in terms of flight envelope will also enable future researchers to analyze the effect of the various parameters on the fuel flow in more detail. This will allow a further refinement of the fuel flow equation. Also it is recommended that more aircraft (and engine types) are tested, both because the number of aircraft in this research is limited, and because the nature of the regression coefficients can then be analyzed. This can possibly result in a generic model, where the regression coefficients can be predicted using aircraft specifications.

APPENDICES

Appendix A Aircraft specifications

The information found in Table A.I is found in the PIM of the aircraft (Beech Aircraft Corporation, 2000, 1984, 1993 & 1976; Piper Aircraft Corporation, 1987; Pilatus Aircraft Ltd., 2005; Socata Groupe Aerospatial, 1990) .

TABLE A.I Aircraft specifications

Model	1900D	A100	B300	C90	PA-42	PC-12	TBM700-A
Manufacturer	Beech	Beech	Beech	Beech	Piper	Pilatus	Socata
1st operational year	1991	1972	1982	1971	1980	1994	1990
Engine type	PT6A-67D	PT6A-28	PT6A-60A	PT6A-21	PT6A-41	PT6A-67B	PT6A-64
# Engines	2	2	2	2	2	1	1
Engine rating [SHP]	1279	680	1050	550	720	1200	700
Nominal RPM	1700	2200	1700	2200	2000	1700	2000
MTOW [lb]	16950	11500	14000	9650	11200	9039	6579
SEW [lb]	10650	6797	8490	6488.7	6389	5439	4050
Fuel capacity [lb]	4484	3151	3614	2595	3768	2737	1949
W/S [lb/ft²]	54.7	41.1	46.2	32.8	38.22	32.5	34
W/P [lb/SHP]	6.6	8.5	6.7	8.8	7.8	9.0	9.4
Max. operating speed [KCAS]	248	226	260	208	246	240	270
# Data points							
<=16000ft AMSL	408	66	81	54	81	108	38
<=60% max. SHP & <=16000ft	101	25	27	21	27	43	1

Appendix B Sample PIM performance table

The following PIM performance table is obtained from Beech Aircraft Corporation (2000).

Beech 1900D Airliner
Section IV - Flight Planning Data

Raytheon Aircraft

HIGH SPEED CRUISE POWER

1550 RPM

ISA

WEIGHT →			16,500 LBS/7484 KG						15,000 LBS/6804 KG						14,000 LBS/6350 KG					
PRESSURE ALTITUDE FEET	IOAT °C	OAT °C	TORQUE	FUEL FLOW	TOTAL FUEL	IAS	TAS	TORQUE	FUEL FLOW	TOTAL FUEL	IAS	TAS	TORQUE	FUEL FLOW	TOTAL FUEL	IAS	TAS			
			PER ENG FT-LBS	PER ENG LBS/HR	FLOW LBS/HR			PER ENG FT-LBS	PER ENG LBS/HR	FLOW LBS/HR			PER ENG FT-LBS	PER ENG LBS/HR	FLOW LBS/HR					
SL	21	15	3731	659	1318	248	250	3690	655	1310	248	250	3685	652	1304	248	250			
1000	19	13	3750	652	1304	248	253	3741	651	1302	248	253	3716	648	1296	248	253			
2000	17	11	3750	642	1284	246	256	3750	642	1284	247	257	3750	642	1284	248	257			
3000	15	9	3750	634	1268	245	258	3750	633	1268	246	259	3750	633	1266	247	260			
4000	13	7	3750	625	1250	244	260	3750	625	1250	245	261	3750	625	1250	246	262			
5000	11	5	3750	616	1232	243	263	3750	616	1232	244	264	3750	616	1232	244	265			
6000	10	3	3750	609	1218	241	265	3750	609	1218	243	266	3750	609	1218	243	267			
7000	8	1	3750	601	1202	240	268	3750	601	1202	241	269	3750	601	1202	242	270			
8000	6	-1	3750	594	1188	239	270	3750	594	1188	240	272	3750	594	1188	241	272			
9000	4	-3	3750	586	1172	238	273	3750	586	1172	239	274	3750	586	1172	240	275			
10,000	2	-5	3750	579	1158	236	276	3750	579	1158	236	277	3750	579	1158	236	278			
11,000	0	-7	3750	574	1148	235	278	3750	573	1146	236	280	3750	573	1146	237	280			
12,000	-1	-9	3750	568	1136	234	281	3750	568	1136	235	282	3750	568	1136	236	283			
13,000	-3	-11	3679	555	1110	231	282	3683	555	1110	232	283	3685	556	1112	233	284			
14,000	-5	-13	3577	539	1078	227	281	3581	539	1078	229	283	3583	539	1078	229	284			
15,000	-7	-15	3475	523	1046	223	281	3479	523	1046	225	283	3481	523	1046	226	284			
16,000	-9	-17	3369	507	1014	219	281	3374	507	1014	221	283	3377	507	1014	222	284			
17,000	-11	-19	3263	491	982	216	280	3266	491	982	217	282	3272	491	982	218	284			
18,000	-13	-21	3157	475	950	212	279	3163	475	950	213	282	3168	476	952	214	283			
19,000	-15	-23	3051	459	918	207	278	3057	460	920	209	281	3060	460	920	211	283			
20,000	-18	-25	2944	444	888	203	277	2950	444	888	205	280	2954	444	888	207	282			
21,000	-20	-27	2842	429	858	199	276	2849	429	858	201	279	2853	430	880	203	281			
22,000	-22	-29	2740	414	828	195	275	2747	415	830	197	278	2751	415	830	199	280			
23,000	-24	-31	2643	400	800	190	273	2651	401	802	193	277	2655	401	802	195	279			
24,000	-26	-33	2547	386	772	186	272	2555	387	774	189	276	2559	387	774	191	278			
25,000	-28	-35	2449	372	744	181	270	2458	373	746	185	274	2463	373	746	186	277			

BT058997

Appendix C Equation regression coefficients

Note that the aircraft which are greyed out in Table C.I use coefficients of synonym aircraft.

$$\text{BADA equations: } TSFC = C_{f1} \cdot \frac{V_{TAS}}{1000} - \frac{C_{f1}}{C_{f2}} \cdot \frac{V_{TAS}^2}{1000} \quad \& \quad FF_{cr} = TSFC \cdot Thrust \cdot C_{fr}$$

$$FF_9 \ \& \ FF_{21}: \quad FF_9 = a_1 \cdot W + a_2 \cdot h + a_3 \cdot KTAS + a_4 \cdot KTAS^2 + a_5 \cdot T$$

$$FF_{21} = b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot h + b_4 \cdot h^2 + b_5 \cdot KTAS$$

TABLE C.I *BADA_{orig}* coefficients

	1900D	A100	B300	C90	PA-42	PC-12
<i>Synonym AC</i>	JS31	D228	PA-42	-	-	C90
C_{f1} [kg/min/kN/knot]	3.00	5.48	5.30	4.80	5.30	4.80
C_{f2} [knots]	1,000,000	1,000,000	2,600	5,000,000	2,600	5,000,000
C_{fr} [-]	1	1.61	1	1	1	1

TABLE C.II *BADA_{new}* coefficients

	1900D	A100	B300	C90	PA-42	PC-12
C_{f1} [kg/min/kN/knot]	15.75	14.74	12.51	18.82	18.06	23.84
C_{f2} [knots]	226.4	246.4	259.3	189.9	217.6	171.0
C_{fr} [-]	1	1	1	1	1	1

TABLE C.III *FF₉* coefficients

	1900D	A100	B300	C90	PA-42	PC-12	TBM-700
a_1 [(lb/h)/lb]	-3.81E-04	3.43E-03	-1.25E-06	5.30E-04	1.24E-03	7.48E-03	5.31E-03
a_2 [(lb/h)/ft]	-1.49E-02	-1.05E-02	-1.08E-02	-8.62E-03	-1.50E-02	-9.71E-03	-1.31E-02
a_3 [(lb/h)/knot]	2.15	0.48	1.13	1.42	2.17	2.11	2.09
a_4 [(lb/h)/knot ²]	4.96E-04	7.49E-03	2.62E-03	1.62E-03	8.50E-04	-1.82E-03	-1.85E-04
a_5 [(lb/h)/lb]	0.290	0.168	0.266	0.219	0.208	0.129	0.037

TABLE C.IV *FF₂₁* coefficients

	1900D	A100	B300	C90	PA-42	PC-12	TBM-700
a_1 [(lb/h)/lb]	-3.65E-02	-8.61E-02	-5.28E-02	-4.57E-02	-3.78E-02	3.12E-02	6.92E-03
a_2 [(lb/h)/lb ²]	1.53E-06	4.65E-06	2.36E-06	3.06E-06	2.53E-06	-1.77E-06	-1.09E-07
a_3 [(lb/h)/ft]	-3.18E-02	-1.67E-02	-2.36E-02	-1.60E-02	-2.51E-02	-1.51E-02	-1.58E-02
a_4 [(lb/h)/ft ²]	1.30E-07	1.16E-07	5.12E-08	1.69E-07	2.05E-07	1.72E-07	1.33E-07
a_5 [(lb/h)/knot]	5.98	5.16	5.30	3.86	4.39	2.04	2.18

Appendix D Equation list

In this appendix all the tested equations are listed. In the equations T denotes the thrust in pounds, SHP the shaft horse power, W the aircraft weight in pounds, $KTAS$ the airspeed in knots and h the pressure altitude AMSL in feet.

$$FF1 = c_1 \cdot W + c_2 \cdot T$$

$$FF2 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot T$$

$$FF3 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS^2 + c_4 \cdot T$$

$$FF4 = c_1 \cdot W + c_2 \cdot h^2 + c_3 \cdot KTAS + c_4 \cdot T$$

$$FF5 = c_1 \cdot h + c_2 \cdot KTAS + c_3 \cdot T$$

$$FF6 = c_1 \cdot W^2 + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot T$$

$$FF7 = c_1 \cdot W^4 + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot T$$

$$FF8 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot SHP$$

$$FF9 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot KTAS^2 + c_5 \cdot T$$

$$FF10 = c_1 \cdot W^2 + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot KTAS^2 + c_5 \cdot T$$

$$FF11 = c_1 \cdot W^2 + c_2 \cdot \frac{h}{T} + c_3 \cdot KTAS + c_4 \cdot KTAS^2 + c_5 \cdot T$$

$$FF12 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot T$$

$$FF13 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot T + c_4 \cdot T^2$$

$$FF15 = c_1 \cdot W + c_2 \cdot W^2 + c_3 \cdot h + c_4 \cdot T + c_5 \cdot T^2$$

$$FF16 = c_1 \cdot W + c_2 \cdot W^2 + c_3 \cdot h + c_4 \cdot h^2 + c_5 \cdot T + c_6 \cdot T^2$$

$$FF14 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot T^2$$

$$FF17 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS$$

$$FF18 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot KTAS + c_4 \cdot KTAS^2$$

$$FF19 = c_1 \cdot W + c_2 \cdot W^2 + c_3 \cdot h + c_4 \cdot KTAS$$

$$FF20 = c_1 \cdot W + c_2 \cdot W^2 + c_3 \cdot h + c_4 \cdot KTAS + c_5 \cdot KTAS^2$$

$$FF21 = c_1 \cdot W + c_2 \cdot W^2 + c_3 \cdot h + c_4 \cdot h^2 + c_5 \cdot KTAS$$

$$FF22 = c_1 \cdot W + c_2 \cdot h + c_3 \cdot h^2 + c_4 \cdot KTAS$$

Appendix E Fuel flow graphs

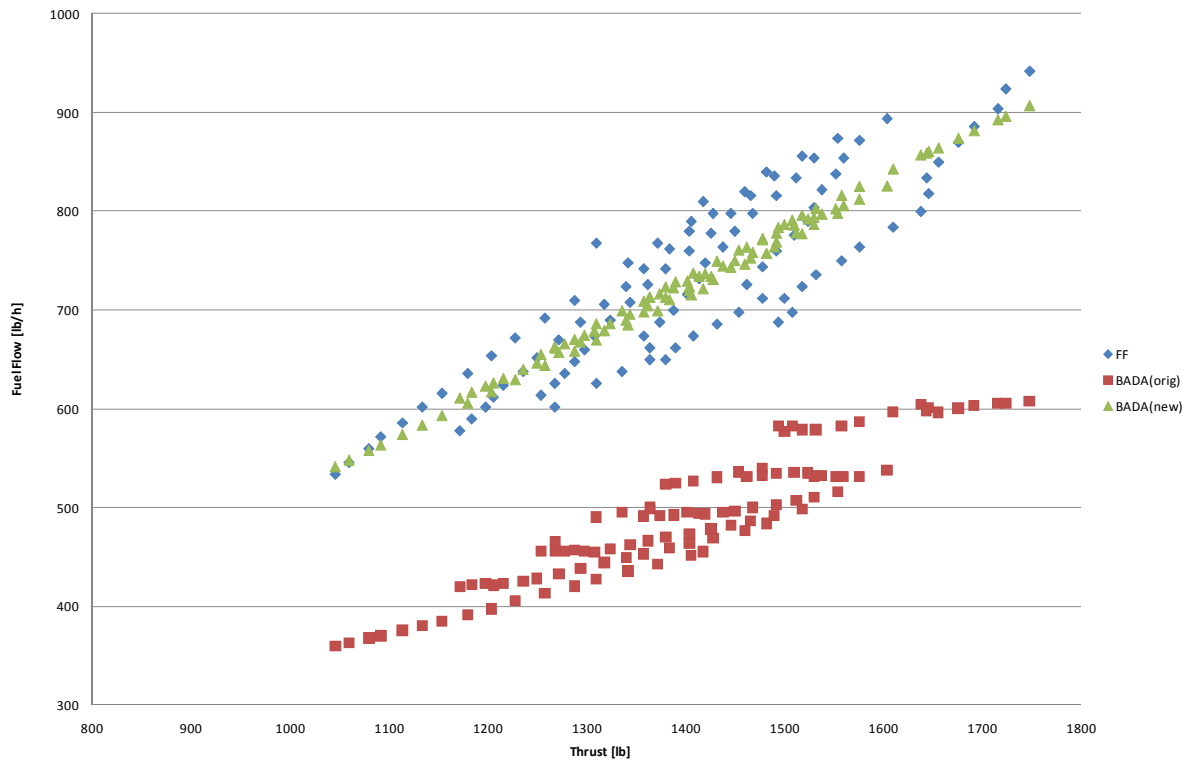


Figure E1: 1900D fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

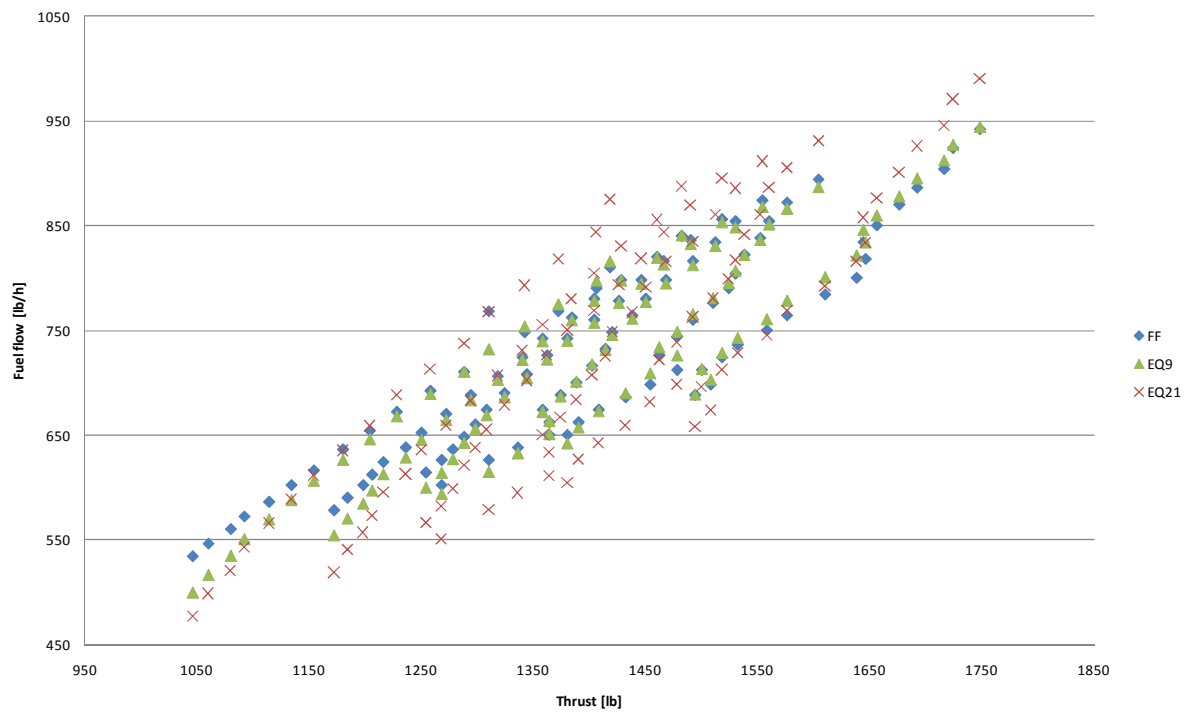


Figure E2: 1900D fuel flow calculation results with FF_9 and FF_{21}

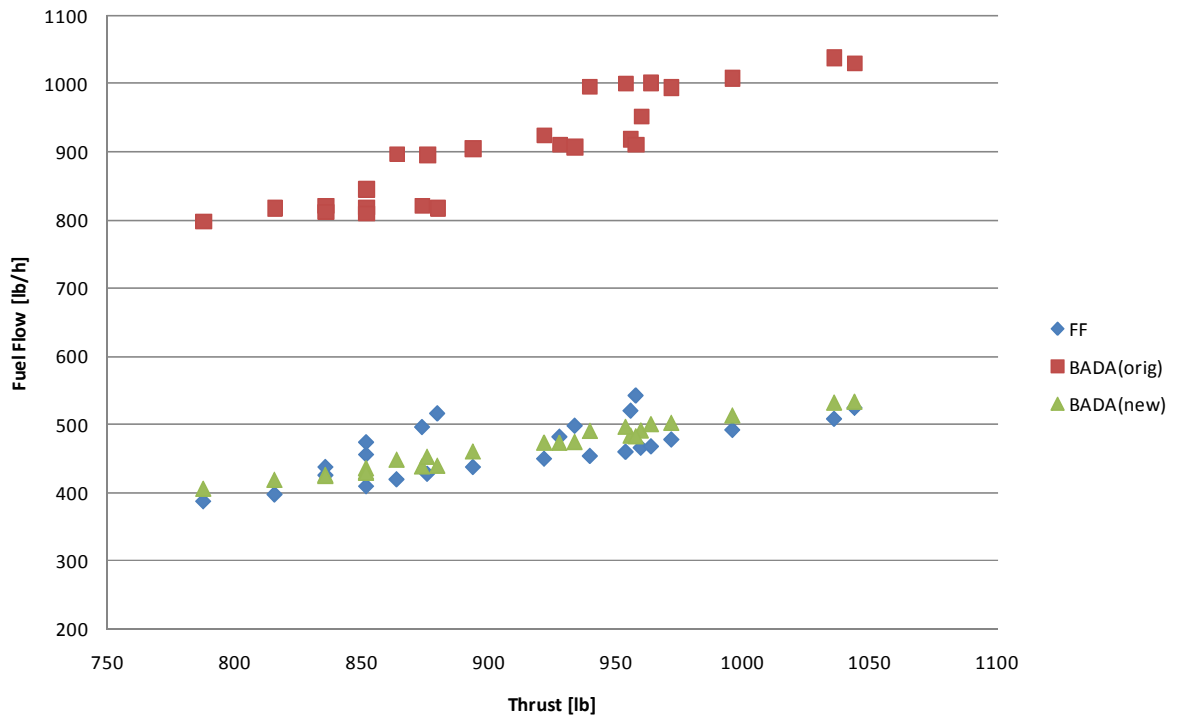


Figure E3: A100 fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

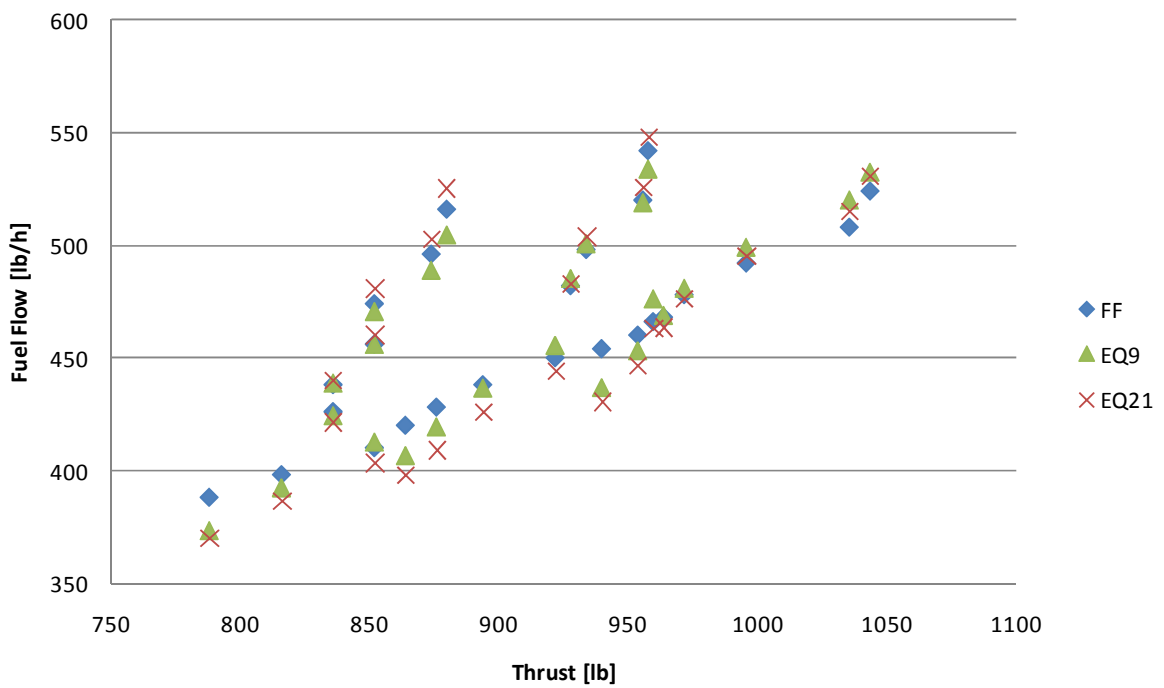


Figure E4: A100 fuel flow calculation results with FF_9 and FF_{21}

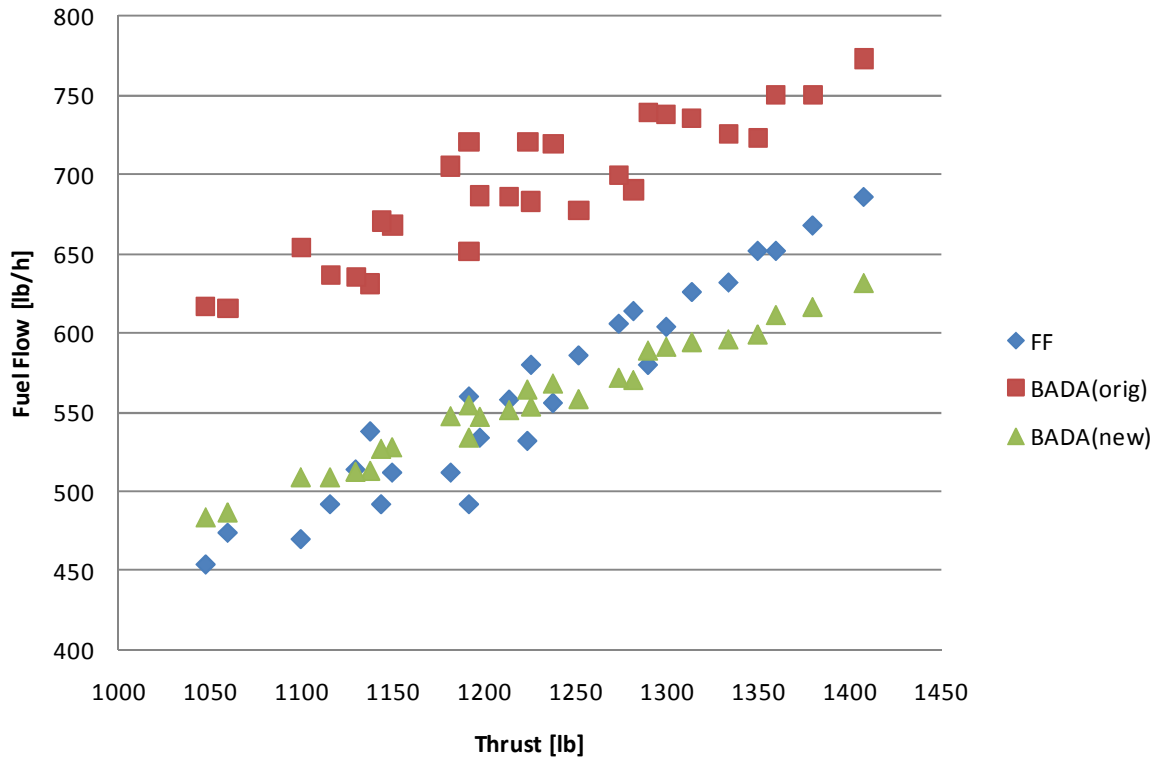


Figure E5: B300 fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

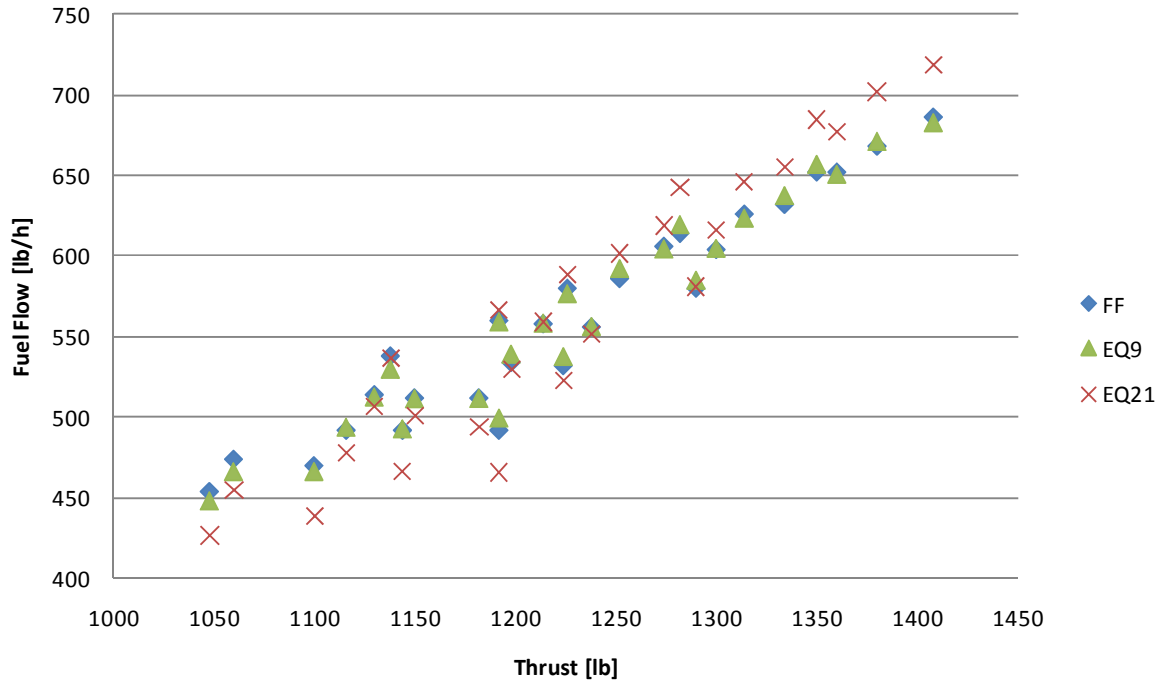


Figure E6: B300 fuel flow calculation results with FF_9 and FF_{21}

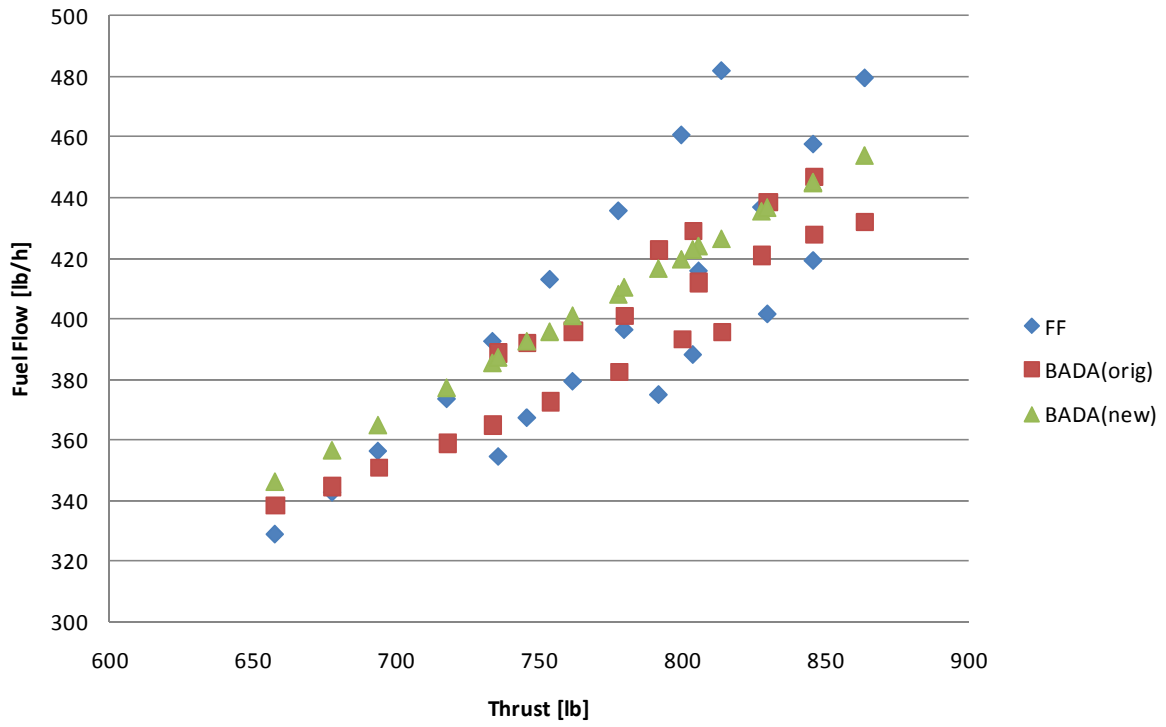


Figure E7: C90 fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

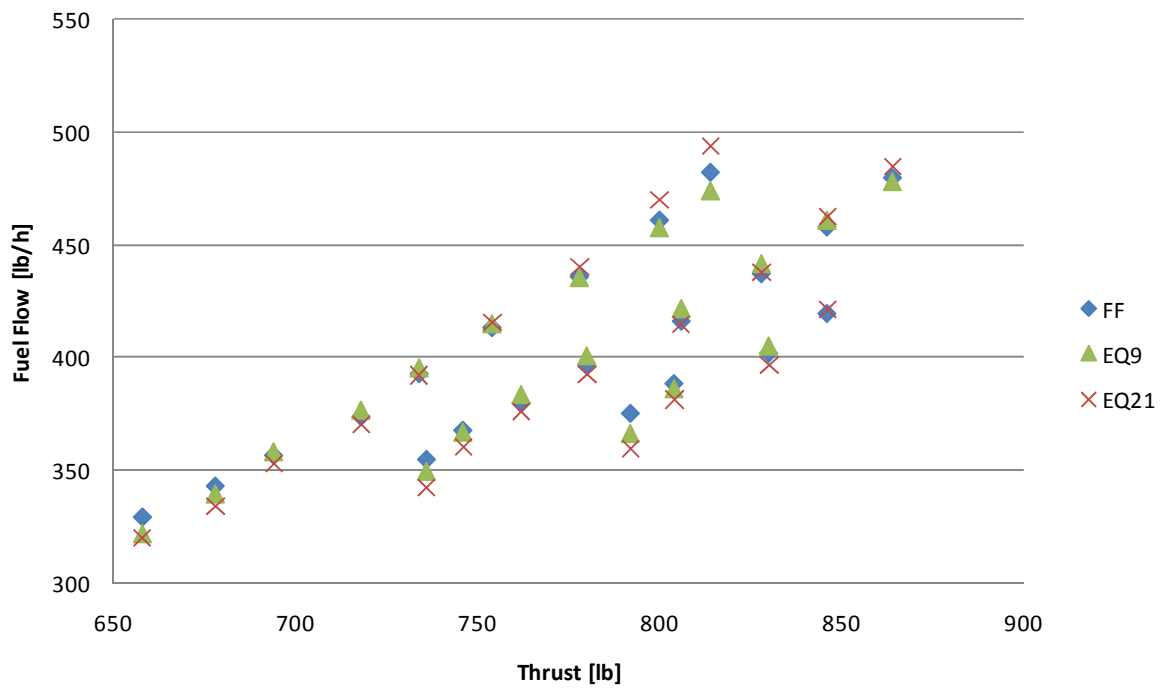


Figure E8: C90 fuel flow calculation results with FF_9 and FF_{21}

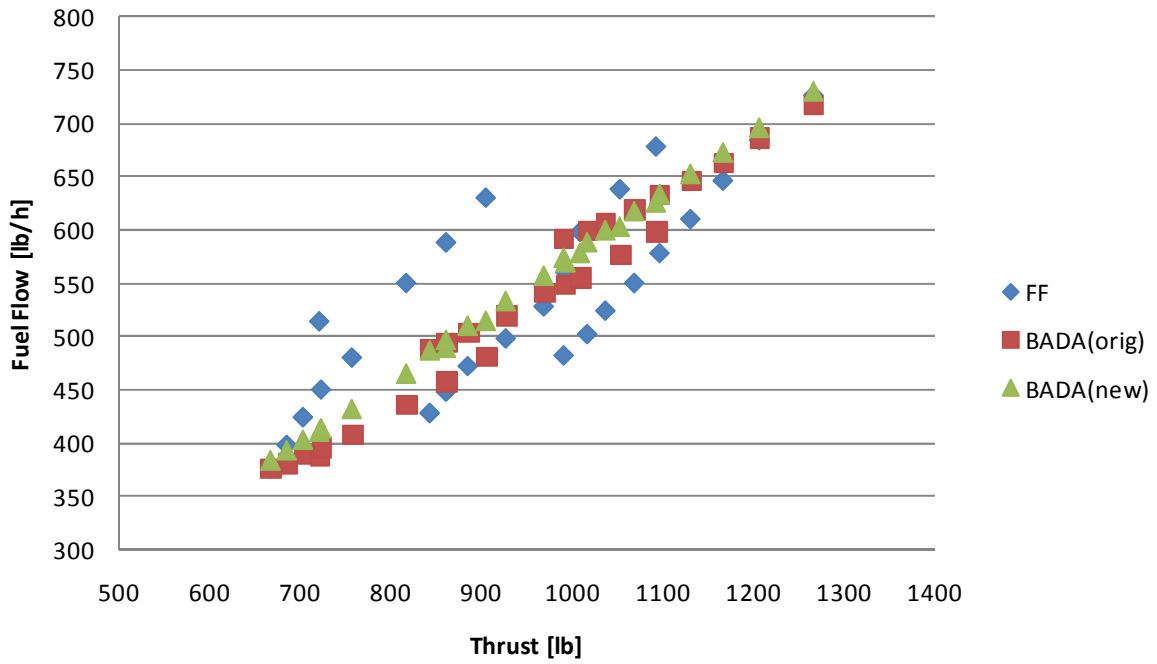


Figure E9: PA-42 fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

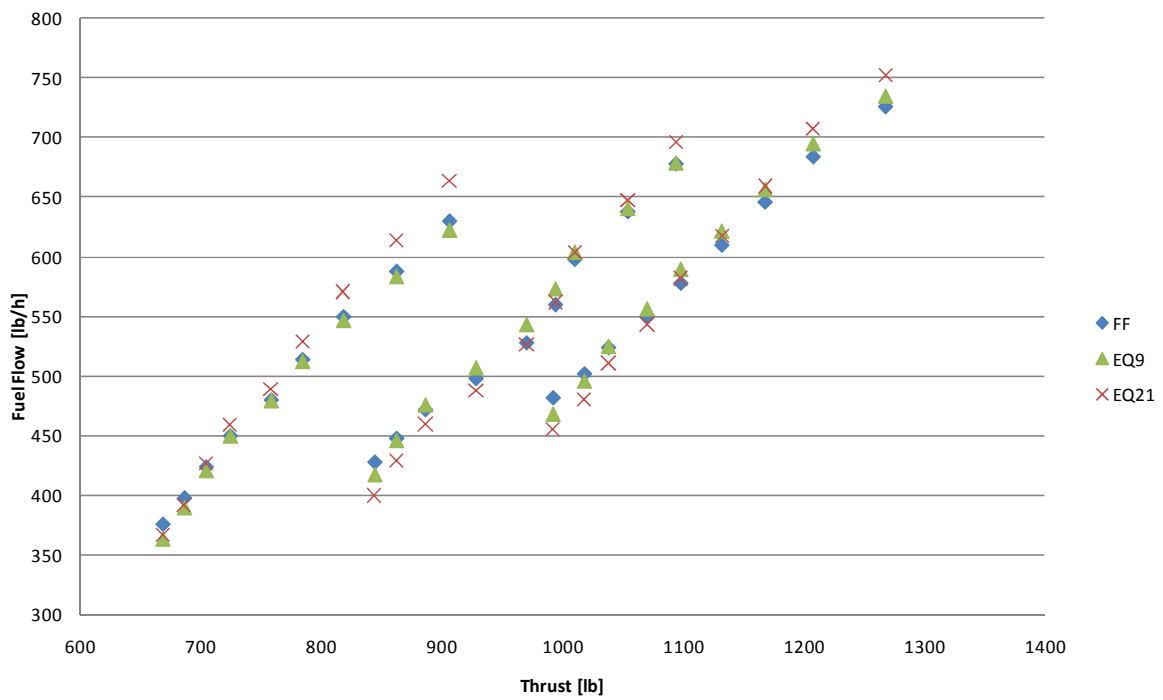


Figure E10: PA-42 fuel flow calculation results with FF_9 and FF_{21}

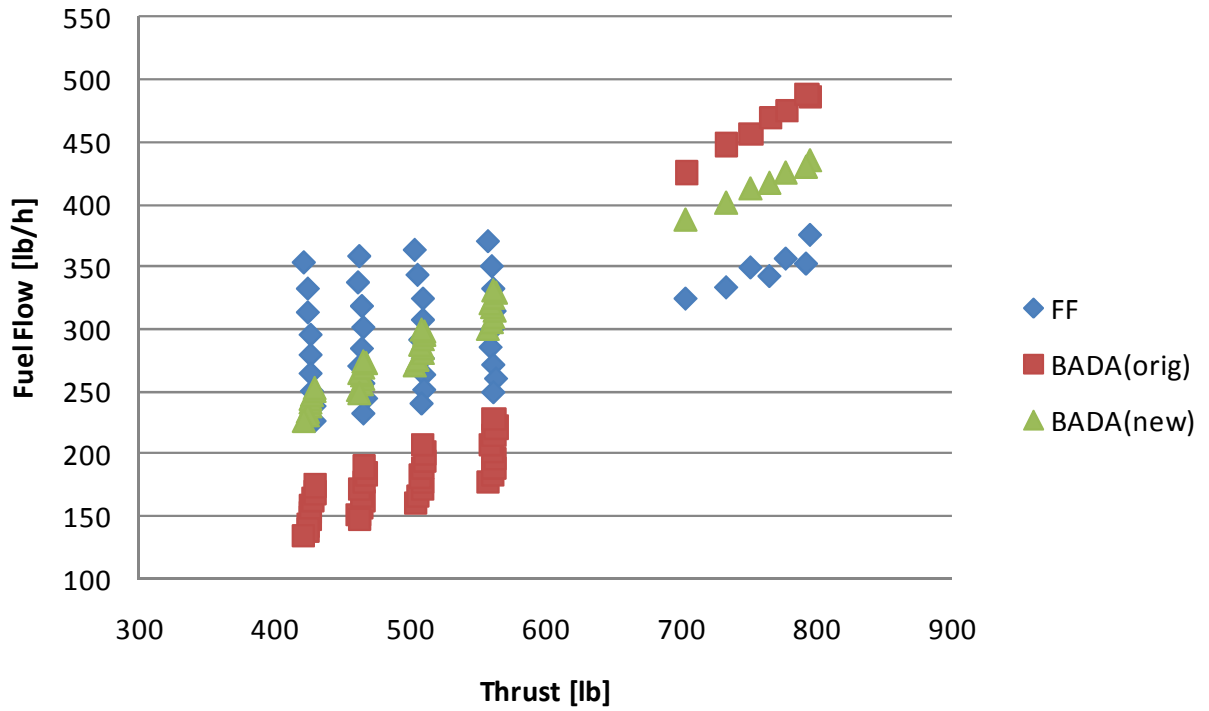


Figure E11: PC-12 fuel flow calculation results with $BADA_{orig}$ and $BADA_{new}$

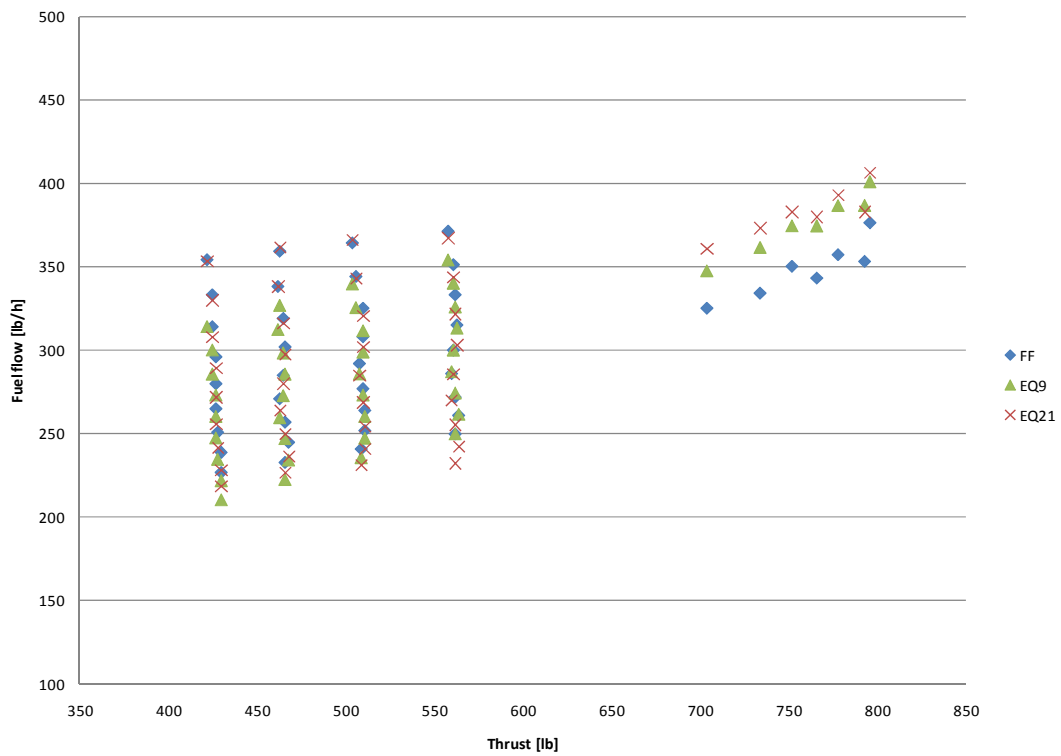


Figure E12: PC-12 fuel flow calculation results with FF_9 and FF_{21}

Appendix F BADA 3.7 results

In this appendix the calculation results of BADA 3.7 are given compared to the values listed in the PIMs. TSFC and fuel flow are calculated using equation (3) and (4). To calculate thrust BADA uses the following method.

In the cruise phase it can be assumed that thrust equals drag and to calculate drag BADA uses the standard aerodynamic equation $Drag = 0.5 \cdot \rho \cdot V^2 \cdot S \cdot C_D$ to calculate the drag (Nuic, 2009). In this equation ρ denotes the density, V the airspeed, S the wing surface area and C_D the drag coefficient. The latter is calculated using two drag coefficients (parasitic and induced) which are specified per aircraft in BADA.

TABLE F.I BADA_{orig} TSFC calculation results

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-44.3%	58.4%	11.0%	-18.0%	-24.7%	-62.0%
MAX	-15.3%	119.2%	46.5%	12.7%	22.8%	38.3%
AVG	-32.6%	95.5%	24.2%	-1.2%	-1.4%	-26.6%
AVG(ABS)	32.6%	95.5%	24.2%	7.2%	10.7%	37.4%

TABLE F.II BADA_{orig} thrust calculation results as compared to the Hartzell thrust

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-4.4%	-52.7%	-40.7%	-21.1%	-32.0%	-13.1%
MAX	6.4%	-47.7%	-32.8%	-16.9%	-14.3%	-1.9%
AVG	2.7%	-50.5%	-36.0%	-19.7%	-26.6%	-7.1%
AVG(ABS)	3.1%	50.5%	36.0%	19.7%	26.6%	7.1%

TABLE F.III BADA_{orig} fuel flow calculation results (using BADA_{orig} thrust)

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12
MIN	-45.5%	-17.1%	-34.2%	-31.8%	-41.1%	-65.3%
MAX	-10.9%	7.1%	-3.5%	-11.1%	-13.5%	23.0%
AVG	-30.7%	-3.4%	-20.4%	-20.7%	-28.0%	-32.3%
AVG(ABS)	30.7%	5.9%	20.4%	20.7%	28.0%	37.8%

Appendix G FF_9 and FF_{21} results on full SHP range

TABLE G.I FF_9 fuel flow calculation results on full SHP range

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12	TBM700
MIN	-6.4%	-3.8%	-1.8%	-2.3%	-3.5%	-11.3%	-2.6%
MAX	2.7%	3.3%	1.4%	1.7%	3.1%	10.2%	1.8%
AVG	0.0%	0.0%	0.0%	0.0%	0.0%	-0.4%	0.0%
AVG(ABS)	0.9%	1.5%	0.4%	0.8%	1.3%	4.5%	1.0%

TABLE G.II FF_{21} fuel flow calculation results on full SHP range

<i>Error</i>	1900D	A100	B300	C90	PA42	PC12	TBM700
MIN	-10.6%	-5.2%	-6.7%	-4.2%	-6.6%	-7.3%	-2.0%
MAX	8.1%	5.2%	5.1%	3.6%	5.3%	11.7%	1.8%
AVG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AVG(ABS)	1.8%	1.9%	1.6%	1.4%	1.8%	4.0%	0.6%

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PRELIMINARY ASSIGNMENT: TERMINAL AREA FUEL BURN CALCULATION IN AEDT

This assignment was given to familiarize the authors with the Aviation Environmental Design Tool. It was made together with A. Haagsma & E. Van Veggel.

INTRODUCTION

In the past, a fair amount of research has already been done on how to model the fuel burn of several types of aircraft in the terminal area. However there are still different types of aircraft, like the turboprop and helicopters, which are not yet covered. To model fuel burn, a combination of two models has been used over the years. These two models are Eurocontrol's Base of Aircraft Data (BADA) and SAE1845.

Analysis of Flight Data Recorder data has shown that the BADA model does not model the fuel burn in the terminal area of airports accurately. The reason for this is that the BADA model was initially designed as an Air Traffic Management tool and the Thrust Specific Fuel Coefficients (TSFC) that are used do not extrapolate well to the speeds that are used in the terminal area.

It is possible that these issues are addressed in the new version of the BADA model, BADA 3.7, and that new version can more accurately model the fuel burned during terminal operations. The goal of this assignment is to investigate if BADA 3.7 is better capable of modeling the fuel burn of turbofan aircraft than BADA 3.6. It is also investigated if AEDT with the BADA 3.6 coefficients is a more accurate method for modeling fuel burn than INM.

First the method used for this assignment is given. Afterwards results & conclusions are given.

METHOD

In short, the work can be summarized as follows:

- Run AEDT with BADA 3.6 and compare the fuel flow modeling results with known results for INM with BADA 3.6¹² and FDR data.
- Run AEDT with BADA 3.7 and compare the fuel flow modeling results with those of AEDT with BADA 3.6

The input for each of the AEDT runs is Flight Data Recorder (FDR) data¹³ which contains the terminal area flight segment of a variety of flights. In order to efficiently obtain the results, a number of scripts and batch files are written to automate the process.

To be able to automate all flights used in the validation, the following flowchart has been used (Fig. 1). The process in this flowchart is repeated for each aircraft that is tested. First there are initial

¹² The results of INM with BADA 3.6 are provided by D. Senzig

¹³ FDR data is provided by D. Senzig

procedures required (1). As AEDT runs with an SQL database, these initial procedures prepare the SQL database to be able to process each aircraft. Then there is a loop in which certain procedures are repeated for every flight (2-6). Each loop processes one flight record. The loop is repeated until all the flight records for one aircraft are processed. Finally some final procedures (7) are performed which process the results obtained from each loop.

The whole process is programmed using SQL scripts, for the tasks within the SQL database, and windows batch files, to automatically execute the SQL scripts. Sample scripts for the Boeing 757-200 are given in Appendix A.

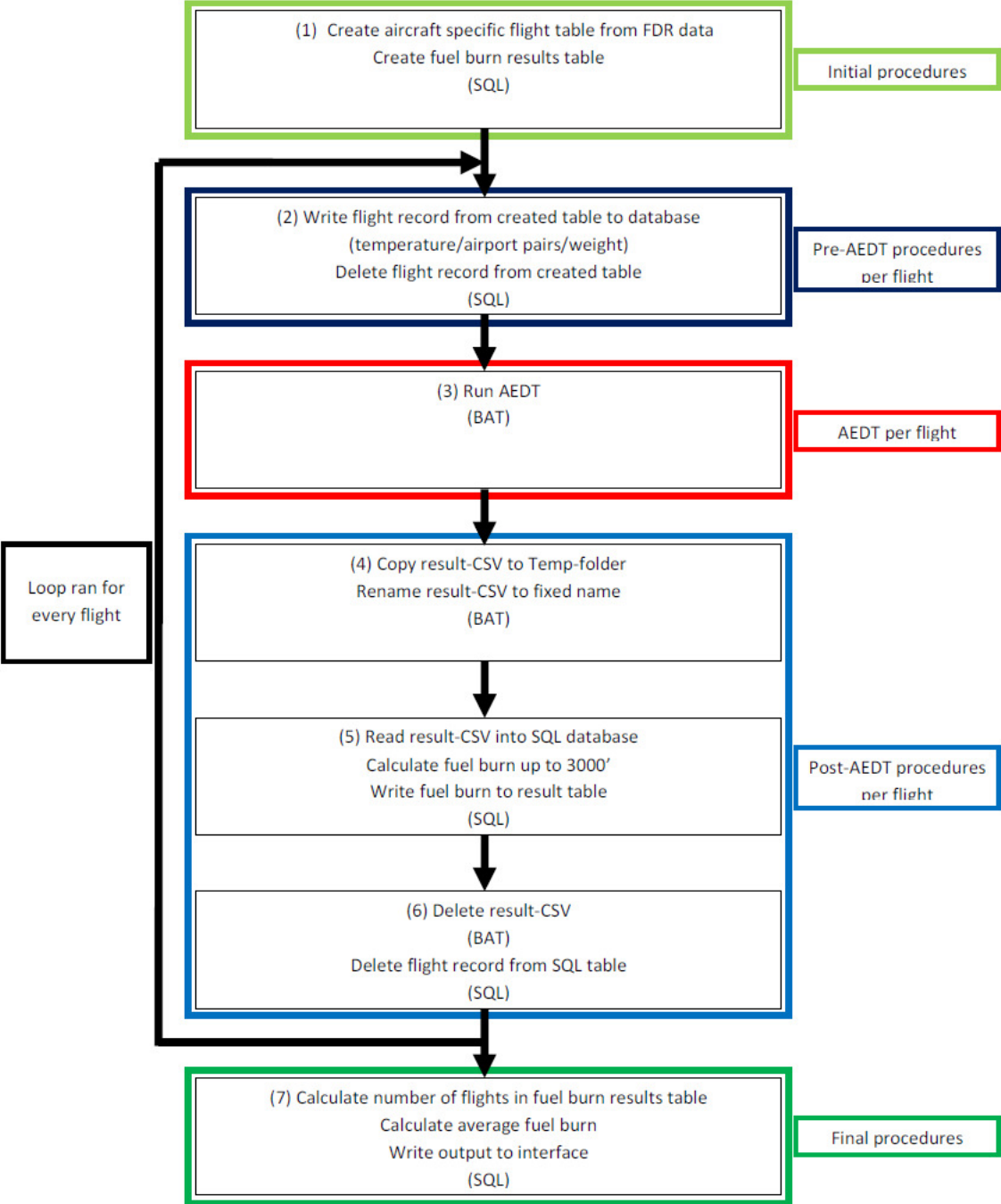


Figure 1: Workflow

RESULTS & CONCLUSIONS

The process described above is ran for all aircraft of which FDR data is available to the authors. These aircraft are:

- Airbus A319
- Airbus A320
- Airbus A321
- Airbus A330-202
- Airbus A330-223
- Airbus A330-243
- Airbus A340-313
- Airbus A340-541
- Boeing 757-200
- Boeing 767-300ER
- Boeing 777-300ER
- British Aerospace BAe-146

The results of the fuel flow calculations of AEDT in conjunction with BADA 3.6 and 3.7 are given in Table I. Also the BADA 3.6 data ran with INM as provided by Senzig (2009) are given. In Table II the INM and AEDT results are compared with each other.

Table I Fuel flow results

Aircraft	Measured [kg] (FDR)	Modeled [kg] (INM + BADA 3.6)	Modeled [kg] (AEDT + BADA 3.6)	Modeled [kg] (AEDT + BADA 3.7)
<i>757-200</i>	328	262	262	349
<i>767-300ER</i>	464	552	545	486
<i>777-300ER</i>	736	1131	1160	822
<i>A319</i>	181	189	202	213
<i>A320</i>	198	278	268	209
<i>A321</i>	241	268	283	266
<i>A330-202</i>	639	769	679	558
<i>A330-223</i>	680	877	725	597
<i>A330-243</i>	539	741	685	562
<i>A340-313</i>	956	1104	1069	842
<i>A340-541</i>	1013	1258	1370	1082
<i>Bae-146</i>	170	388	371	269

Table II Fuel flow results comparison

Aircraft	Difference [%] INM, 3.6 vs FDR	Difference [%] AEDT, 3.6 vs FDR	Difference [%] AEDT, 3.7 vs FDR	Difference [%] INM vs AEDT for 3.6
<i>757-200</i>	-20%	-20%	6%	0%
<i>767-300ER</i>	19%	17%	5%	-1%
<i>777-300ER</i>	54%	58%	12%	3%
<i>A319</i>	4%	12%	18%	7%
<i>A320</i>	40%	35%	6%	-4%
<i>A321</i>	11%	17%	10%	6%
<i>A330-202</i>	20%	6%	-13%	-12%
<i>A330-223</i>	29%	7%	-12%	-17%
<i>A330-243</i>	37%	27%	4%	-8%
<i>A340-313</i>	15%	12%	-12%	-3%
<i>A340-541</i>	24%	35%	7%	9%
<i>Bae-146</i>	128%	118%	58%	-4%

The goal of this part was to investigate whether BADA 3.7 is capable of modeling the fuel burn of turbofan aircraft more accurately than BADA 3.6. In the third and fourth column of table two it can be seen that for nine out of the twelve aircraft, BADA 3.7 is more accurate. Only the A319, A330-202 and A330-223 have a worse accuracy for BADA 3.7.

The other goal of this part was to investigate whether AEDT with BADA 3.6 coefficients is capable of modeling the fuel burn more accurately than the INM program.

In the last column of table two it can be observed that for eight out of twelve tested aircraft AEDT with BADA 3.6 is more accurate than INM. Only for the 777-300ER, A319, A321 and A340-541 INM is more accurate.

APPENDIX A SAMPLE SCRIPTS

The following scripts are used to process the flight records of an aircraft:

- Run_loop.BAT
- Start_SQL_SMS.BAT
- Close_SQL_SMS.BAT
- Export_stop.BAT
- Export_stop.BAT
- Delete_txt.BAT
- Call_SQL_script_createdb.BAT
- Create_Insert.SQL
- Call_SQL_script_update_flightdb.BAT
- Update_flightdb_757-200.SQL
- Run_AEDT.BAT
- Change_CSV_name.BAT
- Call_SQL_script_delete_FR.BAT
- Delete_FR_757-200.SQL
- Call_SQL_script_results.BAT
- Results_Fuel_Burn_runonce.SQL

The code for each of these scripts is given below.

Run_Loop.BAT

```
:: Loop.bat
::
:: This file will run a loop until the variable stop is set to 0
(with SQL script in txt file).
:: In the loop the different procedures can be called

@ECHO OFF

call start_SQL_SMS.bat

call call_SQL_script_createdb.bat

::Set loop variable
SET /a stop = 1

::Run loop till variable stop=0
:LOOP

IF %stop%==0 GOTO END

call call_SQL_script_update_flightdb.bat

call Run_AEDT.bat

call Change_CSV_name.bat

call call_SQL_script_retrieve_CSV.bat

call Delete_CSV.bat

call call_SQL_script_delete_FR.bat

call Export_stop.bat

for /f "tokens=*" %%a in ('type stop.txt') do set /a stop = %%a

GOTO LOOP

:END
```

```
call call_SQL_script_results.bat
```

```
call close_SQL_SMS.bat
```

```
call Delete_TXT.bat
```

To be able to run the loop, a couple of additional batch files have been written:

start_SQL_SMS.BAT

```
:: start_SQL_SMS.bat
```

```
::
```

```
:: This file will open SQL Management Studio
```

```
@ECHO OFF
```

```
::Start SQL Management Studio and wait 6-1=5 seconds to allow for  
start-up
```

```
START C:\aedt\SQL.lnk
```

```
PING -n 6 127.0.0.1 >NUL
```

close_SQL_SMS.BAT

```
:: close_SQL_SMS.bat
```

```
::
```

```
:: This file will close SQL Management Studio
```

```
@ECHO OFF
```

```
::Close SQL Management Studio
```

```
TASKKILL /im ssms.exe /f
```

Export_stop.BAT

```
:: Export_stop.bat
```

```
::
```

```
:: This file will run a loop until the variable stop is set to 0  
(with SQL script in txt file).
```

```
:: In the loop the different procedures can be called
```

```
@ECHO OFF
```

```
bcp FuelBurnEval.dbo.batch_loop out c:\AEDT\stop.txt -  
SVEGGEL8\SQLEXPRESS -T -c
```

Delete_TXT.BAT

```
:: Delete_CSV.bat
```

```
::
```

```
:: This file will delete the renamed file so that in the next run of  
the loop no double files will occur.
```

```
@ECHO OFF
```

```
::Delete the renamed file
```

```
DEL stop.txt
```

call_SQL_script_createdb.BAT

```
:: call_SQL_script.bat
::
:: This file will run the specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\Create_Insert.sql
PING -n 4 127.0.0.1 >NUL
```

Create_Insert.SQL

```
-- This script creates a db for each aircraft and then inserts the entries
listed below for each flight
-- This also creates a table to write the results into
-- Mind line 83!

-- DB KEY
-- Fleet = Fleet from Flights_Master
-- FlightRecord = FlightRecord from F_M
-- TakeoffAirportCode = first 4 characters of TakeoffAirportCode from F_M
(thus the ICAO code)
-- LandingAirportCode = first 4 characters of LandingAirportCode from F_M
(thus the ICAO code)
-- TakeoffTemperature = TakeoffTemperature from F_M in Fahrenheit
-- GrossWeightStartTakeoff= GrossWeightStartTakeoff from F_M in metric tons

USE [FuelBurnEval]
DROP TABLE [757-200]
DROP TABLE [767-300ER]
DROP TABLE [777-300ER]

-----
-- Create database 757-200
-----

USE [FuelBurnEval]
GO

SET ANSI_NULLS ON
GO

SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[757-200] (
    [Fleet] [nvarchar](255) NULL,
    [FlightRecord] [int] NOT NULL,
    [TakeoffAirportCode] [nvarchar](255) NULL,
    [LandingAirportCode] [nvarchar](255) NULL,
    [TakeoffTemperature] [real] NULL,
    [GrossWeightStartTakeoff] [float] NULL,
-- [RowNumber] [int] NULL,
) ON [PRIMARY]
```

```

GO
-----
--INSERT      set db name to AC name and where string to AC name
-----
INSERT INTO FuelBurnEval.dbo.[757-200] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%757-200%' order by FlightRecord

DELETE FROM FuelBurnEval.dbo.[757-200]
WHERE TakeoffTemperature = 32
-- This delete to discard the flights that gave a null value for TO-temp

-----
-----
-- Create database 767-300ER
-----
USE [FuelBurnEval]
GO

SET ANSI_NULLS ON
GO

SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[767-300ER] (
    [Fleet] [nvarchar](255) NULL,
    [FlightRecord] [int] NOT NULL,
    [TakeoffAirportCode] [nvarchar](255) NULL,
    [LandingAirportCode] [nvarchar](255) NULL,
    [TakeoffTemperature] [real] NULL,
    [GrossWeightStartTakeoff] [float] NULL,
    -- [RowNumber] [int] NULL,
) ON [PRIMARY]

GO
-----
--INSERT      set db name to AC name and where string to AC name
-----
INSERT INTO FuelBurnEval.dbo.[767-300ER] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%767-300%'

DELETE FROM FuelBurnEval.dbo.[767-300ER]
WHERE TakeoffTemperature = 32

-----
-----
-- Create database 777-300ER
-----
USE [FuelBurnEval]

```

```

GO

SET ANSI_NULLS ON
GO

SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[777-300ER] (
    [Fleet] [nvarchar](255) NULL,
    [FlightRecord] [int] NOT NULL,
    [TakeoffAirportCode] [nvarchar](255) NULL,
    [LandingAirportCode] [nvarchar](255) NULL,
    [TakeoffTemperature] [real] NULL,
    [GrossWeightStartTakeoff] [float] NULL,
--    [RowNumber] [int] NULL,
) ON [PRIMARY]

GO

-----
--INSERT      set db name to AC name and where string to AC name
-----

INSERT INTO FuelBurnEval.dbo.[777-300ER] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%777-3%' order by FlightRecord

DELETE FROM FuelBurnEval.dbo.[777-300ER]
WHERE TakeoffTemperature = 32

-----
-- Create results table
-----
USE EVENTRESULTS

DROP TABLE Fuel_Burn_AVG

CREATE TABLE Fuel_Burn_AVG
(FLIGHTRECORD INT,
Fuel_Burn_Total FLOAT)

-----
-- Create loop ending table
-----
USE FuelBurnEval
DROP TABLE batch_loop

CREATE TABLE batch_loop
    ([loopvalue] [INT],
    )

INSERT INTO batch_loop (loopvalue) VALUES (1)

call_SQL_script_update_flightdb.BAT
:: call_SQL_script.bat
::

```

```
:: This file will open SQL Management Studio and will run the
specified SQL script
```

```
::
```

```
:: Note: Location of SQL Management Studio must be specified
```

```
:: SQL Server name must be specified
```

```
:: SQL script must be specified
```

```
@ECHO OFF
```

```
::Run the SQL script and wait 4-1=3 seconds to continue
```

```
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\update_flightdb_757-
200.sql
```

```
PING -n 4 127.0.0.1 >NUL
```

update_flightdb_757-200.SQL

```
-- This script updates the movements_aces, fleet and airport db's with the
data from the last flight record
```

```
--
```

```
-- This file is unique for each aircraft => the input database name depends
on the aircraft type
```

```
-- !!! Mind to change the ACCODE and BADA_ID inputs in part 3 and 5 to the
ones of the aircraft that is ran
```

```
-----
--0 Insert FlightRecord as FlightID
-----
```

```
USE [FuelBurnEval]
```

```
GO
```

```
DECLARE @FR_var INT
```

```
SELECT
```

```
@FR_var = FlightRecord FROM FuelBurnEval.dbo.[757-200]
```

```
UPDATE MOVEMENTS_ACES.dbo.FLIGHT
```

```
SET FLIGHT_ID = @FR_var
```

```
-----
--1 Find arrival APT_ID corresponding to the APT_code and insert it into
the flight record
```

```
USE FuelBurnEval
```

```
GO
```

```
DECLARE @LA_APT_code NVARCHAR(255)
```

```
SELECT
```

```
@LA_APT_code = LandingAirportCode from dbo.[757-200]
```

```
DECLARE @LA_APT_ID INT
```

```
SELECT @LA_APT_ID = APT_ID from AIRPORT.dbo.APT_CODE_LU
```

```
WHERE APT_CODE = @LA_APT_code
```

```
UPDATE MOVEMENTS_ACES.dbo.FLIGHT
```

```
SET ARR_APT_ID = @LA_APT_ID
```

```
-----
--2 Find takeoff APT_ID corresponding to the APT_code and insert it into
the flight record
```

```
USE FuelBurnEval
```

```
GO
```

```

DECLARE @TO_APT_code NVARCHAR(255)
SELECT
@TO_APT_code = TakeoffAirportCode from dbo.[757-200]

DECLARE @TO_APT_ID INT
SELECT @TO_APT_ID = APT_ID from AIRPORT.dbo.APT_CODE_LU
WHERE APT_CODE = @TO_APT_code

UPDATE MOVEMENTS_ACES.dbo.FLIGHT
SET DEP_APT_ID = @TO_APT_ID

-----
--3 Insert ACTYPE and ACCODE
-----
UPDATE MOVEMENTS_ACES.dbo.FLIGHT
SET ACTYPE = 'B752',
ACCODE = 'B757-2',
ENG_CODE = '4PW073'

-----
--4 Find weather station number associated with airport, then insert
TO_temp into All entry of that station
-----
DECLARE @TO_temp REAL
SELECT @TO_temp = TakeoffTemperature FROM FuelBurnEval.dbo.[757-200]

DECLARE @WTHR_STN INT
SELECT @WTHR_STN = WTHR_STN from AIRPORT.dbo.APT_MAIN
WHERE APT_ID = @TO_APT_ID

UPDATE AIRPORT.dbo.APT_WTHR_DATA
SET TEMPERATURE = @TO_temp
WHERE STN_ID = @WTHR_STN AND WTHR_MONTH = 'ALL'

-----
--5 Set the weight of all profiles of the A/C to the flight specific one
-- Thus it will pick this weight regardless of stagelength
-----
DECLARE @Weight FLOAT
SELECT @Weight = GrossWeightStartTakeoff from FuelBurnEval.dbo.[757-200]

DECLARE @EQUIP_ID INT
SELECT @EQUIP_ID = EQUIP_ID from FLEET.dbo.EQUIPMENT
WHERE ACCODE = 'B757-2'

DECLARE @ACFT_ID VARCHAR(12)
SELECT @ACFT_ID = ACFT_ID from FLEET.dbo.AIRCOMBO
WHERE EQUIP_ID = @EQUIP_ID

UPDATE FLEET.dbo.[PROFILE]
SET WEIGHT = (@Weight*1000*2.20462262)
WHERE ACFT_ID = @ACFT_ID

Run_AEDT.BAT

:: Run_AEDT.bat
::
:: This file will run AEDT

:: Note: Location of standard directory must be specified

```

```
@ECHO OFF
```

```
::Change directory and back and run AEDT  
cd C:\Program Files\AEDT\FAA_AEE_AEDT_Modules\bin  
start /wait FAA.AEE.AEDT.InventoryProcessor.exe 1  
cd C:\AEDT
```

Change_CSV_name.BAT

```
:: Change_CSV_name.bat  
::  
:: This file will save the AEDT output CSV file to a map for back-  
up. After that it changes the name of  
:: the AEDT output CSV file to a fixed name so the results can be  
retrieved from it.
```

```
:: Note: The folder CSV_TEMP should be created
```

```
@ECHO OFF
```

```
:: Move the file with its original name to the working directory  
cd C:\Program Files\AEDT\FAA_AEE_AEDT_Modules\bin  
MOVE *.csv "C:\AEDT"  
cd C:\AEDT
```

```
:: Copy the file with its original name to a backup folder  
COPY *.csv "C:\AEDT\CSV_BACKUP"
```

```
:: Rename the file to be able to be read  
REN *.csv, AEDT_Flight_Result.csv
```

call_SQL_script_retrieve_CSV.BAT

```
:: call_SQL_script.bat  
::  
:: This file will open SQL Management Studio and will run the  
specified SQL script  
::  
:: Note: Location of SQL Management Studio must be specified  
:: SQL Server name must be specified  
:: SQL script must be specified
```

```
@ECHO OFF
```

```
::Run the SQL script and wait 4-1=3 seconds to continue  
SQLCMD -E -S VEGGEL8\SQLEXPRESS -  
ic:\aedt\CSV_Fuel_Burn_Extraction.sql  
PING -n 4 127.0.0.1 >NUL
```

CSV_Fuel_Burn_Extraction.SQL

```
USE EVENTRESULTS
```

```
GO
```



```
DROP table Fuel_Burn
```

```
CREATE table Fuel_Burn
(NUM varchar(100), DIST varchar(100), LENGTH varchar(100), TIME
varchar(100), ALT1AFE varchar(1005), ALT2AFE float, ALT1MSL
varchar(100), ALT2MSL varchar(100), V1 varchar(100), V2 varchar(100), DELTAV
varchar(100), FND1 varchar(100), FND2 varchar(100), NOISETHRUST1 varchar(100),
NOISETHRUST2 varchar(100), DELTAFND varchar(100), LAT1 varchar(100), LONG1
varchar(100), LAT2 varchar(100), LONG2 varchar(100), X1 varchar(100), Y1
varchar(100), X2 varchar(100), Y2 varchar(100), UNITX varchar(100), UNITY
varchar(100), UNITZ varchar(100), BANKANGLE varchar(100), FUELFLOW
varchar(100), FUELBURN float, WEIGHT varchar(100), TEMP varchar(100), PRESS
varchar(100), MACHNO varchar(100), THETA varchar(100), DELTA
varchar(100), OPMODE varchar(100), EMISS varchar(max))
```

```
BULK
```

```
INSERT Fuel_Burn
FROM 'c:\AEDT\AEDT_Flight_Result.csv'
WITH (firstrow = 2, FIELDTERMINATOR = ',', ROWTERMINATOR = '\n')
```

```
GO
```

```
DELETE FROM Fuel_Burn
WHERE ALT2AFE > '3000'
```

--At this point, the data is written in the created Fuel_Burn_AVG table, of which the script is run at the start of execution

```
DECLARE @flightrecord INT
DECLARE @Fuel_Burn_Total FLOAT

SELECT @flightrecord = Flight_ID FROM MOVEMENTS_ACES.dbo.FLIGHT
SELECT @Fuel_Burn_Total = SUM(FUELBURN) FROM Fuel_Burn

INSERT into Fuel_Burn_AVG
(FLIGHTRECORD, Fuel_Burn_Total)
values (@flightrecord, @Fuel_Burn_Total)
```

```
Delete_CSV.BAT
```

```
:: Delete_CSV.bat
```

```
::
```

```
:: This file will delete the renamed file so that in the next run of the loop no double files will occur.
```

```
@ECHO OFF
```

```
::Delete the renamed file
```

```
DEL AEDT_Flight_Result.csv
```

```
call_SQL_script_delete_FR.BAT
```

```
:: call_SQL_script.bat
```

```
::
```

```
:: This file will run the specified SQL script
```

```
::
```

```
:: Note: Location of SQL Management Studio must be specified
```

```
:: SQL Server name must be specified
```

```
:: SQL script must be specified
```

```
@ECHO OFF
```

```

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\delete_FR_757-200.sql
PING -n 4 127.0.0.1 >NUL

```

delete_FR_757-200.SQL

```

-- This is the script that has to be run after AEDT has processed the
flight and before the next flight is processed
-- Change db names to the ones of your aircraft
-----
-- Delete the flight that has been processed
-----

```

```

USE [MOVEMENTS_ACES]
GO

```

```

DECLARE @FR_var INT
SELECT
@FR_var = FLIGHT_ID FROM MOVEMENTS_ACES.dbo.FLIGHT

```

```

DELETE from FuelBurnEval.dbo.[757-200]
WHERE FlightRecord = @FR_var

```

```

-----
-- Adapt loop ending parameter in dbo.batch_loop if specific A/C db is
empty
-----

```

```

USE FuelBurnEval

```

```

UPDATE batch_loop
    SET loopvalue = (SELECT COUNT(*) FROM [757-200])

```

call_SQL_script_results.BAT

```

:: call_SQL_script.bat
::
:: This file will run the specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

```

```

@ECHO OFF

```

```

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -
ic:\aedt\Results_Fuel_Burn_runonce.sql
PING -n 4 127.0.0.1 >NUL

```

Results_Fuel_Burn_runonce.SQL

```

USE EVENTRESULTS

```

```

DROP table Fuel_Burn_Results

```

```

CREATE table Fuel_Burn_Results
(NumberOfFlights INT, AverageFuelBurn Float)

```

```
DECLARE @numberofentries INT
DECLARE @totalfuelburn FLOAT

SELECT @numberofentries = Count(FLIGHTRECORD)FROM Fuel_Burn_AVG
SELECT @totalfuelburn = SUM(Fuel_Burn_Total)FROM Fuel_Burn_AVG

INSERT into Fuel_Burn_Results
(NumberOfFlights, AverageFuelBurn)
values (@numberofentries, @totalfuelburn / @numberofentries)
```

