Turboprop and Helicopter fuel consumption modeling in Environmental models

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U.S. Department of Transportation

TURBO-PROP & HELICOPTER FUEL CONSUMPTION MODELING

- Work funded through FAA's support of the Air Tour Management Plan
- Work done at Volpe by students from Delft University:
  - Jef Geudens
  - Kurt Wils
  - Alex Haagsma
  - Elgar van Veggel

TURBO-PROP MAIN PROJECT GOAL

- Current aviation environmental models do not accurately modeling low speed, low altitude flights of turboprop aircraft

The development of a method to calculate the fuel flow of turboprop aircraft flying at national parks in the United States

TURBO-PROP METHOD - DATA

- Fuel flow data from pilot information manuals
- 7 turboprop aircraft
- Data points under 16,000 feet AMSL under ISA conditions
- Extracted parameters:
  - Fuel flow, true airspeed, pressure altitude, weight
  - Torque, propeller RPM
- Shaft Horse Power (SHP) and thrust added

Turbo-prop Method - equations and coefficients

- Investigate influence of parameters on fuel flow
- Direct effect can not be determined
- A number of different equations are tested

- Tested equations are of the form:

$$Fuel\ flow = c_1 \cdot P_1 + c_2 \cdot P_1^2 + c_3 \cdot P_2 + c_4 \cdot P_2^2 + \ldots + c_n \cdot P_n + c_{n+1} \cdot P_n^2$$

- Coefficients (c's) are aircraft specific

Turbo-prop Method - equations and coefficients

- Non-linear least squares regression analysis on data set to determine coefficients
  - For each equation and each aircraft
- Equations and coefficients used on data points with SHP <=60% of max. SHP
- Calculated fuel flow compared to fuel flow from aircraft flight manuals
- Find the 'most accurate' equation

Turbo-prop Results

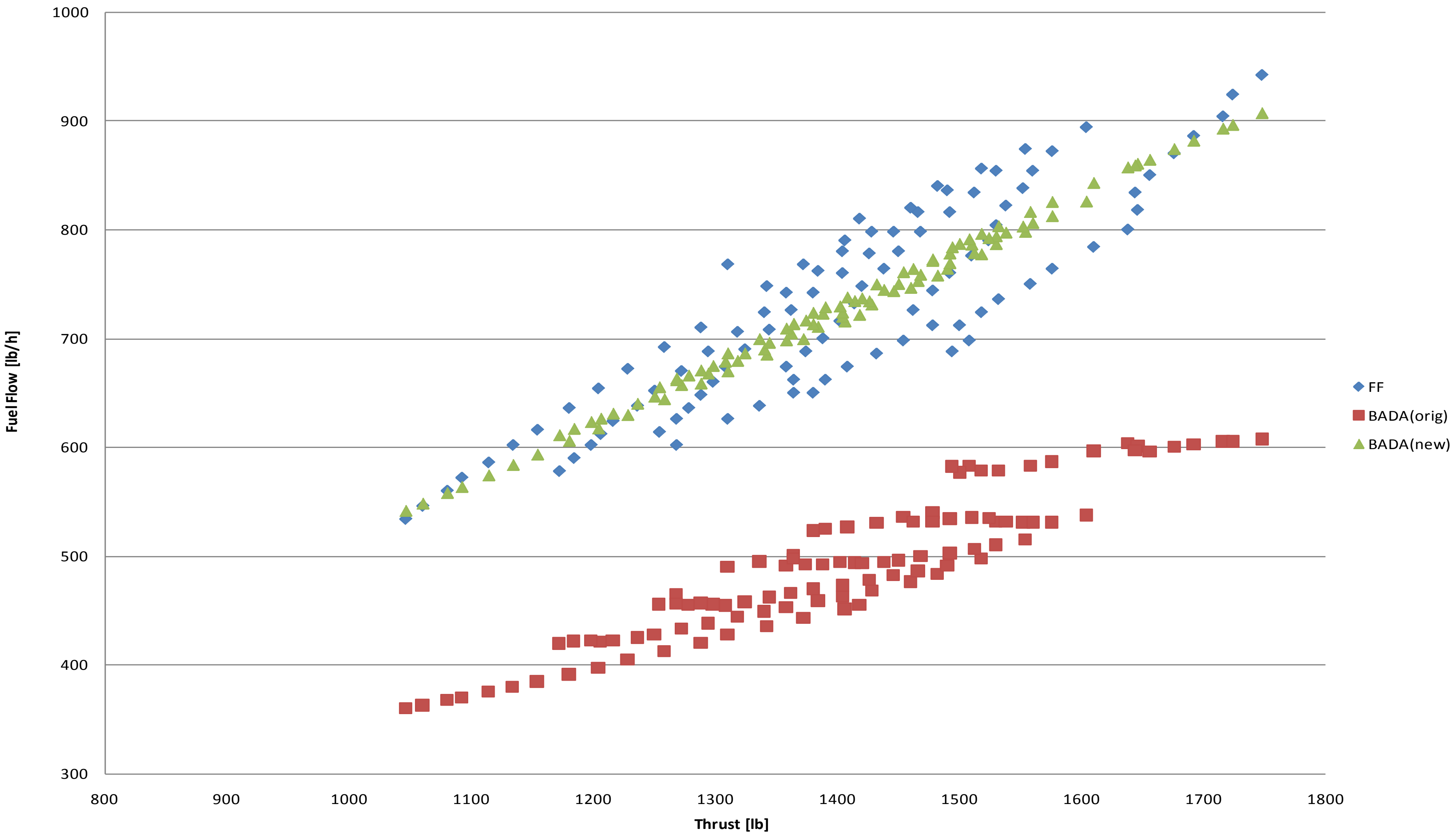
- 22 equations tested
- 2 equations outperformed the others

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

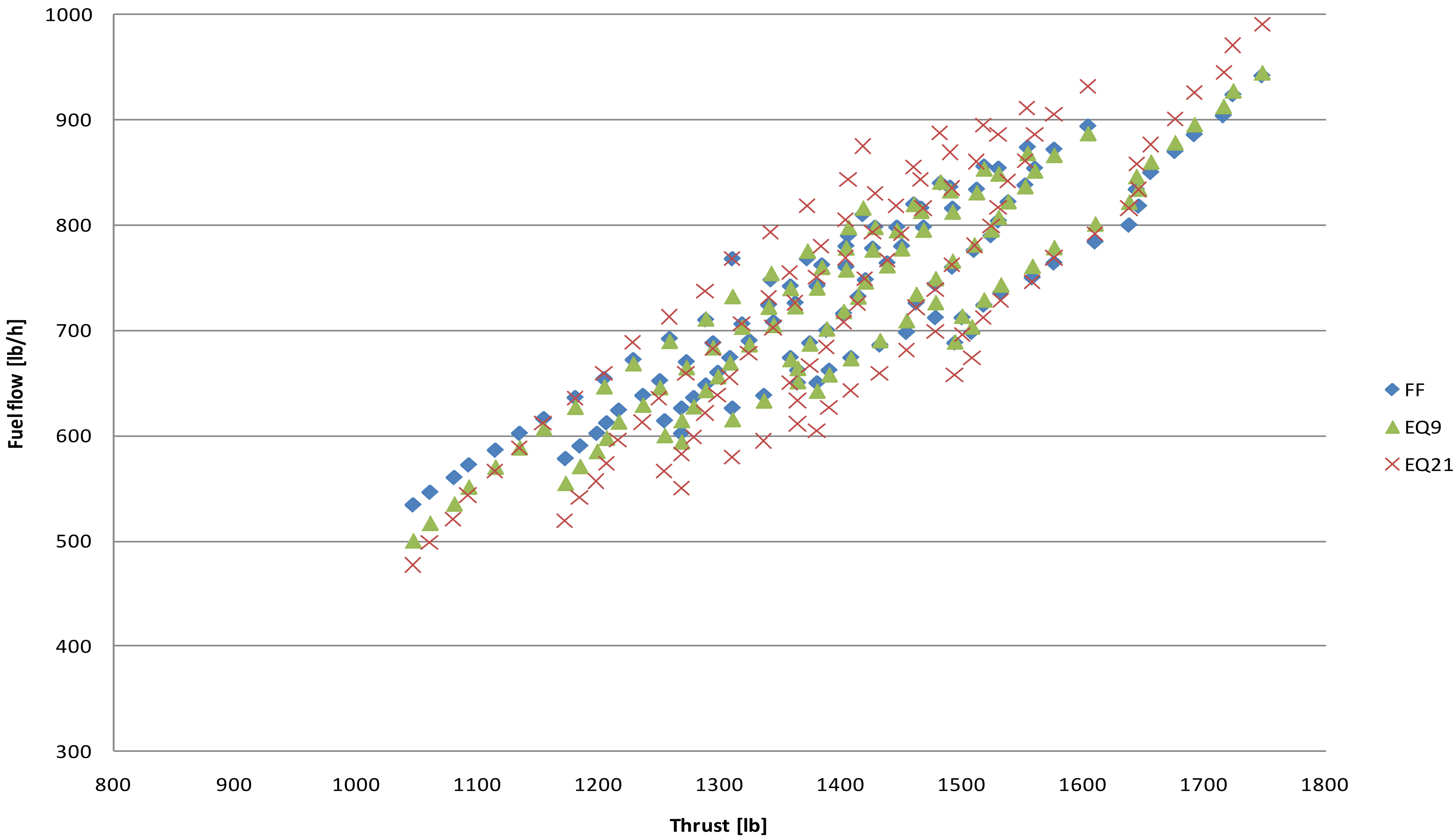
$$FF_{21} = b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot h + b_4 \cdot h^2 + b_5 \cdot KTAS$$

- a_1-a_5, b_1-b_5 found through regression analysis
- Unlike BADA, this method is not based on TSFC

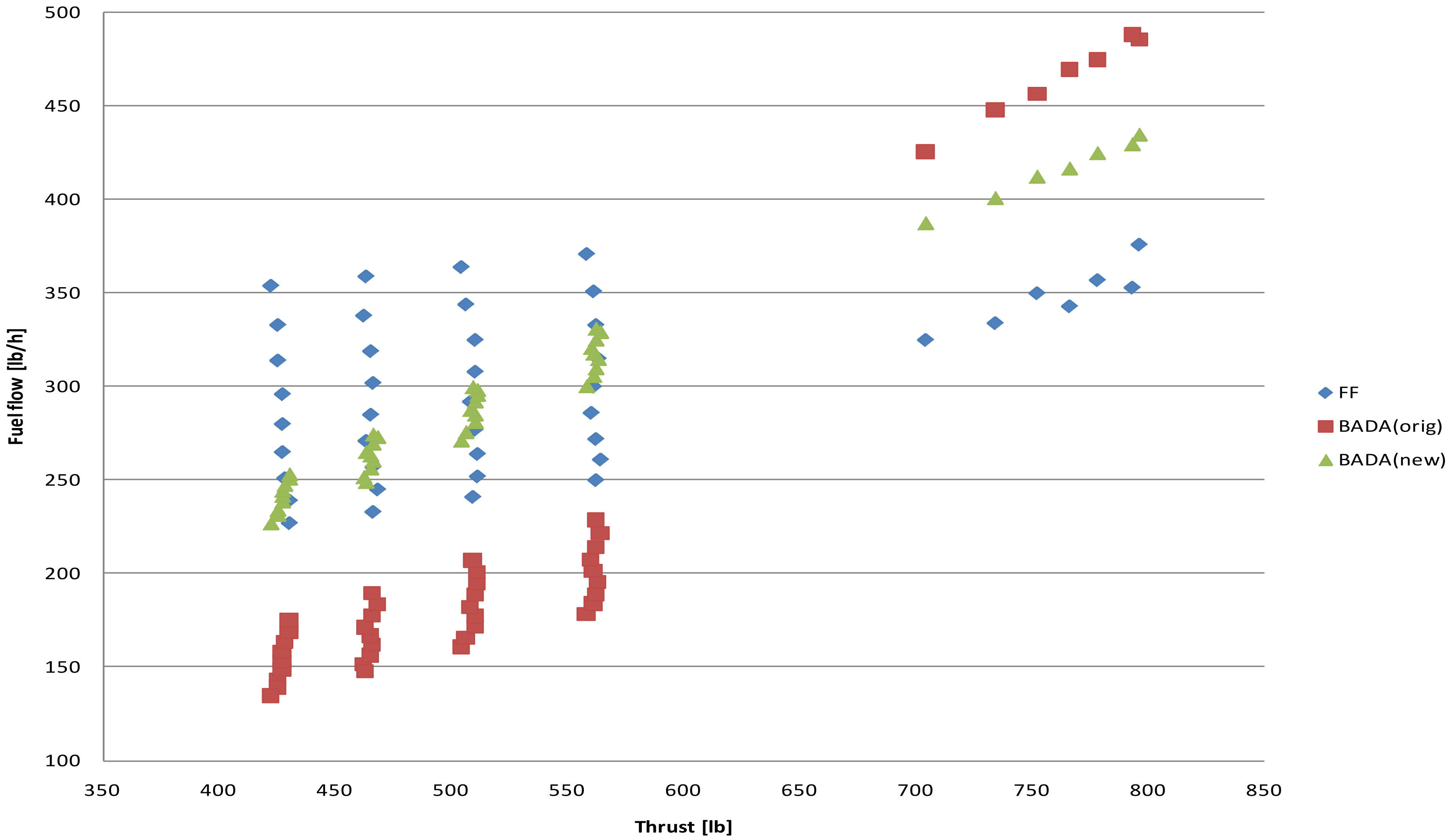
Turbo-prop Results



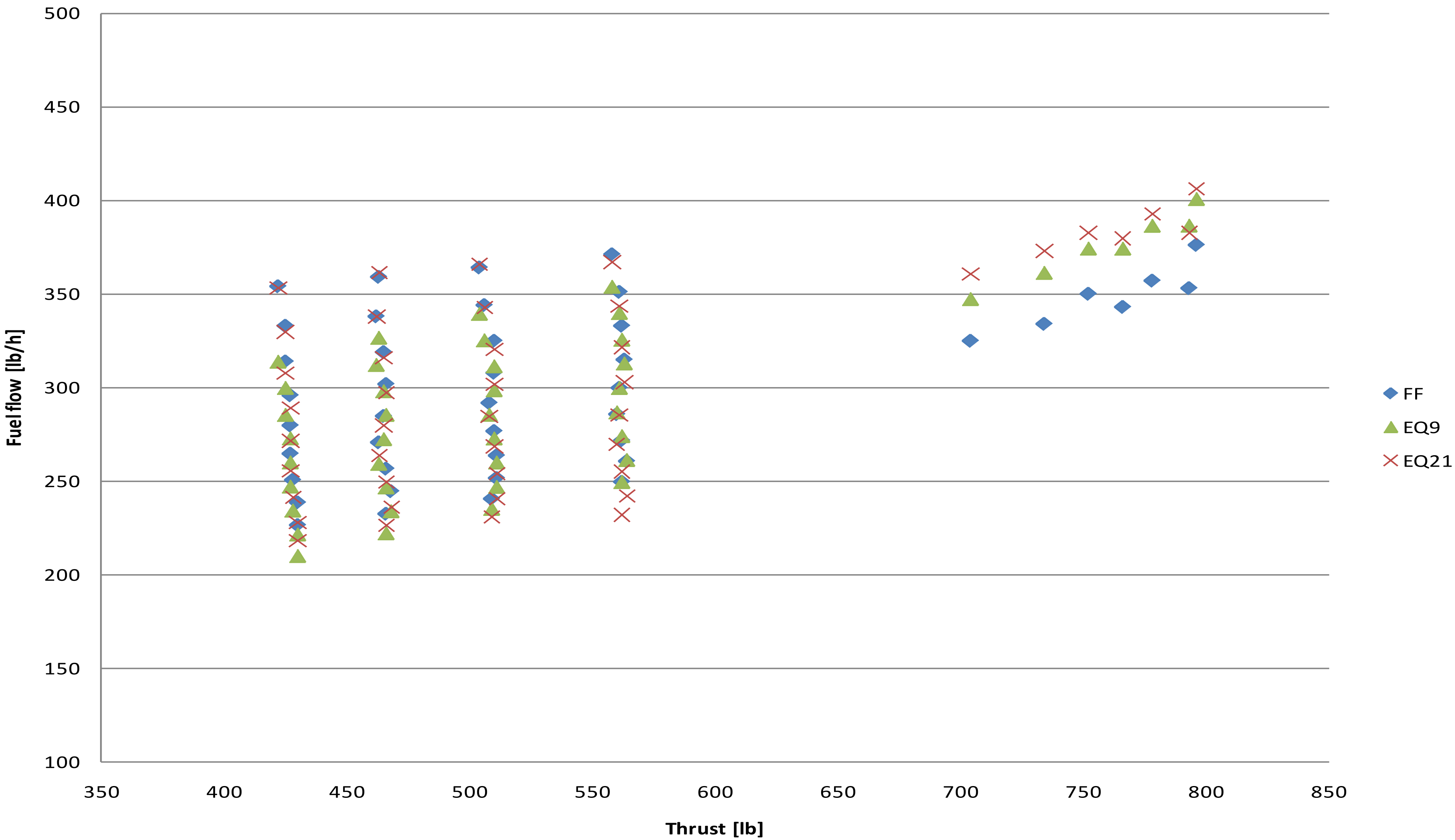
TURBO-PROP RESULTS



TURBO-PROP RESULTS



Turbo-prop Results



Turbo-prop Results

Average of absolute errors (re: AFM data)

	Aircraft 1	Aircraft 2	Aircraft 3	Aircraft 4	Aircraft 5	Aircraft 6
$BADA_{3.7}$	32.6%	95.5%	24.2%	7.2%	10.7%	37.4%
$BADA_{new}$	5.5%	6.2%	5.1%	5.5%	9.1%	15.8%
FF_9	1.1%	1.4%	0.6%	1.0%	1.3%	5.1%
FF_{21}	3.5%	1.9%	3.0%	1.5%	2.6%	4.0%

Turbo-prop Fuel Flow Implementation

- Proposed method uses parameters readily available in aircraft performance models
- Similar to BADA; new EQ and new coefficients
- How to add new aircraft?
- Required parameters: FF, W, h, KTAS, T
- Find data points with as much dispersion as possible
- Best result using different coefficients for different flight phases

Helicopter Fuel Consumption

Helicopter Fuel Consumption – Method 1

Constant Specific Fuel Consumption

- Assumption of a specific fuel consumption of 0.5 lbs/HP/hour for modern turbine engines
- Installed horsepower
- Mission time

$$M_{fuel} = SFC \times HP_{installed} \times t_{mission}$$

Helicopter Fuel Consumption – Method 2

Constant Torque-Fuel Flow relationship

- A direct relation between torque and fuel flow
- Only valid for a specific altitude and temperature
- Coefficients dependent on altitude

$$FF_{flight\ phase} = k_1 \times T^2_{flight\ phase} + k_2 \times T_{flight\ phase} + k_3$$

Helicopter Fuel Consumption – Method 3

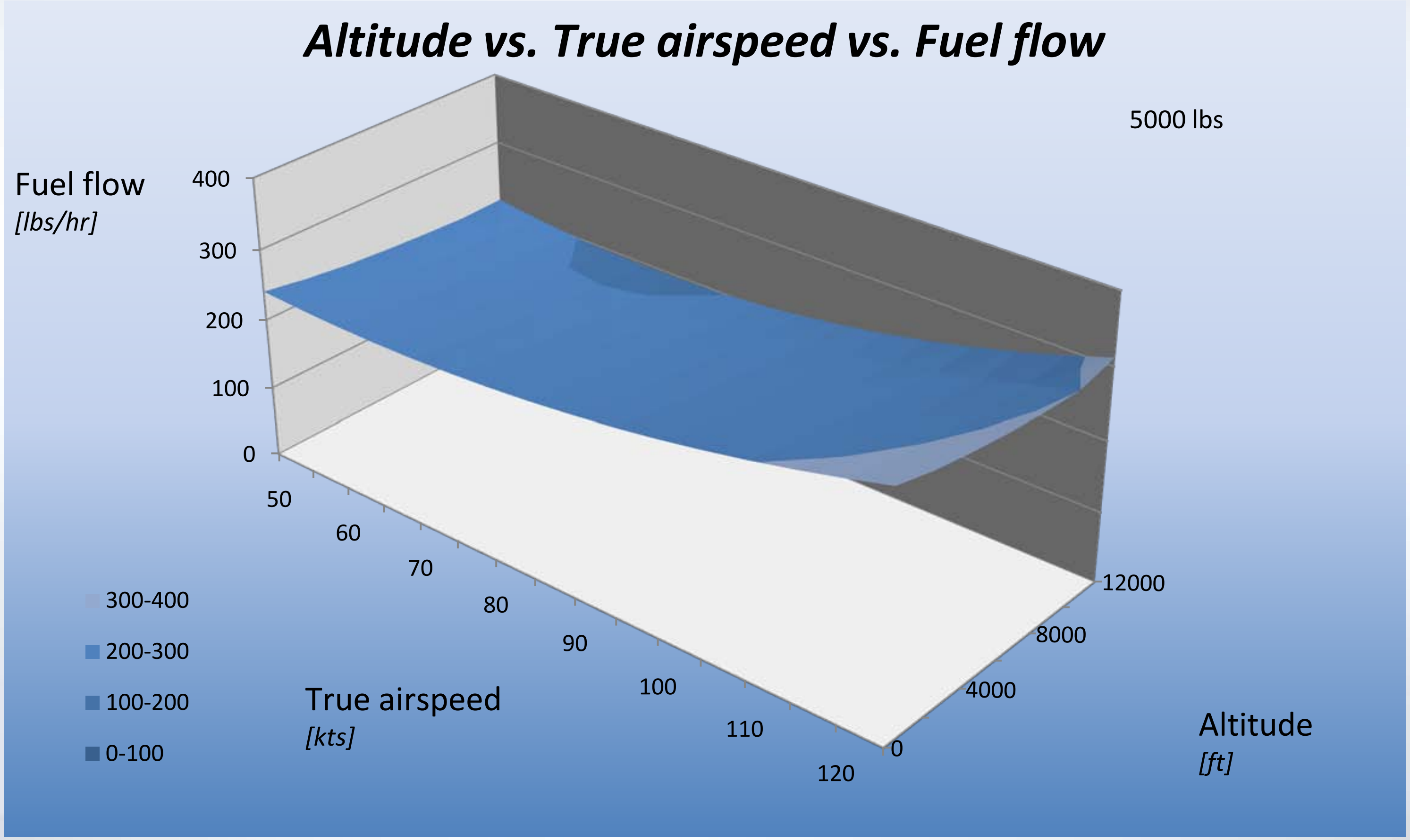
Fuel Flow from the Aircraft Flight Manual

- Fuel flow depends on airspeed, weight, altitude and temperature
- Weight influence on fuel flow are small
- Temperature influence on fuel flow are small
- In the equation below, a different set of coefficients is used for each altitude of interest

$$FF_{cruise} = k_1 V_{cruise}^2 + k_2 V_{cruise} + k_3$$

Helicopter Fuel Consumption – Method 3

Fuel Flow from the Aircraft Flight Manual



HELICOPTER FUEL CONSUMPTION – METHOD 4

POWER REQUIRED METHOD

- Separate calculations for flight modes
- Climb and descent: based on hover power required
- Take-off: based on 100% of the installed power
- Relation needed between horsepower and fuel flow: known to manufacturers

Helicopter Fuel Consumption – comparison of methods

- Cruise flight comparison

Method	*Fuel Burn [lbs]*	*Difference w.r.t. flight manual [%]*
Method 1: fixed specific fuel consumption	204	48.9
Method 2: fixed torque-fuel flow relation	146	6.6
Method 3: fuel flow data from flight manual	135	-1.5
Method 4: power required equations	159	16.1
Bell Flight Manual	137	-

HELICOPTER FUEL CONSUMPTION – COMPARISON OF METHODS

Method 1	PRO: CON:	• Easily calculated • Not accurate	Deviation: 49%
Method 2	PRO: CON:	• No factors needed for different flight phases • No data on torque settings of flight phases • Not depending on fuel burn data	Deviation: 7%
Method 3	**PRO:** **CON:**	**• Based on fuel burn data** **• Factors needed for different flight phases** **• Requires detail AFM data**	**Deviation: 2%**
Method 4	PRO: CON:	• No factors needed for different flight phases • No power–fuel burn relation from manufacturers • Only based on theoretical calculations	Deviation: 16%

Helicopter Fuel Flow Implementation

- Requires validation against actual fuel flows
- Requires validation against different helicopters
- Requires validation in different flight modes
- Not ready for implementation
- Looking for assistance from manufacturers

HELICOPTER & TURBOPROP BACKUP SLIDES

Fuel consumption flight mode scaling example

Mode	*Input H*	*Input V*	*Input t*	*Input C_1*
Level Fly	h	V	$t_{flight\ phase}$	1
App Desc Decel	h_{avg}	V_{avg}	$t_{flight\ phase}$	0.8
App Vertical	h_{avg}	90	$t_{flight\ phase}$	0.8
Hover	h	90	$t_{flight\ phase}$	1.6
Dep Vertical	h_{avg}	90	$t_{flight\ phase}$	1.7
Dep Climb Accel	h_{avg}	V_{avg}	$t_{flight\ phase}$	1.4

An example of an arbitrary flight for testing modes

Flight phase	*Start altitude [ft]*	*End altitude [ft]*	*Phase time [s]*	*Airspeed (TAS) [kts]*
Take-off and initial climb	0	20	120	0
Hover	20	20	120	0
Cruise climb	20	8000	660	80
Cruise	8000	8000	2100	100
Cruise descent	8000	20	480	75
Approach and landing	20	0	120	0