FS Thrust versus Altitude,

A Method to get accurate results

Part 1 Introduction

For several years I have been boring everyone with my complaint about jet thrust drop off with altitude in FS being unrealistic. I came up with a method that did significantly correct the drop off, but I only recently became aware of why the method worked. The problem is not that the FS thrust vs altitude calculation is wrong, as I first thought, it is just not implemented the way it should be in the Turbine tables (1503, 1504, 1502, 1506 and 1507) of most of the air files I have seen. If the table values are accurate, thrust is accurate throughout the flight envelope. My aim in this article is to try to explain how to generate those accurate values. My target audience is FDE designers or anyone who is curious about how FS calculates thrust. Definitions for the tables, terms and equations used in this article are contained in Appendix A.

FS takes a simplified approach to jet engine performance that is based on the use of "corrected" values as used by engineers in the jet engine industry. The best explanation for the use of corrected values I found was in "Introduction to Aircraft Flight Mechanics" which can be viewed on Google books. In other documents the term "Referred" is used instead of "Corrected" Using corrected values allows engineers to calculate engine performance for any combination of altitude, Mach, engine power setting and non-standard atmospheric conditions in a very simple way rather than having to do multiple calculations for every altitude, Mach, engine setting and non-standard atmospheric condition. Being simple it is easily implemented in software like FS.

To start with a well-known example, the static thrust specified for an engine relates to the thrust it would give under standard atmosphere conditions for sea level, 15°C and pressure 29.92 in Hg or 1013.2 millibars, at full throttle.

Chances are that when the static thrust of an engine is tested, the temperature and pressure will not be standard. So the actual test thrust is "corrected" to what it would be in a standard atmosphere at sea level. The correction involves the difference between test temperature and pressure and standard temperature and pressure. Similarly, measured airflow through the engine and fuel consumption can be corrected to the standard sea level atmosphere values, though that will not be discussed in this article.

The basis for the "corrected" method is sea level performance in terms of static thrust for different throttle settings and engine speed (N1 and N2). Using standard equations and flight test results the manufacturers can come up with sea level gross thrust, ram drag and net thrust for any throttle setting and Mach number.

Calculations for altitudes other than sea level have to take into consideration the change in ambient pressure and temperature compared to sea level and these are expressed as pressure ratio and temperature ratio for that specific altitude. By applying pressure ratio and temperature ratio effects to sea level values of N1, static gross thrust and engine airflow, corrected values for a specific altitude can be obtained. Corrected N2 (CN2) and corrected N1 (CN1) are used to generate results of corrected gross thrust and corrected inlet airflow from equations for corrected values. These corrected results are then converted (uncorrected) to actual values by applying slightly different forms of the pressure and temperature equations. Using this method, flight tests at a relatively small number of carefully selected combinations of altitude, power settings and Mach number, can yield comprehensive performance data for all combinations of altitude, power settings and Mach number.

In FS the corrected results are computed using the values in the turbine tables. If these table values have been calculated using the same equations used by the corrected method for working out engine performance at altitude, FS will give accurate results. If, like I did when I started on this issue, the values are intuitive guesses/SWAGS, FS will give inaccurate results.

How do you know your results are accurate or not? The best tool I have found is EngineSim, a free NASA product that can be downloaded at www.grc.nasa.gov/WWW/K-12/airplane/ngnsim.html. Java installation is required for it to operate off-line. A brief description of how to use EngineSim is contained in Appendix B.

EngineSim takes inputs of inlet area aka intake area in FS, throttle percent, altitude and Mach and shows results for gross thrust, net thrust, ram drag, fuel flow TSFC and a bunch of other engine performance related values. One can, for example, do a FS flight test at full throttle at close to sea level, 10K, 20K, 30K, 40K altitude and record stabilized Mach and net thrust, then compare them to what the actual values of thrust should have been for that Mach according to EngineSim. The problem is that FS only outputs net thrust, so if there is a difference between EngineSim net thrust and flight test net thrust, did it come from gross thrust or ram drag errors in FS?

The other tool I use is AirWrench, an excellent program that can be bought at http://www.mudpond.org/ for $20. I use AirWrench to find out whether Gross or Ram errors are responsible for the difference. AirWrench uses the same equations as FS and, if the same Mach, altitude and throttle settings are input that were recorded on the flight test, it will give net thrust and CN1, CN2 values that very closely match the test values. AirWrench net thrust results should be noted for later analysis. AirWrench, like FS, will only give net thrust unless you trick it. The trick is to update your air file with zero values in 1507 then rerun AirWrench. Since net thrust is gross thrust minus Ram drag and zero values in 1507 give zero ram drag, AirWrench outputs gross thrust. Write those results down. The difference between the net thrust values first noted and the later gross thrust values recorded is ram drag.

So by using EngineSim to compare test results with what actual ones should be and AirWrench to give net thrust to start with, then gross thrust and ram drag from the difference between gross and net thrust, is easy to work out what to do to minimize the errors.

Using this procedure, with properly calculated values for 1502, 1503, 1504 and iterations on 1506 and 1507, I have flight test net thrust results that differ from EngineSim by less than 0.3% up to the tropopause, 36,089Ft. At sea level the error is a trivial 8 lbs difference compared to a net thrust of 12465. Above the tropopause, EngineSim uses different equations to calculate pressure ratio and temperature ratio, FS does not, but even so net thrust error in FS is only 1% at 45,000ft and 3% at 50,000Ft.

Part 2. How to calculate the right values for 1502, 1503 and 1504

In logical order, FS uses inputs of throttle position, altitude in the form of Inverse Air Pressure Ratio (IAP) and Mach to calculate corrected N2 in tables 1503 and 1504. Corrected N2 is then used in Table 1502 to calculate corrected N1. Corrected N1 is an input along with Mach in 1506 and is used with scalars to output corrected gross thrust. Corrected N1 and Mach are inputs in 1507 which outputs corrected ram drag. The corrected values for gross thrust and ram drag are then Uncorrected by the program to give actual gross thrust and actual ram drag for the flight conditions. Actual net thrust is calculated as actual gross thrust minus actual ram drag. The corrected values are simply tools used to compute actual thrust related values, they are not used in the aerodynamic calculations in FS.

It can be seen that the key parameter is CN1. The issue is how to get it right by having the right values in 1503, 1504 and 1502.

For zero Mach, using the corrected method, CN1 should increase with altitude according to this equation CN1=N1/Sqrt(theta) where theta is the temperature ratio for the specified altitude. The same equation applies to CN2. As stated earlier, the equations used are listed in Appendix A.

For example at 30K, theta is 0.7940287. 1/Sqrt(theta) is 1.122 so we need to have CN1= 112.2% when N1=100% at full throttle and when Mach is zero at 30K. Not a realistic situation, but it helps understand what FS does.

1503 has inputs of throttle and IAP for zero Mach and outputs CN2.

In logical order, I made CN2= 112.2% at full throttle in the 1503 IAP column for 30K. I then made CN1 = CN2 in 1502. As a result the CN1value for input in 1506 and 1507 is =N1/Sqrt(theta) (at zero mach) as it should be.

At this point a leap in faith is required. Although FS addresses CN1 and CN2 and appears to be designed around a turbofan engine, I have seen no evidence that it differentiates between a single spool or twin spool engine when it calculates engine performance. So for performance purposes as well as making it easier to explain, I made CN1 = CN2 in 1502.

1504 has inputs of throttle and IAP for high Mach and I used Mach 1.0. Although I said above that CN1=N1/Sqrt (theta) this only applies at zero Mach and the equation should be CN1=N1/Sqrt(theta2). Theta2 is the ratio of Total Air Temperature compared to static temperature (T RATIO in Boeing terms) and is expressed as theta*(1+.2(M)^2). At zero Mach, M=0 and theta2=theta. At Mach 1, theta2 is 1.2 times theta. Sqrt(1.2)= 1.095445 and 1/1.095445 =0. 9129. So full throttle (N1=100) would give CN2 = 91.29% at Mach 1 and sea level. At 30000ft, Mach 1 and full throttle (N1=100) CN2 would be 102.45 which is 112.2 *0.9129.

FS linearly interpolates CN2 between 1503 and 1504 depending on Mach, and since I have made CN1 = CN2 then it effectively does the same for CN1.

This way we get CN1 to be the value intended by the Corrected method for the desired altitude and mach number.

1503 and 1504 use Inverse Air Pressure Ratio (IAP) as their altitude input because that is the best way to address look up tables. A big point here is that FS uses linear interpolation between IAP values to calculate CN2 vs throttle percent. That would be fine if IAP vs altitude was a linear relationship, which it is not. The short answer is to have IAP columns in 1503 and 1504 for at least every 10000 ft interval up to the ceiling for the aircraft.

The 1502, 1503 and 1504 Tables that I used are given below. The aircraft I am using for flight test has a low idle RPM, 2500 for a max of 8000, so my idle is 31.25%. In 1502 I use the same values for the Mach 0 and Mach 1 columns because the effect of Mach on engine speed is taken care of by FS when interpolating between 1503 and 1504. The values used in 1502 are not fixed other than they should be the same for all three columns to make CN1 = CN2. Having said that, idle RPM with some engines is affected by Mach number so one could have different idle values in the Mach 1 column to give realistic high Mach idle.

Record: 1502 Turbine CN1 vs CN2 and Mach No.		
columns: 3	rows: 13	
0	0	1
0	0	0
31.25	31.25	31.25
50	50	50
60	60	60
70	70	70
80	80	80
90	90	90
95	95	95
100	100	100
110	110	110
115	115	115
120	120	120

In 1503 the first column is throttle position. In my case I start with an idle of 31.25 and the second column for IAP=1 represents a straight line increase in CN2 = CN1=N1 at sea level to 100% based on zero throttle being 31.25. If the engine idles at 50%, then obviously the 0.5 throttle setting should give 75% in column 2 and the higher values are then calculated to give a straight line up to full throttle.

In 1503, for each IAP column the 1.0 throttle value should be calculated as 100/Sqrt(theta) for that IAP. I used six IAP columns:

Altitude	SL	10,000	20,000	30,000	36,089	50,000
IAP	1.0	1.4538	2.1743	3.3608	4.4593	8.6869
1/Sqrt(theta)	1.0	1.0362	1.0767	1.1222	1.1533	1.1533
Full throttle CN2	100.00	103.62	107.67	112.22	115.33	115.33

In each row of each 1503 column the values are the IAP=1 value times 1/Sqrt(theta) for that column. Note that the last two columns are the same because theta is constant above 36089 ft altitude.

Record: 1503 Turbine LoMach CN2 vs Throttle and Pressure Ratio						
columns: 7 rows: 9						
0	1	1.4538	2.1743	3.3608	4.4593	8.6869
0.00	31.25	32.38	33.65	35.07	35.94	35.94
0.50	65.63	68.00	70.66	73.65	75.47	75.47
0.75	82.81	85.81	89.16	92.93	95.23	95.23
0.90	93.13	96.50	100.27	104.51	107.09	107.09
0.93	95.19	98.64	102.49	106.82	109.47	109.47
0.97	97.94	101.49	105.45	109.91	112.63	112.63
0.99	99.31	102.91	106.93	111.45	114.21	114.21
1.00	100.00	103.62	107.67	112.22	115.33	115.33

Record: 1504 Turbine HiMach CN2 vs Throttle and Pressure Ratio						
columns: 7 rows: 9						
1	1	1.4538	2.1743	3.3608	4.4593	8.6869
0.00	28.53	29.56	30.71	32.01	32.81	32.81
0.50	59.91	62.08	64.50	67.23	68.89	68.89
0.75	75.60	78.34	81.39	84.84	86.94	86.94
0.90	85.01	88.09	91.53	95.40	97.76	97.76
0.93	86.89	90.04	93.56	97.51	99.93	99.93
0.97	89.40	92.64	96.26	100.33	102.81	102.81
0.99	90.66	93.95	97.61	101.74	104.26	104.26
1.00	91.29	94.60	98.29	102.45	105.28	105.28

In 1504 the values for each IAP column are the corresponding 1503 values times 1/Sqrt (1+.2*(M)^2). If High mach is 0.9 the scalar would be 0.9277. My values are for Mach 1.0 so my 1504 scalar is 0.9129, as explained earlier.

Although making CN1 = CN2 in 1502 may seem strange, it appears to be the easiest way to get IAP inputs to create accurate changes of CN1 with altitude. And, it works really well.

Part 3. How to calculate the right values for 1506.

Calculations for 1502, 1503 and 1504 were made using only scientific methods. I found it was necessary to use somewhat more iterative methods with 1506.

1506 has inputs of CN1 and Mach which give an output of corrected thrust according to scalars on static thrust for each CN1 value. The maximum CN1 input should be at least as high as the maximum CN2 in 1503. I used 116% CN1 for that reason.

I initially used two Mach inputs 0.0 and 1.0 Each Mach input has somewhat different scalars for CN1.

My reason for the different scalars was that I wanted to end up with thrust increments at low Mach that followed real world thrust variation with N1, namely a gradual slow increase below about 70% followed by an increasingly steep increase above 70% with thrust at 100% being roughly double thrust at 85%. Since Mach is zero for the low Mach curve I used a 1.0 scalar at 100% CN1.

Most of the iterations came when fitting the high Mach scalars to give minimum errors of gross thrust for full throttle compared to EngineSim, for each of my selected altitudes that were given in the 1503, 1504 discussion.

It should be noted that CN1 varied with altitude as desired and the data points in the charts represent :

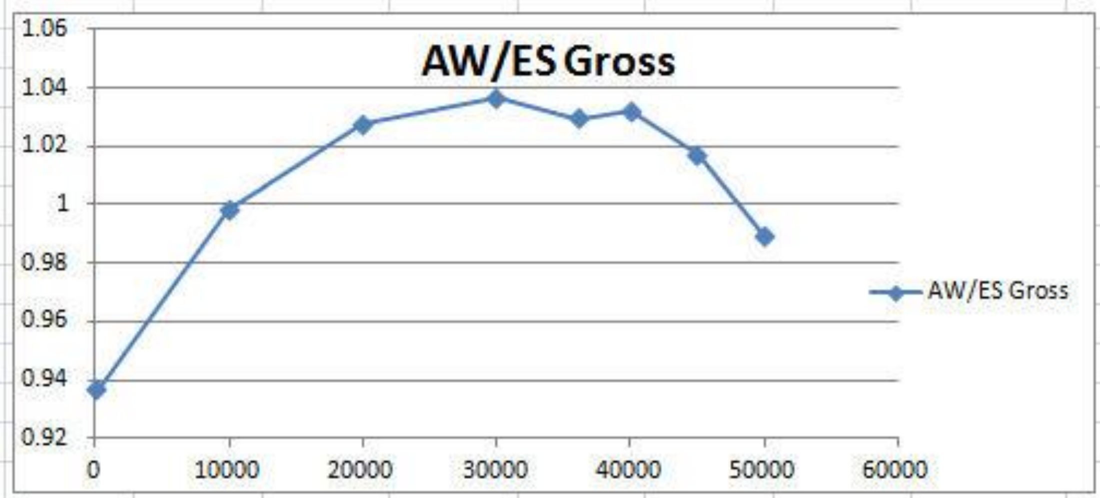
Alt	SL	10,000	20,000	30,000	36100	40,000	45,000	50,000
Mach	0.943	0.949	0.947	0.946	0.944	0.939	0.916	0.900
CN1	91.82	95.06	98.80	102.95	105.84	105.91	106.14	106.30

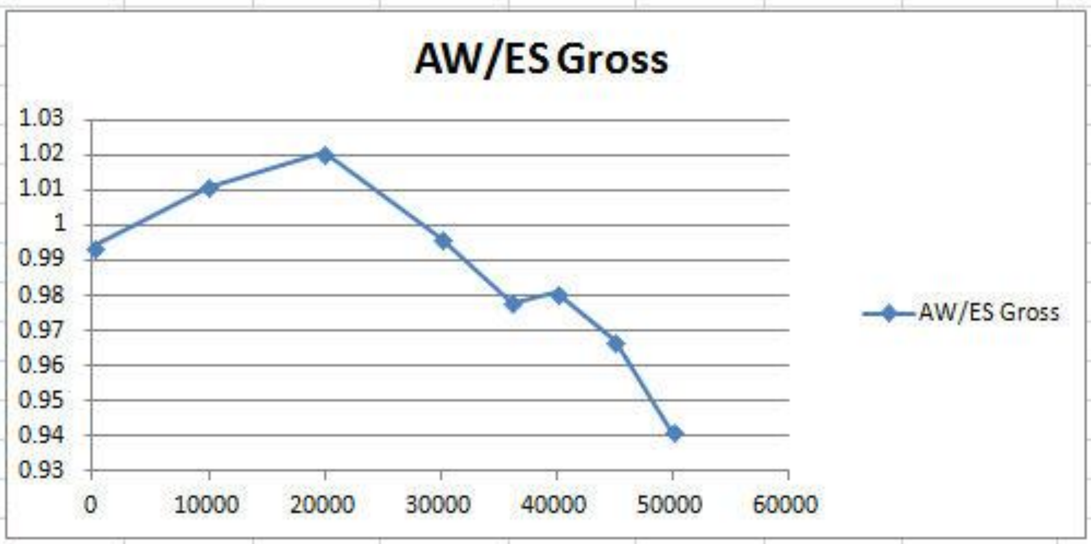
Although not shown, N1 readout was between 99.9 and 100.1 on the test flight where this data was recorded. On some test flights N1 was lower, but never less than 99.6. N1 is an actual, real value and with the right corrected values in the tables the N1 readout is as it should be, close to 100% at full throttle at all speeds and altitudes in FS. If the right corrected values are not in the tables, the readout of N1 is just inaccurate rubbish.

Since I was comparing gross thrust, I compared AirWrench gross thrust (with zero values in 1507) with EngineSim gross thrust.

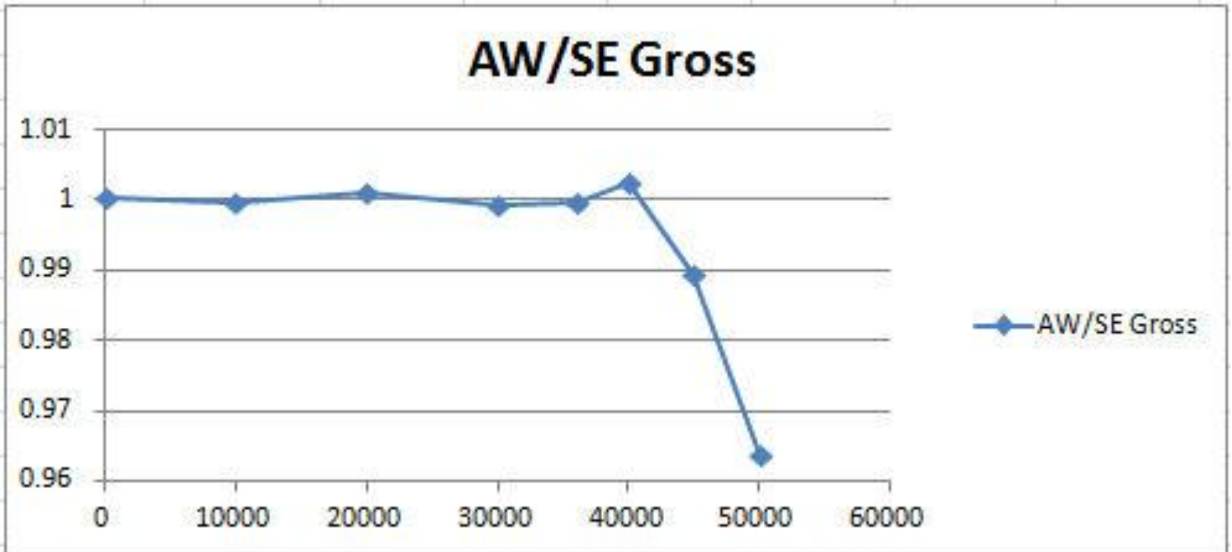
I found that I could vary the slope of the errors by varying the slope of the 1506 scalars.

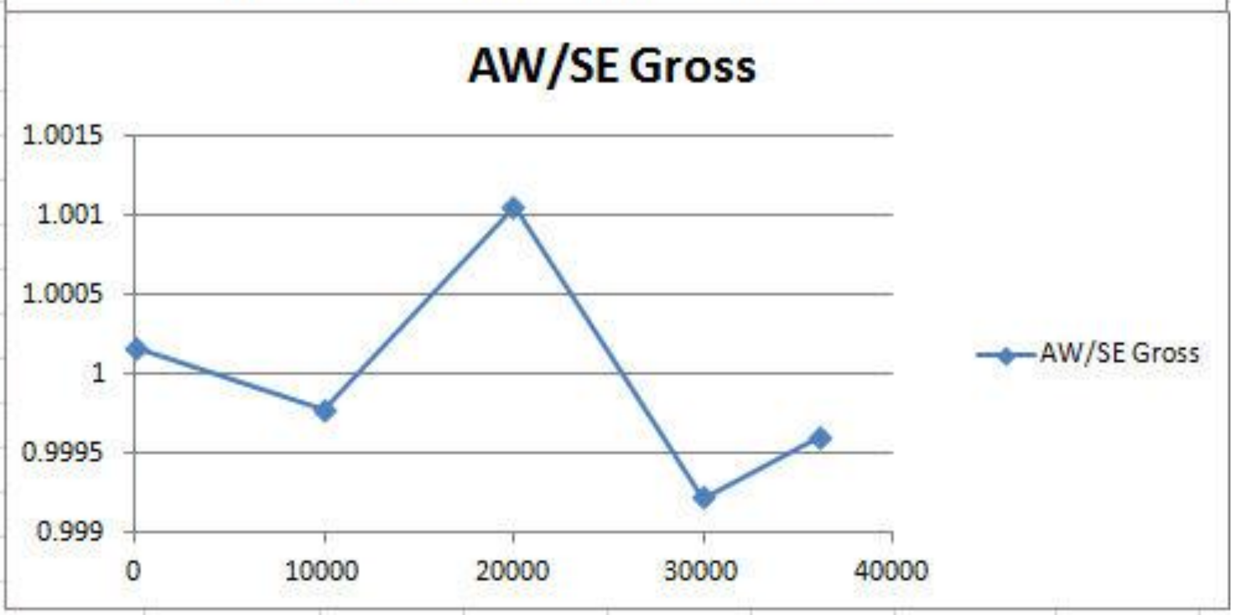
For example, my first plot of AirWrench (AW) divided by EngineSim (ES) gross thrust had low values at low altitude and high values at high altitude as shown in the first chart below. The Y axis at 1.0 represents ES gross thrust and the data points represent how AW varied from ES





The second chart shows my initial attempt to increase low altitude gross thrust and decrease it a high altitudes. I over did the slope change but still was low on thrust overall. After 12 iterations I got the results shown on the next page





It can be seen that there was very good agreement between 1.0 on the Y axis, ES, and the AW results, up to 36100 ft (closest I could get to 36089 using autopilot), then a small rise at 40,000 followed by a drop above that. The drop is due to the fact that FS and AW calculate pressure ratio and temperature ratio the same way above the tropopause as below it, whereas ES uses different equations.

The lower chart just cover altitudes to 36100 ft. The scale has changed, so at first glance it looks bad, but the maximum error in gross thrust at 20,000 feet is 0.1% which was 10 lbs over the ES value. My technique was to set a Mach 1 scalar for

90% CN1 and another higher value at 110% CN1, then automatically calculate intervening values so that they were on a straight line between 90 and 110.

It should be noted that all tests and data discussed so far are for full throttle. The main reason for doing so is that EngineSim's Throttle setting is a bit ambiguous at less than 100%. The EngineSim will not run at zero throttle. So for comparison purposes 100 which is full throttle was used to establish the accuracy of FS thrust.

In passing, I have also applied this method to a low (1.1 to 1) bypass turbofan and needed very minor changes to 1506 because EngineSim gave a very small difference in the rate of thrust decrease with altitude compared to the turbojet I initially modeled. This is the 1506 table I used for the turbojet.

Record: 1506 Turbine Thrust Scalars vs CN1 and Mach No.		
columns: 3 rows: 19		
0	0	1
0	0	0
30	0.1000	0.1075
40	0.1000	0.1075
45	0.1200	0.1290
50	0.1500	0.1613
64	0.2000	0.2150
80	0.4000	0.7311
90	0.5600	1.0733
92	0.6300	1.0974
94	0.7000	1.1215
96	0.8000	1.1456
98	0.9300	1.1698
100	1.000	1.1939
102	1.071	1.2180
104	1.1335	1.2421
106	1.2012	1.2662
110	1.2450	1.3145
116	1.2540	1.3500

The CN1 column has small intervals above 90% because I wanted to be able to simulate the steepness of the thrust increase above 90% at zero Mach, in column two. In columns three, Mach 1.0, the values between 90% and 110% CN1 are linear. Values below 80% can vary according to the idle RPM and the table reflects my 31.25% idle in 1503. I only used two Mach columns for 0 and 1.0. FS interpolates linearly between the columns and I found no need for an intermediate Mach column.

Part 4. How to calculate the right values for 1507.

Having established values for gross thrust (with 1507 all zeros) the next step was to put values in for 1507 using stock data. AirWrench then gave net thrust and by subtracting that from the established gross thrust the results were compared with EngineSim values for ram drag.

After only three iterations I got ram drag agreement with EngineSim within 0.03% from sea level to 36100 ft. I did not have to make any changes to 1507 when I modeled the low by-pass ratio turbofan.

The 1507 values I got were a big surprise.

Record: 1507 Ram Drag Factor vs CN1 and Mach No.		
columns: 3 rows: 9		
0	0	1
0	0	0
90	36.3900	36.39
100	36.395	36.395
102	36.396	36.396
104	36.397	36.397
106	36.398	36.398
116	36.4	36.4

The surprise was that the ram drag factor was almost a constant. 1507 inputs Mach and CN1. Granted my Mach variation was small but my CN1 variation was significant as shown on the next table.

Flight Test Data Points			
Altitude	Mach	CN1	N1
100	0.9433	91.7	99.6
10000	0.9468	96.0	99.7
20000	0.9506	98.7	99.8
30000	0.9533	102.8	99.8
36100	0.9544	105.6	99.9
40000	0.9519	105.7	99.7

Note the fact that N1 was close to 100 all the way up since it is an uncorrected, real value. By using the right corrected values N1 is now always 100% at full throttle and gives an accurate value for engine speed.

Part 5. Conclusions.

FS uses the corrected method for calculating altitude performance. This involves interaction between the corrected values in the turbine tables. If these values are calculated properly, FS will give very accurate results for actual thrust versus altitude.

For the record, I did not consider table 1501 because its content is now largely contained in the aircraft.cfg file [TurbineEngineData] section.

I did not consider table 1505 because my tests were confined to full throttle operations. There is an interaction between idle CN1/CN2 in 1506 and the values in 1505, but it did not affect my results.

I did not consider table 1548 because it is for turboprop/helicopter aircraft and plays no part in thrust calculations for turbojet/turbofan engines.

I welcome inputs on this article, especially suggestions on better ways to explain the points I have made so they would be easier to understand.

Roy

Appendix A. Tables, Terms and Equations

<u>Tables mentioned in the text.</u>

Record	ESP/P3D Token	Input X	Input Y	Output
1502	AIR_70_N2_TO_N1_TABLE	Mach	CN2	CN1
1503	AIR_70_MACH_0_CORRECTED_COMMANDED_NE	IAP	Throttle	CN2
1504	AIR_70_MACH_HI_CORRECTED_COMMANDED_NE	IAP	Throttle	CN2
1506	AIR_70_N1_AND_MACH_ON_THRUST	Mach	CN1	Corrected Gross Thrust/ Static Thrust
1507	AIR_70_CORRECTED_AIRFLOW	Mach	CN1	Corrected Airflow

<u>Terms mentioned in the text</u>.

IAP. Inverse Atmospheric Pressure ratio. The inverse of the ratio of pressure at the aircraft altitude and Standard Sea Level pressure.

N1. Rotational speed of the low speed rotor of a twin-spool jet engine usually expressed as a percentage of some value for its maximum speed. The first stages of the engine compressor are connected to this rotor which is driven by the last stage of the turbine.

N2. Rotational speed of the high speed rotor of a twin-spool jet engine usually expressed as a percentage of some value for its maximum speed. The second stages of the engine compressor are connected to this rotor which is driven by the first stage of the turbine.

Corrected. In the context of this article "Corrected" refers to a method used by engineers and test pilots to calculate jet engine thrust for any combination of power setting, Mach and altitude based on sea level performance. Corrected values are not used in FS aerodynamic calculations they are tools used to calculate actual values.

CN1. Corrected N1, used in FS as part of the calculation of Corrected Gross Thrust and Corrected Airflow/Ram Drag in tables 1506 and 1507

CN2. Corrected N2, calculated in FS from throttle position, IAP and Mach number in tables 1503 and 1505. CN2 drives CN1 according to values in table 1502.

Corrected Gross Thrust is a value calculated in FS from inputs of CN1 and Mach according to scalars associated with CN1 and Mach number. (Table 1506)

Corrected Airflow aka Corrected Ram Drag is a value calculated from inputs of CN1 and Mach number. (Table 1507)

Equations used by FS in thrust calculations.

theta is temperature ratio for a particular altitude compared to standard sea level temperature. theta = (288.15-1.98*altitude/1000)/288.15. This equation is valid for altitudes up to the tropopause 36089 ft, but FS appears to use it for all altitudes

delta is pressure ratio for a particular altitude compared to standard sea level pressure. delta = theta^5.256 and like theta is valid up to the tropopause but FS appears to use it for all altitudes

theta2 = theta*(1+0.2*(M^2)) and is total air temperature ratio for a particular altitude and Mach (M) number. It's validity is the same as for theta.

delta2 = delta*(1+0.2*(M^2))^3.5 and is total air pressure ratio for a particular altitude and Mach (M) number. It's validity is the same as for delta

Gross Thrust =Static Thrust * [Table 1506] * delta 2

Ram Drag = (V/g)* Intake Area * [TBL 1507] * delta2/sqrt(theta2) where V is Mach number in ft/sec and g is 32.174 ft/sec/sec.

Net thrust = Gross thrust - Ram Drag

Corrected equations

CN1 = N1/Sqrt(theta2) Getting CN1 values right is the main issue for accurate altitude performance simulation in FS

CN2 = N2/Sqrt(theta2)

Corrected Gross Thrust = Gross thrust/delta2

Corrected Ram Drag =V/g*intake area*Sqrt(theta2)/delta2 where V is Mach number in ft/sec and g is 32.174 ft/sec/sec.

Conversion from corrected values to actual values

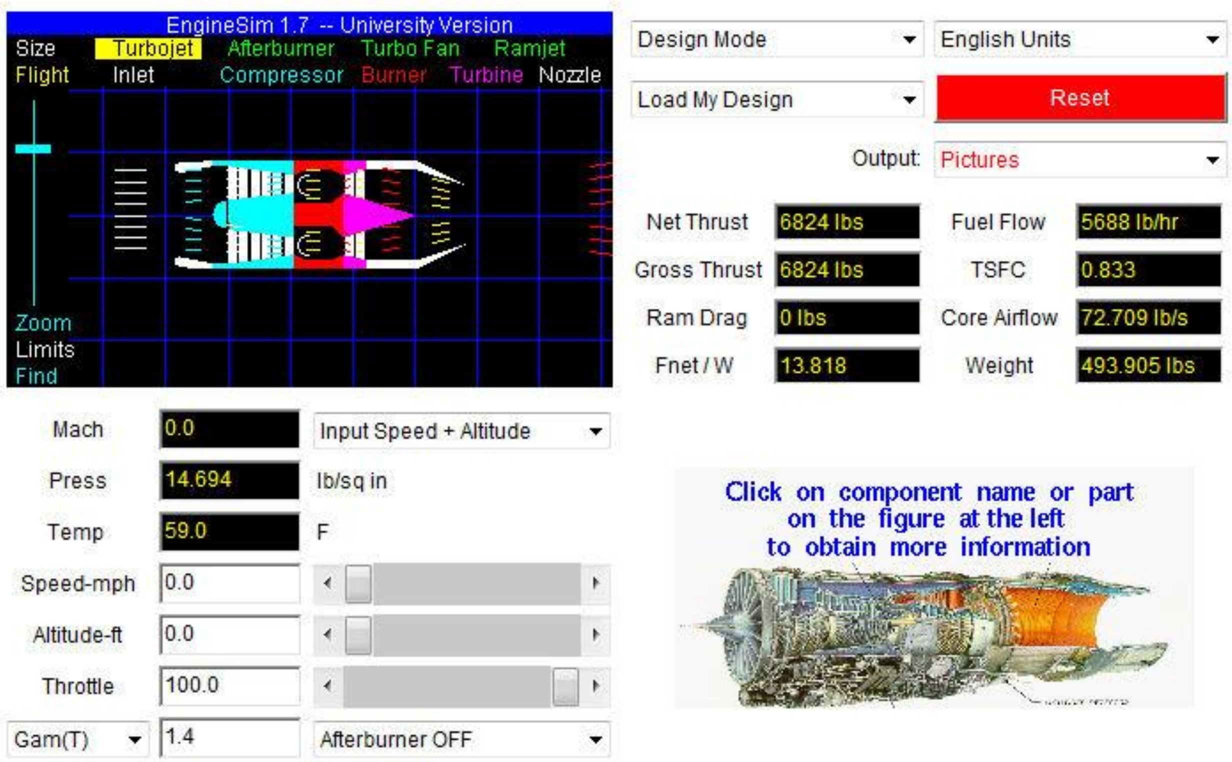
Actual Gross Thrust= Corrected Gross thrust*delta2

Actual Ram Drag =Corrected Ram Drag*delta2

Appendix B. EngineSim a brief guide.

On opening the program you will probably get a message about blocked content, click "Allow Blocked Content"

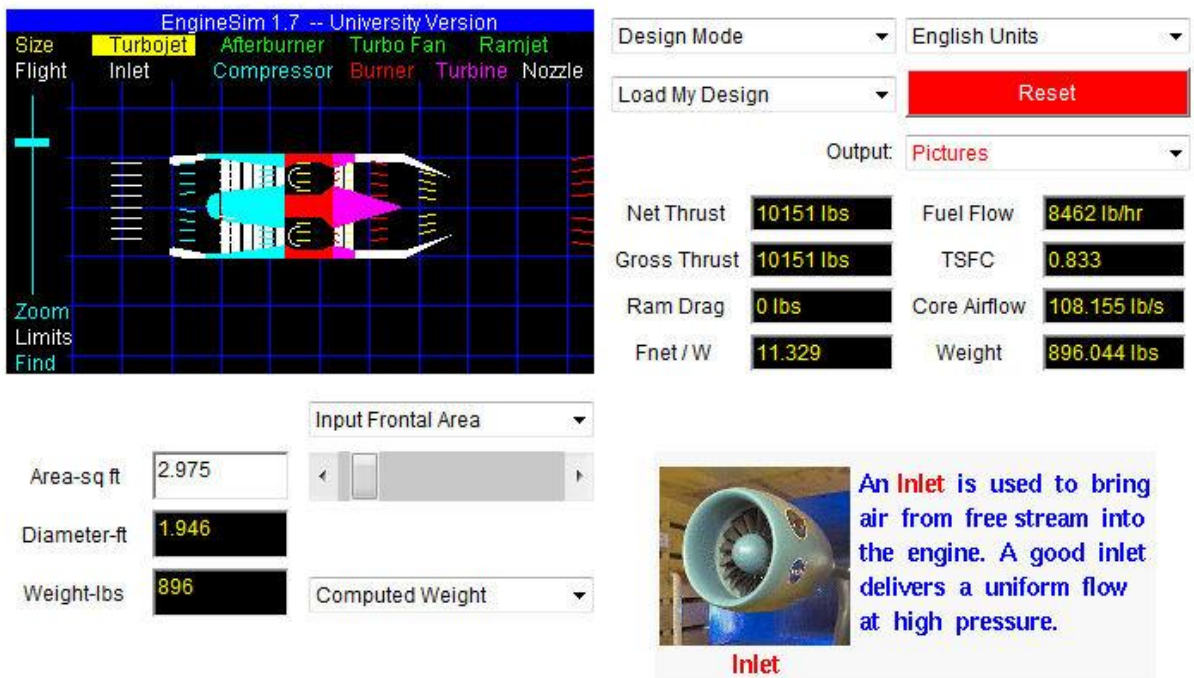
The initial screen appears:



The selected engine is a turbojet. There are readouts for Net thrust, Gross Thrust, and Ram Drag. Ram Drag is zero because Speed-mph is zero. A drop down allows entry of Mach and altitude. The thrust figures are for the default inlet area of 2.0 square feet.

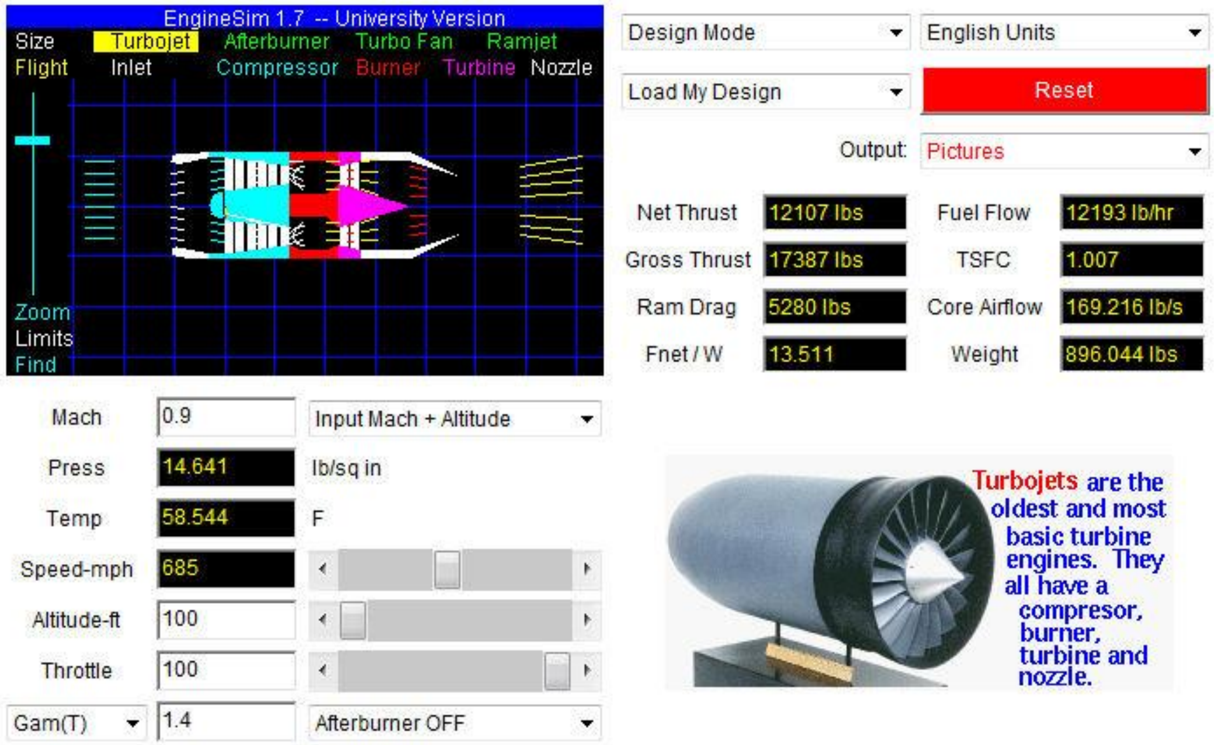
The first thing to do is change the inlet size aka Intake area in FS. Click on Inlet just below Turbojet and then click on size to the left of Turbojet.

The next screen allows you to change the dimensions of the inlet area



In my case the inlet area was 2.975 sq ft. A nice feature of the program is that you can enter different values for size and the Thrust will be adjusted accordingly. I wanted 10150 Gross (static) thrust and found I got that with 2.975 sq ft area.

Once you have the inlet size correct, click on turbojet.



Here I have entered 0.9 Mach, 100 ft altitude and made sure the Throttle was at 100. This gave a Gross Thrust of 17387 lbs, Net of 12107 and Ram Drag of 5280. There is also a readout of fuel flow lbs/hr and TSFC. When you have finished with entering the data, press Enter and the program does its calculations.

I have just touched on how to get the program set up and started. There are a lot of other features in the program but what I have covered gives the type of results described in the text.