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An Evaluation of Performance Metrics for High Efficiency Tube-and-Wing Aircraft Entering Service in 2030 to 2035

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Abstract

An analysis of basic vehicle characteristics required to meet the Fundamental Aeronautics Program's 70 percent energy consumption reduction goal for commercial airliners in the 2030 to 2035 timeframe was conducted. A total of 29 combinations of vehicle parasitic drag coefficient, vehicle induced drag coefficient, vehicle empty weight and engine Specific Fuel Consumption were used to create sized tube-and-wing vehicle models. The mission fuel burn for each of these sized vehicles was then compared to a baseline current technology vehicle. A response surface equation was generated of fuel burn reduction as a function of the four basic vehicle performance metrics, so that any values of the performance metrics up to a 50 percent reduction could be used to estimate fuel burn reduction of tube-and-wing aircraft for future studies.

Introduction

In March of 2008, The NASA Fundamental Aeronautics Program released a set of four high-level performance goals for commercial passenger aircraft expected to enter service between 2030 and 2035. These goals can be summarized as follows.

1. Maintain a 55 dB Day-Night Average Noise Level (55 LDN) at an average airport boundary. This noise level should be sufficient to keep all objectionable noise within the airport boundaries.
2. Decrease Landing/Take-Off (LTO) NOx emissions to 75 percent below the level set at the sixth meeting of the Committee on Aviation Environmental Protection (CAEP/6).
3. Decrease total mission energy consumption (fuel burn, if a constant fuel type is used) by 70 percent over a comparable current state-of-the-art commercial airliner.
4. Increase air traffic capacity by designing aircraft capable of using multiple existing smaller airports within a single metropolitan region, rather than requiring an increase in capacity at the current major airports. This is sometimes referred to as the metroplex concept. This requirement implies that large commercial aircraft be designed to utilize shorter runways (perhaps 5000 ft or less) than are typically available at the principal metropolitan airports.

While each of these requirements can significantly impact aircraft design, the following study focuses on the 3rd goal, the reduction of mission energy consumption by 70 percent. This study was limited to this single performance goal to determine if the reduced energy consumption requirement could be met even without the constraints of the other three requirements, which was not clear at the time the NASA goals were established.

The study that follows is an analysis of basic vehicle characteristics required to meet the 70 percent energy consumption reduction goal. A total of 29 combinations of vehicle parasitic drag coefficient (C_{D0}), vehicle induced drag coefficient (K), vehicle empty weight (W_e), and engine Specific Fuel Consumption (C) were used to create sized tube-and-wing vehicle models. The mission fuel burn for each of these sized vehicles was then compared to a baseline current technology vehicle. A response surface equation was generated of fuel burn reduction as a function of the four basic vehicle performance metrics, so that any values of the performance metrics up to a 50 percent reduction could be used to estimate fuel burn reduction of tube-and-wing aircraft for future studies. The baseline vehicle selected for this study is the Boeing 737-800 with CFM56-7B27 engines. Actual data from the baseline vehicle was not used in preparing the baseline analysis case in order to avoid any use of proprietary information. Instead, models of a similar aircraft and engine combination were created that met the published performance of the 737-800 from company websites and public sources such as Jane's All The World's Aircraft (Ref. 1).

Baseline Vehicle Characteristics and Performance

As a first step, the reference vehicle, typical of a Boeing 737-800 with CFM56-7B27 engines, was modeled. The Conceptual Research Corporation aircraft conceptual design software RDS-Pro (Ref. 2) was used to model the baseline aircraft. Table I gives the publically available data for this aircraft from Reference 3, along with calculated reference values for C, C_{D0}, and K at cruise. Additional detailed geometric data for the reference aircraft, scaled from Reference 3, is given in Appendix A. Geometric data required for the model but not publically available was estimated based on previous modeling activities for similar aircraft and is provided in Appendix B, along with a summary of the principle geometric features of the aircraft as generated by the RDS-Pro software. Figure 1 shows two views of the modeled aircraft, without control surfaces, generated by the RDS-Pro software.

With the geometric data assembled, RDS-Pro was used to generate L/D characteristics and drag curves, Appendix C, and a weight breakdown, Appendix E, for the aircraft. The miscellaneous weight value in the weight breakdown was adjusted slightly to make the calculated vehicle empty weight exactly equal to the published weight. Typical turbofan specific fuel consumption and thrust characteristics were calibrated to published data for the CFM56-7B27 (Ref. 4), and are provided in Appendix D.

As a validation check, a standard commercial airliner mission, including a 200 nmi diversion allowance, was analyzed for the modeled reference vehicle. The mission was optimized for range by varying cruise altitude and Mach number as needed for best performance. The resulting calculation yielded a maximum cruise range of 2774 nmi, which compared acceptably to the published value of 2820 nmi (Ref. 3).

TABLE I.—REFERENCE VEHICLE SPECIFICATIONS

Passengers and Crew	162 to 189
Maximum takeoff weight	174,200 lb
Empty weight	91,990 lb
Maximum fuel load	46,750 lb
Cargo capacity	1,555 ft^3
Cruise speed	0.785 Mach
Engines	2
Cruise specific fuel consumption	0.64 lbm/hr/lbf
Total SLS thrust	54,600 lb
Vehicle length	129.6 ft
Wing span	112.6 ft
Cruise C_{D0}	0.0241
Cruise K	0.0376

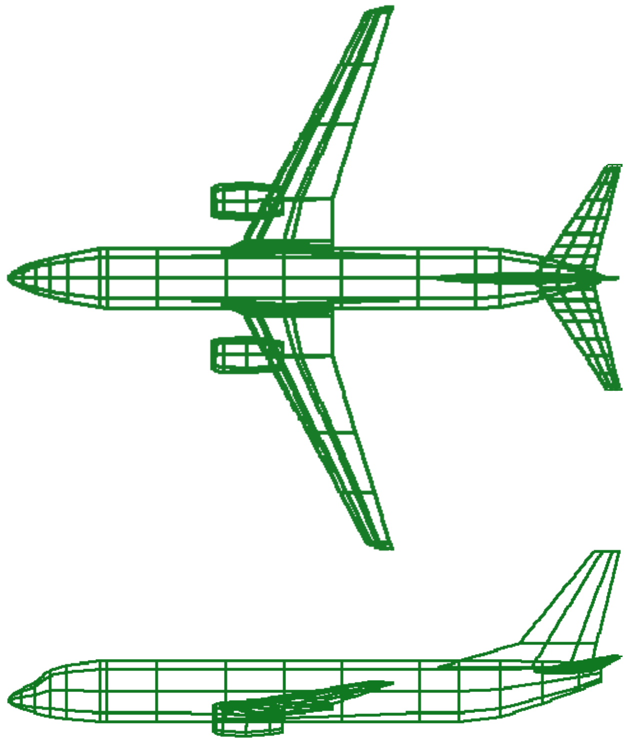

Figure 1.—Top and side views of RDS-Pro 737 model.

Design Parameter Exploration

In order to study the individual and combined effects of the four principle vehicle performance metrics (C_{D0}, K, W_e, and C), a 4-parameter Box-Behnken (Ref. 5) design space exploration was undertaken. Three levels of parameter improvement relative to the baseline vehicle were used, a 50 percent improvement, a 25 percent improvement, and no improvement, in various combinations given in Appendix F. In addition to the 25 cases required for the Box-Behnken design, four cases were added with a 50 percent improvement in a single parameter, representing the corners of the design space.

In performing the vehicle sizing for each case, the vehicle thrust to weight ratio, the wing loading, and the tail volume coefficient were held constant. The fuselage size was held constant to allow for a true-scale representation of the re-sized aircraft. Photo-scaling was not used. Using the RDS-Pro software, it was not necessary to specify exactly how the parameter improvements were achieved technologically, only that the parameter was improved by the specified amount. Each vehicle was required to perform the same sizing mission as the reference vehicle. The resulting fuel burn reduction for each sized vehicle is also listed in Appendix F.

A regression analysis using the statistical analysis software package Sigmastat (Ref. 6) was then performed to fit fuel burn results to the four performance metric values. All of the input performance metrics and the resulting fuel burn were normalized to the values for the reference vehicle, renamed ${C_{D0}}'$, K', C', ${W_e}'$ and F'. An acceptable statistical fit for fuel burn (F') was not found based on the four original vehicle performance metrics. However, since fuel burn is directly proportional to thrust and specific fuel consumption, and thrust is proportional to drag, which is in turn proportional to Take-Off Gross Weight (${W_{TO}}'$) (since wing loading is held constant for this sizing study), then logically F' should be a function of W_{TO}', rather than W_e'. Having determined that W_{TO}' could be accurately obtained from a fit of the four original vehicle performance metrics, Equations (1) and (2) was fit from the values of C_{D0}', K', C', and W_{TO}' and found to accurately predict fuel burn for a tube-and-wing configuration flying the design mission. Since all the values in Equations (1) and (2) are normalized to their values for the reference vehicle, given in Table I, each parameter has a value of unity for no improvement, and an improved value between zero and unity. As a measure of the accuracy of the regression fit, W_{TO}' and F' for the baseline case are calculated to be 0.999 and 0.998, respectively when calculated using these expressions. The standard deviation was calculated to be 0.0024.

$$W_{TO}' = 0.551C_{D0}' + 0.234K' + 0.515C' + 0.0653C_{D0}'^2 + 0.104C'^2 + 0.546W_e'^2 - 0.341C_{D0}'K' - 0.946C_{D0}'C' - 0.52C_{D0}'W_e' - 0.429K'C' - 0.463W_e'C' + 0.23W_e'K'C' + 0.917C_{D0}'W_e'C' + 0.536C_{D0}'K'C' \tag{1}$$

$$F' = 0.0718 - 0.154C_{D0}' + 0.0861K' - 0.0722C' - 0.197W_{TO}' - 0.0652K'^2 - 0.0522C'^2 + 0.175C_{D0}'C' + 0.276C_{D0}'W_{TO}' + 0.579C'W_{TO}' + 0.0504C'K'C_{D0}' + 0.0801K'C_{D0}'W_{TO}' + 0.221C'K'W_{TO}' \tag{2}$$

Using these relationships, exploration into what combinations of vehicle performance metrics could potentially meet the 70 percent fuel burn reduction goal becomes simple. Figure 2 shows the fuel burn reduction as a function of performance metric improvement for each of the metrics taken separately, and also for simultaneous improvement in all four metrics taken together in equal percentages. These calculations are limited to a 50 percent performance metric improvement in any single metric, as that is the extent of the original improvements used to develop the curve fit. Improvements beyond this point represent extrapolation beyond the existing data, and are subject to significant error.

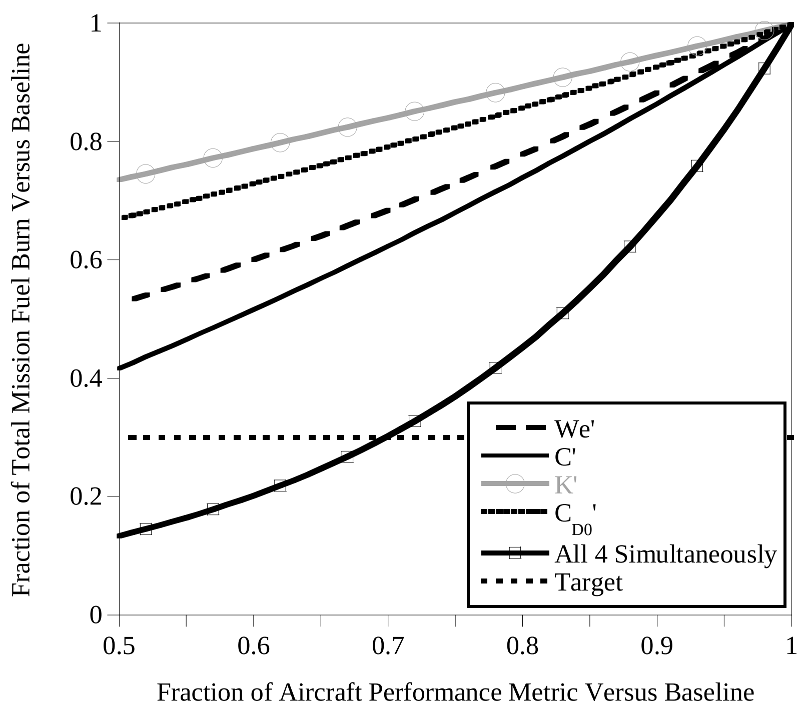

Figure 2.—Performance metric analysis results.

Examination of Figure 2 indicates that even a 50 percent improvement in a single performance metric is insufficient to reach the 70 percent fuel burn reduction goal. It is also evident that improvements in specific fuel combustion yield the greatest fuel burn reduction, followed by empty weight, parasitic drag, and induced drag, respectively. If these improvements are taken in equal proportion simultaneously, it is shown that a 30 percent improvement in all four metrics is required to meet the fuel burn reduction goal. While even a 30 percent improvement in any single metric is very challenging, it is not inconceivable that such an improvement could be made.

Summary and Conclusions

In order to evaluate the possibility of meeting the Subsonic Fixed Wing N+3 generation of aircraft performance goal of 70 percent fuel burn reduction , a total of 29 advanced tube-and-wing aircraft conceptual designs were generated and compared to a validated current technology baseline aircraft flying the same design mission. A statistical curve fit of fuel burn versus the four fundamental performance metrics of vehicle parasitic drag, vehicle induced drag, vehicle empty weight, and engine specific fuel consumption was generated. Evaluation of this curve fit showed that up to a 50 percent improvement in any single vehicle performance metric would not result in an aircraft capable of meeting the fuel burn reduction goal, but that a 30 percent simultaneous improvement in all four of the performance metrics would result in an aircraft capable of meeting the goal.

The statistical curve fit of fuel burn also provides a simple tool for evaluating the overall effect of proposed technology advances on tube-and-wing aircraft performance, provided that their effect on the four fundamental vehicle performance metrics can be estimated, without having to undertake a full vehicle conceptual design.

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2. Raymer, D., “RDS-Professional in Action: Aircraft Design on a Personal Computer,” SAE/AIAA Paper 96-5567, October 1996.
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4. CFM56 Engine Website, URL: http://www.cfm56.com, January 2009.
5. Montgomery, D.C., *Design and Analysis of Experiments*, John Wiley & Sons, New York, 2001.
6. SigmaStat website, URL: http://www.aspiresoftwareintl.com/html/systat.html.

Appendix A—Reference Vehicle (Boeing 737-800) Detailed Geometry

Fuselage:
Length = 124.93 ft
Height = 13.16 ft
Width = 12.34 ft
Cabin width = 11.58 ft
Fineness ratio = 10.21

Wing:
Span = 112.60 ft
Trapezoidal area = 1340.94 ft^2
Aspect ratio = 9.45
Taper ratio = 0.159
Mean aerodynamic
Chord(MAC) = 12.99 ft
Dihedral angle = 6°
1/4 Chord sweep
Angle = 25.02°
Flap span/Wing span = 0.599
Flap area/Wing area = 0.3

Tail Fin:
Height = 23.49 ft
Area = 284.59 ft^2
Rudder area = 56.19 ft^2
Aspect ratio = 1.91
Taper ratio = 0.271
1/4 Chord sweep = 35°

***Tail Horizontal Stabilizer*:**
Span = 47.08 ft
Tailplane area = 352.83 ft^2
Elevators area = 70.50 ft^2
Aspect ratio = 6.16
Taper ratio = 0.203
Dihedral angle = 7°
1/4 Chord sweep
Angle = 30°

Appendix B—Reference Vehicle (Boeing 737-800) RDS-Pro CAD Model Geometry

TABLE II.—AIRFOIL GEOMETRY

Parameter	Wing	Horizontal tail	Vertical tail
Reference area (ft^2)	1255.16	352.84	284.60
Aspect ratio	10.08	6.16	1.91
Taper ratio	0.27	0.20	0.27
Leading edge sweep (degrees)	28.72	34.41	40.38
¼ Chord sweep (degrees)	26.15	30.00	35.00
Airfoil type	Boeing 737	Scaled NACA 64A	Scaled NACA 64A
Thickness/chord ratio (%)	14.90	12.00	12.00
Dihedral (degrees)	6.00	7.00	0.00
Incidence (degrees)	0.00	0.00	0.00
Twist (degrees)	0.00	0.00	0.00
Span (ft)	112.48	46.62	23.32
Root chord (ft)	17.57	12.58	19.21
Tip chord (ft)	4.75	2.55	5.21
Mean Aerodynamic Chord (MAC) (ft)	12.39	8.68	13.55
Distance of MAC from vehicle centerline (ft)	22.74	9.08	9.43

TABLE III.—SUMMARY OF AIRCRAFT COMPONENT GEOMETRY

	Fuselage	Wing	Horizontal tail	Vertical tail	Engine nacelle
Length (ft)	124.93	50.71	23.31	23.32	14.68
Width (ft)	12.34	36.41	18.52	38.20	7.25
Height (ft)	12.34	2.85	1.51	2.55	6.78
A-Max (ft^2)	131.03	45.58	12.59	57.60	40.72
L/D (Equivalent)	9.67	6.66	5.82	2.72	2.04
Total surface area (ft^2)	4316.37	2326.63	721.10	717.38	307.55
Surface area + Ends (ft^2)	4320.34	2372.31	734.22	777.38	351.47
Total volume (ft^3)	12433.46	1360.46	244.63	433.22	503.07

Appendix C—RDS-Pro Reference Vehicle Estimated Aerodynamic Performance

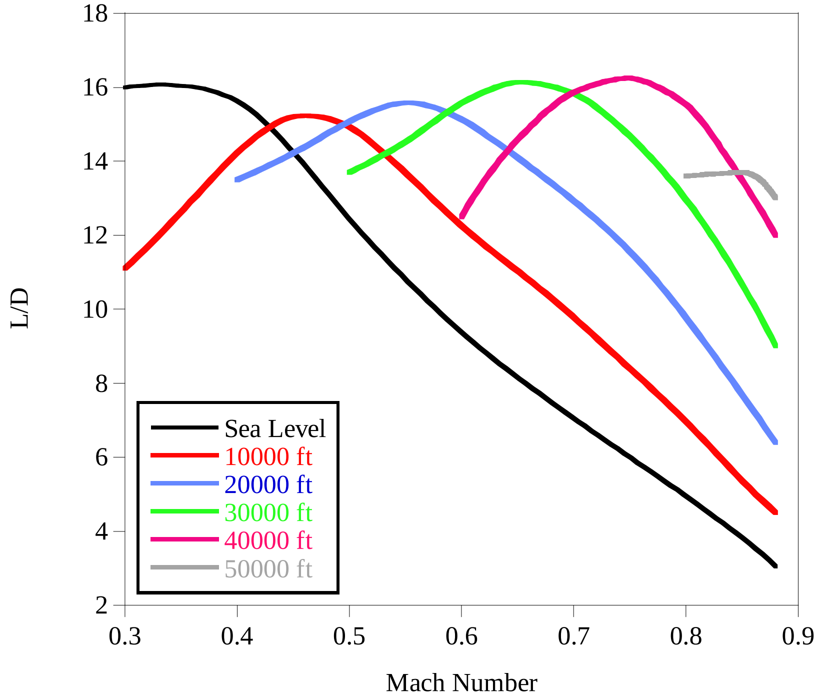

Figure 3.—Vehicle L/D versus free stream Mach number.

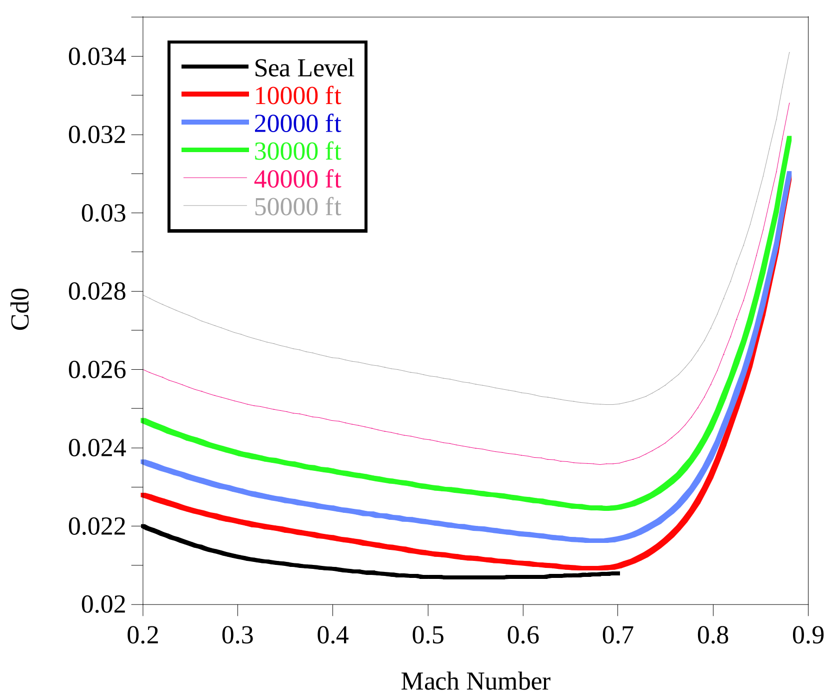

Figure 4.—Vehicle parasitic drag coefficient versus free stream Mach number.

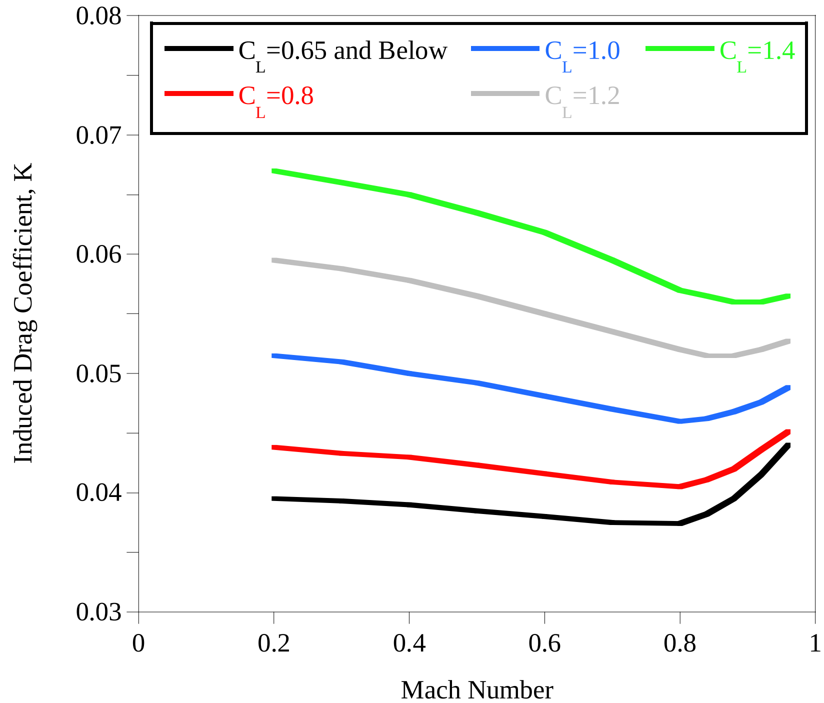

Figure 5.—Vehicle induced drag coefficient versus fee stream Mach number as a function of vehicle lift coefficient, C_L.

Appendix D—RDS-Pro Reference Vehicle Engine Performance

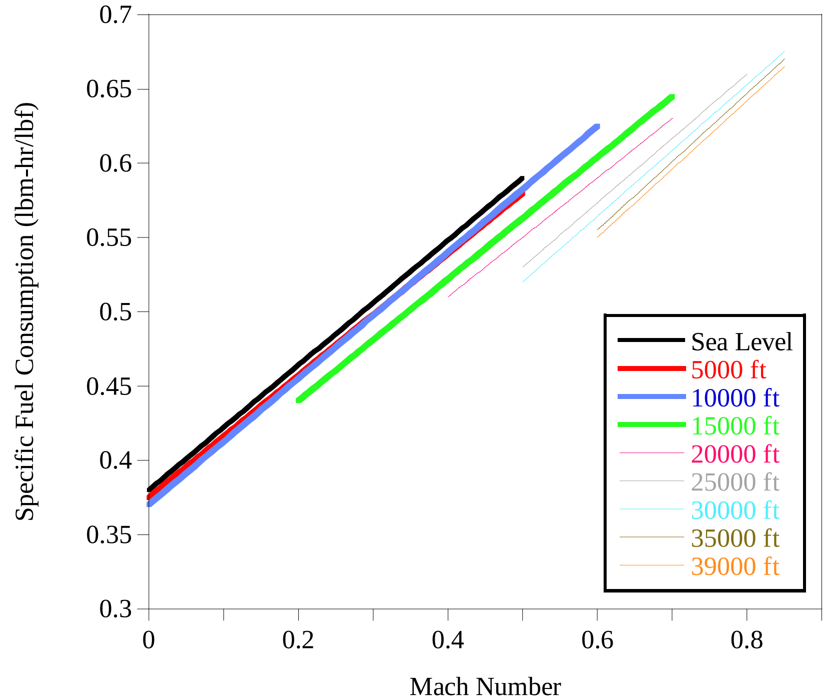

Figure 6.—Engine specific fuel consumption versus free stream Mach number.

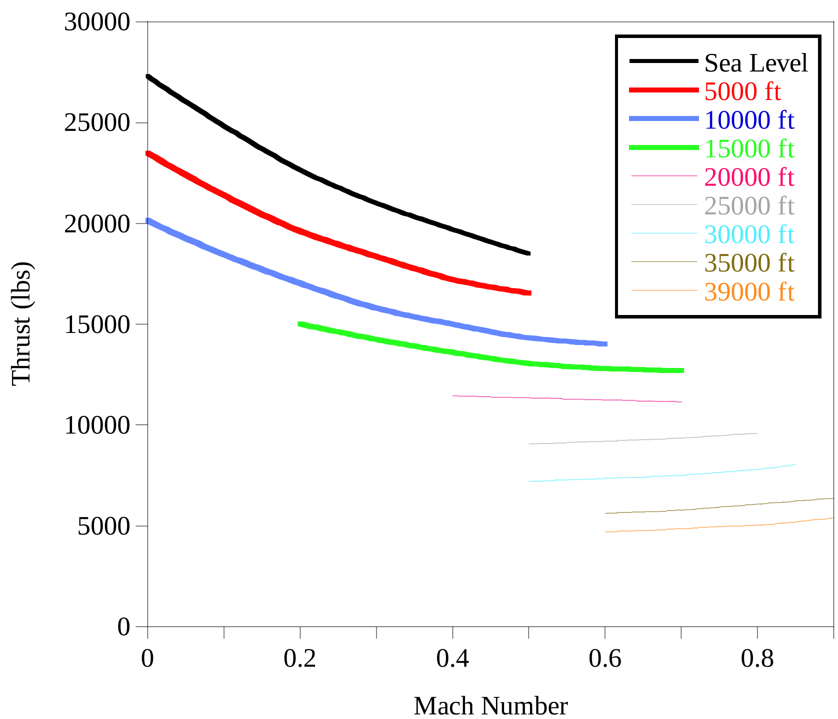

Figure 7.—Engine thrust versus free stream Mach number.

Appendix E—RDS-Pro Reference Vehicle Weights Breakdown (All weights are given in pounds)

Structures:
Wing = 16506.7
Horizontal tail = 2010.8
Vertical tail = 700.5
Fuselage = 17940.3
Main landing gear = 3908.5
Nose landing gear = 908.7
Nacelle = 2921.2

Total = 44896.7

Propulsion:
Engines = 10432.0
Engine controls = 42.0
Starters = 174.9
Fuel system = 623.0

Total = 11271.9

Equipment:
Flight controls = 3758.5
Instruments = 202.1
Hydraulics = 1347.5
Electrical = 2834.8
Avionics = 1840.3
Furnishings = 8147.2
Air conditioning = 2074.7
Anti-ice = 1742.0
Handling gear = 52.3
APU installed = 880.0

Total = 22879.4

Miscellaneous = 12942.5

Total Empty Weight = 91990.5

Useful Load:
Crew = 400.0
Fuel = 38629.3
Oil = 110.2
Payload (Maximum) = 13910.0
Passengers = 29160.0

Total = 82209.5

Total takeoff gross weight = 174200.0

Appendix F—Matrix of Aircraft Performance Metrics

Table IV contains the initial percent improvement in each of the four principle performance metrics for each of the aircraft designs used in the study. The final column shows the percentage reduction in fuel burn for the sized aircraft resulting from the design parameter improvements specified.

TABLE IV.—PERCENT IMPROVEMENT OF EACH PERFORMANCE METRIC AND RESULTING FUEL BURN REDUCTION BY DESIGN CASE

Case	C_{D0}, Percent	K, Percent	SFC, Percent	W_e, Percent	Percent fuel burn reduction
1	0	0	25	25	50.2
2	50	50	25	25	73.2
3	0	50	25	25	62.1
4	50	0	25	25	65.4
5	0	25	0	25	36.3
6	50	25	0	25	57.0
7	0	25	50	25	72.1
8	50	25	50	25	80.0
9	0	25	25	0	39.8
10	50	25	25	0	58.2
11	0	25	25	50	66.8
12	50	25	25	50	76.7
13	25	0	0	25	39.8
14	25	50	0	25	55.2
15	25	0	50	25	73.5
16	25	50	50	25	79.3
17	25	0	25	0	42.9
18	25	50	25	0	56.9
19	25	0	25	50	68.6
20	25	50	25	50	75.8
21	25	25	50	0	68.4
22	25	25	0	0	27.7
23	25	25	50	50	82.0
24	25	25	0	50	61.0
25	25	25	50	25	62.8
26	50	0	0	0	33.1
27	0	50	0	0	26.4
28	0	0	50	0	58.2
29	0	0	0	50	47.3

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14. ABSTRACT
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