Conceptual Design of a 150-Passenger Civil Tiltrotor

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The conceptual design of a short-haul civil tiltrotor aircraft is presented. The concept vehicle is designed for runway-independent operations to increase the capacity of the national airspace system without the need for increased infrastructure. This necessitates a vehicle that is capable of integrating with conventional air traffic without interfering with established flightpaths. The NASA Design and Analysis of Rotorcraft software was used to size the concept vehicle based on the mission requirements of this market. The final configuration was selected based upon performance metrics such as acquisition and maintenance costs, fuel fraction, empty weight, and required engine power. The concept presented herein has a proposed initial operating capability date of 2035, and is intended to integrate with conventional air traffic as well as proposed future air transportation concepts.

Nomenclature

A = rotor disk area, ft^2
AR = aspect ratio
C_T = thrust coefficient, $\frac{T}{\rho A V_{tip}^2}$
C_W = rotor weight coefficient, $\frac{W}{\rho A V_{tip}^2}$
D/q = equivalent flat-plate drag area, ft^2
MRP = engine maximum rated power, hp
SFC = specific fuel consumption, lbs. / hr / hp
V_{cr} = cruise speed, knots
V_{tip} = rotor tip speed, ft/s
W = weight, lbs
W_{empty} = aircraft empty weight
σ = rotor solidity

I. Introduction

THe increasing demand for air travel creates the need for more aircraft, but also places constraints upon the national airspace system. This leads to increasing amounts of delay as increasing numbers of conventional fixed-wing aircraft are forced to compete for limited space in terminal areas and along designated flightpaths. For instance, from 2001 to 2006, annual passenger enplanements increased by 17.6% - far in excess of the maximum expected demand increase of 8%.[1] Predictably, this has aggravated the problem of delays: while the Bureau of Transportation Statistics' June 2012 report shows an on-time arrival rate of 86.26%,[2] approximately one-third of all delayed flights were classified as National Aviation System delays: that is, delays due to airport operations, heavy traffic volume, air traffic control, etc. (Ref. 2). These delays represent a significant expenditure of fuel and time by idling aircraft and are thus a major contributor to airline operating costs; it is therefore advantageous to develop new methods by which these delays may be reduced. The major source of delay is not so much in the airspace system as a whole, but rather the runway. Each flight into or out of a commercial airport must be assigned an arrival or departure slot, and therefore requires runway occupancy time, which is largely independent of aircraft type and capacity: for instance, a 90-seat regional jet will have a runway occupancy time that is virtually identical to a 747. Part of the reason for the congestion currently experienced at airports is the use of smaller-capacity aircraft that carry a passenger load that is disproportionate to the number of flights operating into and out of that airport. For instance, Ref. 2 shows that at airports like Boston, Chicago, and Atlanta, 40% of all arrivals and departures carry only 20% of all passengers.

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The development of a new vehicle concept cannot be justified if there is insufficient demand for it in the marketplace. It is assumed that increased market demand will negatively impact the ability of conventional air traffic to improve its on-time performance, especially without modifications to the current airport infrastructure. The Federal Aviation Administration (FAA) currently predicts that by fiscal year 2032, the total number of yearly passengers in the United States will increase by a factor of 1.5 – from approximately 800 million in 2009 to 1.2 billion in 2032.[3]

Civil tiltrotors (CTRs) address these problems with a very flexible operating envelope. They have the unique ability to operate in either vertical takeoff and landing (VTOL) mode or in short takeoff and landing (STOL) mode at airports, but still retain the ability to cruise at much higher speeds than other rotorcraft. This flexibility makes CTRs uniquely suited to relieving the growing problem of traffic congestion at major city-pairs due to the tiltrotor's ability to perform runway-independent operations (RIO): because tiltrotors require zero runway and are able to perform climbouts and approaches that are impossible for fixed-wing aircraft, they are able to execute their operations within the airport boundary for a much larger portion of a flight. Previous design studies and concepts of operations of CTRs have focused primarily on the smaller end of the spectrum (10 to 120 passengers[4]), with the 90-passenger capacity receiving particular interest as a potential future transport.[5,6] These operational concepts have developed the tiltrotor architecture as a complementary capability to integrate within the larger transport schema of the national airspace system; thus, the design space of 'supplemental CTRs' has already been well-explored.

In order to address the problem of airport congestion in a more permanent fashion, a concept vehicle capable of being considered a direct 'drop-in replacement' for conventional short-haul aircraft is needed. This requires a vehicle capable of carrying 150 passengers on routes of 500 nautical miles, based on observations of current aircraft operating along the routes of interest – particularly in the southwest region of the United States[7]; these assumptions placed the design concept within the same aircraft class as the Boeing 737. The conceptual design presented addresses the problem of runway delays while still carrying sufficient passengers to be considered a viable commercial transport.

II. Design Approach

The mission requirements for the concept vehicle are given as:

- Range: 500 nmi
- Cruise speed: 250 – 300 KTAS
- Passenger capacity: 150
- Cruise altitude: 20,000 – 30,000 ft. standard day

The chosen initial operating capability (IOC) date was selected as 2035, in order to take into consideration technological developments within NextGen that will play a factor in future air transportation. The vehicle's passenger capacity was further justified by current trends in the evolution of short-haul fixed-wing aircraft, which have capacities that continue to increase with each successive generation; for instance, the 737-900ER is certified for up to 220 passengers in single-class layout[8]. It was assumed that this trend will continue, and that tiltrotors would need to be similarly up-sized from the current design space if they are to be viable options against fixed-wing aircraft in terms of passenger throughput. The Boeing 737-MAX was therefore chosen as a baseline aircraft that was felt to typify the potential of future short-haul fixed-wing aircraft.

The cruise altitude was chosen based on previous CTR studies; for passenger comfort, the aircraft must be able to cruise 'above the weather,' however given the vast differences in cruise speed between CTRs and fixed-wing transports, a constraint was imposed that the concept vehicles would not cruise at the same flight levels as commercial fixed-wing traffic; thus, 20,000 and 30,000 feet were selected as the lower and upper bounds of the concept's cruise altitude in order to meet these requirements. The cruise speed requirement is in line with the performance of smaller CTR concepts (Refs. 4 – 6). The design mission of the concept vehicle is shown in Fig. 1. This design mission is given as a high-level view of a typical transport mission, and does not represent the approach or departure profile of any particular airport. Reserves of 30 minutes and 100 nautical miles were built into the design, as was the capability for a one-engine-inoperative hover at 5,000 ft. ISA + 20ºC.

The sizing study for the concept vehicle was done using the NASA Design and Analysis of Rotorcraft (NDARC) software. At the conceptual design level, it is necessary to trade aircraft characteristics and document the impacts those changes have on mission performance; equally necessary is the ability to assess how future progress in materials technologies and manufacturing techniques will impact the final configuration and performance of the vehicle. NDARC performs both design and analysis tasks, and sizes the vehicle based on user-specified design conditions and mission parameters. The sizing task determines the dimensions, weight, and power of a rotorcraft capable of performing the mission specified by the user. Aircraft size is characterized by common aircraft industry terminology: design gross weight, payload capacity, rotor radius, empty weight, and engine power, among others. These relationships generally require multiple iterations in order to achieve optimum results; for the purposes of this design study, critical aircraft parameters – such as payload capacity – were held constant in NDARC when performing geometry sweeps; other parameters – such as wing loading, disk loading, cruise altitude, cruise speed, etc. – were swept to determine their effects on vehicle weights and performance.

NDARC also allows for the design of a vehicle intended to enter service at a future date by accounting for advances in technology ('tech factors') capable of producing results that are superior to the current body of materials and manufacturing knowledge; these tech factors allow the designer to conduct sensitivity studies to identify which areas of development might have the greatest impact on the resulting vehicle's design. Although these sensitivity studies are beyond the scope of conceptual design, they are included as potential future work in further developing the concept presented.

Some key assumptions were made during the design process. First and foremost, the FAA's predictions of future market demand are influenced by several factors: specifically, they appear most sensitive to the price of oil – which would affect the direct operating costs of a given aircraft – and the mergers and acquisitions strategies of air carriers – which would affect the total number of flights available. This is beyond the scope of conceptual design, and is not considered in this paper. For the purposes of conceptual design, it was assumed that the price of crude oil in 2035 has stabilized to \$175/barrel, which is the mean of the predictions presented by the FAA and the U.S. Energy Information Administration in Ref. 3. Given the twelve-month average price of crude oil of \$106.64 per barrel from June 2011 – June 2012[9] and the average price of jet fuel of \$3.07 per gallon during the same time period[10], linear proportionality was used to estimate a fuel cost of approximately \$5.00 per gallon in 2035. A margin of 10% is included in the fuel cost used in NDARC during design to account for possible error in the linear proportionality assumption; from this, a fuel cost of \$5.50 per gallon was assumed.

A mechanical cross-shafting system similar to that of the V-22 was assumed in order to drive both rotors in the case of a one engine inoperative (OEI) flight state; the wing thickness was held constant at 23% in order to accommodate this cross-shafting, similar to the CTR concept presented in Ref. 5. It is possible that materials advancement could permit for thinner-diameter shafts of sufficient capability to handle the torque requirements of the drivetrain, which would reduce the wing volume required for cross-shafting. A thicker wing would also be preferred for the cruise regime of the concept vehicle, since within the speed regime of interest the variation of parasite drag with respect to thickness would be small.[11] In the event of an all-engines-inoperative state, an onboard hydraulic accumulator would deploy the landing gear; should there be insufficient hydraulic power remaining after deployment of the landing gear to rotate the nacelles upward, it is assumed that the rotors will be equipped with a breakaway system to separate the rotors from the rest of the aircraft during landing.

Two engines are housed in each nacelle, and were sized to perform an OEI hover at 5,000 ft. altitude, ISA + 20ºC. Rotor head gimballing and differential collective were assumed in order to effect yaw control, thus obviating the need for a vertical stabilizer; a horizontal stabilizer was employed in order to maintain pitch control in the event of complete power loss. Additionally, a horizontal stabilizer was needed to counteract the nose-down pitching moment produced by the wing.

III. Aircraft Trade Space

Potential design solutions were analyzed using a house of quality matrix, which provided a quick visual comparison between design requirements ('demanded qualities') and potential design approaches ('quality characteristics'). Rotorcraft solutions – including tiltrotors and compound helicopters – were considered, in addition to a cruise-efficient short takeoff and landing configuration, on-demand air taxi services employing aircraft similar to the Embraer Phenom 100 and Honda HA-420, and conventional jet transport options. The resulting house of quality matrix is shown in Fig. 3.

Figure 3 shows that the mission requirements of runway-independent operations and simultaneous non-interfering flight heavily favored a vehicle capable of VTOL flight. From the faceoff matrix on the right, it was seen that a tiltrotor configuration would be best able to fulfill the mission requirements listed in Sec. II. From the results of the house of quality matrix, a conventional twin-rotor tiltrotor configuration was selected as the primary concept study. However, there currently exists no body of publically available literature addressing the characteristics of a 737-sized tiltrotor, which places an aircraft of this size outside the limits of existing CTR research.

IV. Aircraft Sizing

Sizing the aircraft required the selection of certain geometric features – such as fuselage geometry – prior to performing parameter sweeps for variables such as wing loading and disk loading. For sizing sweeps, the fuselage geometry and the fuselage-rotor clearance were held fixed; disk loading was swept at a variety of wing loadings to establish relationships between wing loading, disk loading, and several assessment metrics – i.e. empty weight, fuel weight, engine power required, etc. These results are given in Figs. 4 and 5, which show the behavior of the assessment metrics at constant wing loadings. Wingspan was intentionally left unconstrained, although the final configuration would have required further work if it had been found to be too large to satisfy the constraints of a 737 parking box. NDARC was used to automatically size the concept's tail volume and elevator using a tail volume coefficient of 1.5; per Ref. 12, a typical turboprop transport will have a tail volume coefficient of approximately 0.9, although the tail volume coefficient for the concept presented herein is intentionally oversized to ensure pitch authority during an all-engines-inoperative state. The sizing and iteration methodology is detailed below; sizing sweep graphs are shown in Figs. 4 – 7.

A. Fuselage sizing

The fuselage of the TR150 concept vehicle (twin-rotor, 150-passenger) was sized using the methods presented in Nicolai & Carichner.[12] A single-class economy cabin was assumed in order to maximize the revenue per cubic foot of cabin space; this led to the selection of four-abreast seating for the TR150. Seat pitch was fixed at 26" using currently available airline seats; because the TR150 is a short-haul vehicle intended to operate along high-traffic routes, the amount of revenue generated per cubic foot of cabin volume was considered to be of greater importance than passenger comfort. It is assumed that future developments in seat materials and manufacturing capabilities will result in thinner-backed seats that will increase passenger legroom. Fuselage sizing details are given in Table 1.

Table 1. Fuselage sizing.

Item	TR150
Seat width, in.	18.00
Seat pitch, in.	26.00
Headroom, in.	66.00
Aisle width, in.	13.00
Aisle height, in.	61.00
Seats abreast	4
Cabin length, ft.	81.25
Total fuselage length, ft.	132.8

In accordance with the methods outlined in Ref. 12, the average crew weight was assumed to be 275 lbs (including baggage), with one cabin attendant for every fifty passengers, two lavatories, and two pilots. A crew compartment length of 100 inches was assumed for the cockpit, and an additional 48 inches was assumed for flight attendant seating and a galley. The average passenger weight was assumed to be 177.5 lbs, with each passenger carrying 50 lbs in baggage; this passenger weight was based on data of average American weight, as reported by the Centers for Disease Control and Prevention.[13] Given the historical data listed in Ref. 13, it is possible that the weight of the average American will increase between the time of this design study and 2035; however, the likelihood of this occurring would depend on legal and social factors (e.g. cultural dieting trends, laws regulating nutritional value of foods, etc.) that are well outside the scope of conceptual design. Although a circular fuselage cross-section is most efficient shape from a structural perspective, an oval fuselage was used because it is more volumetrically efficient (Ref. 12).

B. Takeoff wing loading

Wing loading is defined as the aircraft's gross weight divided by the total wing area. Since the TR150 is a range-dominated vehicle, selecting a wing loading (W/S) to maximize cruise efficiency was a critical focal point of the design process. Selection of a wing loading, combined with the selected disk loading and a fixed rotor tip clearance of 1.5 feet from the fuselage, defined the wing's span and aspect ratio, among other parameters, and has a direct impact on the aircraft's parasite drag and induced drag. Typical design manuals for fixed-wing aircraft (e.g. Raymer, Roskam, etc.) show that range-dominated transports have a wing loading in excess of 100 lbs/ft^2 and an aspect ratio of approximately 9, and these values were used as guidelines during design. Generally speaking, it was found that increasing the wing loading reduced the aircraft's equivalent flat-plate drag area, at the expense of increased structural weight and therefore cost.

C. Disk loading

Disk loading is defined as the aircraft's gross weight divided by the rotor disk area; this parameter was varied from 9 to 25 lbs/ft^2 for each wing loading case. This range was chosen to intentionally explore the design space outside of what is considered 'normal' disk loading for a tiltrotor; the CTR studies shown in Refs. 4 – 7 showed that a disk loading in the 19 lbs/ft^2 range was to be expected for this type of vehicle. Typically, a lower disk loading is favorable in terms of power required to produce lift, however too low of a disk loading would not allow sufficient clearance between the rotor tip and the fuselage. Low disk loading also yielded higher aspect ratio wings, which in turn increased the aircraft's structural weight. Because it was assumed that the TR150 would remain in airplane mode during an all-engines-inoperative scenario, performance metrics related to disk loading (such as autorotative index) were not considered.

D. Wingtip extensions

Previous CTR studies and wind tunnel tests have demonstrated that cruise efficiencies may be gained through the use of wingtip extensions attached outboard of the nacelles. The length of these wingtip extensions was varied from 1 to 25 feet, and their effects on weight fractions, power requirements, and specific fuel consumption were recorded. These results are shown in Fig. 6.

E. Cruise condition

The cruise condition (cruise altitude and cruise speed) was found to directly affect the vehicle's profitability. Because the TR150 is intended to be a commercial transport, the ability of the aircraft to turn a profit is as important as its acquisition and maintenance costs. Once the geometry was finalized, cruise sweeps were performed in order to determine the cruise condition for which the vehicle can be operated most profitably. Average pilot and flight attendant salaries for regional carriers, retrieved from websites such as GlassDoor and the Bureau of Labor Statistics, were used to estimate crew costs; the aircraft was assumed to fly eight trips per day, and it was assumed that all of the aircraft's fuel (less reserves) is consumed during each flight. A fare price of $200 per ticket (2011 dollars) was assumed, which during the design phase was the average fare for a 500nmi route for the southwestern United States[14]; for all cruise cases, a passenger load factor of 0.8 was used, in accordance with Bureau of Transportation Statistics average through April 2012.[15] The total operating cost for each flight was taken to be the sum of the crew cost, fuel cost, and maintenance costs.

V. Results

The final configuration chosen for the TR150 tiltrotor concept is shown in Fig. 2; specifications for this aircraft are given in Table 2. The final wing loading and disk loading chosen for the TR150 were 100 lbs/ft^2 and 17 lbs/ft^2, respectively. This wing and disk loading combination represented the best compromise between acquisition cost, takeoff shaft horsepower, fuel consumption, and gross weight, as shown in Fig. 4. Because this combination of wing and disk loading would yield the lowest acquisition and maintenance costs, the selected wing and rotor loading was deemed to be the most favorable (from a profitability standpoint) of all the test cases examined. Figure 4 also shows that a wing loading of 125 lbs/ft^2 and disk loading of 15 lbs/ft^2 would yield lower power requirements, lower fuel fractions, and less equivalent flat-plate drag area, but these advantages would come with increased acquisition and maintenance costs. The assessment metrics within the range of wing and disk loadings between 100 – 125 lbs/ft^2 and 15 – 18 lbs/ft^2, respectively, were found to change by less than 5%: the difference in empty weights was found to be approximately 2,000 pounds, and the differences in acquisition and maintenance costs were found to be $2 million per aircraft and $200 per flight hour, respectively. The power loading differences between these two options was also found to be less than 2.5 lbs/hp. From these observations, it was concluded that this region of wing loading values of 100 – 125 lbs/ft^2 and disk loading values between 15 – 18 lbs/ft^2 shows potential for further optimization during subsequent design cycles.

The cruise condition of 23,000 ft. and 300 knots was selected based entirely upon the potential gross profit of each flight at a given cruise condition, as shown in Fig. 7. It was noted that the cruise condition for minimum fuel fraction (25,000 ft., V_{cr} = 275 kts) was not the cruise condition for maximum gross profit. This is due to the fact that the aircraft's maintenance cost is directly tied to block time; therefore, the advantage gained by flying at the condition for minimum fuel in terms of fuel cost may be obviated by the increased maintenance costs of the slower cruise speed. The 'best-profit' cruise condition yielded a gross profit of $29,871 in 1994 dollars ($45,338.41 in 2011 dollars; 31.11% gross margin) per flight, using the aforementioned assumptions of four flights per day at a passenger load factor of 0.8.

Table 2. TR150 technical specifications.

Geometry and capacity	
Payload	150 passengers *(35,516 lbs)*
Length	132.8 ft
Wingspan	107.0 ft
Wing area	1,280 ft^2
Wing AR	9.5
Wing loading	100 lbs / ft^2
Mean aerodynamic chord	11.61 ft
Wingtip extension	12 ft

Powerplant and Rotors	
Takeoff shaft horsepower, ea.	8,344
SFC, MRP at sea-level standard	0.3831 lb/hp-hr
SFC, MCP at 25,000 ft. standard day	0.3637 lb/hp-hr
Rotor radius	34.61 ft
Tip speed, hover	650 ft/s
Tip speed, cruise	400 ft/s
Hover C_w / σ	0.1510
Rotor AR	8.230
Disk loading	17.00 lbs/ft^2
Power loading	21.64 lbs/hp

Weights	
Maximum takeoff weight	147,369 lbs
Empty weight	77,400 lbs
Rotor weight	*10,035 lbs*
Wing weight	*8,914 lbs*
Powerplant & drivetrain weight	*16,402 lbs*
Mission fuel	*13,423 lbs*

Aerodynamics & Performance	
Rotor solidity, σ	0.1547
Hover C_T / σ	0.1411
Cruise C_T / σ	0.0632
D / q	49.23 ft^2
Cruise altitude, standard day	23,000 ft
V_{cr}	300 kts

VI. Conclusions and Future Work

The issue of runway congestion must be addressed if the national airspace system is to remain a viable short-haul transportation option. Previous research has been done on the feasibility of civil tiltrotors, however a tiltrotor the size of the TR150 is currently outside the limits of existing CTR research; this design shows that a new, larger class of tiltrotor is not only possible, but that such an aircraft would be able to serve a very real market demand. The design solution yielded a tiltrotor capable of carrying 150 passengers (roughly the size of a Boeing 737), with a cruise speed of 300 knots at an altitude of 23,000 feet. The TR150 explores the design space for a larger tiltrotor than has previously been studied; however, the design effort revealed many areas that will require additional development efforts if such a vehicle is to become a reality.

The ability of NDARC to apply tech factors to a design allows for sensitivity studies to be conducted in order to determine which engineering efforts (i.e. aerodynamics, structures, etc.) would have the greatest impact on the vehicle's performance; the tech factors used for the TR150 were inherited from previous CTR studies; however, there exists the possibility that for an aircraft of the TR150's size, different tech factors may be more appropriate. NDARC also has the capability to specific flight profiles, which will permit further optimization of the concept vehicle. The wing and disk loading of the TR150 merits further investigation, especially within the W/S range of 100 – 125 lbs/ft^2 and disk loading range of 15 – 18 lbs/ft^2. In this range of wing and disk loadings, the only advantage that the downselected configuration possessed was acquisition and maintenance costs (approximately $4 million and $200 per hour, respectively); in nearly every other category – power required, fuel fraction, equivalent flat-plate area, etc. – a wing and disk loading of approximately 125 lbs/ft^2 and 15 lbs/ft^2, respectively, was found to be preferable. The rotor tip clearance may also change based on how the cabin is to be shielded from rotor noise.

The unique VTOL capability of civil tiltrotors, as well as the transportation opportunities they provide, creates added flexibility within the national airspace system. CTRs eliminate the need for runways, which not only renders it resistant to runway delays but also creates the potential for the short-haul market to extend into underserved regions. The ability to break free from the constraints of traditional flightpaths allow CTRs to utilize airspace that fixed-wing aircraft cannot, and the ability to climb and descend within the airport boundary allows for potentially quieter operations.

Acknowledgments

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I would also like to thank my teammates on this project: Austen Knapp of the University of Colorado at Colorado Springs, and Daniel Wukelic of the University of Hawaiʻi at Mānoa. Thank you both for your dedication and for your contributions to the evolution of this concept aircraft.

Appendix

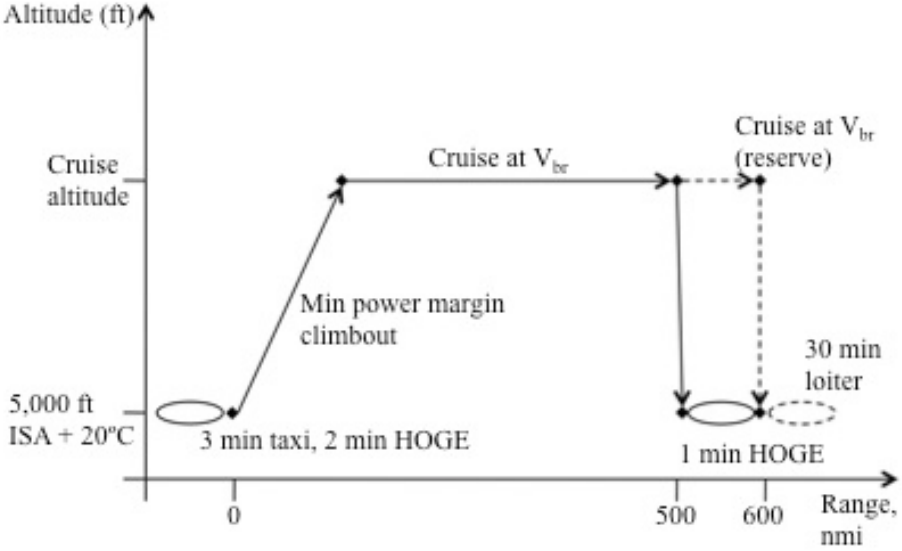


Figure 1. TR150 design mission.

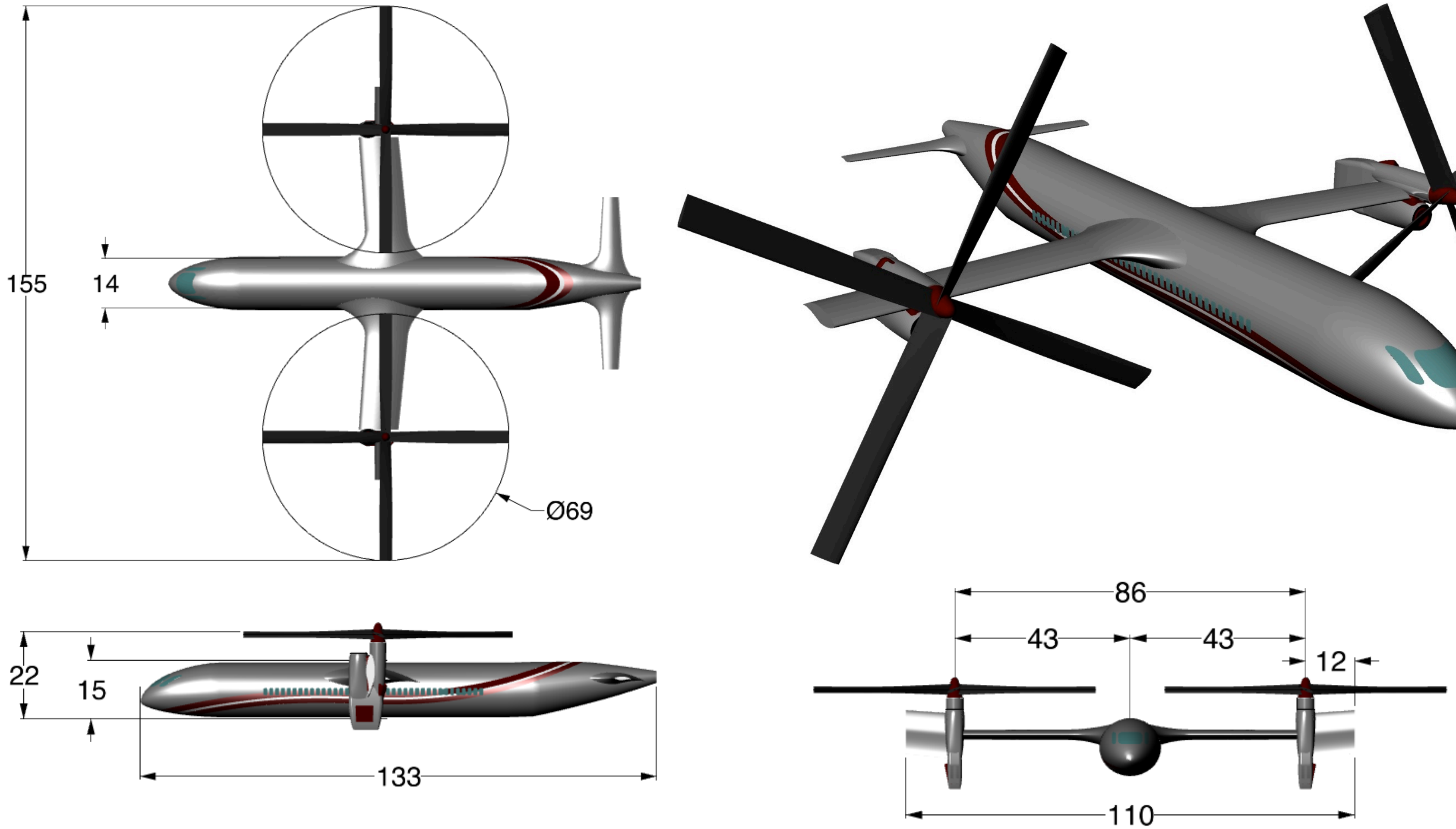
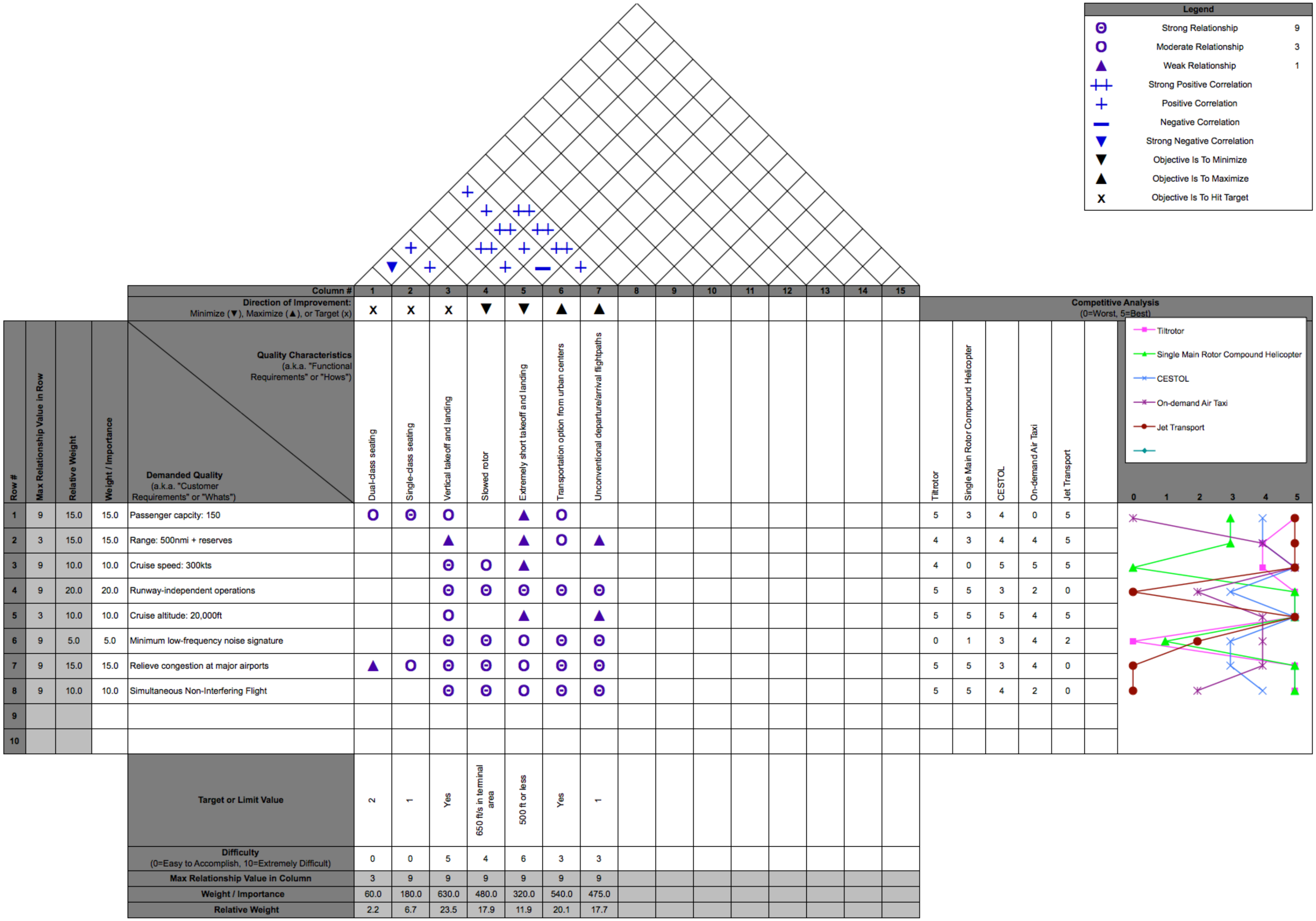


Figure 2. TR150 four-view. All dimensions in feet.



Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Tiltrotor	Single Main Rotor Compound Helicopter	CESTOL	On-demand Air Taxi	Jet Transport
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	x	▼	▼	▲	▲													
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Dual-class seating	Single-class seating	Vertical takeoff and landing	Slowed rotor	Extremely short takeoff and landing	Transportation option from urban centers	Unconventional departure/arrival flightpaths													
1	9	15.0	15.0	Passenger capacity: 150	O	Θ	O		▲	O										5	3	4	0	5
2	3	15.0	15.0	Range: 500nmi + reserves			▲		▲	O	▲									4	3	4	4	5
3	9	10.0	10.0	Cruise speed: 300kts			Θ	O	▲											4	0	5	5	5
4	9	20.0	20.0	Runway-independent operations			Θ	Θ	Θ	Θ	Θ									5	5	3	2	0
5	3	10.0	10.0	Cruise altitude: 20,000ft			O		▲		▲									5	5	5	4	5
6	9	5.0	5.0	Minimum low-frequency noise signature			Θ	Θ	O	Θ	Θ									0	1	3	4	2
7	9	15.0	15.0	Relieve congestion at major airports	▲	O	Θ	Θ	O	Θ	Θ									5	5	3	4	0
8	9	10.0	10.0	Simultaneous Non-Interfering Flight			Θ	Θ	O	Θ	Θ									5	5	4	2	0
9																								
10																								
				Target or Limit Value	2	1	Yes	650 ft/s in terminal area	500 ft or less	Yes	1													
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	0	0	5	4	6	3	3													
				Max Relationship Value in Column	3	9	9	9	9	9	9													
				Weight / Importance	60.0	180.0	630.0	480.0	320.0	540.0	475.0													
				Relative Weight	2.2	6.7	23.5	17.9	11.9	20.1	17.7													

Figure 3. Conceptual design house of quality.

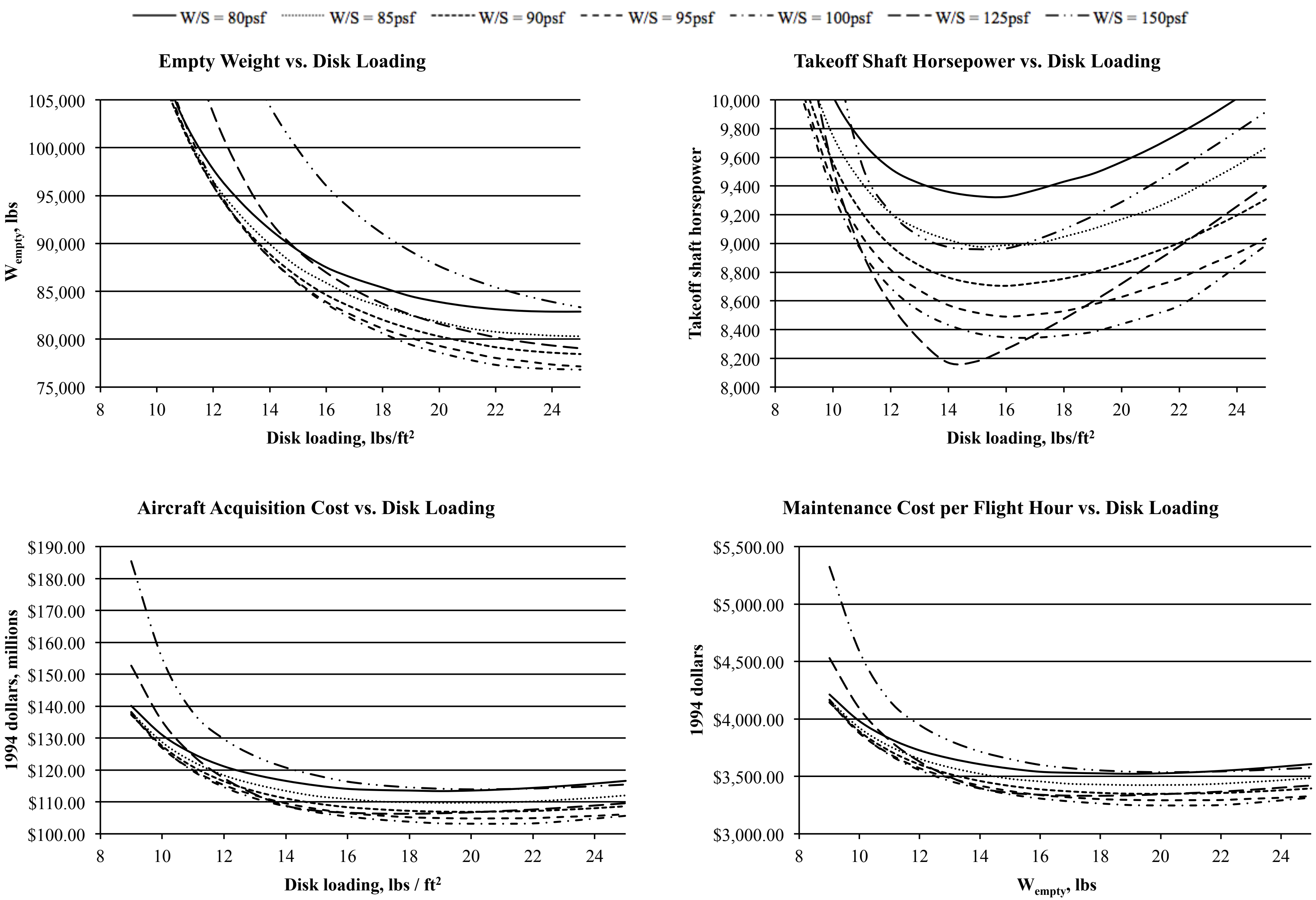


Figure 4a. TR150 geometry sweeps.

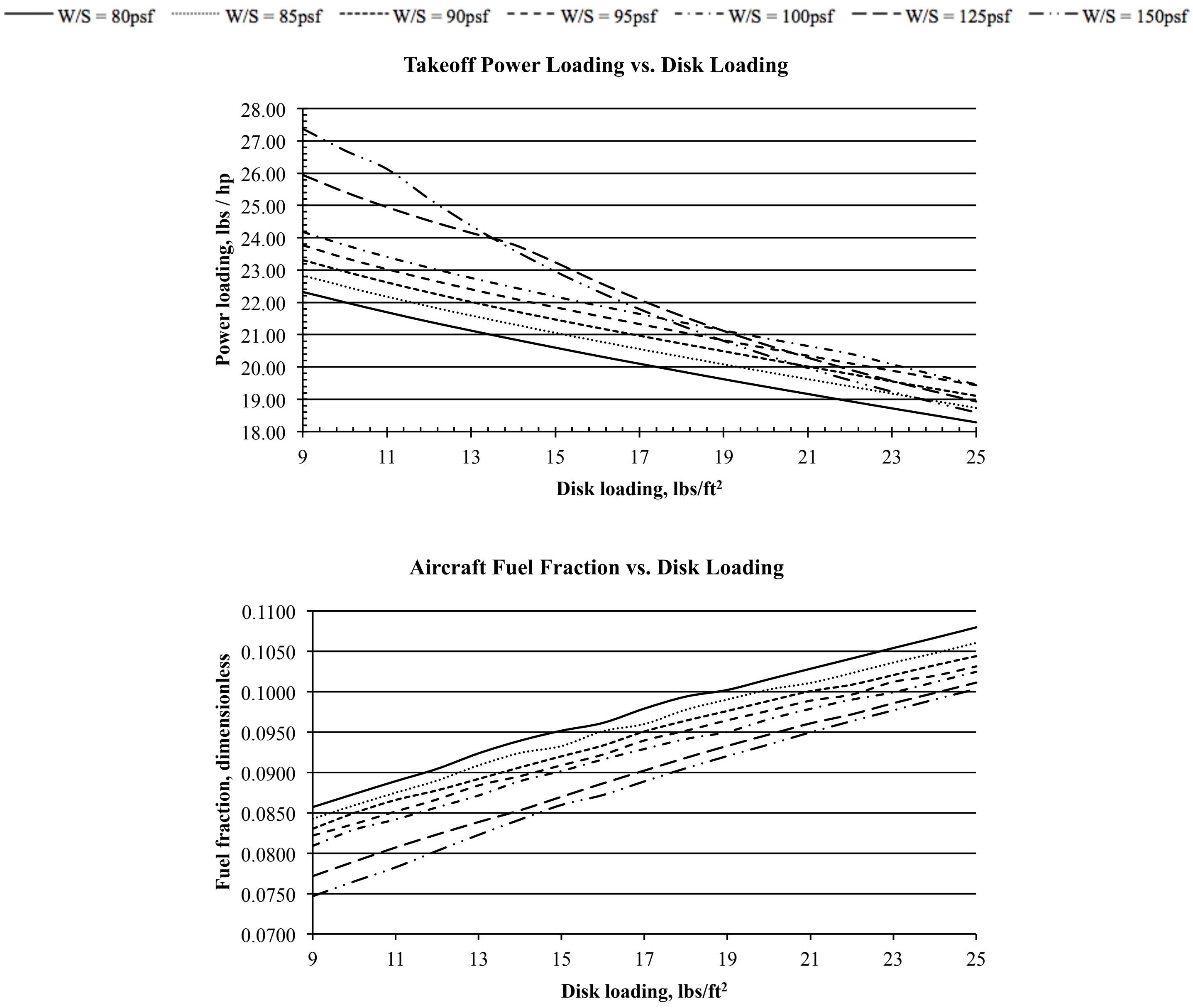
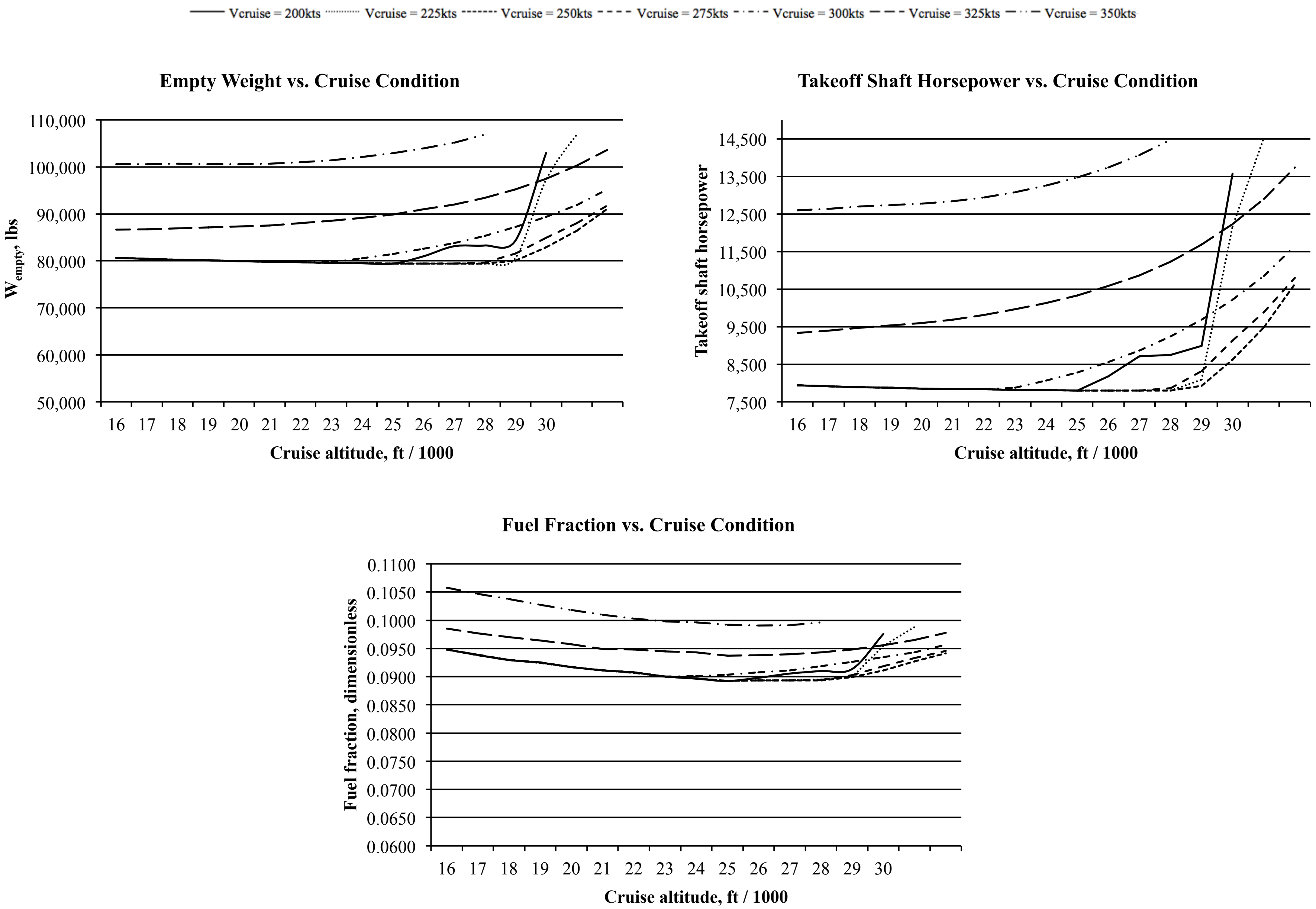


Figure 4b. TR150 geometry sweeps, concluded.



Empty Weight vs. Cruise Condition

Takeoff Shaft Horsepower vs. Cruise Condition

Fuel Fraction vs. Cruise Condition

Figure 5. TR150 cruise condition sweeps.

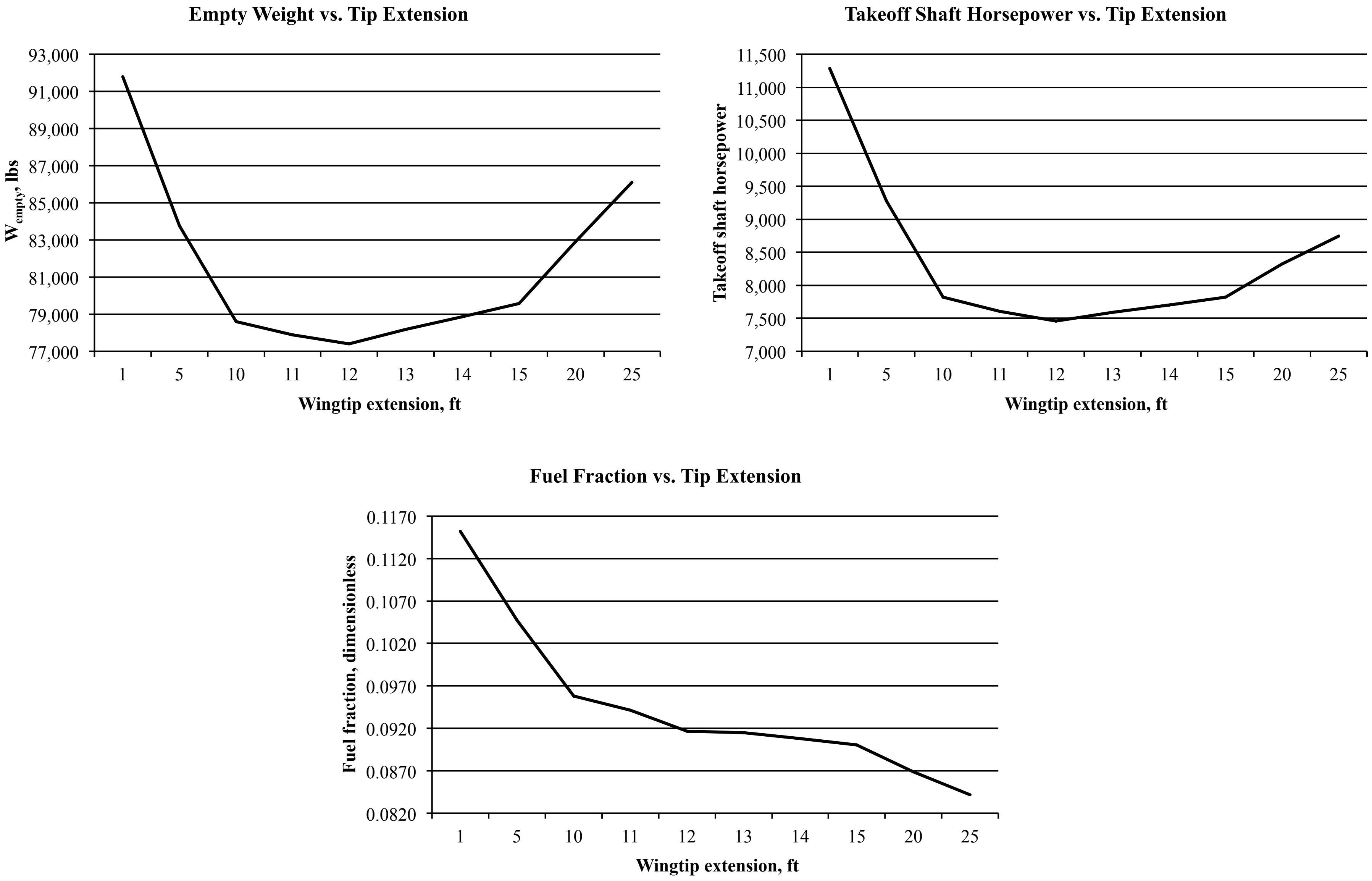


Figure 6. TR150 wingtip extension sweeps.

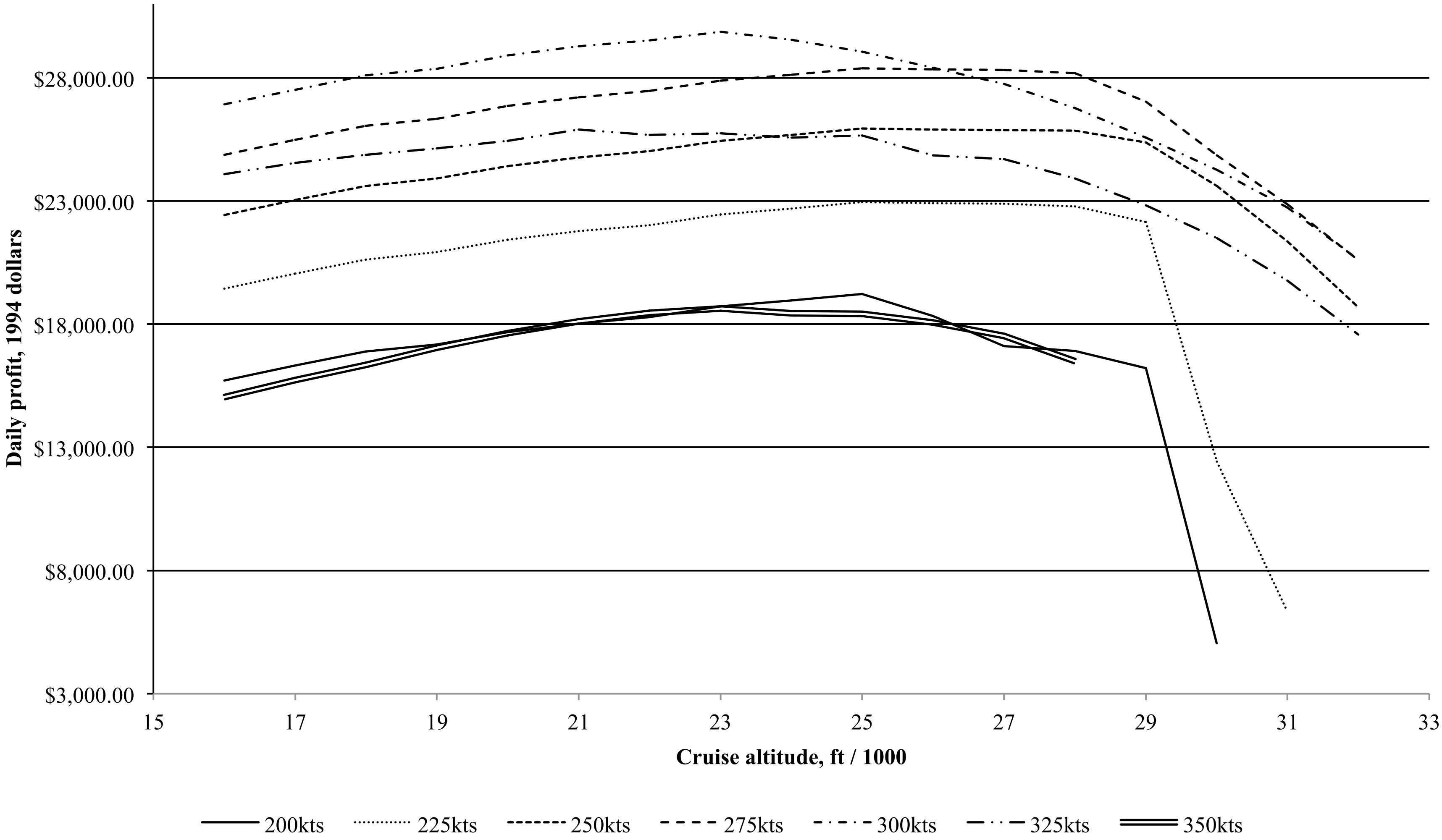


Figure 7. TR150 per-flight gross profit (1994 dollars) versus cruise condition.

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[1] Wilkerson, J. B.; Smith, R. L., “Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft”, NASA CR-2009-214594, 2009.

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