Feasibility Study of a Thrust Vector Control Transport

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Abstract

Thrust Vectored Control (TVC) has the potential to advance the design of commercial transports. This research evaluates the feasibility of a TVC commercial transport concept in three phases; (1) thrust vectoring technology review, (2) parametric sizing of a TVC transport, and (3) stability and control (S&C) FAA certification & safety assessment of the proposed transport. The baseline selected for the study is the long-haul wide-body mission (325 PAX, 8,000nm at M0.85) represented by the B777-300ER. The baseline B777-300ER as well as the modified TVC B777 are sized and compared. The results show a 17% increase in L/D, a 17% reduction of empty weight, a 27% decrease in fuel weight and an 18% decrease in Direct Operating Cost (DOC) from the TVC B777 to the baseline. The S&C analysis shows that the aircraft needs to be flown unstable in order to reduce the control power burden on the engines. It also shows that directional control in cross wind is the most design-constraining flight condition (DCFC) and that the vehicle is uncontrollable with one engine out. Further work is necessary to mature this first generation B777-TVC transport concept into a certifiable thus safe next generation transport.

Introduction

The commercial transport is approaching a fuel burn performance plateau with the typical Tail Aft Configuration (TAC) wing-tube-empennage design. Over its 92 year history, there have been two significant performance paradigm shifts. One in the 1950's, caused by propulsion upgrades with the dawn of the jet age. The other in the late 2000's, caused by the significant weight reduction from full composite structures. NASA projects a need for an additional 70% decrease in fuel burn performance within the next 30 years (N+3), see Figure 1. This demand requires another paradigm shift. The Thrust Vector Control (TVC) commercial transport offers potential to contribute to such innovation because of the significant weight and drag reduction benefits it provides. This paper describes the feasibility of this technology. The first section is a TVC review which includes a literature survey of TVC technologies and a description of effect of removing empennages. The second section is a parametric sizing study that compares the performance of a TVC transport to a convention transport if both are sized to a typical commercial transport mission. The third section evaluates the ability of the vehicle to perform maneuvers required for FAA certification.

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

Figure 1. NASA Subsonic Transport System Metrics1

TVC Technology Review

Thrust vectoring is the deflection of the thrust line in order to create multi-dimensional forces and moments which can enhance aircraft performance and control. It is quite different from differential thrust which involves varying magnitude of thrust of multiple engines. TVC systems can be classified based on actuation mechanism, control axes and operation scheme.

TVC Classification

There are three mechanisms for actuating TVC, namely: external actuation, internal actuation and fluidic actuation. External actuation is the least efficient mechanism. It involves either gimbaling the entire engine or adding deflection devices post-nozzle such as paddles, buckets or flaps. Internal actuation involves controlling the shape of the engine nozzle to produce a desired thrust vector deflection. It is the most efficient TVC mechanism; Ikaza2 claims up to a 7% off-design thrust improvement because of the ability to vary nozzle exit area while thrust vectoring. Fluidic actuation is an experimental mechanism in which TVC is achieved by using a secondary fluid stream to manipulate the primary jet stream3 (See Sparks[4], Mason[5], Gu[6], Sobester7).

The control axes classification of TVC is based on the number of rotational axes (pitch [P], roll [R], yaw [Y]) that are effected. For example, Lockheed Martin's F-22 Raptor is a PTVC because the thrust vector effects only pitch control. On the other hand, The F-16 VISTA with its single Multi-Axis Thrust Vectoring (MATV) nozzle is a PYTVC. It corresponds that a single 2-D nozzle allows single axis control, one 3-D nozzle allows 2-axis control and multiple nozzles allow for 3-axis control.

Gal ‘Or8 gives the operational classification of TVC systems as pure and partial systems. Pure TVC aircraft use only vectored thrust for the entire flight control force. Partial TVC aircraft use a mixture of both thrust vectoring as well as aerodynamic devices for control. This current study examines the feasibility of TVC to by evaluating the feasibility of a pure PYTVC commercial transport (i.e. a tailless commercial transport). Other than some model aircraft and missiles, there are no manned pure TVC aircraft in service9; however, there are many aircraft with partial TVC.

Applications of TVC Technology

TVC has predominantly been used in fighter aircraft for increased maneuverability (e.g. F-22, JSF and Su-37); and for Vertical or Short Take-Off and Landing (VTOL/STOL) capability (e.g. AV-8A Harrier). Some experiments have demonstrated the feasibility of a pure PYTVC fighter (tailless fighter) using the X-31A as a test-bed9[-12]. The results show many benefits for military application with the benefit of reduced cross section area as the key one.

Gal ‘Or[13-14] explores the use of partial TVC to increase the safety of commercial transports. This concept has been proven by successful flights of a partial TVC B727[15] and the patents[16-18] for its TVC technology. NASA also has successful tests of Propulsion Controlled Aircraft (PCA) with MD11 and B747 testbeds[19-21]. Although those experiments use differential thrust control not TVC, they are relevant to the general concept of control augmentation of commercial vehicles using thrust.

Finally, Steer[22] proposes the use of partial TVC on a second generation Supersonic Commercial Transport (SCT). The idea is to improve low speed performance where aerodynamic controls stall and augment supersonic controllability when aerodynamic controls lose effectiveness. There has not been a proposal for a pure PYTVC commercial transport as has been for fighter aircraft; however, such a vehicle will provide benefits as well as unique challenges.

Benefits and Challenges of a PPYTVC Commercial Transport

The benefits of a pure PYTVC commercial transport include:

- Significant weight reduction from removal of empennages.
- Overall drag reduction from removal of tail surface area.
- Trim drag reduction from elimination of induced drag due to tail lift (note that trim drag is not entirely eliminated because of induced drag from the additional wing lift required to counter engine trimming forces. This is a consequence of the stable Tail-Aft configuration [TAC]).
- Improved stall performance and spin recovery due to independence from aerodynamic control effectiveness.

- Decrease in takeoff speed and takeoff field length.

The major challenges include:
- Negative public perception of radical designs.
- Fatality if all engines fail.
- Thrust requirement increase for control power demands.
- Propulsion weight increase from TVC modifications.
- Specific fuel consumption increases from mixed flow turbofan compared to high bypass unmixed turbofan.

The implications of these merits and demerits in a total system context are quantified in the next section via a parametric sizing study.

Parametric Sizing of A TVC Commercial Transport

Parametric sizing is the determination of the size/scale of a vehicle required to meet desired design and mission specifications. The value of the TVC transport is assessed by comparing its predicted performance and cost to a baseline commercial transport. Both vehicles need to be sized to same baseline mission in order to consistently compare them. *AVDSizing* is used in this study to accomplish this task.

Description of AVD^{Sizing}

AVD^{Sizing} is a methodology and tool that arrives at a vehicle, given a set of design parameters and mission specifications, by converging multiple disciplines including aerodynamics, propulsion, trajectory, weights, volume and cost. The tool is a FORTRAN 90 program developed by Coleman[23] based on a process developed by Czyzs[24, 25]. The modular design of AVD^{Sizing} allows for quick adaption of disciplinary methods to handle new design problems such as a TVC commercial transport. A Nassi-Schneiderman diagram of the sizing logic is shown in Figure 2 and the methods that have been used for this study are given in Table 1.

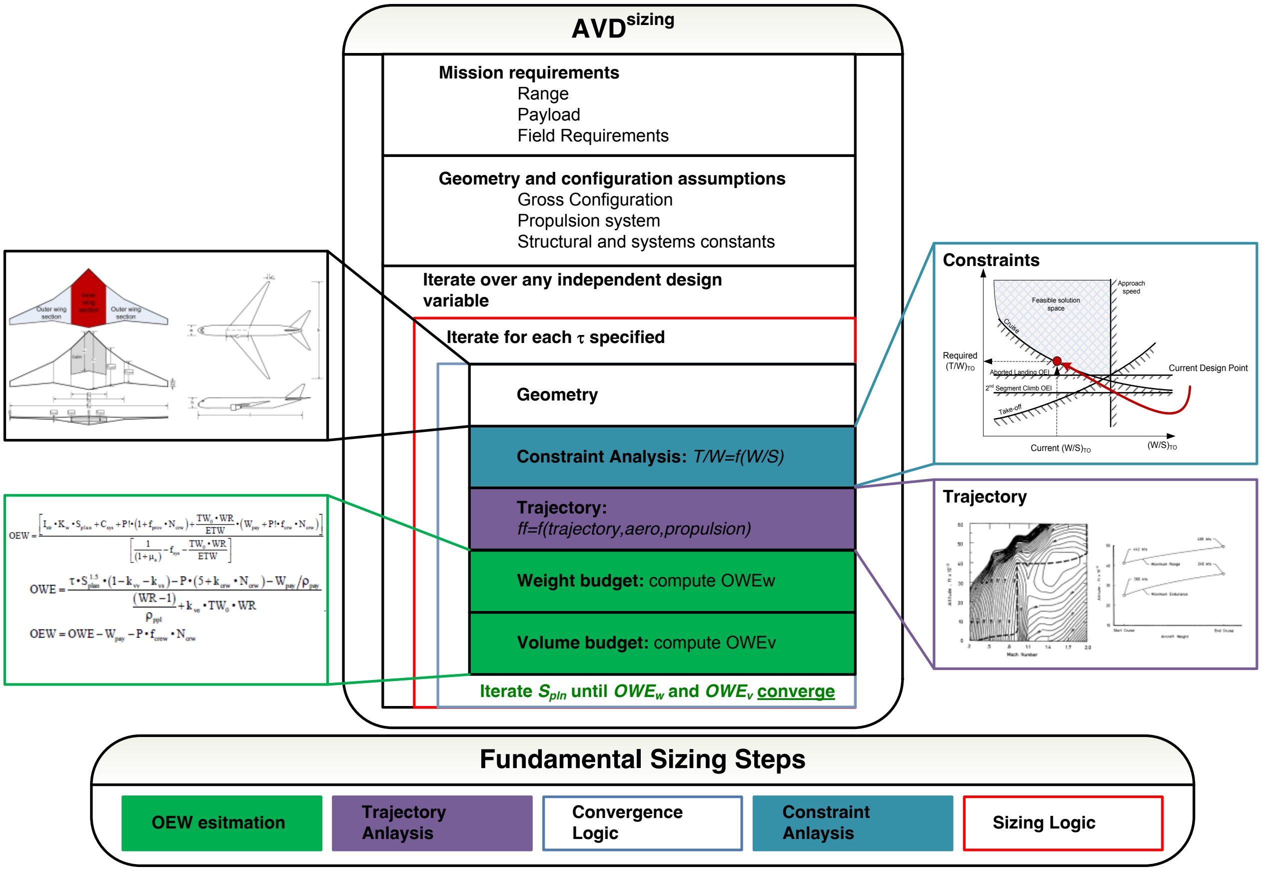


Figure 2. Nassi-Schniderman of *AVD*^{Sizing} Logic

Table 1. Disciplinary Methods Summary

DISCIPLINE	METHOD TITLE	DESCRIPTION	REFERENCE
Geometry	Transonic TAC	Parametric equations for the geometry of a TAC transport	Coleman[23]
	Modified Tail-Volume Coefficient	Parametric equations for the empennage geometry a TAC transport based on its main wing shape	Morris[26]
Aerodynamics	Subsonic Skin Friction Estimation	Construction of the skin friction drag coefficient using an equivalent flat plate method	Smith[27]
	Subsonic partial laminar skin friction estimation	Computation of the skin friction coefficient based on a given transitional Reynolds number for partial laminar flow airfoils.	Roskam[28]

	Drag Due to Flaps and Landing Gear	Typical drag coefficients for flaps effects in take-off and landing configurations	Roskam[29]
	McDonnell Aircraft Company Wave Drag Approximation	Drag rise as a function of Mach no. based on an approximation of the area distribution to the sear hack body.	Coleman[23]
	Induced Drag	Mach number corrections from Vought wind-tunnel testing to the induced drag method presented in DATCOM	Vought[30]
	Lift Curve Slope	3-D wing lift curve slope for strait tapered wings	Hoak[31]
	Maximum Landing Lift Coefficient	Value maximum lift coefficient selected based on similar aircraft	Roskam[29]
	Lift to Drag Ratio	Computes the L/D for a given location on the drag polar	Vinh[32]
Propulsion	Turbofans, Turbojet, and Turboprop SFC variation	Statistical regressions for SFC values for High bypass turbofans, Low bypass turbofans, Turbojets and Turboprop engines	Mattingly[33]
	Turbofans, Turbojet, and Turboprop Thrust lapse	Statistical regressions for thrust lapse values for High bypass turbofans, Low bypass turbofans, Turbojets and Turboprop engines	Mattingly[33]
	Turbofan Engine Preliminary Design Tool	Statistical regression for turbofan weight, dimensions and performance	Svoboda[34]
Performance	Stall Speed Representation	wing loading requirements calculation from lift coefficients at various stall speeds	Roskam[29]
	Landing Distance Representation for FAR 25 aircraft	Approach speed, stall speed and landing wing loading (W/S) requirements calculation from given design landing field length and lift coefficient	Roskam[29]
	Take-off Distance Representation for FAR 25 aircraft	Take-off thrust-to-weight ratio (T/W) requirement calculation from design Take-off field length and lift coefficient	Roskam[29]
	Take-off to Climb performance matching for FAR 25 aircraft	T/W and W/S requirements for flight segment between take-off and climb.	Coleman[23]
	Climb performance matching for FAR 25 aircraft	All Engines Operable (AEO) and One Engine Inoperable (OEI) Climb T/W requirements calculation for take-off and balked landing.	Loftin[35]

	Cruise Matching	T/W and W/S requirements for cruise.	Coleman[23]
	Time to Climb	T/W as a function of W/S and initial climb speed and cruise altitude. Initial climb speed and cruise altitude are solved for iteratively during performance matching	Coleman[23]
	Climb Requirements for Jet Powered Aircraft	T/W as a function of W/S and initial climb speed and cruise altitude. Initial climb speed and cruise altitude are solved for iteratively during performance matching.	Roskam[29], Coleman[23]
	Range and Time to Descent	Assume power reduced to flight idle (power off) the flight path angle, rate of descent range covered and time of descent from cruise altitude is computed.	Roskam[36]
	Maximum Velocity Constraint for Jet Powered Aircraft	T/W requirement for a given wing loading and time to climb	Roskam[29]
	Ceiling Requirements for Jet Powered Aircraft	T/W as a function of W/S and initial climb speed and cruise altitude. Initial climb speed and cruise altitude are solved for iteratively during performance matching	Roskam[29]
	Initial Fuel Weight Estimation	Fuel fractions calculations for each mission segment based on typical values or from the Breguet range and endurance equations with assumed L/D and SFC.	Roskam[29]
Stability and Control	Approximate Trim Solution 1	Simplified 2-D (Lift and pitching moment) trim solution to compute the corresponding basic (untrimmed aircraft) lift and the longitudinal control effectors (LoCE) lift contributions.	Coleman[23]
	Approximate Trim Solution 2	A combination of DATCOM and Torenbeek methods for estimating both the zero lift pitching moment and distance from the c.g. to the wing body aerodynamic center. For use with the Approximate Trim Solution 2.	Hoak[31], Torenbeek[37]
Weight and Volume	V-N diagram and structural limits for FAR 25 aircraft	Construction of the maneuvering and guest V-N diagram based on design trend for FAR 25 commercial transports.	Roskam[38]
	Convergence Empty Weight Estimation	method for estimating the converged empty weight based on volume and mass based on Czysz[25]	Coleman[23]

Wing Structure Group Weight Fraction Method	Estimation of structural weight fraction in terms of ultimate load factor, wing dimensions, and Max Take-off Gross Weight, Max Zero Fuel Weight	Nicolai[39]
Fuselage Mass Estimation	Fuselage mass based on basic geometry and structural constraints	Howe[40]
Tail Structure Group Weight Fraction Method	Estimation of structural weight fraction in terms of ultimate load factor, wing dimensions, and Gross Weight.	Torenbeek[37]
Raymer cargo/ transport aircraft Nacelle Weight Method	Empirical weight estimation for turbojet and turbofan engines	Raymer[41]
Torenbeek Commercial Transport Landing Gear Weight	Empirical landing gear weight estimation for transport type aircraft	Torenbeek[37]
Power Plant Mass Estimation	Correction factor to dry propulsion system weight for installation (nacelles, pods, cowlings, propeller, etc.)	Howe[40]
Refined Hydraulic and/or Pneumatic Group Weight Method	Estimation of Hydraulic systems weight in terms of gross-take-off weight	Roskam[38]
Refined Instrumentation Group Weight Method	Estimation of instrumentation, aviation and electrical n weight in terms of number of engines, pilots, PAX, take-off weight, empty weight	Roskam[38]
APU Weight Method	Typical weight fraction values for APU weight.	Roskam[38]
Furnishings Weight Method	Furnishing weight based on correlation with maximum zero fuel weight	Roskam[38]
Baggage Handling Equipment Weight Method	Empirical correlation for baggage and cargo handling equipment for use in military and commercial freighters	Roskam[38]
Operational Items Mass Estimation	Mass estimation for operating items including crew personal items, safety equipment, freight equipment, water and food, residual fuel	Howe[40]

`Cost	Life Cycle Cost	Life Cycle cost is estimated from the summation of Research, Development, Testing and Engineering Cost (RDTE), Acquisition cost (ACQ),Operations Cost (OPS), and Disposal (DISP)	Roskam[42]
	RAND DAPCA IV RDT&E and Production Cost Model	DAPCA is comprised of Cost Estimating Relationships (CER's) for RDT&E and production broken down by, (1) Engineering (2) tooling (3) manufacturing (4) quality control (5) development support (6) flight-testing and (7) manufacturing material costs.	Hess[43]
	Manufacturing and Acquisition Cost	Build-up of manufacturing and acquisition costs	Roskam[42]
	Direct Operating Cost for Commercial Airplanes: DOC	An adaptation of ATA-method which decomposes direct operating cost into 5 components, (1) Flight (2) Maintenance (3) depreciation (4) landing fees, navigation fees, registry taxes, and (5) financing direct operating costs	Roskam[42]
	Block Mission for Commercial Transports	This method estimates the block, range, speed and time for DOC computation purposes	Roskam[42]

Baseline Mission

A mission derived from the B777-300ER has been selected to test the feasibility of the TVC commercial transport. It is a long-haul wide-body mission to fly 325 PAX a range of 8,000nm at a cruise speed of M0.85. This mission is selected because its long cruise segment can benefit from the weight and drag reduction TVC offers. Table 2 summarizes this design mission.

Table 2. Summary of Baseline Mission

Mission Specification	
Crew weight	
Crew (1-Captin, 1-1st officer, 14 cabin attendents)	1472 kg (3,250 lbs)
Payload weight	
Maximum (175 lbs passenger + 40 lbs cargo) 370 pax (3-cabin), 33,770 kg cargo	69853 kg (154,000 lbs)
Design Passengers (325 pax, 6,474 kg cargo)	38168 kg (84,150 lbs)
Range	

Design	14075 km (8,000 nm)
Velocity	
Design Cruise Speed	0.85 M
Altitude (m)	
Max operating	12,200 m (40,000 ft)
Take-off field length (TOGW)	< 3,048 m (1,000 ft)
Landing field length (max landing weight)	< 1,767 m (5,780 ft)
Fuel reserves	926 km (500 nm)

Sizing Results

Baseline B777-300ER Sizing

AVD^{Sizing} produces a solution space of converged vehicles sized to mission by varying design independent variables such as aspect ratio (AR) and Kuchemann slenderness parameter (τ), see Figure 3. The shaded area represents the unfeasible design space due to the landing wing loading constraint. The design point can be selected from any number of objective functions. In this instance, minimum Direct Operating Cost (DOC) is used for. Table 3 compares the selected design point and the B777-300ER reference[44]. The errors are within acceptable limits for the conceptual design phase, thus the baseline vehicle is validating the methodology.

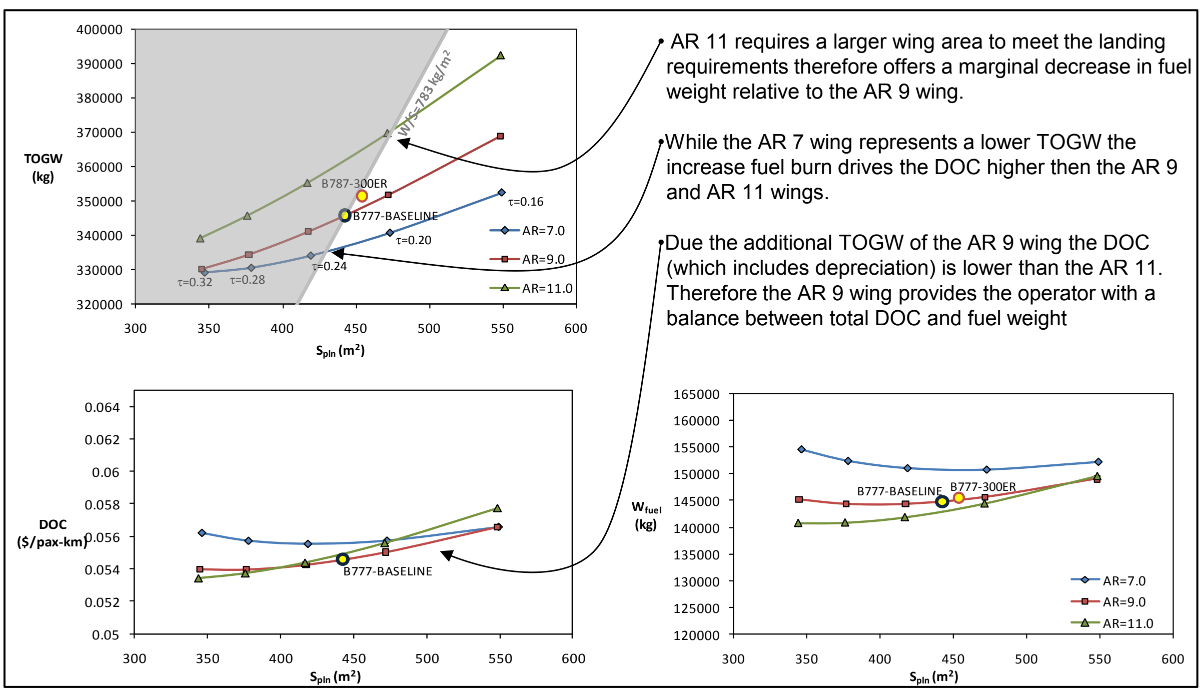
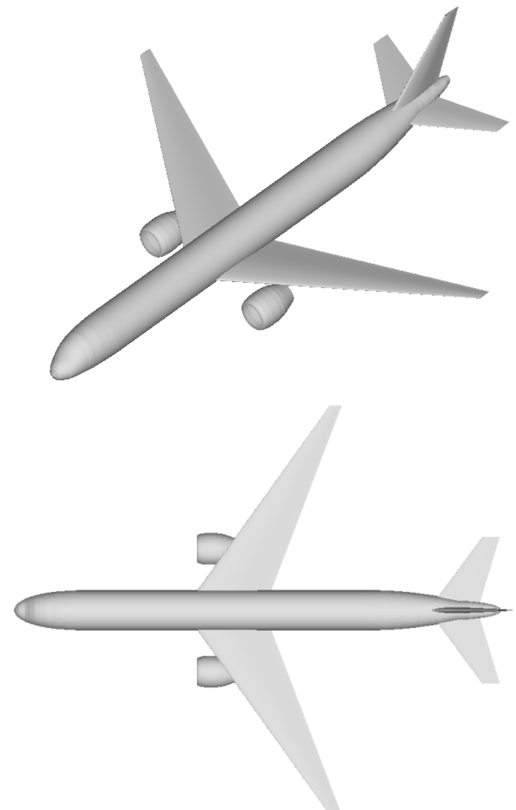


Figure 3. Baseline Solution Space

Table 3. Validation of Baseline B777-300ER Design Point

	B777-300ER	DESIGN POINT	% error	Design Point Geometry
Geometry				
τ		0.21		
AR	9.25	9.00	-2.69%	
S_{pln} (m^2)	454.00	457.49	0.77%	
b (m)	64.8	64.17	-0.98%	
l_{fus} (m)	73.08	74.78	2.32%	
d_{fus} (m)	6.20	6.20	0.00%	
Weight				
TOGW (kg)	351535	359357	2.22%	
W_{fuel} (kg)	145538	148503	2.04%	
MLW (kg)	251290	256868	2.22%	
$(W_{PAY})_{design}$ (kg)	38168	38168	0.00%	
OEW (kg)	167829	172686	2.89%	
Aero-Propulsion				
ff	0.414	0.413	-0.18%	
Thrust (kN/engine)	514	548	6.62%	
$Alt_{cruise\ avg}$ (m)		10722		
L/D_{cruise}		17.46		
SFC_{cruise} (/hr)	0.56	0.56	-0.20%	
Cost				
DOC ($/pax-km)		0.07260		
Unit price ($ M)	202	205	1.67%	



B777-TVC Sizing

The TVC modifications made to the baseline B777-300ER are summarized in Figure 4. The assumptions for DOC calculations are shown in Table 4. Figure 5 shows a comparison between the B777-TVC and B777-300ER. The removal of the empennage results in an overall reduction in weight and wetted surface area (S_{wet}) which leads to an increase in lift-to-drag (L/D) aerodynamic efficiency. This improvement in efficiency allows for the selection of an AR = 7 wing which is lighter and has better stability characteristics. This translates into a 27% decrease in fuel burn for the mission. In addition, the direct operating cost (DOC) decreases by 12%. However, the cost of such state-of-the-art research and development offsets and DOC reduction and causes an increase in unit price. These results show that, if certifiable, the B777-TVC is worth an investment. The issue of airworthiness is addressed in the next section.

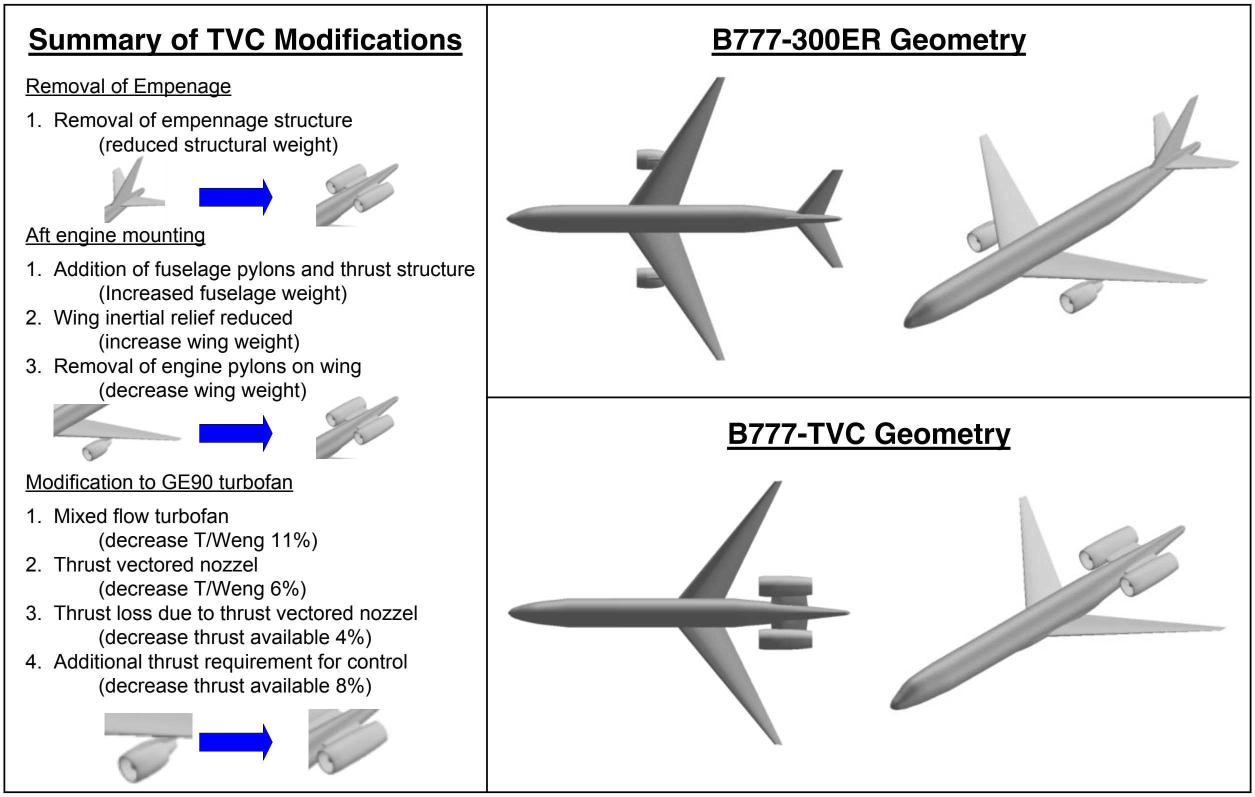


Figure 4. Summary of TVC Modification

Table 4. Direct Operating Cost Calculation Assumptions

Weighting Factor	
Fuel Cost	$5.00/gal
Annual hull insurance rate	0.05
Crew Cost	
Captin	$85,000/yr
1st Officer	$50,000/yr
Attendants	$32,000/yr
System Development Complexity Factors [F x RTDE cost]	
Propulsion Thrust vectored control	1.20
Flight control System (Baseline and statically stable TVC)	1.25
Flight control System (unstable TVC)	1.50
System maintenance Complexity Factors	
Propulsion Baseline Time-Between Overalls [ΔTBO]	16,000 hrs
Propulsion Thrust vectored control [ΔTBO]	-4,000 hrs

Depreiation factor	0.85
Depriation time frame	20 yrs

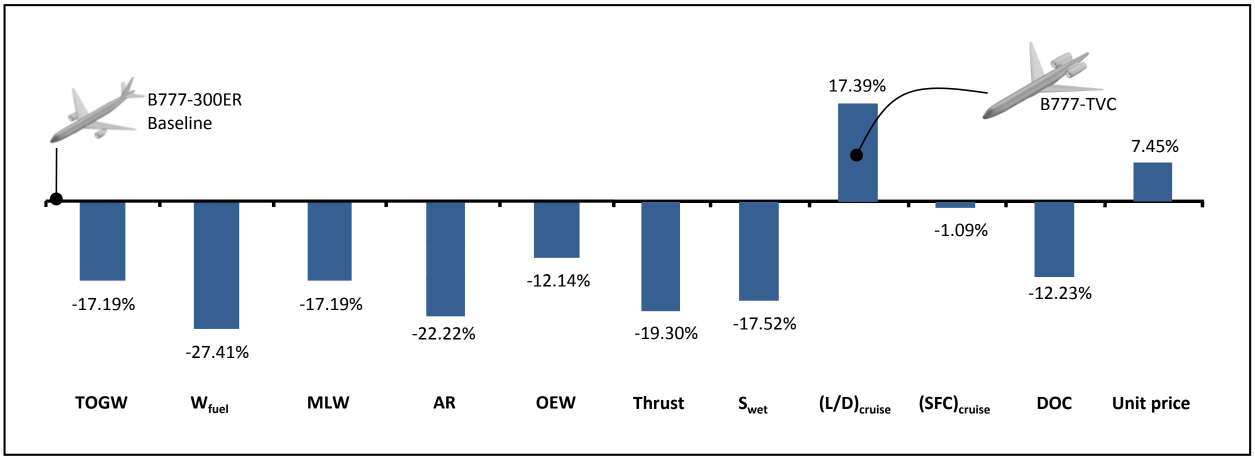


Figure 5. B777-TVC and B777-300ER Comparison

Stability and Control (S&C) FAA Certification & Safety Assessment

The TVC commercial transport needs to meet the Federal Aviation Administration[45] (FAA) and the Joint Aviation Authorities[46] (JAA) regulations in order to be commercially viable. Chudoba[47] translates these regulations into a comprehensive list of Design Constraining Flight Conditions (DCFCs) for sizing aircraft control effectors. The identification of these DCFC's is part of the control power evaluation methodology and simulation tool *AeroMech*[47].

Description of *AeroMech*

AeroMech is an aircraft configuration independent stability and control methodology and tool for conceptual design which provides a means of properly sizing Control Effectors (CEs) such as ailerons early in the design process. The tool is a FORTRAN 90 program written by Coleman[48] based on Chudoba's[47] methodology. Figure 6 shows the structogram of the methodology as it has been implemented.

TVC sizing results provide the required aircraft input data. Subset DCFCs are selected from Chudoba's[47] comprehensive list. Since the aircraft has a traditional wing, the typical stall conditions are critical. The vehicle is engine thrust controlled; therefore, high altitude and high speed conditions, which typically do not size aerodynamic control effectors, are considered. This is because engine thrust limits are reached at these conditions. Figure 7 shows the critical corners of the flight envelope for consideration in assessing the control power of a (TVC) aircraft. A modified version of Digital DATCOM[49] provides aerodynamic prediction at these conditions.

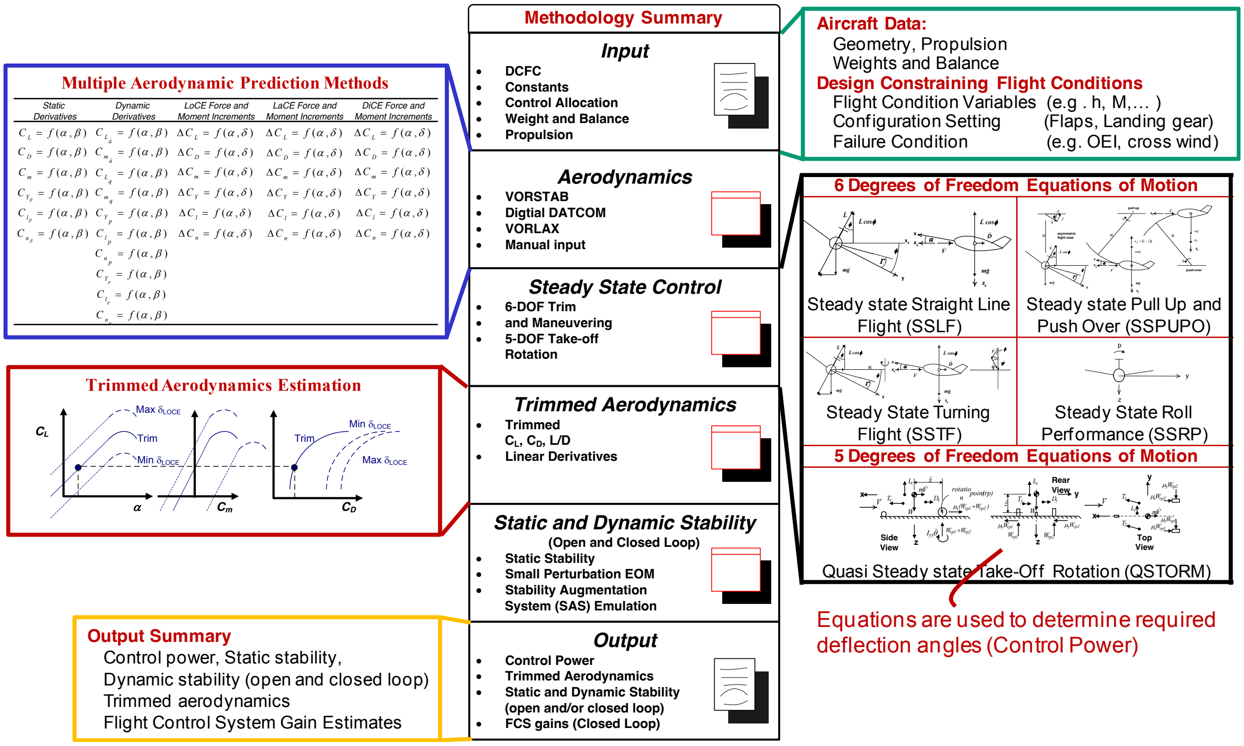


Figure 6. Nassi-Schniderman Diagram of *AeroMech* Methodology

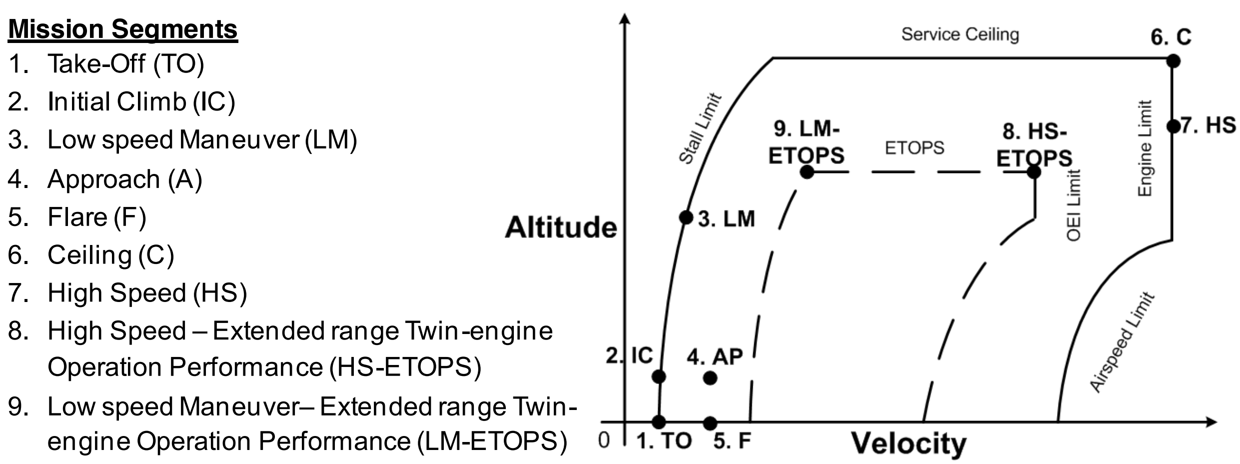


Figure 7. Critical Corners of the Flight Envelope for a TVC transport

TVC Control Power Assessment Results

A summary of observations and recommendations from the TVC commercial transport steady state control power analysis are provided with Table 5.

Table 5. Summary of TVC Transport Control Power Assessment Results

Test Cases	Observations	Recommendations
Statically stable configuration (HS)	Large SM travel between forward and aft cg locations.	Use a fuel transfer system to keep the cg at the forward location
	Insufficient control power for almost all the maneuvers.	Increase LoCE control power by relocating the wings
Wing Location Trades (HS)	There are control power issues at extremely negative SM	Increase the thrust requirement for cruise in a later sizing study
	The most control power is available at -5% SM	Assess control power at off design conditions using the -5% SM wing location
	Insufficient thrust available at -5% SM	
Stall Performance (IC, LM)	Longitudinal Control Effectors (LoCE) saturate during most of the maneuvers in both conditions	Redesign the wing to delay the pitch break
		Use an angle of attack limiter to constrain angle of attack to safe pitching moment regions
Crosswind Performance (A, F)	Only the LaCEs saturate during the approach	Resize the ailerons for more lateral control power
	Both the LoCE and LaCE saturate during the landing flare	Relocate engines for more directional control power
		Add undersized rudders
Engine Limit Conditions (C, HS-ETOPS, LM-ETOPS)	Insufficient thrust available for all the maneuvers with the HS-ETOPS pull-up being the most demanding	Use the thrust requirement for the HS-ETOPS pull-up to size the engines
	The LM-ETOPS condition suffers from the same pitch break problems as the stall conditions	Wing redesign or an angle attack limiter is required to curb the pitching moment problem near stall

The results show that a pure pitch & yaw thrust vector controlled commercial transport cannot fly statically stable at design cruise. The demand on the engine to provide thrust and trim the large pitching moment of the wing is too large. A -5% Static Margin (SM) is the optimum for the vehicle. The statically unstable version performs marginally in stall and cross wind conditions. The biggest limitation for the vehicle is cruise with OEI and at max ceiling with all AEO. The engine thrust in these conditions is insufficient for control. There are too many expensive workarounds required to make the pure pitch & yaw thrust vector controlled commercial transport work; however, a partial TVC option with aerodynamic controls would eliminate these problems.

Summary

A feasibility study of a Thrust Vector Control (TVC) commercial transport including a TVC technology review, a parametric sizing study as well as a safety certification assessment is given. The review has various TVC classification schemes and technologies that motivate the discussion. The parametric study show that there are great benefits in aerodynamic efficiency, weight reduction and fuel burn performance which makes the TVC commercial transport worth an investment. However, the safety and certification assessments indicate that a TVC transport with pure pitch yaw thrust controls without a tail is not a safe aircraft. The recommendation from this study is that a combination of TVC and smaller aerodynamic controls devices could provide the revolution in commercial transport performance.

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